FPInnovations

Technical Guide for the Design and Construction of Tall Wood Buildings in Canada

2022 - Second Edition

Edited by
Erol Karacabeyli
Conroy Lum

Special Publication SP-543E

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Front and back covers: Brock Commons building, Vancouver, British Columbia

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ACRONYMS AND INITIALISMS

AAC	Allowable Annual Cut
ACH	air changes per hour
ADA	airtight drywall approach
AECO	architecture, engineering, construction, and owner-operated
AHJ	authority having jurisdiction
AM&M	Alternate Means and Methods
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTC	Apparent Sound Transmission Class
BIM	building information modelling
BRB	buckling restrained braces
BRIC	Build Reversible In Conception
CBF	concentrically braced frames
CCMC	Canadian Construction Materials Centre
CFD	computational fluid dynamics
CLT	cross-laminated timber
CNC	computer numerical control
CSA	Canadian Standards Association
CTBUH	Council on Tall Buildings and Urban Habitat
D4E	Design for the Environment
DfMA	Design for Manufacture and Assembly
DLT	dowel-laminated timber
EBF	eccentrically braced frame
EEEP	equivalent energy elastic-plastic
EMC	equilibrium moisture content
EMTC	encapsulated mass timber construction
EPA	U.S. Environmental Protection Agency
EPD	Environmental Product Declaration
FIIC	Field Impact Insulation Class
FRP	fibre reinforced polymer
FRR	fire-resistance rating
FSC	Forest Stewardship Council
FSR	flame spread rating
FSTC	Field Sound Transmission Class

GC/CM	general contractor/construction manager
GHG	greenhouse gas
GLT	glued-laminated timber
GWP	Global Warming Potential
HVAC	heating, ventilation, and air conditioning
IBC	International Building Code
IIC	Impact Insulation Class
IPD	Integrated Project Delivery
LCA	life cycle assessment
LCC	life cycle costing
LCI	life cycle inventory
LEED	Leadership in Energy and Environmental Design
LLRS	lateral load-resisting systems
LSL	laminated strand lumber
LVL	laminated veneer lumber
MC	moisture content
MDOF	multi-degree-of-freedom
MEP	mechanical, electrical, and plumbing
MPP	mass plywood panel
MSDS	Material Safety Data Sheet
MURB	multi-unit residential building
NAFS	North American Fenestration Standard
NBC	National Building Code of Canada
NECB	National Energy Code for Buildings
NISR	Normalized Impact Sound Rating
NLT	nail-laminated timber
NNIC	Normalized Noise Isolation Class
NRC	National Research Council of Canada
NRCan	Natural Resources Canada
OSB	oriented strand board
OSL	oriented strand lumber
P3	design-build, public-private partnership
PSL	parallel strand lumber
RC	reinforced concrete
RFP	Request for Proposal

RH	relative humidity
RSFJ	Resilient Slip Friction Joint
SCC	Standards Council of Canada
SCL	structural composite lumber
SDOF	single-degree-of-freedom
SFI	Sustainable Forestry Initiative
SFRS	seismic force-resisting systems
SLS	serviceability limit states
SMM	sustainable materials management
STC	Sound Transmission Class
TCC	timber-concrete composite
UBC	University of British Columbia
UFP	U-shaped flexural plate
ULS	ultimate limit states
UNB	University of New Brunswick
VOC	volatile organic compound
WRB	water-resistive barrier
WSS	water-shedding surface

EXECUTIVE SUMMARY

Canada is a forest nation with a strong culture of building with wood. Although heavy timber buildings as high as 9 storeys were constructed in Canada around the turn of the 20th century, that trend came to an end by the 1950s. Advancements in reinforced concrete and steel resulted in designers and builders shifting their attention away from building in timber, which meant there was little or no interest in improving heavy timber products/systems and modernizing building codes with respect to wood construction. Consequently, while advancements continued to be made in the construction and performance of light-wood-frame buildings (such as energy efficiency), it was no longer permissible to build in wood to the heights that were possible up to the mid-20th century.

In the meantime, several drivers have emerged that are influencing building design:

- a greater awareness of the effects and role green construction and buildings can have in reducing our environmental footprint;
- a growing and aging population with evolving housing needs (e.g., affordability and changes to improve accessibility), and urban densification to enable access to more publicly supported services; and
- the advancement in digital technologies, which have led to greater collaboration, access to visualization tools, and more integrated efforts between design, fabrication, and construction.

For those looking for responses to questions frequently asked about mass timber construction, we have inserted notes throughout the guide that briefly touch on a broad range of considerations:

- Marketability/Profitability
- Regulatory Acceptance
- Project Delivery
- Construction Moisture
- Construction Fire
- Building Performance
- Post-Occupancy Moisture
- Post-Occupancy Fire
- Post-Occupancy Damage

Because of these drivers, the commercialization of large cross-section engineered timber products, or “mass timber”, and the ability to build “taller wood” in North American markets is occurring at an opportune time. Wood from sustainably managed forests is the ideal building material, given the need to continuously reduce our carbon footprint while renewing the built environment to provide affordable housing and services. Advances in wood processing, adhesive technology, and timber engineering are making it possible to produce mass timber from a wider range of wood species. Because mass timber panels, beams, and columns can be precisely machined, wood combined with the development of advanced connection systems can now be used in larger and taller structures that are beyond what can be achieved with light-wood-frame construction or even the structures that were built from solid sawn timbers earlier in the 20th century.

This second edition (2022) of the *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada* replaces the first edition (2014), which was developed to support the Natural Resources Canada Tall Wood Building Demonstration Initiative. This multi-disciplinary, peer-reviewed guide has gained national and worldwide recognition as one of the most credible documents that has introduced the terms "mass timber construction" and "hybrid tall wood buildings" (e.g., wood gravity with steel/concrete lateral load-resisting systems) to the design and construction community, and to authorities having jurisdiction.

Since the publication of the first edition of this guide, substantial regulatory changes have been implemented in the 2020 edition of the National Building Code of Canada: the addition of encapsulated mass timber construction up to 12 storeys, and the early adoption of the related provisions by several provinces are the most notable ones. The 2022 edition of this guide brings together, under one cover, the experience gained from recently built tall wood projects, highlights from the most recent building codes and standards, and research findings to help achieve the best environmental, structural, fire, and durability performance of mass timber products and systems, including their health benefits. The approaches to maximizing the benefits of prefabrication and building information modelling, which collectively result in fast, clean, and quiet project delivery, are discussed. Methods for addressing limitations controlled by fire requirements (through an Alternative Solution) or seismic requirements (through a hybrid solution using an Acceptable Solution in steel or concrete) are included. How best to build with mass timber to meet the higher performance requirements of the Energy Step Codes is also discussed. What makes building in wood a positive contribution toward tackling climate change is discussed so that design teams, in collaboration with building owners, can take the steps necessary to meet either regulatory or market requirements.

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Introduction

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ABSTRACT

To support Natural Resources Canada's (NRCan's) Tall Wood Building Demonstration Initiative (2013–2017), FPInnovations, with a group of 80 experts, led the development of the 2014 edition of the *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada*. The guide has gained national and worldwide recognition as one of the most credible documents for helping introduce the terms "mass timber construction" and "hybrid tall wood buildings" to the design and construction community, and to authorities having jurisdiction.

Since the publication of the 2014 edition of this guide, substantial regulatory changes to the National Building Code of Canada have been made, such as the addition of encapsulated mass timber construction up to 12 storeys, and the related provisions have already been adopted by several provinces. Many tall wood buildings have been and are being designed and constructed worldwide. The 2022 edition of the guide brings together, under one cover, experience gained from recently built tall wood projects, highlights from the most recent building codes and standards, and research findings.

Under the guidance of the Steering Committee, which consisted of representatives from NRCan, Forestry Innovation Investment, BC Housing, and the Canadian Wood Council (CWC), a broad group of technical professionals, including architects, engineers, contractors, and experts from universities, the National Research Council, CWC, and FPInnovations, jointly contributed to the 2022 edition of the guide.

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1.1 WHY USE WOOD IN TALL BUILDINGS?

Building tall in wood is not a new phenomenon. Several countries around the world, including Canada, have a history of constructing tall wood buildings out of large sawn or "heavy" timber elements. Heavy timber buildings up to 9 storeys were common in Canadian urban centres approximately 100 years ago (Koo, 2013).

After more than a century of tall concrete and steel buildings being built to support urbanization, we are entering a new era of building—an era where timber and hybrid (timber with steel and/or concrete) structures offer an alternative way of constructing safe, cost-effective buildings with superior environmental properties. "Mass timber", a term introduced in the 2014 edition of this guide (Karacabeyli & Lum, 2014), includes traditional "heavy timber" but now encompasses timber products that are glued or mechanically fastened to form large, solid beam, column, or panel elements (see Appendix 1A - Glossary).

While the Council on Tall Buildings and Urban Habitat (CTBUH, 2017) developed different categories of definitions for "tall buildings" (see Appendix 1B - Definitions), for the purposes of this guide, a "tall wood building" is defined as a wood building[1] with a height of 7 storeys or more, with or without meeting the height requirements for a "high building" as per the National Building Code of Canada (NBC) (NRC, 2020). Most encapsulated mass timber construction ([EMTC] as defined in the NBC) of 7–12 storeys is considered high building. The technical information presented in this guide will benefit designers of such buildings. Furthermore, the information in this guide is also intended to be used in the design of buildings that go beyond the EMTC code limitations and are addressed under the alternative design paths in building codes and bylaws. It should be noted that height and area limits for tall mass timber buildings vary between jurisdictions. For example, the building code in the United States (ICC 2021) has greater height allowances (up to 18 storeys) for mass timber buildings (Think Wood & WoodWorks, 2021).

For those looking for responses to questions frequently asked about mass timber construction, we have inserted notes throughout the guide that briefly touch on a broad range of considerations:

- Marketability/Profitability
- Regulatory Acceptance
- Project Delivery
- Construction Moisture
- Construction Fire
- Building Performance
- Post-Occupancy Moisture
- Post-Occupancy Fire
- Post-Occupancy Damage

Prior to the introduction of EMTC in the NBC, Canada, through the 2013 NRCan Tall Wood Building Demonstration Initiative, made significant progress in the introduction and implementation of mass timber buildings. The state of mass timber-related developments in Canada has been well

[1] Wood buildings have been built predominantly of light-wood-frame construction and, to a much lesser extent, of large, solid, sawn timbers and glued-laminated beams or columns. In Canada, the code limits light-wood-frame construction to 6 storeys.

documented by NRCan (2021b) and in the GCWood Interactive Database (NRCan, 2021a). Users can access projects by different project categories, and a list of manufacturing facilities by province.

A number of mass timber province-specific (B.C., Alberta, Québec, and Ontario) guides are available or are under development, and can support engineers and architects in designing mass timber buildings (see Section 5.1 of Chapter 5 for details). The Government of B.C. (2021) also launched the Tall Wood Initiative in 2020 in support of the adoption of mass timber in the province.

This guide has been updated with considerable input from the design and construction community, Canadian Wood Council (CWC), National Research Council, and universities to align with the 2020 edition of the NBC (NRC, 2020), 2019 edition of CSA Standard O86 (CSA, 2019), and the CWC *Wood Design Manual* (CWC, 2020). The guide continues to be a multi-disciplinary document that encourages cross-disciplinary and interdisciplinary work on developing innovative ways of building with wood to meet the changing demands of the marketplace. The goal is to make innovative ideas that start as Alternate Solutions more competitive and available to the broader design and construction community, and to identify areas for research and standardization so that the innovations can be converted to Acceptable Solutions.

The target audience of this guide is the design and construction communities, including authorities such as building officials and fire services. The guide can also be used as reference material for instructors and students.

The 2022 edition of the guide builds on 12-storey mass timber gravity systems as an Acceptable Solution in the 2020 edition of the NBC (NRC, 2020). Drawing on information from successful projects, this edition of the guide targets supporting Alternative Solutions that will enable wood to be used beyond 12 storeys (such as the Brock Commons Building at the University of British Columbia). By assisting early adopters, it is anticipated that this guide (similar to the first edition) will support future changes to the NBC and the transition to performance-based codes.

With the urgent need to minimize our environmental footprint, building as much as we can with wood has never been as important. This guide demonstrates that, among the many reasons for considering wood as the predominant material for a tall structure, three fundamental ones prevail:

- Wood is a renewable resource, with relatively low embodied carbon, which reduces environmental impacts.
- Wood provides aesthetics and health benefits for building occupants.
- The use of wood allows for fast, clean, and quiet project delivery, which minimizes disruptions to neighbourhoods.

In addition to highlighting these benefits, the guide provides direction to design teams that wish to further enhance these attributes in their mass timber project(s).

Regulatory Acceptance

A complete mass timber building solution is now recognized in the NBC 2020, specifically encapsulated mass timber construction up to 12 storeys. This establishes a new paradigm for building large buildings, which over the last century evolved to be limited to steel or concrete.

1.1.1 Renewable, Low Embodied Carbon, and Carbon Sequestering Alternative for Urban Structures

Globally, the construction and operation of buildings consumes large amounts of natural resources and contributes to greenhouse gas (GHG) emissions. Buildings, and the communities they create, can exert a powerful influence on the health and well-being of people and ecological systems. Construction material design choices can have a significant and immediate effect on the environmental and social impacts of a building project (see Chapter 4 for details).

With a rapidly urbanizing world, it is important that low-carbon solutions are developed and implemented across all scales of building. Wood building systems can help reduce GHG emissions from buildings by using sustainably harvested and renewable wood resources. Stringent forest management regulations and third-party certification programs help ensure that the long-term health of forest ecosystems is maintained for the benefit of all living things, while providing environmental, economic, social, and cultural opportunities for present and future generations.

Marketability/Profitability

Wood construction's positive attributes can now be realized in larger multi-residential and non-residential buildings by building with mass timber. As municipalities devote efforts toward urban renewal with a reduced environmental footprint, there is growing recognition of the benefits of building in wood.

The construction of tall wood buildings is an important strategy cities can use to lower their GHG emissions while providing for the building needs of dense urban populations. Wood is the only construction material that provides GHG benefits in building construction (e.g., embodied carbon). Although wood buildings have traditionally been constructed on smaller scales, new engineered wood products can be reliably supplied in large sizes with consistent quality, which allows taller and larger buildings to be constructed, and thus expands the potential for using renewable materials in larger, urban-scaled buildings (naturally:wood, 2021; Woodworking Network, 2021).

1.1.2 Aesthetics and Health Benefits

Aesthetics and occupant comfort are desirable and marketable attributes of a building. The use of wood to promote health indoors is a new tool for practitioners of evidence-based design. The presence of wood in the built environment can provide myriad stress-related health benefits (Lowe, 2020). As with any building, design teams for tall wood buildings should consider and address human health, well-being, and comfort. The topics of indoor air quality and occupant well-being are covered in Chapter 4: Sustainability, while the topics of acoustic (noise control) and thermal comfort are covered in Chapter 5, Section 5.4: Building Sound Insulation and Floor Vibration Control, and Chapter 7: Building Enclosure Design, respectively.

In many cases, owners and/or developers would like to see exposed mass timber elements or natural wood surfaces. The project team will need to make a fundamental choice about the aesthetic ambition of the wood building structure; Chapter 2 includes information pertaining to different options for wood structures (exposed, partially exposed, and concealed). Chapter 6: Fire Safety and Protection contains information on techniques for increasing the amount of exposed wood beyond the NBC prescribed limits based on compartment test results and computer modelling.

1.1.3 Fast, Clean, Quiet Project Delivery

Unlike traditional sawn timbers used in buildings more than 100 years ago, the consistent size and quality of engineered mass timber makes it suitable for prefabrication. The ease of which components can then be precisely machined and replicated means that the use of digital tools during the planning, design, fabrication, and construction phases will not only make innovative designs possible, but also help ensure a successful build. In addition to speed and certainty of construction, the use of prefabricated mass timber construction can result in a cleaner and quieter construction site.

As mass timber construction moves beyond the "early adopters" and as more suppliers come on stream, mass timber is expected to be a material to be considered alongside steel and concrete for large and tall buildings. As discussed in Chapter 8, building information modelling (BIM) will play a greater role in the design and construction of the built environment, and how sustainable wood products will be specified as the sector advances from BIM 3D/4D (which address building geometry and scheduling) to BIM 5D/6D (building cost, and sustainability and energy).

Project Delivery

Integrated Project Delivery is very complementary to mass timber construction. There will be an upfront cost when designers involve trades, suppliers, and contractors in preconstruction. However, virtual tools can be used to support effective collaboration and improve the early constructability of the design, which will result in improved worker productivity and fewer change orders.

1.2 PROGRESS SINCE THE FIRST EDITION

The first edition of the guide (Karacabeyli & Lum, 2014) helped focus the efforts of the early adopters who participated in NRCan's Tall Wood Building Demonstration Initiative. Much experience has been gained from tall wood buildings that have been constructed since the first edition. The Natural Sciences and Engineering Research Council of Canada Strategic Network on Innovative Wood Products and Building Systems (NEWBuildS)—which was coordinated by FPInnovations, the National Research Council of Canada, and the Canadian Wood Council, and involved 11 Canadian universities—was also brought to a successful completion. A number of research projects under NEWBuildS contributed new knowledge (e.g., modelling) about tall wood buildings. Some graduates who worked under the NEWBuildS initiative are now helping expand the pool of early adopters and researchers in mass timber construction. Updating and aligning the guide with the 2020 edition of the National Building Code (NRC, 2020) and the latest Canadian wood design standard CSA O86-19: Engineering Design in Wood (CSA, 2019), and sharing the experiences gained from tall wood buildings constructed since the first edition, will not only continue to expand the community of experts, but also help mainstream adoption of mass timber and hybrid wood buildings.

With this update, the guide continues to play a key role in advancing the acceptance of tall wood buildings and other transformative applications by designers, authorities having jurisdiction, inspectors, and contractors. The goals are to support:

- the federal and provincial governments' goals of achieving economic growth under a net-zero carbon economy through the greater use of wood products; and
- the transition to performance-based building and energy codes that should enable wood building projects to play a more prominent role in meeting economic, social, and environmental objectives.

Building Performance

Through the support of government and industry, early adopters (developers, designers, builders, and producers) of new mass timber technologies successfully completed and brought to market a range of mass timber buildings. This generated a wealth of experience prior to formal recognition in the National Building Code.

The recently updated *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019) and *Design Guide for Timber–Concrete Composite Floors in Canada* (Cuerrier-Auclair, 2020) are complementary publications to this guide. Users are encouraged to download these publications.

While society moves to placing greater emphasis on reducing environmental impacts and encouraging design that maximizes health benefits for occupants, cost and value continue to be foremost in the minds of those deciding whether or not to pursue a tall wood building. To address this, the 2022 edition of the guide includes two completely renewed chapters: Chapters 3 and 8. Chapter 3: Cost and Value focuses on how to develop the cost and value proposition for building in mass timber. The approach is meant to be complementary to the costing by a quantity surveyor but focuses on the less tangible considerations that might influence an assessment of project risk. Chapter 8: Project Execution: Design, Prefabrication, and Construction Considerations focuses on how to plan, manage, and execute a mass timber project so that it is successful; that is, what steps can be taken during the execution to reduce uncertainty.

1.3 ORGANIZATION OF THE GUIDE

The guide is not specific to any one structural solution. Rather, it establishes the parameters and resources necessary for a capable team to design a tall wood building that meets the performance requirements of current building codes and the competitive building marketplace.

The guide is not an answer key with specific details and solutions; instead, it is organized to provide the broad information and concepts that design teams will need to consider, address, and further develop within projects that are specific to local jurisdictions, functional requirements, and site and regional contexts. As such, there are three pervasive discussions throughout the guide:

- wood structures—a sustainable, practical, safe, and realistic choice for tall buildings
- the tall wood building, its structure, and its systems

- metrics to consider for a successful project

The chapters of this multi-disciplinary guide are summarized below and illustrated in Figure 1.

Following this Introduction, Chapter 2: The Building as a System deals with the integration of all building systems, and presents principles and potential solutions to help designers, owners, and construction teams navigate through this integration process. It also includes a discussion on code compliance and describes Acceptable and Alternative Solutions under the objective-based code format. Appendix 2 in this chapter contains a brief discussion on the future transition from objective-based codes to performance-based codes in Canada.

Chapter 3: Cost and Value provides an overview of the often-unrecognized value propositions that tall wood buildings present. There is a tendency to focus on the bottom-line construction budget at an early stage, when other positive attributes, such as reduced schedule due to prefabrication, psychological and productivity benefits for occupants, and greater site selection (e.g., softer soils) due to lighter overall building weight, have not been fully explored and incorporated into the overall project financial model. Rather than adjusting the cost to cover uncertainties, the steps that can be taken during the planning and costing phase to reduce the risk for a tall wood project and prepare for unexpected events are discussed.

Chapter 4: Sustainability provides design teams with the guidance needed to arrive at a thoughtful balance between material use and environmental/human health performance within the context of their particular project. The chapter highlights the environmental and human health benefits of building in wood, and what choices the design and construction teams can make to take advantage of or maximize these benefits. Special emphasis is placed on life cycle assessment methodology as the primary means of quantifying the benefits of using wood, followed by a discussion on the various green building certification systems and other tools for evaluating and certifying the sustainability of tall wood building systems.

Chapter 5: Structural and Serviceability has four sections that provide conceptual and specific technical guidance for the structural and serviceability (e.g., sound insulation, and floor vibration control) design of tall wood structural systems according to, and beyond the scope of, the current Canadian codes and material standards. The four sections detail how a structural Alternative Solution can be developed for a tall wood building. This chapter also covers important and unique aspects of wood design compared to other materials, and it reviews ways in which mid- and high-rise wood design differs from low-rise design. A discussion on performance-based structural design is also included.

Chapter 6: Fire Safety and Protection addresses Acceptable Solutions in the National Building Code (NRC, 2020) for mass timber in tall wood buildings. It provides guidelines for developing an Alternative Solution, thereby demonstrating that a tall mass timber building can meet—or even surpass—the level of fire performance currently stipulated in the NBC's

Construction Fire

In order to demonstrate the safety of mass timber construction, a very formal, strict approach was taken to address construction fire risk. Much experience on practical and effective measures has been gained, including recognition that mass timber components and the approach to construction reduces fire risk.

Acceptable Solutions for tall buildings of noncombustible construction. The recently added encapsulated mass timber construction Acceptable Solution is discussed along with considerations for increasing the amount of exposed wood. The potential for using enhanced fire protection systems, including enhanced sprinkler systems and smoke control systems, to compensate for the additional risk of exposed timber is also explored. A discussion on performance-based fire protection design is also included.

Chapter 7: Building Enclosure Design summarizes key building enclosure design considerations, particularly the aspects of design that differ for tall wood buildings within the various climate zones of Canada. The chapter takes the reader from an understanding of the key building enclosure loads, building and energy-related code requirements (National Energy Code of Canada for Buildings, and American Society of Heating, Refrigerating and Air-Conditioning Engineers), through a summary of the fundamentals of building enclosure design, building enclosure assemblies, and detailing strategies. It concludes with a discussion on wood protection and durability, including on-site moisture management and use of wood for exterior applications. Considerations for ensuring durable wood design when meeting the high airtight requirements of the BC Energy Step Code are discussed.

Construction Moisture

Effective construction moisture risk management starts with understanding what happens when mass timber is exposed to moisture, and the aim of corrective actions. This is discussed in Chapter 7. A construction moisture mitigation plan for the project can be then prepared and shared with the team so that responses are effective.

Chapter 8: Project Execution: Design, Prefabrication, and Construction Considerations covers aspects of a tall wood construction project after there is agreement to proceed. The focus is on how to monitor and execute the project so that it is brought to a successful completion. Consideration is given on how to take advantage of prefabrication in order to reduce the labour and schedule risks that occur on many mid- and high-rise projects, while also mitigating the challenges associated with maintaining quality and safety. Recognizing that the full benefit of mass timber's advantages requires a change in some conventional design and procurement methods, the chapter notes the benefits of using BIM as a tool for team member integration, and indicates that even a partial adoption of BIM concepts will have a positive effect on the project.

Chapter 9: Monitoring and Maintenance includes recommendations for performance testing and monitoring of a tall wood building, and provides guidance on building maintenance and repair to help building owners avoid unexpected high repair and replacement costs during operation.

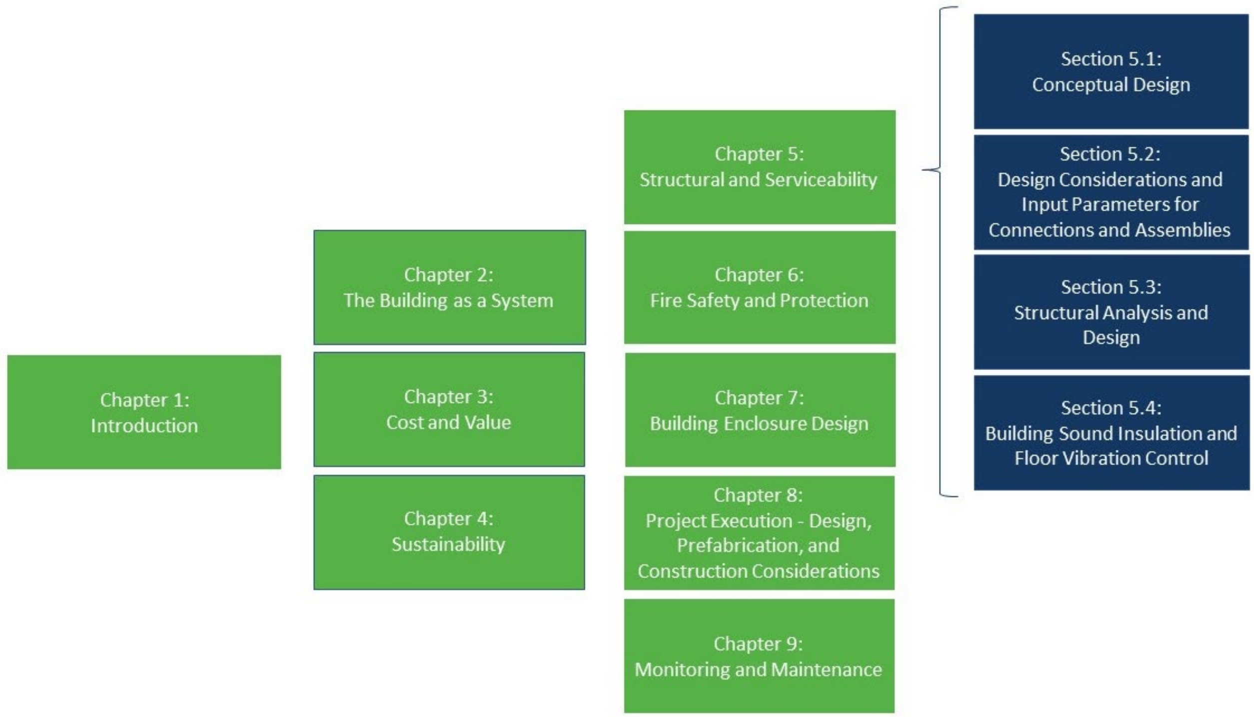


Figure 1. **Layout of the *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada*.**

1.4 TALL WOOD BUILDINGS TO DATE

Building tall in wood is not a new phenomenon. In fact, tall wood buildings have existed for centuries, and have reached as high as 67 m (220 ft.). Tall wood pagodas 19 storeys high were built in Japan 1400 years ago and are still standing today in high seismic hazard zones and wet climate environments. In the Maramures region of northern Transylvania, the 56-m (184-ft.) Barsana Monastery has been standing since 1720. Moreover, several countries around the world, including Canada, have a history of using heavy timber elements to construct tall wood buildings that have reached up to 9 storeys. These buildings have been standing for approximately 100 years (Koo, 2013).

At the beginning of 21st century, a number of modern tall wood buildings had been built worldwide. In 2008, Waugh Thistleton's Stadthaus project in London (Figure 2) was the impetus for continued innovation in "all-wood" building solutions. This 9-storey residential building used cross-laminated timber (CLT), a mass timber product that emerged in Europe in the late 20th century, for its structure above grade. The all-wood structural system consisting of CLT walls and floors used in this building has been adopted in many other buildings in the UK and other places in the world. Other buildings have used a "wood hybrid" approach, such as the 8-storey LifeCycle Tower ONE by CREE (Figure 3), located in Dornbirn, Austria. Additional projects in the 7- to 10-storey range have been completed in Sweden, Australia, Norway, Switzerland, France, Italy, and New Zealand (see Chapter 2 and Section 5.1 of Chapter 5 for more information about these buildings).

In Canada, in addition to 5- to 6-storey light-wood-frame buildings, which have gained popularity since their recognition by building codes nationally (more than 650 buildings built or under design/construction as of 2020), some notable mass timber buildings have been constructed. The Wood Design and Innovation Centre in Prince George, B.C. demonstrated an all-wood approach, using CLT, laminated strand lumber, laminated veneer lumber, and parallel strand lumber in innovative ways (Green & Taggart, 2017). This academic/office building reached 6 storeys and 30 m in height (Figure 4). A 4- and 6-storey residential complex in Québec City, built out of CLT, was the first of its kind in North America. More recent examples[2] include the Brock Commons building in Vancouver, B.C., the Origine building in Québec City, Que., and the Arbora building complex in Montréal, Que. Given the noteworthy number of mass timber structures that have been completed or are in the process of completion, a database was created so that details about these buildings can be shared (NRCan, 2021b). The introduction of EMTC in the National Building Code (NRC, 2020) is anticipated to further increase the uptake of mass timber buildings.

Internationally, mass timber-braced frames were used as the lateral systems in two tall building projects in Norway (14-storey Treet in Bergen [Figure 5], and 18-storey [85.4 m] Mjøstårnet in Brumunddal [Figure 5]). Conversely, some recently constructed tall wood buildings in Canada used a variety of lateral systems (Figure 6). A concrete core was used as the lateral system in the 24-storey (84 m) HoHo building in Vienna, Austria (Figure 7). These projects are discussed in greater detail in Chapter 2 and Section 5.1 of Chapter 5. CTBUH's (2017) *Tall Building in Numbers. Tall Timber: A Global Audit* provides a summary of timber towers built, under construction, and proposed. A manual on multi-storey timber construction in Germany includes 22 case studies, with emphasis on design, planning, prefabrication, and assembly (Kauffmann et al., 2018). The construction of the Sara Cultural Centre in Skellefteå, Sweden was begun in 2021. The building's concept is described in a video, *Sara Cultural Centre – One of the Tallest Wooden Buildings in the World* (Swedish Institute and Architects Sweden, 2020). The Centre was designed to house a 20-storey hotel and provide venues for the arts, performance, and literature. The building is constructed of premanufactured modules in cross-laminated timber (CLT), stacked between two elevator cores. Two mass timber towers 100 m in height (as high as the tallest trees in the world)—a wind turbine in Hanover, Germany (Figure 8), and Pyramidenkogel, a lookout tower in Austria (Figure 9)— provide insight into how high we can build with wood.

[2] The Brock Commons and Origine buildings were supported by NRCan's Tall Wood Building Demonstration Initiative.

Figure 2. Stadthaus, London, UK (courtesy of Waugh Thistleton Architects).

Figure 3. LifeCycle Tower ONE, Dornbirn, Austria (courtesy of CREE).

Figure 4. Wood Innovation Design Centre, Prince George, B.C. (courtesy of MGA | Michael Green Architecture).

Braced mass timber lateral system
Treet, Bergen, Norway
(14 storey)

Braced mass timber lateral system
Mjøstårnet, Brumunddal, Norway
(18 storey)

Figure 5. Braced mass timber lateral systems in Norway.

Brock Commons, Vancouver B.C.
(18 storey)
Gravity system is mass timber, lateral system is concrete core

Origine, Québec City, Que.
(13 storey)
Gravity system is mass timber; lateral system is also mass timber (CLT shear walls)

Tallwood 1 Building, Langford, B.C.
(12 storey)
Gravity system is mass timber (under permit process); lateral system is eccentric steel-braced frame

Arbora Building Complex, Montréal, Que.
(3 × 8 storey buildings)
Gravity system is mass timber; lateral system is also mass timber (CLT shear walls)

Figure 6. Tall wood buildings in Canada.

HoHo, Vienna, Austria
(24 storey)
Gravity system is mass timber; lateral system is concrete core

Figure 7. HoHo building.

Figure 8. Wind turbine, Hanover, Germany (courtesy of TimberTower GMBH).

Figure 9. Pyramidenkogel, Austria.

1.5 REFERENCES

Canadian Standards Association (CSA). (2019). *CSA O86-19: Engineering design in wood*. Mississauga, ON: Author.

Canadian Wood Council (CWC). (2020). *Wood design manual*. Ottawa, ON: Author. https://webstore.cwc.ca/product/wood-design-manual-2020/

Council on Tall Buildings and Urban Habitat (CTBUH). 2017. Tall building in numbers. Tall timber: A global audit. *CTBUH Journal*, 11, 47-49. https://global.ctbuh.org/resources/papers/3350-TBIN.pdf

Cuerrier-Auclair, S. (2020). *Design guide for timber-concrete composite floors in Canada*. Pointe-Claire, QC,: FPInnovations. https://library.fpinnovations.ca/en/permalink/fpipub52903

Government of British Columbia. (2021). *Tall wood initiative.* Victoria, BC: Author. https://www2.gov.bc.ca/gov/content/industry/construction-industry/building-codes-standards/other-regulations/tall-wood-buildings-initiative

Green, M., & Taggart, J. (2017). *Tall wood buildings: design, construction and performance.* Basel, Switzerland: Birkhauser.

International Code Council (ICC). (2021). *International Building Code*. Country Club Hills, IL: Author.

Karacabeyli, E., & Gagnon, S. (Eds.) (2019). *Canadian CLT handbook, 2019 edition*. (Special Publication SP-532E). Pointe-Claire, QC: FPInnovations. https://web.fpinnovations.ca/clt/

Karacabeyli, E., & Lum, C. (Eds.) (2014). *Technical guide for the design and construction of tall wood buildings in Canada* (1st ed.). (Special Publication SP-55E). Pointe-Claire, QC: FPInnovations.

Kaufmann, H., Krötsch, S., & Winter, S. (2018). *Manual of multi-storey timber construction* (English translation of the 1st German edition). Munich, Germany: Detail Business Information GmbH.

Koo, K. (2013). *A study on historical tall-wood buildings in Toronto and Vancouver.* Pointe-Claire, QC: FPInnovations.

Lowe, G. (2020). *Wood, well-being and performance: The human and organizational benefits of wood buildings*. Forestry Innovation Investment.

National Research Council of Canada (NRC). (2020). *National Building Code of Canada*. Ottawa, ON: Author.

Natural Resources Canada (NRCan). (2021a). *Mass timber construction in Canada.* https://www.nrcan.gc.ca/our-natural-resources/forests/industry-and-trade/forest-products-applications/mass-timber-construction-canada/23428

Natural Resources Canada (NRCan). (2021b). *The state of mass timber in Canada 2021*. Ottawa, ON: Canadian Forest Service.

naturally:wood. (2021). *Thermal performance.* https://www.naturallywood.com/wood-performance/thermal/

Swedish Institute and Architects Sweden [Sweden]. (2020, May 11). *Sara Cultural Centre – one of the tallest wooden buildings in the world* [Video]. YouTube. https://www.youtube.com/watch?v=bQZYZrJBeG0

Think Wood & WoodWorks. (2021). *Mass timber design manual*. U.S. edition.

Woodworking Network. (2021, April). *B.C. doles out $4.2M for mass timber demo and research projects.* https://www.woodworkingnetwork.com/news/canadian-news/bc-doles-out-42m-mass-timber-demo-and-research-projects

APPENDIX 1A – GLOSSARY

Mass timber elements may consist of any number of large cross-section timber products, such as solid-sawn timber (heavy timber), glued-laminated timber (glulam), cross-laminated timber, nail-laminated timber, dowel-laminated timber, mass plywood panel, and structural composite lumber. Refer to the products below and Section 5.1 in Chapter 5 for examples of mass timber products.

Glue-laminated timber (GLT) or glulam: composed of individual wood laminations (dimension lumber) that are selected and positioned based on their performance characteristics, and then bonded together with moisture-resistant adhesives; the grain of all laminations runs parallel to the length of the member. Glulam is typically used as beams and columns; however, it can be used for floor or roof decking, and is available in a range of appearance grades for both structural and architectural applications.

Cross-laminated timber (CLT): dimension lumber (typically three, five, seven, or customized layers) oriented at right angles to one another and then glued (with heat-resistant glue) to form structural panels. CLT is well suited to floors, walls, and roofs, and can be used alone, with other wood products, or in hybrid or composite applications. CLT offers exceptional strength, dimensional stability, and rigidity, and can be used in multi-storey and large building applications.

Nail-laminated timber (NLT): individual dimension lumber, stacked on edge, and fastened using nails into a single structural element. Applications for NLT include flooring, decking, roofing, and walls.

Dowel-laminated timber (DLT): common in Europe and is gaining traction in North America. DLT is similar to NLT. Instead of nails or screws, DLT uses wood dowels to join laminations. In application, DLT performs similarly to glulam and NLT. Because its grain runs in one direction, DLT is well suited to flooring and roofing applications.

Mass plywood panel (MPP): consists of several layers of wood veneer that are glued and pressed together to create a large-format wood panel. Applications are similar to those for CLT, and MPP can be used in multi-storey and large building applications.

Examples of structural composite lumber (SCL) products

Laminated veneer lumber (LVL): a type of SCL that is made by layering dried and graded wood veneers with moisture-resistant adhesive into billets, which are then re-sawn into specific sizes. It is often used in applications such as headers, beams, rails, rim boards, and edge-forming material. It can be also used for walls, floor or roof decking.

Laminated strand lumber (LSL): a type of SCL that is made from soft wood or wood strands that are pressure-bonded together using a water-resistant adhesive and then manufactured into consistent shapes that offer strength and stiffness. LSL is commonly used for walls, floors, support beams, door cores, and sill plates.

Oriented strand lumber (OSL): similar to LSL, OSL is made from flaked wood strands that are shorter than those in LSL. Combined with an adhesive, the strands are oriented and formed into a large mat or billet and then pressed. OSL resembles oriented strand board (OSB) in appearance because both are fabricated from similar wood species and contain flaked wood strands; however, unlike OSB, the strands in OSL are arranged parallel to the longitudinal axis of the member.

Parallel strand lumber (PSL): a type of SCL that is made from flaked wood strands that are longer than those used to create LSL; these strands are then formed into a large billet using a waterproof adhesive and are afterward cured to create a uniform, engineered wood. PSL can be used in headers, beams, columns, and lintels.

Heavy timber: a term used for solid sawn timber.

Timber–concrete composites (TCC): a hybrid system in which timber and concrete are structurally connected. Connectors can be bespoke, proprietary, or created by drilling screws between the timber and concrete. TCC can be used for floor panels to reduce cross-sections or to increase spans.

APPENDIX 1B – DEFINITIONS

Tall Wood Buildings

The Council on Tall Buildings and Urban Habitat (CTBUH, 2017) developed standards for measuring and defining "tall buildings". CTBUH does not have an absolute definition of what constitutes a tall building because the definition would be subjective due to factors such as (a) location (e.g., a 10-storey building in a small town may be the tallest building in that location but may be considered a short building in the downtown of a large city), and (b) overall aspect ratio (i.e., a slender building may seem taller than a large-footprint building of the same height). As discussed below and in Section 5.1 of Chapter 5, heavy timber buildings up to 9 storeys were common in Canadian urban centres approximately 100 years ago (Koo, 2013). For the purposes of this guide, a "tall wood building" is defined as a wood building with a height of 7 storeys or more.

Acceptable and Alternative Solutions

According to the National Building Code (NRC, 2020):

- A building or part of a building is permitted to be of encapsulated mass timber construction (EMTC) that contains structural mass timber elements, including beams, columns, and arches, and wall, floor, and roof assemblies, provided they comply with the size and other requirements of the code.
    - Gravity systems in EMTC may be composed of mass timber systems (e.g., columns, walls, beams, and slabs) for residential and office buildings up to 12 storeys.
        - Maximum allowable height for a gravity system of EMTC: the uppermost floor level may be a maximum of 42 m (137 ft.) above the first floor.
    - Lateral systems of a mass timber building may be composed of CLT shear walls up to 10 storeys in low to moderate seismic hazard zones (6 storeys in high seismic hazard zones).

Buildings that are beyond the boundaries of Acceptable Solutions can be designed by following the **Alternative Solutions** path in the building code (see Section 2.5: Building Code Compliance in Chapter 2 for further information).

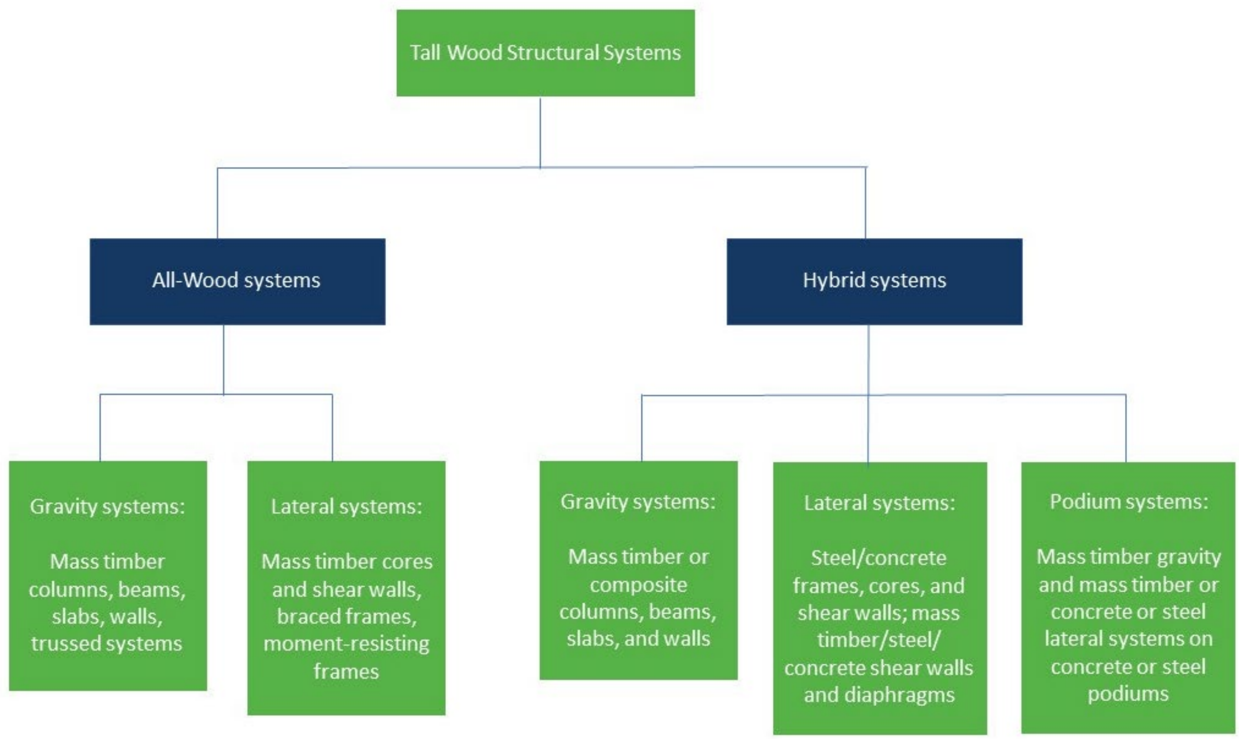
Gravity and Lateral Systems

Building codes and regulations prescribe a variety of building height and area limitations for wood buildings depending on primarily use categories, fire protection requirements, and seismic hazard zones. The structure of a building can be considered to be composed of gravity and lateral systems (in some cases, one system serves both purposes):

- **Gravity system**: designed to resist vertical loads due mainly to self-weight, occupancy, and snow loads.
- **Lateral system**: designed to resist lateral loads mainly from wind and seismic loads.

All-Wood and Hybrid Systems

In the context of this guide, all-wood systems are defined as both gravity and lateral systems that are composed of wood components. Hybrid systems are defined as having gravity and/or lateral systems that are composed of wood, steel, and/or concrete components.



APPENDIX 2 – FUTURE TRANSITION FROM OBJECTIVE-BASED DESIGN CODE TO PERFORMANCE-BASED CODE

Having a material agnostic performance-based building code would facilitate innovation and establish a level playing field among the various construction materials. The Canadian regulatory system took the first step towards achieving this goal by adopting an objective-based format in the 2005 Edition of NBC (NRC, 2005). Although this was seen as a first step towards a more performance-based building code, there has been little movement since then. Currently, the code provides two paths for regulatory acceptance: Acceptable Solutions in Division B and Alternative Solutions that have to be approved by the Authority Having Jurisdiction (AHJ).

Objective based codes define (mostly qualitative) objectives that are linked to acceptable solutions, whereas performance-based codes specify target design performance criteria.

Acceptable Solutions are developed by code committees through a consensus process. These are either acceptable methods of construction or acceptable methods of analysis with accompanying limits (i.e., building height, building area, material properties, material type). They are also jurisdiction specific. For example, a mass timber gravity system according to NBC (NRC, 2020) can be designed as an Acceptable Solution up to 12 storeys in Canada whereas that limit is 18 storeys in the USA (ICC, 2021). Designs of most building systems are carried out by following the Acceptable Solutions path because they are considered “tested and tried solutions”.

While the current NBC does permit Alternative Solutions, which can deviate from the Acceptable Solutions, it must still meet the specified objectives and functional statements for the provision that is being replaced. The Alternative Solutions path provides the designer the flexibility to come up with a code-compliant solution for a new building system, but it requires more effort and resources to demonstrate “equivalent” performance to an Acceptable Solution in the areas identified by the objectives and functional statements. Alternative Solutions are project-specific, meaning acceptance of an Alternative Solution on one project does not warrant acceptance on another project even though the projects may appear to be very similar and located in the same geographical area.

Changes in code provisions for Acceptable Solutions may or may not be easily translated into explicit/measurable performance levels; they may simply be, for example, based on the judgement of the committee based on what is considered good design or construction practice. Rationalizing the existing requirements and converting the implicit level of performance from a time-proven practice into explicit performance criteria that can be confidently applied to any new system, is a critical and challenging step towards performance-based codes. If the resulting performance criteria require extensive review and analysis to apply, it will require a greater commitment of resources.

Several countries, such as Australia, New Zealand, Switzerland and the Netherlands have adopted performance-based provisions in their building codes, whereas United States have introduced a standalone performance-based code in addition to its existing building code (Osborne, 2015; Dagenais, 2016). Code changes in these countries have led to increased opportunities for innovation in design, design efficiency induced cost reductions, and greater ease of international trade.

One possible format to make the transition to performance-based codes in Canada may be to introduce a performance-based path within the Acceptable Solutions path in Division B of the code (Osborne, 2015; Senez Consulting Ltd., 2020). Many early adopters in the design and construction community have already developed and possess the performance-based design tools and if the performance criteria are defined in the code, they will be able to use that new path. The existing Acceptable Solutions could remain as yet an optional compliance path for designers who are more comfortable in the design and construction of conventional buildings.

While it will be challenging to implement quickly significant performance-based changes to the NBC, the existing objective-based code foundation will facilitate the transition as well as several provisions in the current NBC are already performance based. There is a wealth of existing research in Canada and internationally that can be capitalized on to assist in this process.

References

Dagenais, C. (2016). *Development of performance criteria for wood-based building systems.* Pointe-Claire, QC: FPInnovations.

International Code Council (ICC). (2021). *International Building Code.* Country Club Hills, IL: Author.

National Research Council of Canada (NRC). (2005). *National Building Code of Canada*. Ottawa, ON: Author.

National Research Council of Canada (NRC). (2020). *National Building Code of Canada*. Ottawa, ON: Author.

Osborne, L. (2015). *Performance-based fire design and the National Building Code of Canada.* Pointe-Claire, QC: FPInnovations.

Senez Consulting. (2020). *Code change request development of a performance-based compliance path to existing Division B Acceptable Solution.* Delta, BC: Author.

The Building as a System

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ABSTRACT

The design of a tall wood building requires a much broader perspective than simply the development of a structural approach. Design teams must consider the integration of all building systems, the building envelope and performance detailing, as well as architectural form, function, and flexibility, from the very outset of the design process. This chapter addresses these aspects of tall wood buildings and presents principles and potential solutions to help designers, owners, and construction teams navigate through this integration process.

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2.1 ARCHITECTURE AND STRUCTURE

The design of a larger or higher building than one traditionally constructed of wood requires a much broader perspective than a mere shift in structural approach. To benefit from building in wood, the structure and overall design must consider the integration of all building systems, the building envelope, performance detailing, and naturally, the architectural form, function, and flexibility from the very outset of the design process. No component of the building can or should be developed without consideration of the next, and if not coordinated properly, any one of the building's components may tip the design solution out of balance with respect to cost, constructability, performance, or even market acceptance. While the building as a system may be a very broad discussion topic, it is the intent of this guide to provide a catalogue of considerations and possible solutions to help designers, owners, and construction teams navigate through the process. The focus is on "how best can this be done in wood".

While it is useful to define “tall wood” in terms of the number of storeys or the building height (something that the design and construction community can relate to), it is more fitting to describe it as aiming at building heights and areas beyond what building codes have traditionally allowed as acceptable, which was the original aim of Natural Resources Canada’s Tall Wood Building Demonstration Initiative, started in 2013. With this in mind, each of the following broad considerations should be taken into account in design and construction so that a fully integrated “tall wood” structure can be achieved, not a structure that is simply large or tall:

> **Project Delivery**
>
> Using digital tools, builders can visualize installing the building, evaluate how the lifting process works, remove potential for conflicts, and optimize the sequence. These are some of the benefits of Design for Manufacturing and Assembly (DfMA).

- Selecting a full consultant team with broad experience in systems-integrated wood design solutions, and in the development and presentation of Alternative Solutions to the authority having jurisdiction (AHJ);
- Selecting or developing a wood or wood-hybrid structural system appropriate to:
  - the building’s architecture, including its:
    - function and program (Section 2.1.1.1)
    - intended building form and massing
    - region, context, architectural style, and vision
    - market and client ambitions
    - flexibility goals for design and post construction
    - site requirements
    - geotechnical conditions
  - the building's performance expectations and goals, including:
    - building code compliance
    - structural performance (Chapter 5)
    - resilience (e.g., seismic resilience; see Section 5.3.5.2 of Chapter 5)

    - fire protection (Chapter 6)
    - sound insulation/acoustics (Section 5.4 of Chapter 5)
    - vibration mitigation (Section 5.4 of Chapter 5)
    - thermal performance (Chapter 7)
    - cost competitiveness (Chapter 3)
    - constructability (Chapter 8)
    - human health and well-being (Chapter 4)
    - sustainability and Green Building goals (Chapter 4)
- Integrating building services (concealed or visible) into the structural and architectural design:
    - mechanical
    - electrical
    - plumbing
    - fire suppression
    - IT and other communication systems
- Delivering efficient, constructible, and cost-effective solutions

Many of these considerations are addressed in this guide. This chapter provides an overview of potential conceptual approaches to constructing tall wood buildings that will enable effective integration of building systems. At the outset of the design process, a number of decisions will need to be made to set the project direction, including selecting a structural and systems integration approach.

2.1.1 Selecting a Structural Approach

There are three strategies for developing the structure of a tall wood building:

1. Start with a structural system as the driver of the building's design and let the architecture work to that system:

   When selecting a relatively prescriptive structural solution, the building's architecture will have a set of clear defining parameters to work toward, from the outset, that will dictate the optimal structural bay spacing, building massing, and building envelope solutions for that structural system. While deviations are possible, the system itself may create clear rules for the architectural language of the building.

2. Start with an architectural strategy and then apply a structural approach:

   For example, the architect generates a building form, plan, and massing to which the structural engineer adapts a structural system or approach. This may provide the most flexibility for the architectural design but may also generate higher costs, system inefficiencies, and engineering challenges.

3. A hybrid of Options 1 and 2:

   Most owners and design teams will want to select a hybrid of options 1 and 2 and keep an open mind about the appropriateness of any structural approach until the full parameters of the project are established. A back-and-forth exercise between the architecture and structure provides an understanding of the diverse range of potential structural solutions, which helps teams determine the optimal solution for each unique project.

In all these strategies, it is critical that a mass timber product supplier, along with their manufacturing and delivery capabilities, be identified early. Defining the structural performance requirements, including addressing the following items, early in the design process will ultimately help design teams select and refine the best structural approach for their project:

1. Establish the required and/or optimum structural bay spacing and beam depths (if beams are employed). Consider floor panel sizes and suppliers.
2. Establish the floor-to-floor height and "slab" depth, with services integrated and acoustic/fire assemblies considered.
3. Establish the floor and ceiling assembly strategy for strength, building code (particularly fire safety requirements), acoustic performance, and building service integration.
4. Develop a lateral load-resisting approach:
   - Establish the seismic performance requirement for building use and function;
   - Select the suitable system (shear walls, brace frames, etc.) and material (wood, concrete, steel) by evaluating their effectiveness (floor plate layout, flexibility, cost, etc.);
   - Establish layout of the lateral system and the design of the building core(s); and
   - Coordinate these major structural elements with the building plan and architecture.
5. Establish performance expectations for vibration in the structure and its implications on the use of the building as well as code performance.
6. Consider maximizing prefabrication of the system to reduce cost and improve effectiveness of construction delivery.
7. Review design solutions relative to the various performance criteria.

It would be advantageous to understand what approaches are being developed to address the various performance attributes of wood systems. One of the objectives of this guide is to provide background information in this regard.

2.1.1.1 Building Program Considerations

Selecting a structural typology that is suitable for the building's intended use is essential. The unique structural qualities of a wood structure may dictate ideal column spacing and beam depths, for instance, which will drive the height and potentially planning flexibility of the building's overall design. Opportunities for locating continuous, well-proportioned, and well-distributed lateral load-resisting elements will be dictated largely by building use, much in the same way as they are with other materials.

The selection of a structural system with a lateral bracing strategy that is flexible for the intended use is also important. Internal shear walls or bracing may interfere with planning flexibility and are likely to dictate the lateral strategies for the end use, whether office, institutional, academic, or residential. In other words, while the core of a tall wood building is likely to be a major lateral load-resisting element, it clearly needs to be integral on all levels to perform. The addition of other internal shear walls may be problematic for the program. In those instances, other lateral load-resisting systems, including exterior wall systems or moment frames, may be better choices.

As is true in tall buildings of any structure, columns are ideally continuous vertically through the building and into below-grade parking, etc. Some mixed-use building programs may require changing bay sizes to accommodate larger spaces without column obstructions. While it is possible to transfer columns in wood structures, this can become an expensive and challenging issue for maintaining a cost-effective solution. Where possible, longer span spaces should be located on the top levels of the building instead of on the lower levels, or located adjacent to the tower itself in order to optimize the vertical loads.

Project teams should consider the following spatial requirements and their implications, as applicable to their specific project:

- spaces requiring long spans;
- wall-free spaces (limited by internal shear walls, for instance);
- the ability to renovate and move internal program elements (limited with internal shear walls);
- podiums and lobbies with transfer column requirements to encourage longer span program functions;
- spaces with high-performance acoustic demands;
- spaces with higher fire risk; and
- parking garages and foundations.

The use of wood, in general, for some building uses and some applications may be challenging as well in the following situations, though not necessarily impossible depending on the circumstances:

- extremely wet conditions and high humidity locations (though not always—wood is often a good choice for the structure of swimming pools, for example);
- programs/spaces/proximities with unusually high risk for fire that is dictated by fire codes and permitted occupancy;
- programs that require unique clean and sterile room conditions (e.g., some hospital spaces, labs); and
- exterior applications in areas at high risk for vandalism, abuse, damage, and/or infestation, and in areas with weather exposure and exterior fire protection requirements.

2.1.1.2 Planning Considerations of Tall Wood Structures

The desired massing of the building will significantly influence the structural design because the overall proportion (length, width, and height) and effective stability of the building will influence the lateral load-resisting and vibration strategies required. The addition of higher lateral loads due to seismic conditions, wind loading, or increased height will place higher demands on the structural system and may increase the need for shear walls, moment frames, or diagonal bracing. Lateral load resistance may present a significant challenge to the flexibility and functionality of a design, and should be developed from the earliest study of building siting, architectural form and foundation concepts, and budgeting.

Five bracing strategies that can be employed in tall wood buildings are discussed: the use of vertical circulation core(s), perimeter shear and load-bearing walls, interior shear and load-bearing walls, moment frames, diagonal bracing, or a combination of these.

2.1.1.2.1 Planning for Lateral Load Resistance: Vertical Circulation Core

Using the vertical circulation core for lateral load resistance is typical in most tall buildings and therefore in tall wood structures. In some buildings, only a central core will be necessary for bracing, depending on the overall height, massing, and wind or seismic load requirements. With only a central core (or in some cases, noncentral asymmetric core, as in CREE’s LifeCycle Tower ONE, Dornbirn, Austria), designers have greater freedom in planning the building and adjusting the design throughout the process. Depending on regional site requirements and cost considerations, vertical circulation cores may be constructed of mass timber panels, concrete, or braced wood or steel frame.

2.1.1.2.1.1 Mass Timber Panel Core

Selection of a mass timber core must be established during the earliest stages of the design process to ensure that planning integrity is maintained throughout the building. This strategy was employed in the Wood Innovation and Design Centre project in Prince George, B.C., which features a centralized core with switchback exit stairs of timber and an otherwise open floor plan (Figure 1).

Architects should carefully plan a wood core in order to work to the structural engineers' design. Door openings in the core may be quite limited, as the engineer works to ensure continuity around the corners and to provide enough panel width and length to achieve the required strength and stiffness.

An all-wood core may prove advantageous where the building's other vertical structural elements are also wood. The main advantages of using an all-wood core are prefabrication, use of a single trade, and speed of erection.

Prefabrication of building components benefits the project by providing higher quality control in the factory, better coordination of services before the product comes to site, and faster assembly on-site with less exposure to weather.

The erection of the full structure by a single trade helps reduce cost and coordination challenges between multiple trades and allows the remainder of the building structure to be constructed as the core is being installed.

The current tallest all-wood building in North America, the 13-storey high Origine in Québec City, uses cross-laminated timber (CLT) panels in both gravity- and lateral load-resisting systems constructed by the balloon framing method. The erection of the timber structure took only 4 months.

Several tall buildings that have mixed concrete cores with steel columns have had problems arise from differential movement (e.g., shrinkage in one material but not the other), which results in issues with floor levelness over time. This concern exists when mixing a variety of structural materials for vertical load-bearing elements and should be considered early in the design stage.

Often, use of a concrete core will lengthen the construction schedule of a project when compared to the use of an all-wood core. The latter can provide significant schedule advantages for projects. As noted above, not only can the floor assemblies be erected simultaneously with the cores, the elimination of formwork and rebar installation allows the wood core to be erected as soon as panels arrive on-site. However, mass timber cores could become more limited in application as the height of the building increases. This is due largely to the time required for jurisdictional approval, and to potential testing and cost.

Figure 1. Wood Innovation and Design Centre typical floor plan and rendering (courtesy of MGA | Michael Green Architecture).

2.1.1.2.1.2 Concrete Core

A traditional concrete core may also be used, as was done in CREE's LifeCycle Tower ONE, HoHo Wien, and the University of British Columbia (UBC)'s Earth Sciences Building and Brock Commons. In the CREE example and similarly in HoHo Wien, the floor slabs on the core side connect directly into the concrete. The LifeCycle core is asymmetrically planned and complemented by two additional perimeter shear walls (Figure 2). Brock Commons' double concrete cores were poured two levels at a time to facilitate the timber installation during the summer months.


Figure 2. LifeCycle Tower ONE typical floor plan and rendering (courtesy of CREE).

The centralized concrete core in HoHo Wien follows the shape of the building to maximize the efficiency of the prefabricated floor panels (Figure 3). In HoHo Wien, the CLT floor panels span between the exterior concrete ring beam and the concrete core. Brock Commons' CLT floor slabs are supported by glulam columns without beams, similar to a flat concrete slab. See Section 5.1 of Chapter 5 for more details of the project.

The scale of lateral loads and the planning goals will influence the decision on the ultimate location of the core and other shear wall locations, where centralized cores are generally more structurally efficient as loads increase and represent the simplest approach to avoiding torsional issues in high-loading conditions, particularly in high seismic hazard zones.

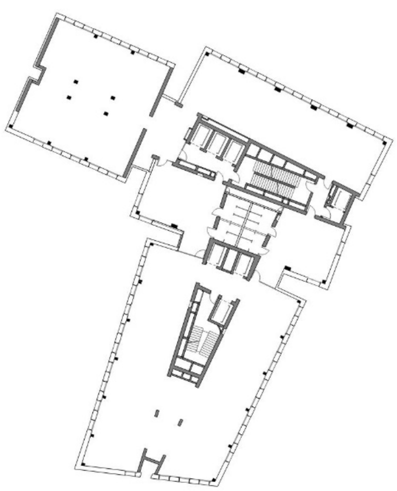



Figure 3. HoHo Wien typical floor plan and rendering, Vienna, Austria (courtesy of Cetus Baudevelopment and RLP Rüdiger Lainer + Partner Architekten).

2.1.1.2.1.3 Steel Core

An alternative option to concrete core is steel-framed core. Steel framing's advantages over concrete core include off-site prefabrication, and installation at the same time as the erection of the rest of the timber structure. The 8-storey Carbon 12 in Portland, Ore. has buckling restrained braces in steel frame at the central elevator and stair core, while the CLT roof and floor act as diaphragms. See Section 5.1 of Chapter 5 for the different types of steel brace frame.

2.1.1.2.2 Planning for Lateral Load Resistance: Perimeter Shear and Load-Bearing Walls

Perimeter bracing requires an integrated approach with the building envelope and typically results in a less transparent exterior. The schematic designs in *The Case for Tall Wood Buildings* (Green, 2012) indicated that perimeter bracing strategies offer interior planning flexibility at greater heights than core-only solutions. If this strategy is used, the perimeter bracings require careful coordination with architectural fenestration and design. Presumably, the more "solid" appearance of an externally braced building will respond well to increasing demands on envelope energy performance, with more opportunities for insulated exterior walls.

2.1.1.2.3 Planning for Lateral Load Resistance: Interior Shear and Load-Bearing Walls

The use of interior shear walls is a reasonable solution for bracing in buildings with fixed plans where structural walls can be coordinated, and the walls will not need to be removed in the future. An interior shear wall approach generally works best in residential applications, and is less likely to work well in office, academic, or other applications. Waugh Thistleton's Stadthaus in the Murray Grove urban housing project, London, UK provides an example of this strategy: a honeycomb-like structure was framed floor-by-floor (Figure 4), and floor plans were adjusted for the "affordable" units on floors 2 to 6.

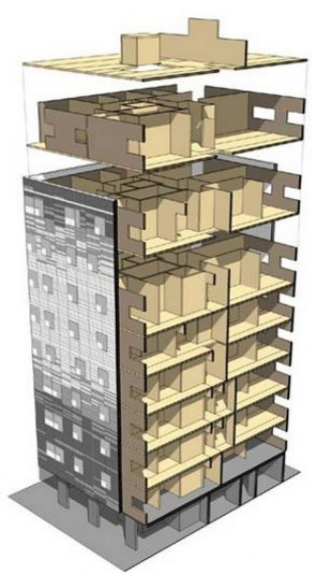


Figure 4. Stadthaus floor plan and axonometric (courtesy of Waugh Thistleton).

2.1.1.2.4 Planning for Lateral Load Resistance: Moment Frames

The use of wood moment frames is challenging at the scale of tall buildings. Built examples have not yet been found, although the FFTT system described in *The Case for Tall Wood* (Green, 2012) introduces a concept to achieve wood panel/steel beam hybrid perimeter moment frames.

2.1.1.2.5 Planning for Lateral Load Resistance: Diagonal Bracing

This strategy was used in the University of British Columbia's Earth Sciences Building, in which a glulam chevron brace with steel connections was incorporated into the east exterior wall of the office wing to complement the asymmetrically located concrete core near the west end of the wing. A key benefit of the brace was the ability to bring daylight to occupied spaces along the perimeter of the building where the brace was located. Additional information on this system is provided in Section 5.1 of Chapter 5.

Completed in 2019, the Mjøstårnet building in Brumunddal, Norway has glulam trusses around the perimeter that are 4 storeys tall and serve both gravity load and lateral loads (Figure 5). The trusses were preassembled in the field prior to erection, and depending on their location, the diagonal braces might have been part of the preassembly (Abrahamsen, 2017).

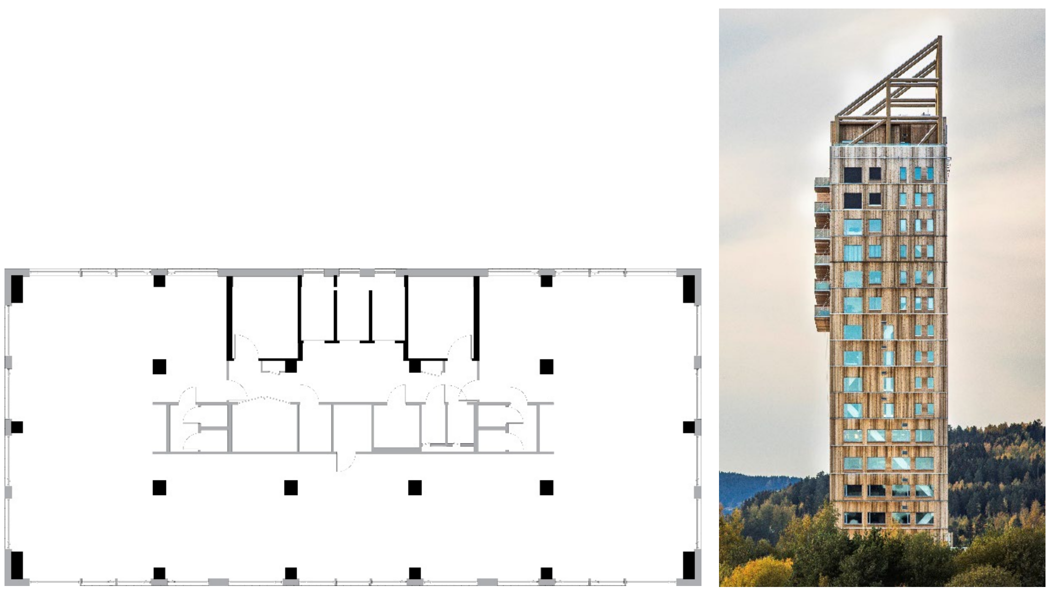


Figure 5. Mjøstårnet floor plan and photo of completed building, Brumunddal, Norway (courtesy of Moelven Limtre AS and Voll Arkitekter).

2.1.2 Selecting Systems Integration and Aesthetic Considerations

The project team will need to make another fundamental choice early in the process with regard to systems integration, the aesthetics of the wood building structure, and AHJ acceptance:

1. Will the wood structure be exposed, partially exposed, or concealed?
    - Exposed wood structures (e.g., CREE's LifeCycle Tower ONE, UBC's Earth Sciences Building, and Wood Innovation and Design Centre solutions) will:
        - generate an expected amount of char;
        - require additional care in detailing to maintain fire separations, smoke separation, and exposure risks;
        - require additional care in acoustic detailing;
        - likely require a solution that integrates the building services and structure to achieve a unified aesthetic;
        - likely require, in lieu of a structural grade mass timber panel, an architectural grade, which will require light sanding and will provide a more consistent appearance with fewer visual defects;
        - be part of, or key to, the building aesthetic and may increase the building's value through market differentiation; and
        - contribute to the biophilic benefit for building users.
    - Partially exposed wood structures (e.g., SOM solution: exposed columns, concealed floor/ceiling; Mjøstårnet) will:
        - require a mix of exposed and encapsulation methods for fire ratings;
        - require additional care in detailing for fire and acoustics;
        - perhaps not require a fully systems-integrated approach because most systems can hang below the structure and be concealed by a dropped ceiling, as is common in most concrete and steel buildings; and
        - have concealed wood structural ceilings.
    - Concealed wood structures (e.g., Stadthaus in Murray Grove and UBC's Brock Commons) will:
        - ultimately not include the wood structure as part of the building aesthetic; and

Marketability/Profitability

Visible natural wood surfaces provide biophilic benefits to occupants. While the maximum amount of exposed wood is prescribed by the code, an Alternative Solution can be developed to permit more exposed wood (see Chapter 6).

- be relevant for some building uses, for higher performance demands of acoustics and fire, for meeting local building code and AHJ requirements, or for market or design intent.

2. Will the building systems need to be integrated into the structural design as part of a complete system or will they be independent of the structural design (though still require coordination)?

- Fully integrated systems (e.g., Wood Innovation and Design Centre, CREE's LifeCycle Tower ONE, HoHo Wien):
  - are typical of higher architectural finish exposed wood structures;
  - floor/ceiling structural assemblies integrate with mechanical, electrical, fire suppression systems, etc. in cavities or coffers or within hybrid concrete slabs; and
  - exposed wood ceiling/slab structures require careful coordination of services.
- Partially integrated systems (e.g., UBC's Centre for Interactive Research on Sustainability):
  - are typical of concealed or partially concealed wood structures;
  - typically, mechanical and electrical components are run in the floor system of the building and require some structural integration; and
  - dropped ceilings simplify the distribution of services; however, coordination with the structure from location to location is required, as is typical of all structures.
- Non-integrated solutions (e.g., UBC's Earth Sciences Building):
  - systems hang below the structure and are:
    - exposed and visible, as may be typical in more industrial buildings; and
    - concealed by dropped ceilings.

3. Which mass timber panel products will be used?

This question is particularly relevant to buildings with exposed wood structures where the choice of material is one of aesthetic appropriateness as well as structure. The project team should consider the following when selecting the appropriate mass timber panel product:

- Architectural aesthetic intent
- Structural capacity and requirements:
  - spanning in a single direction or both directions
- Panel dimensions:
  - Different mass timber panel products are made in different sizes and the sizes will affect structural bay spacing and at times the available finishes of the panels.
  - Material thicknesses that are available potentially determine the span capability or strategy of the structure and its fire performance suitability.

- Material handling and exposure to weather:
    - Some products, such as dowel-laminated panels and nail-laminated panels, are more prone to weather-related damages and other issues if not properly managed due to the exposed vertical space between the boards trapping moisture, which can cause staining and even mould growth.
- Material cost:
    - Some engineered wood products are available in appearance grade. They are more costly than structural grade. The omission or removal of grading stamps and additional sanding for exposed finish may be required.

Construction Moisture

During construction, building components that protect against fire and moisture are not yet in place. In the case of moisture, protection against staining will require different measures than preventing moisture uptake. Consequently, the construction moisture risk mitigation plan may vary for different parts of the building.

- Material availability:
    - Substitution of alternative mass timber panel types may be appropriate to promote competitive bidding on the project. With increasing varieties of mass timber available, market competition will continue to offer flexible alternative material solutions.
- Sustainability objectives:
    - Elimination of off-gassing: Products such as dowel-laminated panels use no glue.
    - Chain of custody certification: Various certification systems are available for different mass timber products.
    - Transportation impact: Some products, such as nail-laminated timber, may be fabricated locally, which can reduce travel distances to the site and thus the carbon footprint.
    - Reduced amount of material: Mass plywood panels might allow for very specific thicknesses that meet structural and fire performance criteria. This minimizes wood usage because of the thinner layers can be used compared to thicker lumber layers required in other products.

Several mass timber panel products are available for use in tall wood buildings. They are discussed in more detail in Section 5.1 of Chapter 5.

2.2 INTEGRATING SYSTEMS

Throughout the design, the project team will need to consider the routing of services between floors, within ceiling spaces, and within walls. This may be done as a fully integrated solution or as a partially integrated one.

2.2.1 Mass Timber and Hybrid Mass Timber Concrete Slabs

Fully integrated solutions allow for the underside of the timber structure to be left exposed, which is often preferable (aesthetically and for biophilic benefits for users and/or marketing of the building) to concealed ceiling systems in tall wood buildings. That said, exposed structure ceilings have limited places to conceal the primary services required, including sprinklers, smoke detectors, and lighting, and potentially air handling or radiant heating and cooling systems.

Many existing wood structural systems are directional in their layout. By using linear panels and beams, wood buildings that have a primary direction for laying services may pose an increased challenge if services have to be run at 90 degrees in the secondary direction. Examples exist in the CREE LifeCycle Tower ONE and Wood Innovation and Design Centre projects. In both cases, panels are staggered with recessed coffers that create raceways for building services. The coffers work well in one direction but can be limiting to services that need to run in a perpendicular direction. Often, the solution requires a drop ceiling for some areas to conceal transitions in direction and allow services to run under primary beams rather than through them. Mono-directional systems are also typically challenged in extending services to the corners of the building without reducing the efficiency of the piping, conduit, or duct runs with 90-degree routing.

Alternatively, a dropped ceiling solution that conceals the structure significantly simplifies these issues, allowing services to run as needed, as would be typical in steel or concrete buildings with dropped ceilings. While this may simplify servicing, it is potentially less desirable in wood buildings where there is often a preference for seeing the beauty of the wood material (although nonstructural wood ceiling tiles are available, generally they require an Alternative Solution), and can result in greater floor-to-floor heights, which may pose challenges in terms of cost and with obtaining municipal approvals. Dropped ceiling solutions, however, also offer increased acoustic and fire resistance performance benefits.

2.2.2 Structural Mass Timber Walls

In Europe, early mass timber panel projects routed services directly into the wood of the panels in order to allow the wood to be the finished surface of the walls in the interior rooms. While this is possible, it is generally significantly more expensive and difficult to coordinate solutions for larger buildings in North America. Instead, most structural walls are furred out with additional light steel (and sometimes wood in lower buildings) framing and drywall, which creates service space for electrical, mechanical, plumbing, and fire suppression.

The addition of furred walls with drywall over the mass timber generally also helps with acoustic and fire performance between spaces.

A design team may want to expose some structural walls as a feature of their design. This would typically be achieved by locating services in adjacent walls to eliminate the need for integrating systems in the panel itself. Integrating systems into a structural panel may reduce or diminish the fire and acoustic performance characteristics of the panel.

Depending on the region, building codes should be reviewed to confirm how much structural wood can be exposed to view in a taller mass timber building.

2.2.3 Floor Assemblies

To date, common approaches to floors in tall wood buildings have been based on a nominal concrete topping over a mass timber panel structure, or a composite concrete–mass timber panel structure, or a composite precast concrete–glulam beam structure. The addition of concrete is sometimes used structurally to add weight to the building to reduce vibration.

In each of these cases, the addition of a concrete topping helps the acoustic and fire performance of the floor assembly and provides space for the integration of wiring and radiant heating and cooling systems. Once in place, however, these systems are difficult to service or access.

In Waugh Thistleton's CLT platform-based Whitmore Road Project (London, UK) and in the system developed by MGA and Equilibrium for the Wood Innovation and Design Centre, concrete toppings were eliminated in lieu of a "dry construction" solution composed of built-up layers that meet acoustic performance criteria. In the case of the Wood Innovation and Design Centre project (Figure 1), the dry construction approach and the coffered cross-section of the mass timber panel structure create an accessible mono-directional raceway for altering wiring or ducting. The raceway on top of the staggered structural panels is deep enough for accommodating ductwork and piping.

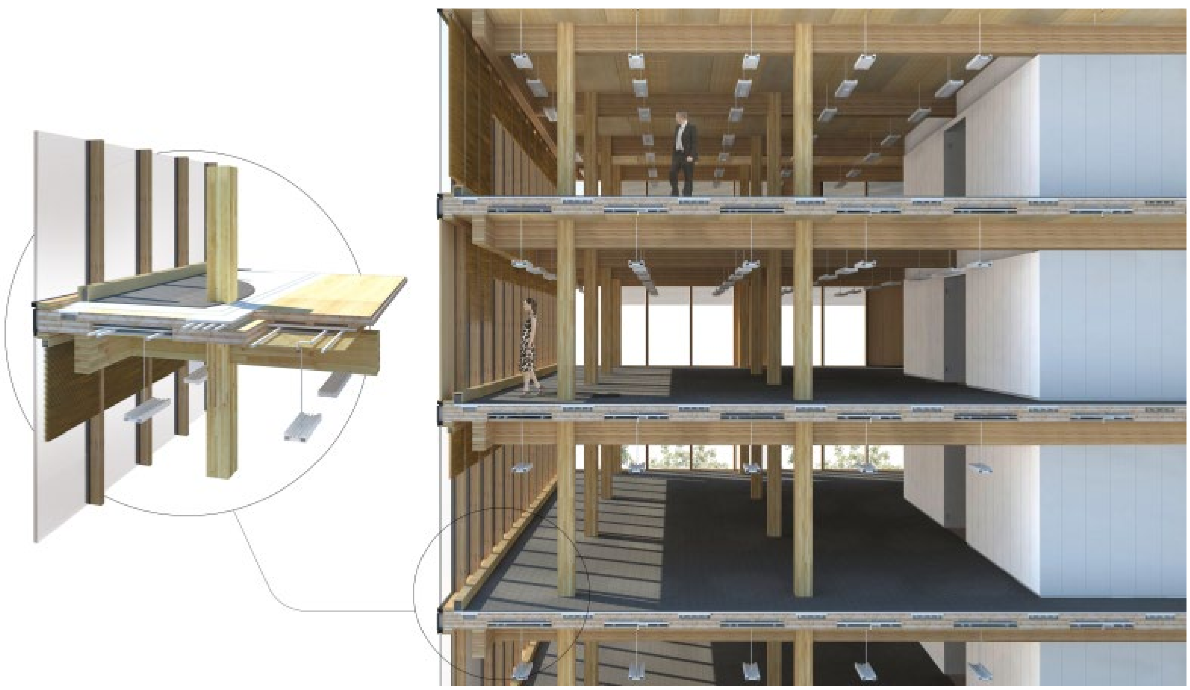


Figure 6. Services integration: Wood Innovation and Design Centre approach (courtesy of MGA | Michael Green Architecture).

2.2.4 Mechanical/Plumbing Systems

Beyond the standard plumbing detailing requirements for fire penetrations, seismic bracing, and acoustic isolation, consideration should be given to some conditions that are unique to wood buildings with respect to plumbing. In exposed wood structure solutions, systems hang below the floor assembly and are exposed or are integrated into the structural solution itself, as in the Wood Innovation and Design Centre (Figure 6). An integrated system needs to resolve the routing of ductwork, piping, and electrical conduit, etc. in all directions. The Wood Innovation and Design Centre and CREE's LifeCycle Tower ONE are directional structural systems in which systems run easily in one direction but are more challenged in the other. The resolution of system access to the corners of these single directional structural layouts can be particularly challenging. As in the case of Brock Commons, the elimination of beams in the two-way CLT flat-plate floor system removed any horizontal restriction to run the mechanical, electrical, plumbing and fire protection systems.

In both exposed and concealed structures, long-term exposure to moisture from water leaks, condensation on plumbing or other mechanical system pipes, and internal rainwater leaders represent a significant concern regarding visual damage and potentially structural damage to the wood structure. Insulation of pipes and provision of drip pans, gaskets, and other measures such as electro-mechanical moisture sensors should be conducted to limit the risk of damage to wood members that may be difficult to access and repair structurally or visually.

Post-Occupancy Moisture

Designing to deal with post-occupancy moisture involves limiting the amount and pooling of water in an accidental release (fire suppression, pipe burst, overflow), or when a slow leak goes undetected (pipe leak, envelop failure, condensation).

Leaks or overflows from washrooms or kitchen fixtures may also cause significant visual damage to the ceiling below. Designers may consider adding a "bathtub" membrane under bathroom and kitchen flooring, as well as adding floor drains to mitigate this risk.

Long-term leaks in concealed locations may become larger risks to the building. The leaks may cause structural damage or affect indoor air quality through the introduction of mould. Ensuring there is appropriate access to visually inspect plumbing from time to time is recommended.

2.2.5 Electrical Systems

One of the unique challenges with electrical systems is the ability to route conduit and locate fixtures within the solid mass timber panels. Often this has been solved by using dropped ceilings and furred out walls with secondary walls of gypsum. This simplifies electrical conduit and fixturing and is similar to how a concrete building would be constructed, but the wood structure is fully concealed.

An alternative exists in CREE's LifeCycle Tower ONE and the Wood Innovation and Design Centre, where service channels are designed into the floor structure/ceiling assemblies. The channels simplify wiring to fixtures and may be covered with any number of architectural finishes. In the case of the Wood Innovation and Design Centre, additional service channels were designed on top of the structural floor assembly to provide flexible wiring of office spaces in a single-directional, partially raised floor assembly. A fully raised floor may also be considered for wiring from the floor. Conduit and fixturing within concrete toppings could also be considered if concrete toppings are to be employed.

For walls, it is possible to route conduit into the mass timber panels, as is done in some European applications. This requires careful coordination and limits future renovations to the system. It is also a costly solution in Canada currently. If the intent is to expose some mass timber walls, it is common to see raceways integrated into baseboard conditions and wider doorframes for locating wall switches, etc. This solution is illustrated in *The Case for Tall Wood Buildings* (Green, 2012) and is shown below where FFTT is described further.

2.2.6 Fire Suppression Systems

All tall buildings in Canada require a sprinkler and standpipe system. Consideration of integration of sprinklers and related piping is necessary. Where timber is encapsulated, no further provisions other than those normally provided in a tall building are required. However, the placement of sprinklers should be taken into consideration in developing the structural system. Where there is exposed timber, there may be requirements for additional sprinklers in void spaces and other typically un-sprinklered spaces. The provision of an on-site water supply tank, in addition to the normal city supply, is recommended (see Chapter 6 for details).

When the intent is to conceal sprinkler systems within the structural floor (and therefore ceiling) assembly of an exposed wood structure, the structural approach and dimensions should include consideration of the coverage, routing, size, and sloping of the sprinkler system.

As an example, in the case of the Wood Innovation and Design Centre project, the design team staggered the structural CLT floor panels with voids in between for the routing of sprinklers. For the voids, the depth needed for the sloping of the piping and the vertical drops of the heads themselves needed to be taken into consideration. Success of the system required the deeper voids to be on the underside (ceiling) rather than on the floor side of the assembly.

2.3 IMPORTANT CONSIDERATIONS

2.3.1 Sound Insulation

2.3.1.1 Types of Sound

A pressure wave propagating through air is referred to as "airborne sound", and a stress wave propagating through a solid structure is "structure-borne sound". "Flanking transmission" is the sound transmission along paths other than the direct path through the common wall or floor/ceiling assembly. These paths are shown in Figure 1 in Section 5.4 of Chapter 5.

Section 5.4 addresses sound insulation in details for demising walls, partitions, and floor/ceiling assemblies between adjacent spaces, such as dwelling units, and between dwelling units and adjacent public areas such as halls, corridors, stairs, or service areas in buildings employing wood construction. Although a list of the terms commonly used to specify the sound insulation performance of assemblies is also included in Section 5.4, a brief overview is provided in this chapter.

2.3.1.2 Measuring Sound

The passage of sound between units of a residential or commercial building, as well as from the outside in, plays a large role in the comfort level (and general happiness) of the building's occupants. There are two ways to measure the passage of sound: Sound Transmission Class and Impact Insulation Class. An overview with some specific details is provided here. A more technical discussion of the topic and design parameters are presented in Section 5.4 of Chapter 5.

2.3.1.2.1 Sound Transmission Class

Sound transmission is defined as sound waves hitting one side of a partition, causing the face of the partition to vibrate. This reradiates as sound on the other side.

Sound Transmission Class (STC) is a numerical rating assigned to a wall or floor assembly to describe how well it impedes the transmission of sound. Sound Transmission Class classifies the average noise reduction (in decibels) for sounds as they pass through an assembly. A high STC rating for an assembly implies good sound attenuation characteristics. For example, loud or amplified speech and loud music would still be audible with an assembly that has an STC rating of 45. In an assembly with a rating of STC 60, loud music would be inaudible except for very strong bass notes (Warnock et al., 2002).

The STC rating ignores low-frequency sound transmission below 125 Hz, which is often associated with mechanical systems, transportation noise, and amplified music. Low-frequency sounds can be a major cause of complaint in multi-family construction. A heavier assembly with the same STC as a lighter assembly may often outperform the lighter assembly at low frequencies.

2.3.1.2.2 Impact Insulation Class

Impact sound is caused by a direct contact or impact on a floor that causes the floor system to react locally and at its resonances. The excitation of the floor structure reradiates as noise in the space below the floor and can potentially be transmitted to other nearby spaces in the building. The standard laboratory test for impact sound performance of a floor assembly results in a rating called Impact Insulation Class (IIC). The standard test method uses a tapping machine that consists of a motor powering a turning shaft that lifts and drops five steel hammers on the floor repeatedly at a rate of 10 times per second. Sound pressure levels are measured in the room below at specific frequencies and are compared against a standard reference curve to quantify the IIC rating.

Impact Insulation Class increases as the impact sound insulation through the floor system improves. Most building codes in North America do not have requirements for acceptable IIC ratings for floors. In some building types such as residential construction, ratings of 50 or higher are mandated in order to minimize complaints. Often, design IIC differs from on-site realities and performs 3–5 points less. The Field Impact Insulation Class (FIIC) includes both flanking transmission and direct transmission through the demising floor, and provides a more meaningful assessment of impact isolation (see Section 5.4 of Chapter 5 for a description of FIIC and typical FIIC requirements).

2.3.1.3 Design Considerations

2.3.1.3.1 Mass

The weight or thickness of a partition is one of the main factors in its ability to block sound. Mass is commonly added to existing walls by adding additional layers of gypsum. When the mass of a barrier is doubled, the STC rating increases by approximately 5 dB, which is clearly noticeable. The denser a product, the better its sound isolation performance (Warnock et al., 2002).

2.3.1.3.2 Discontinuity

An airspace within a partition or floor assembly can also help increase sound isolation. When sound vibrations are allowed to move from one wall face to another through a solid and stiff internal element that is rigidly connected to the wall faces, which creates a sound path, the STC rating decreases significantly. The airspace can be increased or added to a partition by using components such as resilient channels and layers of gypsum board. An airspace of 1½ in. improves the STC by approximately 3 dB, 3 in. improves it by approximately 6 dB, and 6 in. improves it by approximately 8 dB according to the database on light-frame wood stud walls (Warnock et al., 2002). Findings from studies on light-frame wood stud walls may be applicable to mass timber walls, but the degree of improvement may be not the same, depending on the mass timber wall construction details.

There are several ways to create discontinuity in wall partitions in a mass timber building. The use of additional framing and gypsum board with an airspace furred out on one or both sides of the panels is a common solution. This also creates space for other building systems to run without impeding the structural elements. However, a furred-out solution may be more costly than a partially exposed or exposed mass timber panel system. Mass timber panels have been exposed in some buildings where two panels were used and were separated by an airspace. This approach has performed well in Waugh Thistleton's Whitmore Road residential project, as an example. In each instance, flanking sound should be considered in the partition design because transmission through the structure itself is difficult to mitigate.

2.3.1.3.3 Resilient Connections

Fastening horizontal resilient channels to the structural members of an assembly is commonly used to disrupt the sound transmission path. Resilient channels or elastic-clips installed on both sides of a wall may be beneficial where the direct and flanking sound can enter the wall framing from above or below. The position, spacing, and location of resilient channels is important because, if installed incorrectly, they can actually reduce the STC rating. Resilient channels should be oriented with their bottom flange attached to the wall stud framing.

2.3.1.3.4 Sound-Absorbing Materials

Sound-absorbing materials may be installed in a wall cavity or floor to reduce sound transmission between spaces. Sound-absorbing materials are usually porous foams or fibrous layers through which sound cannot easily pass. Examples are mineral wool, glass fibre, cellulose fibre, open cell foams, and acoustical tiles. These materials convert sound vibrations into heat because sound repeatedly reflects from the surfaces of an enclosed space, passes through the sound-absorbing material many times, and decreases with each pass. If both faces of the wall are rigidly connected, the sound-absorbing materials may not be effective, and adding the materials in the cavity would not be cost-effective.

2.3.1.3.5 Assembly Components

A sound rating depends on, and is affected by, the components in a wall or floor assembly. Construction details play a large role in this, from the materials and thickness of layers used (gypsum board or sound absorption material) to the spacing of studs and resilient channels in a wall assembly. In a floor assembly, the same principles apply, where the finishing, topping, subfloor, ceiling boards, sound-absorbing materials, space between layers, and size and spacing of joists and resilient channels all affect sound ratings. An ideal assembly for controlling sound transmission would include an airtight construction (especially at penetrations), two layers that are not connected at any point by a solid material, the heaviest or most dense material that would be practical, and the deepest cavity that is practical, filled with a sound-absorbing material.

The following are examples of floor or ceiling layers that enhance acoustic insulation:

- discontinued finish, topping, and slabs
- concrete topping
- drywall ceiling or acoustic ceiling tile systems hung on resilient hangers
- rubber or other underlayments with high dynamic stiffness (elastic) below topping and floor finishes
- staggered floor
- carpet finish with cushion backing
- flanking controlled installation that determines the final entire building sound insulation performance.

Several solutions, depending on the acoustic requirement and desired ceiling finish, were used in the staggered floor system at the Wood Innovation and Design Centre (Figure 7).

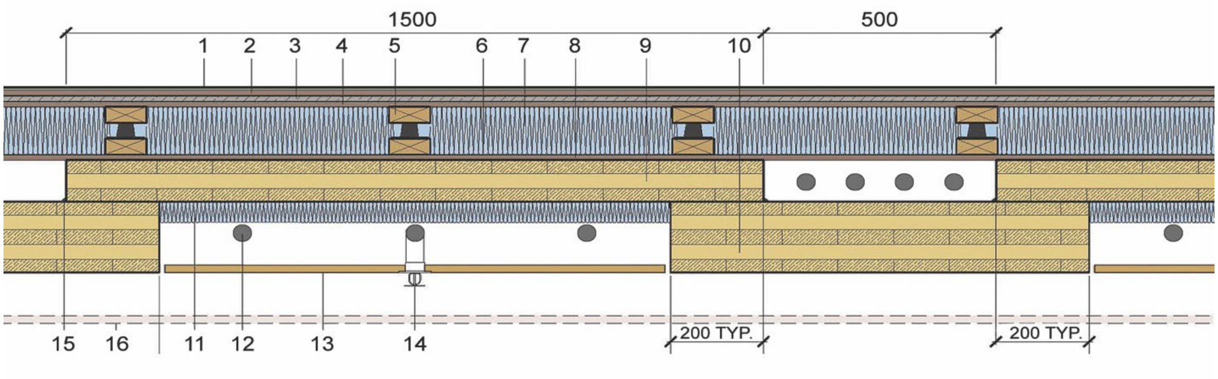


Figure 7. An example of a slab assembly from the Wood Innovation and Design Centre (courtesy of MGA | Michael Green Architecture).

2.3.2 Energy Efficiency

It is estimated that more than 40% of all energy use is consumed within buildings. In Canada, most of the energy in buildings is consumed for space conditioning, including space heating, air conditioning, and tempering ventilation air, and for fan and pump power to distribute heating and cooling throughout the building. In the design of energy-efficient buildings, it is important to consider energy from a whole building perspective. An energy-efficient building enclosure that employs strategies such as well-insulated assemblies, reduction of thermal bridging, airtight construction, thermal mass, and passive solar design can significantly reduce the need for space heating and cooling to ensure thermal comfort. Efficient mechanical systems provide lower energy means of delivering heating, cooling, and hot water to a building. As energy requirements increase, renewable energy systems become increasingly practical and cost-effective, and contribute to sustainable, self-sufficient buildings. Although all these systems help reduce the energy footprint of a building, starting with an energy-efficient enclosure to reduce space-conditioning energy is key to designing energy-efficient buildings and is a primary focus of this guide.

Well-insulated assemblies, airtight construction, and thermally massive assemblies are all desirable features that can be part of an energy-efficient tall wood building. Minimum thermal insulation requirements in the NBC (NRC, 2020) vary by climate zones across Canada and are based largely on space-conditioning needs. Buildings in colder climate zones, such as the Northern Territories, generally require more insulation than those in temperate climate zones, such as coastal British Columbia. As the cost of energy increases, higher thermal resistance targets in all climate zones become economically justifiable and are an important solution to reducing overall carbon emissions from the built environment. However, there are depreciating energy savings and returns on the super-insulation of wall and roof assemblies, and consideration of a whole-building systems design approach is most appropriate. For example, the optimal insulation levels for a tall wood building typically differ from those for a single-family house. High-performance house targets in a cold climate are generally R-40 walls, R-60 roofs, and R-20 below grade. For taller buildings with a lower surface-to-volume ratio and greater window areas, the targets may be in the range of effective R-20 – R-40 for walls, R-30 – R-60 for roofs, with thermal-bridge managed and appropriately insulated below grade detailing in most Canadian climates.

Whole-building energy efficiency takes into consideration the thermal loss or gain through the building enclosure, which affects the mechanical and electrical systems in the building that deliver heating and cooling to compensate for those losses or gains. Heat loss or gain may occur through all parts of the building enclosure, including the above-grade and below-grade walls, roofs, decks, balconies, exposed floors, openings such as exterior windows/doors, skylights, and all the interfaces and details in between. Windows have perhaps the largest thermal effect on the overall thermal performance of the building enclosure. Window components, because of their relatively low thermal resistance compared to insulated walls and roofs, may be considered as large thermal bridges within the building enclosure. Other components that can significantly affect the thermal performance of a tall wood building include uninsulated floor edge details and uninsulated structural columns. Heat loss through all these components needs to be considered in order to design an energy-efficient building enclosure.

The thermal mass of the building enclosure elements, as well as that of the interior floors and walls, can improve the energy efficiency of buildings by storing and releasing energy during different periods of the day or night. For example, during heating periods, thermally massive assemblies with exterior insulation can store heat from the sun during the day and release it at night when indoor temperatures cool down. This may reduce peak utility loads by shifting their intensity and the time at which they occur, and reduce the building's overall energy use and peak demand, while ensuring occupant comfort. The benefits of thermal mass within a building vary with climate and solar radiation, building type and internal heat gains, building geometry and orientation, and the amount and location of thermal mass used, but the use of thermal mass is a common strategy in energy-efficient buildings. The thermal mass effect is typically more significant in continental, mixed climates with larger outdoor temperatures that fluctuate above and below indoor temperatures. Thermal mass is typically associated with concrete or masonry buildings; however, heavy timber framing, including CLT panels plus any additional topping, and drywall finish, has considerable thermal mass, which can provide whole-building, energy-efficiency benefits based on the project climate and building type, and validated by energy modelling.

Passive solar design strategies incorporate windows and exterior shading to maximize solar heat gain during heating periods, while also providing shading during cooling periods to prevent overheating and reduce air conditioning energy. Overheating has become a large issue, particularly in energy-efficient buildings, and is expected to become worse with global warming. The use of passive as well as active cooling measures is important to ensure indoor thermal comfort and reduce cooling energy use. Glazing with high solar heat gain can provide more passive solar heating in the winter, while architectural features can be designed to provide shading during cooling periods. Passive solar design is commonly used in houses with fixed overhangs to shade windows but can also be incorporated into tall wood buildings. When using passive solar design and high solar heat gain glazings, it is important to ensure there is adequate exterior shading in the summer and swing seasons to prevent overheating and reduce cooling energy demands. Passive solar design requires consideration of geographic location and climate, including solar radiation and solar angles as well as heating and cooling degree-days.

To summarize, energy-efficient buildings require a whole-building design approach. Use of an energy-efficient enclosure should be a primary consideration, and should incorporate strategies such as well-insulated assemblies, airtight construction, thermal mass, and passive solar design to reduce the need for mechanical heating and cooling. Tall wood buildings can relatively easily incorporate highly thermally resistant assemblies, minimal thermal bridging, airtight construction, and thermal mass with exterior insulation to create a high–performance, energy-efficient building. See Chapter 7 for in-depth information about building enclosures.

2.3.3 Architectural Finishing

The following aspects should be taken into consideration when providing for architectural finishing:

- exposed or concealed wood structure, including columns within the human touch zone;
- humidity, risk of water damage;
- shrinkage, creep, and other changes over time;
- material selection;
- grades/finishes of mass timber panels and other wood products;
- protection from weather and damage during construction;
- flame spread requirements and potential treatments; and
- quantity of exposed wood area per codes and program use.

Post-Occupancy Damage

Chapter 6 provides background on how mass timber provides fire resistance, which can be used to support an Alternative Solution. In the abuse zone, an architectural wood layer can also provide fire protection, but the thickness and method of attachment will need to be assessed.

Wood finishes exposed in exit lobbies, exit corridors, etc. may require coatings to reduce flame spread. Consider species being used in exposed structures and how other wood finishes (millwork, etc.) and species coordinate/harmonize. See Chapter 6 for additional details on fire protection of exposed wood.

2.3.4 Cost Considerations

2.3.4.1 Cost Implications of Different Assemblies and Comparison to Traditional Assemblies

Mass timber buildings have a distinct scheduling advantage over cast-in-place concrete or steel–concrete composite structures. On-site erection is faster for mass timber due in part to the elimination of temporary shoring after installation, the curing time for concrete, and even the number of crane picks required to form concrete walls, deliver rebar, tie rebar, pour the wall, and strip the formwork. In addition, predrilling and coring at an off-site factory can accelerate the installation of building services fixtures and finishes. However, the scheduling advantage may be somewhat reduced when compared to the construction of structural steel and precast concrete buildings due to challenges related to fire stopping and joint sealing for acoustic separation between walls and floors that require additional effort during the design documentation phase.

Within the industry, it is expected that as design and construction of mass timber buildings advance, there will be a significant improvement in cost savings, primarily due to off-site prefabrication of sections, use of larger panels, and faster installation as companies gain experience and develop systems that improve panel placement and fastening techniques.

Chapters 3 and 8 provide a more detailed discussion on cost and prefabrication considerations for mass timber buildings.

2.3.4.2 Costs of Deconstruction, Salvaging, Recycling, Reuse, and Waste Disposal

Costs associated with the deconstruction of mass timber buildings would be similar to those of structural steel and precast concrete structures. Costs are anticipated to be less than those of cast-in-place concrete buildings due primarily to the ease of removal of panel sections. The material can also be reused and reworked into various sizes for other building or nonbuilding applications (e.g., furniture, wood flooring), thereby reducing disposal requirements.

2.4 STRUCTURAL CAPACITY OF ALTERATIONS

Timber is inherently easy to work with and can be modified with light and simple tools. Small openings can often be accommodated in mass timber elements such as posts, beams, and solid wood panels without the need for scanning or reinforcing. If reinforcing is required, easy-to-install self-tapping screws, now available in a wide range of lengths and sizes, may be specified.

Larger openings can also often be accommodated in solid timber panel walls, since the panel itself is usually much stronger than the connections between the panels, which typically govern the design. If larger openings are required at a panel joint, additional fasteners can be provided to replace those removed. Reinforcing members, if necessary, can usually be secured with simple site-installed connectors.

Few structures are truly demountable and reusable unless they are specifically designed for that purpose. That said, with few exceptions, timber connections are often easily dismantled, particularly in the case of solid panel construction where most of the connectors are self-tapping screws. Likewise, it is easy to add to a timber structure due to the use of light tools and simple, yet versatile, site-installed connection options. Unlike

> Division B of the NBC has traditionally been viewed as the “requirements” of the code. However, Division B simply contains the provisions for Acceptable Solutions. A set of solutions have been reviewed through the Canadian code change process and have been accepted as providing the level of performance required. Other solutions are not prohibited: they may not be included in the NBC because they have not yet been analyzed and accepted through the code change process. An example of other solutions is a 12-storey mass timber building of assembly occupancy. This is not in the NBC Acceptable Solutions (NRC, 2020). Its absence from the NBC does not prohibit its construction: it simply indicates that this type of building has not been studied, reviewed, and accepted through the code change process. The NBC, in recognition of the fact that it does not and cannot include all possible solutions that provide the required level of performance, specifically permits the development of Alternative Solutions.

light framing, however, which is notoriously easy to alter due to the small scale of its components, mass timber construction and deconstruction require heavy lifting equipment.

2.5 BUILDING CODE COMPLIANCE

2.5.1 History of the National Building Code of Canada

The National Building Code of Canada (NBC) is a model building code that sets the minimum levels of performance for building construction in Canada. When adopted by a province or territory, it becomes a regulation in effect in the region. The degree of modification varies from minimal changes in some jurisdictions to significant changes in other jurisdictions.

The NBC is intended to represent a consensus reached by the public regarding the minimum level of safety required in buildings, among other objectives. It has traditionally been "prescriptive", in that code provisions are directly stated in the regulation. While the NBC is revised in each code change cycle, some of the provisions are historical and do not necessarily reflect modern engineering practice and construction technologies. Heavy timber buildings as high as 9 storey (30 m) were built in Canada (see Section 5.1 of Chapter 5) prior to its inclusion (up to 23 m high) as a separate category in the first edition (1941) of the NBC.

The 2020 edition of the NBC (NRC, 2020) permits encapsulated mass timber construction for buildings up to 12 storeys in height for residential and office occupancies, with assembly and retail occupancies permitted on lower floors.

2.5.2 Objective Approach to Building Code Compliance

In 2005, the Canadian Commission on Building and Fire Codes published the National Building Code of Canada as an objective-based code (NRC, 2005) and a step toward a performance-based code in the future. The benefit of the objective-based code is that for the first time, specific code objectives and functional statements are available (in Division A of the NBC), which allows practitioners, builders, and code regulators alike to understand the intent of the NBC and its application, and to develop alternatives to the limited solutions provided.

Regulatory Acceptance

Where explicit NBC requirements of an Acceptable Solution are not suitable for the site or market, an Alternative Solution may be pursued. Although Alternative Solutions apply only to a specific project, the general approach for certain topics, such as more exposed wood, is similar, and thus is covered in this guide.

The objective-based code allows for compliance with the NBC through Acceptable Solutions, which are the prescriptive provisions in Division B of the NBC, or through Alternative Solutions that demonstrate an equivalent level of performance to the Acceptable Solution in the areas identified by the objectives (Figure 8). The main advantage, to some extent, of complying with the prescriptive provisions is that it is easier and faster for designers and authorities having jurisdiction to develop, apply, review, and approve a design.

Unlike performance-based codes, such as those adopted in Australia and New Zealand, the objective-based code does not provide specific performance levels. Instead, it provides objectives that explain the intent behind the prescriptive provisions. Under such a framework, the objective and functional statements in Division A provide the framework for identifying the areas of performance of an Acceptable Solution that must be demonstrated by an Alternative Solution.

The preface of the 2020 edition of the NBC (NRC, 2020) provides a concise overview of the relationship between Division A and Division B, and what is expected of an Alternative Solution.

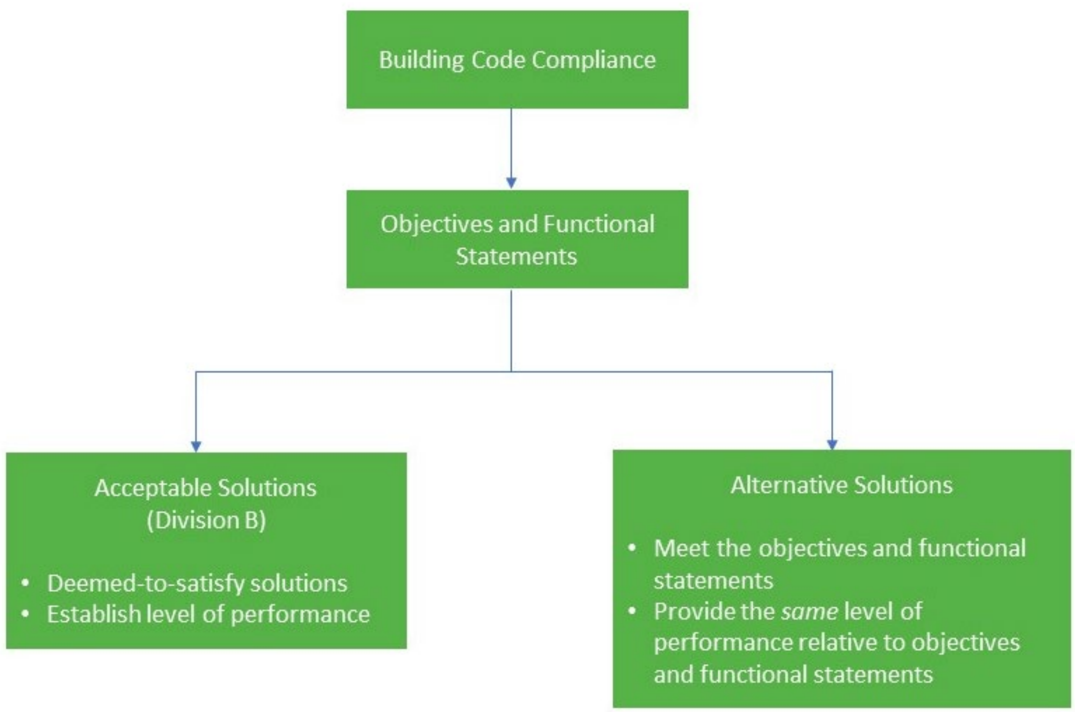


Figure 8. Summary of the two compliance paths in the National Building Code.

The process by which an authority having jurisdiction reviews and accepts Alternative Solutions varies from jurisdiction to jurisdiction and with the complexity of the Alternative Solution. **Peer review may be an appropriate process for a complex Alternative Solution.**

When considering any review process, it is important for all involved to have a clear understanding of the purpose of the Alternative Solutions compliance path. The following are some reasons for using the compliance path:

- New information that has "not yet" been considered in the Acceptable Solutions has become available.
- Additional mitigating measures for offsetting any additional risk that may be associated with the Alternative Solution have been developed.
- A different "solution" than that in the Acceptable Solutions has been created and provides the same level of performance relative to the objectives.

The proponent and peer reviewer(s) must review the Acceptable Solution to establish that the Alternative Solution addresses all the concerns addressed by the Acceptable Solution. Further, the proponent and peer reviewer(s) will need to review other Acceptable Solutions in Division B that may rely on the primary Acceptable Solution for which an Alternative Solution is being developed. For example, Acceptable Solutions for wiring and conduit are based on assumptions of noncombustible construction and will need to be reviewed as part of an Alternative Solution for use of combustible construction.

Conversely, an Alternative Solution may be built on an Acceptable Solution. In this case, it is important that the proponent and peer reviewer(s) of the Alternative Solution carefully consider whether any or all of the prescriptive requirements still apply.

From a fire design perspective, to demonstrate NBC compliance using an Alternative Solution, a qualitative or quantitative fire risk assessment (see Appendix 6A in Chapter 6 for a discussion) must be carried out to establish the level of risk associated with the Division B solution, and then the same assessment for the Alternative Solution must be made so that the level of performance between the two designs can be compared. If this comparative risk analysis shows that the Alternative Solution provides at least the same level of performance as the Division B provision, then the Alternative Solution can be accepted as complying with the building code.

From a structural design perspective, the code compliance for a structural system can be demonstrated following the methodology in Section 5.3 of Chapter 5.

2.5.2.1 Acceptance by Authorities Having Jurisdiction

The AHJ must agree that the Alternative Solution provides the requisite level of performance, although the process for review varies by jurisdiction.

The inclusion of mass timber construction in the NBC (NRC, 2020) has made it substantially easier for the development and acceptance of Alternative Solutions for tall mass timber buildings. However, an Alternative Solution for a tall mass timber building designed beyond the prescriptive provisions of the NBC can still be inherently complex. Depending on the level of complexity of the Alternative Solution, it may be appropriate for the applicant and AHJ to delegate the review process to third-party or peer reviewers with qualifications in timber engineering and fire science, in the case of a solution to address fire safety and protection, or in structural engineering, in the case of a solution to address structural safety and serviceability. The review process and selection of peer reviewers should be agreed upon early in the project, and reviewers and proponents should establish a good dialogue to help find solutions to issues rather than just identifying errors and omissions. In the case of Alternative Solutions to meet fire requirements, further guidance on the peer review process is available from the Society of Fire Protection Engineers (SFPE, 2020).

It is important that all parties, the applicant, AHJs (typically both fire and building departments), and peer reviewers meet early and often to maintain an effective dialogue so that all parties are satisfied with the process and outcome.

The remainder of this section provides examples of Alternative Solutions to meet fire requirements. Text boxes in this section raise points that may be of interest to AHJs that are faced with permitting a project that has one or more Alternative Solutions.[1]

2.5.2.2 Objectives and Functional Statements

> Experience has shown that the peer review process needs to start early and be a consensus process that balances the needs of all stakeholders. Guidelines for the process should be agreed to by the proponent, AHJ, and peer reviewer(s).
>
> One approach, developed by the Society of Fire Protection Engineers (SFPE, 2020), is referenced in this guide. Stuart (2010) provides a discussion and draft outline for structural reviews.
>
> Guidelines for a peer review process generally have the same basic structure. This includes defining the scope of the review, establishing that the proponent and peer reviewer(s) are qualified to develop and review the Alternative Solution, clarifying the responsibilities and extent of liability of all parties, and documenting the review.
>
> The most important and challenging step is identifying the technical issues that should form the basis of the review.

The NBC (NRC, 2020) objectives and functional statements attributed to a particular provision identify the risk areas that the NBC is addressing in that provision. Risks that are not addressed by the objectives are outside the NBC framework and are therefore not considered. For example, the risk of failure due to a terrorist attack is currently not a risk area recognized by the NBC. For conciseness, the following discussion outlines the process for meeting fire requirements. A similar approach should be followed for meeting the other fundamental requirements of the NBC.

The fire safety, health, accessibility, and environmental provisions set forth in the NBC are interrelated with five main objectives. They describe, in very broad and qualitative terms, the overall goals that the NBC's provisions are intended to achieve, namely:

- OS – Safety
- OH – Health
- OA – Accessibility for persons with disabilities
- OP – Fire and structural protection of buildings
- OE – Environmental

The objectives describe undesirable situations and their consequences, which the NBC aims to prevent in buildings. Each objective is further refined with sub-objectives in Parts 2 and 3 of Division A of the NBC. The NBC recognizes it cannot entirely prevent all undesirable events from happening or eliminate all risks; therefore, its objectives are to "limit the probability" of "unacceptable risk".

[1] Guidance in text boxes was prepared by C. Lum, A. Harmsworth, and T. Ryce.

Moreover, an "acceptable risk" is the risk remaining once compliance with the NBC prescriptive solutions has been achieved (NRC, 2020).

Each provision (i.e., Acceptable Solution) prescribed in Division B of the NBC is linked to one or more objectives and sub-objectives and one or more functional statements. A functional statement describes a function of the building that a particular requirement helps achieve. The functional statements are more detailed than the objectives, and similarly, are entirely qualitative. Examples of functional statements that relate to the provisions in Part 3 of Division B of the NBC include:

- F01 – to minimize the risk of accidental ignition
- F02 – to limit the severity and effects of fire or explosions
- F03 – to retard the effects of fire on areas beyond its point of origin
- F04 – to retard failure or collapse due to the effects of fire
- F05 – to retard the effects of fire on emergency egress facilities
- F10 – to facilitate the timely movement of people to a safe place in an emergency.

Additional information on objectives and functional statements is provided in Parts 2 and 3, respectively, of Division A of the NBC.

2.5.2.3 Level of Performance

> Where available, guidelines developed by a representative cross-section of practitioners with expertise in the topic area should be used. The guidelines may include a checklist of items to consider, which will help focus the review. This guide is intended to serve as one such guideline.

The performance targets for the NBC's provisions are implicit in the provisions themselves; the performance attained by the Acceptable Solutions in Division B constitutes the minimum level of performance required. For example, Sentence 3.4.2.5.(1) requires that the maximum travel distance to an exit in a sprinklered office (Group D) floor area be 45 m. The objective and functional statement attributed to Sentence 3.4.2.5.(1) is [F10-OS3.7], which is to facilitate the timely movement of people to a safe place in an emergency in order to limit the risk of injury due to people being delayed in, or impeded from, moving to a safe place during an emergency. The performance target is the measure of time for occupants to reach an exit within the 45-m maximum distance relative to the onset of unsafe conditions. If an Alternative Solution were proposed, it must be demonstrated that the resultant travel distance to the exit meets or exceeds the performance attained by the 45-m travel distance scenario with respect to [F10-OS3.7], assuming all other factors remain unchanged.

2.5.2.4 Fire Implications

This guide provides direction on designing tall wood buildings in order to meet the level of fire safety intended by the NBC's Acceptable Solutions for high buildings (NRC, 2020), as outlined in Chapter 6. The Division B solutions provide for 2-hour fire resistance ratings of floors, structure, and exits. The means of complying with all fire resistance and fire rating requirements currently exist, and are outlined further in Chapter 6.

2.5.2.4.1 Exposed Mass Timber

Mass timber can provide a high level of fire resistance. During a fire, wood chars at a predictable rate, and the wood beneath the char layer is not significantly affected by fire or heat. Therefore, as a means of achieving required fire resistance, a sacrificial layer of wood can be used to protect the required minimum-sized structural elements. Typically, most mass timber components char at approximately 0.65 mm/min when exposed to a standard fire such as that of CAN/ULC S101: Standard Methods of Fire Endurance Tests of Building Construction and Materials (ULC, 2014). This results in a sacrificial thickness of 70–90 mm at the outer layer of the timber element that is exposed to fire. Steel connections between wood/timber elements can also be protected by either recessing the connections into the wood or covering them with sufficient sacrificial wood material to provide thermal protection.

This approach enables mass timber to provide the required fire resistance rating; however, it does not isolate the timber from the fire, and the exposed timber will contribute to both the intensity and duration of the fire. As further discussed in Chapter 6, exposing mass timber in areas of the building where exposed timber finishes are already permitted can provide the level of performance required by the NBC.

It may be desirable to expose a considerable amount of timber, and in many cases, it is also practical to expose the timber within void spaces. In fact, the International Building Code in the United States (ICC, 2021) permits exposed mass timber elements in buildings up to 9 storeys (see Section 6.2.2 of Chapter 6 for details). A recent compartment fire testing program funded by the U.S. Forest Service, managed by the American Wood Council, and performed at RISE in Sweden demonstrated that, compared to the provisions in the International Building Code (ICC, 2021), larger exposed areas are possible, while providing the requisite level of fire safety (Brandon et al., 2021). A code change proposal to increase the allowable amount of exposed mass timber on the ceilings of Type IV-B construction in the International Building Code has been submitted and was approved at the ICC Committee Action Hearings in April 2021. Final consideration of the proposal will be heard at the ICC Public comment Hearings in late 2021.

The development of an Alternative Solution for a fully exposed timber building was, however, beyond the resources and time available in preparing this guide. Nevertheless, with further analysis, it may be feasible to demonstrate that a fully exposed mass timber approach can provide the required level of performance.

2.5.2.4.2 Encapsulation

> The qualification of the peer reviewer(s) should be assessed, and any conflicts of interest that would affect the review should be identified. The peer reviewer(s) need(s) to be familiar not only with the Alternative Solutions but also with the project.
>
> A third party may be retained to resolve differences of opinion between the proponent and peer reviewer(s).

An alternative approach to providing the required fire resistance rating is to protect the wood members. At the simplest level, all mass timber members could be fully encapsulated; that is, wrapped in an acceptable, noncombustible material, such that they will neither be exposed to, or contribute to, a fire for a given period. Early examples of tall wood buildings, including UBC's Brock Commons Tallwood House, were fully encapsulated, but as experience and comfort levels developed, the level of encapsulation was reduced and larger quantities of mass timber were permitted to be exposed in later buildings and in the encapsulation provisions of the NBC (NRC, 2020).

Fully encapsulating all mass timber elements so they are completely protected from fire and do not char or contribute to fire for the 2-hr fire rating period requires an inordinate level of protection—likely four layers of 12.7-mm thick Type X gypsum board. A lesser level of encapsulation that allows some charring of timber has become widely acceptable, as indicated in the partial encapsulation provisions of the NBC solutions (NRC, 2020), which prescribe a 50-min encapsulation rating for 2-hr construction (see Chapter 6 for further discussion).

2.5.2.4.3 Recommended Approach to Fire Protection

There are a number of methods for approaching a fire-safe Alternative Solution for a tall wood building. The complexity of these approaches depends on the extent of the variance from the Acceptable Solutions being addressed. With a tall wood building for which the NBC (NRC, 2020) prescribes noncombustible construction (that is, where the building is more than 12 storeys high and/or contains occupancies other than permitted in a building of encapsulated mass timber construction), it may be necessary to start from the premise that the building will conform to the provisions for a noncombustible construction and to assess the effect on the level of risk arising from the introduction of structural combustible components. An understanding of the basics of tall building fire safety, how wood burns, and how fire and smoke is transmitted through the building is essential to this analysis. The current code provisions in Division B allow exposed wood linings for walls and floors, as well as the construction of interior partitions of solid lumber within fully sprinkler-protected buildings. This provides justification for exposing the timber structure in these and similar locations. Special considerations will be required for all shafts and concealed spaces, as envisioned in the NBC solutions (NRC, 2020). It is likely appropriate to consider encapsulation of all combustible members in exit, elevator, and other vertical shafts, unless more detailed analysis is carried out and compensating measures are taken.

> Where a peer review process is adopted, the role of the AHJ is to facilitate and help document it. This includes ensuring that the review has been completed and that all conflicts and disputes have been resolved. The AHJ may also have specific issues and concerns for the proponent and peer reviewer(s) to address.

2.5.2.4.4 Exterior Fire Spread

Exterior fire spread via windows and exposed cladding requires similar cladding to that used in noncombustible buildings. Currently, Division B provides for a performance test of fire spread up the exterior walls, related to CAN/ULC S134: Standard Method of Fire Test of Exterior Wall Assemblies (ULC, 2013). Whether combustible or noncombustible, all cladding systems must meet this level of performance. However, where there are wood structures that may be exposed to an exterior fire, it will be necessary to either isolate them from the exterior fire or incorporate them in the exterior cladding test.

Post-Occupancy Fire

To reduce water damage, particularly beyond the origin of the fire, consider specifying water mist systems to reduce the amount of water discharged (see Chapter 6).

2.5.2.4.5 Additional Considerations

Depending on the level of variance of an Alternative Solution from the Acceptable Solution in the NBC (NRC, 2020), it may be appropriate to review the performance of the building relative to the first principles, including:

- response to real fires, as opposed to standard fires;
- potential smoke movement through the building;
- occupants' ability to evacuate;
- firefighter safety; and
- response to disaster events, such as earthquakes or another event that may disable water supplies and inhibit firefighter response.

A review of these issues is provided in Chapter 6.

Some Alternative Solutions will require ongoing maintenance and/or may limit what alterations can be made to a building in the future. This should be established by the proponent as part of the Alternative Solution and should be peer reviewed. A mechanism should be provided to advise the owner and subsequent owners of necessary maintenance. This may include, for example, discussion in the fire safety plan and/or notices on title.

2.5.3 Alternative Solutions That May Be Required

In addition to the Alternative Solutions required to address combustibility, it is probable that other Alternative Solutions will be required to address other design details where Acceptable Solutions are not available.

Additional building aspects that may require Alternative Solutions include:

- protection of combustible concealed spaces;
- fire stopping;
- mechanical and sprinkler flexible joints;
- behaviour of mass timber panel shear walls and their connections;
- size effects in mass timber panel construction;

- protection of connections in mass timber panel assemblies;
- prefabrication and erection considerations; and
- weather protection.

As with any engineered solution, the responsibility and liability of the Alternative Solution remains with the proponent.

From a structural perspective, the complexity of an Alternative Solution application for a tall wood building would, in large part, be in assessing the performance of a timber-based, lateral load-resisting system. For this reason, the use of a hybrid structure consisting of a concrete or structural steel lateral load-resisting system and a timber gravity-resisting system would simplify the design and approval process significantly, and help move a project forward in a jurisdiction that may prefer a more conservative approach. This may be necessary in the event that scheduling limits the design as well as the research and development process, or funding is insufficient to cover the full scope of an Alternative Solution application process for an all-timber structure.

In either case, it is expected that a structural Alternative Solution for a fully exposed tall wood structure would include a considerable amount of nontraditional modelling and analysis, and a full independent peer review verification of the design and construction process.

As with any building, whether a high-rise or not, there will be elements that do not directly conform to the solutions in Division B and which may be appropriately addressed with Alternative Solutions.

Section 6.3 of Chapter 6 contains information on the development of a fire-safe Alternative Solution, and Section 5.3.7 of Chapter 5 contains information on alternative structural design solutions for tall wood buildings.

2.6 EXAMPLES OF TALL WOOD BUILDING SYSTEM SOLUTIONS

There is a growing number of systems for tall wood structures. Each has benefits and drawbacks that should be weighed for a particular project, and each offers designers an opportunity to adapt and improve upon those systems or introduce new systems for tall wood buildings. This guide makes no recommendation regarding the appropriateness of any one system; rather, it is the intent to discuss a wide range of approaches, including all-wood, wood–concrete hybrid, and wood–steel hybrid systems.

In the remainder of this chapter, several systems are discussed in detail to highlight system integration concepts. Section 5.1 of Chapter 5 provides an overview of these and other wood and wood-hybrid systems.

> **Building Performance**
>
> While the fabrication precision and stability of mass timber allows for the use of virtual models and building information modelling tools, there may be instances where the concept is not sufficiently developed to invest in a detailed virtual model. In this case, the ease of which innovative concepts can be prototyped in mass timber and transferred to the mass timber building is an advantage.

2.6.1 All-Wood Systems

The ability of any single material to solve all structural issues is relatively unlikely in a tall wood building. In general, steel, concrete, and possibly other structural materials, such as fibreglass and aluminum, may be employed in the finished building. All-wood systems typically use steel connection details and concrete foundation systems but otherwise predominantly use wood for the vertical and lateral load-bearing systems.

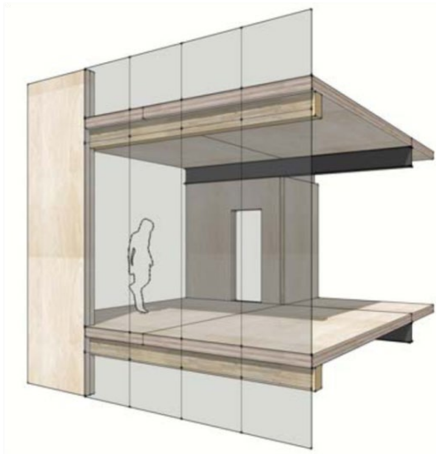
2.6.1.1 FFTT

FFTT is an all-wood and wood–steel system introduced by Michael Green and Eric Karsh in 2008 (Green, 2012). The FFTT system is adaptable to a variety of building types, scales, and locations. The general principle is the use of mass timber panels "tilted up" as balloon frame walls and columns and a central core with either wood or imbedded steel ledgers and beams that receive wood floor slabs. Green and Karsh conceptualized FFTT at heights up to 30 storeys in a Vancouver high-seismic context. In recent years, FFTT has been adapted to several variations that are unique to different applications, with different types of mass timber panels considered.

Several different approaches to the floor structure have been developed by MGA and Equilibrium Consulting. Each variation offers a different benefit, from cost-effectiveness to acoustic insulation performance, and from constructability and prefabrication to systems integration and optimization.

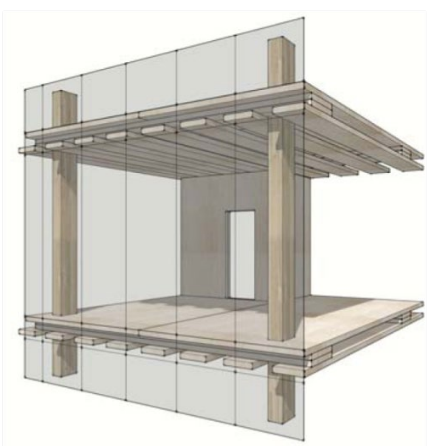
2.6.1.1.1 Structure

FFTT is a tilt-up structural system that effectively balloon-frames mass timber panels in a simple, cost-effective manner. Designed for stability in high-seismic environments, FFTT uses a "strong-column weak-beam" approach, in which energy is dissipated through the yielding of the beams rather than through the columns. The main structure of this system is composed of engineered wood columns and mass timber panels, used for floors, walls, and the building core. Above 12 storeys, steel beams and ledger beams are integrated into the mass timber panels that support the floors, thereby providing for the weak-beam solution and for additional flexibility in the system to achieve greater heights. These structural elements may be organized in a number of ways, including the following configurations (Figures 9 to 12), in order to accommodate a variety of performance criteria:



The original FFTT approach was a simple flat slab and beam system without consideration of systems integration. This configuration is economical and best used with drop ceilings to conceal exposed building systems.

Figure 9. FFTT structural configuration (courtesy of MGA | Michael Green Architecture).



This floor configuration was first developed for the North Vancouver City Hall project to allow for services to be run below the mass timber panels with high acoustic performance and two directional systems integration.

Figure 10. North Vancouver City Hall structural configuration (courtesy of MGA | Michael Green Architecture).

In the Wood Innovation and Design Centre floor system, the floor/ceiling panels are staggered, and beams are added between columns for support. This provides the same structural effect as a thicker slab, while saving in material. In addition, the staggering provides acoustic performance benefits and allows services to be run in the channels above and below the floor.

Figure 11. Wood Innovation and Design Centre structural configuration (courtesy of MGA | Michael Green Architecture).

"W" and "V" profiles are a simplified floor construction method for preassembled "w" or "v" beams made of mass timber. By creating triangular box beams with increased depth, less material than in flat floor slab solutions is needed. The depth of the triangular boxes matches the depth of the main beam line. Triangular forms allow for the integration of services in the coffers above and below as long as the structure is compartmentalized for fire and is sealed. The system was developed for ease of lifting and assembling the prefabricated floors, increased site efficiency, and speed of erection.

Figure 12. "W" floor system (courtesy of MGA | Michael Green Architecture).

2.6.1.1.2 Integration of Services

At a building scale, services are integrated in a manner similar to that for a typical concrete building: continuously through vertical shafts and locally through fire–rated vertical and horizontal penetrations. Within each unit or suite, integration may be handled in one of the following three ways, depending on the method of fire separation employed and the desired interior finish.

1. CNC (computer numerical control) or route out chases within the mass timber panels to receive all services.

This method is popular in Europe but requires a high level of preconstruction coordination that is not typical of North American construction practice. Furthermore, this approach offers no flexibility during construction.

2. Provide noncombustible chases or cavities to run services outside the fire protection layer.

This method, used with the encapsulation approach to fire separation, is the most flexible approach and is most akin to current North American construction practice (Figure 13).

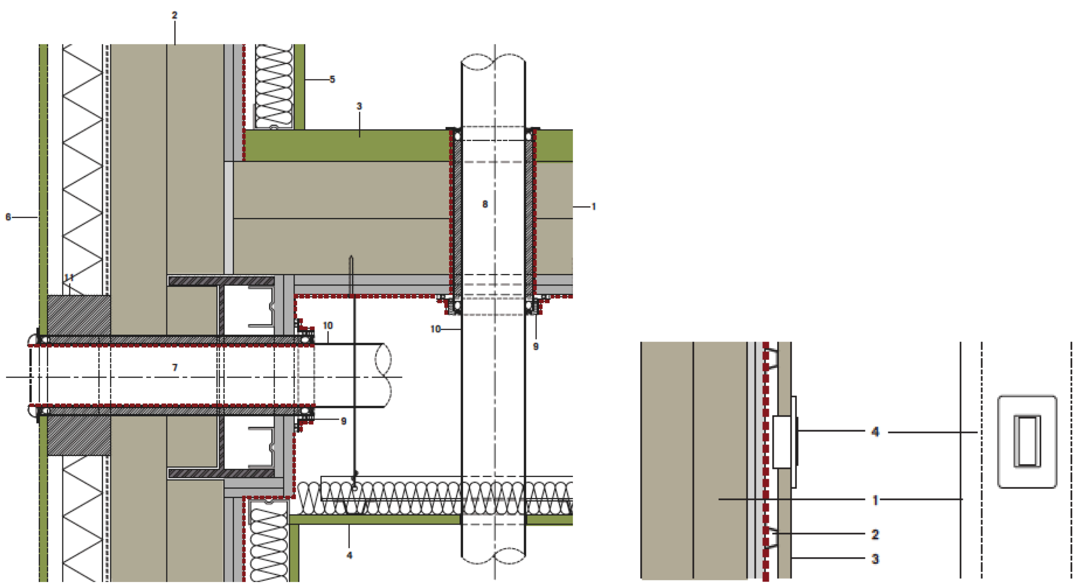


Figure 13. Services integration: encapsulation approach (Green, 2012).

3. Provide a zone of services along the floor perimeter in corridors and at doorways to run services and outlets.

This method requires some preconstruction coordination but retains flexibility during the construction phase (Figure 14). This option could also use a sprinklered cavity at the ceiling level, which could be localized if services are grouped together.

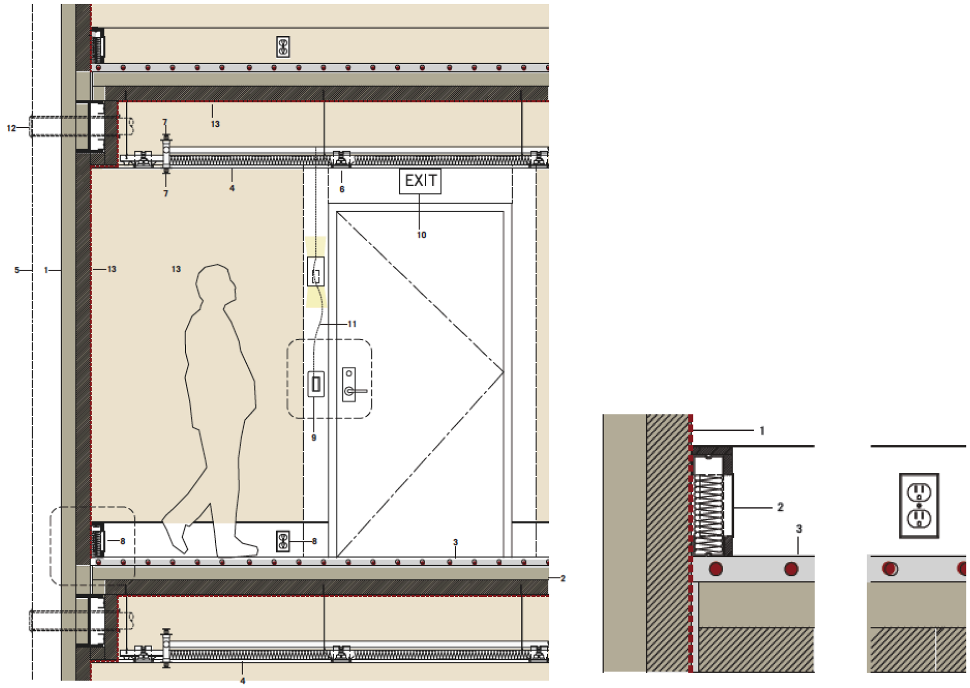


Figure 14. Services integration (Green, 2012).

2.6.1.1.3 Constructability

One of the primary advantages that FFTT construction shares with other tall wood systems is the extensive level of design and fabrication completed off-site, which minimizes on-site errors. In using mass timber panels, the number of trades on-site at any one time can be reduced in comparison to concrete construction, which ultimately results in cost savings. The tilt-up method of construction used to assemble these panels allows for fast erection. This time-saving advantage further drives down the cost of assembly, which increases the cost competitiveness of these wood solutions.

Several factors need to be taken into account when planning for the construction of an FFTT system, including:

- site location, size, and characteristics;
- panel size (dictated by manufacturers' pressing capabilities and transportation limitations);
- availability of adequate access routes from storage to site; and
- availability of one or more tower cranes at the building site.

2.6.1.1.4 Flexibility

To date, engineering with the FFTT system has shown a great deal of flexibility in tower planning and facade design but some decrease in flexibility once the system is used in applications above 20 storeys. Flexibility in tower planning is important for a number of reasons:

- An open plan, where there are no load-bearing interior partitions, allows for a variety of uses, including office or residential. This allows future nonstructural modifications to be made as uses and tenants change.
- Developers typically look to flexibility in the structural system to ensure they can manipulate the solution to meet their market goals.
- It is important to adjust the exterior character and massing of the building to the specifics of a given site. Setback requirements, view corridors, sunlight and shadow conditions, climactic and cultural conditions, neighbourhood context, and architectural expression must all be considered.

2.6.1.2 Platform-Based Approach: Stadthaus

An all-wood platform-based approach was used in Waugh Thistleton's Stadthaus project, a 9-storey residential tower in East London, constructed entirely of CLT from the first floor upward. At the time of construction, there were no precedents for this scheme because building code regulations in Europe had prevented prior development of wood buildings of this height. The construction methods pioneered through this building are now being added to UK Building Regulations in annex form.

2.6.1.2.1 Structure

Stadthaus "is the first [building] of this height to construct load-bearing walls and floor slabs as well as stair and [elevator] cores, entirely from [mass timber panels]" and, as a result, the structure will store 186 tonnes of carbon during its lifetime (Waugh Thistleton, 2013). Standard concrete construction was used for the foundation and first floor use, and CLT was used for the structure above the first floor. The core panels were balloon-framed, and the floor and wall panels were installed systematically one floor at a time, resulting in a highly rigid and structurally redundant cellular structure (Figures 15 and 16). Steel brackets were used to secure the wall panels to the ceiling/floor panels, and were installed quickly and easily with hand tools and screws. Once the panels were in place, they were furred out and encapsulated with gypsum board (Figure 17).

Architect Andrew Waugh worked closely with KLH from Austria throughout the design process in order to integrate the structural technology used in this building without sacrificing important principles of design.

Figure 15. CLT panel structure (courtesy of Waugh Thistleton).

Figure 16. CLT panel structure (courtesy of Waugh Thistleton).

Figure 17. Encapsulated CLT panel structure (courtesy of Waugh Thistleton).

2.6.1.2.2 Integration of Services

Once the CLT panels are in place, services are integrated in much the same way as in standard steel and concrete construction, and are concealed behind gypsum board. However, there are two major differences: speed and ease of installation. In a concrete-frame structure, service elements have to be fastened into the concrete, which can be difficult and time-consuming. With a CLT structure, these elements are quickly and easily secured to the CLT, using simple power tools. Figure 15 shows an example in which the ties for the fire suppression system are screwed directly into the wood, using a power drill.

2.6.1.2.3 Constructability

The prefabricated CLT panels for the platform-based approach are craned into position on-site, which dramatically reduces construction times. In comparison to the "seventy-two weeks programmed for a concrete frame design, Stadthaus took forty-nine weeks to complete. The timber structure itself was constructed in just twenty-seven days by four men, each working a three-day week" (Waugh Thistleton, 2013).

2.6.1.2.4 Flexibility

Because it is an all-wood system, the Stadthaus project provides a certain level of flexibility in that a portion of the structural panels could conceivably be demounted and reused in future building projects. However, it is unlikely that the floor plan of the Stadthaus could be reconfigured for uses other than residential because the interior load-bearing walls on each floor reduce flexibility in the floor plan for some other building types.

The Stadthaus approach has been replicated in several projects in the UK, Australia, and Italy. Depending on seismic- and wind-load conditions, the platform-based approach is simple, efficient, and effective at lower heights.

2.6.1.2.5 Other All-Wood System Examples

Origine, a 13-storey residential building in Québec City, features CLT load-bearing walls, shear walls, floors, and roofs similar to Stadthaus (Figure 18). However, glulam columns and beams were applied in location where floor layout required flexibility. In contrast, the recently completed 18-storey Mjøstårnet's CLT core walls are used only for secondary load bearing of the elevators and staircases and do not contribute to the building's horizontal stability. Glulam trusses with slotted steel plates and dowel connection act as both the load-bearing structure and the braced frame of the lateral load-resisting system. See Section 5.1 of Chapter 5 for more details.

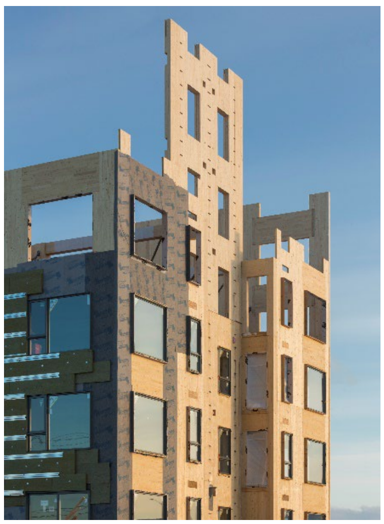


Figure 18. Origine residential building, Québec City (courtesy of Stephane Groleau).

2.6.2 Wood–Concrete and Wood–Steel Hybrid Systems

2.6.2.1 CREE (Creative Resource and Energy Efficiency)

CREE (2014), by Rhomberg, is a wood–concrete hybrid system that provides for buildings up to 30 storeys (100 m), with a 90% improved carbon footprint over comparable steel and concrete structures. In this approach, the building's structure and services are integrated in a modular system, with all components (columns, slabs, core, and facade elements) prefabricated off-site on an industrial scale.

2.6.2.1.1 Structure

In a CREE building, the basement and ground floors are reinforced concrete. Above the ground floor, the structure is composed of unenclosed double glulam columns and glulam–concrete hybrid floor slabs (Figure 19). The wood–concrete hybrid slabs offer multiple benefits, such as providing for a long span (up to 9.45 m), meeting code requirements for fire separation between floors and improved acoustic performance, and allowing for service integration between beams (Figure 20). Simple mortise and tenon joints are used at the connection between the double columns and slabs to prevent separation under lateral forces (Figure 21).

In addition to these structural elements, one or more vertical circulation cores further stiffen the building's structure. The cores may be constructed of wood, reinforced concrete, or steel, depending on regional building regulations and desired performance criteria. The final element of the system is wood-framed exterior walls, which are attached to the double columns (Figure 22). These versatile panels may be outfitted as desired, providing for aesthetic and performance-based customization of the facade. A variety of options can be incorporated, such as a single or double facade, solar screening elements, photovoltaics, living wall systems, manual vents for natural ventilation, and a number of diverse aesthetic configurations.

By using a wood hybrid structural strategy, the CREE approach is 30% lighter than reinforced concrete structures, which allows for a minimized foundation and smaller dead loads overall.

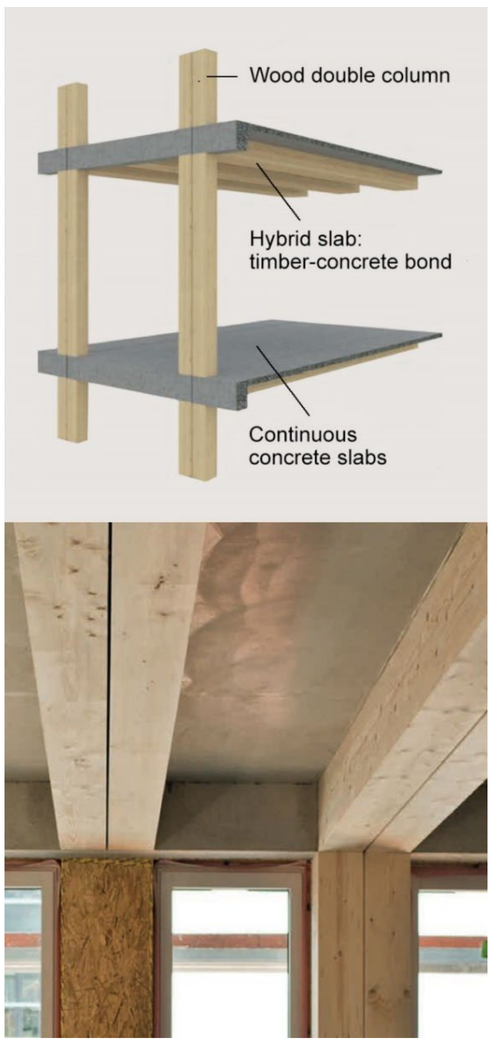


Figure 19. Column and wood–concrete hybrid slab structure (courtesy of CREE).

Figure 20. Service integration between beams (courtesy of CREE).

Figure 21. Column-to-slab connection (courtesy of CREE).

Figure 22. Facade panels (courtesy of CREE).

2.6.2.1.2 Integration of Building Services

The CREE system integrates a number of building services efficiently by providing space within the floor slabs to run service components such as mechanical, electrical, plumbing, and fire protection elements. This space may be left open or covered with a panel to provide a flush ceiling. In order to maximize the sustainability performance of the structure, Rhomberg has accounted for the ability to integrate renewable energy sources, such as geothermal or solar thermal systems, among others, as well as systems for more stringent performance criteria, such as low-energy, passive house, or plus-energy standards. Because the various elements are situated within the slab structure, thinner floor plates and reduced floor-to-floor heights are achievable.

The CREE system successfully integrates an exposed wood structure with localized coffers for building services.

2.6.2.1.3 Constructability

The primary structural elements of the CREE system are prefabricated in the shop (Figure 23) and lifted into place on-site with a crane (Figure 24). Simple connection details are carefully designed, which minimizes the number of complex details that need to be executed on-site. For example, while the floor slab is lifted into place (Figure 24), a round mortise in the slab slides over a tenon integrated into the wall panels. The detailing of connections such as these, in addition to prefabrication, provide for an efficient construction process, proceeding at a rate of approximately 1 storey per day with a crew of five people. This was proven in 2012 when the 8-storey (27-m) prototype LifeCycle Tower ONE building, designed by Hermann Kaufmann, was constructed in 8 days.

Figure 23. Fabrication of facade panels (courtesy of CREE).

Figure 24. Floor slabs lifted into place (courtesy of CREE).

2.6.2.1.4 Flexibility

CREE's primary structural system provides for an open floor plan that may be reconfigured for a variety of uses during its life cycle to accommodate commercial, institutional, or residential spaces. This flexibility can be maintained throughout the building's life span if non-load-bearing walls are integrated in such a way that they can later be removed without causing damage, and if services are carefully planned and integrated from the outset.

2.6.2.1.5 Other Examples of Hybrid Systems

Built on the success of LifeCycle Tower ONE, HoHo Wien employs the same approach of using prefabricated kits of parts while pushing to the height of 24-storey at 84 m. Similar to LifeCycle Tower ONE but different in detail, HoHo Wien has a concrete core, timber wall panels with pre-attached columns, a service-integrated floor panel (Figure 25), and a concrete ring beam (Figure 26).

Figure 25. Floor panels with preinstalled services (courtesy of Cetus Baudevelopment).

Figure 26. Interior of exposed timber structure (courtesy of Cetus Baudevelopment).

Wood–steel hybrid systems take advantage of the ductile properties of steel, its high strength-to-volume ratio, and fast installation. The use of steel braces as a lateral restraint system is common in many wood buildings, including the 12-storey Tallwood 1 in Langford, B.C. See Section 5.1 of Chapter 5 for a list of hybrid projects.

2.6.2.2 Concrete Jointed Timber Frame Solution

This conceptual solution for a 42-storey tower was introduced by Skidmore, Owings & Merrill LLP (SOM, 2013) in their *Timber Tower Research Project* report (Figure 27).

Figure 27. Concrete jointed timber frame (courtesy of SOM).

2.6.2.2.1 Structure

In SOM's hybrid structure, "The Concrete Jointed Timber Frame consists of solid mass timber products connected with steel rebar reinforcement through concrete joints. Mass timber products are used for the primary structural elements such as [CLT] for floors and shear walls, and [glulam] for columns. Steel rebar reinforcement is connected to the primary structural elements by drilling holes in the timber and epoxy bonding reinforcement in the hole. The connection of timber member to timber member is done via lap splicing reinforcement through the concrete joints. The result is a band of concrete at the perimeter of the building and bands of concrete at all wall/floor intersections. Supplementary reinforcement is provided in the concrete perimeter beams to achieve long spans as well as the concrete link beams which couple the behaviour of individual panels. Additional structural steel elements are used at the joint locations to connect the primary timber members during erection and prior to concreting the joints. The system is approximately 80% timber and 20% concrete by volume for a typical floor… [and] approximately 70% timber and 30% concrete by volume when the…

substructure and foundation, [consisting of belled caissons], are considered" (SOM, 2013) (Figure 28).

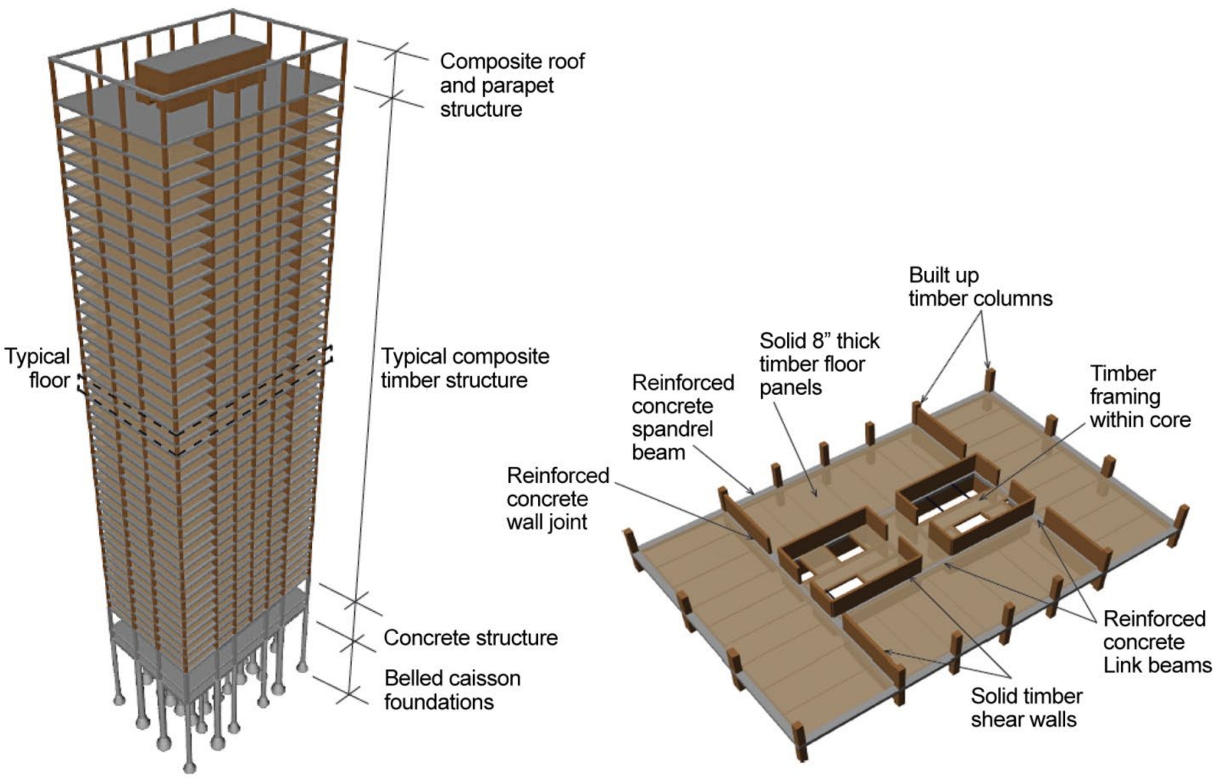


Figure 28. Concrete jointed timber frame (courtesy of SOM).

2.6.2.2.2 Service Integration

Services are integrated into the concrete jointed timber frame system in much the same was as in a standard steel or concrete structure. "Primary mechanical and plumbing systems are routed vertically within the units and distributed on a floor–by-floor basis" (SOM, 2013), and it is expected that penetrations will be required for plumbing. It is recommended that wherever possible, penetrations be routed "through the concrete connecting bands in the shear walls, away from the boundary elements" (SOM, 2013). This is because the concrete bands may be reinforced as required with steel to accommodate penetrations. The remaining services (electrical, telecom, and data) are routed through the core and distributed to the units.

The SOM system assumes a dropped ceiling will be used to conceal the building services.

2.6.2.2.3 Constructability

SOM (2013) states that the structural system may be "constructed similar to a structural steel building with metal deck slabs in terms of erection and sequencing of trades. The vertical column and wall elements are connected to the corresponding vertical elements on the stories above and below with structural steel end fittings. This allows the erection of the timber elements to proceed up the building, without immediate concreting of the joints. The formwork for the concrete joints would be supported on the vertical structure so that re-shoring is not required. The lower portions of the spandrel beams were also designed as precast concrete in order to avoid re-shoring of concrete elements".

2.6.2.2.4 Flexibility

The SOM study focused on a residential structure and used the interior shear wall approach. While long floor spans allow flexible interior layouts, shear walls limit flexibility in the floor plan. Shear walls located within the leased area may be eliminated by using supplementary load-resisting systems on the perimeter of the building. However, this dual system approach is less efficient and more complicated.

2.7 REFERENCES

Abrahamsen, R. (2017). *Mjøstårnet – Construction of an 81 m tall timber building*. Internationales Holzbau-Forum IHF 2017. https://www.moelven.com/globalassets/moelven-limtre/mjostarnet/mjostarnet---construction-of-an-81-m-tall-timber-building.pdf

Brandon, D., Sjöström, J., Temple, A., Hallberg, E., & Kahl, F. (2021). *Fire safe implementation of visible mass timber in tall buildings – compartment fire testing.* (RISE report 2021:40). Gothenburg, SE: RISE Research Institutes of Sweden.

CREE. (2014). *CREE by Rhomburg*. https://www.creebuildings.com/

Green, M. C. (2012). *The case for tall wood buildings: How mass timber offers a safe, economical, and environmentally friendly alternative for tall building structures*. Vancouver, BC: Michael Green Architecture. https://cwc.ca/wp-content/uploads/publications-Tall-Wood.pdf.

International Code Council (ICC). (2021). *International Building Code*. Washington, DC: Author.

National Research Council (NRC). (2020). *National Building Code of Canada*. Ottawa, ON: Author.

National Research Council (NRC). (2005). *National Building Code of Canada*. Ottawa, ON: Author.

Skidmore, Owings & Merrill LLP (SOM). (2013). *Timber tower research project*. New York, NY: Author. http://www.som.com/ideas/research/timber_tower_research_project

Society of Fire Protection Engineers (SFPE). (2020). *Guidelines for peer review in the fire protection design process*. https://www.sfpe.org/standards-guides/guides/peerreviewguide

Stuart, D. M. (2010, August). Project specific peer review guidelines. *Structure Magazine*, 66-70.

Underwriters Laboratories of Canada (ULC). (2013). *CAN/ULC S134: Standard method of fire test of exterior wall assemblies*. Toronto, ON: Author.

Underwriters Laboratories of Canada (ULC). (2014). *CAN/ULC S101: Standard methods of fire endurance tests of building construction and materials*. Toronto, ON: Author.

Warnock, A. C., Quirt, J. D., & Lio, M. (2002). *Fire and sound control in wood-frame multi-family buildings.* Ottawa, ON: Canada Mortgage and Housing Corporation.

Waugh Thistleton Architects. (2013). *Murray Grove: The original timber tower*. https://waughthistleton.com/murray-grove

Cost and Value

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ABSTRACT

This chapter provides an overview of the often unrecognized value propositions that tall wood buildings present. There is a tendency to focus on the bottom-line construction budget of these projects at an early stage, when other positive attributes have not fully been explored and incorporated into the overall project financial model. This chapter presents a more holistic view of project value from a costing perspective; the intent is to prompt greater consideration of using mass timber earlier in the costing process to complement standard practices for costing any building project.

Even though numerous types of tall wood buildings have been built around the world, mass timber towers are still considered innovative. However, the increase in empirical information about these structures has helped address many unknowns that were previously considered risks. An overview of the various forms of contracts that are available, and how each of them affects tall wood buildings in terms of risk transfer and involvement of the team members is discussed.

Some guidance is also provided on how mass timber structures affect both the construction and overall cost of a project based on information from three Canadian projects. This chapter is not intended to be an estimating textbook; therefore, it focuses on the areas that interested parties (developers, consultants, contractors) need to consider, rather than on the process of estimating.

Mass timber is a prefabricated product. Prefabrication provides several benefits to any construction project, particularly with respect to schedule. This chapter is intended to help the reader quantify what those benefits may be so that the costing of a building appropriately reflects them. The prefabricated approach also provides some end-of-life advantages for tall wood buildings, which are also discussed.

Actual or predicted pricing has not been provided because dollar values are valid only for a particular moment in time at a particular location. Where appropriate, approximate costing ratios for comparison with concrete and/or steel structures have been provided. Readers should note, however, that as the mass timber marketplace changes, these ratios will change, on both the demand and the supply side.

3.1 INTRODUCTION

Developing reliable budgets for construction projects that incorporate any innovative technology presents challenges to developers, owners, consultants, contractors, and even authorities having jurisdiction (AHJ). Stakeholders may be uncertain about how to deal with the perceived risks associated with new technology. Often, a typical response to this is to allocate a (sometimes arbitrary) financial value to the risk, whether it is warranted or not.

This chapter presents a more holistic view of mass timber project value from a costing perspective, and attempts to quantify a number of the more intangible components that should be factored into the costing process. These include:

- the effect different contracting environments can have on the success of integrating mass timber into a project
- the effects of mass timber use on the design and construction process
- the schedule benefits that can be realized with tall wood buildings
- the differences in hard and soft cost components of the budget
- the value propositions that tall wood buildings present, including at end of life

Marketability/Profitability

Differentiation is an important aspect of marketing. For buildings, added complexity potentially leads to greater risk. Wood is a simple material for prototyping concepts. Because mass timber lends itself to automation in the fabrication of components, it allows for rapid prototyping and transfer of concepts from prototype to reality.

Information regarding these components has been drawn from three Canadian projects, which are profiled in this chapter.

Absolute costing for tall wood buildings is not provided in this chapter because many variables (e.g., time, location, building design) are involved in the costing of a project. Instead, the areas within a budget in which differences occur between a tall wood building and a concrete or steel framed one are identified. Where appropriate, approximate costing ratios for tall wood buildings are provided for comparison with those for concrete and/or steel structures. As the mass timber marketplace changes and matures, however, these ratios will also change, on both the demand and the supply side.

3.2 OVERVIEW OF REFERENCE CASES

Since the original edition of the tall wood guide was published (Karacabeyli & Lum, 2014), numerous mass timber high-rise projects have been completed, and many more are currently under construction. All of them have provided large amounts of data that have helped, and will continue to help, promote the use of mass timber for tall buildings.

For the costing section of this edition of the guide, more detailed information has been gathered from three projects, all unique in their own way:

- Brock Commons student residence, University of British Columbia (UBC), Vancouver, B.C.
- Origine Condos, Quebec City, Que.
- Tallwood 1, Langford, B.C.

A number of case studies on these projects have been written, which provide useful further reading. We are indebted to the various team members and stakeholders of these projects for the insights and valuable information they have provided. The review of these projects has been based primarily on the author's industry experience and knowledge of the overall construction process rather than on academic studies. As such, the potential benefits and opportunities provided by these projects are more speculative than empirical, having been identified through the lens of the actual life cycle of a construction project.

3.3 COST DIFFERENCES TO EXPECT WITH TALL WOOD BUILDINGS

All projects, regardless of the owner, need a workable cost model or pro forma to make the project viable. The cost model relies on creating enough of a difference between the input costs and the project's value in terms of the revenue it can generate. In this section, the costs of the various components of a tall wood building that may differ from those of a conventional project are highlighted.

3.3.1 Soft Costs

Soft costs typically cover all the non-construction-related activities associated with a project. While many soft costs are unaffected by the project typology (e.g., land purchase/value), others will be influenced by the fact that the building is constructed from mass timber. The key soft cost variables are:

- professional fees
- financing costs
- development charges
- insurances

> **Regulatory Acceptance**
>
> All mass timber is supported by product and design standards which allow it to be an Acceptable Solution as encapsulated mass timber construction (EMTC) up to 12 storeys. The role of this guide is to provide the background that supports EMTC in the NBC and the links to other sources of information to support the use of Alternative Solutions where needed.

3.3.1.1 Professional Fees

Even when a tall building is within the realm of Acceptable Solutions in the National Building Code (NBC) (NRC, 2020), the effort required of the design team is different from that for a concrete or steel-framed building. Additional consultant time/effort is currently required to address acoustics, fire ratings, mechanical and electrical coordination. Certain jurisdictions are also less familiar with mass timber as a structural system. Thus, the designers must conduct additional communication and coordination with the authority having jurisdiction (AHJ) to familiarize them with the design and how it meets the code requirements. Limited knowledge about pricing mass timber buildings can also lead to one (or more) redesigns in order to meet a budget.

All these factors can lead to higher professional fees than those for concrete or steel buildings (at least at the time of writing). However, once more designers and AHJs become familiar with mass timber structures, and more empirical performance data become available, design fees for tall wood buildings should normalize toward those for concrete or steel buildings.

If the right people are at the table, under the right contractual arrangement, the design process for a tall wood building can run as smoothly as that for any other project. Recommendations regarding the most suitable delivery method are provided in Section 3.5. This guide provides insights into Alternative Solutions for achieving the necessary code compliance for tall wood buildings (see Chapters 5, 6, and 7 regarding structural, fire, and energy considerations, respectively**);** however, much of the information provided is equally relevant to projects that meet the NBC Acceptable Solutions (NRC, 2020). This guide can therefore be used as a tool to help the design community achieve project code compliance, especially for those new to mass timber.

When a project is beyond the NBC (NRC, 2020) size limitations for tall wood buildings or it uses an alternative approach to meet code requirements, a premium can be expected for design services, and the design and approvals phase will take longer. The consultant team will have to put more work and time into developing Alternative Solutions. Once these are in place, they will need to be reviewed by the AHJ for acceptance, which may initiate further design work or reviews; this could include additional peer reviews or specialist panels, or the addition of more designers to the project's consultant roster. The effort and cost involved will depend largely on the experience and comfort level of the AHJ, so will vary by location. The premium for design services for the Brock Commons project at UBC was approximately 3% of the construction value, although this project is an extreme example.

Building Performance

The precision of computer numerical control fabrication of mass timber components supports the use of more advanced engineering analysis and design. Where questions still remain, the precision and ease of working with wood facilitates the use of full-scale prototypes to assess field assembly issues or conduct confirmation testing.

A study of the UK construction industry by the Royal Institute of British Architects (2013) found the following specific measured benefits of Design for Manufacturing and Assembly (DfMA) (Dodge Data & Analytics (2020):

- 20–60% reduction in construction time with greater schedule reliability
- 20–40% reduction in construction costs
- 70% reduction in on-site labour
- improved health and safety conditions for the workforce
- reduced need for skilled labour on-site which is lacking in some sectors
- improved construction quality with ± 70% reduction in defects and rework on-site
- reduction in the number of RFIs
- facilitates building deconstruction and reuse of components

Building information modelling (BIM) is an important element when designing a tall wood building. In the past, BIM was seen as a net cost to a project, with specialists required to operate the systems. Now, however, it is a standard tool in most design practices and many contractors' offices/sites. There should be no cost premium to using BIM; it can generate many downstream cost savings, given that it provides the benefits of a more collaborative project delivery model and the need to facilitate communications throughout the building project. In the European market, which generally is further advanced in terms of its adoption of mass timber, use of BIM is a given, especially to transfer information between the base design and the computer numerical control manufacturing equipment. In their *Prefabrication and Modular Construction 2020* report, Dodge Data & Analytics (2020) noted that overall, using prefabrication techniques benefits projects that use BIM. Chapter 8 provides more information on BIM.

3.3.1.2 Financing Costs

The cost of borrowing money to build a project should not be affected by the type of structure being built. However, because tall mass timber construction is a relatively new innovation, financiers may be cautious about lending money for a system that is unfamiliar to them. This reluctance should recede over time, but it is expected to have some effect on the rates available to developers of tall wood building projects in the near future. However, this will be offset by the shorter construction schedule required for a mass timber structure, which will reduce the loan period and associated interest accrual.

An Equity Research report (RBC, 2020) gives favourable predictions for mass timber buildings because of factors such as ease of construction, aesthetic and experiential benefits, and ecological advantage. It is expected that above-market growth will occur over a 15- to 25-year time frame, as the benefits of mass timber become better understood. North American lumber producers are well positioned to drive the change.

Some variation in financing may also result from different insurance premium rates during and post construction. These can affect the amount of the project that investors are willing to finance for both construction and operation of a mass timber building. Section 3.3.1.4 provides additional information on insurance.

3.3.1.3 Development Charges

Certain progressive jurisdictions are considering offering incentives to encourage developers to use mass timber in order to reduce carbon emissions and increase carbon sequestration. These incentives for example, could be in the form of increased density allowances, which could increase a developer's return on a particular property. The City of Vancouver (n.d.) notes in its *How We Build/Renovate* document that "We plan to identify and remove barriers where our existing rules make it difficult to use low carbon construction materials and practices in new buildings. We are also planning incentives to support developers interested in trying out lower carbon materials and construction practices."

Project Delivery

From a developer's perspective, smaller and less costly foundations, shorter on-site construction times, smaller delivery vehicles and cranes, and reduced nuisance to nearby occupants (i.e., noise, runoff) may open more sites to development opportunities.

3.3.1.4 Insurances

Various types of insurances are available throughout a project's life cycle, from concept to operation, including:

- professional liability – errors and omissions (design and construction phase)
- Course of Construction or Builders Risk (construction phase)
- general liability (construction and operational phase)
- property insurance (operational phase)
- new home warranty on residential projects (operational phase)

The insurance industry wants and needs to learn more about the mass timber and tall wood building market. In North America, the industry has not yet fully grasped the difference between mass timber and conventional wood framing as a structure, and perceives risk where it does not necessarily exist. In some cases, this has resulted in much higher insurance rates than those for concrete/steel structures.

As more information becomes available and is shared, including historical claims experience, the insurance industry will gain a greater comfort level with the mass timber construction approach. This should lead to an easing of the premiums for tall wood projects relative to other construction methods. Some insurance carriers are starting to recognize that mass timber buildings are different from conventional wood-framed buildings in terms of risk.

The following are some key insurance factors (M. Leslie Inc., 2019) that mass timber and tall wood building owners, designers, and contractors should be aware of:

- The absence of any real loss history for mass timber buildings means that the insurance industry is approaching this market with caution, and in some cases has been unwilling or unable to price mass timber projects.

- Insurers, conservative by nature, have questions about the effects of fire, water, and delamination on mass timber products, along with the robustness of the supply chain and manufacturers.
- These questions extend into the operational phase of a project, and insurers are uncertain about the effect of fire and moisture damage on mass timber buildings, and the associated remediation costs.
- Above a certain project value, no individual insurer will take on the risk alone; they will require a subscription involving other carriers to pool the risk. At the time of writing, this value in Canada was $30 million. Each additional subscribing carrier raises the premium cost.
- The long-term performance of mass timber and tall wood projects will be an issue for new home warranty coverage for the foreseeable future, until insurers have a greater understanding of the associated loss experiences.

3.3.2 Construction Costs

3.3.2.1 Construction Planning and Project Costing

Good planning is critical to a project's cost-effectiveness. The early involvement of the general contractor and the mass timber trades, through a more collaborative project delivery method (Section 3.5.1) can have a significant effect on the success and cost competitiveness of a mass timber building project. Allowing this planning to occur in parallel with design can influence design decisions that improve the cost-effectiveness of a project.

Construction planning for a tall wood building has many similarities to that for a steel, concrete, or even low-rise conventional wood-framed building. Site layout, materials handling, power requirements, safety, construction quality, work sequencing and schedule, security, fire prevention/protection (Chapter 6), and weather protection (Chapter 7) are all parts of a comprehensive construction plan for any building.

In the U.S., a Wood Products Council report (WoodWorks Wood Products Council, 2021) noted that while mass timber is relatively new in the U.S., the number of buildings has grown significantly over the last decade. As with any new building material or type, insurance challenges are anticipated. The report lists the information now available to help insurance brokers and underwriters evaluate the relative risks of mass timber construction. The report also advises developers, owners, and contractors to work with experienced brokers because this is key to realizing insurance premiums that reflect the benefits of building in mass timber.

Building information modelling can be a valuable asset; if the investment is made to develop and work in a common model with input from all stakeholders, it becomes a powerful planning and communication tool for the construction team. At the tender stage, this is particularly important because it can communicate to trades the many benefits that mass timber structures have, which in turn can reduce the fear factor and associated contingency dollars.

3.3.2.2 Budget Costing Considerations

Building with mass timber, like any major construction material, includes components that can generate savings, and others that must be addressed in order to minimize additional costs. As more tall wood and mass timber building projects are built, these considerations will become better known and will be incorporated into standard industry practices among the architecture, engineering, construction, and owner-operated (AECO) community.

Some key areas to consider when budgeting for a tall wood building project are:

- structural system selection (see also Chapter 2 and Section 5.1)
- moisture management requirements (see also Chapter 7)
- labour requirements and infrastructure
- effective/efficient materials handling and storage
- effect on scopes of other trades
- reduction in on-site construction time

Construction Moisture

Ensure the cost of a construction moisture risk mitigation plan is included,and is adjusted for the project (schedule, time of year, and construction sequence and practices to be used). While there is a learning curve, having an appropriate plan ensures an efficient and effective response. See Section 7.7.1 for guidance on developing a plan.

Construction Fire

Ensure the cost of construction fire risk mitigation plans is included and is adjusted for the project (site access, and construction sequence and practices to be used). Sub-trades should provide input so that the risk mitigation measures of the plan are not inadvertently sidestepped (see Section 6.15 in Chapter 6).

3.3.2.2.1 Structural System Selection

Creating cost-effective mass timber design is possible when the right team members are at the table from the beginning. The Tallwood 1 project in Langford, B.C. has demonstrated this to the project's ownership group: an experienced mass timber designer, working closely with the mass timber supplier/installer and a knowledgeable general contractor configured a project that the team priced out to cost 7% less than the comparable concrete design.

The type of project and the client's requirements will drive the selection of the most suitable mass timber structural system, and so are key in developing a cost-effective mass timber structure. There are a number of options to choose from:

- post, beam, and panel
- post and platform
- tilt up (e.g., balloon)
- platform hybrid on alternative frame (e.g., structural steel)

Each option has different cost implications, so its relative merits need to be factored in, along with material availability. Different types of mass timber panels also vary in price. The type of project being constructed (e.g., multi-family residential versus open plan office) also plays into the structural system selected. Section 5.1 contains examples of structural systems that may be considered given the site conditions and building occupancy. There are likely cost trade-offs between material/connections, labour, and construction time. For some buildings, a hybrid solution (mass timber with steel and/or concrete) may be the most feasible solution. For example, while two concrete cores are used as the lateral load-resisting system in the Brock Commons building, it may be more feasible in some markets to use eccentrically braced steel frames as the lateral load-resisting system. Alternatively, where seismic loads are low, CLT shearwalls may be used as the lateral load-resisting system, which was the case for the Origine building.

Urban planning can also influence/affect the type of structural system selected, and can lead to increased costs for mass timber structures. Building setbacks and height restrictions are often based on what has historically been achieved with concrete structures, but they are not necessarily suitable for mass timber structures. Setbacks can affect grid layouts, which in turn can result in reduced structural efficiencies and increased floor structure depths to accommodate load transfer elements. This increases the overall building height, which increases costs and makes meeting the building height restrictions more challenging.

3.3.2.2.2 Labour Needs

Prefabricated mass timber elements are far less labour intensive to use than other structural systems because the labour force required on-site during erection of the structure is significantly reduced. The Brock Commons building at UBC was erected with an average crew of just 10 (Figure 1) (UBC, 2016). A comparable cast-in-place concrete structure would typically require a crew of about 40 workers. The reduced workforce required to erect a structure with prefabricated mass timber elements will help reduce overall project costs.

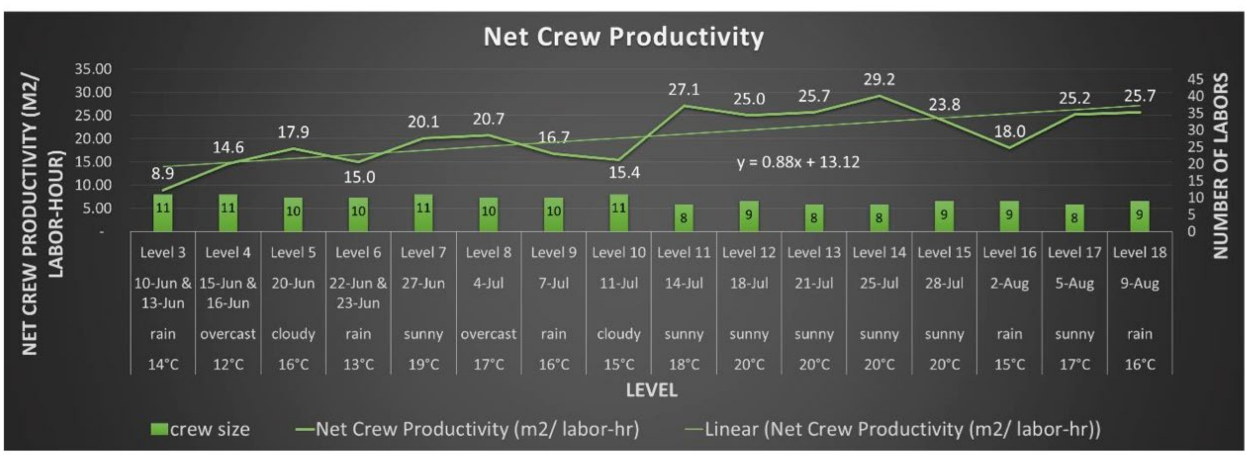

Figure 1 **Brock Commons net mass timber crew productivity chart (Kasbar, 2017).**

3.3.2.2.3 Materials Handling

The speed with which mass timber structures can be erected changes the dynamics of materials handling on-site. With conventional construction, raw materials must be delivered to the building site in order to start the work; thus lay-down areas are required and double handling of materials occurs. This affects efficiency, and leads to extra cost and construction time.

By comparison, mass timber elements are ready to be installed right off the truck. A single crane hoist can typically lift a piece directly off the truck and place it in its final installation spot. Mass timber manufacturers typically work on a just-in-time delivery basis for their materials, so they load the materials on the trucks in the correct sequence to facilitate this. However, collaboration with the manufacturer can provide some flexibility in the construction schedule in order to deal with unexpected events, particularly when there are unusual site restrictions or delivery time constraints.

Crane selection can be influenced by the type of structure being built. Depending on the project, the use of a mobile rather than fixed tower crane may now be a viable option for building a mass timber structure. Chapter 8 provides further details on this.

3.3.2.2.4 Effect on Other Trade Scopes

All construction projects involve the work of a diverse range of specialty construction trade contractors, including mechanical, electrical, drywall, excavation, and concrete forming. The types of systems these trades can use in a tall wood building are affected, some positively, some negatively; therefore, the associated cost and time implications should be identified and quantified during the design phase. Some examples include:

- drywall encapsulation measures
- plumbing and electrical materials and systems
- ceiling finishes

The differences in these systems are discussed in more detail in Chapter 8 (Section 8.2.3.5).

Trades that have worked on a mass timber structure have acknowledged that there are scheduling benefits associated with these projects. Trades that worked on Brock Commons at UBC felt they could reduce their costs on future tall wood building projects to reflect not only the shorter on-site duration of the work, but also a greater degree of reliability regarding the schedule. On a multi-phase mass timber project in Langley, B.C., trade pricing for the third phase was lower than that of the previous two phases because a cost-benefit had been achieved in the earlier phases.

3.3.2.2.5 Cost Savings Associated with Reduced On-Site Time

Construction managers/general contractors include General Requirements within their costing on all projects; these are also sometimes called General Conditions or Division 1 costs. General Requirements are the support resources needed to build the project—the people and equipment, etc., that are required during the construction phase.

There are two main categories of General Requirements: those that are time dependent, and those that are fixed, regardless of the schedule. Typically, time-dependent items account for approximately

80% of the General Requirement costs. Any time reduction will therefore save the contractor on-site staff and equipment costs. However, the design period for a tall wood building can be longer than that for a concrete or steel frame building, so the contractor may use more senior staff time during preconstruction planning, which would offset some of the savings.

These same General Requirement savings may also be realized by some of the trade contractors, particularly those that are typically on-site for the duration of the project, such as mechanical and electrical.

3.3.2.3 Managing Project Uncertainty

Every project, regardless of structure type, has a risk profile that affects the overall cost of the project. Tall wood buildings have their own risks and opportunities to reduce the risk profile. Owners and designers should be aware of these. Some key ones are:

- limited experience of contractors and designers with mass timber systems (at the time of writing)
- expectations and acceptance of authorities having jurisdiction
- reduced effect of industry labour shortages
- effect of shorter timelines on financing costs

From a contractor's perspective, some of the major risks and opportunities include:

- the ratio between labour and material costs of the structure
- moisture protection
- improved safety and waste management opportunities
- opportunities created due to tighter fabrication tolerances
- risks associated with tolerance differences between site and prefabricated components

These are discussed in more detail in Chapter 8 (Section 8.3.2).

3.4 QUANTIFYING THE SCHEDULE BENEFITS OF TALL WOOD BUILDINGS

The building of tall wood structures has a number of scheduling advantages, starting at the foundation stage and continuing through to the finishes. Every project is somewhat unique, and the degree to which the different phases of work contribute to those cost savings will vary. However, regardless of where any improvement in the project delivery timeline is achieved, it can positively affect the cost of the project. The following are some examples:

Foundations: tall wood buildings impose lower loads on the ground, which often allows smaller or simpler foundation systems to be used compared to concrete buildings.

Parallel work streams: the prefabrication of mass timber components can occur simultaneously with the on-site early works; thus, the completed products can be assembled with far less effort and time on-site compared to cast-in concrete.

Shorter cycle time: an efficient design will allow storeys of a tall wood building to be erected faster than those of a concrete building.

Weather tight faster: the envelope in a mass timber structure can be installed far closer to the live floor than can be achieved in a concrete-framed building (Figure 2).

Figure 2 Brock Commons envelope installation within 2 storeys of "live" structure floor (UBC, 2016) (courtesy of KK Law).

Following trades start earlier: being weathertight (against wind, rain, etc.) sooner allows finishing trades to start their work a number of weeks earlier compared to cast-in place concrete structures.

On the Origine project, the decision was made to use CLT panels for the exterior walls. As a result, there was no lag time between the floor being erected and the walls below being installed, and the prefabrication panel prep allowed windows to be installed rapidly once the walls were erected. While the decision to use CLT panels was driven primarily by the project's vision of being the world's first all mass timber tall wood building, Nordic noted that the accelerated enclosing of the building had a positive effect on when the subsequent trades were able to commence their tasks.

In combination, the many scheduling benefits associated with constructing a tall mass timber structure can be significant. For example, the on-site schedule for constructing a 12-storey building on a site with poor soil conditions could be reduced by up to 4 months compared to concrete structures. For a developer, this would represent some significant cost advantages to their project pro forma.

Figure 3 shows the potential construction schedule time savings for mass timber buildings compared to steel and concrete buildings (WoodWorks Wood Products Council, 2019).

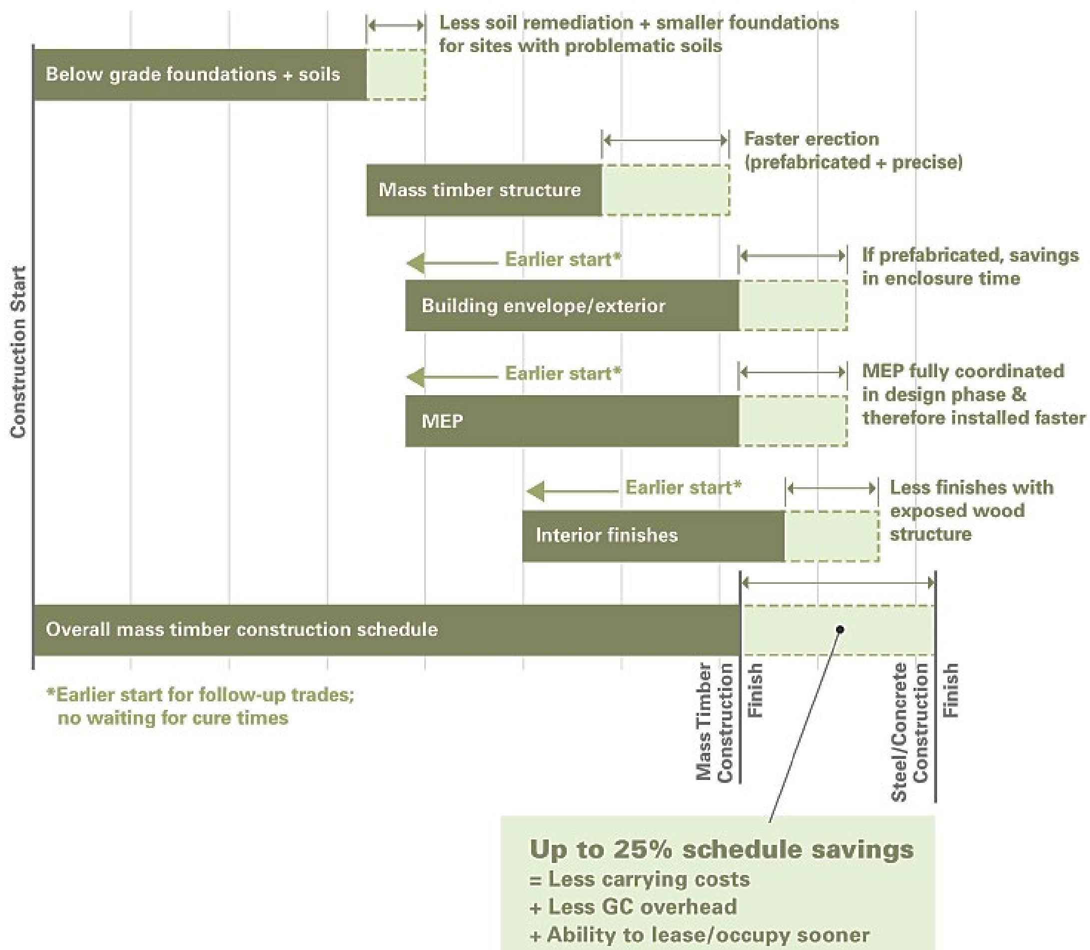

Figure 3 **Compressing the typical construction schedule with mass timber, and potential schedule savings compared to steel and concrete construction.**

3.5 CONTRACTUAL FORMATS AND BUSINESS RELATIONSHIPS

3.5.1 How Contract Type Can Affect the Successful Use of Mass Timber

A contract is a vehicle for agreeing not only the roles and responsibilities of the respective parties, but also the transfer of risk (and the associated reward). This applies to both the prime and subcontract levels. While there are different methods of construction project delivery (Figure 4), some are more advantageous if the project uses a high degree of prefabrication.

Summary of common forms of project delivery in Canada Source: Canadian Handbook of Practice for Architects[35]

Method of construction project delivery	Standard form of contract	Description
Design-Bid-Build	RAIC Document Six: Canadian Standard Form of Contract for Architectural Services *Followed by* CCDC 2 Stipulated Price Contract (CCDC 3 or CCDC 4 may also be used)	Owner engages the architect to provide design services and prepare construction documents which are issued for competitive bids. General contractors submit bids for the project and the construction contract is typically awarded to the lowest bidder. The architect administers the construction contract.
Construction Management	CCDC 5a - Construction Management Contract for Services CCDC 5b - Construction Management Contract for Services and Work	Owner engages the architect to provide design services and prepare construction documents. The Construction Manager works for the Owner as a consultant providing services that normally include design input on constructability, cost estimating, scheduling, bidding, coordination of contract negotiations and award, timing and purchase of critical materials, cost control and coordination of construction activities. Depending on the type of contract used, the Owner may or may not engage the Trade Contractors directly.
Design-Build	CCDC 14 Design-Build Stipulated Price Contract CCDC 15 Design-Builder / Consultant Contract (subcontract)	A method of project delivery in which the Owner contracts directly with a single entity that is responsible for both design and construction services for a construction project.
Public Private Partnership (P3)	No standard form of contract	A form of partnership between the public and private sectors where a combination of financing, design, construction, operation and maintenance of public projects relies on alternate sources of financing and revenue to cover all or part of the capital costs (including debt servicing, principal payment and return on equity), as well as operating and maintenance costs of for the project.
Single Purpose Entity for Integrated Project Delivery (IPD)	CCDC form of contract for IPD to be released 2017 In the UK, JCT Constructing Excellence In the US, AIA Document C195	This new form of project delivery creates a new single purpose entity or limited liability company, which includes members such as the owner, architect, construction manager and other key project participants in the design and construction the project. The entity enters into contracts with non-members for design, trade contractors and suppliers for services, labour and materials. The entity enters into a separate agreement with the Owner to obtain project funding.

Figure 4 Common forms of construction delivery in Canada (Royal Architectural Institute of Canada, 2009).

Contract types that include greater collaboration between all team members early in the project life cycle have an increased chance of integrating prefabrication into a project; therefore, the use of contract forms such as Construction Management, Design Build, and Integrated Project Delivery is most appropriate. These agreements help increase early information flow between key team members. When a mass timber manufacturer can work directly with the designers, general contractor, and other trade contractors, more efficient and fully embedded prefabricated solutions can be achieved. The design and construction team will have a greater understanding of fabrication, transportation, and installation requirements, and can factor them in as details are developed

The *Prefabrication and Modular Construction 2020* report (Dodge Data & Analytics, 2020) (Figure 5) highlights the effect of project delivery method on successfully integrating prefabrication into a project. The most commonly cited obstacle to using prefabrication was that the project delivery method prevented effective prefabrication planning.

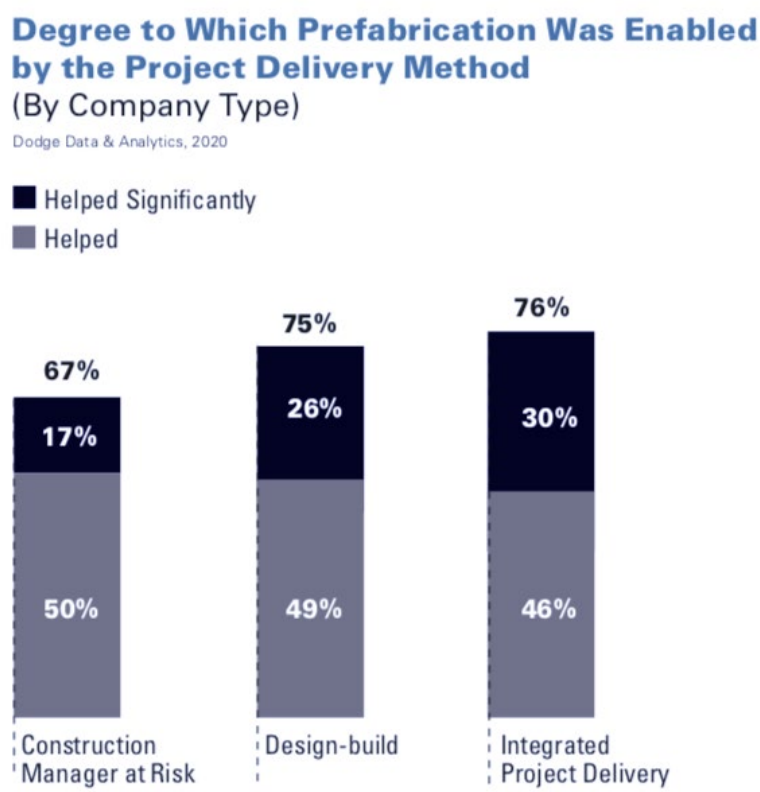

Figure 5 How project delivery method affects the ability to use prefabrication on a project (Dodge Data & Analytics, 2020).

Under the design-build, public-private partnership (P3) and Integrated Project Delivery (IPD) models, contractual responsibilities change the procurement process: the general contractor is given the ability to select key trade partners to join the team at the appropriate time to achieve the maximum benefit. IPD also involves shared risk and reward, so having the right people at the table at the right time creates the optimum result for the whole team. However, P3 and IPD methods are typically efficient only on larger projects (> $50 million).

3.5.2 The Effect of Tall Wood Buildings on Conventional Relationships and Interactions among Team Members

Using prefabricated mass timber components on a project can change relationships and interactions among team members. It will affect both the roles of the team members and how they interact.

By definition, "pre"-fabrication refers to work that is done ahead of time. In order to facilitate this, mass timber work needs to be incorporated into a project's design at an early stage, ideally by engaging the manufacturers (or at least a knowledgeable specialty consultant) at that time and understanding what services they may be able to provide. They can then work with the designers on developing the details for building the engineered wood components and how they will interact with the site-built work.

With this design component added to the manufacturer's responsibilities, Design Assist or even Design Build contracts can be used to engage their services. Where this design scope and responsibility starts and stops as it relates to the base building consultants' work needs to be clear.

Using mass timber on a project will alter conventional interactions among team members by changing the lines of communication. On more traditional mid- and high-rise projects, the lines of communication are long established, with practitioners going through a learning curve to become proficient/efficient. In this guide, we hope to accelerate this learning by providing some insight into what team members should ask and when, and how to best optimize the process.

3.5.3 Procuring Mass Timber Specialists Early While Retaining Competitive Pricing

The construction industry already has experience integrating prefabrication into the procurement chain, often as material suppliers or specialty trade contractors. Advances in design and construction technology, and in particular BIM, have facilitated the use of off-site techniques.

Despite the many benefits, project teams often have concerns about engaging a mass timber supplier at the preliminary stage of the project when limited information is available: the fear is insufficient cost certainty to make this decision. However, this does not need to be the case. A project team has the option of engaging a mass timber manufacturer (through a Request for Proposal [RFP] process) just for preconstruction services. While this may lead to engaging the company for the actual construction, it is not a given.

The mass timber supply chain includes a wide range of services and companies, such as:

- full service, proprietary systems that provide end-to-end service, including design, manufacture, value-added processing, and potentially installation
- supply-only manufacturers, who may or may not include value-added processing beyond simple "blanks"
- specialist fabricators who offer end-to-end services but purchase blanks from supply-only manufacturers rather than manufacturing their own

Each will bring different skill sets and knowledge to the preconstruction stage, so a project team should determine what is of most value to the project as a whole.

Because definitive pricing will not be possible and cannot be used as the sole evaluation tool for comparing proponents, it is helpful to consider what else each company brings to the table. Suppliers can be asked to respond to a Request for Qualifications/Request for Proposal that allows them to detail the following areas:

- experience supplying (and potentially installing) materials for similar sized and scoped projects
- production capacity to manufacture the project
- typical project lead times
- typical protection and storage of finished materials ahead of shipping
- technology capabilities and digital interaction with other team members

Cost can still be used to compare proposal responses. Proponents can be asked to provide the following types of pricing:

- hourly rates for their installers,
- fixed pricing ($/m^3, $/m^2) for the anticipated structural elements (e.g., 5-ply CLT),
- their cost to be involved in the design development process, and
- their proposed overhead and profit margins.

Pricing for offshore suppliers should include any duties/ tariffs. Those suppliers should also be able to demonstrate that their proposed materials have been approved for use in North America.

In issuing an RFP, the project team should provide parameters for the work that will help the proponents respond fairly and accurately. This should include the anticipated timelines for the various stages of the project, and any specific requirements that need to be included, such as surface finishing, weather protection requirements, and hoisting responsibility.

A mass timber supplier/installer can be integrated into a project at the optimum time to maximize the benefit it can bring to the overall process.

Understanding mass timber prefabrication costs

Mass timber suppliers can provide their pricing in a variety of formats, depending on the contract type or budgeting stage. However, this does not provide an insight into how that pricing is arrived at. For example, a side-by-side comparison of the cost of a cubic metre of CLT material and a cubic metre of concrete cannot be made because it will not capture the additional time and effort expended in manufacturing the products, the shipping costs, and the labour savings prefabrication generates during construction.

Each manufacturer will have different ratios, but the following all form part of a supplier's pricing:

- Facility overhead – the cost of the factory, equipment, management, and administration
- Raw materials – primarily lumber and adhesives
- Factory labour – material handling between different production stages
- Design input – structural engineers, design technologists, BIM modellers
- Shipping – transport of finished product to site

3.6 INHERENT VALUE AT PROJECT END OF LIFE

Over the last number of years, many municipalities and governments at different levels have focused on reducing construction, renovation, and demolition waste. Statistics Canada data suggest that this waste accounts for approximately 12% of all solid waste generated in Canada, and historically, most of it has been disposed of in landfills.

Tall wood buildings offer a major end-of-life advantage over their concrete and steel counterparts. Significant energy input is needed to remove conventional tall building structures, whether to reuse the materials or merely demolish the buildings, whereas mass timber should often be reusable in its "as-is" state.

Demolition by implosion or progressive brute force removal typically renders the raw materials unusable. In contrast, mass timber structures are a series of prefabricated elements that are more easily disassembled. At the time of writing, no (modern) tall wood buildings had been deconstructed, but the following can be expected:

- Removed pieces can more readily be salvaged whole for reuse than those from demolished buildings.
- Salvaged mass timber material will have a higher value than demolished concrete or steel materials.

- Mass timber can be reused for a variety of alternatives, which can provide different markets for the resource.

A cost-benefit analysis should be performed for each project to assess the viability of reusing the tall wood structure. Because salvaged mass timber components can be readily remodelled for reuse in other projects, there is the potential to account for the net present value of the recovered resource (essentially, considering the building as a resource asset bank).

3.7 OTHER VALUE PROPOSITIONS FOR TALL WOOD BUILDINGS

Using mass timber for construction in general, but particularly for tall buildings, can create other value propositions that a project team should consider when examining the costing of a tall wood structure. These can be divided into two major categories:

- those that enhance the construction process or reduce risk, and
- those that create additional value for the end users.

When considering the factors that enhance the construction process or reduce risk, the following should be assessed:

- increased opportunity for prefabrication by other trades (Chapter 8, Section 8.3.2.6)
- reduced schedule-related risks; e.g., labour availability, weather (Chapter 7)
- reduced temporary site infrastructure requirements and costs

When considering the factors that add value for the client and end users, the following should be assessed:

- psychological and productivity benefits for occupants due to biophilia (Chapter 4)
- potential for increased lease rates for buildings that create healthier workspaces, are more environmentally friendly, and improve worker productivity
- detrimental environmental effects of material choices on the future carbon economy and global warming potential (Chapter 4)
- increased site selection possibilities due to lighter overall building weight

The benefits of a lighter structure merits further discussion. Real estate and land prices have consistently risen over the years. Although there is significant demand for land, not all sites are suitable for high-rise construction, often due to soil conditions; weak bearing soils may be incapable of supporting the load of a concrete building. This will either preclude use of these sites for greater building density or require expensive piled foundation solutions.

Lighter tall wood buildings reduce the load imposed on soils; therefore, less costly foundation solutions can be used on sites that would require piled foundations for concrete structures. For example, the Brock Commons project at UBC was able to use smaller foundations. As a result, the construction manager (Urban One) indicated that it led to cost savings.

Land with weak bearing soils may be lower priced because of the perceived reduced development/density potential. Consequently, if a developer can make a mass timber tower work on the site, their project pro forma will benefit significantly. Areas with poor soil conditions may also be prone to flooding; in these cases, use of a podium structure (mass timber on 1- or 2-storey concrete) is an option.

3.8 CONCLUSION

Accurate costing of a tall wood building project is critical to ensuring it is viable. However, construction industry stakeholders' limited experience with mass timber often leads to high preliminary budgeting. A lack of information or appropriate knowledge results in the addition of contingency funds to address perceived risks, which are frequently not real. In many cases, this makes a tall wood building project seem financially unviable and causes it to be dismissed as an option too early in the budgeting process.

In reality, there are many cost benefits associated with using mass timber. When they are properly identified and accounted for, tall wood buildings can be economically competitive with the more conventional alternatives. Cost savings (and additional revenue generation) due to shorter construction schedules can be realized. Fewer workers on-site and reduced site equipment needs also have positive effects on a project's cost. While the raw material cost of mass timber is, at the time of writing, higher than that of concrete or steel, as more production facilities come on stream, material costs can reasonably be expected to decline. At the same time, the global movement on reducing the embodied carbon in our buildings can only further reduce the gap between building with mass timber versus steel or concrete.

For developers, the use of wood as a major project element will have an increasingly greater effect on their project pro forma. Changes in municipalities' approach to embodied carbon, such as that of the City of Vancouver, will provide incentives to use mass timber. More locations become viable for mass timber building sites as a result of reduced soil loading. Faster construction will lead to faster revenue generation and return on investment. And as the science regarding biophilia gains greater awareness, selling the stress-reducing properties of tall wood buildings to homeowners, or the employee productivity gains to business tenants, can only provide opportunities to price this additional value accordingly.

3.9 REFERENCES

Canadian Wood Council (CWC). (2018). *Origine case study*. Ottawa, ON: Author. https://cwc.ca/wp-content/uploads/2019/03/Origine-Case-Study.pdf

City of Vancouver. (n.d.). *Climate Emergency Action Plan – How we build/renovate*. Vancouver, BC: Author. https://vancouver.ca/files/cov/how-we-build-and-renovate-targets-and-actions.pdf

Dodge Data & Analytics. (2020). *Prefabrication and modular construction 2020*. Smart Market Report. Bedford, Massachusetts: Author. https://proddrupalcontent.construction.com/s3fs-public/PrefabModular2020SMR_11Feb-compressed.pdf

Karacabeyli, E., & Lum, C. (Eds.) (2014). *Technical guide for the design and construction of tall wood buildings in Canada* (1st ed.). (Special Publication SP-55E). Pointe-Claire, QC: FPInnovations.

Kasbar, M. (2017). *Investigating the performance of the construction process of an 18-storey mass timber hybrid building*. (Unpublished master's thesis). University of British Columbia, Vancouver, BC. https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0347252

Koo, K. (2013). *A study on historical tall-wood buildings in Toronto and Vancouver*. Québec, QC: FPInnovations.

M. Leslie Inc. (2019). *Current builders risk and professional liability insurance markets for wood mid-rise and mass timber buildings*. North Bay, ON: Ontario WoodWORKS!

McLain, R., & Brodahl, S. G. (2021). *Insurance for mass timber construction: assessing risk and providing answers*. Washington, DC: WoodWorks Wood Products Council. https://www.woodworks.org/wp-content/uploads/wood_solution_paper-MassTimber_INSURANCE.pdf

National Research Council (NRC). (2020). *National building code of Canada*. Ottawa, ON: Author.

Royal Architectural Institute of Canada. (2009). *Canadian handbook of practice for architects*. (2nd ed.). Manotick, ON: Author.

Royal Bank of Canada (RBC). (2020). *Mass timber: Build it, and they will come* (Equity Research Report). RBC Capital Markets.

Royal Institute of British Architects. (2013). *RIBA plan of work 2013: Designing for manufacture and assembly.* London, UK: RIBA Publishing.

University of British Columbia (UBC). (2016). *Brock Commons tallwood building case study: Construction overview*. Vancouver, BC: Author.

WoodWorks Wood Products Council. (2019). *Mass timber cost and design optimization checklists*. Washington, DC: Author. https://www.woodworks.org/wp-content/uploads/wood_solution_paper-Mass-Timber-Design-Cost-Optimization-Checklists.pdf

WoodWorks Wood Products Council. (2021). *Insurance for mass timber construction: Assessing risk and providing answers.* Washington, DC: Author. https://www.woodworks.org/wp-content/uploads/wood_solution_paper-MassTimber_INSURANCE.pdf

Sustainability

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GLOSSARY

Acidification potential is the deposition and accumulation of substances that contribute to acidification.

In the environment, acidification can affect buildings (e.g., corrosion) and the productivity and diversity of ecosystems.

Bill of Materials (also referred to as a Bill of Quantities) is a summary of the estimated quantity of materials that is used to estimate the cost of constructing a building.

This information is used as the basis for life cycle assessment (LCA) calculations.

Biophilia refers to humans' innate need for connections to nature and other forms of life.

Edward O. Wilson (1984) introduced and popularized the hypothesis in his book *Biophilia*. He defines biophilia as "the urge to affiliate with other forms of life", and discusses how when individuals have contact with nature, their neurological, physiological, and psychological responses result in less stress, lower blood pressure, more relaxation and positive moods, and increased concentration.

Building information modelling (BIM) is an intelligent 3D model-based digital process.

BIM gives architecture, engineering, and construction professionals the insight and tools to efficiently plan, design, construct, and manage buildings and infrastructure.

Carbon cycle refers to the constant movement of carbon from the land and water through the atmosphere and living organisms.

This cycle is fundamental to terrestrial life. The Earth's physical climate system is affected by the biogeochemical cycles of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These three greenhouse gases have increased in the atmosphere since pre-industrial times, and this increase is the main driving cause of climate change (Ciais et al., 2013).

Carbon storage or sequestration: Trees absorb and store carbon while they grow. A portion of harvested wood is incorporated into long-lived products such as buildings and furniture, which can continue to store carbon for decades (CWC, n.d.).

Concrete carbonation is a chemical reaction whereby, over time, CO_2 in the atmosphere reacts with the calcium oxide in concrete to form calcium carbonate.

According to the Concrete Centre in London,[1] this is essentially a reversal of the chemical process that occurs when making the cement used in concrete; i.e., the calcination of lime in

[1] https://www.concretecentre.com/Performance-Sustainability/Circular-economy/Whole-life/Carbonation-of-concrete.aspx

cement kilns, which accounts for roughly half of concrete's embodied CO_2. Carbonation is a slow and continuous process that progresses from the outer surface inward.

Cradle-to-cradle refers to the design and production of products in such a way that at the end of their life, they can be truly recycled (upcycled), thereby imitating nature's cycle, with everything either recycled or returned to the earth, directly or indirectly through food, as a completely safe, nontoxic and biodegradable nutrient.

Cradle-to-gate is an assessment of a partial product life cycle from resource extraction (cradle) to the factory (gate) (i.e., before it is transported to the consumer).

Embodied carbon is the total greenhouse gas emissions (in tonnes CO_2 eq) generated to produce a built asset. This includes emissions caused by extraction, manufacture, transportation, and assembly of every product and element in the asset.

Environmental Product Declaration (EPD) is a third-party verified document that provides a set of environmental impact data for a product based on a life cycle assessment that has been conducted in compliance with ISO 14025 (ISO, 2006a).

EPDs are developed by professionals following ISO-prescribed criteria to enable manufacturers to communicate environmental impacts of their products consistently. An EPD includes information about the environmental impacts associated with a product, such as raw material acquisition; energy use and efficiency; content of materials and chemical substances; emissions to air, soil, and water; and waste generation. EPDs may be used by designers on a product-by-product basis to compare a range of environmental impacts.

Eutrophication potential: nutrient enrichment of aquatic ecosystems which results in increased biological productivity of phytoplankton and subsequently affects the availability of oxygen for aquatic animals (Bare, 2012).

Eutrophication can cause algal blooms that alter species diversity in the affected area, and which can produce toxins that have human health effects (e.g., shellfish poisoning) (Knockaert, 2021).

Fuel substitution involves converting all or a portion of existing energy use from one fuel type to another with the goal of reducing greenhouse emissions.

For example, using combustible waste materials such as sawmill residues to produce energy avoids the use of other energy sources.

Global Warming Potential (GWP): changes in atmospheric greenhouse gas concentrations affect the planetary energy balance, with implications for the global climate (e.g., temperature change, precipitation volume and frequency, storm frequency, etc.).

According to the U.S. Environmental Protection Agency (n.d.a.), GWP was "developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2)".

Greenhouse gases are emissions that trap heat in the earth's atmosphere.

These include carbon dioxide, methane, nitrous oxide, and fluorinated gases (such as chlorofluorocarbons, hydrochlorofluorocarbons, and hydrofluorocarbons found in refrigerants).

Leadership in Energy and Environmental Design (LEED) is the dominant voluntary green building rating system in North America, and is used extensively around the world.

Administered in Canada by the Canada Green Building Council, certification is on a scale ranging from Certified, Silver, Gold, and Platinum at the highest level, and is based on the total points achieved.

Life cycle is the consecutive and interlinked stages of a product from raw material acquisition or generation of natural resources to the final disposal.

Life cycle assessment (LCA) is the internationally standardized approach (ISO 14040 ISO, 2006b]; ISO 14044 [ISO 2006c]) for evaluating a product, assembly, or whole building's potential environmental impacts on air, land, and water over its entire life cycle from resource extraction to its end-of-life disposition.

LCA can provide reports on a range of lifetime environmental burdens like smog creation, water pollution, and resource depletion. More information is available from the UN Life Cycle Initiative.[2]

Life cycle inventory (LCI) refers to the inputs and outputs at each stage of the life cycle of a product, such as log inputs to a sawmill and combustion stack emissions.

Material Safety Data Sheet (MSDS) is a document that contains information on the potential hazards (health, fire, reactivity, and environmental) of a chemical product and how to work safely with it.

Natural capital refers to the stock of renewable and non-renewable resources such as plants, animals, air, water, soils, and minerals that "combine to yield a flow of benefits to people".[3]

Particulate matter comprises a mixture of solid particles and liquid droplets found in the air.

[2] www.lifecycleinitiative.org

[3] https://naturalcapitalcoalition.org

Particulate matter is one of the categories of primary air pollutants referred to by the Government of Canada as Criteria Air Contaminants.[4] Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye.

Product Category Rules are a set of specific rules, requirements, and guidelines for developing environmental product declarations for one or more product categories.

Ozone depletion potential refers to the emission of substances to the atmosphere that cause a reduction in the ozone layer.

The ozone layer blocks damaging radiation from reaching the earth's surface. Loss of the ozone layer can increase damaging radiation reaching the earth's surface, which can have implications for human health (e.g., skin cancer and cataracts)[5], and plant health (including agricultural crops) (USDA, 2016; U.S. EPA, 2015 n.d.b.).

Smog potential refers to the creation of ground-level ozone, a form of air pollution, commonly composed of nitrogen oxides, particulate matter, and volatile organic compounds.

Photochemical smog is known to contribute to lung disease (Gakidou et al., 2017).

Volatile organic compounds (VOCs) are organic chemicals that off-gas from materials into the air. They can be dangerous to human health or cause harm to the environment. Like particulate matter, VOCs are one of the categories of primary air pollutants referred to by the Government of Canada as Criteria Air Contaminants.

Wood supply is the timber harvesting opportunities associated with a specific forest condition, management strategy, and timber flow policy.[6]

[4] https://www.canada.ca/en/environment-climate-change/services/air-pollution/pollutants/common-contaminants.html

[5] https://www.epa.gov/ozone-layer-protection/health-and-environmental-effects-ozone-layer-depletion

[6] National Forestry Database http://nfdp.ccfm.org/en/glossary.php

ABSTRACT

The construction and operation of buildings are major consumers of natural resources and contributors to greenhouse gas (GHG) emissions. Buildings, and the communities they create, can exert a powerful influence on the health and well-being of people and ecological systems. Construction material design choices can have a significant and immediate effect on the environmental and social impacts of a building project.

Wood structural systems can help reduce the GHG emissions from buildings by using sustainably harvested and renewable wood resources. Stringent forest management regulations and third-party certification programs help ensure that the long-term health of forest ecosystems is maintained for the benefit of all living things, while providing environmental, economic, social, and cultural opportunities for present and future generations. Once harvested and processed, wood products can then store carbon throughout their life cycle and can substantially reduce the environmental impacts of a given structure. When properly designed and maintained, wood structures are durable. At the end of the building's service life or when it is repurposed, wood components have the potential to be reused, recycled, or down-cycled with minimum additional expenditure of energy.

On the health side, research shows that there are clearly established links between wood and human well-being and performance. There is evidence of human and organizational benefits associated with wood's biophilic properties. Biophilic design introduces natural elements into the construction and interiors of buildings. When people are in contact with nature, they feel better—they experience less stress, lower blood pressure, and a more positive frame of mind.

The UN Sustainable Development goals, the UN Environment Programme International Resource Panel, and the principles of sustainable consumption and production emphasize a life cycle-based framework for considering the impacts of materials and products used in buildings. Within this context, this chapter highlights the benefits of using wood to (1) reduce the impacts of buildings on the environment, with specific emphasis on reducing GHG emissions, and (2) improve occupant health and well-being in buildings.

The objective of this chapter is to provide design teams with the guidance needed to arrive at a thoughtful balance between material use and environmental/human health performance within the context of their project. Special emphasis is placed on using life cycle assessment methodology as the primary means of quantifying the benefits of using wood. This is followed by a discussion of the various green building certification systems and other tools available for evaluating and certifying the sustainability of tall wood building systems.

4.1 INTRODUCTION

The United Nations defines sustainability as the ability to meet the ecological, social, and economic "needs of the present without compromising the ability of future generations to meet their own needs".[7] In the face of what many countries and communities are recognizing as a climate emergency, reducing both operational and embodied greenhouse gas (GHG) emissions from buildings is a top priority for policymakers and building designers.

Embodied Carbon

Embodied carbon is the total greenhouse gas emissions (in tonnes CO_2 eq) generated to produce a built asset. This includes emissions caused by extraction, manufacture, transportation, and assembly of every product and element in the asset.

Globally, the building sector is an important contributor to global warming as a result of the production of GHGs from direct and indirect (electricity) energy use during building operation (20%) and embodied carbon from the construction materials (8%) used in buildings, infrastructure, and other capital projects (UNEP, 2019). Further, for buildings constructed between 2021 and 2050, embodied carbon could be responsible for up to 50% of cumulative, life cycle GHG emissions from buildings (Bionova Ltd., 2018).[8] In 2017, energy consumption in homes and buildings in Canada accounted for 17% of total GHG emissions (Government of Canada, 2017) or about 92.5 million tonnes CO_2 eq/year.[9] Embodied carbon from residential and non-residential building construction in Canada is estimated to be about 20 million tonnes of CO_2 eq.[10]

Construction is one of the most resource-intensive industries. Globally, about 60 billion tonnes of construction minerals, ores and industrial minerals, fossil fuels, and biomass are extracted each year, most of which is non-renewable. Worldwide, the consumption of materials continues to increase, with the greatest increases occurring in the consumption of construction minerals, ores, and industrial minerals.[11] Furthermore, according to the U.S. Environmental Protection Agency (EPA), "the

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[7] https://www.un.org/en/academic-impact/sustainability

[8] Assumes that initially, embodied carbon represents 20% of total life cycle GHG emissions for buildings.

[9] www.canada.ca/en/environment-climate-change/services/environmental-indicators/greenhouse-gas-emissions.html

[10] This GHG emission estimate is equivalent to 4.3 million cars driving for 1 year and would cost Can$400 million in carbon offsets. The calculation is based on the following sources:

- Statistics Canada. GDP at basic prices, by industry, annual average. Table: 36-10-0434-03. www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3610043403
- Statistics Canada. Direct plus indirect energy and GHG emissions intensity, by industry. Table: 38-10-0098-01. https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3810009801
- Car equivalencies are per the U.S. EPA GHG equivalencies online calculator.
- Carbon cost is calculated at $20/tonne (http://www.offsetters.ca).

[11] www.resourcepanel.org/reports/decoupling-natural-resource-use-and-environmental-impacts-economic-growth

extraction, transportation, use and disposal of these materials can result in substantial environmental and health impacts, including emissions to the air, water and land, energy and petroleum consumption, use of non-renewable mineral resources, expenditure of fresh water, and land and habitat use."[12] Within this context, this chapter highlights the use of wood as a positive and immediate solution to addressing climate change and providing healthy, productive indoor environments. It also offers a series of tools that can assist designers in quantifying those benefits.

Regulatory Acceptance

High-level initiatives such as the UN Sustainable Development Goals are adapted by the various levels of government that then become actionable at the local level. For example, the City of Vancouver will take a phased approach to achieve zero operational greenhouse gas emissions and 40% lower embodied emissions in all new construction by 2030.

4.2 CARBON DYNAMICS IN FORESTS AND BUILDINGS

Forests play an essential role in the global carbon cycle by absorbing and releasing carbon dioxide in a dynamic process of growth, decay, disturbance, and re-establishment of new seedlings.[13] Over the past four decades, forests have moderated climate change by absorbing about one-quarter of the carbon emitted by human activities such as burning fossil fuels and land use change.[14] Carbon uptake by forests reduces the rate at which carbon accumulates in the atmosphere, and thus reduces the rate at which climate change occurs.[15] Carbon storage occurs during the life cycle of the tree when carbon dioxide is removed from the atmosphere through photosynthesis and is broken down into oxygen, which is released, and carbon, which is stored within the tree's biomass. Wood contains about 50% carbon by dry weight (Lamlom & Savidge, 2003), and solid wood contains around 0.23 tonnes of carbon per cubic metre.[16] At the end of the tree's life, the carbon stored in the tree is released back into the atmosphere through respiration and forest fires, thereby completing the carbon cycle.

How well forests will continue to remove carbon from the atmosphere that is emitted by human activities will affect the future rate of carbon increase in the atmosphere. This will be dictated by how

[12] www.epa.gov/smm/basic-information-about-built-environment

[13] For more information about forest carbon, and how forests function as carbon sources and sinks, see www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/forest-carbon/13085

[14] www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/forest-carbon/13085

[15] Ibid.

[16] Data sourced from the EPD for softwood lumber: https://www.awc.org/pdf/greenbuilding/epd/AWC_EPD_NorthAmericanSoftwoodLumber_20200605.pdf. Note that the EPD also converts this to 0.84 t CO_2eq per cubic metre of lumber, but using CO_2eq to describe the carbon content of something is not good practice. A CO_2 eq has physical units of Watts/m^2 and describes the net effect on the planet's energy balance from a GHG emission to the atmosphere. For carbon stored in a product, we are not referring to emissions or removals of GHGs.

much land remains forested and how well those forests are managed. However, forest management is not the only factor affecting the carbon balance of Canada's forests.

Marketability/Profitability

The current general lack of explicit regulations to achieve sustainability goals is an indication of how difficult it will be to direct individuals or firms to take the relevant actions within their control to address broader global issues such as climate change. There is, however, strong evidence that the move toward more wood construction is a step within reach.

Metsaranta et al. (2010) found that if the trend of increasing forest fire disturbances continues in Canada, forests could remain net carbon emitters for the rest of the century. Increases in the area and intensity of insect outbreaks could also cause carbon losses.[17] At the same time, some aspects of climate change, such as longer growing seasons or greater concentrations of carbon dioxide in the atmosphere, may cause increased tree productivity (at least initially) and contribute to the expansion of the treeline further north, which could cause further warming (Fischer, 2011). A warmer, wetter climate may also enhance decomposition rates. Northern regions of Canada are expected to warm faster than more southerly areas, resulting in the melting of permafrost; this may release methane from frozen soils and initiate decomposition of previously frozen organic carbon.

Tall wood building systems store carbon within their wood mass during their service life. When a tree is manufactured into a wood product, a portion of the carbon remains sequestered within the wood biomass. While the priority should always be to find new uses for building products at the end of their service life, it is worth noting that the carbon stored in wood products will return to the atmosphere if used to produce energy. If wood products are landfilled, methane and carbon dioxide will be released from anaerobic decomposition, and carbon may remain in long-term storage in the landfill (Towprayoon et al., 2019).

A portion of the carbon contained in harvested logs is released through activities such as the decay of logging residue in forests, burning of sawmill residues for energy, and the disposal of short-lived products like paper and packaging.

[17] Ibid.

Design teams should note that while the use of wood products is not a permanent mechanism for removing GHGs, collectively, cities continue to store more biomass carbon in buildings over time to accommodate a growing population (Bergsdal et al., 2007; Dymond, 2012), some of which ends up permanently stored in landfills. In Canada, the cumulative effects of increasing carbon storage in wood products over time contribute to a net carbon sink when both managed forest land and harvested wood products are considered (Environment and Climate Change Canada, 2020). Note that Environment and Climate Change Canada reports emissions from natural disturbance separate from the carbon balance on managed forest lands. Emissions from natural disturbances have led to Canada's forests being a net carbon emitter in recent years.

Project Delivery

Wood used in the built environment places a portion of the forest carbon cycle in a suspended state for as long as the building serves its function. With mass timber, it is now possible to specify wood for larger and more complex buildings. The mass timber product specifications also allow a broader range of wood species to be used interchangeably.

Addressing the carbon-related impacts of buildings through material selection offers an immediate response to global climate change, whereas reductions in operational GHG emissions for new buildings accumulate and compound over time. According to the Intergovernmental Panel on Climate Change, "rapid and far-reaching" reductions in carbon emissions need to be made within the next 20 years if irreversible consequences of global warming are to be averted,[18] and the use of wood can help achieve these goals quickly. Zero waste design strategies and efforts to optimize the durability and longevity of buildings to extend carbon storage in the wood structure are discussed in Sections 4.3.3.3 and 4.3.3.7. Several of the green building rating systems presented in Section 4.5.3 can help design teams understand and account for the factors that influence this capacity. For example, Leadership in Energy and Environmental Design (LEED) and the Living Building Challenge recognize the benefits of durable building design and the value of repurposing existing assets. While policies aimed at encouraging building disassembly and reuse as a means of retaining the carbon stored in wood structures are at an early stage in development in Canada, there are numerous efforts under way in Europe, such as the Buildings as Material Banks initiative (see following text box). Other considerations that designers should bear in mind include the suitability of a product for an application, the associated tree species and harvest practices, and the product's service life and fate at end of life. Design teams must account for these factors early in the design process to ensure that the product is properly managed at the various stages of its life cycle and to extend the length of time carbon is stored in products.

[18] www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments

Building as Material Banks

Buildings as Material Banks[19] is a European organization that is working to create ways to increase the value of building materials. Dynamically and flexibly designed buildings can be incorporated into a circular economy, which allows materials in buildings to sustain their value. That will lead to waste reduction and the use of fewer virgin resources. The organization is developing and testing new theories, business models, policies, and pilot projects for concepts such as "Materials Passports" and "Reversible Building Design", with the goal of creating buildings that have positive effects on the environment. One of the projects is "Build Reversible In Conception" (BRIC), an education tool and showcase in Brussels, Belgium that consists of a wood structure and prefabricated walls, floor, and roof boxes.[20] As of October 2018, BRIC had been dismantled, reconstructed, and transformed three times.

4.3 ENVIRONMENTAL CONSIDERATIONS OF USING WOOD

As action to address climate change becomes more pressing, most building codes have implemented energy efficiency standards for the operation of buildings during the "use" phase. Policymakers have begun to consider the significant environmental and health implications upstream and downstream of building operations in order to consider the impacts arising over the entire building life cycle from the harvest/extraction, manufacture, installation, and disposal of construction materials (see text box below). The UN Sustainable Development goals,[21] UNEP International Resource Panel,[22] and principles of sustainable consumption and production[23] (see text box below) together provide a life cycle-based framework within which to consider the environmental and health impacts of materials and product choices.

This section introduces the principles of life cycle thinking, which is key to understanding and quantifying the benefits of using wood. Then, because the life cycle of a wood building starts with harvesting trees, this section provides an overview of sustainable forestry management practices in Canada and how building with wood sourced from sustainably managed forests can help reduce the overall embodied carbon impacts of a building and improve quality of life. A discussion on the carbon storage or sequestration properties of wood is followed by a series of considerations and approaches for how wood structural systems can help reduce the GHG emissions at the design, construction, and operation/end of life phases of a building project.

[19] www.bamb2020.eu

[20] www.bamb2020.eu/pilots/bric-event

[21] www.un.org/sustainabledevelopment/sustainable-development-goals

[22] www.resourcepanel.org

[23] www.un.org/sustainabledevelopment/sustainable-consumption-production

Sustainable Consumption and Production

The key principles of sustainable consumption and production are described under the UN Sustainable Development Goal 12,[24] and include:

- improving the quality of life without increasing environmental degradation and compromising the resource needs of future generations
- decoupling economic growth from environmental degradation (i.e., improving the rate of resource productivity ["doing more with less"] faster than the economic growth rate) by:
    - reducing material/energy intensity of current economic activities and reducing emissions and waste from extraction, production, consumption, and disposal
    - promoting a shift in consumption patterns toward groups of goods and services with lower energy and material intensity without compromising quality of life
    - applying life cycle thinking, which considers the impacts from all life cycle stages of the production and consumption process
- guarding against the rebound effect, where efficiency gains are cancelled out by resulting increases in consumption

For more information about environmental performance considerations for mass timber products (and cross-laminated timber [CLT] in particular) and evaluation methodologies and standards for mass timber materials, see Chapter 11 of the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019).

4.3.1 Principles of Life Cycle Thinking

A product or material life cycle is defined as the "consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal" (ISO 14040 [ISO, 2006b]). By examining the life cycle of a product, assembly, or whole building, it is possible to find new opportunities to reduce environmental and health impacts, conserve resources, and reduce costs.[25] The scope of activities that can contribute to environmental impacts over a building's life cycle is illustrated in Figure 1. It shows a typical depiction of the life cycle of products, assemblies, and whole buildings, and highlights how three aspects of a building contribute to environmental impacts: material use, operational energy use, and operational water use.

Building Performance

In addition to wood's lower embodied carbon, the foundation requirements of wood construction compare favourably to concrete of the same size. Operationally, mass timber construction can be designed to meet the higher performance levels of the Energy Step codes. How this is achieved is discussed in Chapter 7.

[24] www.un.org/sustainabledevelopment/sustainable-consumption-production/

[25] www.epa.gov/smm

Life Cycle-Based Policies are Being Implemented Across Canada

The following are examples of Canadian policies that strive to address the impacts of building materials from a life cycle perspective:

- **City of Vancouver**: Currently, developers seeking a rezoning application need to report the embodied carbon of their proposed project. The City has set a 2030 target for the embodied emissions in new buildings and construction projects to be reduced by 40% as compared to 2018 typical practice.[26]
- **Québec**: Under Québec's Wood Charter, a comparative analysis of greenhouse gas emissions is required for structural materials in provincially funded new building projects.[27]
- **Greening Government Strategy**: The Canadian government has committed to reducing the environmental impact of structural construction materials[28] by:
    - disclosing the amount of embodied carbon in the structural materials of major construction projects by 2022, based on material carbon intensity or a life cycle analysis;
    - reducing the embodied carbon of the structural materials of major construction projects by 30%, starting in 2025, using recycled and lower-carbon materials, material efficiency, and performance-based design standards;
    - conducting whole building (or asset) life cycle assessments by 2025 at the latest for major buildings and infrastructure projects; and
    - minimizing the use of harmful materials in construction and renovation, including using low volatile organic compound materials in building interiors.

[26] https://vancouver.ca/green-vancouver/zero-emissions-buildings.aspx

[27] Quebec Charte du bois: www.mffp.gouv.qc.ca/publications/forets/entreprises/charte-du-bois-anglais-Web.pdf

[28] https://www.canada.ca/en/treasury-board-secretariat/services/innovation/greening-government/strategy.html

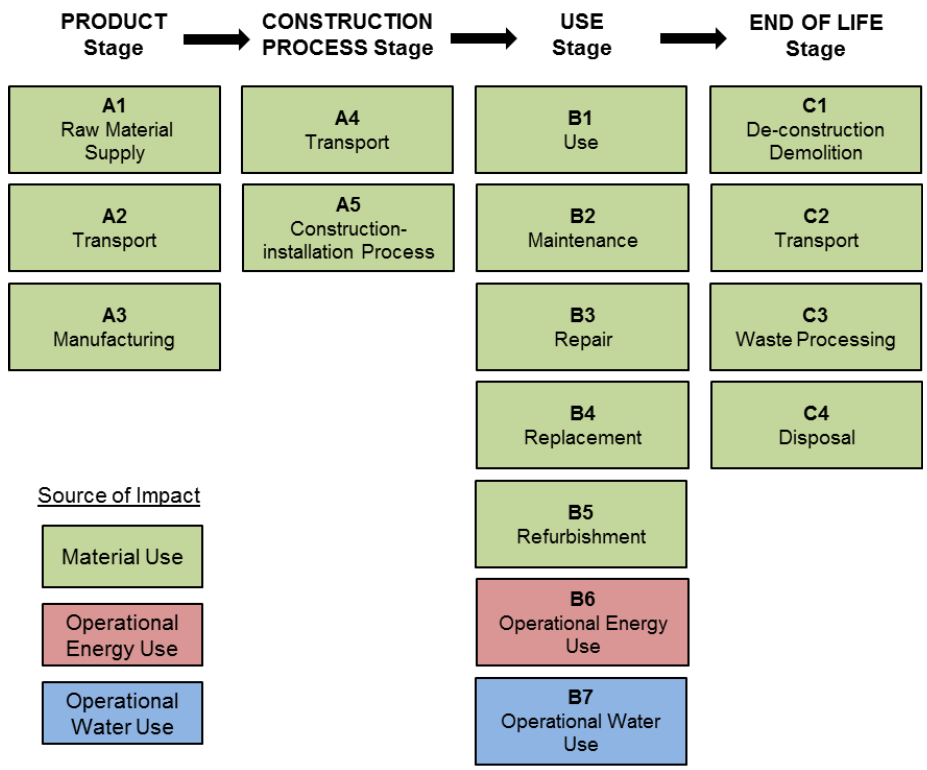

Figure 1. Elements contributing to the embodied environmental impacts over the life cycle of a building product, an assembly, or a whole building.[29]

Examples of the types of impacts buildings and building products can have over their lifetime are presented in Figure 2. Each indicator in Figure 2 is a separate consideration and has its own field of scientific study. The quality of data gathered to quantify these impacts is improving rapidly, as is the prevailing understanding of how best to minimize the impacts. Of all the different impacts that can arise from buildings and building products over their life cycle, the current focus on climate change has placed greatest emphasis on greenhouse gas emissions—not only from building operations but also from the embodied carbon, which refers to the GHG emissions associated with the manufacturing, maintenance, and decommissioning of a structure (Zizzo et al., 2017).

[29] Per EN 15804 (CEN, 2012)/15978 (CEN, 2011). See Appendix 2 for full citations of all ISO and EN standards referenced in this report.

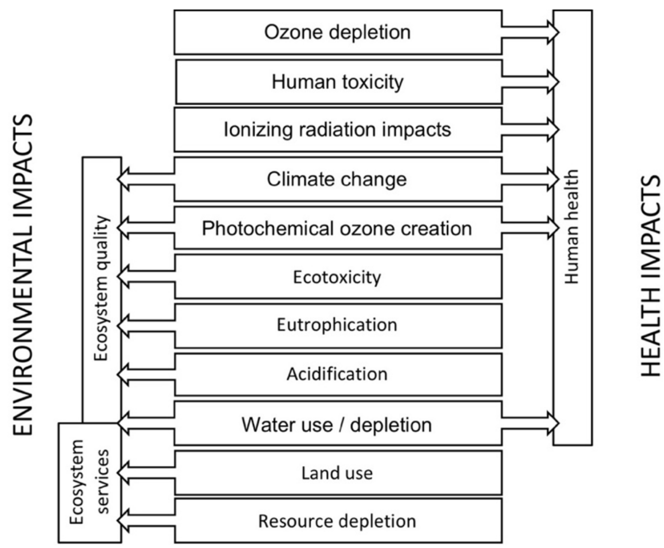

Figure 2. Impacts of buildings and building products over their life cycle.

Both positive and negative carbon emission impacts occur throughout the wood product life cycle. Wood processing is a significant source of GHG emissions associated with wood buildings (although emissions are often much less than those for alternative materials). However, Canada's forest products manufacturers are increasingly using clean technologies to minimize GHG emissions. From 1990 to 2017, direct GHG emissions from Canada's wood products industry declined by 20% (Griffin, 2019).

Global Warming Potential

Within many life cycle assessment tools, embodied carbon is reported as Global Warming Potential (GWP). This is a relative measure of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide and is expressed as a factor of carbon dioxide (whose GWP is standardized to 1).

For more information about the GWP of mass timber materials, see the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019).

Building codes in many jurisdictions are aiming for zero energy and/or zero GHG emissions in operations within the next decade. For many projects, addressing operational emissions remains the priority action, particularly in regions where grid emissions (GHG emissions associated with generating electricity) are high and the building type is energy intensive (e.g., a laboratory). However, as the operational impacts of buildings decrease through better envelope performance and cleaner energy solutions, it is important for designers to consider and control for potential corresponding increases in "embodied" impacts of products and materials (stages A1 – A5 in Figure 1) given that operationally energy-efficient buildings may have thicker walls, more insulation, triple-glazed windows, etc., which could add to embodied impacts.

Further, considering only operating carbon may lead to a zero-sum game, or worse, if it shifts operating carbon to embodied carbon without a net life cycle reduction in carbon, particularly in areas where GHGs for operational energy use are already low. For example, adding more materials to a building (e.g., insulation) will shift emissions between life cycle phases, thus reducing operating emissions while increasing embodied emissions. The resulting energy savings need to pay back the initial increase in environmental impacts in a reasonable period. A total life cycle carbon calculation solves the problem of “burden-shifting” from one life cycle phase to another by ensuring that design choices result in a truly optimized carbon solution that takes a holistic view. Numerous tools are available to assist designers in undertaking a life cycle assessment, and a selection of the leading resources are presented in Section 4.5.2.

4.3.2 Sustainable Forest Management

As tall wood building systems gain in popularity, it is important to understand if there is a corresponding increase in demand for wood resources. This demand can be met in different ways. Within the constraints imposed by sustainable forest management and the wood supply,[30] the standardization of mass timber components allows mass timber to be produced from a range of commodity wood products (i.e., feedstock can potentially be diverted to mass timber production from different grades and species of dimensional lumber, or by using structural composite wood). Market adoption of mass timber is still in the early stages, so the share of the total wood harvest used for mass timber is currently relatively minor. Nevertheless, it is important to acknowledge the key role that sustainable forest management plays in the life cycle assessment of a wood building.

The life cycle of wood buildings begins with the harvest of trees. This section begins with an overview of sustainable forestry management practices to provide designers with an understanding of the benefits and impacts of using Canadian wood products that occur upstream of the building project.

The Canadian Council of Forest Ministers defines sustainable forest management as "management that maintains and enhances the long-term health of forest ecosystems for the benefit of all living things, while providing environmental, economic, social, and cultural opportunities for present and future generations".[31] This definition serves as the foundation for forest policies in Canada, with the underlying goal being to achieve a balance between the demands placed on Canada’s forests and the maintenance of forest health and diversity.

[30] The National Forestry Database defines the term “wood supply” as the timber harvesting opportunities associated with a specific forest condition, management strategy, and timber flow policy. Allowable annual cut (ACC) is used interchangeably with wood supply in the remainder of this chapter.

[31] https://www.ccfm.org/releases/a-shared-vision-for-forests-in-canada-toward-2030/

4.3.2.1 Regulatory Frameworks

In Canada, there are 347 million hectares of forest and other land with tree cover, which account for 38% of the total surface area[32] and represent about 9% of the world's forests.[33] More than 90% of Canada's forests are on publicly owned land (CCFM, n.d.; NRC, 2020), most of which is under the responsibility of provincial and territorial governments, which have legislative authority over the conservation and sustainable management of forest resources on public lands. Forest management decisions in each jurisdiction are governed through robust legal and regulatory frameworks that are backed by monitoring and enforcement measures to ensure forests are harvested legally and sustainably. Public ownership status is accompanied by legislation that governs such aspects as land use, forest management practices, designation of protected areas, licensing, allocation of wood, public consultations, and Indigenous participation.[34] These regulatory frameworks set the standard for sustainable forest management practices in Canada (Rostad & Sleep, 2014). Forestry companies are required to develop a management plan, consult with communities, and receive provincial or territorial approval prior to harvesting (Natural Resources Canada, 2020).

Under this legislation, less than 0.5% of Canada's forest is harvested annually. Because public lands harvested for commercial timber must be regenerated, either naturally or by planting and/or seeding, each province and territory has implemented regeneration standards and regulations[35] that address various aspects including tree species composition, tree density, and stocking levels (Natural Resources Canada, 2020) to ensure that forests are replenished. It is also mandatory to provide stream buffer zones to prevent erosion and damage to fish habitat. Forest management in Canada operates under some of the most stringent sustainability laws and regulations in the world (Cashore & McDermott, 2004; Gilani & Innes, 2020; Indufor, 2009, 2016). The 2016 Indufor study found that "Canadian forest management frameworks for public forests exceed certification standards in the promotion of sustainable productivity of natural forests (with a strong emphasis on sustainable harvest levels, prevention of forest conversion, and protecting forests from fires and pests) and protecting the ecological and conservation values of forests."

Regardless of forest type or jurisdiction, components of laws and regulations for forest management practices in Canada are reviewed regularly and evolve with changing expectations about what sustainable forest management entails and what indicators should be used for sustainable forest management in Canada.[36, 37] Further, Canada is a member of the Montréal Process which outlines

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[32] https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/state-canadas-forests-report/how-much-forest-does-canada-have/17601

[33] https://www.ccfm.org/wp-content/uploads/2020/08/A-Shared-Vision-for-Canada%E2%80%99s-Forests-Toward-2030.pdf

[34] Summary of Canada's Forest laws https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/sustainable-forest-management/canadas-forest-laws/17497

[35] Most harvested forests in Ontario and Québec are naturally regenerated and therefore are not planted. For a definition of terms, see FAO FRA 2015: http://www.fao.org/3/ap862e/ap862e00.pdf and http://www.fao.org/3/ad665e/ad665e04.htm

[36] https://cfs.nrcan.gc.ca/pubwarehouse/pdfs/23636.pdf

[37] https://www.fs.fed.us/research/sustain/docs/montreal-process/2009-criteria-indicators.pdf [38] www.montreal-process.org

internationally agreed-upon criteria and indicators for the conservation and sustainable management of temperate and boreal forests.[38] Also, Canada's ratification of the Convention on Biological Diversity has contributed to the development of a framework,[39] along with goals and targets,[40] to help conserve biodiversity in Canada's ecosystems, including forests.

Sustainable forest management legislation is important given the increasing global demand for wood. In Canada, provincial and territorial governments regulate harvest levels on public lands by restricting the wood supply that can be harvested annually, for example using an allowable annual cut (AAC), based on a wide range of environmental, social, and economic factors.[41] In practice, annual harvest volumes may be above or below regulatory limits such as the AAC, but they must balance out over the regulation period (generally 5 years) (National Forestry Database, n.d.b).

In Canada in 2019, 115 million cubic metres of softwood was harvested, which was well below the estimated wood supply of 159 million cubic metres (National Forestry Database, n.d.a, n.d.b) (Figure 3).

Greenhouse Gas and Air Quality Benefits Afforded by Sustainable Forest Management

Sustainable forest management can generate climate benefits, either by increasing carbon sequestration (the removal of carbon from the atmosphere, and subsequent storage) or by avoiding emissions. Activities such as reforestation, fertilization, and tree improvement can significantly increase carbon sequestration in forests, while reducing slash pile burning reduces emissions and improves air quality.[42]

[38] www.montreal-process.org

[39] https://biodivcanada.chm-cbd.net/documents/biodiversity-outcomes-framework

[40] https://biodivcanada.chm-cbd.net/2020-biodiversity-goals-and-targets-canada

[41] http://nfdp.ccfm.org/en/data/woodsupply.php

[42] The B.C. Forest Carbon Initiative was launched in 2017 as an example of sustainable forest management that supports climate change goals. It is intended to help meet provincial and federal climate change targets by delivering GHG benefits in the short term (2030), medium term (2050), and beyond through investments on the land base, changing practices, and education and outreach. https://www2.gov.bc.ca/gov/content/environment/natural-resource-stewardship/natural-resources-climate-change/natural-resources-climate-change-mitigation/forest-carbon-initiative

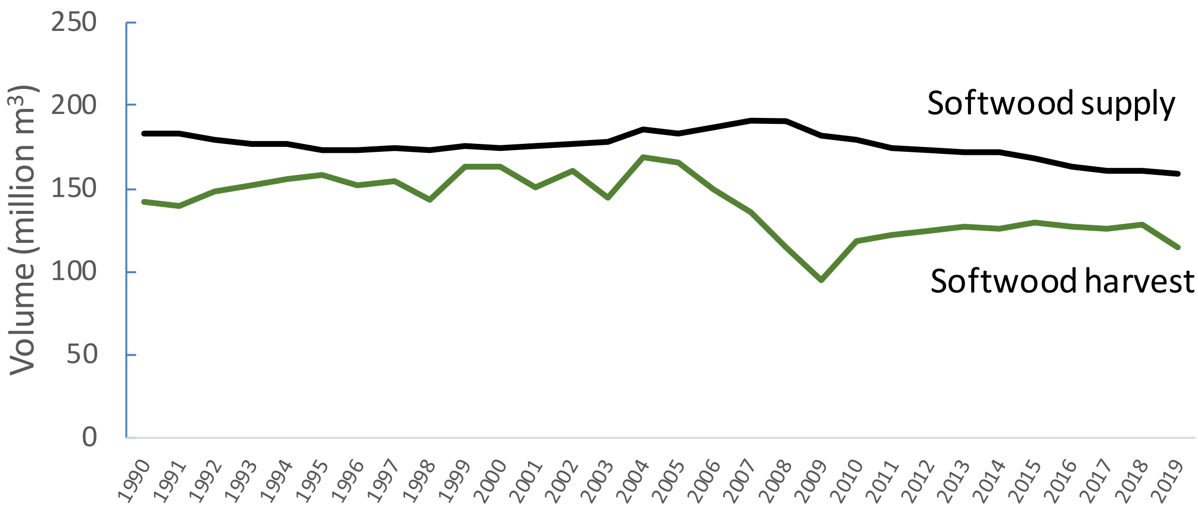

Figure 3. Annual softwood supply versus annual softwood harvest in Canada.

Between 1990 and 2018, the difference between the available supply (allowable annual cut) and harvest of softwood in Canada ranged from 10 to 87 million cubic metres per year, with an average of 36 million cubic metres per year (National Forestry Database, n.d.a, n.d.b).

In Canada, requirements for regeneration of harvested forests and restrictions on the AAC help prevent the loss of forest area and the depletion of forest stocks. As the global demand for forest products increases, the gap between harvest and the sustainable wood supply may narrow (note: the decline in wood volume in Canada's forests since 1990 is attributed largely to increased disturbances from fire and insects) (NRCan, 2020). Currently, however, harvest levels remain below the sustainable wood supply levels (NRCan, 2020). Additional information about the state of Canada's forests is provided by the Canadian Forest Service, which publishes annual reports that offer a national snapshot of the social, economic, and environmental status of forests and forestry in Canada.[43]

While Canada's strong regulatory measures should give designers the confidence to use Canadian wood products, there are still knowledge gaps related to the environmental effects of using forest products (e.g., biodiversity implications of increased wood harvesting; transparency and impacts of pesticide and fertilizer use in Environmental Product Declarations) (Boutin et al., 2009; Venier et al., 2014). As an additional measure of assurance, design teams can choose products that are certified by one of the three forest certification systems operating in Canada (Section 4.3.2.2).

4.3.2.2 Forest Certification

Since forest certification programs were introduced in Canada in the mid 1990s, they have become a widely respected means of demonstrating that Canadian forest companies meet high standards of

[43] https://cfs.nrcan.gc.ca

sustainable forest management, thereby complementing the nation's already stringent laws and regulations.

Under the forest certification process, independent third-party auditors evaluate, measure, and certify the sustainability of the forest management practices and forest products associated with a particular organization. A variety of factors are considered during the audit, including forest inventory; management; silvicultural and harvesting practices; protection of water, soil, and biodiversity; road construction and other related activities; and the environmental, social, and economic impacts of forest activities. Ultimately, this evaluation process results in a written statement attesting to the origin of the wood material and its qualification as a sustainably harvested product, and the right to use the certification system label or logo.

There are more than 50 independent forest certification systems worldwide, which address a variety of forest types and tenures. In Canada, there are three sustainable forestry certification systems: the Sustainable Forestry Initiative (SFI), the Forest Stewardship Council (FSC), and the Canadian Standards Association (CSA) Group's Sustainable Forest Management Standards (Table 1). When design teams specify the use of certified wood products, they should note that certain products may not be available under all three certification systems. Some flexibility may be necessary in working among the three systems. If pursuing green building certification system credits, design teams should consult the appropriate guidelines to determine which forest certification systems and products may be used and how this may best be achieved in the context of the project. An overview of the credits to date related to certified wood products required in green building rating systems is provided in Section 4.5.3.

Certification Canada notes that the CSA, FSC, and SFI standards for forest management practices "are reviewed regularly and evolve with changing expectations about what sustainable forest management entails".[44] Certification Canada[45] lists the common elements and requirements of these standards as follows:

- conservation of biological diversity
- maintenance of wildlife habitat and species diversity
- protection and/or maintenance of special sites (biological and cultural)
- maintenance of soil and water resources
- ensuring harvest levels are sustainable, and harvested areas are reforested
- protection of forest lands from deforestation and conversion to other uses
- Aboriginal rights and involvement
- public disclosure
- compliance with laws, including legal harvesting

[44] https://certificationcanada.org/en/programs/programs-used-in-canada/common-elements/

[45] Ibid.

Table 1. Forest certification systems in Canada

Organization	Description	Area of Canadian forest certified (hectares)*
Sustainable Forestry Initiative (SFI)	SFI is an independent, non-profit, charitable organization with a forest management standard developed specifically for North America forests. It is based on sustainability principles and measures that include both land management fiber sourcing objectives. SFI Inc. is governed by a three-chamber Board of Directors that represents environmental, social, and economic sectors equally. • SFI 2015-2019 (Extended through December 2021) Forest Management Standard includes measures to protect water quality, biodiversity, wildlife habitat, species at risk, and forests with exceptional conservation value, and applies to any organization in the United States or Canada that owns or manages forest lands. • SFI 2015-2019 (Extended through December 2021) Chain-of-Custody Standard is an accounting system that tracks forest fiber content (certified forest content, certified sourcing, and recycled content) through production and manufacturing to the end product.	122 million
Forest Stewardship Council (FSC): Canada	FSC is an international, non-profit, multi-stakeholder organization that promotes responsible management of the world's forests through its global market-based certification program. FSC is governed by a three-chamber Board of Directors that represents social, environmental, and economic sectors equally. FSC has several policies and standards, including: • **FSC-STD-CAN-01-2018 EN V1 Forest Management Certification** is used to assess if a forest is responsibly managed. It addresses the most pressing issues facing Canadian forests now, including woodland caribou; Indigenous Peoples' Rights; Workers' Rights, including gender equity; landscape management; and conservation. • **FSC-STD-40-004 (V3-0) EN Chain of Custody Certification** is for use by businesses that manufacture or trade forest products. Chain of custody certification verifies that products are handled correctly at every stage of production from forest to shelf.	48 million
Canadian Standards Association (CSA) Group's Sustainable Forest Management Standards	CSA Group is one of the largest standards development organizations in North America. It conducts research and develops standards for a broad range of technologies and functional areas. CSA provides two standards for sustainable forestry management, both of which are endorsed by the Program for the Endorsement of Forest Certification Schemes: • **CSA Z809-02** (CSA, 2003)**,** which is applicable to any defined forest area • **CSA Z804-08** (CSA, 2013), which is applicable to woodlots and other small area forests	

*Source: Certification Canada (n.d.).

The broader programs run by FSC, SFI, and CSA in partnership with the Program for the Endorsement of Forest Certification Schemes also include:

- chain of custody certification
- labels for products (for use with a certified chain of custody)
- balanced decision-making processes
- audits by independent third parties

As of the end of 2020, Canada had more than 164 million hectares of independently certified forest land (Certification Canada, n.d.). That represents more than 75% of Canada's publicly managed forest area and 36% of all certified forests worldwide, the largest area of third-party certified forests in any country (NRCan, 2020). Many forested lands are certified by more than one system, for a total of 182 million hectares of certified forests.

4.3.3 Reducing Greenhouse Gas Emissions Associated with the Use of Wood as Construction Materials, Including Product Substitution

This section presents strategies and approaches that designers can use to reduce GHG emissions when building tall wood structures, which can include the following:

- Design phase
    - material substitution
    - resource efficiency
    - designing for deconstruction and zero waste
    - using local materials to reduce transportation effects
- Construction phase
    - efficient construction processes
    - reducing construction waste on-site
- Use phase and end of life
    - optimizing durability and longevity
    - minimizing the impacts associated with end of life

4.3.3.1 Material Substitution

Substituting wood for materials such as steel and concrete that produce more GHG emissions is important because it can curb rising carbon emissions in the short term. This substitution, equivalent to avoiding fossil emissions, can be more significant than the carbon storage benefit provided by wood materials alone (Leskinen et al., 2018). It should be noted that factors such as changes in the carbon stored in forests (Section 4.2), end of life solutions, can affect the resulting net GHG effect of material substitution.

Mass timber solutions can substitute for concrete and steel in larger and taller buildings and allow designers to promote a shift in consumption patterns toward construction goods and services that have lower energy and material intensity without compromising building performance and functionality or the quality of life of building occupants. Not only is wood less GHG intensive than concrete (see comparison of mass timber and concrete buildings in Section 4.5.1: Life Cycle Assessment), it is only about 20% of the weight of concrete; therefore less concrete may be required for the foundations of mass timber structures.[46] For example, using wood instead of other materials in the 13-storey Origine apartment building in Québec City (Figure 4) avoided the equivalent of 1000 tons of CO_2 emissions.[47]

Figure 4. Origine apartment building in Québec City, fabricated out of CLT (courtesy of Cecobois).

4.3.3.2 Resource Efficiency

In a 2019 study, the UN International Resource Panel determined that the GHG emissions from the material cycle of residential buildings in the G7 countries or nations and China could be reduced by 80% by 2050 through strategies such as creating higher occupancy of homes, designing with fewer materials, and improving recycling of construction materials (UNIRP, 2019).

Various frameworks can help designers select the right materials for their building projects, including Design for the Environment (D4E) and sustainable materials management (SMM). D4E is an approach to reducing the overall human health and environmental impact of a product, process, or service across its life cycle. The Organisation for Economic Co-operation and Development defines SMM as "a systemic approach to using and reusing materials more productively over their entire life cycles".[48] SMM emphasizes a holistic approach to keeping materials out of the waste stream, influencing upstream behaviours of the various actors in the construction supply chain to reduce waste, and informing the design and manufacture of products and buildings in a way that reduces their environmental footprint. SMM involves integrating actions targeted at reducing negative environmental impacts and conserving natural capital throughout the life cycle of materials, taking into account economic efficiency and social equity (OECD, 2012).

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[46] www.masstimberinstitute.ca/faq

[47] https://cecobois.com/wp-content/uploads/2020/04/CECO-11410_Etude_Cas_Origine_paysage_Ang_WEB.pdf

[48] www.oecd.org/env/waste/smm.htm

When it comes to resource efficiency, a mass timber structural system can appear to consume more wood than a traditional light-frame wood wall or floor. However, it is important to consider the metric used to estimate resource efficiency. Examples of resource efficiency metrics that are relevant for buildings include quantity per square metre of building area, and quantity per occupant. Wood use intensity for structural wood products in Canadian single-family homes is about 13 m^3/occupant compared to 8 m^3/occupant for multi-family wood-frame apartment buildings.[49] Considering the range of wood use factors for mass timber buildings shown in Table 2, per capita wood use in apartments constructed of mass timber could be in the range of 7–18 m^3/occupant.[50] Cross-laminated timber apartment buildings, therefore, represent a per capita use of wood that is similar to the per occupant wood use for current multi-family residential building construction in Canada.

Table 2. Structural wood use in tall timber buildings

Building	Structure	Location	Wood Use		Storeys (no.)	Height (m)
			m^3/m^2 floor area	m^3/ occupant		
Wood Innovation and Design Centre	CLT floors, CLT elevator and stair cores, glulam columns and beams	Prince George, B.C.	0.32	14	7	29.5
Brock Commons	CLT floors, glulam and parallel strand lumber columns	Vancouver, B.C.	0.15	7	18	54.0
Stadthaus	CLT floors, CLT interior and exterior partition walls	London, UK	0.33	18	9	29.0

Sources: Athena Sustainable Materials Institute (2015); naturally:wood (2016); Stadthaus (2018); Wood WORKS! and Canadian Wood Council. (n.d.).

4.3.3.3 Designing for Deconstruction and Zero Waste

Major decisions about the configuration, composition, process, and schedule for a building project tend to be made during the earliest stages of the project planning process. This suggests that the most effective opportunity to inform waste reduction strategies (such as design for disassembly, selection of sustainable materials, etc.) is as early as possible in the building life cycle.

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[49] This assumes (1) 0.20 m^3/m^2 floor area for single family homes and 0.18 m^3/m^2 for multi-family homes (McKeever & Elling, 2015); (2) 2.8 persons per household for single family homes and 1.8 persons per dwelling for apartments with 5 or more storeys (Statistics Canada, 2012); and (3) 180 m^2/unit for the average size of a new single family home and 83 m^2/unit for new condos (Canadian Mortgage and Housing Corporation, 2013; Marr, 2016), scaled up to account for common areas (hallways, etc.). In McKeever & Elling (2015), floor area represents the finished floor area measured from the outside of exterior walls (gross floor area). For multi-family homes, this includes hallways and lobbies, and for all buildings, garages and unfinished basements are excluded.

[50] Assuming an average of 75 m^2/unit for new condos (Canadian Mortgage and Housing Corporation, 2013; Marr, 2016), and 1.8 persons per unit (Statistics Canada, 2012).

With tall wood building systems, material flows can be controlled before the materials arrive on-site, which minimizes waste, effluent, and pollution. To achieve the economies and efficiencies of using mass timber, builders can prefabricate certain structural elements by carefully planning panel sizing and layouts to maximize material efficiency and using computer numerical control machinery to make necessary cuts. This will also substantially reduce the amount of waste generated on-site. To address any offcuts and sawdust created during prefabrication, many Canadian mass timber panel producers have invested in biomass energy solutions that reclaim and use wood waste to generate the energy used in their manufacturing facilities. This can be beneficial from a carbon emission mitigation standpoint, depending on the type of fossil fuel being substituted and conversion efficiency.

Post-Occupancy Fire

Designing to address post-occupancy fire damage is important for maximizing a mass timber building's service life. Charred structural members can be repaired, and more repair options are available if appearance is not critical. Therefore, a separate appearance layer, even in wood, is preferred.

Structural wood products have an inherently long lifespan, and in an optimal scenario, the wood products used in a building can be demounted at the end of that building's life and reused in another project. However, providing for an extended product lifespan requires planning early in the design process. To ensure that the integrity of the material is maintained and that, ultimately, the wood can be reused or recycled, design teams should take the following into consideration:

- The choice to treat wood products must be weighed against a variety of considerations, including the requirements of authorities having jurisdiction. In some cases, the use of treated wood or naturally durable wood may be required to meet service life expectations.
- To minimize the need for wood treatments wherever possible, design teams should ensure that the building envelope provides optimal weather protection, and that future maintenance can be easily performed.
- The reuse of treated wood in secondary applications is very common, but design teams and building owners should be aware that in residential applications, there are regulations prohibiting the use of wood treated with certain preservatives (see Section 4.4.1.3).
- Most treated wood used in buildings is currently not recyclable. Technologies are being developed[51] to address this problem, so it is possible that treated wood will be recyclable in the future. Nevertheless, if additional fire protection, moisture protection, or protection from wood-destroying organisms is needed, design teams should do their best to identify where treated wood must be used and specify wood treatments that will have a minimum impact on the end of life of the wood product (and on occupant health if the product is used for an interior application).

[51] For example, the Enerkem waste-to-energy facility in Edmonton is able to tolerate a small proportion of treated wood, and Enerkem is also developing methods for extracting biofuels from treated wood products such as telephone poles https://enerkem.com/process-technology/circular-economy/.

- Using mechanical fastening systems, rather than irreversible chemical bonding systems, to connect wood products can improve reusability by making it easier to separate materials.
- To ensure that high-value products do not end up in a landfill, design teams should consider developing a plan that identifies the building products to be reused over time and describes their subsequent destination.

If wood products are kept out of landfills, they can be used in place of other products (or energy), which would avoid creating GHGs associated with the production of those products. The “circular economy” represents a common objective whereby all waste is reduced, and products are sold, consumed, collected, and then reused, remade into new products, returned as nutrients to the environment, or incorporated into global energy flows (Figure 5). To facilitate “zero waste” outcomes, the building needs to be designed with the end of its life in mind, whereby components can be easily accessed for maintenance and replacement, and then the building materials can be separated into their original constituents at the end of the building’s life.

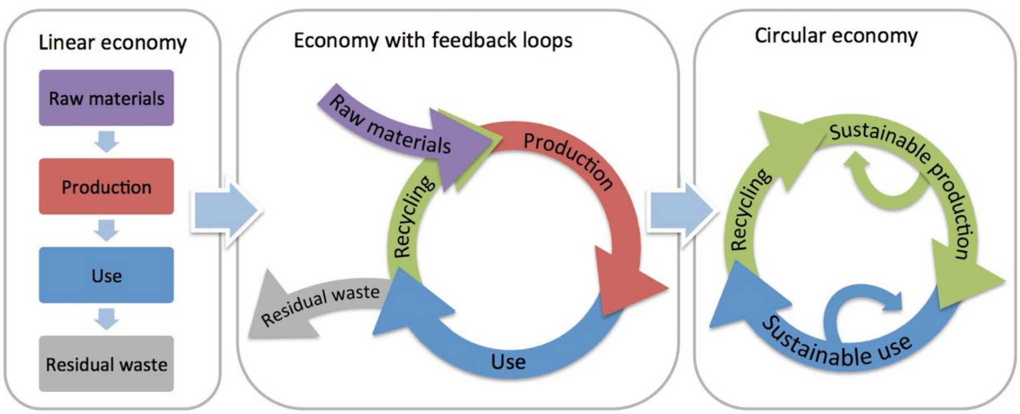

Figure 5. Transition from a linear to a circular economy.

While a great deal is required to establish a circular economy for the construction sector in Canada, inspiration can be found elsewhere. For example, the city of Rotterdam, Netherlands has already committed to reducing material consumption and/or the impacts of materials by 50% by 2030 in order to create to a circular economy for the construction sector by 2050.[52] Key to the success of such policies may include:

- using materials in a way that allows for easy disassembly or renovation instead of demolition;
- using sturdy, long-life materials; and
- reusing materials and components in a way that construction and demolition is connected.

Although some of these ideas may seem a long way off, urban “mining” of existing buildings is already being discussed as a potentially important source of construction materials in the future, and

[52] https://constructionclimatechallenge.com/2018/10/26/rotterdam-targets-construction-waste-circular-economy-drive

designers are starting to consider how to ensure their new projects can become material "banks" for the future.[53]

4.3.3.4 Using Regional Materials to Reduce Transportation Impacts

The impacts of shipping materials to the construction site are determined by both the mode of transportation and distance travelled. For example, moving freight by truck emits three times more GHGs per tonne-kilometre than transporting by rail or coastal shipping (see Figure 8.6 in Sims et al., 2014). Sourcing local materials has the following advantages:

- The use of regional materials provides savings in transportation costs, both economically and in terms of the environmental footprint.
- The use of regional materials contributes to local economic growth and stability.
- Most green building certification systems award credits for using regionally sourced materials (see Section 4.5.3).

Design teams may refer to the environmental impacts reported in Environmental Product Declarations (EPDs) (see Section 4.5.1.1) to evaluate and compare available options for transportation from initial logging through construction on-site to ensure that the overall impact of transportation is minimized within the context of their project.

4.3.3.5 Efficient Construction Processes

Sustainable materials management is closely linked to sustainable manufacturing. The application of new technical innovations is key to enabling industry to create new business value while also benefitting people and the planet. In the construction sector, unprecedented investment is being made in new processes and technologies aimed at digitizing and industrializing the entire design and construction supply chain; these include:[54]

> **Digital tools** such as building information modelling (BIM) can enhance design visualization, improve data exchanges, reduce construction waste, improve productivity, and deliver higher product quality.
>
> **Lean methods**, which "seek to develop and manage a project through relationships, shared knowledge and common goals. Traditional silos of knowledge, work and effort are broken down and reorganized for the betterment of the project rather than of individual participants. The objective is to deliver significant improvements in schedule with dramatically reduced waste, particularly on complex, uncertain and quick projects" (Goodland et al., 2019).

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[53] www.bamb2020.eu

[54] www.weforum.org/press/2016/05/the-long-overdue-transformation-of-the-construction-industry

Lean Project Delivery is a highly collaborative process that comprises the application of target value design and lean methods during construction. The goal of Lean construction is the elimination of waste (in the form of wasted materials, time, and energy).[55]

Integrated Project Delivery "is an emerging construction project delivery system that collaboratively involves key participants very early in the project timeline, often before the design is started. It is distinguished by a multiparty contractual agreement that typically allows risks and rewards to be shared among project stakeholders."

Application of these new tools and practices can help achieve significant reductions in environmental impacts associated with the construction process, particularly in terms of improving resource efficiency and reducing waste (Goodland et al., 2019). Due to factory-controlled processes and tight inventory controls, prefabrication and modular construction are material- and resource-efficient, which can streamline project delivery at the construction site and reduce waste on-site. This results in a cleaner, quieter site for neighbours and a faster, safer, cleaner, more productive building process for the owner and project team. For example, the Mosaic Centre in Edmonton was a technically demanding project comprising multi-tenant office space for 130 workers, a child-care centre, and a restaurant (Figure 6). Completed in 2014, the 2,812 m^2 (30,250 sq. ft.) 3-storey glulam and steel hybrid structure was the first to be certified LEED Platinum and Living Building Challenge Petal in Edmonton and the first net-zero commercial building in Alberta. It followed an Integrated Project Delivery process that leveraged lean project delivery and building information modelling, facilitating delivery on budget and 4 months ahead of schedule.

Figure 6. LEED Platinum Mosaic Centre, Edmonton, Alta. (courtesy of Mosaic Centre and Western Archrib).

[55] More information is available at the Lean Construction Institute of Canada: www.lcicanada.ca

Wood lends itself to prefabrication because it is light weight and versatile, and it allows for precise fabrication. As a result, off-site construction with wood has a long history in Canada. Trusses and panelized walls have been produced for many years (see Chapter 8). With the introduction of mass timber products and the application of digital tools, there is an opportunity to dramatically improve the efficiency of construction while reducing environmental impacts.

Construction Fire

Prefabrication reduces the amount of wood waste at the construction site. Large amounts of wood waste at a construction site is a fire risk and requires efforts to clear the site at completion. Keeping clean wood waste at the fabrication plant allows the wood to be accumulated and efficiently directed toward other uses (i.e., energy).

4.3.3.6 Reducing Construction Waste On-Site

In Canada, approximately 4 million tonnes of construction and demolition waste is disposed of in landfills every year; wood comprises 40% of that waste, only half of which is classified as clean (i.e., not glued, painted, or treated) (CCME, 2019). Construction site waste is an indicator of inefficiency: it has environmental impacts and is a cost to the project in terms of materials, storage, haulage, and disposal.

Using mass timber structural solutions can help reduce the amount of waste generated on-site due to the prefabrication of panels, precutting of openings, and pre-installing of connectors. To reduce wood waste from other elements of the construction process, the "Five Rs" should be followed: Reduce, Reuse, Recycle, Recover (for energy), and then deal with Residuals. A waste management plan with diversion goals needs to be in place prior to construction and should be implemented for residual waste that is generated on-site. Discussing this with the contractor early in the design process will ensure that a system has been designated for reclaiming waste materials, keeping wood waste clean, and sorting and distributing the materials to the proper reuse, recycling, or waste diversion location. In addition to the environmental benefits provided by waste management planning, green building certification systems often award credits for successfully diverting construction waste from local landfills. Managing wood waste at the end of life is discussed in Section 4.3.3.8

4.3.3.7 Optimizing Durability and Longevity

Tall wood structures have been used in Canada since the early 1900s (Figure 7). Durability and longevity (discussed in Chapter 7) are critical components of the overall environmental performance and sustainability of a building. From a life cycle perspective, the longer a building remains in service, the smaller the relative share of total impacts attributed to materials will be. This is especially true for wood structures, which not only have a lower embodied impact than steel and concrete structures, but they also store carbon throughout their service life.

Figure 7. Vancouver's first tall timber structure was the Kelly Douglas building (now known as The Landing) built in 1905 at 375 Water Street (Source: Canadian2006, CC BY-SA 3.0, via Wikimedia Commons).

As with any building, the durability of tall wood structures is a function of the quality of building materials used, the way the materials are connected and detailed, the environment the building is in, the proper protection of the materials from the elements, and the ease of maintenance over time. Designers of tall wood buildings must also consider material properties that are unique to wood, including moisture content and humidity effects, exposure to UV light, shrinkage, creep, and the natural movement of materials, all of which may affect the structure's long-term performance. If these factors are taken into consideration early in the design process and agents of deterioration are managed through design and maintenance, engineered wood structures can achieve life spans of 120 years or longer (Lenz et al., 2011). Several mid-rise post-and-beam wood structures built throughout Canada before 1950 remain in use today; the oldest, constructed in 1859, was still standing as of 2013, 154 years after being constructed (Koo, 2013).

O'Connor (2004) examined the average service life of demolished commercial/institutional and residential buildings in Minneapolis based on the main structural materials: wood, concrete, steel, and hybrid structural materials. Half of the residential wood buildings were at least 75 years old at the time of demolition, while more than half of the demolished concrete building were between 26 and 50 years old, which indicated that "wood structural systems are fully capable of meeting longevity expectations" (O'Connor, 2004). The buildings in the study were typically demolished because of area redevelopment or lack of maintenance, or because they were no longer suitable for their intended use (O'Connor, 2004). Because many of the buildings were not demolished because of their physical state, the study highlights the potential for wood buildings to have a longer average service life than that of other buildings, especially when they are designed to accommodate changing needs of building occupants.

Post-Occupancy Damage

Primary mass timber members can be repaired. Designing to address post-occupancy damage is important for ensuring a building's long service life. Where damage is anticipated, the creation of an abuse zone either in wood or another material is recommended. Mass timber provides a wider range of options for attaching the abuse layer; however, differential movement between the abuse layer and mass timber should be allowed.

4.3.3.8 Minimizing Impacts Associated with End of Life

Canada generates about 1.7 million tonnes of waste from the demolition of buildings every year (CCME, 2019). Governments are working to reduce waste sent to landfill but finding ways to use treated and painted wood remains a challenge (CCME, 2019). Research to remove contaminants and then recycle treated wood waste is ongoing (Guy Perry and Associates & Kelleher Environmental, 2015).

Clean and engineered wood products are increasingly being diverted from landfill due to policies like landfill bans on wood waste. According to the Canadian Council of Ministers of the Environment, most clean wood waste currently goes into "low-value products, such as alternative daily landfill cover", which "is able to consume a large percentage of the wood waste stream, but is energy/GHG intensive, commands a low dollar value and is [environmentally] only marginally preferable to landfilling" (CCME, 2019). By comparison, it is very difficult to keep painted or treated wood waste out of landfills. Pressure treatments and fire protective coatings may allow the service life of wood elements to be extended, which has benefits in terms of durability and longevity, but these treatments may also affect the ability of the material to be reused or recycled in the future. Project teams are encouraged to consult the regulations in their region regarding the disposal of treated wood.

Landfilling wood waste is likely to result in reduced direct GHG emissions from biomass compared to many other wood waste disposal strategies because wood products undergo minor degradation in anaerobic landfills (Towprayoon et al., 2019; Ximenes et al., 2019).

With growing awareness about the importance of indoor environmental quality in buildings, low- or non-toxic paint is increasingly being used, which may make it easier for waste management facilities to accept larger proportions of painted wood waste over time. Similarly, wood treated with modern preservatives or sometimes with small amounts of creosote may be accepted by recycling facilities

(CCME, 2019). However, most older wood preservatives contain hazardous or toxic substances, such as arsenic and chromium. Currently, most waste facilities can accept contamination levels of only about 10%. Designers who wish to reduce the amount of treated wood waste that goes to landfill should consider weather protection strategies that minimize the use of preservatives where possible (see Section 4.3.3.7 and the design recommendations provided in Chapter 7). For more information about the end-of-life impacts of CLT, see Info Sheet #14 in the TallWood Design Institute's *Cross-Laminated Timber Info Sheets* series.[56]

4.4 HEALTH CONSIDERATIONS OF USING WOOD

Human health and the health of the planet are inextricably intertwined. What is good for one is almost always good for the other. So, as with any building, design teams for tall wood buildings should address human health, well-being, and comfort. Several aspects need to be considered, including indoor air quality and how wood can contribute to a healthful indoor environment; this is discussed below. Other aspects are covered elsewhere in this guide—notably, acoustic comfort (Chapter 5), and thermal comfort (Chapter 7).

4.4.1 Indoor Air Quality

Indoor air quality refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants. Health effects from indoor air pollutants may be experienced soon after exposure or years later. According to the U.S. EPA, several health effects are linked to exposure to pollutants in indoor air. Short-term effects can include "irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue". Long-term effects can include "respiratory diseases, heart disease, and cancer".[57] Understanding what pollutants may be associated with wood products and controlling for them indoors can help reduce the risk of indoor health concerns.

Inadequate ventilation in any building can lead to increased concentrations of indoor air pollutants by not supplying fresh air within the interior, and not ventilating air pollutants out of the building. Building codes generally address the removal of point sources of air pollutants that are released within buildings so they do not accumulate in concentrations greater than those permitted by applicable provincial or territorial requirements. This is generally accomplished by installing good heating, ventilating, and air-conditioning systems that are designed to minimize the growth and spread of biocontaminants. In North America, best practice approaches are set by standards bodies such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)[58] and should be considered for any building project irrespective of the materials used.

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[56] http://tallwoodinstitute.org/sites/twi/files/Info%20Sheets_Final_200616.pdf

[57] www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality#immediate

[58] ANSI/ASHRAE Standards 62.1 (ANSI/ASHRAE, 2019a) and 62.2 (ANSI/ASHRAE, 2019B) are the recognized standards for ventilation system design and acceptable indoor air quality. Expanded and revised for 2019, both standards specify minimum ventilation rates and other measures for minimizing adverse health effects on occupants.

Indoor air quality can be affected by building materials and other indoor elements such as furniture, carpets, and coatings that release volatile organic compounds (VOCs) and other dangerous substances into the air. Each of the major building structural types (steel, concrete, and wood) may have negative impacts on indoor air quality that must be considered and mitigated wherever possible. For example, isocyanates are highly reactive, low molecular weight chemicals, and are essential ingredients of polyurethane products such as structural wood adhesives, furniture foam, and spray polyurethane foam insulation, which are a known asthma trigger. [59] By comparison, steel structural systems typically require primers and treatments for fire and rust protection, and concrete systems often require formwork release agents, curing compounds, and protective coatings for reinforcing steel. While each of these treatments improves the service life of the building structures, they also can have negative effects. This is also true for treatments used in wood building systems.

Post-Occupancy Moisture

Designing to address post-occupancy moisture exposure damage is important to ensuring a building's long service life. While chemicals for delaying mould growth are available, cleaning with a brush and soap to remove mould and maintaining good drying conditions will generally be sufficient (see BC Housing's [2019] Mould Management Guide).

The wood used in solid and engineered structural wood products is inherently benign and hypoallergenic, but a variety of additives may contact the wood material and must be considered by the design team; they include adhesives, treatments to protect against wood-destroying organisms and wood rot, and treatments used for fire protection. These are discussed in Sections 4.4.1.1–4.4.1.3.

Green building rating systems provide best practices regarding air filtration and ventilation rates for removing indoor air contaminants. For information about the chemicals in building products and the potential hazards they may present to human health, designers should refer to the Material Safety Data Sheets (MSDSs). The MSDS includes information on the properties of each chemical; the physical, health, and environmental hazards they present; protective measures to use; and safety precautions for handling, storing, and transporting the chemicals.

4.4.1.1 Structural Adhesives

Structural adhesives are used in engineered wood products for lamination purposes and to transfer stresses between adjoining wood surfaces. Typically, the selection, application, and curing of adhesives, as well as testing for VOC emissions, reliability of bond, and performance under various environmental factors, are controlled at the point of manufacture. As a result, the adhesives used for wood products in Canada may differ by both product and manufacturer, and may include the following, among others: phenol formaldehyde, resorcinol formaldehyde, phenol resorcinol formaldehyde (PRF), polymeric diphenylmethane diisocyanate, emulsion polymer isocyanate,

[59] Valette et al., 2014.

polyurethane/emulsion polymer, polyurethane polymer, polyvinyl acetates, and melamine formaldehyde (MF) (Table 3).

CLT suppliers use a variety of adhesives to facilitate manufacturing and to ensure a light-coloured bond line. Polyurethanes are typically used for CLT finger joint and face bonds, while PRF is typically used for glulam face bonds, and PRF or MF is used for finger joint bonds. (For more information about the manufacture of CLT, see the *Canadian CLT Handbook* [Karacabeyli & Gagnon, 2019].) Each of these adhesives provides significant performance benefits, but their impacts on indoor air quality and human health should be checked. Design teams should consult with manufacturers and available resources, such as MSDS, EPDs (discussed in Section 4.5.1.1), and other health-focused product declarations and certifications such as Health Product Declarations, Cradle to Cradle Certifications, or Declare Labels to better understand the health effects linked to specific products. Structural adhesives are known to off-gas during the glue-setting period which occurs in the factory. Once cured, these adhesives are usually safe for human contact (Frihart & Hunt, 2010) and pose a low risk to building occupants.

4.4.1.2 Formaldehyde

Many structural wood products use formaldehyde-based adhesives. Although formaldehyde is a naturally occurring chemical, it is also well known as an irritant and carcinogen (IARC, 2004). Different formaldehyde-based products have different levels of chemical stability that either reduce (high stability) or increase (low stability) their emissions of VOCs under different environmental conditions. For example, in contrast to the more volatile urea formaldehyde (which is not used for glued wood products with a structural rating), phenol formaldehyde, resorcinol formaldehyde, phenol resorcinol formaldehyde, and melamine formaldehyde polymers “do not chemically break down in service; thus no detectable formaldehyde is released” (Frihart & Hunt, 2010).

Due to regulations requiring lower formaldehyde emissions, new adhesive formulations have been, and are being, developed to significantly reduce levels of formaldehyde emissions, both during manufacturing and in bonded wood products. There are two categories of resins: “ultra low-emitting formaldehyde resins”, which include melamine-urea formaldehyde, phenol-formaldehyde, and resorcinol-formaldehyde resins, and “no-added formaldehyde resins”, which include soy, polyvinyl acetate, and polymeric diphenylmethane diisocyanate resins (Weyerhaeuser, 2013). See also CWC (2013) for an overview of emissions from wood product adhesives.

4.4.1.3 Treatments for Wood-Destroying Organisms and Wood Rot

The first step to preventing rot in any wood building is to select the right species of wood; the second is to minimize water-to-wood contact and allow the wood to dry if it does get wet (see Chapter 7). If necessary, a variety of treatments may be used to prevent the occurrence of wood-destroying organisms and wood rot. Various safe, water-based treatments are registered by the Pest Management Regulatory Agency for use in residential applications (Wood Preservation Canada, 2013). Prior to selecting a treatment, teams should consult available resources, such as Pest Management Regulatory Agency labels and MSDS sheets, which provide additional details on the human and environmental impacts associated with these products. Although water-based treatments are safer than the heavy-duty wood treatments, some negative impacts on human health may still be cited in some cases.

Table 3. Types of adhesives used in wood products (AWC, 2013)

Engineered Wood Products	Type of Thermosetting Adhesive Used
Wood Structural Panels	
Oriented Strand Board (OSB)	Phenolic, Polymeric MDI
Softwood Plywood	Phenolic
Wood I-joists	
Web (OSB or Softwood Plywood)	Phenolic, Polymeric MDI
Flange (Finger-Jointed Lumber)	Melamine, Phenol resorcinol, Resorcinol, Polyurethane polymer adhesive, Emulsion polymer isocyanate adhesive, Polyurethane/Emulsion polymer adhesive
Flange (Structural Composite Lumber)	Phenolic, Polymeric MDI
Web/Flange Joint	Phenol resorcinol, Polyurethane polymer adhesive, Polyurethane/Emulsion polymer adhesive, Emulsion polymer isocyanate adhesive
Web/Web Joint	Phenol resorcinol, Polyurethane polymer adhesive, Polyurethane/Emulsion polymer adhesive, Emulsion polymer isocyanate adhesive
Glued Laminated Timber (Glulam)	
Laminating	Melamine, Phenol resorcinol, Polyurethane polymer adhesive, Emulsion polymer isocyanate adhesive
Finger Joint	Melamine, Phenol resorcinol, Resorcinol, Polyurethane polymer adhesive, Emulsion polymer isocyanate adhesive, Polyurethane/Emulsion polymer adhesive
Structural Composite Lumber	
Laminated Veneer Lumber (LVL)	Phenolic, Polyurethane polymer adhesive, Emulsion polymer isocyanate adhesive, Polyurethane/Emulsion polymer adhesive
Laminated Strand Lumber (LSL)	Phenolic, Polymeric MDI
Parallel Strand Lumber (PSL)	Phenolic
Oriented Strand Lumber (OSL)	Phenolic, Polymeric MDI
End-jointed Lumber	Polyvinyl acetate, Polyurethane, Phenol Resorcinol, Melamine

Note: The information above refers only to examples. Modern wood product manufacturers may use other types of adhesives or a combination of adhesives.

4.4.2 Biophilic Design

There is growing interest in how buildings contribute to occupants' psychological well-being, which is particularly important in the context of employers' efforts to address workplace mental health issues, especially stress and burnout. Biophilic design introduces natural elements into the construction and interiors of buildings. Biophilia refers to the need for connection to nature. When people are in contact with nature, they feel better: they experience less stress, lower blood pressure, and a more positive frame of mind. According to a recent review (Lowe, 2020), wood is one of the few natural elements that can simultaneously achieve four important goals: reduced carbon emissions; increased sustainability in a building's life cycle; improved occupant well-being; and increased organizational benefits from having happier, healthier, and more productive employees. Tall wood structures offer designers the opportunity to bring nature indoors and to express the wood structural elements to building occupants.

For businesses, the benefits of biophilic design include increased worker productivity as a result of reduced absenteeism, increased employee retention, and reduced fatigue (Lowe, 2020). Evidence also suggests that there are health benefits of using wood interiors in schools and hospitals (Lowe, 2020). Wood used in healthcare interiors has been shown to aid patient recuperation times. Wood in school classrooms results in improved learning outcomes. These findings reinforce the more general understanding that humans thrive in natural settings. Fell (2010, 2011) also established a link between wood and human health by showing that the presence of visual wood surfaces in a room lowered sympathetic nervous system activation. The sympathetic nervous system in humans is responsible for physiological stress responses. These findings suggest that a myriad of stress-related health benefits may be possible by using wood in the built environment.

4.5 TOOLS FOR QUANTIFYING THE BENEFITS OF USING WOOD

4.5.1 Life Cycle Assessment

Life cycle assessment (LCA) is an internationally standardized approach (ISO 14040 [ISO, 2006b]; ISO 14044 [2006c]) for estimating the potential environmental impacts (on air, land, and water) of a product, an assembly, or a whole building over its entire life cycle (from resource extraction to end-of-life disposal). LCA reports lifetime environmental impacts for indicators such as smog creation, water pollution, and resource depletion (see Figure 2 in Section 4.3.1). The LCA approach aims to measure all flows between a product and ecosystems, estimate the potential environmental (and in some cases health-related) impacts from these flows, and help identify opportunities for reducing harmful effects.[60] LCA is an evolving field of study: standards have been created recently and are being refined (ISO 21930 [ISO, 2017]; EN 15978 [CEN, 2011]; EN 15804:2012 + A2:2019 [CEN, 2012)] in order to adopt standardized terminology and indicators. This is particularly relevant when discussing the "carbon footprint" of a product or whole building (see text box below).

[60] A broader explanation is provided at http://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/environmental-lca

Carbon Footprint of a Product = Embodied Carbon + Operating Carbon

The product carbon footprint standard (ISO 14067 [ISO, 2018]) defines a carbon footprint of a product as the "sum of GHG emissions and GHG removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change". Today, the term "carbon footprint" in the context of buildings is often applied—incorrectly—to just the process of operating the building (i.e., to the exclusion of embodied impacts). In addition to heating and lighting, etc., operating plugged-in equipment such as computers may be included, and occasionally GHG emissions from commuter or business travel is considered. All these emission sources are categorized as "operating carbon", but they represent only part of the building's total life cycle carbon footprint. Embodied carbon comprises the GHG emissions from all other stages of the building's life cycle, including resource extraction (e.g., mining and harvesting), processing and manufacturing of materials, building construction, building maintenance and repair, demolition, and disposition of materials at the project's end of life (e.g., landfilling and recycling). These emissions are sometimes referred to as "Scope 3 emissions".[61] For most types of buildings (inhabited or civil infrastructure), embodied carbon accounts for a significant amount of the building's total GHG emissions, most of which occur upstream of (i.e., prior to) building occupancy.[62]

As whole building LCA becomes more common as an environmental management tool, it is likely to be used more frequently to support buildings designed with reduced operating and embodied environmental impacts (such as carbon, energy, and water). LCA may be used to determine an optimal suite of measures customized for a specific building in a particular location based on internationally accepted standards. LCA not only provides a more complete account of a project's environmental performance, but it also allows comparison of the relative merits and impacts of alternative building designs. For example, not only can different materials and structural systems (steel, concrete, wood) be compared impartially, the operational performance benefits provided by the structure (such as thermal mass) can be considered and potentially "traded off" against the more intensive embodied impacts. France's newly adopted environmental regulation for new buildings (RE2020) replaces its previous building energy code (RT2012), and introduces, in addition to energy efficiency requirements, requirements for managing GHG emissions from both operational energy use and embodied carbon from materials.[63] Inevitably, low-carbon materials such as wood may give the designer more choice when selecting building systems.

[61] Scope 3 emissions are those for which an organization is responsible but which happen outside of the organization itself; for example, the emissions related to products purchased and disposed of. For more information, see www.ghgprotocol.org.

[62] For more information about the importance of embodied energy and carbon in relation to energy consumed in building operation in the context of life cycle environmental impacts, see Institute for Building Environment and Energy Conservation. (2016).

[63] https://www.actu-environnement.com/ae/news/RE-2020-premier-decret-arrete-exigences-methodes-calcul-batiments-neufs-38046.php4

Due to increased focus on the embodied impacts of materials, the efforts of some manufacturers to incorporate efficient "closed-loop" production processes, such as using mill waste for higher value products (wood fibre insulation or thermoplastics) and fuel in lumber drying kilns, have resulted in lower GHG emissions, which will be accounted for in LCA.

Performing LCA for a complete building is being streamlined due to increased availability of data and more efficient tools, like using BIM to develop a material inventory for a building LCA. Whole-building LCA may now be employed as a design tool, like energ, and ventilation/air flow modelling. Currently, whole-building LCA tools estimates the environmental impacts associated with building materials, operational energy use, and operational water use (Bowick et al., 2014). By comparison, embodied carbon analysis focuses strictly on the building materials and excludes analysis of operational energy and water use (Walker et al., 2020).

For LCA findings to meaningfully inform the design of a building (as opposed to simply documenting the resulting impacts), analysis should commence as early as possible and be iterated as the project design evolves. The LCA model may then be used throughout the design process to allow designers to explore trade-offs and refine a design for optimum LCA performance, ideally leading to a final design with a lighter footprint.

In many studies, [64] the LCA of wood buildings has demonstrated a lower overall embodied environmental impact than either steel or concrete, with wood showing the least impact on energy, climate (Global Warming Potential), and air pollution. For example, a comparison of two student residence towers at the University of British Columbia—a mass timber hybrid building (Brock Commons Tallwood House) and a concrete building (Ponderosa Commons Cedar House) (Figure 8)—showed that Tallwood House had 36% lower GWP impacts than Cedar House, despite extra layers of type-X gypsum boards (required for fire protection) being used in the mass-timber structure of Tallwood House (Teshnizi, et al., 2018).

[64] There is a list of studies related to life cycle assessment, wood and mass timber in the Think Wood research library: https://research.thinkwood.com/en/list?q=&p=1&ps=20&topic_facet=Environmental%20Impact&keywords_facet=Life-Cycle%20Assessment

Figure 8. (a) Brock Commons Tallwood House, and (b) Ponderosa Commons Cedar House, University of British Columbia (courtesy of Zahra Teshnizi).

For other whole building LCA results of mass timber buildings, refer to the Think Wood research library,[65] Athena Sustainable Materials Institute (2015), Grann (2013), Ruuska & Häkkinen (2012), and TallWood Design Institute (2019). More information about CLT life cycle analysis is provided in Info Sheet #12 in the TallWood Design Institute's *Cross-Laminated Timber Info Sheets* series.[66]

LCA data and tools are evolving quickly. As more is understood about the environmental impacts of buildings and the materials that go into them, new questions arise that need to be addressed. For example, according to the TallWood Design Institute, there are information gaps in EPD data about the environmental impacts of CLT because there is no standard way of quantifying the environmental effects of different forest management practices. Certifications communicate certain forest management practices, but EPD results are likely not affected by forest management practices that are affected by certification (e.g., effects on coarse woody debris, wetlands, or riparian zones) (TallWood Design Institute, 2019).

There are also emerging environmental effects related to the production and long-term performance of construction materials—notably in the context of forest management and carbonation of concrete—that are being considered within the research community but have yet to be embedded into codes and standards (and therefore are rarely included in LCA studies at present). These effects include biogenic carbon, albedo, evapotranspiration, aerosols, black carbon, and the potential for increased

65 https://research.thinkwood.com/en

66 http://tallwoodinstitute.org/sites/twi/files/Info%20Sheets_Final_200616.pdf

forest growth rates due to the carbon fertilization effect (summarized in the following text box and discussed in detail in Chapter 11 of the *Canadian CLT Handbook* [Karacabeyli & Gagnon, 2019]).

Emerging Considerations in the Context of Forest Management Impacts

The following topics currently dwell within the realm of researchers but may become increasingly relevant to LCA practitioners and the design community as the science evolves.

Biogenic Carbon

Biogenic carbon refers to emissions related to the natural carbon cycle, as well as those resulting from the combustion, harvest, digestion, fermentation, decomposition, or processing of biologically based materials. Ongoing research focuses on the role of forest-sourced bioenergy in climate mitigation efforts due to the long rotation lengths associated with forest biomass. Valuing biogenic carbon sequestration is debated due to its reversibility; however, dynamic biogenic carbon modelling methodologies are being developed to capture and quantify both emissions and removals.

Albedo

Albedo refers to the fraction of the sun's energy that an object reflects. Designers may be familiar with the term in the context of the urban heat island effect. However, at northern latitudes, there is a potential cooling "landscape albedo" effect (negative Global Warming Potential) following forest disturbance as the landscape, without a forest canopy, becomes more reflective in the winter due to seasonal snow cover. While albedo effects are not commonly considered in building life cycle assessments, the Intergovernmental Panel on Climate Change states that albedo effects are an important climate consideration for agriculture, forestry, and land use sectors (Smith et al., 2014).

Evapotranspiration

During evapotranspiration, water moves from the soil to the atmosphere through plants. With rising global temperatures and where changes in humidity levels occur, the rate of evapotranspiration may increase.

Black Carbon

Black carbon is formed from the incomplete combustion of fossil fuels, biofuel, and biomass, and is emitted in both human-caused and naturally occurring soot. In climatology, black carbon is a climate forcing agent. It warms the Earth by absorbing sunlight and heating the atmosphere, and by reducing albedo when deposited on snow and ice (direct effects) and when interacting with clouds (indirect effects). Black carbon is a short-lived particulate emission; there is a significant uncertainty associated with its contributions to net climate forcing. In Canada, most black carbon emissions are produced by mobile sources, particularly diesel engines. In the context of forestry management, black carbon refers either to deposited atmospheric black carbon or to directly incorporated black carbon from vegetation fires.

4.5.1.1 Environmental Product Declarations and Material Ingredient Reporting Tools

Two basic categories of data can be included in a life cycle inventory (LCI): product-specific information and industry averages. Environmental product declarations were created to help standardize the reporting of environmental impact results for products, and standards guide their scope. Essentially, an EPD is a third-party verified report that provides a set of quantified environmental impact data for a product based on an LCA that has been conducted in compliance with ISO standards (ISO 14040 [ISO, 2006b], 14044 [ISO, 2006c], and 14025 ISO, [2006a]). An EPD includes information about the environmental impacts associated with a product, such as raw material acquisition; energy use and efficiency; content of materials and chemical substances; emissions to air, soil, and water; and waste generation. EPDs may be used by designers on a product-by-product basis to compare a range of environmental impacts. The Canadian Wood Council offers numerous examples of forest product EPDs[67] that are applicable to Canadian wood products.

There are also numerous material ingredient reporting tools that provide architects and designers with additional information about the contents in products and the manufacturing process. Leading solutions for material ingredient reporting include:

- Cradle to Cradle Certified[68]
- Health Product Declarations[69]
- Living Product Challenge Certified[70]
- Global GreenTag International[71]
- GreenScreen Certified[72]
- “Declare” labels designated as Red List Free[73]

These labels form the basis of credits within green building rating systems (see Section 4.5.3) which are driving uptake by forest product manufacturers. For example, a CLT product has received Cradle to Cradle certification.[74] There are also numerous reporting schemes that provide information about

[67] https://cwc.ca/why-build-with-wood/sustainable/green/epds/

[68] www.c2ccertified.org

[69] www.hpd-collaborative.org

[70] https://living-future.org/lpc

[71] www.globalgreentag.com

[72] www.greenscreenchemicals.org/certified

[73] The Red List contains the “worst in class” materials that are prevalent in the building industry: https://living-future.org/declare/declare-about/red-list

[74] https://www.c2ccertified.org/products/scorecard/cross-laminated-timber-clt-egoin-sa

the ethical and sustainability practices of companies. Leading programs include the Global Reporting Initiative,[75] B-Corp,[76] and FairTrade.[77]

The following additional resources can be consulted regarding different substances of concern:

- **Healthy Building Network**[78] is a third-party, non-profit organization that publishes research related to healthy building materials.
- **Green Science Policy Institute**[79] offers a good introduction to six chemical classes of concern: per- and polyfluoroalkyl substances or highly fluorinated chemicals, antimicrobials, flame retardants, bisphenols and phthalates, some solvents, and certain metals.
- **Perkins + Will Transparency Site**[80] publishes information on substances of concern and the associated human and ecological health effects.

In the absence of an EPD, information on the environmental impacts of a product can be obtained from direct research or estimates based on analysis of similar products. Industry averages can also help address information gaps and provide more appropriate estimates to account for uncertainty. Industry averages can be derived from various sources, such as aggregated data gathered by industry associations, NGOs, or market research organizations, or an economic input-output life cycle assessment.

The following example for a CLT panel manufactured in B.C. illustrates the type of data that is usually provided in an EPD. In this case, the product contains wood = 1 m^3 (417.03 kg oven dry basis) and resin = 3.45 kg. The environmental indicators reported in the EPD include:[81]

- total energy = 3345.83 MJ (of which 44% is non-renewable fossil fuel)
- global warming potential = 89.80 kg CO_2 eq (does not include biogenic carbon sinks and sources)
- acidification potential = 44.24 H+ moles eq
- eutrophication potential = 1.06E-01 kg N eq
- smog potential = 17.46 l kg Ox eq
- ozone depletion potential = 2.15E-07 kg CFC-11 eq

[75] https://www.globalreporting.org/

[76] https://bcorporation.net/

[77] https://www.fairtrade.net/

[78] https://healthybuilding.net

[79] https://greensciencepolicy.org

[80] https://transparency.perkinswill.com

[81] Based on Structurlam's CrossLam panel™ output at the mill gate: www.structurlam.com/wp-content/uploads/2016/10/Structurlam-R-EPD.CrossLamCLT-APA-SLP-2013.pdf

Energy consumption based on life cycle phase indicates that about 5% is consumed by logging, 50% by sawmilling, and 45% by manufacturing.

At the start of 2020, more than 7000 construction product EPDs had been published globally, and the numbers are continuing to increase (Anderson, 2020). With the introduction of increasingly sophisticated LCA tools (Section 4.5.2), manufacturers are motivated to develop more EPDs. EPD publication must be administered by a program operator in accordance with ISO 14025 (ISO, 2006a). There are at least 10 EPD administration programs currently in operation in North America. However, because EPDs are still relatively new, standards, harmonization, and alignment across programs are still developing. Several of the leading North American EPD program operators are working together to harmonize the way product category rules—the overarching criteria that govern the preparation of EPDs—are developed.

EPDs currently exist for several wood products and may be provided by individual manufacturers or may be obtained from the Canadian Wood Council[82] and FPInnovations.[83] For more information about CLT EPDs and biogenic carbon, refer to Info Sheet #10 in the TallWood Design Institute's *Cross-Laminated Timber Info Sheets* series.[84]

4.5.2 Life Cycle Assessment Tools and Development in Canada

Proprietary software tools that assess several environmental impacts (climate, water quality, etc.) are available for use in North America. These tools bring regionally specific life cycle inventory databases and LCA methods together, and help practitioners address assumptions, all of which influence the results and outcomes of an LCA.

The U.S. Life Cycle Inventory database is the largest database for LCA in North America. Two common LCA databases that are used globally, including in Canada, are ecoinvent[85] and GaBi.[86] However, life cycle inventory data can be influenced by geography (e.g., energy sources used to generate electricity, and regulations affecting emissions controls) and can vary across regions; therefore, efforts are underway to create regional and/or national databases. In Canada, this work is being initiated through the National Research Council's Low-Carbon Assets through Life Cycle Assessment (LCA^2) Initiative,[87] which is developing a Canadian-specific life cycle inventory (LCI) database and associated LCA guidelines to enable the public sector (federal, provincial, territorial,

[82] https://cwc.ca/why-build-with-wood/sustainable/green/epds/

[83] http://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Pages/default.aspx

[84] http://tallwoodinstitute.org/sites/twi/files/Info%20Sheets_Final_200616.pdf

[85] www.ecoinvent.org

[86] www.gabi-software.com

[87] More information about the LCA^2 initiative, which is being led by the National Research Council and managed collaboratively by the NRC's Energy, Mining and Environment Research Centre and the Construction Research Centre, is provided on the Government of Canada website: https://nrc.canada.ca/en/research-development/research-collaboration/programs/low-carbon-assets-through-life-cycle-assessment-initiative

and municipal governments) and private sector to incorporate the quantification of life cycle carbon and total cost of ownership of built assets (real property, public infrastructure) into their procurement processes. The primary objectives of the LCA² Initiative are to (1) establish a national LCI database of construction materials that can be easily integrated with existing LCA tools, (2) develop procurement specifications, (3) establish guidelines for LCA-based estimation of the carbon in buildings and infrastructure (embodied and operational), and (4) develop low carbon benchmarks.

The choice of LCA software used by designers and consultants depends on several factors, such as the project's location, availability of a BIM or 3D model, software cost, and expertise with the software. The following summary of the main LCA software tools currently in use in Canada is based on (and expands on) a comparison presented in Walker et al. (2020):

- **Impact Estimator for Buildings**[88] was developed by Canada's Athena Sustainable Materials Institute. It is free, and can import data from a Bill of Materials or allow for custom design inputs. It also comes preloaded with standard assemblies. It accesses Athena's proprietary LCI database and can generate results as graphs and/or reports for a wide range of environmental impacts.
- **OneClick LCA,**[89] developed by Bionova in Finland, is a highly functional tool that can develop results for a wide range of environmental impacts. It costs about Can$700 per year to license and can integrate into BIM systems such as Autodesk Revit® or access data from a Bill of Materials. It provides a wide range of design options and comparisons, relies on a large number of EPDs as well as generic data that are applicable to the Canadian context, and can produce intuitive charts, graphs, reports, and rankings.
- **Tally**® [90], developed by KT Innovations, requires access to (and therefore knowledge of how to manipulate) a detailed Revit model. It costs about Can$1000 per year to license, and accesses data from EPDs and the GaBi LCI database. Assuming users have proficiency with Revit, it is easy to learn and can present results for a wide range of environmental impacts in various chart or report formats.
- **Embodied Carbon in Construction Calculator** (EC3)[91] is a new, free, cloud-based, open-access tool that focuses specifically on embodied carbon. It was launched by the U.S.-based Carbon Leadership Forum in 2019. It allows for benchmarking, assessment, and reductions that are focused on the upfront (cradle-to-gate) supply chain emissions of construction materials. The EC3 tool uses building material quantities from construction estimates/Bill of Materials and/or BIM models and a database of EPDs.

[88] https://calculatelca.com/software/impact-estimator

[89] www.oneclicklca.com

[90] https://choosetally.com

[91] www.carbonleadershipforum.org/projects/ec3

- **Gestimat,**[92] developed within the framework of Québec's Timber Charter, is a tool for estimating GHG emissions that are linked to the manufacture of structural materials and for comparing different building scenarios in a Québec context. Scenarios can be modelled by using estimates of the quantities of materials used according to typical buildings or by entering quantities of materials that are specific to a given project. The tool is currently being adapted for use in other provinces.

4.5.3 Green Building Certification Systems

The World Green Building Council provides a complete list of the leading green building rating systems.[93] Systems that are commonly used in Canada and the United States and that are applicable to tall wood projects are summarized below.

4.5.3.1 Leadership in Energy and Environmental Design

Organization: Canada Green Building Council

Website: www.cagbc.org

Leadership in Energy and Environmental Design (LEED) is the dominant voluntary green building rating system in North America and is used extensively around the world. Certification is on a scale ranging from Certified, Silver, and Gold to Platinum at the highest level, and is based on the total points achieved. Over the years, the emphasis has evolved to a performance-based approach to design, operations, and maintenance that calls for measurable results throughout a project's life cycle. From a materials standpoint, this means there has been a shift from considering the total amount of materials used to evaluating the impact of those materials on human health and the environment.

Credit categories in LEED for Building Design and Construction that are applicable to tall wood structures are Materials and Resources, and Innovation, and focus on the following technical areas to address impacts on the environment and human health:

- **Construction and Demolition Waste Management**

  These credits are designed to reduce the amount of waste materials generated on-site and to divert construction and demolition debris from incineration and landfills. This credit also promotes the redirection of recyclable resources back to the manufacturing process and reusable materials to appropriate reclamation sites. Construction waste management and by-product use for tall wood buildings is discussed in more detail in Section 4.3.3.6. However, it is important to emphasize that mass timber is largely prefabricated, which substantially reduces the amount of waste generated on-site. LEED prerequisites include planning for construction waste management and establishing waste diversion goals for the project.

[92] https://gestimat.ca

[93] www.worldgbc.org/rating-tools

- **§Building Life Cycle Impact Reduction**

  This series of credits is intended to encourage adaptive reuse and optimize the environmental performance of products and materials. It serves as an incentive for design teams to use low-impact materials and reuse salvaged materials in order to reduce the overall environmental footprint of the project. To demonstrate compliance, the team must conduct a whole-building LCA. Points are awarded if the "final design" demonstrates a quantitative impact reduction compared to a "reference design" for a selection of LCA measures (one of which must be Global Warming Potential), and no measure performs worse than the reference design.[94] Credits are available for incorporating building reuse and/or salvage materials into the project's structure and enclosure for the proposed design.

- **Building Product Disclosure and Optimization – Environmental Product Declarations**

  This set of credits stipulates that a portion of materials must demonstrate environmental impact reductions based on a current third-party EPD or verified LCA that conforms to the comparability requirements of ISO 14025 (ISO, 2006a) and ISO 21930 (ISO, 2017). Impact analysis must include Global Warming Potential. Other categories may include depletion of the stratospheric ozone layer, acidification of land and water sources, eutrophication, formation of tropospheric ozone, and depletion of non-renewable energy resources/depletion of fossil fuels.

  Credits for the preparation of a Life Cycle Impact Reduction Action Plan and for demonstrable life cycle impact reductions in embodied carbon are also available. The use of timber structures manufactured from sustainably sourced forest products that carry an EPD contributes to these credits.

- **Building Product Disclosure and Optimization – Sourcing of Raw Materials**

  The purpose of these credits is to (1) foster the use of products and materials for which life cycle information is available and that have environmentally, economically, and socially preferable life cycle impacts, and (2) reward project teams for selecting products that are verified as having been extracted or sourced in a responsible manner.

  To achieve these credits, a certain proportion of the materials in the building project must be sourced from a manufacturer (producer) that participates in an Extended Producer Responsibility program[95] (or is directly responsible for extended producer responsibility), or must be bio-based products from a sustainable source, or certified wood products (under FSC or an approved equivalent) (see Section 4.3.2.2 for a summary of the forest certification programs in Canada).

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[94] Whether referenced in policy or not, LEED influences international construction practices and standards. To date, more than 1 billion square feet of construction in Canada has been LEED-registered. As an example of market penetration, 22% of all new commercial buildings and approximately 30% of all new institutional buildings constructed in Canada in 2014 were LEED certified. Source: LEED in Motion: Canada, Green Business Certification Inc., 2017. www.cagbc.org/cagbcdocs/advocacy/LEED_IN_MOTION_CANADA_2017_UPDATE.pdf

[95] Extended Producer Responsibility claims must be made in accordance with ISO 14021 (ISO, 2016).

- **Building Product Disclosure and Optimization – Material Ingredients**

  These credits are focused on disclosing the chemical ingredients in (or applied to) a product, and reward designers for selecting products that have been verified to minimize the use and generation of harmful substances. Achieving these credits relies on the use of material ingredient tools (see Section 4.5.1.1) or third-party verified information to show that the product or material does not off-gas and/or cause harm to human health.

  For wood products, this means selecting adhesives, paints, stains, and coatings that have been developed using green chemistry, are non-toxic in their application or operation, and do not cause harm at the end of life (see Section 4.4.1).

  Design teams should consult with manufacturers, as well as MSDS, Health Product Declarations, and EPDs, early in the design process to understand the contents of a given product and ensure that the product will not have a negative impact on indoor environmental quality and human health.

- **Innovation**

  This credit is intended for projects that achieve significant, measurable environmental performance using a strategy not addressed in the LEED green building rating system. For example, tall wood building design teams may choose to pursue points for environmental performance aspects, such as carbon storage (see the Glossary and Section 4.2) or design for disassembly (see Section 4.3.3.3).

Recently, the U.S. Green Building Council launched LEED Zero[96], a complement to LEED that verifies the achievement of net zero goals and signals market leadership in the built environment.

LEED Zero Carbon recognizes net zero GHG emissions from operational energy consumption and commuting habits of building occupants over a period of 12 months using avoided GHG emissions, which are also known as carbon offsets. LEED Zero Waste may be relevant to wood structures for building projects that pursue Green Business Certification Inc.'s TRUE Zero Waste certification[97] at the Platinum level.

4.5.3.2 Canada Green Building Council Zero Carbon Building Standard

Organization: Canada Green Building Council

Website: https://www.cagbc.org/

The Canada Green Building Council launched a Zero Carbon Building program specifically to support a transition to a low-carbon construction industry. The program offers design teams two levels of certification: design and performance certification.

[96] https://new.usgbc.org/leed-zero

[97] www.gbci.org/#certification

The standard focuses on reducing greenhouse gas emissions in the three performance areas outlined below.

1. **Carbon requirements:** requires teams to calculate carbon emissions across the building life cycle. At a high level, the following carbon calculations are required:
    a. model zero carbon balance;
    b. report embodied carbon;
    c. report total quantity of refrigerants;
    d. provide a quote and proof of purchase of Renewable Energy Credits or carbon offsets (Performance Certification); and
    e. provide a transition plan for onsite combustion.
2. **Energy requirements**: offering flexibility, three options for compliance are available:
    a. Flexible approach: Thermal Energy Demand Intensity of 30–40 kWh/m^2/year as a function of climate zone, and Site Energy Use Intensity 25% better than the National Energy Code of Canada for Buildings (NRC, 2017)
    b. Passive Design Approach: Thermal Energy Demand Intensity of 30–40 kWh/m^2/year as a function of climate zone
    c. Renewable Energy Approach: Thermal Energy Demand Intensity of 30–40 kWh/m^2/year as a function of climate zone, and zero carbon balance for operational carbon achieved without green power products or carbon offsets
3. **Impact and innovation requirements:** projects are required to implement two strategies identified under the performance category of Impact and Innovation:
    a. 5% on-site renewable energy generation or solar photovoltaics covering 75% of the roof area;
    b. use electric heat pump systems designed to meet at least 50% of the annual heating load;
    c. install any size of building integrated photovoltaics;
    d. realize a 20% embodied carbon reduction as compared to a baseline; and/or
    e. show that upfront carbon emissions are equal to or less than zero, using products that are available on the market.

More information about each of these measures is described in the updated standard.

4.5.3.3 Living Building Challenge
Organization: International Living Future Institute

Website: www.ilbi.org/lbc

The Living Building Challenge, developed by the International Living Future Institute, is a third-party audited system that is one of the most rigorous and challenging systems in the marketplace. To date, it has been active primarily in Canada and the United States and seeks "to define the most advanced measure of sustainability in the built environment possible today and acts to diminish the gap between current limits and ideal solutions" (Living Building Challenge).

Within the materials requirements, projects must calculate the total embodied carbon due to construction materials and processes and purchase an offset from an approved provider of offset credits. This task requires whole-building LCA, although only the carbon portion is reported. This may be the only green building rating program with a requirement to measure—and offset—embodied carbon. Increasingly, elements of the Living Building Challenge are being incorporated into LEED, and further convergence is expected over time due to the launch of LEED Zero.

All wood used in a Living Building Challenge project must be either FSC-certified, salvaged, or harvested on-site. Pine beetle-killed wood may qualify as salvaged material if the timber supplier can document that sustainable forestry management practices have been used to harvest the timber.

In addition, practitioners must pay particular attention to the Materials Red List to ensure that those substances are not used in the manufacturing and installation of wood-based products in a building. However, the Living Building Challenge currently states that a temporary exception is made for glulam beams that have phenol resorcinol formaldehyde adhesives.

4.5.3.4 BuiltGreen Canada High Density Program

Organization: BuiltGreen Canada

Website: www.builtgreencanada.ca

The BuiltGreen Canada High Density Program takes a holistic approach with a key focus on energy efficiency and includes other critical aspects of sustainable building—such as materials and methods, water conservation, and waste management—and rewards innovative sustainable building practices that go above and beyond what is contained within the program.

Tall wood building systems used in residential and mixed-use applications may achieve certification in the "High Density" category of the BuiltGreen program. The level of certification depends on the number of points achieved, and ranges from Bronze, Silver, and Gold to Platinum at the highest level.

Credits related to tall wood building systems are captured in the Materials and Methods and Indoor Air Quality sections. The program recognizes the efficient use of framing materials, and alternatives to using large sawn lumber sizes. BuiltGreen Canada High Density also recognizes products and finishes that are more durable or are made with recycled content, or wood products from sustainably managed forests (from the FSC, SFI, or CSA; see Section 4.3.2.2). Credit is given to the use of materials that are low in VOCs (see Section 4.4.1) and products that are made from all-natural materials.

More information about the BuiltGreen Canada High Density program and a complete checklist for potential point areas are available at http://www.builtgreencanada.ca/high-density.

4.5.3.5 Green Globes Design for New Buildings

Organization: Operated by ECD Energy and Environment Canada Ltd.

Website: www.greenglobes.com

Green Globes is an online rating tool developed in Canada, originally as an adaptation of the British BREEAM system, and can be used for a wide range of commercial and institutional building types. The Green Globes program is presented as a user-friendly and affordable certification system. It comprises a questionnaire-based tool consisting of approximately 150 questions, which take an estimated 2–3 hours to answer. This process is not third-party audited.

Credits are given for selecting materials with the lowest life cycle environmental and embodied energy burden, and the program encourages the completion of a whole building life cycle assessment. It also recognizes the use of wood products that originate from certified and sustainable sources (certified by the CSA, FSC, or SFI) and avoid the use of tropical hardwoods.

For more information on Green Globes Design for New Buildings and Retrofits, see www.greenglobes.com/design/Green_Globes_Design_Summary.pdf

4.6 REFERENCES

American National Standards Institute and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ANSI/ASHRAE). (2019a). *ANSI/ASHRAE Standard 62.1: Ventilation for acceptable indoor air quality*. Washington, DC: Author; Atlanta, GA: Author. https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2

American National Standards Institute and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ANSI/ASHRAE). (2019b). *ANSI/ASHRAE Standard 62.2:Ventilation and acceptable indoor air quality in residential buildings*. Washington, DC: Author; Atlanta, GA: Author. https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2

American Wood Council (AWC). (2013). *Adhesives awareness guide*. Leesberg, VA: Author.

Anderson, J. (2020, October 12). *Construction LCA*. [Web log post]. https://constructionlca.co.uk/2020/10/12/over-7000-en-15804-environmental-product-declarations-epd-were-available-at-the-start-of-2020-with-numbers-continuing-to-increase/

Athena Sustainable Materials Institute. (2015). *Wood Innovation and Design Centre: An environmental building declaration according to the EN 15978 standard*. https://research.thinkwood.com/en/permalink/catalogue2156

Bare, J. (2012). *Tool for the reduction and assessment of chemical and other environmental impacts (TRACI): User's manual*. Cincinnati, Ohio: U.S. Environmental Protection Agency. https://nepis.epa.gov/Adobe/PDF/P100HN53.pdf

BC Housing. (2019). *Mould management guide for BC housing residents*.

Bergsdal, H., Brattebø, H., Bohne, R. A., & Müller, D. (2007). Dynamic material flow analysis for Norway's dwelling stock. *Building Research & Information*, 35, 557-570. doi: 10.1080/09613210701287588

Bionova Ltd. (2018). *The embodied carbon review: embodied carbon review in 100+ regulations and rating systems globally*. Helsinki, Finland: One Click LCA Ltd. https://www.oneclicklca.com/embodied-carbon-review/

Boutin, S., Haughland, D. L., Schieck, J., Herbers, J., & Bayne, E. (2009). A new approach to forest biodiversity monitoring in Canada. *Forest Ecology and Management*, 258, Supplement 14, S168-S175.

Bowick, M., O'Connor, J., & Meil, J. (2014). *Athena guide to whole-building LCA in green building programs*. Ottawa, ON: Athena Sustainable Materials Institute.

Canadian Council of Forest Ministers (CCFM). (n.d.). *Canada's legal forest products*. Ottawa, ON: Author. www.sfmcanada.org/en/forest-products/legal-forest-products#Prov

Canadian Council of Ministers of the Environment (CCME). (2019). *Guide for selecting policies to reduce and divert construction, renovation and demolition waste*. Ottawa, ON: Author.

Canadian Mortgage and Housing Corporation. (2013). *Canadian housing observer 2013*. https://publications.gc.ca/site/eng/360371/publication.html

Canadian Standards Association (CSA). (2003). *CSA Z809-02: Sustainable forest management: requirements and guidance.* Mississauga, ON: Author.

Canadian Standards Association (CSA). (2013). CSA Z804-08: *Sustainable forest management for woodlots and other small area forests.* Mississauga, ON: Author.

Canadian Wood Council (CWC). (n.d.). *Wood products and carbon sequestration*. Ottawa, ON: Author. https://cwc.ca/wp-content/uploads/2013/11/WOOD-Products-and-Carbon-Sequestration.pdf

Canadian Wood Council (CWC). (2013). *Adhesives*. Ottawa, ON: Author.

Cashore, B., & McDermott, C. (2004). Global environmental forest policies: Canada as a constant case comparison of select forest practice regulations. International Forest Resources. https://www.nrdc.org/sites/default/files/media-uploads/the_study_itself_0.pdf

Certification Canada (n.d.). *Canadian statistics*. https://certificationcanada.org/en/statistics/canadian-statistics/

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J.,…Thornton, P. (2013). Carbon and other biogeochemical cycles. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung,…P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter06_FINAL.pdf

Dymond, C. C. (2012). Forest carbon in North America: annual storage and emissions from British Columbia's harvest, 1965–2065. *Carbon Balance and Management,* 7**,** 8.

El Asmar, M., Hanna, A. S., & Loh, W-Y. (2013). Quantifying performance for the integrated project delivery system as compared to established delivery systems. *Journal of Construction Engineering and Management*, 139(11). https://ascelibrary.org/doi/10.1061/%28ASCE%29CO.1943-7862.0000744

Environment and Climate Change Canada. (2020). *National inventory report 1990–2019: greenhouse gas sources and sinks in Canada: executive summary*. https://publications.gc.ca/site/eng/9.816345/publication.html

European Committee for Standardization (CEN). (2011). *Standard EN 15978:2011: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*. Brussels, Belgium: Author.

European Committee for Standardization (CEN). (2012). *Standard EN 15804:2012+a2:2019: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products* Brussels, Belgium: Author.

European Forest Institute. (2018) *Substitution effects of wood-based products in climate change mitigation.* https://efi.int/sites/default/files/files/publication-bank/2018/efi_fstp_7_2018.pdf

Fell, D. (2010). *Wood in the human environment: restorative properties of wood in the built indoor environment*. (Unpublished doctoral dissertation). University of British Columbia, Vancouver, BC.

Fell, D. (2011). Wood and human health. *Wood and Human Health Series, Issue 1*. Vancouver, BC: FPInnovations.

Fischer, D. (2011). Shift in northern forests could increase global warming. Scientific American. https://www.scientificamerican.com/article/shift-northern-forests-increase-global-warming/

Frihart, C. R., & Hunt, C. G. (2010). Adhesives with wood materials: bond formation and performance. In *Wood handbook: Wood as an engineering material*. (General Technical Report FPL–GTR–190) (10-1 – 10-24). Madison, WI: U.S. Department of Agriculture, Forest Products Laboratory. www.fpl.fs.fed.us/documnts/fplgtr/fplgtr190/chapter_10.pdf

Gakidou, E., Afshin, A., Abajobir, A. A., Abate, K. H., Abbafati, C., Abbas, K. M., … Murray, C. J. L. (2017). Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2016: A systematic analysis for the Global Burden of Disease Study 2016. *Lancet*, 390(10100), 1345–1422.

Gilani, H., & Innes, J. (2020). The state of Canada's forests: A global comparison of the performance on Montréal Process Criteria and Indicators. *Forest Policy and Economics*, 118, 102234.

Goodland, H., Lam, A., Chudasma, D., Staub-French, S., & Zadeh, P. (2019). *Strategies for collaborative construction: integrated project delivery case studies*. Burnaby, BC: BC Housing. www.bchousing.org/research-centre/library/building-science-reports/strategies-collaborative-construction

Government of Canada. (2017). Build smart: Canada's building strategy. A key driver of the Pan-Canadian Framework on clean growth and climate change. *Energy and Mines Ministers' Conference*. St. Andrews by-the-Sea, New Brunswick. https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/emmc/pdf/Building_Smart_en.pdf

Grann, B. (2013). *A comparative life cycle assessment of two multistory residential buildings: Cross-laminated timber vs. concrete slab and column with light gauge steel walls*. Vancouver, BC: FPInnovations.

Griffin, B. (2019). *Energy use and CO_2 emissions in Canadian wood products industries 1990 to 2017*. Ottawa, ON: Forest Products Association of Canada. https://www.sfu.ca/content/dam/sfu/ceedc/publications/forest/CEEDC%20-%20Wood%20Products%20Report%202019.pdf

Guy Perry and Associates & Kelleher Environmental. (2015). *Characterization and management of construction, renovation and demolition (CRD) waste in Canada*. Environment Canada.

Indufor. (2009). *Comparison of selected forest certification standards*. Vancouver, BC: Forestry Innovation and Investment.

Indufor. (2016). *International comparison of forest management legal frameworks and certification standards*. Forest Products Association of Canada, Forestry Innovation Investment Ltd., Natural Resources Canada, Canadian Forest Service, Canadian Council of Forest Ministers.

Institute for Building Environment and Energy Conservation. (2016). *Guidelines for policy makers: Evaluation of embodied energy and CO2eq for building construction*. http://www.annex57.org/wp/wp-content/uploads/2017/05/Guidelines-for-Policy-makers.pdf

International Agency for Research on Cancer (IARC). (2004). *IARC classifies formaldehyde as carcinogenic to humans*.

International Organization for Standardization (ISO). (2006a). *ISO 14025:2006: Environmental labels and declarations — Type III environmental declarations — Principles and procedures*. Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2006b). *ISO 14040:2006: Environmental Management: Life Cycle Assessment: Principles and Framework.* Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2006c). *ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines.* Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2016). *ISO 14021:2016: Environmental labels and declarations — Self-declared environmental claims (Type II environmental labelling)*. Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2017). *ISO 21930:2017: Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services*. Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2018). *ISO 14067:2018: Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification*. Geneva, Switzerland: Author.

Karacabeyli, E., & Gagnon, S. (Eds.) (2019). *Canadian CLT handbook, 2019 edition*. (Special Publication SP-532E). Pointe-Claire, QC: FPInnovations. https://web.fpinnovations.ca/clt/

Knockaert, C. (2021). *Possible consequences of eutrophication*. http://www.coastalwiki.org/wiki/Possible_consequences_of_eutrophication

Koo, K. (2013). *A study on historical tall-wood buildings in Toronto and Vancouver*. Québec, QC: FPInnovations.

Lamlom, S. H., & Savidge, R. A. (2003). A reassessment of carbon content in wood: variation within and between 41 North American species. *Biomass and Bioenergy*, 25(4), 381-388.

Lenz, B., Schreiber, J., & Stark, T. (2011). *Sustainable building services* (1st ed.). Munich, Germany: Institut für internationale Architektur-Dokumentation GmbH & Co. KG.

Leskinen, P., Cardellini, G., González-García, Hurmekoski, E., Sathre, R., Seppala, J.,…Verkerk, P. J. (2018). *Substitution effects of wood-based products in climate change mitigation.* Joensuu, Finland: European Forest Institute. https://efi.int/sites/default/files/files/publication-bank/2018/efi_fstp_7_2018.pdf

Lowe, G. (2020). *Wood, well-being and performance: the human and organizational benefits of wood buildings*. Forestry Innovation Investment.

Marr, G. (2016, 26 October). Canadians have the third-largest homes, but they may downsize to deal with affordability: Report. *Financial Post*. https://financialpost.com/personal-finance/mortgages-real-estate/canadians-have-the-third-largest-homes-but-they-may-downsize-to-deal-with-affordability-report

McKeever, D., & Elling, J. (2015). *Wood products and other building materials used in new residential construction in the United States, with comparison to previous studies 2012* (p. 75). Tacoma, WA: APA - The Engineered Wood Association. www.fpl.fs.fed.us/documnts/pdf2015/fpl_2015_mckeever001.pdf

Metsaranta, J. M., Kurz, W. A., Neilson, E. T., & Stinson, G. (2010). Implications of future disturbance regimes on the carbon balance of Canada's managed forest (2010-2100). *Tellus*, 62B, 719-728.

National Forestry Database (n.d.a). *Harvest*. http://nfdp.ccfm.org/en/data/woodsupply.php

National Forestry Database (n.d.b). *Wood supply*. http://nfdp.ccfm.org/en/data/woodsupply.php

National Research Council (NRC). (2017). National energy code of Canada for buildings (NECB). Ottawa, ON: Author.

Natural Resources Canada (NRCan). (2020). The state of Canada's forests: annual report 2020. https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/state-canadas-forests-report/table-contents-state-canadas-forests-report/18934

naturally:wood. (2016). *Brock Commons Tallwood House design and preconstruction overview.* https://www.naturallywood.com/wp-content/uploads/2020/08/brock-commons-design-preconstruction-overview_case-study_naturallywood.pdf

O'Connor, J. (2004, October). *Survey on actual service lives for North American buildings*. Paper presented at the Woodframe Housing Durability and Disaster Issues Conference, Las Vegas, NV.

Organisation for Economic Co-operation and Development (OECD). (2012). *Sustainable materials management: making better use of resources.* https://www.oecd.org/env/waste/smm-makingbetteruseofresources.htm

Rostad, K., & Sleep, D. (2014). *Compilation of Canadian provincial and federal regulations relevant to forest management activities* (Special Report No. 14–03). Cary, NC: National Council for Air and Stream Improvement, Inc. www.ncasi.org/Programs/Forestry/Resources/Compilation-of-Canadian-Regulations/Index.aspx

Ruuska, A., & Häkkinen, T. (2012). *Potential impact of wood building on GHG emissions.* VTT Technical Research Centre of Finland.

Sims R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'Agosto, M., Dimitriu, D., …Tiwari, G. (2014). Transport. In O., Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth,…J. C. Minx (Eds.). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., … Tubiello, F. (2014). Agriculture, forestry and other land use (AFOLU). In O., Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth,…J. C. Minx (Eds.) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY: Cambridge University Press.

Stadhaus. (2018). *Wikipedia*. https://en.wikipedia.org/wiki/Stadthaus

Statistics Canada. (2012, 19 September). *2011 Census of Canada: Household type (17), household size (9) and structural type of dwelling (10) for private households of Canada, provinces, territories, census metropolitan areas and census agglomerations*. https://www12.statcan.gc.ca/census-recensement/2011/dp-pd/tbt-tt/Index-eng.cfm

TallWood Design Institute. (2019). *Cross-laminated timber*. (Info Sheets). Corvallis, OR: Oregon State University.

Teshnizi, Z., Pilon A., Storey S., Lopez D., & Froese T. M. (2018). Lessons learned from life cycle assessment and life cycle costing of two residential towers at the University of British Columbia. *Procedia CIRP*, 69, 172-177.

Towprayoon, S., Ishigaki, T., Chiemchaisri, C., & Abdel-Aziz, A. O. (2019). Solid waste disposal. In *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Waste* (Vol. 5). Geneva, Switzerland: Intergovernmental Panel on Climate Change https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol5.html

Tsunetsugu, Y. Miyazaki, Y., & Sato, H. (2006). Physiological effects in humans induced by the visual stimulation of room interiors with different wood quantities. *Journal of Wood Science*, 53, 11-16.

United Nations Environment Programme (UNEP). (2019). *Global status report 2019: Towards a zero-emission, efficient, and resilient buildings and construction sector*. www.unenvironment.org/resources/publication/2019-global-status-report-buildings-and-construction-sector

United Nations International Resource Panel (UNIRP). (2019). *Resource efficiency and climate change: material efficiency strategies for a low-carbon future*. https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change

United States Department of Agriculture (USDA). (2016, 12 August). *Ozone effects on plants*. https://www.ars.usda.gov/southeast-area/raleigh-nc/plant-science-research/docs/climate-changeair-quality-laboratory/ozone-effects-on-plants/

United States Environmental Protection Agency. (U.S. EPA). (n.d.a). *Greenhouse gas emissions*: u*nderstanding global warming potentials*. Washington, DC: Author. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

United States Environmental Protection Agency (U. S. EPA). (n.d.b). *Health and environmental effects of ozone layer depletion*. https://www.epa.gov/ozone-layer-protection/health-and-environmental-effects-ozone-layer-depletion

Valette, J., Schettler, T., & Wolfe, M. (2014, October). *Asthmagens in building materials: the problem & solutions*. Presented at Greenbuild 2014, New Orleans, LA. https://s3.amazonaws.com/hbnweb.dev/uploads/files/gb2014-asthmagen-paper.pdf

Venier, L. A., Thompson, I. D., Fleming, R., Malcolm, J., Aubin, I., Trofymow, J. A.,…Brandt, J. P. (2014). Effects of natural resource development on the terrestrial biodiversity of Canadian boreal forests. *Environmental Reviews*, 22, 457-490.

Walker, G. M. Lopez, D. Teshnizi, Z., & Pilon, A. (2020). *Policy review of carbon-focused life cycle assessment in green building design and performance at the University of British Columbia*. Vancouver, BC: University of British Columbia & Forestry Innovation Investment. https://sustain.ubc.ca/sites/default/files/UBC%20ECP%20Report-LCA%20Review_2019.pdf

Weyerhaeuser. (2013). *Questions and answers about adhesives and formaldehyde emissions*. (Technical Resource Sheet 1505). Federal Way, WA: Author.

Wilson, E. O. (1984). *Biophilia*. Harvard University Press.

Wood Preservation Canada (WPC). (2013). *Residential use*. Ottawa, ON: Author.

Wood WORKS!, & Canadian Wood Council. (n.d.). *Wood Innovation and Design Centre: A technical case study*. https://wood-works.ca/publication-category/case-studies/

Ximenes, F. Björdalb, C., Kathuriaa, A., Barlazc, M., & Cowied, A. (2019). Improving understanding of carbon storage in wood in landfills: Evidence from reactor studies. *Waste Management* 85, 341-350.

Zizzo, R., Kyriazis, J., & Goodland, H. (2017). Embodied carbon of buildings and infrastructure. naturally:wood. www.naturallywood.com/resources/embodied-carbon-buildings-and-infrastructure

CHAPTER 5

Structural and Serviceability

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CHAPTER OVERVIEW

The four sections in this Structural and Serviceability chapter provide an outline for the design of tall wood structural systems according to, and beyond the scope of, the current Canadian codes and material standards. According to the 2020 National Building Code of Canada (NBC), structural elements that are part of the gravity load-resisting system can be made of mass timber in buildings up to 12 storeys (note: this height limit is governed by fire protection design requirements). Also, due to seismic design requirements, wood-based lateral force-resisting systems have various height limitations. For example, CLT platform-type shearwalls can be used as part of the seismic force-resisting system in buildings up to 30 m in height in seismic categories 1 to 3, which are low to moderate seismic hazard zones, but only up to 20 m in seismic category 4. Beyond these height limits, the structural systems need to be designed under the Alternative Solutions provisions. The following four sections detail how a structural Alternative Solution can be developed for a tall wood building. This chapter covers important and unique aspects of wood design compared to other materials, and it presents ways in which mid- and high-rise wood design differs from low-rise design.

> **Regulatory Acceptance**
>
> A hybrid structural solution consists of using different materials for different structural functions. The prescribed encapsulated mass timber construction in the NBC 2020 is an Acceptable Solution up to 12 storeys. As demonstrated by Brock Commons, building beyond that limit is possible by using mass timber for the gravity system (columns, walls, and floors) and a non-wood Acceptable Solution for the lateral load-resisting system (e.g., concrete or steel). In this case, the Alternative Solution needs to demonstrate fire performance that is equivalent to a similar size building of non-combustible construction (see Chapter 6).

Chapter 5 is not prescriptive. Instead, it follows performance-based principles that provide several possible methods of design and analysis. It is still up to the structural engineer to ensure that the chosen solution is acceptable. Chapter 5 covers necessary topics that span the entire structural design process, from conceptual design (Section 5.1), to gravity and lateral design and analysis (Sections 5.2 and 5.3), to serviceability design (Section 5.4). Instead of providing a step-by-step building design method, Chapter 5 raises important issues, highlights relevant research, and presents the designer with possible options. For instance, Section 5.1: Conceptual Design presents a discussion on several built and proposed tall wood and wood-hybrid buildings. These case studies are meant to provide the designer with insight into what has been built and can be built, and the materials that are available. Section 5.1 is a good starting point for developing the concept of the structural system, and provides resources that can be used to obtain further information on the conceptual design.

Tall wood buildings may require structural systems that have not been used before. Section 5.2: Design Considerations and Input Parameters for Connections and Assemblies, and Section 5.3: Structural Analysis and Design provide information on how to obtain input data from testing and how to conduct the structural analysis and design of building systems for gravity and lateral loads. Regarding novel connections and systems, Section 5.2 provides a detailed guide of testing requirements and analysis methods for obtaining useful test data for building analysis

(Section 5.3). Section 5.2 is also a valuable resource for timber connection design concepts that are relevant to all wood structures, but especially tall buildings. For instance, the effects of shrinkage and creep may be tolerated in a 2-storey building but need to be tightly controlled in a 20-storey building. Section 5.4: Building Sound Insulation and Floor Vibration Control deals with the causes and mitigation of sound transmission and vibration as important serviceability design considerations for multi-family or multi-party occupancies in tall wood buildings.

Although this chapter provides a holistic approach to design for structural and serviceability building performance, coordination with other chapters in this guide remains crucial. Just like in any building project, the structural and serviceability aspects should be coordinated with other disciplines.

CHAPTER 5

SECTION 5.1

Conceptual Design

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ABSTRACT

This section presents considerations for the conceptual structural design of tall timber buildings. It is an overview of the structural codes, key design considerations, and many of the structural systems available. Examples of modern tall timber buildings are included throughout the chapter. The purpose of this section is to assist a structural engineer with concept development of tall timber buildings and to provide insight to others on important structural considerations. The chapter is divided into the following sections:

Structural Codes

This section covers both the National Building Code of Canada (NBC) (NRC, 2020) and, briefly, the International Building Code (IBC) in the United States (ICC, 2021). The code changes in the NBC and IBC related to tall wood buildings are highlighted, and a discussion of Alternative Solution pathways is included.

Project Parameters and Schematic Design Considerations

A critical step in the concept development of a tall wood building is ensuring that the basic project parameters are covered. These often include coordination with other consultants and team members (mechanical, electrical, plumbing, code, architect, contractor), and are meant to provide a basic understanding of how the structure plays a role in the holistic building system, as well as an understanding of key questions to ask during the early project phases. Many of these parameters are expanded on in other chapters in this guide.

Structural Systems

The remainder of the chapter focuses on specific structural systems and approaches that can be used for the building structure, including gravity load-resisting systems and lateral load-resisting systems. This section includes examples of existing tall timber buildings, both as inspiration and as sources for further research.

5.1.1 INTRODUCTION

Tall wood building design and construction is no longer in its infancy. Several projects have been completed, and many more are in progress. This section builds on what has been done and what is in progress, and introduces the basic considerations for the conceptual structural design of tall timber buildings. It includes a brief overview of structural codes, important project parameters and considerations, and typical gravity and lateral systems. Throughout this section, ideas and images from many tall mass timber projects that have been designed, built, or conceptualized are presented.

This section has changed substantially from the original Section 4.1 in the first edition of the *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada* (the guide) (Karacabeyli & Lum, 2014). When the first edition was produced, the concept of tall wood buildings was much more theoretical: examples were few and far between, and Canadian codes were limited to timber buildings up to 6 storeys. Now there are many examples of tall wood buildings in Canada and around the world. Since there are endless different solutions for tall wood building design, this section focuses less on a series of specific case studies, and instead provides overviews of the most important concepts in the structural design of tall wood buildings.

5.1.2 CURRENT STRUCTURAL CODES

5.1.2.1 Canada

The National Building Code of Canada (NBC) (NRC, 2020) is objective-based.

the functional objectives are stated, and specific Acceptable Solutions are provided. However, the Acceptable Solutions are not the only means of meeting the code's objectives. The code also allows for new building solutions through the Alternative Solutions path, provided that the code's objectives are fully met. Prior to the adoption of the 2020 NBC, timber buildings taller than 6 storeys needed to follow an Alternative Solution process or obtain a site-specific regulation.

Brock Commons at the University of British Columbia (UBC) was designed and built using a site-specific regulation, which is generally a more rigorous process than using Alternative Solutions. Obtaining a site-specific regulation involves an extensive review process to verify that the building will perform acceptably, and the regulation applies only to the site in question (UBC Centre for Interactive Research on Sustainability, 2016). Chapter 1 and Chapter 2 of this guide provide more information on regulatory compliance.

The NBC (NRC, 2020) introduced a new construction type—encapsulated mass timber construction (EMTC)—with a height limit of 12 storeys or 42 m. Part 3 of the NBC and the National Fire Code (NRC, 2020) outline EMTC requirements, including fire protection requirements, area limits, occupancy requirements, and measures to be taken during construction. Part 4 of the NBC places a height limit on timber seismic force-resisting systems of 15 m, 20 m, or 30 m in medium-to-high seismic hazard zones, as discussed in 5.1.5 in this section. Thus, a 12-storey mass timber building may be permitted by the code where mass timber is used for the gravity system of the building, but the seismic force-resisting system may be limited to non-timber systems unless an alternative solution is developed.

The Canadian O86 Standard for Engineering Design in Wood (CSA O86) (CSA, 2019) provides component and assembly design guidance that could be used for a tall wood building; however, there are no provisions or considerations specific to tall wood buildings.

The NBC (NRC, 2020) permits Alternative Solutions provided that the functional objectives of the code are met. This is stated in Clause 4.1.1.5 (2) of Part 4 of the NBC as follows:

> Provided the design is carried out by a person especially qualified in the specific methods applied and provided the design demonstrates a level of safety and performance in accordance with the requirements of Part 4, buildings and their structural components falling within the scope of Part 4 that are not amenable to analysis using a generally established theory may be designed by (a) evaluation of a full-scale structure or a prototype by a loading test, or (b) studies of model analogues.

The NBC Appendix notes that this provision is usually used to permit the acceptance of new and innovative structures, provided that the level of safety and performance is at least equivalent to that of structures that meet the requirements for Acceptable Solutions.

The CSA O86 (CSA, 2019) includes Clause 4.3.2:

> New or special systems of design or construction of wood structures or structural elements not already covered by this Standard may be used where such systems are based on analytical and engineering principles, reliable test data, or both, that demonstrate the safety and serviceability of the resulting structure for the purpose intended.

If a project may require an Alternative Solution, the authority having jurisdiction should be contacted early to determine whether they will consider a structural alternative solution and what the specific submission requirements will be.

Several documents that have been released or are under development in Canada provide guidance on tall timber buildings; they can be used to help demonstrate that the functional objectives of the NBC can be met with a mass timber or hybrid alternative solution. The first edition of this guide (Karacabeyli & Lum, 2014) provided fundamentals of tall wood building design and served as a basis for subsequent provincial guides. Four province-specific guides are available or are under development, and can support engineers and architects in designing mass timber buildings that are taller than 6 storeys:

- *Ontario's Tall Wood Building Reference* (Ontario Ministry of Natural Resources and Forestry, 2017) provides an Alternative Solutions path for mass timber buildings based on the Ontario Building Code. It is intended for engineers, architects, and developers, and it covers fire and structural design.
- *Mass Timber Buildings of Up to 12 Storeys* (Gouvernement du Québec, 2015), published in English and French (*Bâtiments de construction massive en bois d'au plus 12 étages*), also covers fire and structural provisions. It is expected to be updated in 2021–2022.
- The *Joint Professional Practice Guidelines*: *Encapsulated Mass Timber Construction Up to 12 Storeys* (AIBC & EGBC, 2021), jointly prepared by the Architectural Institute of British

Columbia and Engineers and Geoscientists British Columbia, are multidisciplinary and include architectural, building enclosure, fire protection, acoustical, structural, mechanical, and electrical considerations, along with quality assurance.

- To support a Building/Fire Code variance, the *12-Storey Encapsulated Mass Timber Construction STANDATA Users Guide* (SCC, 2019) was published to permit buildings up to 12 stories of encapsulated mass timber construction to be built in Alberta.

5.1.2.2 United States

Beginning with the International Building Code (IBC) (ICC, 2021), mass timber buildings with gravity systems up to 18 storeys will be allowed in the United States. The IBC will include the following new construction types with the associated fire-resistance ratings (see also Table 2 in Chapter 6):

a. Type IV-A – fully encapsulated mass timber – buildings up to 18 storeys under certain occupancies; 3-hour fire resistance is required for vertical components, 2-hour for floors, and 1.5-hour for roofs
b. Type IV-B – some of the mass timber must be fully encapsulated, and some may be unprotected – buildings up to 12 storeys under certain occupancies; 2-hour fire resistance is required for floors and vertical components; 1-hour fire resistance is required for the roof.
c. Type IV-C – mass timber that is unprotected – buildings up to 9 storeys under certain occupancies; 2-hour fire resistance is required for floors and vertical components; 1-hour fire resistance is required for the roof.

Additional information on these categories is provided in the U.S. edition of *Mass Timber Design Manual* (Think Wood & WoodWorks, 2021).

The U.S. codes do not include mass timber as a permitted seismic load-resisting system for these tall buildings. Some U.S. authorities having jurisdiction have made project-specific allowances. The state of Oregon has published a statewide Alternate Method approving the use of cross-laminated timber (CLT) shearwalls with an R = 2 (State of Oregon Building Codes Division, 2015).

In the United States, buildings that do not meet the IBC require an Alternate Means and Methods (AM&M) submission that uses a performance-based approach outlined in the IBC (ICC, 2021) and the ASCE-7 codes (American Society of Civil Engineers, 2017). Some authorities having jurisdiction will allow AM&M submittals; others will not. Requirements for AM&M submissions may include one or more of the following: peer review, nonlinear modelling, nonlinear time-history analysis, full-scale structural testing, fire testing.

5.1.3 PROJECT PARAMETERS AND SCHEMATIC DESIGN CONSIDERATIONS

The following sections provide a road map of key concerns that relate specifically to the structure of tall wood buildings.

5.1.3.1 Occupancy and Gridline Spacings

A building's occupancy typically defines the wall and column spacing, which in turn informs the mass timber framing system chosen. Table 1 provides a general guideline for structural systems that are possible for different occupancies and support spacing.

Table 1. Mass timber structural systems for different occupancies

Support spacing	Type of occupancy	Ideal mass timber systems
Less than 4 m (13 ft.)	• Residential • Hotel • Student residence	• 1-way mass timber slab • Point-supported CLT or other mass timber
4 m to 7.3 m (13 ft. to 24 ft.)	• Residential • Office	• 1-way mass timber slab • 1-way timber-concrete composite slab • Post-and-beam
7.3 m to 9 m (24 ft. to 30 ft.)	• Office • Healthcare	• Post-and-beam with timber-concrete composite

5.1.3.2 Acoustics

The structural system has a significant effect on the acoustic performance of a building, particularly where the timber structure is exposed. Timber's structural advantages (light weight, relatively stiff material) are acoustic disadvantages. Collaboration with an acoustics engineer is critical on tall wood building projects. Connections between walls and floors can heighten sound transmission. Often, added mass in the form of concrete or gypcrete topping is used to improve acoustics performance, and has an effect on the weight of the building and the floor vibration performance. Documents such as the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019) and some Woodworks references (McLain, 2018; Woodworks, 2020) provide relevant information on acoustics for mass timber assemblies. Additional information is provided in Section 5.4.

Building Performance

Mass timber mock-up or prototypes can be assessed to check design assumptions. The objectives of the prototyping should be prioritized. Where the concepts being assessed (e.g., buildability) are not sensitive to the quality or grade of the mass timber, the prototype (full scale or reduced scale) can be built with lower cost mass timber. A decision can then be made to continue with the concept development virtually or to continue making refinements with a physical model.

5.1.3.3 Vibration

Walking across floors induces a type of vibration in the structure called footfall vibration. This is a serviceability limit state rather than an ultimate limit state. Footfall vibration can range from slightly annoying to highly disruptive and uncomfortable depending on the occupancy of the space, the presence of sensitive equipment (e.g., a projector). When occupants can feel footfall vibrations, the building structure is often perceived to be of lower quality than one that feels more solid. All floors vibrate, but not all floor vibrations can be felt by occupants.

The factors that influence the performance of a floor system are generally:

- mass – greater mass is generally preferred. However, caution should be exercised because mass reduces the floor natural frequencies. Humans have less tolerance for low-frequency vibration than high-frequency vibration;
- stiffness – greater stiffness is generally preferred; and
- damping of the floor – higher damping is preferred.

Common building materials and their properties that relate to vibration are shown in Table 2.

Table 2. Common building materials and their vibration properties

Material	Floor dead load (kPa)	Damping (% of critical)	Material modulus (GPa)	Vibration design reference
Concrete	4.8–7.0	1–5	22–40	*Design Guide for Vibrations of Reinforced Concrete Floor Systems* (CRSI, 2019); CCIP-016
Steel	2.4–4.8	0.5–5	200	*Design Guide 11: Vibrations of Steel-Framed Structural Systems Due to Human Activity* (AISC, 2016); SCI P354
Mass timber	0.8–3.2	1–6	6–10	*Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019); CSA O86-19
Light frame	0.5–1.9	2–12	6–13	CSA O86-19

Floor vibration is more of a design issue than a material one, but because mass timber has a lower mass and stiffness than other materials, designs in which vibration governs the span of a floor system are required. With a proper combination of mass and stiffness, timber floors and timber-concrete composite floors can have good vibration performance. While assessment of fundamental frequencies is an indicator of good vibration performance (that is, the fundamental frequency outside the range detectable by occupants), it is not the only indicator, and if it is not used properly, it can lead to misleading information. Some designers are moving to an acceleration-based approach using finite element analysis, as referenced in the CCIP-016 – *Design Guide for Footfall Induced Vibration* *of Structures* (Willford & Young, 2006). The success of such an approach depends greatly on the accuracy and reliability of the calculation tools and the finite element models. Because of the broad range of parameters that might affect vibration performance, the tools and models must be verified using test data obtained from a mock-up of the designed floor. More information on vibration of mass timber buildings is provided in Section 5.4 and in the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019).

5.1.3.4 Mechanical, Electrical, and Plumbing Systems

Coordinating the construction of mechanical, electrical, and plumbing (MEP) systems with the building's structure is an ongoing process that should start during the schematic design stage and often is not completed until the building is ready for occupancy. For projects with substantial MEP systems, the use of a flush-framed floor system is preferable. Where floor beams and girders are used, MEP systems can penetrate them, provided there is adequate and advance coordination during the design stage. Ideally, this occurs during design or shop drawing review (e.g., using the building information modelling process). When this coordination occurs during erection (which it frequently does), a project can be slowed by design changes and site modifications. If needed, the structural engineer can provide guidance on field drilling and coring of beams and slabs. The American Plywood Association's (2020) technical note *Field Notching and Drilling of Glued Laminated Timber Beams* can be a useful resource.

A common item that requires coordination is the sprinkler system (i.e., the location and size of the sprinklers). According to the industry standard, the mechanical consultant provides the general design intent, and the sprinkler contractor provides the final sprinkler design. However, the sprinkler layout is usually not known during the mass timber shop drawings phase, so the creation of penetrations through structural elements cannot be coordinated in advance. A better approach (structurally) is to have the mechanical consultant design the sprinkler system or procure it earlier in the project so that the creation of penetrations through the structural elements can be coordinated ahead of time.

Mass timber floor systems tend to be deeper than concrete or steel equivalents for similar spans, which puts more pressure on the design team to carefully integrate the MEP with the structure. Furthermore, in cases where the mass timber structure is exposed, the MEP should also be visually appealing. The requirements for coordinating the construction of MEP systems based on structural floor systems are listed in Table 3.

Table 3. Mechanical, electrical, and plumbing (MEP) coordination for different structural systems

Floor system	Mechanical coordination
Post-and-beam	Column spacing can be reduced to maintain minimal beam depths, or beams can be designed so that services run through them. The latter option can be challenging to coordinate fully in design and is not ideal. Ideally, the layout of mechanical systems complements the direction of the beam spans so that most services run parallel to the beams and do not cross them.
Composite beam/slab	The use of timber-concrete composite tends to reduce the beam/slab depth, which leads to easier MEP integration and greater floor-to-ceiling heights.
Point-supported CLT slab	This option requires the tightest column spacing; therefore, it allows for the easiest MEP coordination, by far, because there are no drop beams. See Figure 1.

Figure 1. Point-supported CLT, UBC, Brock Commons (courtesy of www.naturallywood.com)

5.1.3.5 Geographical and Climatic Conditions

5.1.3.5.1 Seismic Loads

The magnitude of seismic forces influences the choice of lateral force-resisting system used. In areas with high seismic loads, the seismic force-resisting system needs to exhibit ductility while maintaining adequate strength and stiffness to comply with the drift limits according to Part 4 of the NBC (NRC, 2020). The seismic hazard zone also dictates whether a mass timber lateral system is permitted by code. There are no restrictions on the height of some timber lateral systems in a building if $I_E F_a S_a(0.2)$ is less than 0.35. The 12-storey Tallwood 1 Building in Langford, B.C. (Figure 2) is an example of a tall wood building in one of Canada's highest seismic hazard zones. The seismic force-resisting system is an eccentrically braced frame in steel.

Regulatory Acceptance

In high seismic harzard zones, a hybrid solution consisting of a steel or concrete seismic force-resisting system and a mass timber gravity system up to 12 storeys is an Acceptable Solution under the NBC. Beyond 12 storeys, the hybrid solution is still an Acceptable Solution, but fire safety considerations will require an Alternative Solution.

Figure 2. Tallwood 1, Langford, B.C. will have eccentrically braced frames (courtesy of Design Build Services).

5.1.3.5.2 Wind Loads

Wind loads influence the design of tall wood buildings under both ultimate limit states and serviceability limit states. Under ultimate limit states, the strength of the lateral load-resisting system needs to be adequate to elastically resist the imposed wind loads. Under serviceability limit states, the storey drift and wind vibration experienced by the occupant need to be within acceptable limits.

Compared to heavier steel and concrete buildings, lighter timber structures may exhibit wind accelerations that exceed acceptable thresholds for a given building height. In other words, wind-induced acceleration can become the governing consideration for buildings that are much shorter than similar steel or concrete structures. The NBC Commentary provides a range of limits on acceleration due to wind (NRC, 2017), and input from a qualified wind consultant is strongly recommended for taller timber buildings. Current industry practice is to set the target accelerations a little higher than what is stated in the literature for steel and concrete buildings. The current lack of testing and data on tall wood buildings and occupancy comfort due to wind acceleration necessitates further study and careful design, particularly with very tall buildings that use mass timber lateral load-resisting systems (LLRSs). The *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019) recommends a damping ratio of 2% for wood buildings without finish, and 3% for wood buildings with finish. These numbers should be reviewed for their applicability to the project and should be tuned as more buildings with mass timber LLRSs are built and tested. There will likely be a large difference between the damping ratio of a light wood-frame building and a mass timber building of the same height. The use of tuned mass dampers is an option for very tall timber buildings because they can allow some late stage tuning to be done during construction if the damping ratio turns out to be higher or lower than expected. This type of allowance can compensate for uncertainties in these early groundbreaking projects. Additional options for mitigating the acceleration of a tall wood building could involve adding more mass, particularly at upper levels. The TREET building in Norway took this approach by adding concrete topping at certain levels to increase mass (Rune Abrahamsen, 2014). Additional information on wind-induced building vibrations is provided in Sections 5.3 and 5.4.

5.1.3.5.3 Precipitation

Most wood products, except those with architectural finishes, can withstand some wetting during construction, provided there is an opportunity for the product to dry before being covered by finishes. A product's resilience to water exposure is dictated by the duration of exposure, the amount of exposed end-grain (which absorbs moisture more rapidly) versus side grain, and the presence of gaps that not only trap moisture or allow wood surfaces to stay wet but also impede drying. Each product type responds differently when exposed to moisture. Because nail-laminated timber (NLT) and dowel-laminated timber (DLT) laminations are not face bonded, there are more exposed wood faces (i.e., gaps between laminations) for moisture to penetrate the wood and increase its moisture content. Furthermore, within the gaps, drying is hindered, even

Construction Moisture

The automated fabrication process allows mass timber components to be created with a wide range of shapes and connection details. Attention should be paid to areas where more end-grain is exposed, particularly surfaces that will accumulate water or receive runoff. Wood sealers may be effective, but they have limited benefit under severe exposures.

though ambient conditions may be favourable to drying. When wood moisture content increases, NLT, DLT, and glued-laminated timber (GLT) swell perpendicular to the grain, whereas CLT's cross-plies restrain moisture-induced movement. While avoiding dimensional instability problems is important, ensuring wood products have an acceptable moisture content before finishes are applied is equally important in order to avoid durability issues. Adding the floor sheathing (OSB or plywood) in the shop to create the diaphragm, and taping the seams and ends of the panels are also good strategies if done properly and consistently. Coatings, particularly on the end-grain, can also help protect the timber.

Connections should be protected from moisture as much as possible during construction. The following considerations should be given to addressing the effects of moisture on connections:

- Connections with steel finishes should be painted or galvanized to prevent rust stains from forming on the wood.
- If a connection restricts normal swelling or shrinkage of a timber element, the member may have more checking at the points of restriction, or in some cases, the connection may be overstressed and fail. Careful consideration of dimensional compatibility is warranted.
- If connectors such as screws are designed for indoor final use, extended construction periods may expose them to more moisture than they are designed to withstand.

In general, the best practice is to keep wood products dry during construction if they are intended to be used under dry service conditions (i.e., untreated). Where this is not possible, a construction moisture risk mitigation plan is required. Additional information on moisture risk is provided in Chapter 7.

5.1.3.5.4 Sun Exposure

A structure's exposure to sun during installation or the use of the building informs the type of coating needed to prevent UV discoloration. Constant exposure of areas of mass timber members to sun can lead to a reduced moisture content, which may result in increased checking of the members. This will also occur if indoor relative humidity levels are low (see Chapter 7).

Post-Occupancy Moisture

For scheduled inspections to be effective, there should be multiple layers of defence against moisture penetration. Where failure of the primary moisture barrier is possible, designing a drainage path and ensuring good drying capacity is valuable. For example, a drainage path allows a single sensor to cover a large area and assist with inspections.

Post-Occupancy Damage

A separate architectural wood layer can be added to mass timber to retain the aesthetics of exposed wood but allow damaged surfaces to be repaired. A lower mass timber component's appearance grade can be specified and does not require as much physical protection during construction or refinishing after construction. See Chapters 6 and 7 for considerations.

Sun exposure is typically not a structural issue if the structure is detailed to allow normal member shrinkage. If a significant reduction in moisture content occurs on only one side of the members, it can cause warping, especially of narrow beams.

5.1.3.5.5 Outside Temperature

Wood is typically not susceptible to temperature variations because its thermal expansion coefficient is quite low compared to other materials. Mass timber products are also not susceptible to cold temperatures, and installation is typically done with screws or pins/bolts, not adhesives. However, where systems and connections rely on a field-applied adhesive, temperature during installation should be considered. Furthermore, when using a structural concrete topping in timber-concrete composite systems, temperature should be considered in scheduling the concrete pours.

In a steel–timber hybrid building, steel beams may shorten noticeably in low temperatures and not be compatible with the rest of the structure; therefore, appropriate consideration should be given to the support conditions of the steel beams.

5.1.3.6 Geographical Location of the Project

The geographical location of a project relates not only to climatic conditions but also to a few other factors that need to be considered in the design phase.

The proximity of potential suppliers to the project's location may dictate which suppliers can provide products for the project. Not all suppliers operate in the same geographical areas. This, in turn, can inform which building products should be considered in the conceptual design of the building.

Transportation to the building site and to site storage and staging areas should be considered early in the planning stage. Many building sites have a limited area for laydown and staging; therefore, materials have to be delivered to the site when needed rather than stockpiled. If deliveries come by shipping containers, a staging area off-site may be required to unload the products and prepare them for delivery to the site. When building in urban areas or city centres, it may not be practical to have large trucks coming to the site at any given time of the day, and it is good practice to schedule deliveries to avoid rush hours or predictable traffic events.

5.1.3.7 Materials and Suppliers

Several mass timber products have been on the market for a long time and are considered established products with standard design and detailing requirements; a few other products are considered new and emerging (Figure 3). The following lists these products and their suppliers:

- Glulam: an engineered wood product that is manufactured by gluing together typically 38-mm thick dimensional lumber to form simple structural beams and columns or more complex arches and members curved along two axes. The strength of the section can be engineered based on the grade of each lamination and where it is placed along the member depth. Glulam can also be used as glued-laminated timber (GLT) panels, where narrow glulam beams are used on flat as a floor or roof panel.
    - Suppliers: There are many suppliers around the world.

- Cross-laminated timber (CLT): three or more layers of dimensional lumber with the grain of adjacent layers at right angles to one another. Layers are glued and pressed together to form a strong and dimensionally stable panel product. Layers can vary in grades and thicknesses to achieve different strengths and stiffnesses. Ideal for floors, roofs, shearwalls, and diaphragms.
    - Suppliers: There are many suppliers in Canada, the United States, and Europe.
- Structural composite lumber (SCL): many products are defined as structural composite lumber, including:
    - laminated strand lumber (LSL)/laminated veneer lumber (LVL)/parallel strand lumber (PSL)/oriented strand lumber (OSL): proprietary engineered wood products that use smaller strands or veneers of wood pressed together with adhesive into beams or billets.
        - There are many suppliers in Canada, United States, and Europe.
    - edgewise LVL: LVL with the veneer orientated along the depth of the panel, which produces a thick lined panel or beam product that can be visually appealing. Ideal for beams, columns, floors, and roofs but not for diaphragms.
        - This product has limited availability in North America and Europe.
    - mass plywood panel (MPP): produced by pressing layers of plywood together to produce much thicker panels. Plies can be cross-laminated for strength and stiffness in both the strong and weak axes. MPP is very dimensionally stable and can be produced in sizes comparable to CLT panels. It is ideal for floors, roofs, shearwalls, and diaphragms.
        - This product has limited availability in North America.
- Nail-laminated timber (NLT): dimensional lumber placed on edge and nailed together to produce panels. Ideal for floors and roofs; however, additional sheathing is typically needed to achieve a diaphragm. Variants in depth of laminations can produce visual benefits or improve room acoustics.
    - Suppliers: Any contractor can produce NLT; see the *Nail-laminated Timber: Canadian Design & Construction Guide* (BSLC & FII, 2017).
- Dowel-laminated timber (DLT): similar in concept to NLT, except hardwood dowels are used to fasten the plies together instead of nails. DLT is ideal for floors and roofs; however, the panels require additional sheathing to achieve a diaphragm.
    - Suppliers: There is a limited number of suppliers in Canada and the United States.

Most of the mass timber supply chain in North America is still relatively new and developing, and is presently focused on the Pacific Northwest, Alberta, Manitoba, Ontario, and Québec; there are smaller/future productions in Alabama and Arkansas.

GLT (courtesy of BMC)

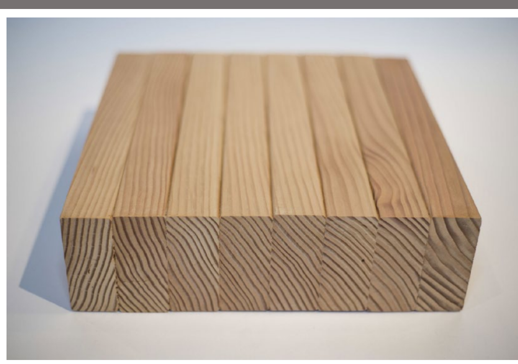
CLT (courtesy of Technology and Architecture)

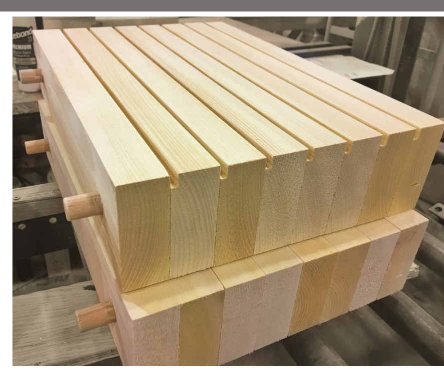
LSL (courtesy of APA)

LVL (courtesy of Pinterest)

PSL (courtesy of Fast+Epp)

MPP (courtesy of Comag)





NLT (courtesy of Fast+Epp)

DLT (courtesy of naturally:wood)

Figure 3. Different mass timber materials.

Suppliers not only need to be able to produce a product, they should also be able to assist the project team:

- by providing technical documentation of the products supplied
- with selecting appropriate sizes and details of the required products
- with managing manufacturing and shipping constraints
- with undertaking the shop drawing process

An early evaluation of available products and suppliers is useful for gauging the overall direction and feasibility of the project. Table 4 shows a series of questions the project team can ask to gain a good understanding of the supply chain and the project.

Table 4. Questions regarding the mass timber supply

Questions to ask a supplier	Follow-up questions for the project team
What geographical area do they operate in?	Is the supplier able and willing to bid and supply the project?
What products and sizes do they supply?	What is the supplier's product range, do they have suitable products for the project, and are the depths and sizes suitable for the gridlines or floor depth requirements?
What level of building information modelling (BIM) coordination/shop drawing process can they provide?	Can the supplier's level of BIM coordination help resolve conflicts?
What level of prefabrication can they provide?	What is the supplier's overall process and effect on site logistics and installation?
What is their annual output?	How much of the supplier's annual output capacity will the project require? (Ideally, a project does not require more than 15–20% of a supplier's output; otherwise, specific arrangements should be made.)
What is their current production forecast?	Does the supplier have the ability to serve the project?

Unlike other structural products, mass timber comes in set dimensions and grades determined by the supplier. Different suppliers produce products with different sizes and structural properties, due in large part to the fabrication equipment used (e.g., the press bed). As a result, gathering information about available suppliers early in the planning stage will help optimize the design and layout of the project. Table 5 provides some examples of the effects suppliers can have on the structural design of a project.

Table 5. Effects mass timber suppliers can have on structural design

Supplier-specific products and compliance	Project effect
Panel width	Available maximum panel widths generally range from 2.4 m to 4 m. For projects in which the gridline spacing is directly affected by panel widths (e.g., point-supported CLT panels), layout out the gridlines appropriately for different suppliers will be critical. A 3.5-m column spacing will limit the suppliers that can supply the project. Consideration should be given to the finished panel width, which will often be slightly smaller than the total panel width that a supplier can produce due to trimming of the panel edges.
Panel length	As above, the grid spacing should take into consideration available panel lengths: 12-m to 19-m lengths are available. For both panel widths and lengths, the designers need to verify that transportation of the panels is possible. Designers should also consider using efficient multiples of maximum panel widths and lengths to minimize panel waste. For example, if maximum panel lengths are 12 m, efficient panel lengths to produce for the project will be 6 m or 12 m. Using 9-m panel lengths for the project will result in substantial waste unless the project uses 3-m long panels of the same size and grade elsewhere.
Grades and layups	Material grades and CLT layups will have an effect on the member depths. North American-produced CLT will adhere to PRG 320 (ANSI/APA, 2019), and various lamination thicknesses are permitted, so different strength and stiffness levels can be achieved. Products from outside North America use wood with different grades; therefore, they have different performance levels.
Code compliance	Depending on the project location and authority having jurisdiction, specific local code compliance may be a requirement for the project.

One option for minimizing risk to the project is to establish an early agreement with a single supplier so that the design can be tailored to the products the supplier produces. Another option is to identify a few different suppliers, products, or depths, and ensure that the design is flexible enough to allow for slightly different dimensions and the gridlines suit the use of any of the products. Additional information on procurement is provided in Chapter 8.

5.1.3.8 Connections

The effect of connections on early design cannot be underestimated. Connections can sometimes drive up the element sizes, particularly when the mass timber is exposed to fire. There are typically two approaches to connection design on a project:

a. The prime structural engineer designs the connections.

The advantage of this approach is that the members can be sized appropriately for the connection. The disadvantage is that without a supplier on board during connection design, there will be some considerable unknowns, including whether the supplier has the fabrication capabilities for the connectors.

b. The connections are engineered by the supplier's structural engineer.

This approach is similar to how steel connections are detailed by specialty engineers in many places in Canada. In this case, the tender drawings will include all the information the specialty engineer requires to design the connections, including loads and fire protection requirements. The advantage is that the connections can be designed to be most efficient with the supplier's preferred connection approaches and tailored to the supplier. The disadvantage is that sometimes the member sizes will need to be increased after tendering a project to suit the connection requirements. To avoid size changes, the prime structural engineer should be aware of the connection approach and sizes during early design. As a result, the engineer's awareness of available connectors and sizes for the connection loads will ensure that the members are designed correctly.

Connection types can be divided into the following categories:

- Bolts and tight-fit pins: These are code approved and widely available in Canada.
- Self-tapping screws: These are available from a number of suppliers in Canada and the United States (e.g., MTC Solutions, Rothoblaas, Simpson). The screws are well-suited for mass timber and can resist substantial withdrawal and shear loads.
- Glued-in connectors: Glued-in rods and proprietary systems such as Ticomtec's HSK glued-in systems can be used with timber. There are currently no code approvals or code allowances for glued-in rods in Canada or the United States; however, glued-in rods are included in the Eurocode, and there are European approvals for glued-in systems.
- Pre-engineered beam hangers: These include hangers from several suppliers (e.g., Simpson, Pitzl, Rothoblaas, Sherpa, and Knapp), and are typically knife plate or dovetail connectors that use screws and/or tight-fit pins to fasten members together. These connectors are typically tested, sometimes fire-tested, and often have published design values. A caveat of using these hangers: Canadian and American design values are not always available. The designer should use European design values with caution and be aware of the different load factors, material factors, and duration factors between Canadian and European codes.
- Custom beam hangers: These include elements such as knife plates, bearing plates, bolts or tight-fit pins, and self-tapping screws. All of these elements can be designed using Canadian codes and/or Canadian code approvals. An advantage of custom hangers is that

they can be custom suited to the project; the disadvantages are that they require increased design time, and they have not had the benefit of being tested.

- Beam and column bearing plates: These are often as simple as a knife plate and bearing plate, or a bearing plate with glued-in rods. Bearing plates can be simple and unobtrusive.
- Column splice connections: The use of connectors at column splices that allow floor members to frame into them is critical for achieving end-grain-to-end-grain bearing. Mass timber construction should avoid cross-grain loading, so column-to-column splices are needed. An example is shown in Figure 4.

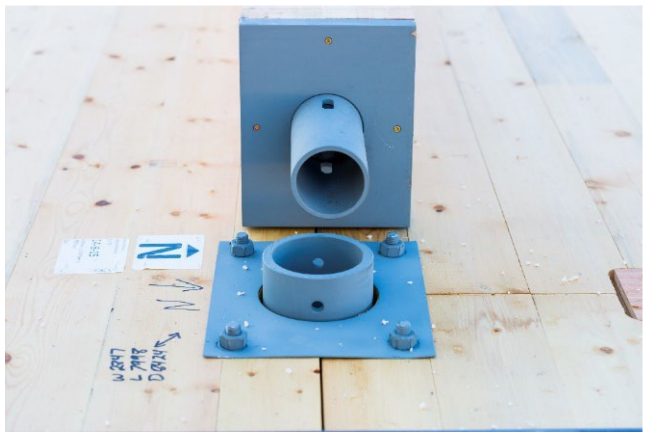


Figure 4. Column splice connection, UBC, Brock Commons (courtesy of www.naturallywood.com).

The following are some of the most important things about connections that should be considered, regardless of whether the connections are being detailed by the engineer-of-record or by a specialty engineer:

- Drift compatibility: Tall wood buildings typically undergo more drift than shorter and squatter buildings. As such, the connections need to accommodate the drift without failure and without imposing unexpected loads on the other structural elements.
- Integrity: The elements should be well connected to meet general integrity requirements.
- End-grain bearing: All cross-grain bearing locations should be avoided in tall wood buildings.
- Cost: The cost of connections can be a significant part of the building's structural costs. The use of efficient connections will make a considerable difference to the project's bottom line.
- Fire: If the wood is exposed, the connection generally needs to be designed for a possible fire event, either by recessing it into the timber elements or by using intumescent paint.
- Erection: Tall wood buildings should be efficient to erect, both to control cost and to enclose and protect the structure as quickly as possible. Connections should fit together quickly with little effort.
- Exposure to moisture: Typically, connections on tall wood projects are not exposed to moisture long term. However, installation in wet environments sometimes cannot be avoided. The finish of steel elements should be considered in order to avoid rust stains on

wood. The connector hardware (such as self-tapping screws) should also be considered. Screws installed in dense wood during moist conditions may become damaged and can be prone to rusting. In very wet environments, the use of self-tapping screws with better coatings should be considered. Connections should generally be kept away from significant moisture after installation.

- Ductility: The yield mode of the connector should be considered. Smaller diameter tight-fit pins are preferred over larger diameter pins so that the steel yields before the wood crushes.

Figure 5 shows examples of timber connections.

Figure 5. Brace and beam detailing, Synergia Complex, Saint Hyacinthe, Que. (courtesy of ©Nordic Structures).

5.1.3.9 Construction

The design of a tall mass timber project must take into account how the project will be built. Fast erection generally results in more cost-effective and successful projects but will require careful coordination of trades. The parameters and considerations discussed in this section all contribute to constructional implications. Some key elements previously mentioned are compiled here to demonstrate how they affect the project from a construction standpoint:

- Building code requirements: Construction fire regulations in the National Fire Code of Canada (NRC, 2020) include standpipe installation requirements and a limit of 4 contiguous storeys of timber that can be temporarily left unprotected by drywall and concrete topping. Similar requirements are included in the 2021 IBC. Drywall and concrete topping must be applied to relatively dry timber since both will slow down drying of wetted wood. Once installed, the drywall should be protected against further wetting, and the façade should be installed shortly thereafter. The timeline for structure erection, building enclosure, drying of wetted components, façade installation, and encapsulation must be well coordinated to avoid slowing down construction progress.

- MEP systems: Front-loading MEP coordination to the design stages will result in fewer changes and delays in construction. Further, the use of flat slab systems like point-supported CLT can help improve MEP coordination and installation.
- Climatic conditions: The wetter, colder, and/or sunnier the site, the more the climatic conditions will be a driver of the construction schedule and weather protection considerations. A very fast erection followed closely by the building enclosure and concrete topping will also be a factor in the weather protection measures needed. The contractor should develop an appropriate moisture management plan for the product, and the design team should review and approve it. Trade coordination is critical here.
- Geographic location: Site specifics will affect how and when material arrives on-site, and where it is deposited. A just-in-time approach to material delivery requires more coordination with the contractor when the site does not include a lay-down area.
- Materials and suppliers: Maximizing prefabrication and reducing the interaction of different trades and different materials will minimize site work. Allowing for different construction tolerances of different materials will also reduce site fixes.
- Connections: Simple connections designed for fast site install will minimize site work and allow the structure to be completed and enclosed quickly. Connections need to be designed for the expected weather exposure and time exposed. There must be clarity between the design team and the contractor regarding how much weather exposure the connections can tolerate.

Project Delivery

For large mass timber components (including panels with large openings, or beams and columns with reducing cross-sections), lift points may need to be identified and designed into each component. Guidance on CLT lift points is provided in the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019) or U.S. *Mass Timber Design Manual (*Think Wood & WoodWorks, 2021)

5.1.3.10 Fire Performance

Fire performance is addressed in depth in Chapter 6; the following are key considerations for the structure:

- Preliminary member sizing: If any fire resistance rating is provided through charring of the wood, the fire load case can frequently govern the member design.
- Exposed timber: While there are limitations on the amount of exposed timber allowed in 7- to 12-storey buildings, at that height a 2-hour fire resistance rating will be required. When using the “char” approach to provide the required fire resistance rating, 2 hours has a substantial effect on member sizing.

- Connection design: The fit and size of connections must take into consideration any charring that is removed for the fire resistance rating. Connections themselves must be recessed or encapsulated to be protected in a fire.
- Lateral system: Connections and elements that do not contribute to the gravity system and are only part of the lateral load-resisting system are not required to be fire protected.

5.1.3.11 Integrity and Redundancy

Integrity is defined in the NBC Commentary B as "the ability of the structure to absorb local failure without widespread collapse" (NRC, 2017). NBC Clause 4.1.1.3 (1) gives the design requirement:

> Buildings and their structural members and connections, including formwork and falsework, shall be designed to have sufficient structural capacity and structural integrity to safely and effectively resist all loads, effects of loads and influences that may reasonably be expected, having regard to the expected service life of buildings, and shall in any case satisfy the requirements of this section.

Appendix A-4.1.1.3(1) expands on structural integrity requirements and provides a general indication of how integrity can be achieved:

> The requirements of Part 4, including the CSA design standards, generally provide a satisfactory level of structural integrity. Additional considerations may, however, be required for building systems made of components of different materials, whose interconnection is not covered by existing CSA design standards, buildings outside the scope of existing CSA design standards, and buildings exposed to severe accidental loads such as vehicle impact or explosion.

The NBC Commentary B states that medium-rise and high-rise buildings made of components of different materials are structures that require special attention to integrity (NRC, 2017). Mass timber buildings are typically built with individual prefabricated components fastened together on-site, similar to precast concrete or other prefabricated construction types; therefore, they may be in a category of buildings that require special attention to integrity.

CSA O86 Clause 4.3.3 requires that the structural system and connections provide positive resistance to widespread collapse from local failure (CSA, 2019). Neither the 2020 NBC nor CSA O86 provide tie loads to connect members for integrity.

Structural integrity is addressed in more detail in Part 1 of the Eurocode EN 1991-1-7:2006 (European Committee for Standardization, 2006). EN 1991 requires buildings to be constructed so that an accident does not result in collapse disproportionate to the cause. The code categorizes buildings by consequence classes, with each class having recommended approaches for design and detailing. Tall wood buildings are typically designated as Class 2B buildings. The three approaches for designing Class 2B buildings are summarized as follows:

- Indirect design method: This method has prescriptive design and detailing rules for members and requires that end connections be capable of sustaining a code-defined load. Horizontal and vertical ties are used to connect elements.

- Notional element removal: This method requires the overall structure to remain stable with limited floor collapse when individual supporting elements are notionally removed. Multiple columns may need to be removed simultaneously to meet the intent of this requirement for systems with closely spaced columns.
- Key element design: As an alternative to the two other methods, elements can be designed for an accidental design load of 34 kPa.

For taller and larger buildings, particularly those consisting of prefabricated elements, integrity and redundancy should be given due structural consideration. Providing horizontal and vertical ties between members, as well as connections with ductile failure modes, can improve a mass timber structure's integrity.

For more information on structural integrity, robustness, and progressive collapse, see Section 5.3.2.2.

5.1.3.12 Height-Specific Considerations

There are considerable differences between mass timber buildings that are about 6 storeys and those that are more than 6 storeys. Matters that seem minor for mid-rise wood buildings need to be carefully thought through for taller buildings. The following are some of those considerations:

- Codes and fire protection requirements: The fire protection requirements for mass timber buildings in the 7- to 12-storey range in Canada are more restrictive than those for buildings up to 6 storeys. Chapter 6 provides additional details. In the United States, fire protection requirements for mass timber buildings between 12 and 18 storeys are even more rigorous, per the IBC (ICC, 2021).
- Seismic systems available: Acceptable Solution timber lateral systems in low-to-moderate and high seismic hazard zones are limited to 30 m or 20 m in height, respectively. Taller wood buildings need to have either a non-wood lateral system (steel or concrete) or a wood-based lateral system designed under the Alternative Solution path in the building code. Section 5.3 provides additional information.
- Cumulative shrinkage and elastic shortening: Taller mass timber buildings require careful design for cumulative shrinkage, and measures to reduce shrinkage in a building. For hybrid buildings, shrinkage of the timber elements relative to the non-timber elements needs to be understood and accounted for. More information is provided in Section 5.2 and Chapter 7.
- Construction sequencing: Code requirements and good practice dictate that in mass timber buildings between 7 and 12 storeys, only 4 contiguous floors are permitted to be exposed at a time, according to the National Fire Code of Canada (NRC, 2020). Drywall and building enclosures need to follow the structure erection closely.

5.1.4 GRAVITY SYSTEMS

5.1.4.1 Mass Timber Post-and-Beam

Post-and-beam structures (Figure 6) are the most common framing systems for mass timber buildings, and generally consist of three elements:

- floor framing, which is most commonly a mass timber panel product (CLT, NLT, DLT, etc.);
- beams, usually single span so they do not interrupt the columns' compression continuity at the connections; and
- columns, ideally continuous through the height of the building with end-to-end bearing connections.

A key requirement is that the columns do not transfer their load through wood beams or slabs. Timber is much stiffer and stronger in compression parallel to the grain than perpendicular to grain. This arrangement avoids deformations due to perpendicular-to-grain bearing stresses and shrinkage, and thus minimizes the component of vertical shortening of a tall wood building. A differentiator between low-rise mass timber and tall mass timber buildings is the number of stacked columns and the types and amounts of deformation that occur between the bottom ends of the columns. Columns are typically 1 or 2 storeys tall. By not inserting beams or girders between columns, much of the deformation due to perpendicular-to-grain stresses and shrinkage is eliminated. However, there are other sources of deformation at each column-to-column end bearing point which will accumulate over the height of the building. An understanding of whether the deformation is instantaneous, time dependent, and/or load dependent will help determine if there will be compatibility issues with other vertical elements in the building (e.g., concrete cores, MEP services, curtain walls).

Beams in a post-and-beam system can be top flush with the floor framing, or they can be dropped below it. The latter option allows the floor framing to be double or triple span, which reduces deflections and vibration. It is economical to span beams about 6–9 m. Beams that make up the roof structure can span to approximately 25–30 m before the use of a truss becomes more economical.

Panels that span longer than about 6 m are typically governed by their vibration performance. Multi-span panels improve performance; however, limitations associated with the production of panel products need to be considered before multi-span panels are specified. Timber-concrete composite can also be used for longer panel spans.

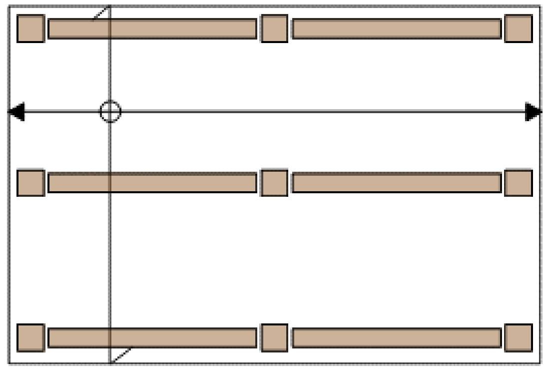


Figure 6. Post-and-beam concept plan view (courtesy of Aspect Structural Engineers).

Slab bands (Figure 7) can be used to reduce the overall depth of the structure and the span of the floor framing. Slab bands are wide and shallow members, and can be glulam beams on a flat or mass timber panel product (CTL, NLT, DLT, etc.). Economical spans for timber slab bands are 5–6 m. For longer spans, the use of a hybrid system, such as timber-concrete composite, is likely more efficient. Column sizes and unbalanced loading are important considerations for this system.

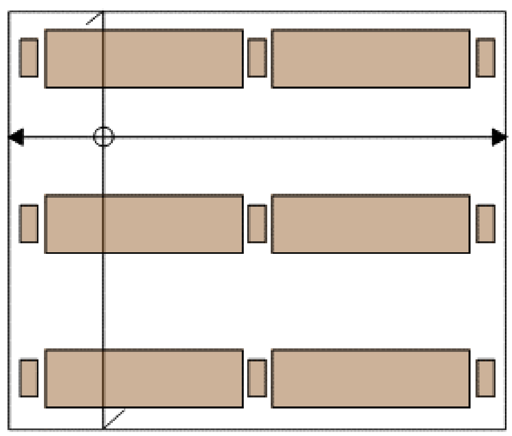


Figure 7. Post and slab band concept plan view (courtesy of Aspect Structural Engineers).

A variant of the slab bands concept involves the use of CLT as corrugated panels to minimize structure depth and provide opportunities for mechanical integration in the structure, as used in the Wood Innovation Design Centre in Prince George, B.C. (Figure 8).

Figure 8. Posts and beams, Wood Innovation Design Centre (courtesy of MGA | Michael Green Architecture).

The following are some of the many modern tall wood buildings that use post-and-beam gravity systems:

- 25 King (Brisbane, Australia, 2018)
    - 10 storeys
    - 8-m floor span
- Arbora (Montreal, Que., 2017–2019)
    - three 8-storey buildings
    - 6-m floor span
- UBC, Earth Sciences Building (Vancouver, B.C., 2012)
    - 5 storeys
    - 4.8-m to 9.6-m floor spans
- Wood Innovation Design Centre (Prince George, B.C., 2014)
    - 7 storeys
    - 5.8-m floor span
- Maison de L'inde (Paris, France, 2013)
    - 8 storeys
- Bullitt Center (Seattle, Wash., 2013)
    - 6 storeys (Figure 9)
- Carbon 12 (Portland, Ore., 2018)
    - 8 storeys
- T3 Atlanta (Atlanta, Ga., 2019)
    - 7 storeys

Figure 9. Bullitt Center (left, middle: courtesy of John Stamets; right: courtesy of Ben Benschneider).

5.1.4.2 Mass Timber Point-Supported Panel

Point-supported floors (Figure 10) eliminate the need for drop beams and instead rely on CLT panels supported at their corners. While it is advantageous to have a flat slab floor system, the columns must be closely spaced and well-coordinated with the panel layout and sizes. A point-supported floor system induces bending in both the longitudinal (major) direction and transverse (minor) direction of CLT panels. The rolling shear capacity of the CLT panel is often the limiting factor and dictates the column spacing. Column spacing of approximately 3.0–3.5 m is ideal for CLT panels that are produced in Canada; however, this tight column spacing limits the types of occupancies that are possible. Point-supported CLT is well-suited for some residential occupancies, student residences, and hotels. There are significant advantages to this system, including very easy MEP coordination and application of finishes.

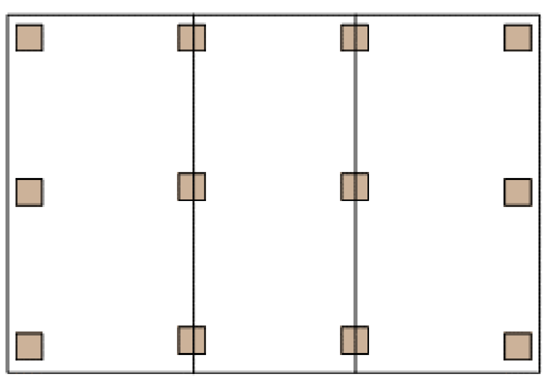


Figure 10. Point-supported CLT concept plan view (courtesy of Aspect Structural Engineers).

The Brock Commons student residence (Figure 1) at the University of British Columbia contains point-supported CLT panel framing. Brock Commons is 18 storeys high and was completed in 2017. The floor system is composed of CLT panels that are supported at their corners and mid-panel edges by glulam and PSL columns (naturally:wood, 2016). The columns are connected with steel tubes (Figure 4) between each storey to transfer gravity loads directly from column to column (Canadian Wood Council, 2018).

5.1.4.3 Bearing Walls

Bearing wall systems use mass timber walls to support the floor structure. CLT is often used and can serve a dual purpose as the lateral load-resisting system. Other mass timber panel types are also suitable, but they are less common. Where the CLT wall is used as fire separation and relies on "charring" to provide the resistance, the face grain orientation should be carefully considered because it will be the sacrificial layer, and the adjacent layer may be used to provide the fire resistance.

Bearing walls can be constructed as platform framed or balloon framed. In platform framing, the floor panels and beams rest on top of the walls of the storey below, which requires the cumulative load from the storeys above to transfer through the floor structure perpendicular-to-grain. As discussed previously, perpendicular-to-grain loading is best avoided in tall wood buildings unless bearing strength and shrinkage issues are carefully resolved. In balloon framing, the floor structure is supported on the wall faces, which allows the gravity loads to transfer down to the foundation entirely in desirable parallel-to-grain loading.

The following modern tall wood buildings use mass timber bearing walls:

- Forté (Melbourne, Australia, 2012)
    - The walls and elevator and stairwell cores are composed of platform-framed CLT.
- Origine (Québec City, Que., 2017)
    - The building has balloon-framed CLT bearing walls mixed with post-and-beam (Cecobois, 2018)
- Bridport House (London, UK, 2010)
- Dalston Lane (London, UK, 2017)
    - Structural grout is used to reduce perpendicular-to-grain loads on the platform-framed floor panels (Schuler, 2018).
- Joensuu Lighthouse (Joensuu, Finland, 2019)
    - The building has 13 storeys of LVL panel bearing walls supported on a concrete podium (Keskisalo, 2019).
- Stadthaus (London, UK, 2009)
- Trafalgar Place (London, UK, 2015)

5.1.4.4 Timber-Concrete Composite Systems

Timber can efficiently be combined with steel and/or concrete to produce hybrid systems. Concrete is most commonly combined with timber in a composite system. The post-and-beam or post and slab band concepts previously discussed can be combined with concrete to become a timber-concrete composite (TCC) system. In those cases, the beam/slab band, the slab, or both can be made a composite with concrete. In single span elements, the concrete should carry the compressive stresses, the timber should carry the tensile stresses (parallel to grain), and a shear connector transfers the shear between the two. In multi-span elements, the reinforcement in the concrete takes the tension, and the timber carries the compression over a support. Shear connectors can be screws, notches, plates, or perforated plates. TCC slabs can turn panels that are simple span into multi-span continuous panels, which allows deflections and vibrations to be significantly reduced. Examples are shown in Figure 11 and Figure 12. The University of Massachusetts John W. Olver building (Figure 12) uses perforated steel plates to provide the shear connection between the concrete and the CLT panels. The *Design Guide for Timber-Concrete Composite Floors in Canada* (Cuerrier-Auclair, 2020) provides additional information.

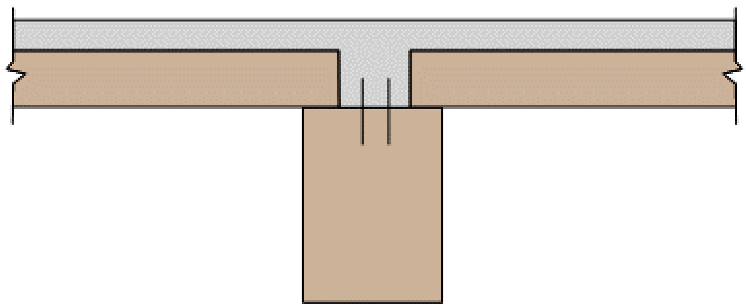


Figure 11. Timber-concrete composite beam section (courtesy of Aspect Structural Engineers).

Figure 12. Timber-concrete composite slab system, University of Massachusetts, John W. Olver Building (courtesy of Alex Schreyer/ University of Massachusetts).

5.1.4.5 Other Hybrid and Proprietary Systems

Built-up timber elements or timber and steel elements can also be combined to produce composite systems. These systems are often key to spans exceeding 9 m. Ribbed mass timber panels are produced as a variant of regular flat panels. The ribs typically consist of timber beams attached to one side of the panel to create a composite T-shaped beam where the panel contributes to the strength and stiffness of the assembly. The T-shape offers improved bending strength and stiffness compared to a flat panel of the same volume. Ribbed panels are typically prefabricated, and the assembly can be installed on-site similar to regular mass timber panels, with some additional consideration required to accommodate the ribs. The Adidas Headquarters uses ribbed glulam/CLT double tees supported by a precast concrete system for an efficient hybrid structure (Lever Architecture, 2020).

The ribbed concept can be taken further with two layers of panels, separated by ribs, to create a hollow-core cross-section with further improved bending strength and stiffness. Ribbed panels can also be used for wall elements. As with floor/roof systems, the cavities between the ribs are suitable for MEP services and insulation; however, fire requirements for these cavities (see Chapter 6) must be considered. Ribbed panels have been used predominantly in Europe. The Limnologen project in Sweden, for example, has a floor consisting of a composite ribbed panel system in which CLT slabs make up the top flange, glulam beams on edge provide the web, and additional glulam beams on flat make up the bottom flange. Components are glued and screwed together (Gagnon & Hu, 2007). Several more products, such as stressed skin panels and pre-tensioned box beams, are in development worldwide.

The following are some current proprietary systems:

- Peikko produces Deltabeam, which are steel forms for concrete beams that can be used efficiently with timber slabs to produce a timber-steel-concrete composite system (Figure 13). This system originated in Finland and was developed as a flush beam system for precast concrete slabs. It can be used in combination with either a pure mass timber floor system (purlins or panels) or with a timber-concrete composite system. An advantage of the system is the inherent fire resistance of the concrete beam without any additional fire proofing (Peikko Group, 2017).

Figure 13. Peikko Deltabeam (courtesy of Peikko Group).

- Skidmore, Owings & Merrill LLP (2013) conceptualized a structural system for tall buildings called Concrete Jointed Timber Frame. This composite system uses precast concrete beams and precast timber-concrete composite planks. The company also examined a steel alternative with steel beams supporting timber-concrete composite slabs.
- Neue Holzbau is developing a glued-in-rod connection technology to provide high-strength connections that can be automated for many different systems, including complex trusses (Gehri, 2010).
- Ticomtec developed a timber-concrete composite connector called HBV, and a timber-steel-composite connector called HSK. Both connectors facilitate strong and stiff composite design for connections and floor systems (Karsh, 2014).
- Timber elements can be reinforced with fibre reinforced polymer (FRP) to create a composite material. Research has shown improved bending strength and stiffness with FRP attached to the underside of timber beams (Balmori et al., 2020). Other applications of timber-FRP composites are possible, such as wrapping FRP around timber columns. Despite the potential benefits identified in research, FRP-timber composites have received limited use in practice.
- The Austrian firm CREE GmbH developed a unique concept that can be expanded to wood buildings up to 30 storeys, with LCT One as the prototype (Figure 14). The floor slab is a timber-concrete composite that can span up to 9 m (Zangerl & Tahan, 2013).

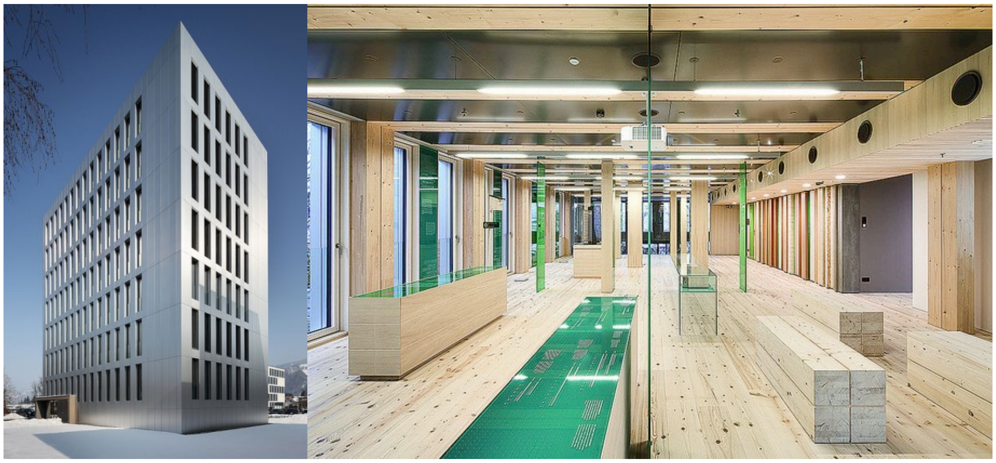


Figure 14. LCT One Tower by CREE (courtesy of CREE by Rhomberg).

5.1.4.6 Prefabricated Systems: 2-D Prefabrication and Volumetric Modular

Many mass timber systems naturally use 2-D prefabrication concepts: beams, columns, wall panels, and floor panels are prefabricated off-site in controlled conditions. Figure 15 shows an example of prefabrication that extends beyond just structural elements, with the incorporation of windows into structural wall panels for the mass timber building HoHo in Vienna, Austria.

3-D prefabrication (volumetric modular) is an attractive alternative that can combine structural prefabrication with finishes, MEP, etc., and can be prebuilt in a controlled environment, protected, shipped to site, and installed rapidly. Most tall wood buildings constructed to date have not used mass timber 3-D prefabricated systems; however, many projects and firms are exploring this possibility. Mass timber panel products like CLT are ideal for this kind of massive prefabrication. However, the many advantages of 3-D prefabrication are balanced by some hefty challenges:

- A lateral load path suitable for high seismic hazard zones can be challenging to establish.
- Additional material and floorspace is needed due to doubling up of walls and floors/roofs between adjacent volumetric units.
- Greater construction tolerances of the site-built portions of the building may create installation challenges.
- Fire protection of concealed spaces between volumetric units will have to be considered.
- Shipping constraints and costs: Instead of flat packing structural elements efficiently, modules are shipped individually. Furthermore, module widths and heights may be governed by shipping limitations.

Figure 15. Prefabricated panel installation, HoHo (courtesy of cetus Baudevelopment + Thomas Lerch).

Stora Enso developed a comprehensive modular building system for 3- to 8-storey timber buildings. The company publishes a guide that reviews the system holistically, considering the structure, assembly, HVAC, protection, etc. at a preliminary design level (Stora Enso, 2016). The modular system is based on CLT wall, floor, and roof panels, and the company provides structural drawings and details on its website.

The following are some examples of modern projects that maximized on prefabrication:

- Treet (Bergen, Norway) is a 14-storey apartment building that was completed in 2015. The building is composed of 12 multi-storey prefabricated apartment modules (Trifkovic, n.d.) that are supported by a glulam truss around the building perimeter. Prefabricated concrete panels are placed at the 5th and 10th floors, and at the roof to brace the perimeter trusses and improve dynamic behaviour via added mass (Abrahamsen & Malo, 2014).
- HoHo (Vienna, Austria) is a 24-storey concrete-and-mass-timber hybrid building that was completed in 2019. The building has CLT floors and walls, glulam columns, and a central concrete core. Prefabrication was used for the CLT-concrete composite floor panels and the mass timber façade panels. The façade panels consist of glulam columns and CLT panels with pre-installed windows (Figure 15). Precast concrete ring beams are placed at the top of each storey to connect the individual prefabricated mass timber elements (Timber Architecture, 2019).
- Puukuokka One (Jyväskylä, Finland) is an 8-storey apartment building that was completed in 2015. The building is composed of prefabricated CLT modules, with two modules used to form each apartment. The use of prefabrication reduced the on-site construction time to 6 months (OOPEAA, 2020).
- Hotel Jakarta (Amsterdam, Netherlands) is a 9-storey hotel built out of 176 CLT modules in 2018. The modules were manufactured in 2.5 months, and the structure was erected on-site in only 13 days (Ursem, n.d.).

5.1.5 LATERAL LOAD-RESISTING SYSTEMS

5.1.5.1 Governing Lateral Loads

Mass timber tall buildings differ from their steel and concrete counterparts primarily based on weight, which can be either an advantage (lower seismic demands) or a disadvantage (greater susceptibility to wind-induced vibrations). The height, type, and layout of the lateral load-resisting system (LLRS), and the footprint of a tall timber building and the region in which it will be built typically determine whether the building's LLRS is governed by wind accelerations or seismic drifts. The approximate guidelines in Table 6 apply to mass timber buildings in high seismic hazard zones.

Table 6. Approximate guidelines for mass timber building lateral loads in high seismic hazard zones

Building height	Governing lateral loads (in high seismic hazard zones)
Less than 8 storeys	Seismic strength or seismic drift are likely to govern the design.
Between 8 and 12 storeys	Seismic drift or wind accelerations may govern the design, depending on the region, LLRS layout, footprint, aspect ratio, and storey weight.
More than 12 storeys	Acceleration due to wind is likely to govern design of the lateral system. The overturning moment is likely to be substantial.

A building governed by seismic loads (and when seismic strength governs, not drift) needs to include considerable ductility as well as stiffness. The seismic demand is lower in a mass timber building than in a comparable concrete or steel building due to reduced mass. In general, a concrete or steel lateral system can be a reasonable option (and sometimes the only option) when it comes to the LLRS of tall mass timber buildings in high seismic hazard zones.

When wind governs the performance of the building, stiffness is of greater importance than ductility. Compared to concrete, timber is more susceptible to vibration because it is lighter weight. Inherent damping of mass timber buildings has not yet been fully tested and codified, so conservative estimates are required until adequate testing has been done. A mass timber lateral system in a tall timber building needs to be stiffer than in other building types, which can be achieved by including more elements (braces, moment frames, or shearwalls) and locating bracing toward the perimeter of the building rather than only at the core. Section 5.3 provides additional information.

5.1.5.2 Code Comparisons of Seismic Force-Resisting Systems

Table 7 provides a summary of various available seismic force-resisting systems according to the NBC (NRC, 2020). Only a selection of possible systems is presented here. Further details are provided following this table.

Table 7. NBC mass timber seismic force-resisting systems (NRC, 2020)

System	Height limits		R factors	Additional notes
	Seismic category SC4	Seismic categories SC1 to SC3		
Moderately ductile cross-laminated timber shearwalls: platform-type construction	20 m	30 m	R_d = 2.0 R_o = 1.5	Covered in CSA O86-19 and the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019)
Limited ductility cross-laminated timber shearwalls: platform-type construction	20 m	30 m	R_d = 1.5 R_o = 1.5	Covered in CSA O86-19 and the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019)
Braced or moment-resisting frames with moderately ductile connections	20 m	NL-20 m	R_d = 2.0 R_o = 1.5	Presently not explicitly covered in CSA O86-19
Braced or moment-resisting frames with limited ductility connections	15 m	NL-15 m	R_d = 1.5 R_o = 1.5	Presently not explicitly covered in CSA O86-19
Post-tensioned mass timber systems	No R factors in the code. However, can be designed under the Alternative Solutions path (the same applies to other systems, such as balloon-type construction)			Substantial research is being done on post-tensioned moment frame and post-tensioned wall systems; shows promise for high ductility and a period shift of the building
Ductile concrete shearwalls	NL	NL	R_d = 3.5 R_o = 1.6	Well understood and well tested; however, there can be challenges with timber and concrete coordination
Moderately ductile concentrically braced steel frames: tension compression braces	NL	NL-40 m	R_d = 3.0 R_o = 1.3	Well understood and well tested; fast erection comparable to timber systems
Moderately ductile concentrically braced steel frames: tension-only braces	NL	NL-20 m	R_d = 3.0 R_o = 1.3	

System	Height limits		R factors	Additional notes
	Seismic category SC4	Seismic categories SC1 to SC3		
Limited ductility braced steel frames: tension compression braces	NL	NL–40 m	R_d = 2.0 R_o = 1.3	Well understood and well tested; fast erection comparable to timber systems
Limited ductility braced steel frames: tension-only braces	NL	NL-20 m	R_d = 2.0 R_o = 1.3	
Ductile eccentrically braced steel frames	NL	NL	R_d = 4.0 R_o = 1.5	Well understood and well tested; fast erection comparable to timber systems; possible use as hybrid systems (timber columns, steel braces); high ductility
Ductile buckling restrained steel-braced frames	40 m	NL-40	R_d = 4.0 R_o = 1.2	

Note: SC1 is where $I_E S(0.2) < 0.2$ and $I_E S(1.0) < 0.1$; SC2 is where $0.2 \le I_E S(0.2) < 0.35$ and $0.1 \le I_E S(1.0) < 0.2$; SC3 is where $0.35 \le I_E S(0.2) \le 0.75$ and $0.2 \le I_E S(1.0) \le 0.3$; SC4 is where $I_E S(0.2) > 0.75$ and $I_E S(1.0) > 0.3$. NL indicates that the system is permitted and not limited in height as an SFRS.

5.1.5.3 Mass Timber Shearwalls (Platform and Balloon Framed)

Mass timber shearwalls offer several advantages to a tall mass timber project. For example, the same supplier can supply both the floor and wall material, with less coordination needed between trades. Mass timber walls can also provide more stiffness than braced frames, which is valuable for taller, wind-governed projects.

CLT walls can provide an efficient shearwall system for wind loads due to their relative stiffness; however, when using CLT shearwalls for tall timber buildings in higher seismic hazard zones, their low ductility and stringent detailing requirements need to be considered. CSA O86 (CSA, 2019) includes a detailed discussion of load path and capacity design, and how they relate to a platform-type CLT shearwall system. The energy dissipation required in a moderately ductile system can be provided from yielding of the connectors when the wall segments rock; therefore, the aspect ratio of the wall segments is critical to the system design and performance. The code requires careful design of the strength and stiffness of hold-downs and panel connectors so that this rocking can occur. Connections are divided into energy-dissipative connections (a yielding mode governs the resistance) and non-energy-dissipative connections (remains elastic). Careful reading of CSA O86 and detailed information about connections, including stiffness, yield, and ultimate resistance, is required to design CLT shearwall systems. The lateral deformation of CLT shearwalls is shown in Figure 16.

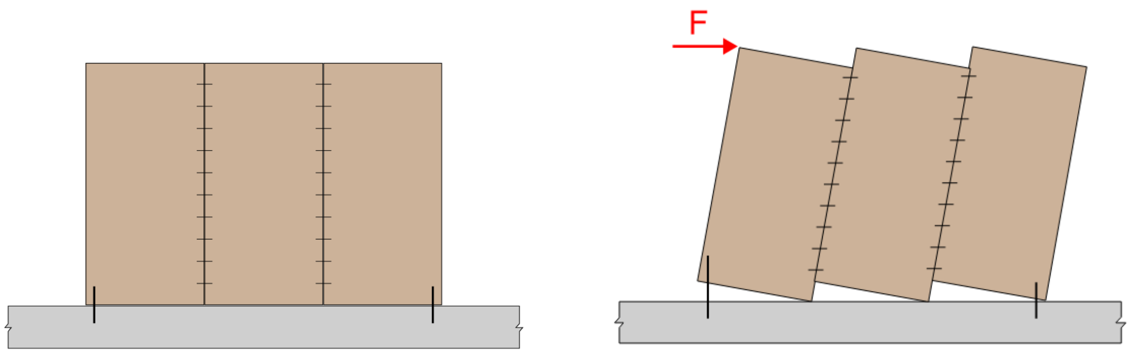


Figure 16. CLT shearwall system and deformation (courtesy of Aspect Structural Engineers).

The following requirements apply to CLT as a lateral system, per the NBC (NRC, 2020) and CSA O86 (CSA, 2019):

- platform construction
- building height is 20 m or less in seismic category SC4 (high seismic hazard zone)
- building height is 30 m or less in seismic categories SC1, SC2, and SC3 (low and moderate seismic hazard zones)
- moderately ductile walls (R_D = 2.0, R_O = 1.5)
- limited ductile walls (R_D = 1.0, R_O = 1.3)
- aspect ratio of wall segments is between 2:1 and 4:1, otherwise, $R_D R_O$ = 1.3
- shearwall minimum thickness is 87 mm

The design of balloon-framed CLT shearwalls (an example is given in Figure 17) is under development and is not yet included in the NBC (NRC, 2020) or in CSA O86 (CSA, 2019). CSA O86 refers designers of balloon-framed and other alternative CLT shearwall systems to Clause 4.3.2 (new or special systems of design and construction). This clause generally permits the use of systems and elements not covered by CSA O86 if the design is based on analytical and engineering principles and reliable test data, and if it demonstrates adequate safety and serviceability.

Information on designing CLT balloon-framed systems and other CLT shearwall systems is provided in the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019). The handbook contains additional design information, including diaphragm design and the design of an 8-storey mass timber building for structural and fire considerations.

Although CLT tends to dominate the mass timber shearwall discussion in Canada, and only CLT is explicitly permitted in the NBC as part of the seismic load-resisting system, other mass timber panel products, such as LVL, LSL, and mass plywood panels, can be used as shearwalls. Strength, stiffness, and interaction with connectors must be established if using panels other than CLT, and an alternative solution may be required. FPInnovations recently performed tests on LVL balloon-framed shear walls (Cuerrier Auclair & Popovski, 2020). The development of seismic force modification factors for a given system is covered in Section 5.3.3.

Figure 17. Shearwalls and details, University of Massachusetts, John W. Olver Building (courtesy of Alex Schreyer/ University of Massachusetts).

The following modern tall wood buildings have mass timber shearwalls:

- Forté (Melbourne, Australia, 2012)
- Wood Innovation Design Centre (Prince George, B.C., 2014)
  - The balloon-framed CLT elevator shaft and stair cores provide the LLRS in this wind-governed building.
- Origine (Québec City, Que., 2017)
  - Balloon-framed CLT application. Knife plates connecting the CLT shearwalls to the foundation are used to dissipate energy through yielding of the connections' metal dowels (Cecobois, 2018)
- Bridport House (London, UK, 2010)
  - The building's LLRS is platform-framed CLT shearwalls.
- Dalston Lane (London, UK, 2017)
- Joensuu Lighthouse (Joensuu, Finland, 2019)
  - The building's LLRS is LVL shearwalls, with overturning resistance provided by post-tensioned steel rods. The rods restrain the building from overturning at every third storey (Keskisalo, 2019).
- Stadthaus (London, UK, 2009)
  - All partition walls are platform-framed, load-bearing CLT walls that form part of the LLRS (Techniker, 2010).
- Arbora (Montreal, Que., 2017–2019)
  - The buildings' LLRS is balloon-framed CLT shearwalls.
- Trafalgar Place (London, UK, 2015)
  - The building has 3 storeys of CLT shearwalls supported on 2 storeys of concrete.
- Limnologen (Växjö, Sweden, 2008)
  - The LLRS consists of CLT panels, both interior partition walls and exterior load-bearing walls, secured to the foundation with steel rods that extended upward to the entire height of the building (Gagnon & Hu, 2007).

- Jules Ferry Residence (Saint-Dié-des-Vosges, France, 2014)
    - The building's LLRS is CLT shearwalls, which are connected to the foundations by steel rods (Hering, 2020).

5.1.5.4 Mass Timber Braced Frames

Mass timber braced frames have been used throughout North America on many projects. Like any braced system, the lateral loads are resisted through the diagonal members acting in tension and compression. Concentrically braced timber frames provide energy dissipation through yielding of the connections at the end of the diagonals. All other elements of the frame are typically designed to remain elastic. Left exposed, they can be very attractive and can contribute to the architectural expression of the entire building, as shown in Figures 18, 19, 20, and 21.

Figure 18. Synergia Complex (courtesy of ©Nordic Structures).

The NBC (NRC, 2020) recognizes two types of timber braced frames as an acceptable seismic force-resisting system with the appropriate level of ductile detailing:

- moderately ductile: R_D = 2.0, R_O = 1.5 and 20-m height limit for high seismic hazard zones
- limited ductility: R_D = 1.5, R_O = 1.5 and 15-m height limit for high seismic hazard zones

With R factors similar to those of CLT shearwalls, mass timber braced frames are challenging to apply to taller buildings. Furthermore, unlike CLT shearwalls, there is currently no explicit CSA O86 (CSA, 2019) guidance for the design and detailing of braced timber frames and their connections. It is generally accepted practice that connections with a highly ductile yielding mode will provide a moderately ductile performance. Sections 5.2 and 5.3 provide further guidance on connections for seismic design. The following are examples of typically ductile connection types; however, they have not been verified to meet a "moderately ductile" performance level:

- Tight-fit pins designed to form a single or double plastic hinge. A tight-fit pin where the wood fails in bearing is not desired and will lead to poor performance. Designing for a yielding mode leads to brace connections with many small diameter pins.
- Bolted connections with slender bolts designed to form a single or double plastic hinge with end distance higher than the minimum, and reinforced with self-tapping screws to prevent splitting
- Perforated steel plates that have been tested to show ductile failure modes can be glued or bolted to wood members to provide a ductile "weak link" in the connection.
- Double-sided timber rivets designed to fail in rivet-yielding mode

Figure 19. Timber bracing, University of Massachusetts, John W. Olver Building (courtesy of Alex Schreyer/University of Massachusetts).

Like CLT shearwalls, mass timber braced frames can be very effective as a lateral system in tall buildings in low seismic hazard zones. Because tall timber buildings have a sensitivity to wind-induced vibration, particularly buildings that are much taller than 12 storeys, the use of a braced-frame exoskeleton is an excellent opportunity to express the lateral system, expose timber, and maximize on stiffness of a timber braced system, as was done in the Mjøstårnet building in Norway (Figure 20).

Figure 20. Glulam bracing, Mjøstårnet (courtesy of Moelven Limtre AS & Voll Arkitekter).

The following modern tall wood buildings have mass timber braced frames:

- 25 King (Brisbane, Australia, 2018)
  - The building has an LLRS of glulam chevron braces.
- UBC Earth Sciences Building (Vancouver, B.C., 2012) (Figure 21)
  - Glulam chevron braces are included as part of the LLRS, with ductile connections provided by means of steel knife plates and pins.
- John W. Olver Building (Amherst, Mass., 2017)
  - Glulam braces with ductile connections are used in the LLRS.
- Mjøstårnet (Brumunddal, Norway, 2019)
  - The building's LLRS is glulam exterior braces.
- Synergia Complex (Saint Hyacinthe, Que., 2016)
  - Glulam chevron bracing and CLT walls comprise the LLRS.
- Treet (Bergen, Norway, 2015)
  - The building's LLRS is a glulam space truss.

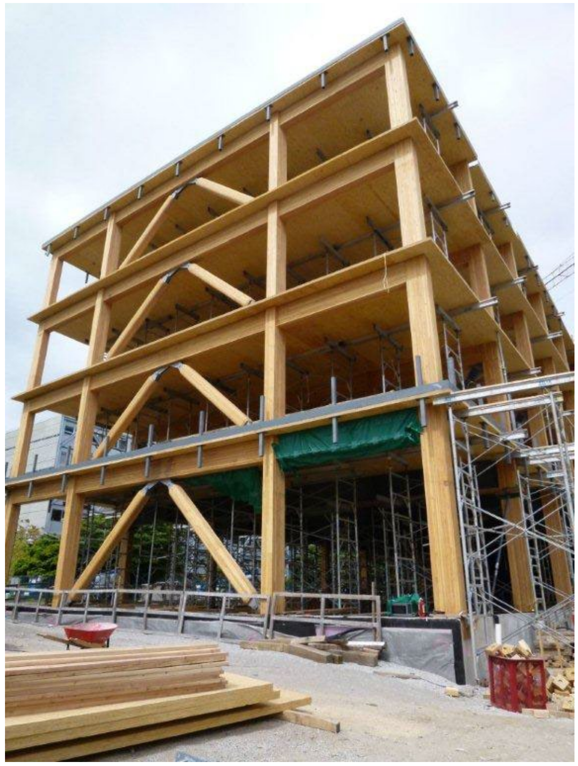


Figure 21. Braced frames, UBC, Earth Sciences Building (courtesy of Equilibrium Consulting).

5.1.5.5 Mass Timber Moment Frames

Mass timber moment frames have been used as LLRSs in Canada and worldwide, albeit infrequently. Mass timber elements are more challenging than steel or concrete to connect rigidly due to issues of stiffness, strength, and long-term performance. Good practice dictates that connections should be reasonably ductile and that careful thought be given to the shrinkage and checking of the mass timber elements. The following are some examples of moment connections:

- glued-in connections, such as glued-in steel rods or glued-in perforated plates
- bolted connections using small-diameter tight-fit pins
- designating a steel element within the connection as the ductile weak link; i.e., a bar or a strap

The UBC Bioenergy Research Demonstration Facility provides an example of a moment connection (Figure 22). The connection consists of an open steel box at the intersection of a beam and column and is designed to resist lateral loading. The steel box is connected to its column and beam with a proprietary connector (BVD). The system consists of a grooved, drop-forged insert, locked into place by tight-fit steel pins (Karsh, 2014).

Figure 22. Moment connection, UBC, Bioenergy Research Demonstration Facility (courtesy of Don Erhardt).

Another example of a timber moment connection is the tapered CLT columns at the UBC Okanagan Fitness and Wellness Centre (Figure 23). Moment connections were achieved at each end of thin CLT columns with perforated steel connectors called HSK, by Ticomtec. The top connection is a T-shaped connector; the bottom is a vertical steel plate and base plate. The HSK connectors were factory-installed into the columns. The vertical plate at the base connection elevates the CLT column above the floor to isolate it from water (Canadian Wood Council, 2019).

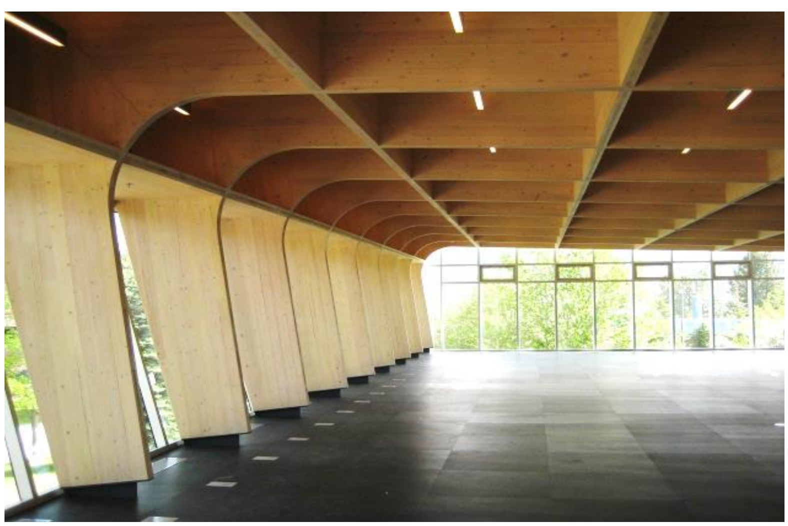


Figure 23. CLT moment frame using glued-in steel connections (courtesy of McFarland Marceau Architects).

5.1.5.6 Post-Tensioned Mass Timber systems

Considerable research is being conducted and advancement is being made on post-tensioned mass timber systems. Post-tensioned systems take advantage of the timber's "rocking" mechanism, and complement it with discrete energy dissipation as well as post-tensioned self-centring elements. The basic components of these systems, whether used in a moment frame or a shearwall, are as follows:

- Timber components are designed to remain elastic.
- Energy dissipation is provided, typically in the form of U-shaped flexural plates used as dissipators that yield in bending.
- Post-tensioned rods are steel rods that are tensioned after the wall/frame/building is erected. The tensioning serves two purposes: (1) holding down the element from overturning, and (2) centring the system. These rods are designed to remain elastic during a seismic response.

The following are some unique features of post-tensioned systems:

- Relatively high ductility can be achieved (Holden et al., 2012). However, since this system is not codified, it must be pursued as an Alternative Solution, which will likely involve conducting a nonlinear time history analysis.
- The elastic tension rods soften the building relative to a traditional CLT shearwall that is rigidly anchored down at the base. This softening reduces the seismic demand of a mid-rise building, as it pushes the building down the response spectrum (period shift). However, this softening can be a disadvantage for a building that is already drift-governed or is resisting primarily wind loads.
- Connecting a horizontal diaphragm to a vertical shearwall system that allows the shearwall to "rock" requires careful detailing.

Figure 24 shows an example of post-tensioned CLT shearwalls. See Section 5.3.5.2.1 for additional information.

Joensuu Lighthouse (Joensuu, Finland) and Oregon State University's Peavy Hall (Corvallis, Ore.) are modern tall wood buildings that have post-tensioned mass timber LLRS systems.

Joensuu Lighthouse is a 14-storey student residence at the University of Eastern Finland. Construction was completed in 2019. The building has a 1-storey concrete podium and is composed of timber from the 2nd storey through to the roof. The floors are CLT, and the walls are LVL. Overturning resistance for the building is provided by post-tensioned steel rods. Prefabrication of the exterior wall panels was done at the construction site, with weather protection provided by a tent. The exposed timber was protected from weather during installation by a temporary roof. The mass timber section of the building was constructed at a rate of 1 storey every 1 to 2 weeks (Keskisalo, 2019).

Figure 24. Post-tensioned shearwall, Oregon State University, Peavy Hall (courtesy of Equilibrium Consulting).

5.1.5.7 Concrete Shearwalls

Concrete shearwalls and cores are very common in mass timber buildings and consist of individual concrete walls or walls forming a "C" shape or rectangle in plan. The system resists the lateral loads through its bending and shear resistance. Given their shape and monolithic behaviour, cores typically act more like a tube than a single wall. The behaviour and design of such systems is well understood and documented. The elevator and stair shafts are frequently used as shearwalls, as shown in Figure 25.

The main advantages to using concrete cores in a mass timber building include the following:

- Concrete shearwalls can be ductile and high performing, and they do not have a prohibitive height limit in the NBC (NRC, 2020). Thus, they are Acceptable Solutions as the LLRS for a tall wood building in a high seismic hazard zone.
- There are well-established trades for concrete, particularly in Western Canada.

The following are some challenges associated with concrete shearwalls:

- Tolerances: Concrete and wood have substantially different tolerances. Mass timber can be fabricated to much lower tolerances than cast-in-place concrete, and the placement of embeds for mass timber connections is typically very challenging. Building sufficient adjustability into the mass timber system and connectors to allow for this difference in tolerance is a necessity, especially at embed locations.
- Timing: Concrete forming, pouring, and curing takes substantial time and effort. The greatest efficiency can be achieved if the timber is fabricated while the cores are being

erected; however, the lead time necessary to erect the cores must be considered in the schedule. The scheduling challenge of erecting the core in advance of the timber structure can be sidestepped by using a floor-by-floor approach, a jump form system, a slip form system, or a self-climbing system. Depending on the city, some of these options will be viable; others will not.

Figure 25. UBC, Brock Commons (courtesy of www.naturallywood.com).

The following modern tall wood buildings have concrete shearwalls:

- UBC, Brock Commons (Vancouver, B.C, 2017)
    - The building has two concrete cores designed as ductile shearwalls (R_d*R_o = 3.5*1.6) and ductile partially coupled walls (R_d*R_o = 3.5*1.7).
- HoHo (Vienna, Austria, 2019)
    - Once the concrete core was completed, the timber components were constructed at a rate of 1 storey per 4 days (Timber Architecture, 2019).
- LCT One (Dornbirn, Austria, 2012)
    - Constructing the building core using timber was considered possible; however, concrete was chosen for ease of permitting (Zangerl & Tahan, 2013).
- Holz 8 (Bad Aibling, Germany, 2011)

  - Once the concrete core was completed, the mass timber components were erected at a rate of 1 storey per 2 days.
- T3 Minneapolis (Minneapolis, Minn., 2016)
  - One central concrete core comprises the building's LLRS.

5.1.5.8 Steel Lateral Systems

Steel lateral systems are another option for code-approved non-wood lateral systems. Steel systems include braced frames, moment frames, and plate walls.

Braced frames are the most common steel lateral system used on taller buildings, and they pair nicely with mass timber buildings because both steel and timber are prefabricated off-site and assembled piecemeal on-site. Steel braced buildings can have steel braces within timber column and beam frames, or entirely steel frames with steel columns and beams.

Options for braces systems include the following:

- Concentrically braced frames: resist lateral loads through the resistance of the diagonal members acting in tension and compression. Energy dissipation is achieved through yielding of the tension brace (Figure 26, left image, Figure 27).
- Buckling restrained braces (BRBs): resist lateral loads through the resistance of the diagonal members acting in tension and compression. Energy dissipation is achieved through yielding of the braces in tension and compression. This is a very ductile and high-performing system (Figure 26, middle image, Figure 28).
- Eccentrically braced frames (EBFs): dissipate energy by yielding links that form part of the beam in the braced frame. All other elements are designed to remain elastic (Figure 26, right image, Figure 29).

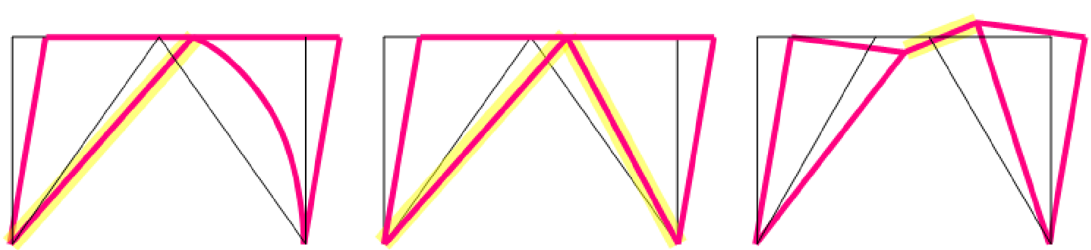


Figure 26. Brace configurations showing the yielding element in yellow: concentrically braced frame of chevron type (left), buckling restrained brace (middle), eccentrically braced frame (right) (courtesy of Aspect Structural Engineers).

Figure 27. Steel-timber hybrid, Spain (left); Scotia Place, New Zealand (right).

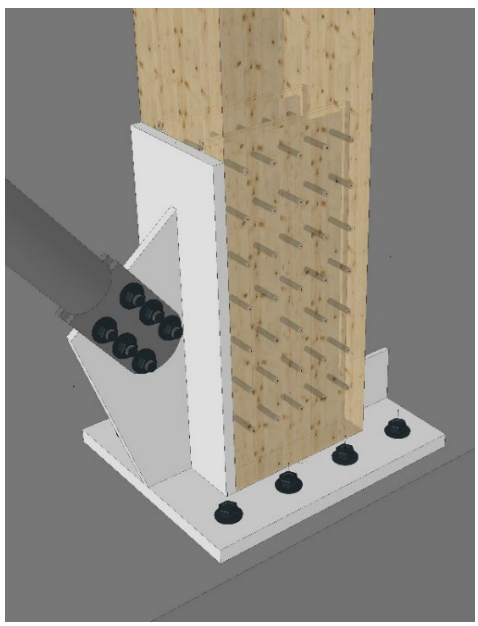


Figure 28. BRB renderings (courtesy of Structurlam).

Figure 29. Steel EBF (courtesy of Andrew Seeton).

Moment frames are composed of rigidly connected beams and columns that are often arranged to form a grid of portal frames. For seismic loads, the beam ends are designed to yield in bending. Moment frames are well-suited for achieving open floor plans and unobstructed windows.

Steel plate walls consist of a beam and column frame that is infilled with a steel plate. The system is analogous to a cantilever column with web stiffeners: the columns are the flanges, the plates are the web, and the beams are stiffeners. Buckling of the plate is used as the system's yielding mechanism for seismic design.

The following modern wood buildings have steel lateral systems:

- Mountain Equipment Co-op Head Office (Vancouver, B.C., 2014)
    - This 10,000 m^2 building has a post-and-beam structure and steel BRB frames (Figure 30).
    - 4 storeys
- T3 Atlanta (Atlanta, Ga., 2019)
    - The building has a steel concentrically braced frame LLRS.
    - 7 storeys
- Bullitt Center (Seattle, Wash., 2013)
    - Steel cross braces at the building core comprise the LLRS.
    - 6 storeys
- Carbon 12 (Portland, Ore., 2018)

    - The LLRS consists of steel BRBs located at the elevator and stairwell core (Structurlam, 2017).
    - 8 storeys
- Tallwood 1 (Langford, B.C., under construction)
    - The building will have 11 storeys of mass timber on 1 level of concrete with steel EBFs above level 2.

Figure 30. Mountain Equipment Co-op Head Office (courtesy of Ed White Photographics and Proscenium Architects).

5.1.5.9 Other Lateral Systems

New products are always being introduced to provide high-performing seismic systems, and many of them can be used in timber buildings. There are also opportunities to combine lateral systems to produce unconventional and higher performing building systems. The following are some additional lateral systems:

5.1.5.9.1 Spandrel and Tube Systems

Often, lateral load-resisting elements like braces and shearwalls are located centrally around the building's core. With taller timber buildings, particularly those exceeding 12 storeys and governed by wind loads, creative approaches to placement of the lateral system can be advantageous. An alternative approach to using only the cores is to place steel or timber braces at the exterior of the building to create an exoskeleton, or tube system, which can be a very efficient and stiff option for a very tall timber building. Likewise, stiff trusses can be used as spandrels to engage columns as part of the LLRS, and increase stiffness of the building's lateral system and reduce uplift forces (see also Section 5.1.7).

5.1.5.9.2 Coupled Walls and Tubes

Conventional shearwalls can be further improved by coupling them together, particularly with a ductile steel element. Coupling walls provides a useful source of additional ductility and increases the stiffness of the lateral system. Shearwall cores can also be coupled with a stiff enough coupler, which can be a beam or truss element.

5.1.5.9.3 Resilient Slip Friction Joints

Tectonus in New Zealand produces self-centring seismic devices designed to be resilient and dissipative joints for timber systems. They can be used as parts of braces, moment frames, or hold-downs for shearwalls. Recently, they have been used as hold-downs in a 4-storey mass timber office building in Vancouver, B.C. (Figure 31 and Section 5.3.5.2.2), and they are slated to be used in brace frames and shearwalls for a 10-storey office building in Vancouver.

Figure 31. Tectonus resilient slip friction joint used as shearwall hold-down (courtesy of Fast + Epp).

5.1.5.9.4 Friction Dampers

Friction dampers can be used as a breaker as part of a bracing system to limit the seismic loads of a building. They can be high performing, with high equivalent R factors. A secondary moment system is typically required for self-centring since there is no restoring force with the friction dampers.

5.1.5.9.5 Specialized Yielding Link Products

Simpson Strong Tie, Cast Connex, and others have developed specialized energy dissipators to concentrate energy dissipation into a single fuse that can be used in a brace or moment frame system.

5.1.5.10 Diaphragms

Regardless of the type of lateral system used in a timber building, the timber often forms some part of the diaphragm. Understanding the diaphragm requirements, load paths, and capacity design requirements is critical to a mass timber building's lateral system. Assumptions about rigid or flexible diaphragms should be checked (see Section 5.3 for additional information under diaphragm flexibility), and ideally the model should consider both conditions. Custom or proprietary products can be used for mass timber diaphragm splines. Like any prefabricated system, special consideration should be given to how the mass timber panels are connected together to form a continuous single diaphragm. In some buildings, particularly buildings with timber-concrete composite floors, the concrete topping provides the diaphragm. Some panel products, such as NLT, GLT, and DLT, require additional sheathing to provide the diaphragm continuity. Figure 32 shows one of the storeys in UBC's Brock Commons building which has a CLT diaphragm, plywood splines, and steel plate drag struts. Additional information on in-plane performance of some configurations of mass timber diaphragms is being compiled in a report by FPInnovations, which is planned to be released in 2022.

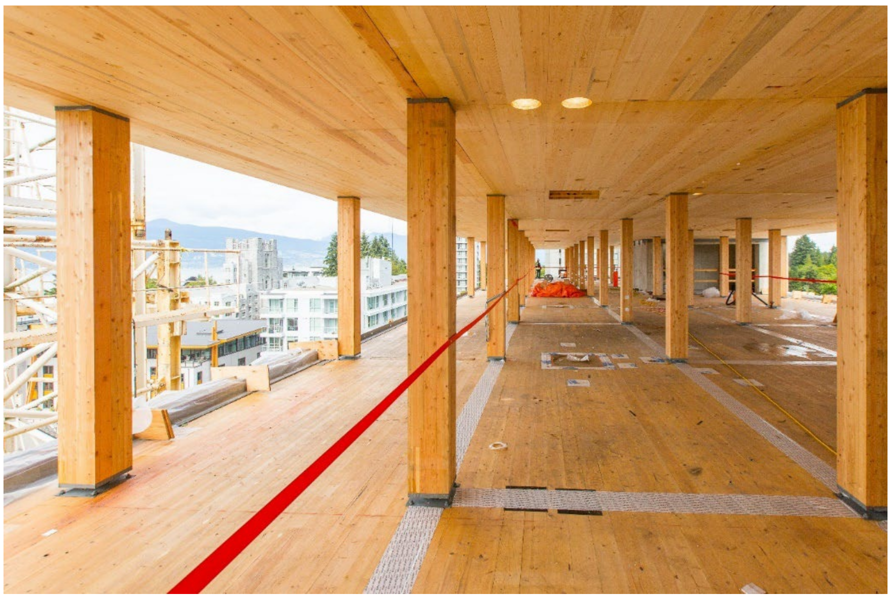


Figure 32. UBC, Brock Commons (courtesy of www.naturallywood.com).

5.1.6 PODIUMS

Mass timber buildings frequently include a concrete, and in some cases a steel, podium level that can provide open spaces for commercial clients and can meet occupancy separation and fire code requirements. Typically, a podium is a deep concrete slab or a steel structure that supports the transfer of columns above the podium to a different column layout below. A concrete podium can provide valuable mass to anchor the timber superstructure in high seismic hazard and wind zones and prevent overturning. Section 5.3 provides additional information on podium buildings.

Podiums are common in 5- to 6-storey light-wood-frame buildings or light-wood-frame/mass timber hybrid buildings. In the United States, 5-storey wood frame on a 2-storey concrete or steel podium is an acceptable system.

In some podium buildings, the LLRS of the podium continues all the way up the building; for example, concrete cores with a concrete podium (such as UBC Brock Commons) (Figure 33) or steel braced frames with a steel podium. In that case, the lateral load distribution and building period determination is straightforward and depends only on the mass of each floor and the stiffness of the lateral system. In other buildings, the lateral load-resisting system might change between the podium level and the timber superstructure, necessitating either a two-staged analysis using capacity design principles or a performance-based design. The heavier podium may transfer substantial load up the building if the lateral systems are similar in stiffness; however, if the lateral stiffness of the podium is significantly stiffer, as is often the case with timber lateral systems above the podium paired with concrete shearwalls below, the podium will have a lower impact on the system above. The connection between the timber and concrete portions, the relative height of the podium and the timber component, and the relative stiffness between the two dictates the amount of force transfer that takes place.

Figure 33. Concrete podium, UBC, Brock Commons (courtesy of www.naturallywood.com).

If the lateral system is discontinuous at the podium level, the design team should still provide direct vertical support under braced-bay columns and wall ends. At these high-tension and compression loads, a direct and stiff load path to the foundation is ideal to avoid softening the superstructure and altering the building performance, particularly under seismic loads. For example, a braced bay supported fully on a concrete wall below attracts more load than a braced bay that lands on a transfer slab with no concrete columns directly below.

The following modern tall wood buildings have a concrete podium:

- UBC, Brock Commons (Vancouver, B.C., 2017)
- Arbora (Montreal, Que., 2017–2019)
- Origine (Québec City, Que., 2017)
- Bullitt Center (Seattle, Wash., 2013)
- Forté (Melbourne, Australia, 2012)
- Joensuu Lighthouse (Joensuu, Finland, 2019)
- Stadthaus (London, UK, 2009)

- Dalston Lane (London, UK, 2017)
- Limnologen (Växjö, Sweden, 2008)
- Wagramer Strasse (Vienna, Austria, 2013)
- Tallwood 1 (Langford, B.C., under construction)

5.1.7 FOUNDATIONS

One of the main structural advantages of timber buildings, when compared to other materials, is the reduction in weight, which may translate into reduced foundation costs. For example, Bridport House in London, UK had a foundation that needed to bridge an underground storm sewer; the lighter CLT building significantly reduced the demand on the foundation. Skidmore, Owings & Merrill (2013) found that foundations for their prototypical building required only 65% of the material used for the concrete benchmark building. And if it were not for high overturning moments due to wind loads, the materials needed would have been 55% of that used for the benchmark building. However, in high seismic hazard zones or areas with high wind loads, lower mass could result in less resistance to overturning forces, and overturning can be the limiting factor for the foundation.

The designer can take certain steps to improve a building's overturning resistance by either reducing uplift forces or improving resistance to uplift. Shearwalls or lateral resisting elements that are closer to the perimeter of the building will create a building with a larger moment arm, which is better able to handle overturning moment and reduce uplift. Carefully planning the load path to maximize the amount of gravity load supported by the LLRS will also reduce uplift forces (Skidmore, Owings & Merrill LLP, 2013). Transferring the tension forces from the timber to the foundation needs to be considered and may be efficiently achieved by using steel tension elements at building extremities. Using tension piles, caissons, or soil anchors will help handle uplift once the load is transferred to the foundation.

All other matters related to foundations of buildings, such as relative movement between footings, are treated no differently in a mass timber building than in any other tall building.

5.1.8 REFERENCES

Abrahamsen, R., & Malo, K. (2014). Structural design and assembly of TREET: A 14-storey timber residential building in Norway. *World Conference on Timber Engineering.* Quebec City, QC.

American Institute of Steel Construction (AISC). (2016). *Design guide 11: Vibrations of steel-framed structural systems due to human activity*. (2nd ed.). Chicago, IL: Author.

American National Standards Institute and APA. (ANSI/APA). (2019). *PRG 320: Standard for performance-rated cross-laminated timber*.

APA. (2020). *Field notching and drilling of glued laminated timber beams.* (Technical Note S560J). Tacoma, WA: Author.

American Society of Civil Engineers. (2017). *Minimum design loads and associated criteria for buildings and other structures.* Reston, VA: Author.

Architectural Institute of British Columbia and Engineers and Geoscientists British Columbia (AIBC & EGBC). (2021). *Joint professional practice guidelines: encapsulated mass timber construction up to 12 storeys*.

Balmori, J.-A., Basterra, L.-A., & Acuna, L. (2020). Internal GFRP reinforcement of low-grade maritime pine duo timber beams. *Materials*, *13*, 571.

Binational Softwood Lumber Council & Forestry Innovation Investment (BSLC & FII). (2017). *Nail-laminated timber: Canadian design & construction guide v1.1.*

Canadian Standards Association (CSA). (2019). *CSA O86-19: Engineering design in wood.* Mississauga, ON: Author.

Canadian Wood Council. (2018). *Brock Commons Tallwood House: The advent of tall wood structures in Canada.* Ottawa, ON: Author.

Canadian Wood Council. (2019). *UBCO Fitness and Wellness Centre: A case study.* Ottawa, ON: Author.

Cecobois. (2018). *Origine Point-aux-Lievres Ecocondos, Quebec City.* https://cwc.ca/wp-content/uploads/2019/03/Origine-Case-Study.pdf

Concrete Reinforcing Steel Institute (CRSI). (2019). *Design guide for vibrations of reinforced concrete floor systems.* Schaumburg, IL: Author.

Cuerrier-Auclair, S. (2020). *Design guide for timber-concrete composite floors in Canada*. Pointe-Claire, QC,: FPInnovations.

Cuerrier-Auclair, S., & Popovski, M. (2020). *Expanding wood use towards 2025: testing of innovative connections and mass timber shear walls under lateral loads.* Pointe-Claire, QC: FPInnovations.

European Committee for Standardization. (2006). *Eurocode 1: Actions on structures.* Brussels, Belgium: Author.

Gagnon, S., & Hu, L. (2007). *Trip report: Sweden, Norway and France - November 1-11, 2007.* Quebec City, QC: Forintek Canada Corp. http://wood-works.ca/wp-content/uploads/2013/12/History-And-Use_TripReportSwedenNorwayFrance2007.pdf

Gehri, E. (2010). High performing jointing technique using glued-in rods. In A. Ceccotti (Ed.), *11th World Conference on Timber Engineering 2010.* Trees and Timber Institute, National Research Council.

Gouvernement du Québec. (2015). *Mass timber buildings of up to 12 storeys: Directives and explanatry guide.* http://collections.banq.qc.ca/ark:/52327/bs2553717

Hering, H. (2020). *8 French tall timber storeys*. https://www.woodsolutions.com.au/blog/8-French-Tall-Timber-Storeys

Holden, T., Devereux, C., Haydon, S., Buchanan, A., & Pampanin, S. (2012). Innovative structural design of a three storey post-tensioned timber building. *Proceedings of the World Conference on Timber Engineering.* Auckland, New Zealand.

International Code Council (ICC). (2021). *International Building Code.* Country Club Hills, IL: Author.

Karacabeyli, E., & Gagnon, S. (2019). *Canadian CLT Handbook.* (2nd ed.). Pointe-Claire, QC: FPInnovations.

Karacabeyli, E., & Lum, C. (Eds.). (2014). *Technical guide for the design and construction of tall wood buildings in Canada*. (1st ed.). (Special Publication SP-55E). Pointe-Claire, QC: FPInnovations.

Karsh, E. (2014). Modern timber connections. *Structure Magazine*, 16-19. https://www.structuremag.org/?p=4061

Keskisalo, M. (2019). Use of tension rods in wood construction - 14 storeys - with laminated veneer lumber as shear walls: Lighthouse Joensuu. *New Zealand Timber Design*, 17-37.

Lever Architecture. (2020). *Adidas North American Headquarters expansion*. https://leverarchitecture.com/projects/adidas_north_american_headquarters_expansion

McLain, R. (2018). *Acoustics and mass timber: Room-to room noise controll*. Woodworks Wood Products Council. https://www.woodworks.org/wp-content/uploads/wood_solution_paper-MASS-TIMBER-ACOUSTICS.pdf

National Research Council of Canada (NRC). (2017). *Structural Commentaries (User's Guide - NBC 2015: Part 4 of Division B).* Ottawa, ON: Author.

National Research Council of Canada (NRC). (2020a). *National Building Code of Canada.* Ottawa, ON: Author.

National Research Council of Canada (NRC). (2020b). *National Fire Code of Canada.* Ottawa, ON: Author.

naturally:wood. (2016). *Brock Commons Tallwood House; design and preconstruction overview*.

Ontario Ministry of Natural Resources and Forestry. (2017). *Ontario's tall wood building reference*. Toronto, ON: Queen's Printer for Ontario.

OOPEAA. (2020). *Puukuokka 1*. https://oopeaa.com/project/puukuokka-one/

Peikko Group. (2017). *Deltabeam frame technical manual.* Quebec City, QC: Peikko Group.

Rune Abrahamsen, K. M. (2014). Structural design and assembly of "Treet" a 14-storey timber residential building in Norway. *World Conference on Timber Engineering.* Quebec City, QC.

Safety Codes Council (SCC). (2019). *12-storey encapsulated mass timber construction STANDATA users guide*. Edmonton, AB: Alberta Municipal Affairs.

Schuler, T. (2018). *Dalston Works, the largest CLT building in the world*. https://www.architectmagazine.com/technology/detail/dalston-works-the-largest-clt-building-in-the-world_o

Skidmore, Owings & Merrill LLP. (2013). *Timber tower research project.* New York, NY: Author.

State of Oregon Building Codes Division. (2015). *No. 15-01 cross laminated timber provisions.* https://www.oregon.gov/bcd/codes-stand/Documents/sam-15-01-crosslaminatedtimber.pdf.

Stora Enso. (2016). *Building systems by Stora Enso: 3-8 storey modular element buildings.* https://www.storaenso.com/-/media/Documents/Download-center/Documents/Product-brochures/Wood-products/Design-Manual-A4-Modular-element-buildings20161227finalversion-40EN.pdf

Structurlam. (2017). *Structurlam case study - Carbon 12 - Portland, Oregon.* https://www.structurlam.com/wp-content/uploads/2017/04/Carbon-12-Case-Study-2.pdf

Techniker. (2010). *Tall timber buildings: The Stadthaus, Haxton, London - Applications of solid timber construction in multistorey buildings.* London, UK: Author.

Think Wood & WoodWorks (2021). *Mass timber design manual*. U.S. edition. https://info.thinkwood.com/masstimberdesignmanual

Timber Architecture. (2019). *HoHo, Vienna nearing completion*. http://timber-architecture.com/hoho-vienna-nearing-completion/

Trifkovic, M. (n.d.). *Treet – World`s tallest timber building*. http://wood-works.ca/wp-content/uploads/Edmonton_wood-fair_marina.pdf

University of British Columbia (UBC) Centre for Interactive Research on Sustainability. (2016). *Brock Commons Tallwood House: code compliance.*

Ursem (n.d.). *Hotel Jakarta*. https://www.ursem.nl/en/projects/hotel-jakarta/

Willford, M.R., & Young, P. (2006). *A design guide for footfall induced vibration of structures: A tool for designers to engineer the footfall vibration characteristics of buildings or bridges.* CCIP-016. Camberley, England: The Concrete Centre.

WoodWorks. (2020). *Acoustically-tested mass timber assemblies.* https://www.woodworks.org/wp-content/uploads/Acoustically-Tested-Mass-Timber-Assemblies-WoodWorks.pdf

Zangerl, M., & Tahan, N. (2013). LCT One. *Wood Design & Building*, *61,* 25-28.

CHAPTER 5

SECTION 5.2

Design Considerations and Input Parameters for Connections and Assemblies

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ABSTRACT

This section reviews the structural design considerations when specifying wood-based products and selecting input parameters for the analysis and design of tall wood buildings.

Engineering properties such as the strength, stiffness, and dimensional stability of wood products that are used in tall wood structures are considerably different from those of other construction materials such as concrete and steel. An understanding of those properties is a requirement for effective design of structural wood members, connections, and assemblies.

In tall wood buildings, the strength and displacement of the structure is normally determined by the strength, stiffness, and ductility of the connections and assemblies. For connections with generic fasteners, such as bolts and dowels, nails and spikes, timber rivets, lag screws, and wood screws, the input data can be derived from the Canadian standard on *Engineering Design in Wood* (CSA O86), and if needed, other available design standards. For connections with proprietary fasteners, such as self-tapping screws and/or other specialty hardware for which such design information is not yet covered in CSA standards, the input data can be derived from product evaluation reports issued by evaluation agencies such as the Canadian Construction Materials Centre, and from manufacturers' design brochures, or test data from procedures specified by the authorities having jurisdiction.

Input data for assemblies can be derived from testing, numerical modelling, or engineering mechanics using material properties information provided in CSA O86 or other available design standards. Where numerical modelling is used to obtain these parameters, it is critical that the selected model is able to replicate the behaviour of the wood members and connections, the boundary conditions, and applied loads on assemblies as accurately as possible.

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5.2.1 INTRODUCTION

Wood as a structural material is in many ways different from other structural materials such as steel, concrete, or masonry. Some of the most important aspects related to the unique properties of wood and wood products are discussed in this section to help designers better understand the behaviour of wood members and connections. While certain design aspects are equally applicable to low- and mid-rise wood buildings, the focus of this section is mainly on design issues associated with tall wood buildings.

Marketability/Profitability

Innovative connector systems for mass timber may be available in other jurisdictions before they are commercially available in Canada. While a process is available through the Canadian Construction Materials Centre to obtain formal regulatory acceptance, it may not have been initiated. If there are benefits, a designer may undertake a review to justify their use on a project.

Connections in timber structures have a major influence on the strength, stiffness, damping, ductility, and stability of the structure. Consequently, the performance of the connections often governs the performance of the gravity and lateral load-resisting systems and the overall performance of a timber building. This is even more critical for tall wood buildings.

Due to the emergence of structural composite wood products (as summarized in Section 5.1) and the recent interest in developing tall and hybrid systems, development of innovative connection systems and designs is required. Although some of these connection systems have been developed over the past 20 years, many of these systems and assemblies are not covered in the Canadian standards. It is necessary to establish some guidelines for evaluating their performance through laboratory testing so they can be incorporated into the development of Alternative Solutions.

This section provides guidance on the various design parameters and considerations for connection systems and assemblies. It also provides procedures for interpreting test data and deriving design properties for use as input data in analysis procedures presented in Section 5.3.

5.2.2 WOOD PROPERTIES AND DESIGN CONSIDERATIONS

5.2.2.1 Mechanical Properties of Wood

Wood has different strength properties in different directions relative to the grain; therefore, it is categorized as an anisotropic material. The Canadian standard on *Engineering Design in Wood*, CSA O86 (CSA, 2019a), provides different values of specified strengths for wood products in the compression and tension parallel- and perpendicular to grain directions. Consequently, when modelling stresses in wood members, strength and stiffness properties have to be entered for parallel- and perpendicular to grain directions, and one set for tension and another for compression. Proprietary engineered wood products, such as laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL), have properties that differ from those of sawn lumber. Designers should contact manufacturers to obtain the appropriate properties and resistances of various wood products. For non-proprietary wood products included in CSA O86 (CSA, 2019a), such as glued laminated timber (glulam) or cross-laminated timber (CLT), values for their strength should be taken from that standard. However, both glulam and CLT also offer custom grades; in these situations, the product manufacturers' design literature should be consulted.

When designing members, connections, assemblies, and structural systems of wood or wood-based products, details that stress the wood in tension perpendicular to grain should be avoided as much as possible due to wood's low strength and brittle failure mode (Figure 1). Tension perpendicular to grain strength design values are not provided in CSA O86 (CSA, 2019a), except for very specific conditions. More details on tension perpendicular to grain are provided in Section 5.2.2.5. Compression parallel-to-grain behaviour of wood is generally ductile and tends to have the linear elastic and non-linear response more clearly defined. The failure mode of a beam in bending can be a combination of compression parallel to grain in the compression zone, and a brittle failure mode in the tension zone of the member. Some of the other properties of wood and wood products that affect their strength and stiffness are mentioned in Sections 5.2.2.2 to 5.2.2.7.

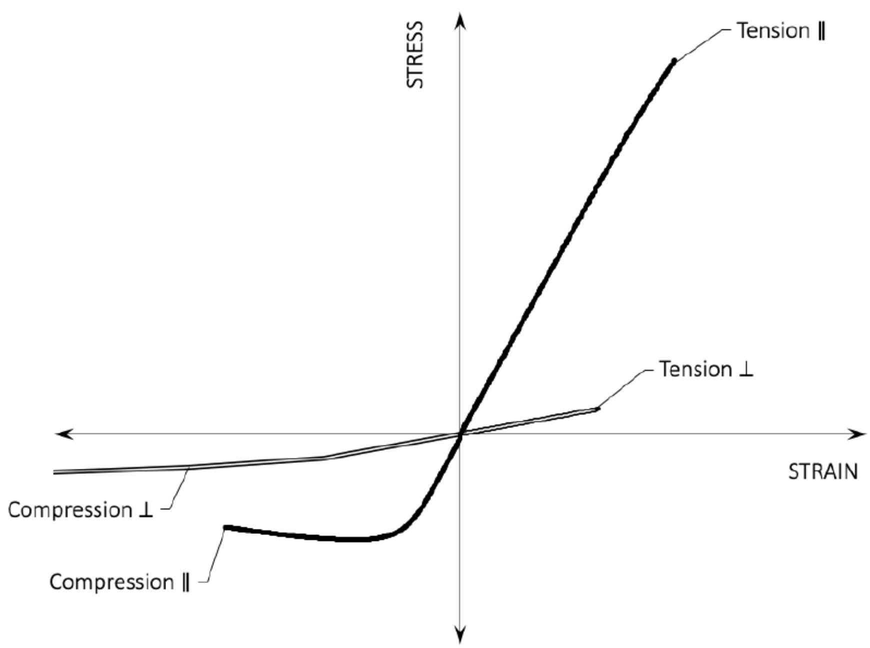


Figure 1. Typical stress-strain curves of clear wood parallel and perpendicular to grain (courtesy of A. Salenikovich).

5.2.2.2 Size Effect

Some resistances of wood and wood-based products depend on the size of the member. This can be explained by the weakest link concept (Weibull, 1939), which states that the resistance of a member depends solely on the resistance of its weakest link. Since the probability of encountering major defects (knots and other imperfections) is greater in a larger volume of wood than in a smaller volume, the resistance decreases as the size of the member increases in some loading applications. The effect of size on resistance is taken into account in CSA O86 (CSA, 2019a) by the size factors. Size factors are product and property dependent. For example, for glulam, effects on tension perpendicular to grain are taken into account by the factor K_{Ztp} for curved or double-tapped members. Effects on bending moment and compression parallel to grain are taken into consideration by the factor K_{Zbg} and K_{Zcg}, respectively. The effect on shear is reflected by incorporating the beam volume into the calculation of shear resistance. In the case of CLT, the size effects are included in the assigned strength of the laminations used to determine the specified strengths of the primary CLT panel grades.

> Under some loading conditions, strength decreases as member size increases because of the increased probability of encountering a zone of low strength.

Due to higher gravity loads and fire design considerations, the use of members with larger cross-sections in the design of tall wood buildings is to be expected. This will especially be the case for columns of structural systems of a spatial frame type, and less so for buildings that use wall panels such as CLT or LVL for the gravity or lateral load-resisting system. Size factors for elements made of proprietary engineered wood products should be determined based on information from the manufacturers, Canadian Construction Materials Centre (CCMC) evaluation reports, or available research. If such information is not available, a size factor based on testing and analysis should be determined (see Barrett et al., [1975] for an example showing the basic steps, which can be adapted to use the finite element method).

5.2.2.3 Compression Perpendicular to Grain

> Resistance in compression perpendicular to grain (bearing) in wood and wood-based products is much lower than compression resistance parallel to the grain.

As wood buildings are built taller, the traditional platform-type construction adopted in low-rise buildings, where the posts bear on beams and girders, becomes challenging. Gravity loads accumulate at the lower storeys and may cause excessive deformations due to stress in compression perpendicular to grain at the interface between the posts and the beams or massive slabs (Figure 2).

The compression perpendicular to grain is generally considered ductile and rarely causes catastrophic failures, except at the ends of deep and relatively narrow structural members. However, it can be the limiting and governing design aspect in many structural details related to tall wood buildings; therefore, designers should develop connection and interface details that minimize or

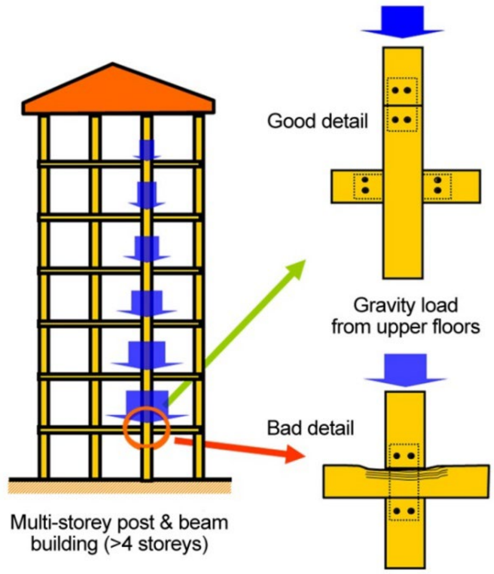


Figure 2. Excessive compression perpendicular to grain deformation due to gravity loads.

eliminate excessive compression perpendicular to grain deformations, which could be achieved using the following approaches:

> The compression failure perpendicular to grain is generally considered ductile and rarely causes catastrophic failures. However, it can be the limiting and governing design aspect in many structural details related to tall wood buildings. Different design details are available to mitigate this effect.

1. The connections in some historical post-and-beam wood buildings in Canada that are 8 and 9 storeys high were designed to transfer the load from upper storey posts to those below without subjecting the timber beams or girders to compression perpendicular to grain stresses through their depths (Figure 3a). Similar concepts have been adopted in certain modern mid-rise buildings in Europe (Figure 3b).
2. In post-and-beam construction, continuous posts can be used. Beams and girders can be connected to the posts through metal hangers, concealed plates, or other connection systems attached to the posts. Alternatively, the beam or girder can be designed to have a larger section profiled to rest partially on the post. Both posts and beams can be profiled to optimize the connection (Figure 4).

(a) Historical building, North America (b) 7-storey post-and-beam building, Berlin

Figure 3. Post-to-beam connection details for avoiding excessive compression perpendicular to grain deformation due to gravity loads.

3. Post-to-post connections can be located away from beam-to-post connections to provide simplified design and ease of assembly (as shown in the "good detail" in Figure 2). This arrangement is typically used in steel design to avoid complex connections and facilitate construction work.

4. For mass timber construction, the floor slabs and wall panels may be profiled at the edges to allow a portion of the upper wall panel to directly contact the lower panel. This would provide a partial bearing of the floor slab on the wall, while allowing the direct transfer of gravity loads from the walls above to the walls below through the edges. An example of this is shown in Figure 5. This solution, while technically feasible, may be expensive to fabricate and may not be suitable if site conditions cannot be kept dry (see Chapter 7).

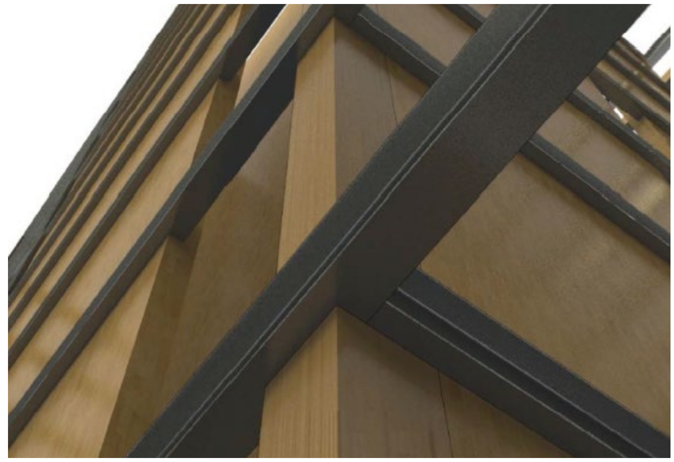
Alternatively, systems such as CREE (www.creebuildings.com) and FFTT (mgb et al., 2012) could be used to ensure an efficient transfer of gravity loads from upper to lower storeys without subjecting the wood members of the floor system to compression perpendicular to grain stresses (Figure 6a and 6b). More details about the CREE system are provided in Section 5.1.

The case study in the Timber Tower Research Project (SOM, n.d.) presents yet another interesting system called "concrete jointed timber frame", which uses mass timber, concrete, and steel. The system relies primarily on mass timber for the main structural elements, with supplementary reinforced concrete at the highly stressed locations of the structure (Figure 6c). More details are provided at SOM (n.d.).

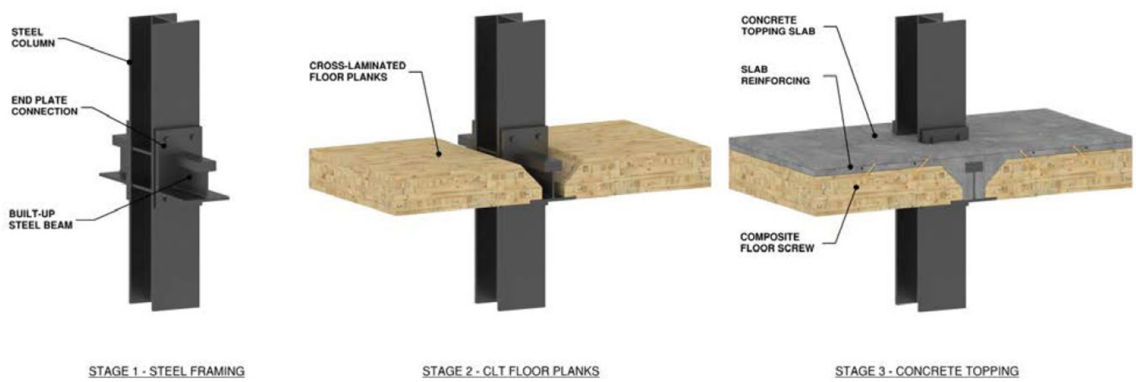
Figure 4. Continuous posts in a mid-rise wood building Fondaction CSN Building, Québec.

Figure 5. Minimizing compression perpendicular to grain and shrinkage using profiled panel ends (courtesy of Eurban).

(a) CREE hybrid concrete-wood system (Source: CREE)



(b) FFTT system for tall wood buildings consisting of balloon mass timber walls with steel beams embedded in the wall (Source: The Case for Tall Wood Buildings)



(c) Concrete jointed timber frame (Source: SOM, n.d.)

Figure 6. Examples of efficient transfer of gravity load without excessive deformations.

5.2.2.4 Shrinkage and Swelling

> Changes in the moisture content of wood cause shrinkage or swelling. The cumulative effect of the shrinkage and swelling is very important in a tall wood building.

Wood is a hygroscopic material that gains or loses moisture depending on ambient conditions. Moisture content (MC) is a measure of the amount of water present in wood, and is expressed as a percentage of the mass of the water in the wood with respect to its mass in an absolutely dry (oven-dry) condition. For example, lumber is generally kiln-dried before being shipped to users, and the MC at the time of surfacing is shown on the grade stamp. The "S-Dry" (surfaced dry) on a North American grade stamp indicates that the lumber was surfaced at an MC of 19% or less; "KD" (kiln-dried) indicates that the lumber was dried in a kiln to an MC of 19% or less but may or may not be surfaced. The nature of the manufacturing process for glued wood products is such that panel products and other engineered wood products are typically shipped at a lower MC. For example, plywood and oriented strand board are usually produced at an MC of 4–8%. At the time of manufacturing, the moisture content of PSL, LSL, and LVL is between 4% and 12%, and is between 7% and 15% in glulam and CLT. More information is provided in *Introduction to Wood Design* (CWC, 2018).

The loss and gain of moisture below the fiber saturation point at approximately 30% affects the dimensional stability of the wood and causes shrinking or swelling, respectively. Figure 7 shows shrinkage of wood in the three principal directions, with the shrinkage values expressed as percent reduction from the green dimensions. In service, wood never experiences drying from "green" to "oven-dry"; therefore, the related shrinkage is usually much smaller. For engineering design, the shrinkage in the parallel-to-grain direction is approximately 1/40 of the shrinkage (dimensional change) in the perpendicular to grain orientation. For this reason, shrinkage parallel to the grain is usually ignored in most low-rise wood buildings. For tall buildings, however, it is recommended that both parallel-to-grain and perpendicular to grain dimensional changes be included in the shrinkage calculations. Calculation of shrinkage or swelling is provided in CSA O86 A5.4.6 (CSA, 2019a).

Project Delivery

Mass timber is typically fabricated at a low moisture content that is close to what might be expected under interior service conditions. Except in very dry conditions (see Chapter 7), further shrinkage will be limited to at most 1% perpendicular-to-grain, if any. However, during construction, wetting may cause swelling, and any resulting dimensional changes will need to be accommodated.

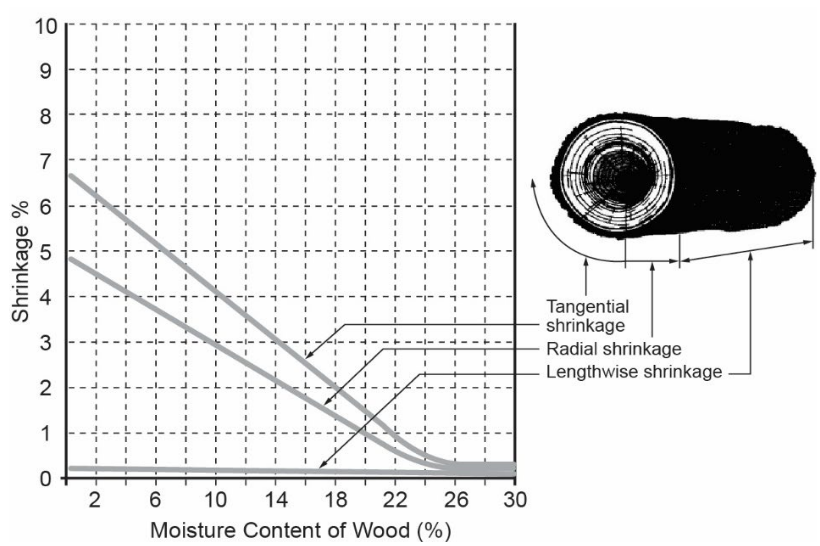


Figure 7. Shrinkage of wood (Source: CWC, 2018).

In tall wood buildings, a significant portion of a building's movements, depending on the design, may be attributed to wood shrinkage or swelling caused by moisture loss or gain. (The other contributing factors are elastic and creep deformations of members and connections or construction tolerances.) Differential movements due to changes in ambient conditions and loads can be accommodated relatively easily in low-rise wood buildings. In mid-rise and tall wood buildings, however, proper detailing to accommodate building movements is important due to the cumulative effect over the height of the structure.

Designers should pay special attention to the MC of wood and wood-based products at the time of delivery, during installation, and when the building is closed in, and to the equilibrium moisture content (EMC) that the wood and wood-based products will reach in service. The EMC that solid wood will reach in service depends mainly on the ambient relative humidity and temperature in the building; therefore, it varies by region and fluctuates throughout the year. Due to the manufacturing processes and adhesives used, engineered wood products have slightly lower EMC than sawn lumber of the same wood species. Note that this is aside from the lower initial moisture content (compared to solid sawn lumber) for engineered wood products at the time of shipping. Typical EMC values of lumber are listed in Table 1 (CWC, 2018).

Table 1. Typical equilibrium moisture content of lumber in various regions of Canada

Region		Average (%)	Winter (%)	Summer (%)
West Coast	Indoors	10–11	8	12
	Outdoors under cover	15–16	18	13
Prairies	Indoors	6–7	5	8
	Outdoors under cover	11–12	12	10
Central Canada	Indoors	7–8	5	10
	Outdoors under cover	13–14	17	10
East Coast	Indoors	8–9	7	10
	Outdoors under cover	14–15	19	12

Connections need to account for shrinkage of connected elements. Differential shrinkage between wood and other materials may cause splitting and affect overall behaviour.

Particular attention should be paid to proper detailing of connections in order to prevent wood members from splitting due to differential movement. When using fasteners in a steel plate, it is important to follow the specified maximum distance between the outer rows of fasteners, as per CSA O86 (CSA, 2019a), to avoid potential split. If a connection restrains wood from movement, tension stresses perpendicular to grain may develop and cause the timber to split. An example of a poor detail, and suggestions for improvement, are shown in Figure 8. In this case, because of shrinkage, the beam no longer bears on the bracket directly; instead, a large portion of the weight of the beam is carried by tension perpendicular to grain stresses under the bolt group. While moving the bolt group to the bottom of the backet may help, it may cause the top of the beam to not be flush with the top of the girder, which may create unevenness in the floor surface. This type of split often occurs with treated timber, which generally has a high moisture content compared to non-treated timber. While end splitting reduces the shear strength of the member, some splitting is accounted for in the assignment of design values. It should be noted that modern timber connection designs include concealed metal hardware milled through the beams, which improves the aesthetics and enhances the fire resistance of the connections (Figure 9). The perpendicular to grain width and location of the hidden knife plates also have to be assessed for how they accommodate potential shrinkage if the MC at the time of installation differs significantly from the EMC in-service.

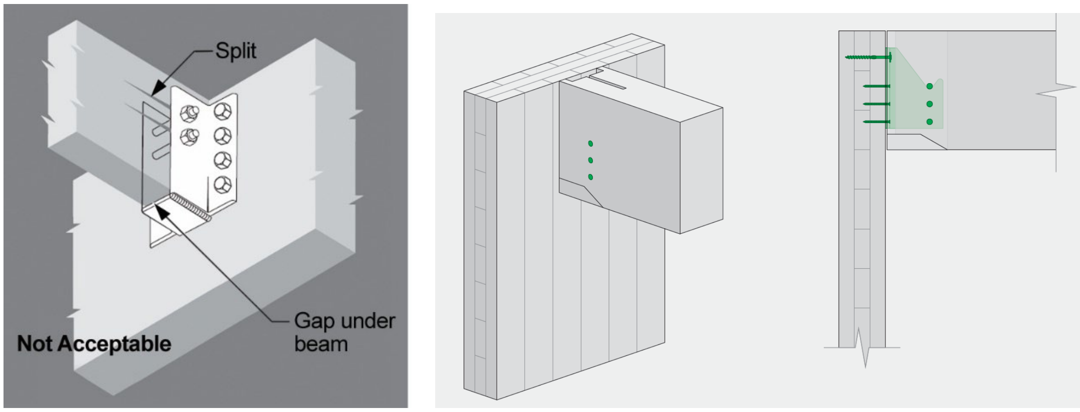


Figure 8. Example of poor detailing practice (left) (Source: CWC, 2020), and suggestions for improvement to avoid splitting (right) (courtesy of Nordic).

Figure 9. Concealed beam to girder connections.

To mitigate potential shrinkage and swelling and their adverse effects in tall wood building design, the following practices must be considered:

1. Installing wood and wood products with MC close to the in-service EMC will greatly reduce the amount of vertical movement that could occur.
2. It is very important to protect wood and wood-based products from wetting during construction and in service. Unprotected outdoor storage of wood products on the construction site should be minimized or eliminated. Where possible, materials should be delivered just in time for installation in order to prevent potential wetting. All products should arrive on-site wrapped. Wood-based composites and engineered wood products usually require more attention during storage and handling because most of them are manufactured at a low MC. These products may be more sensitive than lumber or timber to damage from moisture uptake during wetting incidents. The use of a weather-protected construction site is highly recommended (see Chapter 7).

3. Good construction sequencing also plays an important role in reducing wetting and the resulting shrinkage and other moisture-related issues. Swelling due to moisture from on-site wet construction, such as the pouring of a concrete topping, should be taken into consideration. The use of dry, prefabricated, wood-based or concrete elements is recommended; however, the care taken to protect them should be the same as that for engineered wood products. Chapter 8 provides additional information regarding prefabrication.
4. Wood products under protected conditions can dry out naturally when they are well ventilated and relative humidity is less than 65%. Sufficient time should be provided for this drying to occur. If timber elements are exposed to rain during transportation or construction, walls and roofs should not be enclosed until the framing materials have dried to an acceptable level of moisture. In cold and damp conditions, the use of space heating, together with air circulation, can efficiently dry wood and improve construction efficiency. Rigid components (services, pipes, elevator shafts, rigid cladding) that need to be anchored to the building for stability should be installed as late as the building code and construction sequencing allow in order to minimize damage due to subsequent settling of the wood structure. Alternatively, when rigid components are installed, measures should be taken to ensure that interfaces and anchor points accommodate vertical movements of structural members.
5. Differential shrinkage between the various types of wood-based products and between wood and other materials, such as steel and concrete, must also be taken into account. Examples of such shrinkage occurs where the wood elements in the structure are connected to rigid assemblies of other materials, such as masonry (e.g., cladding), concrete (e.g., elevator shafts), and mechanical services and plumbing, and where mixed wood products, such as lumber, timber, and engineered wood products, are used. In steel components of the connections, the use of slots that allow movement of dowels and prevent direct contact between concrete, masonry, and wood-based members is one of the common preferable design details. Other examples of good connections detailing are provided in the *Wood Design Manual* (CWC, 2020). Recommendations and solutions for dealing with differential movement are provided in the design fact sheet *Vertical Movement in Wood Platform Frame Structures: Design and Detailing Solutions* (Doudak et al., 2013).

5.2.2.5 Tension Perpendicular to Grain

Wood and wood-based products are weakest in tension perpendicular to the grain or strand. Members with perpendicular-to-grain tensile stresses include double-tapered, curved and pitch-cambered beams, notched members, members with holes, tension- or compression-brace members with eccentricity in connections, moment-resistant connections with dowels, and members with cross connections. Moment-resistant connections should be detailed to minimize perpendicular to grain tensile stresses as they rotate and yield.

Perpendicular to grain tensile stresses may also occur in wood members due to changes in moisture content. If perpendicular to grain tensile stresses are expected and cannot be avoided in some areas of the structural system, strengthening of that part using self-tapping screws, glued-in rods, or other means of reinforcement is necessary. More information about reinforcement techniques is provided in Section 5.2.2.8.

5.2.2.6 Load Duration and Creep

One of the key characteristics of wood is that its design strength and deformation is dependent on the time under the design load. The effect related to strength is referred to as "duration of load"; the effect related to deformations is referred to as "creep". Generally, wood is able to carry greater short-term loads than long-term loads.

In CSA O86 (CSA, 2019a), K_D, the duration of load factor, is used to account for the effect of the duration of load on strength. Values for the K_D factor for wood products and connections are indicated in Table 4.3.2.2 of CSA O86 (CSA, 2019a). K_D = 1.0 for standard-term duration of loading, $K_D = 1.15$ for short-term duration of loading, such as wind and seismic events, and $K_D = 0.65$ for sustained loading, such as dead loads. It must be noted that for seismic loading, K_D of 1.15 may be too conservative. Karacabeyli & Ceccotti (1998) suggested that K_D should be at least 1.25 for nailed shearwalls (users are advised to consult future updates of CSA O86). For load combinations where the load duration is expected to exceed that of the live load or snow load, the sustained load factor of $K_D = 0.65$ may be conservatively used, or the factor may be calculated using Equation [1]:

$$K_D = 1.0 - 0.50 log\left(\frac{P_L}{P_S}\right) \geq 0.65 \quad [1]$$

where P_L = specified long-term load, and P_s = specified standard-term load.

Creep refers to the time-dependent increase in deformation or deflection under constant load. That is, the deformation increases even though the load is constant. Part of this deformation may not be recoverable when the load is removed. Like most other construction materials, wood experiences creep deformations. The polymeric and hygroscopic nature of wood components makes its creep behaviour sensitive to moisture fluctuations. Extended wetting/moisture exposure during construction should be avoided because it will tend to make the product or assembly more susceptible to creep deformations when it is exposed to loading while at a high MC.

Creep needs to be considered in structures with high levels of sustained load or where wood members are subjected to frequent large changes in MC or to continuously wet service condition under bending or compression perpendicular to grain. Calculation of creep deformation is not explicitly provided in CSA O86 (CSA, 2019a). However, based on Eurocode 5, long-term creep may be estimated as 0.6 times the instantaneous deformation under total load for wood used in typical indoor conditions with a temperature of 20°C and the relative humidity of the surrounding air exceeding 65% for only a few weeks per year. In the National Design Specification (NDS) for wood construction, the creep factor varies with wood product and service condition. For example, the long-term creep (additional deflection) is 0.5 times instantaneous dead load deformation for seasoned lumber, glulam, I-joist, and structural composite lumber (SCL) in dry service condition, and 1.0 times for seasoned or unseasoned lumber or glulam used in wet service condition. For wood used in conditions where MCs are high, such as indoor swimming pools, long-term creep may be twice the instantaneous deformation under total load.

ASTM D6815 (ASTM, 2015b) provides a procedure for testing wood-based products with long-term load to determine if the duration-of-load and creep effects are similar to those of solid wood. The intent is not to develop specific duration-of-load or creep factors for wood-based materials, but rather to demonstrate the engineering equivalence of wood-based products used in dry service conditions in terms of duration-of-load and creep effects compared to those of sawn lumber. If all criteria are met, it is considered acceptable to use the duration-of-load and creep factors that are applicable to lumber (Karacabeyli, 2001).

5.2.2.7 Punching Shear

Punching shear can lead to a type of failure associated mainly with slabs that are subjected to high localized forces at column support points. Mass timber panels, such as CLT, LVL or LSL, supported by wood or steel columns (Figure 10) may be subjected to punching shear forces. Such forces could cause excessive compression perpendicular to the grain and potentially a rolling-shear failure. Rolling shear is defined as shear leading to shear strains in a plane perpendicular to the grain direction. This phenomenon is not restricted to tall wood buildings but is important in situations where panels are used as part of a two-way floor system. However, each wood product will have unique considerations because of wood's anisotropic nature and, in the case of SCL, the way in which the product is manufactured.

There is no established design method for punching shear. However, based on European research findings (Maurer et al., 2018; Mestek et al., 2011; Thomas & August, 2015), several options are available for mitigating punching shear and reducing excessive compression perpendicular to the grain associated with such applications:

- Reinforcement techniques using self-tapping screws. Installing inclined, self-tapping wood screws can substantially improve the load carrying capacity of CLT panels against rolling-shear failures (Mestek et al., 2011). This is particularly critical when CLT is manufactured with cross lamina not glued on edge or when relief grooves are used. The amount of improvement depends very much on the number of screws and on screw spacing, diameter and type, and installation angle. Under two-way load-carrying action, an even more significant increase in the load-carrying capacity of the plates can be achieved.
- Other options involve distributing the load at the interface between the column and the CLT, through a wide steel-bearing plate. Alternatively, a wooden cap (i.e., a small massive-wood panel) could be used to further reinforce the slab, help distribute the load over a larger area, and mitigate stress concentration.
- Rothoblaas Spider connection and reinforcement system is another alternative: https://www.rothoblaas.com/products/fastening/brackets-and-plates/multi-storey-connectors/spider#spider

Figure 10. Massive-wood floor plate on posts where punching shear is likely to govern design (courtesy of KLH).

5.2.2.8 Reinforcement of Connections

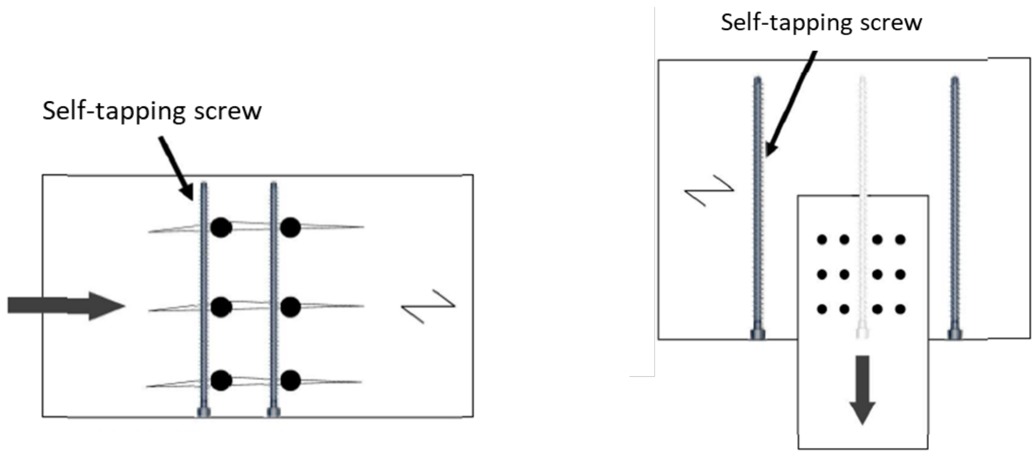
Tensile and compressive strengths of timber perpendicular to grain are much lower than the respective strengths parallel to the grain. Sections 5.2.2.4 and 5.2.2.5 provide examples of structural members in which tensile stresses perpendicular to grain may occur, such as double-tapered curved and pitch-cambered beams, and details such as notched beam supports, connections loaded perpendicularly to the grain, beams with holes, and connections with multiple fasteners in a row.

Various reinforcing techniques have been developed for timber members and connections (especially dowelled connections), such as glued-on plywood plates, truss plates, and fibre-reinforced polymer, or internal reinforcement using glued-in threaded rods to prevent wood members from splitting at the connection (Mohammad et al., 2006). While this method of reinforcement is not particular to high-rise construction, an understanding of it will serve as an important tool for the designer.

Self-tapping screws or glued-in rods can be used for transverse reinforcement. Fully threaded, self-tapping screws are preferred due to their ease of installation and effectiveness in reinforcing structural members and connections.

Transverse reinforcement using self-tapping screws is a common technique because the screws have a high withdrawal resistance and are easy to install. Compared to other means of reinforcement, self-tapping screws do not require surface preparation and drilling. With diameters of 12 mm and larger and lengths up to 1000 mm, fully threaded screws can be used in many structural members as reinforcement to carry tensile stresses perpendicular to the grain. The design approach for reinforcement is provided in *Self-Tapping Screws and Threaded Rods as Reinforcement for Structural Timber Elements – A State-of-the-Art Report* (Dietsch & Brandner, 2015). A recent state-of-the-art report (Branco et al., 2021) contains additional information on the reinforcement of timber elements in existing structures.

Transverse reinforcement with self-tapping screws not only increases lateral resistance, but also improves stiffness and ductility of connections (Bejtka & Blass, 2005, 2006; Blass & Schmid, 2001; Dietsch et al., 2013; Mohammad et al., 2006). Either partially or fully threaded self-tapping wood screws can be used for this purpose. Reinforcement may be necessary in poor-connection detail cases where end and edge distances of dowel-type fasteners are small and increase the risk of brittle failure modes (Figure 11).



(a) Bolted connection (b) Perpendicular connection

Figure 11. Transverse reinforcement of bolted connections using self-tapping screws (Source: MTC Solutions).

5.2.2.9 Fire Performance of Timber Connections

There are no specific requirements in the National Building Code of Canada (NRC, 2020) with regard to fire resistance of connections in wood buildings. In principle, connections should have the same degree of fire resistance as the supported structural elements or assemblies.

Connections with exposed metal parts may perform poorly under fire conditions because the intensity of a well-developed fire can be sufficient to weaken or plasticize metal components and hardware. For connections that carry gravity loads in tall wood buildings, a strategy must be developed to prevent the collapse of the building in the event the connections are exposed to fire.

> Connections should have at least the same degree of fire resistance as the supported structural elements or assemblies.
>
> Division B of the NBC is generally interpreted to permit steel connections in heavy timber construction to be unrated; however, this is not applicable to or appropriate for a tall wood building.

It is not necessary to consider the combination of fire with lateral loading due to wind and earthquakes unless a specific component is responsible for most of a building's lateral resistance; therefore, exposed steel connections needed to resist lateral wind or seismic loads are generally acceptable as long as it can be demonstrated by engineering analysis (or testing) that a fire incident is unlikely to significantly impair the overall building's lateral load-resisting system. The combination of fire and lateral loading should be considered for gravity-induced lateral loads (e.g., to prevent progressive collapse) or as part of elements that brace gravity members for stability.

> Under fire conditions, timber will char. In mass timber, the potential depth of char can be reliably calculated (i.e., roughly 0.65 mm/min.). Steel connections located entirely inside the residual cross-section are considered appropriately protected.

In a fire, serviceability failures, such as the crushing of wood or deflection, may be acceptable as long as they do not lead to the collapse of the building floors or walls or the failure of fire safety systems. In the design, this type of serviceability failure may necessitate providing alternate load paths that do not rely on exposed steel connections. As discussed in detail in Chapter 6, mass timber will char in a fire, and the potential depth of char may be reliably calculated as roughly 0.65 mm per minute. A sacrificial 7-mm zero-strength layer can be added to provide the required fire protection. It is generally accepted that if steel connections are located entirely inside the residual cross-section, they are considered appropriately protected. Calculation of the actual depth of char is discussed further in Chapter 6. When concealed connections are designed, it is necessary to recess the dowels and bolts in the side wood members and to use wooden caps for further thermal protection. If this is not done, the dowels and bolts may conduct heat into the connection and locally char the connection from the interior, which can create a failure mechanism. The details of the concealed connections should be approved by the fire protection engineer of record.

In many cases, the mass timber element will be protected with gypsum wallboard or another material to protect the wood and reduce the level of charring; making this protection continuous over the steel connections then provides the required protection for the connections. This, too, is discussed further in Chapter 6.

Connections can also be protected with various fire-protection products used for steel, such as spray-on paints, coatings, or cementitious materials. Care must be taken at the interface between the wood and the protective material to ensure the continuity of the protection when the wood chars in a fire, and to ensure that the temperature of the steel is not sufficient to cause charring of the wood.

One such material that has been used to protect steel connections is intumescent paint; however, recent testing has indicated that intumescent coating may not perform as well as expected when used to protect steel components in timber connections. Cracking and peeling may occur, especially at the interface between wood and steel, and while still structurally sound, the steel may get hot enough to char the wood and cause premature failure of the connection. These concerns may be alleviated if specific fire testing or analysis is available to demonstrate the effective and durable protection of the connection.

To enhance connection performance under fire conditions, the following should be considered:

1. Concealed connections should be used whenever possible, and all metal components should be embedded inside the structural wood members or beneath the potential char layer (sacrificial wood). Current CNC (Computer Numerical Control) technology and the availability of innovative connection systems facilitate such a design approach. The depth of the char layer and the thickness of protection should be calculated as discussed in Chapter 6.
2. In certain connection systems (e.g., post-to-beam using two-way moment-resisting metal plates as in steel construction), wooden caps could be used to cover the steel plates and

dowels at the interface between posts and beams to provide fire protection. The thickness of the wooden caps should be calculated based on the char rate, as discussed in Chapter 6.

3. Where the wood is encapsulated or protected with gypsum wallboard or another material, this protection may be made continuous over the connections. Further analysis will be required based on the material properties of the steel, wood, and protective material. Additional information on encapsulation of mass timber is provided in Chapter 6.
4. It is possible to design connections for redundancy, which would allow an alternate load path to develop in the event of the yielding of exposed metal components under fire conditions, as has been done in historical tall wood buildings in North America (Figure 3a).
5. Care should be taken with the use of spray-on fire-protection material at the interface between wood and steel, and with the charring effect that hot steel may have on the mass timber.
6. The use of intumescent paint should be avoided unless specific fire testing or analysis is available to demonstrate effective protection of the connection.

5.2.2.10 Cost Considerations

In estimating the cost of connection systems, one must account for the following key elements:

- availability
- ease of design
- performance
- complexity of installation

The lack of costing information for connection systems used in tall wood buildings is a challenge, but as these buildings become more common, more costing information will become available. One possible strategy for minimizing the risk of cost overruns is to use a systems approach. New systems like CREE are becoming available in North America, but their number is currently very limited.

The cost analysis should include all construction costs, including indirect costs, such as transportation, as well as the complexity of installation and any required finishing. The choice or selection of the type of assembly or connection should also take into account the cost of maintenance during the life expectancy of the structure.

Typically, the cost of the various types of connection systems depends on several factors. In general, generic traditional fasteners cost less than proprietary fasteners, especially if the latter are imported. However, some proprietary connection systems and fasteners provide more efficient and more reliable performance, which makes the connection more economical for certain applications.

In estimating the overall cost of connection systems, the following elements must be considered:

- availability;
- ease of design (complex systems take more time to design) and regulatory acceptance (generic traditional fasteners are included in the codes. If the proprietary product does not have a CCMC listing, the designers have to review the manufacturer's literature and overseas codes);
- performance;

- complexity of installation (how quick and easy it is to assemble and potentially disassemble the connection system without sophisticated or specialized tools);
- serviceability;
- compatibility with mechanical and electrical installations;
- need to conceal for aesthetic reasons; and
- fire protection.

Chapters 8 and 9 provide additional information on cost considerations.

5.2.3 INPUT DATA FOR CONNECTIONS

Connections are generally the critical factor in the design of wood structures. The strength of the structure is often determined by the strength of the connections; their stiffness and ductility greatly influence the behaviour of the system, and member sizes are often determined by the number and types of connectors used rather than the resistance of the members.

A wood connection consists of two or more wood-to-wood or wood-to-steel or wood-to-concrete components attached together using mechanical fasteners or a combination of mechanical fasteners and structural adhesives. The mechanical fasteners could be generic, such as bolts, nails, or wood screws, or proprietary, such as self-taping screws. Examples include post-to-post or post-to-beam/girder or purlin connections with bolts, timber rivets, or wood screws.

Connections with generic fasteners can be designed using the CSA O86 standard (CSA, 2019a) and, if needed, other CSA standards (e.g., CSA S16 for steel hardware [CSA, 2019b]). Connections with proprietary fasteners are not covered in CSA standards but can be found in the product evaluation reports issued by approved product evaluation organizations, such as the CCMC, or manufacturers' design brochures. Where manufacturers' design brochures are used, designers and engineers need to verify the testing and engineering analysis that was done to support the design values claimed by the manufacturers.

Connections that resist gravity and wind loads or that are required to be non-dissipative under the seismic load are designed to remain elastic. In this case, only the strength and stiffness of the connections are required for the design. Connections that are required to be energy-dissipative under the seismic load must be designed to meet all the following requirements:

(a) the connection resistance is governed by a yielding failure mode;

(b) the connections possess sufficient ductility to meet the required ductility of the structural system; and

(c) the connections possess sufficient deformation capacity to accommodate the building's drift.

5.2.3.1 Strength

Moisture content and load duration are important factors in connection design. Design to avoid brittle failure modes, especially in high seismic hazard zones.

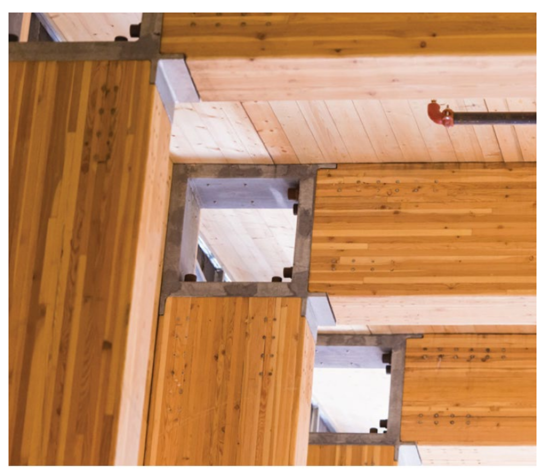
Connections must be designed to transfer the forces from one member to another.

When connections are designed to dissipate energy under seismic load, connections for which strength is controlled by wood failure (brittle failure, in particular) should be avoided. To ensure adequate wood strength, consideration must be given to how moisture and other service factors that influence the strength of wood (or other materials) are integral to any connection design. Guidance on how to adjust the strength to take the wood moisture content and other service conditions into account is provided in CSA O86 (CSA, 2019a) and other material design standards, such as the EC5 (CEN, 2004) in Europe and the NDS (ANSI/AWC, 2018) in the United States. CSA O86 (CSA, 2019a) is the standard that is referenced by the building codes in Canada and should be used in design.

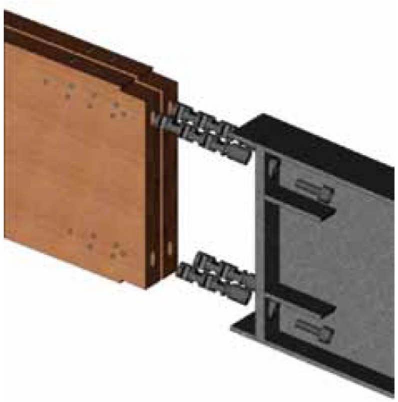
The behaviour of timber structures under seismic loads is controlled largely by the connections, which must be ductile and maintain integrity under overload conditions.

For connections formed with traditional metal dowel-type fasteners, the moment-resisting curve, to varying degrees, exhibits semi-rigid behaviour due to combined embedment and fastener deformation. At the present time, moment-resisting connections are not explicitly covered under CSA O86 (CSA, 2019a). However, current design information in the standard could be used to design a moment-resisting connection with traditional metal dowel fasteners if the connection is assumed to be rigid. Section 5.3.6 of this guide includes numerical modelling techniques that can be followed to assess the rigidity of a connection. Several proprietary moment-resisting systems have been developed for rigid moment-resisting connections. Figure 12 shows some modern moment-resisting systems. Designers should obtain technical information from manufacturers about the performance of the connection systems.

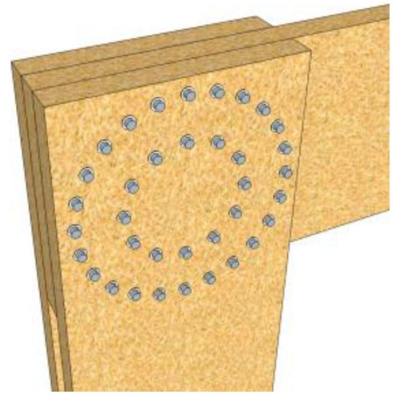
Pitzl – RIGID connection
(Source: https://www.pitzl-connectors.com/fileadmin/user_upload/Neuigkeiten/04_RIGID/Prospekt_-_RIGID_EN_web.pdf)



Box moment frame connector
(Source: Equilibrium Consulting)



BVD moment connection
(Source: Karsh, 2014)



Moment connection with dowel type fasteners

Figure 12. Examples of modern moment-resisting systems.

5.2.3.2 Stiffness

Stiffness is a measure of resistance to deformation and is demonstrated by the slope of the load-deformation curve (Figure 13). Since the stiffness of most connections varies with the load in a non-linear fashion, it is useful to make certain simplifications to the load-deformation curve, to the extent necessary for the appropriate analysis method (see Section 5.3).

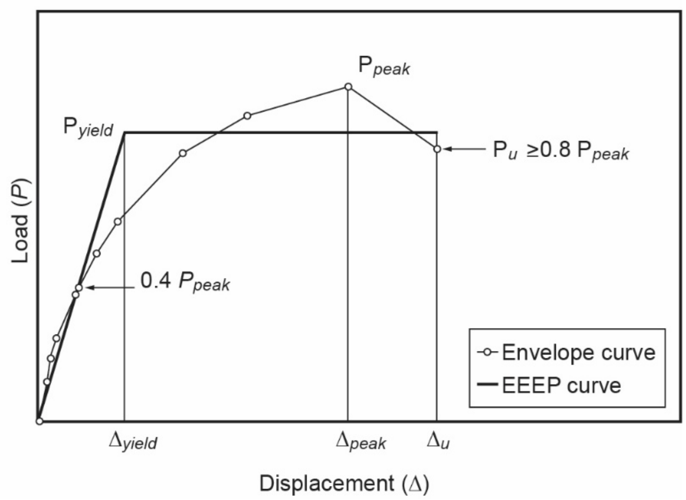


Figure 13. Load-displacement curve of a connection (EEEP = equivalent energy elastic-plastic) (Source: ASTM E2126).

Usually, the initial elastic stiffness is defined as a secant between two load points of the load-displacement curve (or envelope curve from cyclic tests). The first load point may be either the load at zero or the load at 10% of the maximum load, for example, while the second load point may be the load at 40% of the maximum load, as shown in Figure 13. The initial stiffness may then be determined using Equation [2]:

$$k_e = \frac{P_2 - P_1}{\Delta_2 - \Delta_1} \qquad [2]$$

where P_1, P_2 = loads at the first and second points (N), and Δ_1, Δ_2 = displacements corresponding to the first and second load points (mm).

A consistent method should be used for deriving stiffness values for various connections so they are compatible in numerical modelling and analysis.

In CSA O86 Annex A (CSA, 2019a), the load-slip relationships in the elastic region are provided for connections with lag screws, wood screws, nails, and spikes. For connections with other types of fasteners, such as bolts and dowels, the stiffness values are not provided in CSA O86 (CSA, 2019a), so they should be determined from tests, modelling, or other available resources (for example, other design codes, product evaluation reports, or research literature). Dowel-type connectors that require pre-drilling are typically sensitive to manufacturing tolerances. Bolts and tight-fitting dowels are quite different in terms of their applications, which may negatively affect the stiffness of the connection. The use of prefabricated products may reduce those effects.

In Eurocode 5 (CEN, 2004), the elastic stiffness, referred to as slip modulus, is given for the serviceability limit state (SLS), K_{ser}. For the ultimate limit state (ULS), K_u is used. The stiffness for design at the SLS is taken as the secant modulus of the load-slip curve at a load level of approximately 40% of the maximum load, while the stiffness at the ULS is taken as the secant modulus of the load-slip curve at a load level of approximately 60–70% of the maximum load, and is expressed according to Equation [3]:

$$K_u = \frac{2}{3} K_{ser} \qquad [3]$$

Formulas for the slip modulus, K_{ser}, per shear plane per fastener under serviceability limit state for different metal dowel-type fasteners and split-ring and shear-plate connectors are shown in Table 2. In the formulas, d (mm) is the fastener diameter, and ρ_m (kg/m^3) is the mean density of the wood materials at 12% MC. Where the connection includes members of different densities, ρ_{m1} and ρ_{m2}, ρ_m is calculated as shown in Equation [4]:

$$\rho_m = \sqrt{\rho_{m1} \cdot \rho_{m2}} \qquad [4]$$

For steel-to-timber or concrete-to-timber connections, the slip modulus, K_{ser}, is based on ρ_m of the wood member and may be multiplied by 2.0. These formulas may overestimate the real stiffness of the connections with steel plates and ignore the initial slack and rotation of the fasteners in pre-drilled holes.

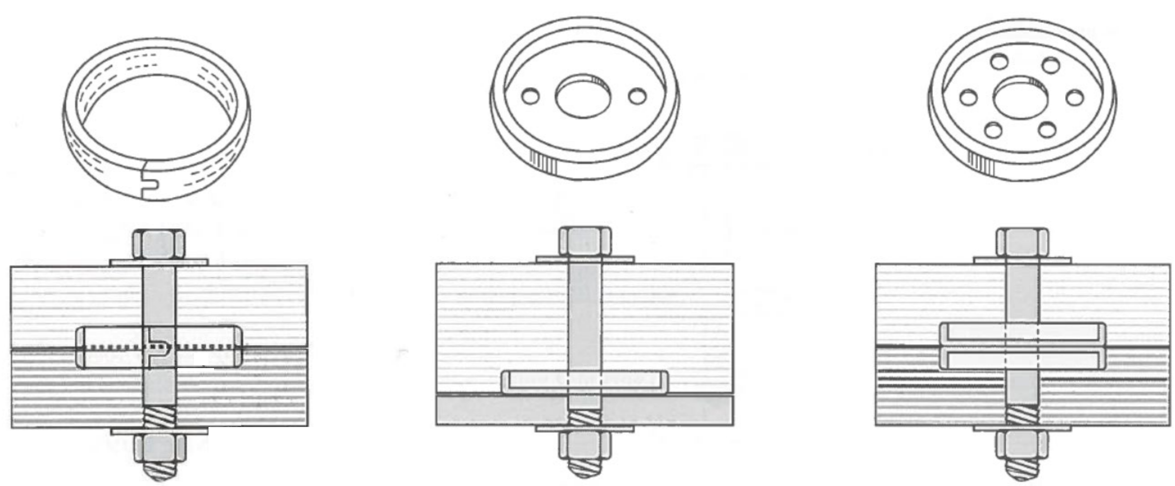
The Eurocode 5 (CEN, 2004) formulas adjusted to the CSA O86 (CSA, 2019a) format are shown in the last column of Table 2. The adjustment includes conversion from the mean density at 12% MC to the mean relative density on oven-dry mass and volume basis (1000/0.957 = 1045) provided in CSA O86 Table A.12.1 (CSA, 2019a) for calculating resistance of connections at 15% MC.

It is worth noting that the EC5 (CEC, 2004) stiffness values may not necessarily match test results. In situations where stiffness is critical, actual test data from connection tests conducted in accordance with the acceptable standards to determine connection stiffness should be used. For seismic design, the elastic stiffness should be determined based on the envelope curve obtained from cyclic tests.

Table 2. Elastic stiffness of timber-to-timber and wood-based panel-to-timber connections per shear plane per fastener (N/mm).

Fastener type	K_{ser}	K
Dowels Bolts with or without clearance[a] Screws Nails (with pre-drilling)	$\frac{{\rho_m}^{1.5} d}{23}$	$1470 G^{1.5} d$
Nails (without pre-drilling)	$\frac{{\rho_m}^{1.5} d^{0.8}}{30}$	$1125 G^{1.5} d^{0.8}$
Split-ring connector type A (Figure 14a) Shear-plate connector type B (Figure 14b)	$\frac{\rho_m d_c}{2}$	$520 G d_c$

[a] The clearance should be added separately to the deformation.



(a) Split-ring connector type A (b) Shear-plate connector type B

Figure 14. Split-ring and shear-plate connectors (Source: Porteous & Kermani, 2007).

For "pinned" joints and many other joints in timber construction that are assumed to be "pinned", the rotational stiffness of connections is typically not required by the designer. It should be noted that joints that are assumed to be pinned may not necessarily perform as pins and can attract some moment. Furthermore, pinned connections in gravity systems need to maintain displacement compatibility with the lateral load-resisting system. See Section 5.3 regarding "Compatibility of Gravity Systems for Lateral Load Demand". Designers need to pay attention to potential pinned connection failure due to moment. If this is the case, it is suggested that a semi-rigid connection assumption should be used in the design.

5.2.3.3 Ductility

Connections should be designed not only to resist design loads, but also to absorb energy and maintain the integrity of the structural system in the event of overloading.

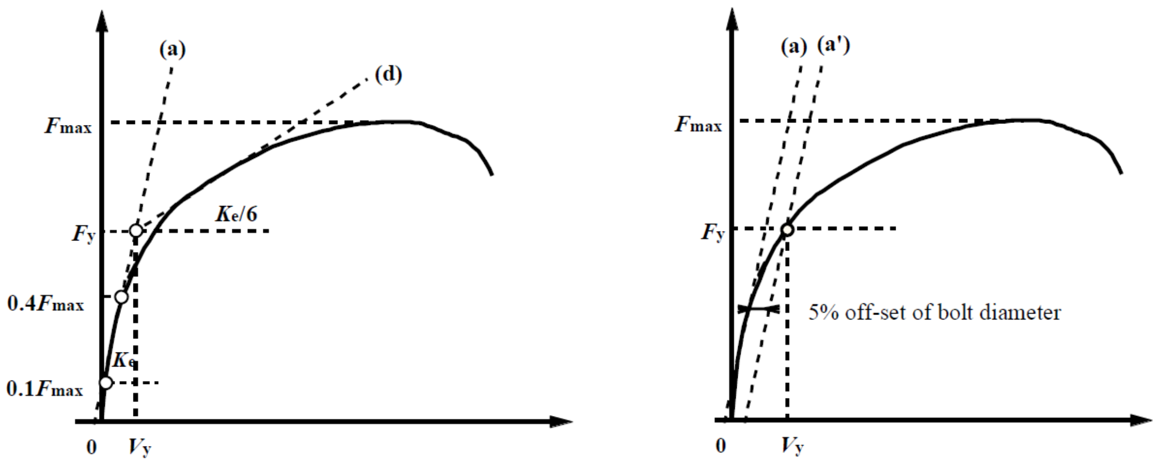
Ductility is defined as the ability of a material to undergo large deformations in the inelastic range without failure. Ductility of connections may be determined based on an analysis of test data on timber connections. Ductility is usually expressed as the "ductility ratio (μ)", which is defined as the ratio of the displacement at the failure (ultimate, u) load to that at the yield load (Figure 13) according to Equation [5]:

$$\mu = \frac{\Delta_u}{\Delta_{yield}} \qquad [5]$$

where Δ_u = displacement at failure load, P_u, and Δ_{yield} = displacement at yield load, P_{yield}.

For timber connections where the load-slip curves in the elastic range are nonlinear, the yield point is not obvious. There are different methods for determining the yield point for timber connections, but none has yet been adopted in the Canadian standards. According to ASTM E2126 (ASTM, 2019), the yield point of an assembly can be determined by using the equivalent energy elastic-plastic (EEEP) curve, as shown in Figure 13. Although this standard was originally developed for assemblies, it can also be used for connections.

In Europe, the CEN bilinear elastic-plastic approach is used (EN, 2001a), whereas in the United States, ASTM D5652 (ASTM, 2015a) uses the 5% diameter offset for connections with dowels, as shown in Figure 15. A unanimous universal approach for determining the yield point and ductility would help harmonize standard testing and analysis procedures for the seismic design of timber systems. The ultimate displacement is defined in ISO 16670 (ISO, 2014) and 21581 (ISO, 2010), but its value may vary depending on the circumstances.



(a) EN 12512 (CEN, 2001a) (b) ASTM D5652 (ASTM, 2015a)

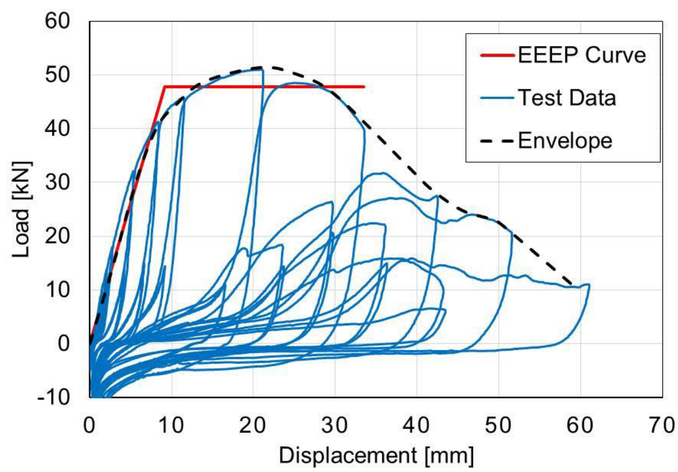
Figure 15. Different methods for determining the yield point.

Currently, there is no universal classification for ductility categories. In Eurocode 8 (CEN, 2001b), three ductility classes for timber connections are included, depending on the type of fastener (e.g., nails, screws, and dowels), loading conditions, and failure mode. In Canada, preliminary ductility categories were proposed (Table 3), in which connections were classified based on the failure mode as "brittle", "low ductility", "moderate ductility", and "high ductility" (Smith et al., 2006). It should be emphasized that the ductility of the connections (local ductility) is not a guarantee of a ductile performance of the seismic force-resisting system (global ductility). Guidance on how to link the local (connection) ductility with the global (system) ductility for various types of connections and structural systems is currently being developed. The advanced modelling guidance in Section 5.3 should be used to assess the local ductility demands for a given global ductility.

Table 3. Proposed ductility classes for connections (Smith et al., 2006)

Classification	Average ductility ratio (μ)
Brittle	$\mu \leq 2$
Low ductility	$2 < \mu < 4$
Moderate ductility	$4 < \mu \leq 6$
High ductility	$\mu > 6$

According to CSA O86 (CSA, 2019a), energy dissipative connections in CLT structures must be at least moderately ductile. Connections tested under cyclic loading in accordance with ASTM E2126 (ASTM, 2019), and having a minimum ductility ratio of 3.0 determined using the EEEP methodology as defined in ASTM E2126, may be considered to be moderately ductile. Connections with steel brackets, steel side plates, or knife-plate can be considered moderately ductile if their resistance is governed by the fasteners (nails, screws, or slender pins) that fail in yielding modes (d), (e), and (g) (Gavric, 2012; Schneider, 2015; Schneider et al., 2014). Figure 16 shows the load-displacement curve from a one-sided cyclic test of a typical light-gauge steel bracket connection with 18 spiral nails, loaded in uplift parallel to the grain of the face CLT lamination. Figure 17 shows the behaviour of the same connection in sliding under reversed cyclic load perpendicular to grain of the face CLT lamination (CWC, 2020).



(a)

(b)

Figure 16. (a) Load-displacement curve of a bracket connection in CLT loaded in uplift; (b) the tested bracket with 18 spiral nails (d = 4.2 mm, L = 89 mm).

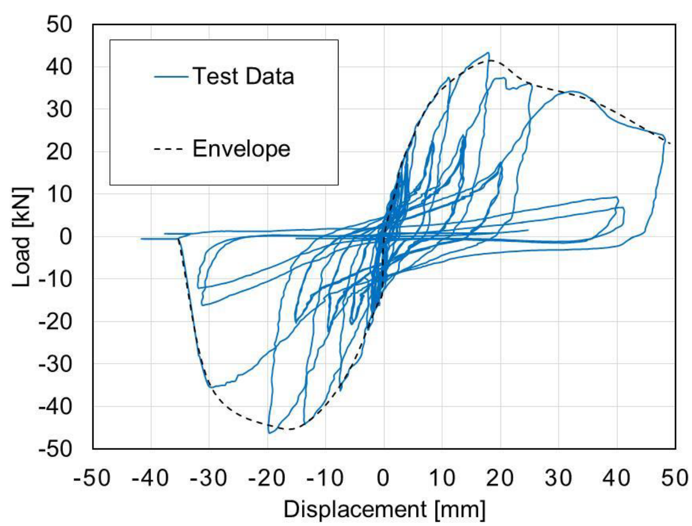


Figure 17. Load-displacement curve of a bracket connection in CLT loaded in sliding (18 spiral nails d = 4.2 mm, L = 89 mm).

Based on their performance, connections with internal or external steel side plates attached with mild steel dowel-type fasteners such as bolts or dowels driven perpendicular to the face of the CLT can be considered moderately ductile and can be used in CLT structures if their resistance is governed by the fastener yielding modes (d), (e), and (g) and the fasteners have a slenderness ratio $t/d_F \geqslant 10$ (Gavric 2012, Gavric et al. 2015). The term *t* is the dowel-bearing length in the CLT member, and d_F is the fastener diameter. It is recommended that fasteners with a diameter of 19 mm or less be used. Note that the type of steel can have a significant effect on the strength and behaviour of the connection.

Nailed connections with or without splice plates are also considered moderately ductile. In the case of connections with self-tapping screws (e.g., in half-lap joints), fastener manufacturers should be contacted to obtain the performance data, which are needed to confirm that the screws will yield as required.

Other connections should be tested under cyclic load to confirm that they satisfy ductility and displacement capacity requirements. Until a harmonized approach is adopted, the ductility ratio should be calculated according to ASTM E2126 (ASTM, 2019), using the EEEP curve (Figure 13). Screws loaded in withdrawal only are generally considered non-dissipative connections because they behave in a brittle manner. More information on the cyclic behaviour of typical metal connectors (hold-downs and angle brackets), along with recommendations for better mechanical performance, are provided in Gavric et al. (2015).

5.2.3.4 Deformation

Connections should possess sufficient deformation capacity to accommodate a building's drift. In seismic design, engineers must use the connections that have sufficient deformation capacity to allow structural systems to develop their assumed deformation behaviour. For connections that are designed to remain elastic under force and displacement demands, the connection deformation should not be greater than the yield displacement, Δ_y, which can be determined either by testing, as described in Section 5.2.3.5, or by calculation, as shown in Equation [6]:

$$\Delta_y = \frac{P_y}{K} \qquad [6]$$

where P_y is the yield strength of the connection, and K is the stiffness of the connection.

The energy-dissipative connections under the seismic load used in CLT shearwalls must be designed to develop yielding failure modes, must be at least moderately ductile, and must allow the rocking motion of CLT shearwalls before reaching the ultimate displacement. Additional information on seismic design f connections in CLT shearwalls is provided in Section 5.3 and in Karacabeyli & Gagnon (2019). The ultimate displacement of the connection can be determined from the envelope curves according to ASTM E2126 (ASTM, 2019).

5.2.3.5 Evaluation of Connections

Proprietary connection systems and fasteners are evaluated based on test data produced by the manufacturer, with interpretations of evidence performed by product certification organizations such as the CCMC in Canada or the International Code Council Evaluation Service (ICC-ES) in the United States. Such organizations produce reports of their recommended design values for the tested system. For Canada, CCMC evaluation reports publish design values in accordance with the reliability-based design principles of CSA O86 (CSA, 2019a).

Testing of connections should be performed in accordance with established test standards, such as ASTM D1761, D5764, and D7147.

The authority having jurisdiction may accept a connection system, with or without an independent third-party evaluation, if it is convinced that the proper engineering due diligence has been undertaken. If, however, it requires confirmation from a third-party evaluation agency, evaluation reports from recognized product certification organizations must be provided.

The following describes a common approach in testing and deriving the design values for proprietary connection systems that are beyond the generic types of fastening systems referenced in CSA O86 (CSA, 2019a). This approach is based on accepted ASTM standards.

Regulatory Acceptance

New structural systems or elements not covered by CSA O86 are permitted, provided they are demonstrated by engineering analysis, testing, or both to meet the intended performance requirements of the proposed structure. This chapter provides considerations for this assessment.

1. Test assemblies should bound (i.e., cover the range of) the connection systems in the field and be representative of the standard manufactured product. The sampling strategy for the wood-based components of the connection assembly should comply with standardized ASTM or international practice. Wood density usually must be considered during sampling and may need to be biased toward the lower end.

   The number of tests should first reflect the inherent variability of the test method. Guidance on the minimum required sample size is provided in ASTM D5457 (ASTM 2020a) and ASTM D2915 (ASTM 2017). Product assessment organizations, such as the CCMC, or an engineer should determine the number of tests required based on the variability of the results. If there are other sources of variability of concern (e.g., workmanship, service condition), consider each of them to determine if they should be assessed separately or as part of a larger test sample. Testing as part of a large test sample has the advantage of capturing any interaction between the test parameters; however, the cost of testing will increase greatly, and each of the parameters of interest should be

General considerations must be taken into account prior to testing connections and assemblies, including:

- specimen configuration
- representativeness of the material (e.g., wood density)
- wood moisture content of components when installed and in-service
- load application, rate of loading, and type of loading
- workmanship

properly represented in the sample in terms of its likelihood of occurrence and magnitude. Typically, this is handled by random sampling; however, this is usually not practical.

2. Testing should be conducted in accordance with established test standards. In North America, examples of testing standards include ASTM D1761 (ASTM, 2012), D5764 (ASTM, 2018a), and D7147 (ASTM, 2018b). Testing procedures should be adopted based on the type of fastening system and intended applications. However, other testing protocols, such as the universally accepted ISO 16670 (ISO, 2014) could also be used.

   The following considerations must be taken into account prior to testing:

   - wood moisture content (connections must be fabricated in the appropriate state, according to the target service conditions prior to testing);
   - load application, rate of loading, and type of loading need to be determined (i.e., static versus cyclic or reverse cyclic, short term versus sustained loading, etc.); and
   - workmanship, in terms of assembly fabrication.

> **Construction Moisture**
>
> For new systems that lack a history of use under North American construction practices, differences such as the effect of construction moisture should be reviewed. For example, construction moisture may cause mass timber to swell and snap self-tapping screws. More protection or a change in construction sequence may be needed.

3. All necessary data should be collected to determine the ultimate capacity and deformation characteristics of the connection.
4. Observations of failure modes must be recorded, and wood density and moisture content within the vicinity of the connection must be measured.

Testing is best applied once the source of materials and types of connectors have been identified. Representative samples of each can then be collected for testing. In most cases, resource and time constraints will limit the sample size, so judgement will need to be used in interpreting the results. In these cases, resources are better directed at designing a test program to confirm the modes of failure that design needs to address (or the modes of failure that will not be likely given the design details selected). With an understanding of wood behaviour, more relevant insight into the connector capacity may be obtained by testing that uses, for example, lower density wood or smaller edge or end distances.

5.2.3.6 Deriving Design Values for Connections Based on Test Data or Design Data from Other Jurisdictions

To derive the specified design values that correspond to those in CSA O86 (CSA, 2019a) for generic fastening systems, the following procedure may be adopted:

- Establish the characteristic strength property from test data: The characteristic value is determined from test data (see Section 5.2.3.5) on connections or assemblies, following

ASTM D5457 (ASTM, 2020a). The characteristic design value is taken as the lower 5th percentile estimate determined as per established parametric or non-parametric procedures with a 75% confidence level. Weibull or Normal distributions (whichever provides a better fit for the test data) should be adopted for parametric analysis. Typically, test data are fitted to Weibull 2-parameter distribution models (CSA, 2001).

- Determine the specified design value: In order to be consistent with current design values in CSA O86 (CSA, 2019a), the specified design value is determined following reliability-based design principle, and then by applying a 0.8 factor to bring it from a short-term laboratory test to standard load duration.

> The procedure for deriving the design values for connections should be based on reliability analysis.

- Factored resistance: The specified design value is further adjusted by a resistance factor. The appropriate material factor to apply depends on the ductile or brittle behaviour of the connection assemblies.

5.2.3.7 Requirements for Proprietary Connections

Modern concealed metal hardware for wood construction is invariably proprietary, and design information is based on recommendations of third-party product assessment organizations such as the CCMC, ICC-ES in the United States, and technical approvals in Europe. Products vary in complexity. There is typically a balance intended among structural capability, ease of construction, and aesthetic requirements.

5.2.3.7.1 Glued-in Rods

Glued-in or bonded-in rods are used mainly in Europe for reinforcements and for moment-resisting connections in heavy timber structures. The rods are inserted into pre-drilled holes and are subsequently bonded-in with an adhesive. Compressive, tensile, and shear forces can be accommodated, and rigid connections can be achieved. End-grain connections can be established, which allow for the transfer of heavy loads. Several innovative concealed systems have been developed by various manufacturers, mainly in Europe (see Sections 5.1.5.5 and 5.2.3.1). Designers should be cautioned, however, that some large glued-doweled moment connections are particularly susceptible to shrinkage checking. Using mild steel as well as more rods of smaller diameter properly spaced from each other and from the edges generally achieves better ductility (Parida et al., 2013).

5.2.3.7.2 Self-Tapping Screws

Self-tapping screws are one of the most commonly used fasteners for mass timber construction because they are easy to install in a range of mass timber products (CLT, glulam, and SCL). Originally developed in Europe, they have become the proprietary fastener of choice in recently built mass timber buildings in North America. While this has provided many choices for designers of mass timber structures, the lack of standardization prevents these screws from being listed among other fasteners in North American timber design codes.

Self-tapping screws have features that make them distinct from lag screws and wood screws, the conventional threaded fasteners. The following are some of their key distinctive features:

- greater length
- pre-drilling is usually not required
- screw threads that allow the maximum withdrawal resistance to be developed while keeping the torque to install the screw to a minimum
- large screw head diameter (or shape designed) to improve head pull-through capacity in wood side members

Self-tapping screws are inserted either perpendicular to or at an angle to the face of the timber member. Lateral load design capacity of a self-tapping screw connection can be determined either through calculation using mechanics-based models or direct testing of the connection in accordance with recognized test standards. Mechanics-based models developed to date require material properties such as embedment strength, fastener yield strength, and withdrawal strength as an input. Moreover, design checks are also required to ensure that the fastener does not fail in either shear or tension under design load and during fabrication of the connection.

Design information for some self-tapping screws can be found in CCMC's evaluation reports. In the United States, the ICC-ES product evaluation criteria AC 233 (ICC-ES, 2015) has been developed for evaluating alternative dowel-type threaded fasteners, which include self-tapping screws.

In Europe, test standards for dowel-type fasteners such as bolts, dowels, nails, or stakes are also used for evaluating the mechanical properties of self-tapping screws. Due to the current development of self-tapping screws with regard to greater length and diameter and the use of high-strength steel, these test standards do not fully account for the screws' specific properties. CUAP 06.03/08 (EOTA, 2010) provides general requirements for assessing the application of self-tapping screws in timber structures. These requirements have been used in European technical approvals to assess the mechanical properties of self-tapping screws.

As a common practice, Johansen's equations in Eurocode 5 are used to determine the load-carrying capacity of self-tapping screw connections loaded perpendicular to the screw axis. The load-carrying capacity of self-tapping screw connections loaded parallel to the screw axis is determined from European Technical Approvals of the products. Due to different code systems, the design equations/provisions in the European Technical Approvals will need to be calibrated to fit to the Canadian code system.

5.2.4 INPUT DATA FOR ASSEMBLIES

Wood assemblies include typical wood wall panels such as shearwalls, floor and roof diaphragms, and infill walls.

Information on parameters needed to numerically model a structural assembly is provided in Sections 5.2.3.1–5.2.3.4. Testing, numerical modelling of the subcomponents, or engineering mechanics using material properties information provided in CSA O86 (CSA, 2019a) are some possible approaches. When numerical modelling is used to obtain these input parameters, it is critical that the selected model is able to define the properties and behaviour of the wood members and connections, the boundary conditions, and the applied loads on assemblies as accurately as possible. Apart from the principal quantities, such as geometric, materials, and cross-section characteristics, it is also necessary to account for production and assembly imperfection, and environmental and other effects.

5.2.4.1 Evaluation of Wall, Floor, or Roof Assemblies by Testing

The guidance for deciding on the number of assembly types for testing is similar to that given for connections in Section 5.2.3.7. Much of the uncertainty can be addressed by combining numerical analysis with strategically selected test assemblies, either in terms of the configurations tested or the materials used. The latter is important given the relatively large variability in wood properties compared to other engineering materials.

Because the costs of conducting assembly tests can be considerable, the number of assembly specimens tested is often limited. Aside from the guidance noted above, applicable test standards will specify the required minimum number of tests and other considerations. For example, ASTM E2126 (ASTM, 2019) requires that a minimum of two test specimens be included for each shear wall configuration. A minimum of three tests should be included if the strength varies by more than 10% of each other with respect to the lower value of the two tests. While meeting the test standard is important, it is also beneficial to design the testing program work alongside numerical analysis; this includes conducting preliminary numerical analysis to help determine the test configuration that will yield the most insight on the assembly performance.

Building Performance

Prototypes developed to help with decisions on DfMA can also be used to demonstrate performance to support an Alternative Solution. They may also be useful for assessing the effectiveness of construction moisture risk mitigation procedures or how finishing steps can be re-sequenced to facilitate drying after a severe wetting event.

Depending on the nature of applied load on the assemblies, either monotonic, cyclic, or monotonic and cyclic displacement-controlled tests should be performed:

1. Monotonic loading: Specimens should be tested to deformations corresponding to failure. Test specimens should be tested in both directions for assemblies that have significant asymmetric behaviour.
2. Cyclic loading: Specimens should be tested with standardized cyclic displacement schedules, such as those provided in ASTM 2126.

For each test specimen, the load-displacement curve and failure modes should be recorded. The following parameters should be obtained from the test data:

1. ultimate load;
2. ultimate deformation, taken as the deformation at 80% of the ultimate load on the descending portion of the curve;
3. initial stiffness, determined in accordance with Section 5.2.3;

Parameters that need to be determined from test data include:

- ultimate load and deformation
- initial stiffness
- yield load and deformation
- assembly ductility

4. yield deformation, determined in accordance with recognized standards; and
5. ductility, which is the ultimate deformation divided by yield deformation.

For the cyclic test data, values of each parameter can be measured from envelope curves (positive and negative), as illustrated in Figure 18, or from an average envelop curve of the positive and negative envelope curves. If one set of performance parameters (ultimate load, ultimate deformation, initial stiffness, effective yield deformation, and effective ductility) is selected to characterize both envelope curves, the parameters should be determined from the average envelope curve of the positive and negative envelope curves. If parameters of both positive and negative performance need to be determined, they should be calculated and evaluated separately for each loading direction. It is also beneficial to determine the energy dissipation during a cyclic test because this parameter is indicative of performance of a system under seismic loading.

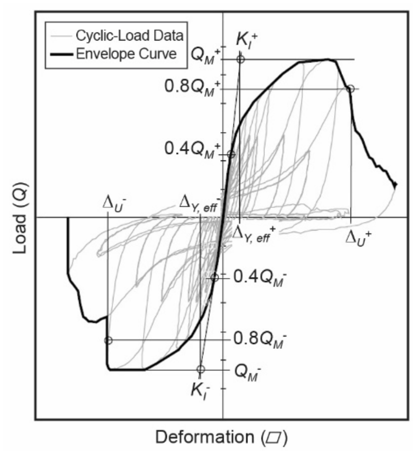


Figure 18. Example of envelope curves of cyclic test data for a wall assemblies (Source: FEMA 795, 2011).

5.2.4.2 Deriving Design Values for Wall, Floor, and Roof Assemblies

Due to limited test specimens, it is difficult to derive the characteristic values of the properties of assemblies. However, the test data can be used to estimate the mean values of the properties. These test-based mean values can be used to verify design values that are derived through modelling or engineering mechanics using material properties information provided in CSA O86 (CSA, 2019a). The design values can also be further verified based on established methods recognized in other jurisdictions. For example, according to ASTM D7989 (ASTM, 2020b), the allowable shear strength for a shear wall in the United States is approximately equal to the average ultimate load-carrying capacity of a tested shear wall divided by a component overstrength factor of α.. The α is given a range between 2.5 and 5.0 to meet the equivalency in seismic performance criteria required in ASTM D7989 (ASTM, 2020b) so that the same seismic modification factors for light-wood-frame construction can be used.

5.2.5 REFERENCES

American National Standards Institute & American Wood Council (ANSI/AWC). (2018). *2018 National design specification (NDS) for wood construction*. Leesburg, VA: American Wood Council.

ASTM International (ASTM). (2012). *ASTM D1761-12: Standard test methods for mechanical fasteners in wood.* West Conshohocken, PA: Author.

ASTM International (ASTM). (2015a). *ASTM D5652: Standard test methods for single-bolt connections in wood and wood-based products.* West Conshohocken, PA: Author.

ASTM International (ASTM). (2015b). *ASTM D6815-09: Standard specification for evaluation of duration of load and creep effects of wood and wood-based products*. West Conshohocken, PA: Author.

ASTM International (ASTM). (2017). ASTM D2915-19: *Standard practice for sampling and data-analysis for structural wood and wood-based products*. West Conshohocken, PA: Author.

ASTM International (ASTM). (2018a). *ASTM D5764-97a: Standard test method for evaluating dowel-bearing strength of wood and wood-based products*. West Conshohocken, PA: Author.

ASTM International (ASTM). (2018b). *ASTM D7147-11: Standard specification for testing and establishing allowable loads of joist hangers*. West Conshohocken, PA: Author.

ASTM International (ASTM). (2019). *ASTM E2126-19: Standard test methods for cyclic (reversed) load test for shear resistance of vertical elements of the lateral force resisting systems for buildings*. West Conshohocken, PA: Author.

ASTM International (ASTM). (2020a). *ASTM D5457-12*: *Standard specification for computing reference resistance of wood-based materials and structural connections for load and resistance factor design*. West Conshohocken, PA: Author.

ASTM International (ASTM). (2020b). *ASTM D7989-20*: *Standard practice for demonstrating equivalent in-plane lateral seismic performance to wood-frame shear walls sheathed with wood structural panels*. West Conshohocken, PA: Author.

Barrett, J. D., Foschi, R. O., & Fox, S. P. (1975). Perpendicular-to-grain strength of Douglas-fir. *Canadian Journal of Civil Engineering*, *2*(1), 50–57.

Bejtka, I., & Blass, H. J. (2005). Self-tapping screws as reinforcements in connections with dowel-type fasteners. *CIB-W18/38-7-4: Proceedings of the International Council for Research and Innovation in Building and Construction. Working Commission W18 – Timber Structures*. Meeting 38. Karlsruhe, Germany.

Bejtka, I., & Blass, H. J. (2006). Self-tapping screws as reinforcements in beam supports*. CIB-W18/39-7-2: Proceedings of the International Council for Research and Innovation in Building and Construction. Working Commission W18 – Timber Structures*. Florence, Italy.

Blass, H.J., & Schmid, M. (2001). Self-tapping screws as reinforcement perpendicular to grain in timber connections. In *RILEM Symposium – Joints in Timber Structures* (S. 163–72). Stuttgart, Germany.

Branco, J., Dietsch, P., & Tannert, T. (Eds.) (2021). *Reinforcement of timber elements in existing structures: State-of-the-art report of the RILEM TC 245-RTE.* New York, NY: Springer.

Canadian Standards Association (CSA). (2001). *CSA O86: Standard practice relating specified strengths of structural members to characteristic structural properties (supplemental document)*. Mississauga, ON: Author.

Canadian Standards Association (CSA). (2019a). *CSA O86: Engineering design in wood.* Mississauga, ON: Author.

Canadian Standards Association (CSA). (2019b). *CSA S16: Design of steel structures*. Mississauga, ON: Author.

Canadian Wood Council (CWC). (2018). *Introduction to wood design*. Ottawa, ON: Author.

Canadian Wood Council (CWC). (2020). *Wood design manual*. Ottawa, ON: Author. https://webstore.cwc.ca/product/wood-design-manual-2020/

Canadian Wood Council & Wood Works (CWC & Wood Works). (n.d.). *Innovating with wood: a case study showcasing four demonstration projects*. Ottawa, ON: Author. https://wood-works.ca/wp-content/uploads/publications-casestudy-Four-demonstration-Case-Study_May_30.pdf

Dietsch, P., Kreuzinger, H., & Winter, S. (2013). Design of shear reinforcement for timber beams. *CIB-W18/46-7-9: Proceedings of the International Council for Research and Innovation in Building and Construction. Working Commission W18 – Timber Structures*. Vancouver, BC.

Dietsch, P., & Brandner, R. (2015). Self-tapping screws and threaded rods as reinforcement for structural timber elements – A state-of-the-art report. *Construction and Building Materials, 97*, 78-89.

European Committee for Standardization (CEN). (2001a). *Standard EN 12512:2001: Timber structures - Test methods - Cyclic testing of joints made with mechanical fasteners*. Brussels, Belgium: Author.

European Committee for Standardization (CEN). (2001b). *Standard prEN 1998-1: Eurocode 8: Design of structures for earthquake resistance - Part -1: General rules, seismic actions and rules for buildings* (Draft No. 4). Brussels, Belgium: Author.

European Committee for Standardization (CEN). (2004). *Standard EN 1995-1-1:2004: Eurocode 5: Design of timber structures – Part 1-1: General – common rules and rules for buildings*. Brussels, Belgium: Author.

European Organisation for Technical Approvals (EOTA). (2010). *CUAP 06.03/08: Common understanding of assessment procedure for European technical approval for self-tapping screws for use in timber construction.* Vienna, Austria: Author.

Federal Emergency Management Agency (FEMA). (2011). *Quantification of building seismic performance factors: component equivalency methodology.* (FEMA P-795). Washington, DC: Author.

Gavric, I. (2012). *Seismic performance of cross-laminated timber buildings.* (Unpublished doctoral dissertation). University of Trieste, Italy.

Gavric, I., Fragiacomo, M., & Ceccotti, A. (2015). Cyclic behavior of typical screwed connections for cross-laminated (CLT) structures. *European Journal of Wood and Wood Products, 73*, 179–191.

International Code Council Evaluation Service (ICC-ES). (2015). *AC233: Acceptance criteria for alternate dowel-type threaded fasteners used in wood*. https://icc-es.org/acceptance-criteria/ac233/

International Organization for Standardization (ISO). (2010). *ISO 21581:2010: Timber structures - Static and cyclic lateral load test methods for shear walls.* Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2014). *ISO 16670:2003 (R2014): Timber structures - Joints made with mechanical fasteners - Quasi-static reversed-cyclic test method.* Geneva, Switzerland: Author.

Karacabeyli, E. (2001). Wood: creep and creep rupture. *Encyclopedia of Materials: Science and Technology* (9616-9620).

Karacabeyli, E., & Ceccotti, A. (1998). *Structural engineering world wide*. (Paper Reference T207-6). SEI-ASCE. Elsevier Science Ltd.

Karacabeyli, E., & Gagnon, S. (Eds.). (2019). *Canadian CLT handbook, 2019 edition*. (Special Publication SP-532E). Pointe-Claire, QC: FPInnovations.

Karsh, E. (2014). Modern timber connections. *Structure*. https://www.structuremag.org/?p=4061

Maurer, B., Maderebner, R., Zingerle, P., Färberböck, I., & Flach, M. (2018). Point-supported flat slabs with CLT panels. In *Proceedings of 2018 World Conference on Timber Engineering (WCTE)*. Seoul, South Korea.

Mestek, P., Kreuzinger, H., & Winter, S. (2011). Design concept for CLT - reinforced with self-tapping screws. In *Proceedings of the 44th Meeting, International Council for Research and Innovation in Building and Construction, Working Commission W18 - Timber Structures, CIB W18* (Paper 44-7-6). Alghero, Italy.

mgb Architecture & Design (mgb), Equilibrium Consulting, LMDG Ltd., and BTY Group. (2012). *The case for tall wood buildings*. https://cwc.ca/wp-content/uploads/publications-Tall-Wood.pdf

Mohammad, M., Quenneville, P., & Salenikovich, A. (2006). Reinforcement of bolted timber connections using self tapping screws. In *Proceedings of the 9th World Conference on Timber Engineering (WCTE)*. Portland, OR.

National Research Council of Canada (NRC). (2020). *National Building Code of Canada (NBC)*. Ottawa, ON: Author. www.nationalcodes.nrc.gc.ca

Parida, G., Johnsson, H., & Fragiacomo, M. (2013). Provisions for ductile behavior of timber-to-steel connections with multiple glued-in rods. *Journal of Structural Engineering, 139*(9),1468-1477.

Porteous, J., & Kermani, A. (2007). *Structural timber design to Eurocode 5.* Oxford, UK: Blackwell Publishing.

Schneider, J. (2015). Conventional and novel timber steel hybrid connections: Testing, performance and assessment. (Unpublished doctoral dissertation). Vancouver, BC: University of British Columbia.

Schneider, J., Stiemer, S. F., Karacabeyli, E., Popovski, M., & Tesfamariam, S. (2014). Damage assessment of connections used in cross laminated timber subject to cyclic loads. *ASCE Journal of Performance of Constructed Facilities (Special Issue: Performance of Timber and Hybrid Structures), 28*(6), A4014008.

Skidmore, Owings & Merrill (SOM). (n.d.). *Timber Tower Research Project*. https://www.som.com/ideas/research/timber_tower_research_project

Smith, I., Aziz, A., Snow, M., & Chui, Y. H. (2006). Possible Canadian/ISO approach to deriving design values from test data. In *Proceedings of the CIB-W18 Meeting* (Paper No. 39-17-1). Florence, Italy.

Thomas, B., & August, J. R. (2015). *Concentrated load introduction in CLT elements perpendicular to plane.*

Weibull, W. (1939). *A statistical theory of the strength of materials.* Stockholm, Sweden: Swedish Royal Institute Engineering Research Proceedings.

CHAPTER 5

SECTION 5.3

Structural Analysis and Design

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ABSTRACT

Section 5.3 provides some of the fundamental background information on advanced analysis and design of structural systems used in tall wood buildings. The information guides the reader to available procedures, methodologies, and steps taken for the analysis of tall wood buildings under gravity, wind, and seismic loads. For gravity structural systems, aspects such as analysis and design approaches, structural integrity, progressive and partial collapse, blast protection, and compatibility of the gravity system for lateral load demand are discussed.

Under analysis and design of structural systems for earthquake loads, force modification factors are discussed, along with procedures for determining and suggesting R-factors for dual and hybrid systems. Also, methods for seismic analysis that are appropriate for the design of tall wood buildings, and the input parameters that are unique to wood structures and are needed for the analyses, such as effective damping, are discussed. In addition, the main design methods such as force-based design, displacement-based design, and performance-based design are presented. The basics of capacity-based design procedures for timber structures and the impact of wood diaphragm flexibility on seismic response are also discussed.

The subsection on analysis and design for wind loads deals with various aspects related to wind design and performance. These include static and dynamic analyses, experimental analyses and testing methods, effects of vortex shedding, and wind-induced vibration-controlled (deflection-controlled and acceleration-controlled) design.

The analysis and design of tall wood buildings require complex and innovative thinking. Designers should review the available literature and the state-of-the-art of analysis, design, and detailing for seismic and wind loading. The analysis of tall wood buildings for seismic loading and detailing for capacity design will require nonlinear analysis in conjunction with dynamic and modal analyses to identify the load-displacement backbone curve of the system, in a global sense, and the load-displacement or moment-curvature demand on the ductile elements, which in the case of timber structures are generally the connections. The appropriate force reduction factor used in the design should be established based on rigorous analysis and experimental testing if the available data and literature do not adequately address the system being considered. In the case of a hybrid system in which the lateral load-resisting ductile elements are steel or reinforced concrete components and the gravity load-resisting elements are wood, the analysis and design for lateral loads should be in line with conventional practices for structures made of the respective materials. In such a case, maintaining displacement compatibility between the wood-based gravity system and the lateral load-resisting elements while the structure undergoes lateral drift requires attention.

The use of timber panels to construct the lateral and gravity load-resisting systems of tall mass timber buildings makes the buildings lightweight and less stiff than buildings made from conventional construction materials. As a result, frequent exposure to wind-induced oscillations could cause discomfort to the buildings' occupants. Hence, depending on the dynamic properties, the analysis and design of tall mass timber buildings for wind loads should be carried out using the provisions of building codes and wind tunnel testing procedures.

The analysis, design, and peer review of a tall wood building should be conducted by experienced and knowledgeable structural engineering teams that are well versed in linear and nonlinear dynamic analyses and capacity-based design principles in timber design.

This updated section aligns with the 2020 National Building Code of Canada (NRC, 2020), the 2019 edition of CSA O86: Engineering Design in Wood (CSA 2019), and the 2019 edition of the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019).

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5.3.1 NATIONAL BUILDING CODE OF CANADA

The National Building Code of Canada (NBC) (NRC, 2020) is an objective-based national model code which, when adopted by provincial and territorial governments, becomes a regulation. The NBC is a model code in the sense that it provides consistency among provincial and territorial building codes. Since the NBC sets out technical provisions for the design and construction of new buildings, the structural and serviceability performance of all newly built tall wood buildings should comply with the NBC and provincial or territorial code requirements.

5.3.1.1 Objectives and Functional Statements

National Building Code requirements are published in objective-based format by establishing requirements to address the main code objectives. The objectives describe, in very broad terms, the overall goals that the NBC's requirements are intended to achieve. They describe undesirable situations and their consequences that the NBC aims to avoid in buildings. The objectives are classified according to four main categories: Safety (OS), Health (OH), Accessibility (OA), and Fire and Structural Protection (OP). The structural and serviceability performance of tall wood buildings should satisfy NBC objectives specified under:

- OS2 – Structural safety;
- OP2 – Structural sufficiency of the building; and
- OH4 – Vibration and deflection limitation.

National Building Code objective-based code requirements are supported by a set of functional statements that are more detailed than the objectives. The functional statements describe conditions in the building that help satisfy the objectives. The functional statements and objectives are interconnected; several functional statements may be related to an objective, and a given functional statement may describe a function of the building that serves to achieve more than one objective. Like objectives, functional statements are entirely qualitative and are not intended to be used on their own in the design and approval process. The structural and serviceability performance of tall wood buildings should satisfy the NBC functional statements under:

- F20 – to support and withstand expected loads and forces;
- F21 – to limit or accommodate dimensional change;
- F22 – to limit movement under expected loads and forces;
- F80 – to resist deterioration resulting from expected service conditions; and
- F82 – to minimize the risk of inadequate performance due to improper maintenance or lack of maintenance.

5.3.1.2 Building Code Compliance

The structural design of tall wood buildings should be compliant with NBC and CSA material standards, as well as with provincial and territorial codes, and municipal bylaws. The NBC allows for the use of encapsulated mass timber construction as an acceptable gravity load-resisting system for buildings up to 12 storeys (NRC 2020). The height limitations for the lateral load-resisting systems are dependent on seismic zones. For example, the cross-laminated timber (CLT) platform-type seismic force-resisting system is an acceptable lateral load-resisting system for buildings up to 30 m in height (typically 10 storeys) in low to moderate seismic hazard zones, and 20 m in high seismic hazard zones (typically 6 storeys). A code comparison of CLT shear walls, mass timber braced frames, and selected concrete and steel seismic force-resisting system is provided in Section 5.1. If the height of the building is within the code limits and the structural system for lateral loads is referenced in the NBC, the Acceptable Solutions path can be used. In all other cases, beyond these limits, the Alternative Solutions approach is required to demonstrate the level of performance required in the code objectives mentioned in Section 5.3.1.1. In other words, by using an Alternative Solution, the designer needs to show (to the authority having jurisdiction) that the objectives, as illustrated by the functional statements, will be met through whatever means the designer is able use and prove while achieving the same or a better level of performance as the Acceptable Solution.

Marketability/Profitability

A hybrid mass timber and non-wood structural system is one approach to building beyond the current NBC height limits for wood and still retains the benefits of mass timber construction (e.g., aesthetics, reduced foundation requirements) in high seismic hazard zones.

Since current design guidelines for tall wood buildings are not directly implemented in CSA O86: Engineering Design in Wood (CSA, 2019a), such buildings can be designed according to Clause 4.3.2 of the standard. The clause states that "New or special systems of design or construction of wood structures or structural elements not already covered by this Standard may be used where such systems are based on analytical and engineering principles and reliable test data, or both, that demonstrate the safety and serviceability of the resulting structure for the purpose intended". More information on the alternative design solutions is provided in Section 5.3.7.

5.3.1.3 Performance Levels

The NBC does not specify exact performance levels for the performance-based design of buildings under various loading conditions. If performance-based design solutions are pursued, the designers should use appropriate performance criteria based on available literature, such as ASCE/SEI 7-16: Minimum Design Loads for Buildings and Other Structures (ASCE, 2016), ASCE 41-17: Seismic Rehabilitation of Existing Buildings (ASCE, 2017), or other building codes, and decide on their appropriateness given the applicable NBC objective and functional statements. The NBC Commentary A provides guidelines that should be used for deriving the strength and stiffness properties of new materials. Clause 6 of Commentary A indicates that the material resistance should be defined based on a 5% exclusion limit (5^{th} percentile of the statistical distribution), and the material stiffness should be defined on the basis of a 50% exclusion limit (mean value). It is recommended that these criteria be used for determining the design resistance of new wood products and connections being specified for tall wood buildings. The NBC, however, specifies objectives and expected performance intents for seismic design that are consistent with the overall objectives of NBC:

1. To protect the life and safety of building occupants and the general public as the building responds to strong ground shaking;
2. To limit building damage during low to moderate levels of ground shaking; and
3. To ensure that post-disaster buildings remain occupied and functional following strong ground shaking, though minimal damage can be expected.

The NBC 2015 Commentary (Section 193) states:

> The damage caused to buildings by earthquake ground motions is a direct consequence of the lateral deflection of the structural system. The ability of a building to withstand such ground motions arises largely from the capability of the structural system to deform without significant loss of load-carrying capacity. NBC Article 4.1.8.13 is concerned with both the determination of lateral deflections and the placement of the limits on those deflections to ensure satisfactory performance.

The NBC then provides explicit guidance for the determination of realistic values of anticipated maximum deflections, including the effects of torsion. The NBC Commentary (Section 196) also states:

> The deflection parameter that best represents the potential for structural and non-structural damage is interstorey deflection, also known as interstorey drift. Lateral deflection at the top of a structure is not a good indicator of damage potential because the various types of SFRSs [seismic force-resisting systems] have different deflection profiles along their heights. Sentence 4.1.8.13.(3) specifies a limit, known as drift limit, on the largest interstorey deflection at any level of the structure. Ordinarily the limit is $0.025h_s$, where h_s is the interstorey height, but for post-disaster buildings and High Importance Buildings, the drift limits are $0.01h_s$ and $0.02h_s$, respectively. An interstorey deflection of $0.025h_s$ defines a state of extensive damage in a building; larger interstorey drifts are in the realm of severe damage and are to be avoided.

The more stringent drift limit of $0.01h_s$ in the NBC for post-disaster buildings reflects the need for facilities such as hospitals, power generation stations, and fire stations to remain operational following an earthquake.

In the NBC, input ground shaking is defined as having a 2% probability of exceedance in 50 years at a mean confidence level, which corresponds to a 0.04% annual probability of exceedance. Although stronger shaking than this could occur, in most situations it is typically economically impractical to design for such rare ground motions; therefore, the 2% in 50-year level may be termed as the maximum earthquake ground motion to be considered, or more simply, the design ground motion. This ground motion should be taken as an input for the seismic analysis and design of tall wood structures. Even though design forces for wind may be greater than seismic design forces for tall wood buildings in some situations (i.e., wind "governs" the design), the design should clearly define the seismic force-resisting system, and detailing that corresponds to the seismic forces calculated for the building should be conducted using the capacity-based design procedures.

5.3.1.4 Pathways for Analysis and Design

The pathways for the analysis and design of tall wood buildings that are included in this guide are summarized in Figure 1.

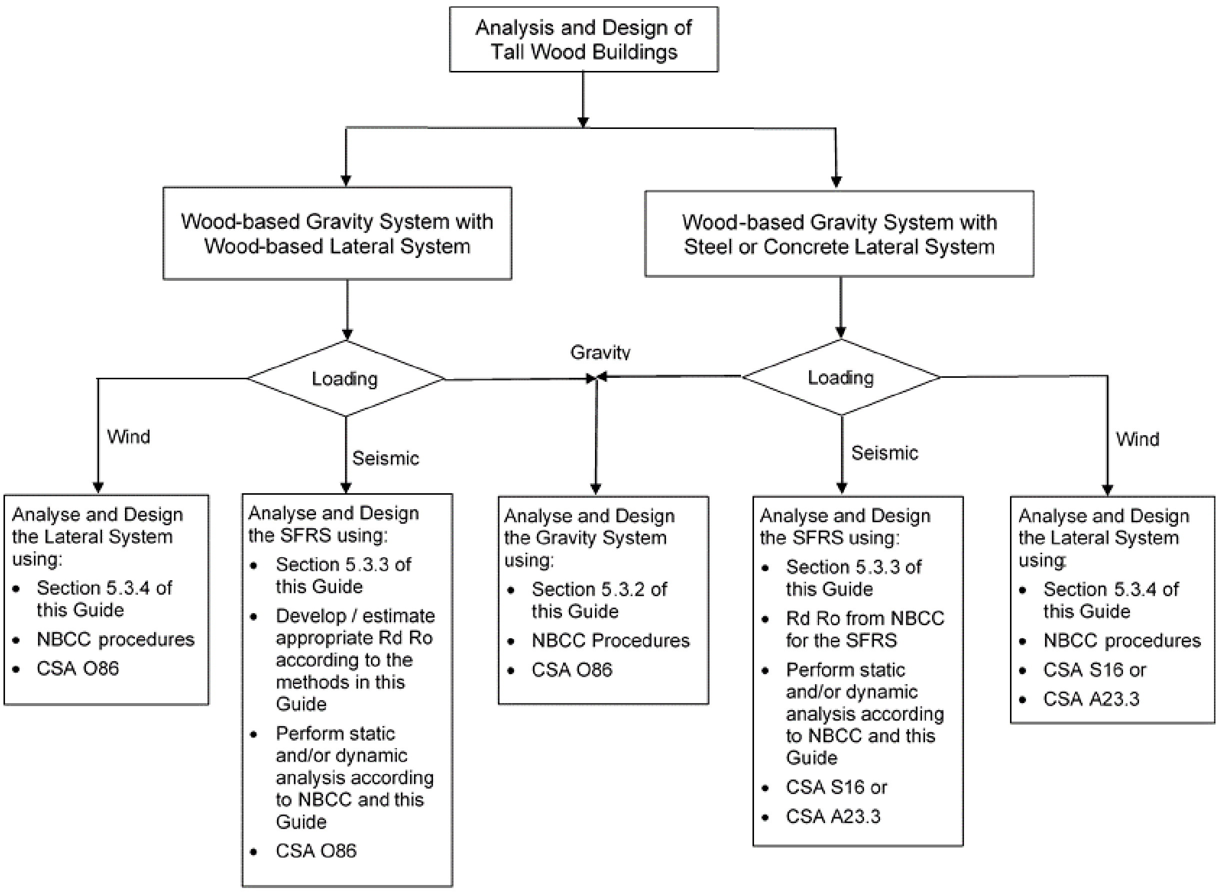


Figure 1. Main pathways for the analysis and design of tall wood structures (SFRS = seismic force-resisting systems).

To further clarify the wood design option, a simplified flowchart for wind analysis and design according to the NBC is provided in Figure 2. The flowchart is a simplification of the one presented in Figure I-1 of Commentary I of the NBC.

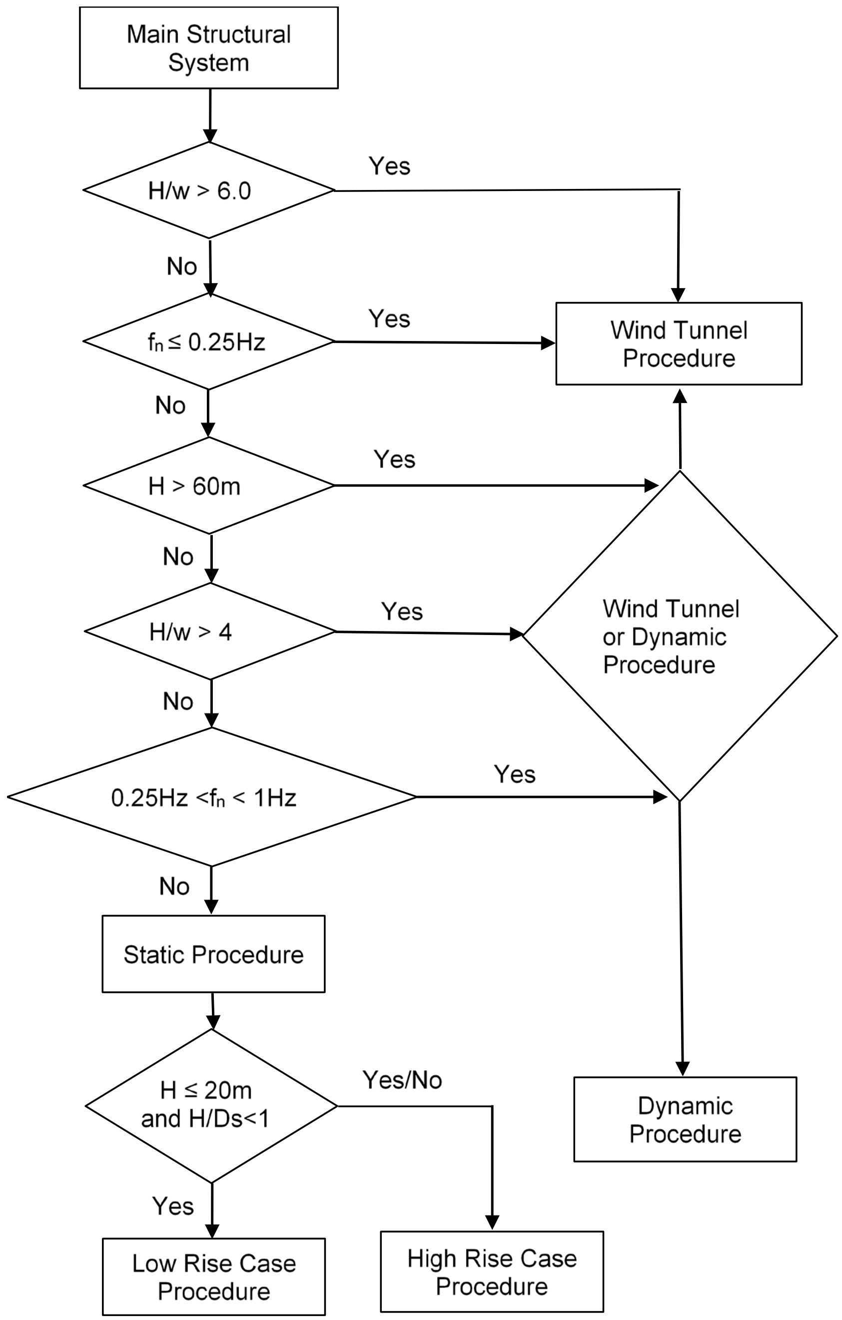


Figure 2. Simplified flowchart for determining wind loads and wind design of buildings.

5.3.2 ANALYSIS AND DESIGN FOR GRAVITY LOADS

5.3.2.1 General Analysis and Design Approach

The general approach for the design of tall wood buildings entails column/wall load takedown for gravity loads, such as dead (including superimposed), live, and snow loads. The load takedown may include live load reduction factors, as indicated in the NBC. Several linear elastic structural analysis programs can be used in the modelling of the system, including beams, columns, wall panels, and floors, to arrive at the design loads for the gravity system. Construction staging analysis should also be considered to ensure the design follows the construction sequencing for loading various support members, including transfer elements. The design of the elements of the gravity system should be conducted according to the requirements in CSA O86 (CSA, 2019). Modelling of the short-term and long-term deformations, where applicable, should be taken into account.

5.3.2.1.1 Wall/Column-to-Foundation Interface

The connection of walls/columns carrying gravity loads to the footings is typically accommodated using steel plates with direct bearing on concrete. The interface bearing stresses on wood (e.g., bearing stresses including eccentricities) and concrete (e.g., punching shear) must be examined for code check. A reasonable eccentricity of the axial load on the wall/column should be considered based on the possible tolerances within the connection detailing. The interface of soil and concrete footing may also be modelled, as area springs, in consultation with the geotechnical consultant, to provide upper and lower bounds of the soil modulus for the subgrade.

5.3.2.1.2 Compatibility of the Gravity System for Lateral Load Demand

It is of paramount importance to ensure that the gravity load-carrying system in tall wood buildings can accommodate the lateral drift associated with the seismic response of the buildings. The building drift may produce secondary forces and moments in the gravity system that must be considered in the design. The larger and stiffer the gravity load-carrying system, the more it will interact with the seismic force-resisting system in a tall wood building. The entire structural system should be designed to sustain the anticipated P-Δ effects. Sprinkler systems should also be designed to accommodate deflections/drift arising from seismic loads and should be functional after the design earthquake to limit the damage of potential post-earthquake fires. Queen’s University conducted cyclic tests on glulam beam-to-column beam hanger connection (Leach, 2018). Although proprietary in nature, these connectors are commonly used in the industry. The objective of the research was to ensure that the connection and gravity system can go “along for the ride” while the seismic force-resisting system undergoes nonlinear deformations.

Regulatory Acceptance

In a tall hybrid mass timber and non-wood structural system, the lateral seismic resistance is provided by steel or concrete (both Acceptable Solutions with much greater height limits than for wood), while mass timber is used as an Acceptable Solution for the gravity system (i.e., columns, walls, and floor slabs).

5.3.2.2 Structural Integrity, Robustness, and Progressive Collapse

This section begins with a general review of design approaches and requirements to improve structural integrity and robustness, and to minimize the occurrence of progressive collapse. These are important concepts for all large and tall buildings.

5.3.2.2.1 General

Buildings are expected to protect human lives and provide shelter throughout their lifetime. To fulfil their protective function, buildings are required to survive both expected and unexpected load scenarios. Established design rules and codes and standards aim to ensure that buildings withstand expected loads during the building's lifetime. Designing for unexpected loads requires a different approach because neither the magnitude nor location of these loads is known. Disproportionate collapse and progressive collapse are frequently used terms related to the nature of the failure mechanism of buildings due to unexpected loads. A disproportionate collapse is a structural collapse in which the initial cause and its subsequent extent are in a disproportionate relationship to each other. Progressive collapse is defined as the spread of an initial local failure from element to element, which eventually results in the collapse of an entire structure or a disproportionately large part of it. Usually, the initial failure spreads like a chain reaction in such types of collapse. The term progressive describes how a collapse develops; the term disproportionate describes how much damage the collapse leads to compared to the initial damage. The two terms are often used interchangeably in the literature.

The cause of the initial local failure can be attributed to abnormal loadings coming from various sources such as unintentional or willful misuse, explosions resulting from the ignition of gas or other liquids, boiler failures, vehicle impact, impact of falling objects, effects of adjacent excavations, gross construction errors, very high winds (such as tornadoes), terrorist activities, sabotage, and other unforeseen extreme events. Generally, such abnormal events would not form part of normal design considerations for the building. Consequently, the building resistance to progressive collapse can be defined as the ability of the structure to accommodate, with only local failure, the notional removal of one or more structural members (e.g., columns, walls) that can be considered damaged during an extreme event.

The NBC currently does not have any criteria directly related to the structural integrity and collapse of buildings. Some material standards have a general design requirement for structural integrity. For example, CSA O86 Clause 4.4.3 states:

> The general arrangement of the structural system and the interconnection of its members shall provide positive resistance to widespread collapse of the system due to local failure.

CSA A23.3: Design of Concrete Structures (CSA, 2019b) provides some requirements for the structural integrity of precast panels. The goal of the design requirements in the NBC and material standards is to ensure that structures have minimum interconnectivity of their elements, and that a complete lateral force-resisting system is present and has sufficient lateral strength to provide stability under both gravity and lateral forces. Conformance with these criteria will provide tall wood buildings with structural integrity for normal service and minor unanticipated events that may reasonably be expected to occur throughout the lifetime of the structure.

Tall wood buildings that house large numbers of people, protect public safety, or have occupancies that may be the subject of intentional sabotage or attack need to be designed with more rigorous protection than that provided in the basic NBC requirements. For such structures, additional precautions should be taken in the design to limit the effects of local collapse and prevent or minimize progressive collapse. Some aspects of these additional precautions are discussed in this section. Throughout this section, requirements from some other national building codes and design guides are used. They include ASCE/SEI 7-16 (ASCE, 2016), the United Kingdom Building Regulations (UKBR Consultancy, 2004), *Practical Guide to Structural Robustness and Disproportionate Collapse in Buildings* in England (IStructE, 2010), EN 1991-1- 7 (2006): Eurocode 1 Actions on Structures – Part 1-7: General Actions – Accidental Actions (CEN, 2006), *Review of International Research on Structural Robustness and Disproportionate Collapse* (Arup, 2011), *Alternate Path Analysis & Design Guidelines for Progressive Collapse* (GSA, 2016), and *Design of Buildings to Resist Progressive Collapse* (U.S. Department of Defense, 2016).

The purpose of this section is to direct the designer's attention to the problem of progressive collapse and present broad guidelines for its handling in different types of structural systems. This guide does not intend to introduce specific events to be considered during the design, or to provide specific design criteria to minimize the risk of progressive collapse.

5.3.2.2.2 Probabilistic Definition of Disproportionate Collapse

Equation [1] can be used to quantify the probability of disproportionate collapse $P[DC]$ in a building (Ellingwood & Dusenberry, 2005). In a structural design context, $P[H_i]$ is the probability of exposure of any load-bearing element to a given abnormal load (H_i). $P[D|H_i]$ is the probability of initial damage (D) given the occurrence of H_i, defined as the vulnerability of the structural element. Structural robustness $P[F|DH_i]$ can be defined as the probability of collapse propagation or further failure (F) given H_i and D. Presenting $P[DC]$ as a function of these three components helps to focus on appropriate strategies for disproportionate collapse prevention: hazard prevention by reducing $P[H_i]$, initial damage prevention by reducing $P[D|H_i]$, and collapse propagation prevention by reducing $P[F|DH_i]$. Consequently, reducing $P[DC]$ may be achieved by reducing these components, assumed as statically independent, either separately or collectively (Mpidi Bita 2019).

$$P[DC] = P[Hi] \cdot P[D|Hi] \cdot P[F|DHi] \qquad [1]$$

Only vulnerability and robustness are structural properties that may be affected by the structural design process. Whether or not the damage can spread is an intrinsic property of any given structure and therefore is independent of any abnormal event.

Comprehensive risk assessments will help identify any foreseeable events and hazards (*Hi*) that may affect the building during its life span. After identifying possible threats, solutions and mitigations that reduce *P[Hi]* may be implemented. These may include changes in building site and access, use of a minimum standoff distance for restricted areas, rigorous control of hazardous substances within the building, and quality control and supervision during analysis, design, component manufacturing, and construction stages. However, it is unpractical to control all abnormal loads in the design process given that their sources cannot always be determined. In addition, unforeseen events (e.g., natural catastrophes) may also affect building safety. Consequently, it becomes unpractical and uneconomical to design the buildings for all abnormal loads. Given these limitations, structural engineering generally focuses on reducing building vulnerability and increasing structural robustness as main focal points in collapse prevention. Reducing vulnerability may be achieved by increasing the resistance of the load-bearing elements to withstand specific abnormal loads. For example, for disproportionate collapse prevention, the key element design approach in CEN (2006) and U.S. Department of Defense (2016) consists of applying at least 34 kPa in horizontal and vertical directions, one direction at a time. Although this direct design approach increases local resistance, hence reduces vulnerability, the overdesign of structural members and connections may lead to uneconomical solutions; therefore, it should be used only as a last resort. The best approach is always to sufficiently increase the robustness of the building.

5.3.2.2.3 Analysis and Quantification of Robustness

In general, the analysis and quantification of robustness may be based on (a) risk analysis, (b) reliability analysis, or (c) deterministic analysis (Čizmar et al., 2011). Risk and reliability analyses are probabilistic approaches and thus take into account probability distributions regarding building exposure or material parameters. Both probabilistic and deterministic analyses may yield measures to quantify robustness. The generic formulations of robustness measures are similar and are based on the insensitivity of the system to a disturbance in a variable. In a deterministic analysis of robustness, the structural response of the building is evaluated against either the assumed initial damage or a specific exposure. The term “notional damage” is used in the literature to indicate hypothetical damage to a structure (Huber et. al., 2019). Notional local damage of the global structure may, for example, be the failure of a single structural element in the building (e.g., the failure of a column). Specific exposures may, for example, include explosion, malicious (terrorist) attack, earthquake, or fire. Analysis approaches that consider notional damage are referred to as scenario-independent, and approaches that consider a specific exposure are referred to as scenario-dependent (Arup, 2011). In a scenario-independent approach, the exposure that caused the initial damage is disregarded in the analysis in order to evaluate the building’s built-in ability to sustain damage of any type. The sudden removal of a load-bearing element is the most accepted method in a scenario-independent approach. IStructE (2010) indicates that the removal of a load-bearing element may refer to a column, wall, or support structure for columns or walls. Elements should be removed one at a time, on each storey, unless it can be shown that element removal in different storeys leads to similar results. In a scenario-dependent analysis, a specific exposure on a building is considered. This analysis may be used to demonstrate structural robustness in specific events, whereas the scenario-independent approach may be used to establish a baseline of robustness (Arup, 2011). The rest of this section focuses on scenario-independent approaches.

5.3.2.2.3.1 Alternative Load Path Analysis

To analyze the structural response of a building to the notional removal of an element, an alternative load path analysis should be performed. The objective of an alternative load path analysis is to assess how loads are absorbed along alternative paths in the structure after the initial damage, and to quantify the extent of collapse progression. In a model of the building, a load-bearing element is notionally removed and the structural consequences are studied. Because the notional removal is carried out suddenly, dynamic load effects should be taken into account (Arup, 2011). Debris loading from falling parts during collapse need to be considered in some cases (Arup, 2011; IStructE, 2010). The extent of the removal is often specified by the nominal length. This length usually does not exceed 2.25 H, where H is the storey height. For an external timber or steel stud wall, the length between vertical lateral supports (e.g., columns or perpendicular walls) should be used (CEN, 2006; IStructE, 2010). The choice of removed elements can be summarized as follows (IStructE, 2010):

- The removed element may be a support column, the nominal length of a load-bearing wall section, or structures supporting these two elements.
- Elements should be removed one at a time, on each storey, unless it can be shown that element removal on different storeys leads to similar results.
- If several columns are located within a diameter of nominal length, they should be removed simultaneously.
- In corners, the length of load-bearing walls removed should be H in each direction, but not less than the distance between expansion or control joints.

It should be noted that there is no clear reason in the literature why 2.25H is used as the maximum removal length for load-bearing walls. Since this value represents an upper limit, it is also unclear how much wall length should be removed. Arup (2011) mentions that the design against the removal of a single column or a nominal length of a load-bearing wall results in sufficient robustness for most buildings, and that these uniform removals could standardize robustness. Detailed guidance regarding loads that should be applied in an alternative load path analysis is provided in GSA (2003) and U.S. Department of Defense (2016). In these documents, the gravity loads for floor areas above the removed column or wall section are generally a combination of dead load and live load (or snow load). In the case of static calculations, the loads are multiplied by a dynamic load factor to account for dynamic load effects.

Five calculation procedures for an alternative load path analysis are recommended in the literature: linear static procedure with a dynamic load factor; gravity nonlinear static procedure with a dynamic load factor; linear dynamic procedure; nonlinear dynamic procedure; and nonlinear static pushover procedure with a simplified dynamic response. More information on the procedures is provided in Arup (2011), Ellingwood et al. (2007), Huber et. al. (2018), and U.S. Department of Defense (2016). Figure 3 shows a model for a pushover analysis of a building subsystem: P is the gravity load, u is the vertical displacement above the removed element, and M is the lumped mass.

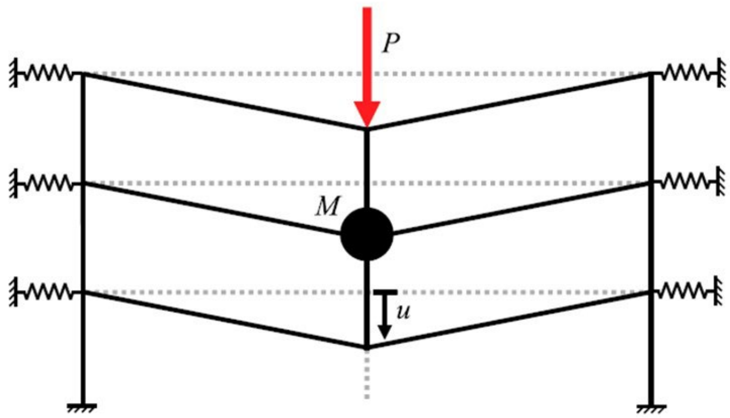


Figure 3. Pushover analysis with load P, lumped mass M, and displacement u (Huber et. al. 2019).

A corresponding load–displacement curve is shown in Figure 4, illustrated by the continuous curve. The examples of pushover curves in Figure 4 are included for (a) small and (b) large gravity loads. The work performed by the static force P_{stat} is represented by the hatched area, while the total strain energy is shown by the grey area under the pushover curve. If we assume that the two areas are equal at maximum displacement, u_{dyn} (and corresponding force P_{dyn}) can be calculated. If a solution for u_{dyn} cannot be found, the energy released after removal of the element cannot be balanced by the strain energy, and collapse will occur (Byfield et al., 2014).

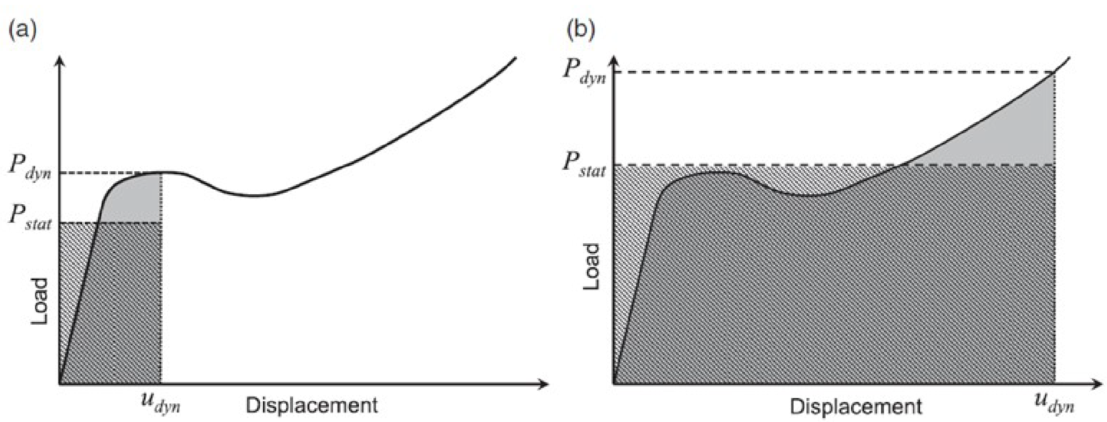


Figure 4. Vertical load–displacement curves with the strain energy (grey) and external work (hatched) for (a) small gravity loads and (b) large gravity loads (Huber et al., 2019).

Usually, the complexity of the five numerical procedures and their conservatism are inversely related. It is recommended that designers start with a less complex numerical procedure and then apply increasingly more complex ones until the result shows that the collapse does not progress. The suggested order is linear static, nonlinear static, linear dynamic, and nonlinear dynamic. If procedures with a lower complexity show that collapse does not progress, the same can be assumed for procedures with a higher complexity (Huber et. al., 2019). The finite element method is the first choice for conducting the structural analyses of notional removal of a column. Softening and element erosion (deletion) during simulation may be modelled in the finite element method by applying adequate failure criteria. The applied element method can also be used for this type of structural analysis. It uses discrete rigid cubic elements, coupled by translational and shear springs which take into account the elastic and plastic deformations, crack initiation and propagation, element separation, and element collision (Kwasniewski et al., 2009). In contrast to the finite element method, the applied element method allows element connections along an entire element face and is not bound to nodes.

5.3.2.2.3.2 Analytical Quantification of Robustness

There are different ways to quantify robustness in a deterministic way. They are based mostly on the consequences of an assumed initial damage in the structure. Some methods for quantifying robustness are based on changes in structural properties, such as stiffness or strength, while others quantify collapse progression using damage or energy.

A simple, binary-valued, damage-based measure for robustness can be obtained by comparing the extent of the resulting damage after an assumed initial damage to a given limit. If the resulting damage is below the limit, the building may be deemed to be structurally robust. If the resulting damage is above the limit, the building may not be called robust, as the damage is disproportionate. Limit values for acceptable damage can be found in other national building codes and design guidelines. They usually specify either the area in square metres or a percentage of the total floor area that may collapse in the storey above or in the storey adjacent to that in which the initial element was removed. For example, Eurocode 1 (CEN, 2006) recommends 100 m^2 or 15% of the floor area, whichever is less, in each of the two adjacent storeys as a maximum limit for the collapse area. Starossek & Haberland (2010) proposed a robustness index (measure), R_d (not to be mixed with the seismic R_d factor), which is based on the total building damage after the initial damage. The authors suggested that the damage be quantified by affected mass, volume, floor area, or cost. In the calculation, the total additional damage after the initial damage, denoted as p, is compared to a given level of acceptable total additional damage, denoted as p_{lim}, as shown in Equation [2]:

$$R_d = 1 - \frac{p}{p_{lim}} \qquad [2]$$

If the additional damage p is equal to zero, then $R_d = 1$. If $p = p_{lim}$, then $R_d = 0$. For larger values of p, the index becomes negative. To account for the progression of total damage and for different extents of initial damage, Starossek & Haberland (2010) provide integral formulations of the robustness measure given in Equation [2]. Same authors have also proposed an energy-based approach to quantifying the robustness of the structure, R_e, as shown in Equation [3]:

$$R_e = 1 - max\frac{E_{r,j}}{E_{f,k}} \qquad [3]$$

where R_e depends on the maximum value of the ratio of the energy release after failure of a structural element j, denoted as $E_{r,j}$, to the energy required for failure of a successively affected element k, denoted as $E_{f,k}$. $E_{r,j}$ includes only the energy released that contributes to the damage in the element k. So, a value of R_e = 1 is obtained for the highest possible robustness, while $0 \leqslant R_e \leqslant 1$ is for structures with some susceptibility to collapse given the initial damage. Finally, $R_e = 0$ is obtained for a certain collapse. This measure may be most adequate if predominantly single elements are affected after local element failure, as in structures that consist of similar elements.

Robustness of a structure can also be obtained using the ratios of the determinants of the stiffness matrices of the damaged and undamaged structure. Furthermore, robustness can be measured using the Reserve Strength Ratio, which is the ratio of the characteristic strength of the system to the load that would lead to the system's collapse. A similar measure of robustness is given by Brett & Lu (2013), who use strength reserve factors that relate the ultimate strength of structural members to their required strength in the structure. Another measure of this kind is the Demand–Capacity Ratio which, for example, is used in U.S. Department of Defense (2016). The Demand–Capacity Ratio is the ratio of resulting actions (internal forces and moments) to the expected strength of structural elements. Finally, robustness can be expressed using the pseudo-static capacity of a system. This is defined as the gravity load above a notionally removed element, for which the resulting dynamic displacement is less than or equal to the system's ductility limit (Izzuddin et al., 2007). This measure uses a ductility-based Demand–Capacity Ratio as opposed to most of the force-based Demand–Capacity Ratios. It quantifies the reserve ductility of the structural system. The more reserves that exist, the more robust the structure is.

5.3.2.2.4 Design for Robustness

A number of design methods can be used to ensure structural robustness in a building. They are generally classified as either direct or indirect design methods. Indirect design methods follow some prescriptive rules that aim to ensure structural robustness and existence of alternative load paths without any explicit calculation of a damage scenario. Direct design methods are based on structural evaluations of damage scenarios, such as an alternative load path analysis. Based on these evaluations, the building is directly designed to survive specific damage, such as notional element removal.

5.3.2.2.4.1 Indirect Methods

Indirect methods are closely related to the use of redundancy in the design and use of continuity by ties. Redundancy exists when a failure of any single critical component does not result in structural collapse. Under some circumstances, redundancy can make a structure more robust. Redundancy may also be linked to the existence of alternative load paths. A redundant structural system is usually statically indeterminate, with several members acting in parallel when loaded (IStructE, 2010). Redundancy may be of an immanent (active) type, where the load is already shared among parallel members at low load levels, or it may be of a passive (fail-safe) type, where the parallel members start to take up loads only after a certain amount of damage has occurred in the system. In a redundant system, a ductile behaviour of connections or assemblies should always be preferred over a brittle behaviour. Overloaded structural connections and elements should tolerate deformation without failure to allow alternative load paths to be engaged in the load sharing. If a connection or element fails in a brittle manner after been overloaded, the remaining elements and connections need to sustain all created overload. If the failure is ductile, however, the remaining connections and elements need only to sustain the additional load above the yield point of the failed element or connection (IStructE, 2010).

In some cases, however, redundancy can have a detrimental effect on structural robustness. If the alternative load paths cannot sustain the resulting loads in the damaged structure, then redundancy may promote collapse progression. The detrimental effects of structural redundancy in two timber hall buildings are discussed in Munch-Andersen & Dietsch (2011). The authors state that a less redundant design would have enhanced the robustness of one of the buildings.

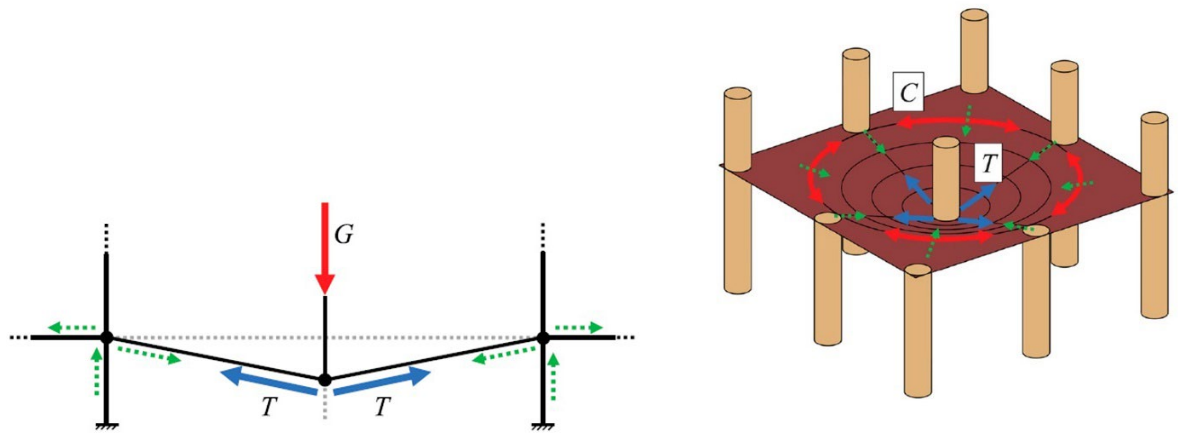
A building's robustness can also be increased by providing structural continuity through the use of horizontal and vertical ties. Ties are links between building components. Their main function is to provide continuous load paths in the structure and limit displacement between the components (ISE 2010). Like redundancy, continuous ties increase the possibility of load transfer in the event of local failure in the structure (Arup, 2011; IStructE, 2010; U.S. Department of Defense, 2016). Designing a building with ties may provide a minimum level of robustness and may therefore be adequate for low-risk buildings. Ties should be continuous along the entire length, width, or height of the building, and their force paths should be straight. Continuous horizontal ties should be designed for each storey along the building's perimeter and internally in the perpendicular directions. All ties should have sufficient anchorage in the walls or other elements (IStructE, 2010). Vertical ties should be continuous from top to bottom and well anchored to the foundation. Vertical continuity should enable floors above failed vertical elements to be suspended from the ties above. For example, vertical tie forces required in Eurocode 1 (CEN, 2006) depend on the building height in the case of framed buildings, and on the wall dimensions in the case of load-bearing wall structures. There is some doubt about whether tying alone is sufficient to ensure that a structure will span over a locally failed region (Arup, 2011; IStructE, 2010). In order to ensure that alternative load paths develop, ductility would also need to be specified, but it is omitted in building codes (IStructE, 2010).

5.3.2.2.4.2 Direct Methods

Direct methods of design for robustness include (a) alternative load path design, (b) compartmentalization, and (c) key element design. This section provides the basics of these approaches. A discussion on their application to tall wood buildings is provided in Section 5.3.2.2.4.3.

The basis for alternative load path design is an alternative load path analysis, where the extent of the collapse and the development of alternative load paths after notional removal of an element can be calculated. Alternative load paths in the structure should be able to bridge local failures. The design may be improved until it matches any given requirement for robustness; e.g., the amount of collapsed floor area specified in some codes. Ductile failure in a structure is preferable over a brittle failure because ductile failure is usually preceded by large deformations. Plastic strain hardening after yielding in materials such as steel may increase the resistance to loads at large deformations and may be beneficial for robustness in wood-hybrid buildings. A structural fuse element (such as connection or other energy dissipator) along an alternative load path can be used to limit the force that may be transferred in these paths, and to keep the force at a specific level. Fuse connections and elements used in the seismic design may also be employed to avoid collapse progression in a building. They may also be used to avoid the transfer of destructive forces between building compartments or to ensure that a building compartment that is failing may safely disconnect at a specified location, which is the basics of the compartmentalization approach.

Some mechanisms that can develop in the structure after a local failure has occurred can prevent the collapse of the entire building. One such mechanism, catenary action, uses the tensile capacity of a beam or floor to distribute the load above the notionally removed element. For the mechanism to develop, the connections need to allow sufficient rotational capacity and deformation, while the beam (or floor) needs to possess sufficient tensile capacity. Formation of this mechanism in a simple multi-bay structural system is shown in Figure 5a, where the gravity load from the removed column is taken by a tensile catenary force in the beam. The effects on the remaining structure are indicated by dotted green arrows (Huber et al., 2019).



(b)

(a)

Figure 5. (a) Catenary action, with a tensile force T and gravity load G; (b) membrane action, with compressive ring forces C and tensile membrane forces T (Huber et al., 2019).

The development of catenary action after element or connection failure depends on the ductility supply in the surrounding connections. As shown in Figure 4, related to the nonlinear static pushover procedure, ductility and deformation capability is a desired property for increasing the capacity of the structure to withstand a suddenly applied load.

Membrane action, which sometimes is also referred to as diaphragm action, is similar to catenary action but acts in the entire diaphragm plane to form a membrane (Figure 5b). Tensile forces develop in the membrane plane toward the centre where the column has been removed. Compression forces develop along the perimeter of the membrane, between the remaining columns. As with catenary action, sufficient tensile capacity in the radial direction and sufficient joint rotation capability are necessary in this case.

Arching action is a mechanism created when the upper parts of two deep beams or floor slabs lock and thus prevent further displacement at the place where the vertical element was removed. The point where these two beams meet at the top forms an arch with their lower connection points (Figure 6).

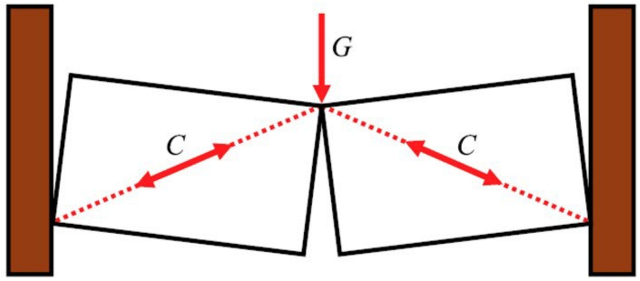


Figure 6. Arching action with a compressive forces C and gravity load G (Huber et al., 2019).

Compartmentalization is a design process that divides the structure into independent structural parts (compartments) which are robust on their own. The compartment borders are then either strengthened to sustain high loads, or their continuity is reduced in order to sustain large deformation and displacements. Structural fuse elements may be used to limit the transferred forces between compartments to a certain extent and thus avoid collapse progression from one compartment to the next. Compartmentalization design may be combined with the design of key elements for effective compartment borders (Starossek, 2006). Compartmentalization may be less applicable to tall buildings, where the avoidance of vertical collapse usually dominates the consideration of robustness. However, the design of intermittent strong floors may be a compartmentalization approach that is suitable for capturing falling debris in tall buildings (Ellingwood et al., 2007).

Alternative load path design and compartmentalization are conflicting design objectives. An alternative load path design may be more suitable for vertically aligned structures (high-rise buildings), whereas compartmentalization may be more suitable for horizontally aligned structures (i.e., bridges, hall buildings). In some structures, an alternative load path design may promote collapse progression instead of supressing and localizing it. Starossek (2006) claims that the partial collapse of the Charles de Gaulle airport terminal in 2004 could have been avoided by using a compartmentalized design, which would have avoided alternative load paths.

Key element design is a scenario-dependent design approach in which certain critical load-bearing elements (or connections) are designed to resist a specific load or exposure scenario (Ellingwood et al., 2007). This method addresses the vulnerability component of Equation [1], not the robustness component. This method is also referred to as "hardening" (Starossek & Haberland, 2010), "the enhanced local resistance method" (U.S. Department of Defense, 2016), or "the increased local resistance method" (Starossek & Haberland, 2010). If a specific exposure scenario (e.g., blast, impact, or fire) governs key element design, the term "specific local resistance method" is also used (Ellingwood et al., 2007).

If the design of key elements is required, codes and guidelines often recommend a specific resistance value for them. For example, Eurocode 1 (CEN, 2006) requires that 34 kPa is applied separately in horizontal and vertical directions when a key element is designed, and that components attached to the key element are loaded to their connection capacity. To avoid unreasonably high loads, IStructE (2010) recommends that 34 kPa be applied on a maximum area of 6 m × 6 m. Key element design should be used as a method of last resort in cases where the building cannot be designed to tolerate element removal by the alternative load path method. If a key element fails, the capacity of the structure will decrease abruptly, which can result in a disproportionate collapse. High-risk buildings may require key element design in addition to other design features to ensure robustness (Arup, 2011).

The design of adequate connection is a key aspect of obtaining structural robustness in tall wood buildings. Connections should be ductile and able to sustain large deformations without failure, mainly to make catenary action possible. The correct assessment of the ductility capacity of a connection is also crucial for an alternative load path analysis. Usually, connections used in seismic design are ductile and can tolerate multiple cycles of load reversal. An exact estimation of connection strength, stiffness, and ductility is needed to avoid brittle failure in tall timber structures. In the absence of test data, full 2D or even 3D modelling of connections may be needed to achieve a rigorous assessment of connection behaviour in specific cases. Dynamic material strain rate affects the behaviour of connections and may need to be considered in the modelling. To reduce model complexity, deformable areas in the connection may be replaced by nonlinear spring elements, which has yielded reliable results in the past (Byfield et al., 2014).

5.3.2.2.4.3 Specifics of Robustness in Timber Buildings

The low density of timber and its high strength-to-weight ratio can be an advantage in terms of structural robustness. Lower weight leads to lower inertial effects and smaller debris loads during collapse. However, timber and most engineered wood products fail in brittle failure modes when loaded in tension, bending, and shear. Compression parallel and perpendicular to grain are usually the only ductile failure modes. Timber-based systems will have to develop catenary action and other redundancy concepts through the plastic deformation capacity in the connections. Connections need to be designed to fail in any of the yielding modes according to CSAO86 that are the result of fastener yielding and wood crushing. Ductility and deformation capacity of the connections may be increased further by reinforcements with self-tapping screws or fibre composites.

In general, seismic design approaches and designs for robustness possess certain similarities. In seismic design, ductility under dynamic cyclic loading is desired for energy dissipation, primarily in the horizontal direction. For timber buildings, earthquake safety has received more attention in the literature than structural robustness. Seismically resistant timber buildings are able to survive unusual load events by providing a high degree of redundancy and ductility, properties that are also desired for robust buildings. Similar to a seismic design, capacity-based design should be used to ensure ductile failure in timber structures and the possibility of load distribution after a local failure. In this design approach, the strength of ductile components in the system (fuses) is less than the capacity of brittle components. More information on this approach is provided in Section 5.3.3.6. The main difference between seismic design and design for robustness is that seismic resistance requires ductility, and thus energy dissipation, mostly along horizontal load paths, whereas robustness requires dissipation mostly along vertical load paths. Seismic design also needs to resist many load reversals, whereas robust buildings may need to resist no load reversals or only a few cycles. Nevertheless, ductile connectors could also be used to dissipate kinetic energy after vertical element removal in a robust timber building.

The knowledge gained from modelling timber buildings in earthquake scenarios could be used for modelling timber buildings in element removal scenarios. Timber elements should be modelled as linear elastic in finite element models, while nonlinear models should be used for connections. The structural system should be analyzed, including the geometrical nonlinearities (large deformations). Sørensen (2011) showed that for redundant timber structures, system reliability decreases if the statistical correlation between elements increases, and vice versa. Thus, if properties of structural elements are highly correlated, a redundant design should be avoided, and compartmentalization may be a preferred option. For large-span timber roof structures, a compartmentalization approach may also be preferable if sufficient alternative load paths cannot be formed (Dietsch, 2011).

Floor slabs that remain intact after element removal may contribute to the load distribution after column removal in post-and-beam construction (Hewson, 2016). In these types of systems, the lateral resistance usually consists of diagonal braces or timber shear walls. Failures in the lateral system, especially during construction, can be a main reason for collapse of these structures (Arup, 2011). Post-tensioned frames, which use tensioned steel cables inside the beams, may be used to increase the tying of members in post-and-beam structures and to enhance the development of catenary action after column removal. The use of post-tensioned frames or walls with energy dissipators can be beneficial for the robustness of the structure. More information on the use of post-tensioned systems as seismic force-resisting systems is provided in Section 5.3.5.2.1.

Building systems based on mass timber panels, such as CLT floor and wall panels, may provide an increased level of redundancy in timber structures. Currently, the most common building element among mass timber panels is CLT. Advantageous properties of CLT regarding robustness are (a) the capability to span in two directions, (b) the capability for walls to act as deep beams, and (c) the potentially high connection capacity between CLT panels (Hewson, 2016). Disadvantages include the inherent brittleness of CLT as a wood-based product and the greater weight of panels compared to lighter timber frames, which may lead to higher dynamic loads and increased debris loads of falling panels. To design a CLT building for robustness, it may be more economical to apply notional element removal instead of attempting to satisfy tie force requirements (Hewson, 2016). Eurocode 1 (CEN, 2006) and the U.S. Department of Defense (2016) also explain that an alternative load path analysis would be the most practical choice for load-bearing wall structures in certain risk categories of buildings. It is generally unclear how to design horizontal ties in CLT buildings (Arup, 2011). To conduct an alternative load path analysis, a length of at least 2.25 H (where H is the storey height) or the length of a wall between joints should be removed (Hewson, 2016).

CLT wall panels in the storey above a removed element can be assumed to act as a deep beam and span over the gap. Deep beam action may be enabled only if the strength capacity in the connections between the CLT walls is sufficient. CLT floors may be assumed to develop membrane action if internal or external load-bearing walls are removed underneath. Membrane action may be possible only if sufficient deformation capacity and strength capacity after deformation exist in the connections between the CLT panels and between the CLT floors and the walls below. Connections loaded in the axial direction need to have sufficient tension capacity, so screws should be preferred fasteners. The location of connections in the CLT panels may play an important role in avoiding buckling of a CLT panel that acts as a deep beam after element removal.

For example, the 9-storey Stadthaus building in London, which is a platform-type CLT residential building, was designed to sustain a notional shock load of 7.5 kPa and the removal of one wall panel or a floor panel by establishing alternative load paths (Wells, 2011). Floors and walls were connected by commonly used brackets and screws, and the floors were designed to span in two directions and act as cantilevers if one support was removed.

Four residential buildings in Milan were designed as 9-storey platform buildings with walls and floors of CLT (Bernasconi, 2016). To satisfy robustness requirements, the loss of entire wall panels was assumed, and alternative load paths were designed for the remaining structure. CLT walls with openings and interruptions required detailed analysis due to the reduction in cross-section and continuity, and a number of connections required reinforcement to meet the requirements.

Mpidi Bita (2019) conducted three-level, structural idealization, finite element analyses to investigate the probability of disproportionate collapse in a 12-storey, platform-type CLT building following a sudden removal of internal and external ground floor load-bearing walls. The following results were obtained:

(a) The static behaviour from slowly removing load-bearing elements was not a sufficient analytical approach. The analysis needed to capture both the dynamic behaviour and the nonlinearities. For the building case analyzed, the forces from the dynamic simulation were approximately 150% higher than those from the static analysis.

(b) The design of buildings under extreme loading situations should account for force reversal in all removal scenarios, and twice the original floor span for internal wall removal. For the latter, the main causes of failure were the applied bending moment and deflection at the location of the removed element.

(c) Optimization showed that CLT panel should be at least 200 mm thick, regardless of the number of plies, with E1 stress grade, to satisfy serviceability and ultimate limit states conditions, as well as disproportionate collapse prevention requirements for quicker element removal.

(d) In the presence of uncertainties in material properties, connection stiffness, and speed of removal, the case study building had a probability of collapse as high as 32% at the component level if it was simply designed to be code compliant without specific consideration of the complexities associated with disproportionate collapse prevention.

Mpidi Bita (2019) also presented an improved tie-force procedure for disproportionate collapse prevention of mass timber buildings with platform-type construction. The procedure is based on linear-elastic principles of engineering mechanics and is best applied to residential and office buildings up to 30 m in height with no structural irregularities. The procedure considers internal, external, and corner load-bearing wall removals at any floor level as worst-case scenarios. It states that the tie-force requirements should consider catenary action of the floors in longitudinal and transverse directions, as well as cantilever action of walls, as separate collapse-resistance mechanisms. The tie-force requirements should also account for the compatibility between the floor panel's deflection and the axial deformation of the connections. This method requires the designer to have data on the deformation capacity of the proposed connection detail. While it was found that additional considerations were needed for the floor-to-floor joints given the axial demands for catenary action, the deformation demands for cantilever action were adequately supplied by conventional detailing. However, additional consideration should be given to the strength demands because tie forces were up to three times higher than the seismic demands, especially in low to moderate seismic hazard zones. In cases where conventional connection detailing becomes uneconomical and unpractical, the study suggests a novel detail that uses cantilever action.

Currently, there is no research and design information on the robustness of timber buildings made of modules. However, research on light steel modular construction indicates that connected volumetric modules can bridge over removed modules, and that the necessary tying forces after element removal are lower than those required by the tie force method (Lawson et al., 2008). A high degree of prefabrication could be advantageous for robustness because automation and industrial quality control may reduce manufacturing tolerances and the probability of human error, at least concerning the finished modules.

5.3.2.2.5 Blast Design Considerations for Timber Structures

5.3.2.2.5.1 Overview of the CSA S850 Canadian Blast Standard

While the design of structural timber members under typical loads (e.g., dead, live, snow loads) is conducted using specified strengths obtained from CSA O86 (CSA, 2019a), blast design uses the average values of design parameters and increases from the effect of high strain rates. The strain rate (ε) is defined as the strain at failure (ε_f) divided by the time to failure (t_f). This is calculated using the strength increase factor (SIF) and dynamic increase factor (DIF), which can be obtained experimentally (e.g., Lacroix & Doudak, 2015) or by using the values provided in CSA S850: Design and Assessment of Buildings Subjected to Blast Loads (CSA, 2012) (reproduced in Table 1). At the time of development of CSA S850, the research into the behaviour of various wood products was scarce; therefore, the values provided in Table 1 represent the state-of-the-art knowledge at that time (Jacques et al., 2014; Lacroix & Doudak, 2015). Subsequent research has shown that the value of DIF is highly influenced by the lamination quality of the structural elements, especially for engineered wood products (Lacroix & Doudak, 2018; Poulin et al., 2018). See Section 5.3.2.2.5.2 for glulam member design considerations.

Table 1. Strength increase factor (SIF) and dynamic increase factor (DIF) for wood for far field explosions ($Z \geq 1.2$ m / kg$^{1/3}$)*

Wood product type	SIF	DIF	
		Failure mode	
		Flexure	Compression
Visually graded lumber	1.9	1.4	1.4
Machine-graded rated (MSR) lumber	1.5	1.4	1.4
Glulam and engineered wood products	1.2	1.4	1.4
*Reproduced from CSA (2012)			

The general approach for obtaining the dynamic bending strength (M_{r-D}) of a flexural wood member is shown in Equation [4]:

$$M_{r-D} = \phi\ [\mathrm{f_b}(\mathrm{K_D K_H K_{Sb} K_T})] S \cdot \mathrm{K_{Zb}} \cdot K_L \cdot SIF \cdot DIF \qquad [4]$$

where the specified static bending moment capacity is multiplied by the SIF and DIF. A value of unity can be used for the material resistance factor (ϕ) due to the uncertainties and rarity of occurrence of the blast loading (ASCE/SEI 59-11: Blast Protection of Buildings [ASCE, 2011]).

In blast design, it is often desirable to describe the behaviour of the flexural member using what is known as a resistance function, which relates the mid-span displacement of the flexural member to the applied loading. The shape of the resistance function of wood members varies depending on the type of element being designed (e.g., light-frame stud wall, glulam, CLT). In general, wood is considered brittle in flexure, and the resistance function can be described as linear elastic, defined by a maximum resistance R_{max} (Equation [5]) occurring at a given displacement known as the elastic limit (Equation [6]):

$$R_{max} = \frac{\alpha M_{r-D}}{L} \qquad [5]$$

$$x_e = \frac{R_{max}}{K} \qquad [6]$$

where L is the clear span of the wood member, α is a dimensionless coefficient that is a function of the boundary conditions and loading pattern, and K is the stiffness of the flexural member. Values of α and K can be derived, or obtained from the literature (Biggs, 1964).

5.3.2.2.5.2 Design of Glulam Members

An experimental program that investigated the behaviour of generic and proprietary glulam cross-sections showed no significant difference between the static and dynamic resistances of the specimens that failed at a finger joint or away from a finger joint (Lacroix & Doudak, 2018). A DIF of 1.14 on the flexural strength of glulam beams was determined to be statistically significant only in the absence of continuous finger joints for single laminate width beams or closely aligned finger joints for wide beams with side-by-side laminations in the outer tension layer. Similar analyses were conducted for the stiffness and failure strain; the results showed no evidence of a dynamic increase (Lacroix, 2017). These findings were corroborated by Viau (2020), who conducted a study on similar glulam beams. Both studies reported that glulam beams under dynamic loading showed no significant post-peak resistance. Therefore, it is suggested that glulam beams be modelled by a linear elastic resistance function with no post-peak resistance. For the purpose of developing this resistance function, a material factor (ϕ) of unity, duration of load factor (K_D) of 1.25 can be used. All other factors can be determined using the provisions in CSA O86 (CSA, 2019a). The static strength can be expressed according to CSA O86 (CSA, 2019a), as shown in Equation [7]:

$$M_r = \min\{\varphi[f_b(K_D K_H K_{Sb} K_T)] S K_X K_L;\ \varphi[f_b(K_D K_H K_{Sb} K_T)] S K_X K_{Zbg}\} \qquad [7]$$

To obtain the dynamic strength of a glulam beam, Equation [7] is modified by a SIF of 1.2 in accordance with Table 1, and a DIF of 1.14 when no continuous defects are found in the outer tension laminations. Otherwise, a DIF of 1.4 may be used.

5.3.2.2.5.3 Design of CLT Panels

An experimental program that investigated the out-of-plane behaviour of CLT under static and simulated blast loading of 18 panels with different panel thicknesses reported an average DIF of 1.28 for the flexural strength of CLT (Poulin et al., 2018). Early onset of rolling shear failure in some dynamic specimens was also reported. Panels where rolling shear damage was documented following a dynamic test were later tested statically to determine their residual stiffness. The degraded stiffness of the panels varied between 20% and 35% of that observed in their undamaged condition (Viau et al., 2018). The dynamic flexural failure modes were similar to those under static loading with tension-side failure initiation at a defect or finger joint, followed by damage propagation throughout the section (Poulin et al., 2018). No high strain rate effects on the stiffness were observed. These findings were corroborated by Viau & Doudak (2019a), who conducted a study on similar CLT panels. The CLT panels tested by Poulin et al. (2018) had some level of post-peak resistance under dynamic loading. Based on the experimental static and dynamic test results, a maximum ductility ratio of 2.5 was deemed appropriate for CLT panels (Poulin et al., 2018).

Static strength can be expressed according to the wood design standard for the major strength axis (CSA, 2019a), as shown in Equation [8]:

$$M_r = \varphi[f_b(K_D K_H K_{Sb} K_T)]S_{eff} K_X K_{rb} \qquad [8]$$

where S_{eff} is the effective section modulus of the CLT member, and K_{rb} is a calibration factor (0.85 in the major strength axis). To obtain the dynamic strength of a CLT bending member, Equation [8] is modified by a SIF of 1.2 in accordance with Table 1, and a DIF of 1.28. The initial stiffness of the CLT panels under uniformly distributed load is heavily influenced by shear deflections. CSA O86 (CSA, 2019a) provides an equation for determining the deflection of a CLT bending member subjected to a uniformly distributed load, accounting for the effective bending stiffness and in-plane shear rigidity. The stiffness of CLT panels, *K*, can be obtained using Equation [9]:

$$\mathrm{K} = \frac{1}{\frac{5}{384} * \frac{L^3}{(EI)_{eff}} + \frac{1}{8} * \frac{L\kappa}{(GA)_{eff}}} \qquad [9]$$

where L is the clear span, $(EI)_{eff}$ is the effective bending stiffness, κ is the form factor, and $(GA)_{eff}$ is the effective in-plane (planar) shear rigidity.

Based on the resistance curves obtained by Poulin et al. (2018), Viau et al. (2018) proposed a generalized approach for constructing the resistance curve for flexure and rolling shear failures. The flexural behaviour can be described as initially linear elastic, after which the loss of the bottom longitudinal laminates would cause a sudden drop in resistance. For 3-ply specimens, this post-peak behaviour was modelled as a drop-in resistance to a value equal to 20% of the ultimate resistance (Poulin et al., 2018). For 5-ply specimens, the loss of the outermost laminates means that the specimen would behave as a 3-ply specimen.

The world's first blast tests on full-scale structures made of CLT were conducted at the Tyndall Air Force Base in Florida. Tests that varied the blast force, material grade, number of plies, and other factors were conducted by WoodWorks U.S. in collaboration with Karagozian & Case Inc., the University of Maine, and the Air Force Civil Engineer Center. The results showed that mass timber structural systems can effectively resist blast loads in the elastic response range with little noticeable damage (WoodWorks US, 2019).

5.3.2.2.5.4 Design of Timber Connections for Blast Loads

The design of connections in timber assemblies subjected to blast loads is critical to the integrity of the structure because premature connection failure may lead to failure of structural load-bearing elements and progressive collapse. CSA S850 (CSA, 2012) stipulates that timber connections should be designed to fail in a ductile failure mechanism (e.g., bearing failure, yielding), based on a force that is 20% higher than that in the load-bearing member. This design approach is consistent with that of non-energy-dissipative connections, which are put in place to protect the integrity of specific system components. In addition to this, CSA S850 (CSA, 2012) currently stipulates that no SIF and DIF should be applied to the capacity of the connections unless it can be justified with experimental test results. These issues have been discussed in recent studies (e.g., Côté & Doudak, 2019; Viau, 2020; Viau & Doudak, 2019a).

Currently, there is no generalized approach for developing resistance curves for connections. Studies have indicated that light-frame (Viau & Doudak, 2016), CLT (Viau & Doudak, 2019a), and glulam (Viau, 2020) assemblies with realistic connections designed to yield and dissipate energy in a well-controlled failure mechanism were capable of withstanding a greater amount of blast energy prior to failure in the wood member compared to identical assemblies tested with overdesigned connections. The variabilities of both the wood member and energy-dissipative connections must, however, be considered when using this design approach in order to avoid potentially unwanted failure sequence within the assemblies (Jorissen & Fragiacomo, 2011; Viau, 2020).

The choice of appropriate analysis will depend on the type of connections being designed. For timber assemblies with overdesigned connections, which can be defined as having a yield capacity greater than that of the timber member and an initial stiffness that is at least 10 times greater than that of the timber member, single-degree-of-freedom analysis can be used to predict the behaviour of the assembly. Otherwise, more refined analysis methods, such as finite element analysis and two-degree-of-freedom analysis must be used (Viau, 2020; Viau & Doudak, 2019a, 2019b).

5.3.2.2.5.5 Fenestration

Although the use of special, non-frangible glass for fenestration does not directly add structural integrity for the prevention of progressive collapse, it can greatly reduce risk to occupants during exterior blasts. To the extent that non-frangible glass isolates a building's interior from blast shock waves, it can also reduce damage to interior framing elements from exterior blasts (e.g., supported floor slabs could be made to be less likely to fail due to uplift forces).

5.3.2.2.6 Testing to Support Gravity Load Analyses and Design

Where information from the literature is lacking, testing may be conducted for gravity load-carrying elements to identify the axial/buckling strength of the gravity system (e.g., columns/walls). The testing may be conducted full scale, as assembly and multi-bay, multi-storey systems.

When a new gravity system or assembly is used in a tall wood building to support gravity loads, testing (or a combination of testing and analysis, including hybrid simulation [Section 5.3.6.3.3]) should be conducted to determine the main system properties and performance, such as:

- axial/buckling resistance (strength) of the main gravity load-carrying elements (e.g., columns or walls);
- resistance and performance of the connections linking the vertical-to-horizontal elements (e.g., beam-to-column connections);
- deformation compatibility or ability of the gravity system to "ride along" with the lateral load-resisting system when the lateral load-resisting system is subjected to lateral loads, and the ability to sustain the gravity loads at the largest expected lateral drifts;
- susceptibility of the gravity system to compression perpendicular to grain stresses (if applicable);
- susceptibility of the gravity system to duration of load and creep deformation;
- deformation and vertical movement compatibility of the lateral load-resisting system and the gravity system, especially if the lateral load-resisting system is a non-wood-based system; and
- any effects on the system due to shrinkage and swelling.

The testing should be conducted full scale on a connection, element, and assembly level. Full-scale testing on a system level is also desirable, if possible, consisting of at least a two-bay, 2-storey system. When designing the testing program, the inherent variability of the wood and fabrication tolerances should be taken into consideration. It is recommended that testing be conducted at an accredited laboratory and that the component sampling and test plan be developed in consultation with experts who are familiar with the wood products. More information on sampling, testing of connections and assemblies, and the parameters that need to be obtained from testing is included in Section 5.2.

5.3.3 ANALYSIS AND DESIGN FOR EARTHQUAKE LOADS

The seismic forces on a structure depend on several factors, including the type, size, and frequency of the earthquakes, the site geology, and the characteristics of the seismic force-resisting system. The need for immediate post-earthquake use and for minimizing the consequences of failure of the structure will also influence the level of seismic design forces. The most common procedures used for analysis of buildings under seismic loads are presented in this section.

5.3.3.1 Equivalent Static Force Procedure and Seismic Force Modification Factors

The response of a structure to earthquake-induced forces is a dynamic phenomenon; consequently, a realistic assessment of the design forces can be obtained only through a dynamic analysis of building models. Although linear dynamic analysis is a default analysis in the NBC, it is infrequently used in routine designs of timber buildings; the equivalent static force procedure as defined in NBC Section 4.1.8.11 (NRC, 2020) is normally used. In the equivalent static force procedure, the inertial forces are specified as equivalent static forces using empirical formulas. The empirical formulas do not explicitly account for the dynamic characteristics of the structure being analyzed. The formulas were, however, developed to adequately represent the dynamic behaviour of what are called "regular" structures. These regular structures have a reasonably uniform distribution of mass and stiffness, and vibrate predominantly in their fundamental mode in each direction.

Building Performance

Where a lateral load-resisting non-wood system (steel or concrete) is used with a mass timber gravity system, the key design objectives are (1) to ensure the gravity system is able to deflect with the lateral resisting system, and (2) to ensure the wood components only collect and transfer loads to, but not alter the seismic response of, the non-wood system.

Equivalent static force analysis can work well for some tall wood buildings that satisfy the criteria for use of such analysis as stated in NBC Section 4.1.8.7.1 (NRC, 2020). To be applicable, tall timber structures should not have significant coupling of the lateral and torsional modes or the irregularities defined in the NBC. For buildings taller than 60 m and with periods longer than 2 seconds, or in all buildings in which second and higher modes and torsional effects are significant, a dynamic analysis should be used to specify and distribute the seismic design forces.

In some timber structures, due to the lower stiffness of the seismic force-resisting system, the nonstructural elements and components may have a profound effect on the building period, and the influence of nonstructural components may need to be taken into account when determining the building period. According to Section 4.1.8.3 of the NBC (NRC, 2020), if stiffness is imparted on the seismic force-resisting system from elements that are not part of that system, they should be considered when calculating the building period of the structure if the added stiffness reduces the fundamental period of the building by 15%. Elements that are not part of the seismic force-resisting system should also be considered when calculating the irregularity of the structure.

One of the key steps in using the equivalent static force procedure for seismic design of tall wood buildings is the determination of force modification factors (R_d and R_o) for the structural system that will be used. The R_d factor is based on system ductility. The R_o factor, which is related to overstrength, can be calculated using Equation [10] provided in Mitchell et al. (2003):

$$R_o = R_{size} R_{\varphi} R_y R_{sh} R_{mech} \qquad [10]$$

where R_{size} is the overstrength arising from restricted choices for sizes of members and elements, as well as rounding of sizes and dimensions; R_{φ} is a factor accounting for the difference between nominal and factored resistances, equal to $1/\varphi$, where φ is the material resistance factor, as defined in CSA O86 (CSA, 2019a); R_y is the ratio of "actual" yield strength to minimum specified yield strength; R_{sh} is the overstrength due to the development of strain hardening; and R_{mech} is the overstrength arising from mobilizing the full capacity of the structure so that a collapse mechanism is formed.

In the NBC (NRC, 2020), four wood-based seismic force-resisting systems are included in Table 4.1.8: wood-frame shear walls, braced frames, moment-resisting frames, and platform-type CLT shear walls. Each of these systems has its own R-factors and height limits based on its seismic performance and design detailing. In general, the R-factors account for the overstrength and capability of the structure to undergo ductile nonlinear response, which dissipates energy and increases the building period. This allows the structure to be designed for seismic forces smaller than the forces that would be generated if the structure remained elastic, without increasing displacements from the seismic loads. The R-factors for each seismic force-resisting system reflect their seismic performance during past earthquakes, and the ability to undergo nonlinear response with limited loss of strength as the structure goes through several cycles of motion. Most of the current values for the R-factors in the building codes are based on past seismic performances of the structural system and nonlinear time-history dynamic analyses and testing.

If a tall wood building uses an established concrete or steel seismic force-resisting system while the wood system carries only the gravity loads, the seismic force-resisting system should be designed using the R-factors in the NBC and the design guidelines in the applicable CSA material standards (CSA S16: Design of Steel Structures [CSA, 2019c]l and CSA-A23.3 for concrete). In cases where there is a wood-based gravity system with a wood-based seismic force-resisting system, and the seismic force-resisting system used is not included in the NBC, the designer has to decide what R-factors should be used for that system, and provide the necessary research, testing, and analysis to justify their decision to the authority having jurisdiction and any building project peer reviewers. In the case of a wood building being placed on one or more storeys of concrete podium, a two-step procedure similar to the one proposed by Chen & Ni (2020) is recommended.

Currently, there is one procedure for the development of R_d factors for new systems in Canada (CCMC, 2021), and two such procedures in the United States: FEMA P-695 (FEMA, 2009a) and FEMA P-795 (FEMA, 2011). A brief summary of these procedures is provided in the following sections. Designers are cautioned that there is a difference between the R-factors in Canadian and U.S. codes: the U.S. codes generally have higher values for the R-factors for the same systems. R-factors should always be used in the context of the applicable code because they represent more than just the ductility of the system. Also, these factors must be used only in conjunction with the corresponding ground motion design levels. At the time of publishing of this guide, the National Research Council of Canada and the Standing Committee on Earthquake Design are working on updating the methods for determining the NBC R-factors.

5.3.3.1.1 FEMA P-695 Procedure

FEMA P-695 (FEMA, 2009a) contains a procedural methodology for quantifying the inelastic response characteristics and performance of typical structural systems, and the adequacy of the structural system provisions to meet the desired safety margin against collapse. The methodology directly accounts for potential variations in the structural configuration of buildings, variations in ground motion to which these structures may be subjected, and laboratory data on the behavioural characteristics of structural elements. The procedure establishes a consistent and rational method for evaluating building system performance and the response parameters (R, C_d, Ω_0) used in current building codes in the United States. The primary application of the procedure is for the seismic evaluation of new structural systems so that they have an equivalent margin against collapse for the maximum considered earthquake (Figure 7). The drawbacks of the FEMA P-695 procedure are that it is complex, very time-consuming, and therefore very expensive to apply. A large number of nonlinear dynamic analyses are required on a number of different building models with different configurations. In addition, the procedure requires peer panel oversight throughout the process. Consequently, this procedure is typically used to obtain code recognition of a seismic force-resisting system and its variations, as opposed to assessing a seismic force-resisting system for a specific building project.

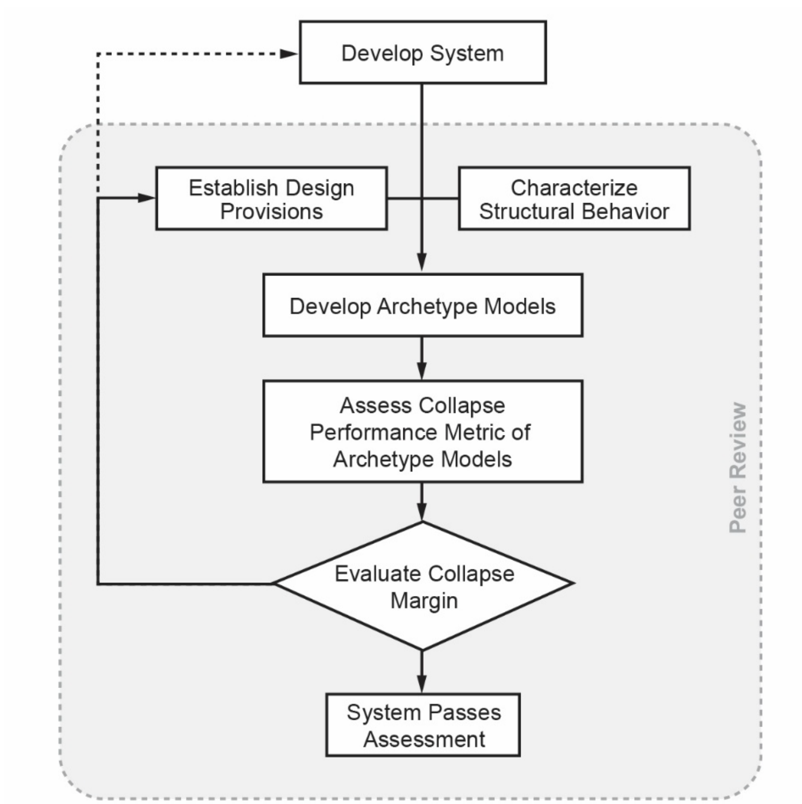


Figure 7. Flowchart of the FEMA P-695 (FEMA, 2009a) methodology for system performance assessment.

5.3.3.1.2 FEMA P-795 Procedure

FEMA P-795 (FEMA, 2011) was developed for evaluating the seismic performance equivalency of structural elements, connections, or assemblies whose inelastic response controls the collapse performance of a seismic force-resisting system. The FEMA P-795 methodology, also referred to as the Component Equivalency Methodology, is a statistically based procedure for developing, evaluating, and comparing test data on new components (proposed components) that are proposed as substitutes for selected components (reference components) in a current code-approved seismic force-resisting system. The Component Equivalency Methodology is derived from the general methodology in FEMA P-695 (FEMA, 2009a) and ensures that code-designed buildings have adequate resistance against earthquake-induced collapse. In the case of component equivalency, this intent implies equivalent safety against collapse when proposed components are substituted for reference components in the reference seismic force-resisting system. The equivalency is established in terms of the component's resistance, ductility capacity, and energy dissipation. Proposed components that are found to be equivalent according to the Component Equivalency Methodology may be substituted for components of the reference seismic force-resisting system, subject to design requirements and seismic design category restrictions on the use of the reference seismic force-resisting system. Reference seismic force-resisting systems include the seismic force-resisting systems contained in ASCE/SEI 7-16 (ASCE, 2016). In general, this methodology may be more applicable (as opposed to P-695 procedure) to a tall wood building project and may be used to introduce any new substituting element in a structural system that is already implemented in the code (Figure 8).

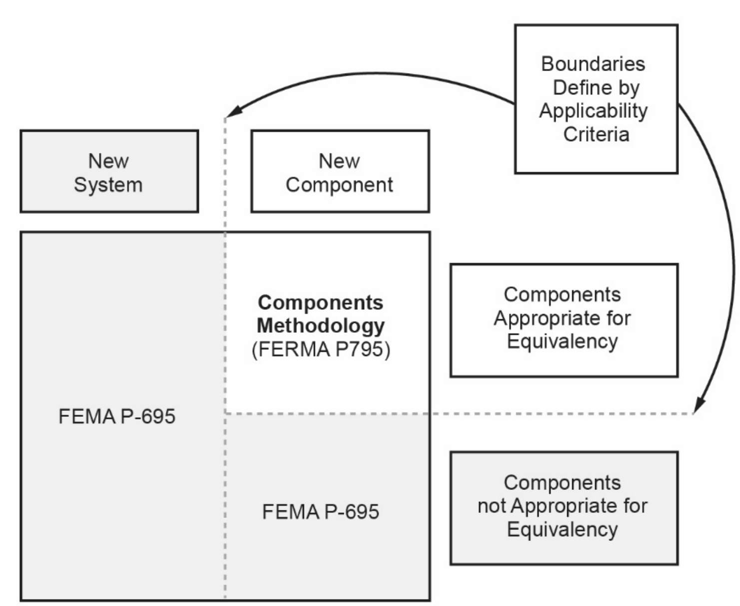


Figure 8. Conceptual boundaries defined by applicability criteria of the Component Equivalency Methodology (FEMA, 2011).

5.3.3.1.3 Canadian Construction Materials Centre Procedure

A panel of Canadian experts and international collaborators have developed the Canadian Construction Materials Centre (CCMC) *Technical Guide for Evaluation of Seismic Force Resisting Systems and Their Force Modification Factors for Use in NBC with Concepts Illustrated Using a Cantilevered Wood CLT Shear Wall Example* (CCMC, 2021). At the time of writing this section, only the first part of the technical guide had been completed, and work had been initiated on an example. The objective of the technical guide is to provide a systematic procedure for evaluating the performance of a seismic force-resisting system and for determining the appropriate ductility-related (Rd) and overstrength-related (Ro) force modification factors of the system for implementation in the NBC. The guide can be considered as a simplified version of the FEMA P-695 procedure on "Quantification of Building Seismic Performance Factors" (FEMA, 2009a). Similar to the FEMA procedure, the CCMC technical guide relies on the application of nonlinear dynamic analysis for quantification of the seismic performance of the seismic force-resisting system. The procedure in that guide is also suitable for assessing force modification factors of systems already implemented in the NBC. In addition, the procedure can be used by a team that is developing an alternative design solution for a specific project and to seek acceptance from the authority having jurisdiction anywhere in Canada.

The CCMC procedure requires the project team to study a wide variety of combined parameters that may affect the seismic performance of a structure, such as the building location and anticipated earthquake intensities, geometry of the building (building height, number of floors, storey height), geometry of the seismic force-resisting system (number of bays and aspect ratio of the system), location and types of the energy-dissipative elements used, and cyclic, nonlinear, inelastic behaviour of those energy-dissipative elements. In other words, this is a large sensitivity study of the parameters that can affect the seismic performance of the seismic force-resisting system and how they affect the performance when the structure is designed using the proposed Rd and Ro values. The procedure requires that the work be guided by an experienced peer review panel from the initial concept stages to the development of the conclusions and recommendations.

Because analytical modelling alone cannot adequately predict the seismic response of a seismic force-resisting system, the CCMC technical guide requires that a comprehensive experimental investigation program be conducted to establish the material properties, determine the structural component properties, calibrate and validate the component models, and calibrate the numerical analyses for a proposed seismic force-resisting system. The combination of experimental and analytical data should be sufficient to achieve the main objectives of the numerical analyses, with a goal of adequately assessing the ductility-related force modification factor (Rd) for the selected system.

Several seismic hazard zones should be chosen as locations for the analyzed structures in order to develop appropriate requirements that are efficient for the target locations of the tall wood buildings. The choice of ground motions for the nonlinear analyses should be made in collaboration with a ground motions expert and the peer review panel. When evaluating and determining Rd values for a suite of archetypes, it is recommended that ground motions for Site Class D are used in the analyses. Since structures designed for high seismic hazard zones (e.g., Vancouver and Victoria) typically perform well in lower seismic hazard zones, the design requirements for lower seismic hazard zones will be governed by those needed for high seismic hazard zones. In such cases, the project team and peer review panel may decide not to use the full set of analyses for locations in low seismic hazard zones. The project team, however, may determine that it is desirable to relax the requirements for lower seismic hazard zones and have a second set of less stringent requirements for those zones. In such cases, the study must be completed in full for sites in lower seismic hazard zones by using the less rigorous requirements.

5.3.3.1.4 R-Factors for Dual and Hybrid Systems

If the seismic force-resisting system consists of two different systems that have different R-factors (dual or hybrid systems), the NBC requires that the dual system be designed with the lower R-factors of the two (NRC, 2020). It is recommended that this approach be used in the case of tall wood buildings with dual or hybrid systems. Because this is a conservative approach, some research has been conducted on using intermediate values for the hybrid system consisting of mid-rise wood-frame shear walls and portal frames (Chen et al*.*, 2014c); however, this method still needs to be proven for other systems and taller buildings. The seismic force-resisting systems made of material other than wood (i.e., steel or concrete) should be designed according to the applicable material standard. If the non-wood seismic force-resisting system is not listed in the NBC, derivation of the R-factors should follow the same procedures as presented in previous sections (5.3.3.1.2, 5.3.3.1.3, and 5.3.3.1.4). Displacement compatibility of the non-wood seismic force-resisting system and the wood-based gravity system should be taken into account in the design. For example, the gravity system should be capable of undergoing the required lateral deformation of the seismic force-resisting system during and after the seismic event without collapse.

5.3.3.2 Response Spectrum or Modal Analysis

Response spectrum analysis, also referred to as modal analysis, is one of several methods recognized in the NBC but is the norm for analyzing the seismic behaviour of tall buildings. Modal analysis calculates the linear response of a multi-degree-of-freedom structure under earthquake motion as a superposition of the responses of individual natural modes of vibration (mode shapes) with their own frequency and modal damping. In the NBC, the modal forces and their distribution along the height of the structure are emphasized to highlight the similarity to the equivalent static force procedure traditionally used in the code. This correlation helps clarify the fact that the simplified modal analysis is simply an attempt to specify the equivalent lateral forces on a structure in a way that directly reflects the individual dynamic characteristics of the structure. Once the storey shears and other response variables for each of the predominant modes are determined and combined to produce design values, the values are then used in basically the same manner as the equivalent lateral forces.

For wood buildings of a moderate height, three to five modes of vibration in each direction may be sufficient to determine the earthquake response and design forces, but for tall wood structures, more than five modes will likely need to be considered. The NBC requires that the combined participating mass of all modes considered in the analysis should be equal to or greater than 90% of the effective total mass in each of the two orthogonal horizontal directions as well as in the torsional direction of the building (NRC, 2020). In the case of podium construction, the mass and stiffness of wood superstructure can be relatively low compared to those of podiums constructed with concrete or steel. It is possible that the podium mass will not appear to contribute to the total effective mass until a large number of modes is considered. In other words, 90% mass participation might be difficult and unpractical to achieve. Further investigation would be required to determine the approach for properly analyzing podium construction. One option may be to use a two-stage approach, where the upper part of the building is analyzed separately from the podium. Such approach is adopted in ASCE/SEI 7-16 (ASCE, 2016), which has explicit clauses on when the designer can and cannot use a two-stage analysis.

Modal periods should be associated with moderately large but still essentially linear structural response, and should include only those elements that are effective at those amplitudes. Such periods are usually longer than those obtained from ambient vibration tests on completed structures because the latter include the stiffening effects of nonstructural and architectural components of the structure at small amplitudes. A wide variety of methods for calculating natural periods of linear models and associated mode shapes exist. Therefore, no particular method or software is suggested here. It is essential, however, that the software uses one of the generally accepted principles of linear dynamics, such as those provided in well-known textbooks on structural dynamics and vibrations (Chopra, 2017; Clough & Penzien, 1993; Newmark & Rosenblueth, 1971), and that the software's accuracy and reliability are well documented and widely recognized. Effects of the nonstructural components should be taken into consideration when determining the periods. It should be noted that design values determined by a modal combination rule are not in equilibrium. It implies that, for example, storey shears cannot be used to calculate roof or inter-storey drift ratios.

5.3.3.3 Nonlinear Static Analysis Procedures

The use of nonlinear static analysis procedures, also commonly referred to as pushover analyses, is becoming a common engineering practice in seismic performance assessment and design of buildings. Although seismic demands are best estimated using nonlinear time-history analysis, which accounts for mass inertia and damping forces, nonlinear static analysis procedures are frequently used in ordinary engineering applications to avoid the intrinsic complexity and additional computational effort required by the former. Nonlinear static analysis procedures are based on monotonically increasing lateral loads of a predefined load pattern that is applied in increments to a nonlinear model of the building. The strength and stiffness properties of every structural component are updated after each lateral load increment to account for the reduced resistance of yielding components. This process is continued until the structure becomes unstable or a predetermined target displacement is reached. Because nonlinear behaviour is considered, R-factors are not needed.

The primary objective of these analyses is to estimate the global lateral strength, displacement, ductility, and failure mechanism of the structure under lateral forces. Some nonlinear static analysis procedures are based on the idea that the nonlinear pushover curve obtained for the entire structure can be idealized as obtained from a single-degree-of-freedom nonlinear system. In other words, an equivalent single-degree-of-freedom system can be developed to capture the actual global behaviour of the detailed multi-storey structural model (Naeim, 2008). In all cases, the obtained behaviour of the building (e.g., the base shear versus roof displacement curve) is independent of any specific seismic shaking demand.

Most nonlinear static analysis procedures assume that the shape of the lateral loading is equivalent to the first mode response of the building. When modes higher than the first mode are expected to contribute to the response, these simplified procedures may not be appropriate for predicting inelastic seismic demands (Goel & Chopra, 2004; Gupta & Kunnath, 2000). To overcome some of these drawbacks, a number of enhanced procedures that consider different loading vectors (derived from mode shapes) have been proposed (Kalkan & Kunath, 2006). These procedures attempt to account for higher mode effects and use elastic modal combination rules.

For tall wood buildings, designers should use the nonlinear static analysis procedure methods in ATC-40: Seismic Evaluation and Retrofit of Concrete Buildings (ATC, 1996) or ASCE 41 (ASCE, 2017). The nonlinear static analysis procedure used in ATC-40 is based on the "capacity spectrum method". In this method, the capacity (pushover curve) is generated by subjecting the detailed nonlinear structural model of the building to the first-mode inertia vector of lateral forces. The load deflection curve (base shear versus roof displacement) is then converted to a "capacity spectrum curve" in the spectral acceleration versus spectral displacement domain using relationships given in the document. The seismic hazard is represented by a 5% damped acceleration response spectrum, which is reduced using expressions prescribed in ATC-40 based on the effective damping ratio of an equivalent linear system. This spectrum is usually referred to as the "demand spectrum" and is plotted on the same graph as the capacity spectrum to find their intersection point, which corresponds to a condition for which the seismic capacity is equal to the demand imposed on the structure. This point is called the "performance point", which is an estimate of the actual maximum displacement expected during an anticipated earthquake. For a design that uses the seismic hazard spectrum, this point can be treated as the target displacement of a pushover analysis. System degradation should not occur prior to this point. The capacity spectrum method determines the performance point iteratively by adjusting the effective damping ratio. The individual structural components are then checked against the acceptable limits, which depend on global performance goals, observations from tests, and collective judgment of the design team. The design of Resilient Slip Friction Joints described in Section 5.3.5.2.2 is based on the capacity spectrum method.

The nonlinear static analysis procedure method provided in ASCE-41 is based on a modified version of the displacement coefficient method that was first introduced in FEMA 273 (FEMA, 1997) and was later improved in FEMA 356 (FEMA, 2000) and FEMA 440 (FEMA, 2005). An inelastic model that directly incorporates the nonlinear load-deformation behaviour of the individual components of the building is subjected to a monotonically increasing lateral load pattern that is representative of inertial forces developed during an earthquake until a target displacement is achieved at the control node (usually the roof). This target displacement is intended to represent the maximum displacement likely to be experienced during the design earthquake.

5.3.3.4 Nonlinear Dynamic Analysis

Although nonlinear time-history analysis is usually used for special and complex structures, it can be used for the design and quantification of the seismic response of tall wood buildings. The method of analysis is similar to the linear response history analysis described in subsection 5.3.3.2, except that the numerical models of the structural components are nonlinear. The models are formulated in such a way that the stiffness, strength, and even connectivity of the elements is directly modified based on the deformation state of the structure. This permits the effects of element or connection yielding and other nonlinear behaviour of structural response to be directly accounted for in the analysis. It also permits the evaluation of other nonlinear behaviour, such as foundation rocking, opening and closing of gaps, and nonlinear viscous and hysteric damping. This ability to directly account for these various nonlinearities allows nonlinear response history analysis to provide a relatively accurate evaluation of the response of the structure when subjected to strong ground motion, provided the model is developed correctly. The nonlinear behaviour is considered without using the R-factors as needed in the linear dynamic analysis.

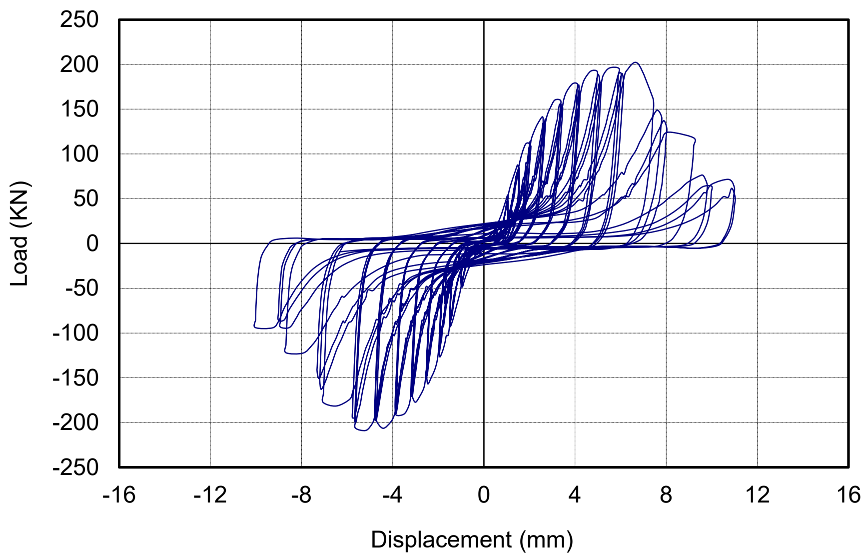


Figure 9. Typical hysteresis behaviour of a timber connection or assembly.

In timber structures, the connections are usually the main providers of nonlinearity in the system. Adequate nonlinear models that properly represent the nonlinear performance of the connections or assemblies should be chosen. The models should adequately account for the strength, stiffness, and ductility of the modelled connection/component in both the initial (virgin) cycle and all subsequent cycles (Figure 9). This includes the strength and stiffness degradation as well as the hysteretic properties of the modelled connection/component. The models should be verified against test data.

When nonlinear response history analysis is used in the design process, one or more suites of earthquake ground motions have to be considered, as per the guidelines in the Appendix to Commentary J of the NBC (NRC, 2020). For the selection and scaling of ground motions, a period range should be considered. It should cover the periods of the vibration modes that significantly contribute to the dynamic response of the building. Input earthquake motions for a site should be provided by a geotechnical consultant based on the area's seismicity and soil profile. The Department of Civil Engineering at the University of British Columbia has developed a set of input earthquake records for various seismic hazards in the Lower Mainland of B.C. that are applicable to soil site class C. It would also be appropriate to perform sensitivity studies, in which the assumed hysteretic properties of elements vary within expected bounds, to evaluate the effects of such uncertainties on predicted responses.

Because relatively minor changes to the assumptions used in performing a nonlinear structural analysis can significantly affect the results, designs and the models should be subjected to independent design peer review to provide a level of assurance that the designer's judgment is appropriate and compatible with that of other competent practitioners.

The input properties needed to develop the numerical model of a structure in order to perform static and dynamic analyses are discussed in Section 5.2. The relevant parameters for solving the equation of motion during a nonlinear dynamic analysis are as follows:

1. Element properties

   Elements in tall timber buildings usually consist of engineered wood products that are used as beam/column elements, structural wall panels, or a combination thereof. In hybrid buildings, some steel, concrete, or even masonry elements may be present. Depending on the hybrid structural system used, some of the steel or concrete elements may be designed to yield, while others are typically capacity protected and should remain elastic. For analysis and modelling purposes, the elements can be elastic with the appropriate stiffness to save computation effort and time but should be checked during post processing to ensure that the capacity design principle is properly implemented. For wood elements, stiffness can be determined by reviewing test/analytical data in the literature (including data from engineered wood products producers and proprietary connection developers) or may be obtained by carrying out additional experimental tests on representative samples for specific applications (see Section 5.2).

2. Mass distribution

   In a nonlinear dynamic analysis, the distribution of mass is as important as the magnitude of mass. The spatial distribution in plan and elevation affects not only torsional behaviour but also the response to ground vertical excitation. It is typical to place mass on the floor elements or the nodes of a numerical model. It is important to understand how the software deals with the mass distribution, for example, when the diaphragm is defined as perfectly rigid.

3. Effective damping

   Effective viscous damping in timber buildings is usually similar to that in steel and concrete buildings. In numerical models of wood structures, effective damping can be assumed to be in the range of 3–5% unless there is justification to use higher values based on experimental or field data. Rayleigh damping is typically used. Proper modes should be selected when calculating Rayleigh damping coefficients to avoid overdamping in the higher modes. The effect of hysteresis damping should be explicitly included in nonlinear models. No viscous damping should be assigned to members that contain friction devices.

4. Hysteresis and backbone models for connections and assemblies

The nonlinear load-deformation relationships (backbone and hysteresis curves) (Figure 9) for the yielding parts of the seismic force-resisting system (connections and assembles) should be obtained when nonlinear dynamic analysis is conducted. This includes initial and post-yielding stiffness, yielding and ultimate strength, and cyclic strength and stiffness behaviour/degradation. Lower bound, upper bound, and best estimate of the strength and stiffness properties should be determined for sensitivity analysis. If information from the literature is lacking for a specific geometry and application, tests should be conducted on representative samples that will be used by accredited laboratories to establish the hysteresis/backbone curves suitable for the analysis. See Section 5.2 for additional information.

5. Soil properties and soil–structure interaction

   Due to its relatively light weight, wood may be the preferred building material for areas with poor soil conditions. For tall buildings, the interaction between the soil and building foundation could affect the building's overall performance, and the soil–structure interaction should be modelled accordingly when developing the nonlinear building models. Usually, the soil properties are modelled using a series of horizontal and vertical springs. There are well-established procedures for determining the properties of vertical and horizontal soil springs. The geotechnical consultant should provide suitable properties of the soil springs for the prescribed geometry of the foundation and soil conditions at the base of the footings. The spring properties of both upper and lower bounds should be used to bound the response of the building in force and displacement demands.

5.3.3.5 Methods of Seismic Design

Designers can use several different types of seismic design for tall wood buildings. Some of them are more mainstream; others are used only by experts in this field. This section provides a brief explanation of the basics of different seismic designs.

5.3.3.5.1 Force-Based Design

Earthquake motions induce predominantly lateral (horizontal) accelerations and displacements on the structure that create lateral earthquake forces due to mass inertia. Traditionally, seismic structural design has been based primarily on forces. The reasons for this are largely historical and related to how we design for other actions, such as dead and live load (Priestley et al., 2007). In such cases, it is known that force considerations are critical: if the strength of the designed structure does not exceed the applied loads, then failure will occur. Consequently, seismic design provisions included in the NBC and many other building codes in the world currently use a force-based seismic design approach. In a force-based design approach, the seismic design forces are determined using either linear response spectrum dynamic analysis or equivalent static force procedures, while displacements are checked later in the design process. Force-based design procedures may be used for the design of tall wood buildings if they fulfill the NBC's (NRC, 2020) requirements for such procedures.

For example, the equivalent static force procedure for wood structures includes the following steps:

1. Estimate the seismic mass of the structure, as defined by the NBC.
2. Estimate the natural period of the structure based on the code formula or other established methods of mechanics, with the upper limit as specified by the NBC. This step requires special considerations for wood and tall wood buildings, as discussed below.
3. Calculate the elastic base shear on the structure based on the spectral acceleration at the site of the building.
4. Select the ductility- and overstrength-related force modification factors R_d and R_o based on the chosen seismic force-resisting system.
5. Obtain the design base shear by dividing the elastic base shear by the R-factors. If the period of the building is determined by the mechanics-based approach or other means, and the selected structural system is susceptible to the development of soft-storey failure mechanism, the designer may increase the design base shear by 20%, as per the NBC.
6. Distribute the design base shear along the height of the building, as specified by the NBC, with a portion of the base shear (F_t) applied at the top of the building if the building period exceeds 0.7s, as per the NBC.
7. Analyze the structure under the seismic design forces.
8. Design the connections that act as the energy dissipation or yielding components.
9. Apply the capacity design principle to the connections and members that do not yield.
10. Calculate the lateral deflections of the building and compare them to the code limits. If the deflections are larger than the limits, iterate Steps 8 to 10. If no feasible structural solution can be obtained, the design should be revised by restarting from Step 1.
11. Check the structural period against that from Step 2 to ensure they are comparable, or the design should be revised.

If a dynamic analysis procedure is used, the period from Step 2 will be calculated based on the developed analytical model of the structure, as will the distribution of forces along the height of the building. The force-based seismic design approach is relatively simple to use. As a result, the method has been widely used over the past decades and remains the cornerstone of seismic design requirements in current editions of design codes. The main shortcomings of the force-based design are as follows:

- The determination of the seismic design force starts with an estimated structural period. This can be done by using the code formula or numerical models with assumed member/wall/connection sizes and stiffness. In either case, iterations are required to ensure the lateral deflection limits are satisfied and to confirm the period. While this iterative procedure is not always conducted for low-rise buildings, it is important that it be conducted for tall buildings.

- Inherently in the force-based design, structural period is generally related to member stiffness, but member stiffness is treated as independent of its capacity, which is not always true.

- The force-based design process is initiated with an estimate of the elastic fundamental period of the structure. The empirical period equations provided by design codes are not customized for wood buildings. In fact, the whole notion of elastic period is questionable since most wood buildings exhibit nonlinear response over the entire range of lateral deformations. Due to this phenomenon, most designers find that twice the empirical code period governs. Also because of this consideration, the use of the building period from an ambient vibration test (see Chapter 9) may not be appropriate.

- In the codes, the force modification factors (R-factors) are assigned for only a handful of structural systems. Using a system that is not listed in the code would require significant research into the global system response and ductility. Since the R_d factor is closely related to the ductility of the structure, a proper definition of the displacement ductility for wood buildings is needed. Currently, there is no consensus within the engineering community on the appropriate definition of yield displacement for wood-based lateral load-resisting systems. It is suggested that the Equivalent Energy Elastic Plastic approach provided in ASTM E2126: Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings (ASTM, 2019) be used for determining these values.

- A large portion of the structural and nonstructural damage to wood-frame buildings and tall steel and concrete buildings in the past was attributed to excessive lateral displacements. Consequently, limiting excessive deformations is paramount for proper design of any seismic force-resisting system. Deformation limit states, however, are not directly addressed by force-based design procedures.

- The reduction of the elastic base shear by the R-factors indirectly implies use of the equal displacement rule in the design. This means that the maximum displacement that the structure would undergo if it remained elastic is equal to the maximum displacement of the actual inelastic structure. While this equal displacement approximation is inappropriate for short period structures, it should be valid for tall wood buildings.

5.3.3.5.2 Displacement-Based Design

Displacement-based design procedures have been developed over the past two decades to mitigate deficiencies in the current force-based design, and can be used as an Alternative Solution approach for the seismic design of tall wood buildings. Since deflection and inter-storey drift are key parameters for controlling damage in structures, it is rational to examine a procedure in which displacements are considered at the beginning of the seismic design process. In the force-based design, the building is designed for predetermined seismic forces and then is checked against the allowable lateral displacements. In displacement-based design, the seismic design problem is reduced in order to evaluate the allowable lateral displacements of the building and then determine the required strength of the structure that ensures such displacement performance objectives will be satisfied. Since lateral displacements are directly related to damage to structural and nonstructural components, in displacement-based design, displacement is used as a design criterion that controls this damage and the expected economic losses due to an earthquake. In the literature, eight different displacement-based design methods are mentioned: (a) initial stiffness deformation control approach, (b) initial stiffness iterative proportioning approach, (c) yield point spectra approach, (d) inelastic spectra approach, (e) capacity spectrum approach, (f) Structural Engineers Association of California approach, (g) direct displacement-based design approach, and (h) advanced analytical techniques approach (Sullivan et al., 2003). The most commonly used approaches are the direct displacement-based design approach, the Modal approach, and the N2-displacement-based design approach. While the direct displacement-based design and the Modal approach are used worldwide, the N2-displacement-based design approach is used mainly in Europe. The most comprehensive information on displacement-based design procedures is provided in Priestley et al. (2007), while a comprehensive summary of the procedures used in timber structures is provided in Loss et. al. (2018). Only the direct displacement-based design is discussed in detail in this section.

The direct displacement-based design procedure characterizes the multi-degree-of-freedom structure as a single-degree-of-freedom system (representation) with equivalent elastic lateral stiffness and viscous damping properties that are representative of the global behaviour of the structure at the target peak displacement response (Figure 10d) (Loss et al., 2018). The fundamental philosophy behind the design approach is to design a structure that would achieve, rather than be bounded by, a given performance limit state under a given seismic intensity. This would result in essentially designing uniform-risk structures, which are philosophically compatible with the objectives of design codes. The design procedure is used to determine the strength required at designated plastic hinge locations to achieve the design goals in terms of defined displacements. Then, the procedure must be combined with capacity design procedures to ensure that inelastic dissipative regions (plastic hinges) occur only where intended, and that non-ductile modes of deformation do not develop. These capacity design procedures must be calibrated to the displacement-based design approach and may result in generally less onerous requirements than those for force-based designs, which results in more economical structures.

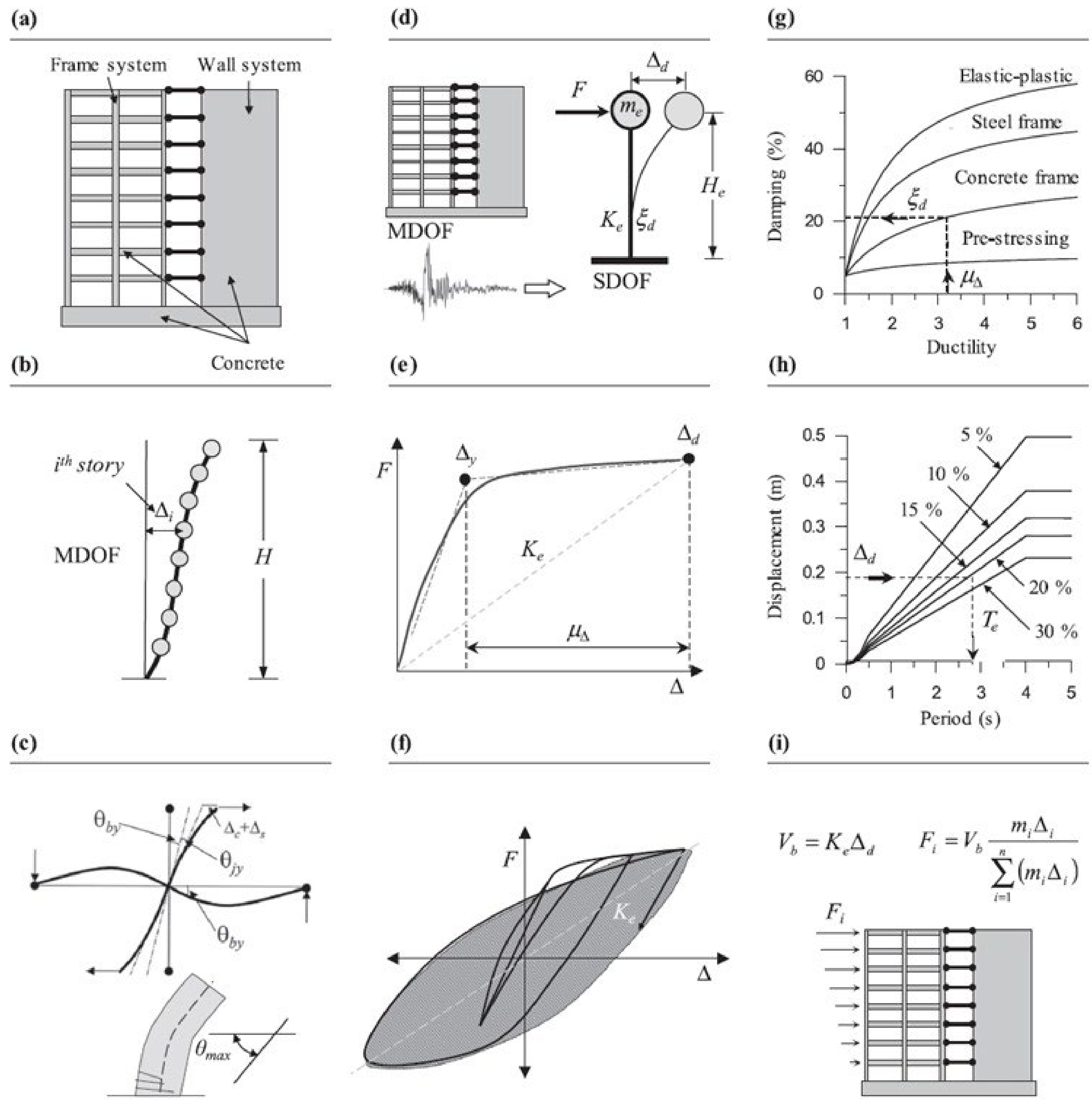


Figure 10. Fundamentals of direct displacement-based design: (a) description of the structural system, (b) displacement shape of the multi-degree-of-freedom system (MDOF), (c) drift and strain limits, (d) single-degree-of-freedom (SDOF) substitute structure, (e) bilinear force-displacement relationship of the SDOF, (f) hysteretic behaviour of the structure, (g) evaluation of damping, (h) evaluation of effective period, and (i) distribution of the seismic design forces along the height (Loss et al., 2018).

The steps of the procedure are summarized in Figure 10 and are described below (Loss et al., 2018). Although the steps are taken from a reinforced concrete example with some slight modifications, they can be used for timber structures.

The first step in the design procedure consists of evaluating the design displacement based on the code drift limits for structural and nonstructural elements, and deformation limits of the most critical members (Figure 10c). For regular buildings, considering the mass to be lumped uniformly at the centre of each storey, the design displacement (Δ_d) of the equivalent single-degree-of-freedom system (Figure 10d) is given by Equation [11]:

$$\Delta_d = \sum_{i=1}^{n} \frac{(m_i \cdot \Delta_i^2)}{(m_i \cdot \Delta_i)} \qquad [11]$$

where m_i and Δ_i are the mass and lateral displacement of the i-th storey, respectively. Depending on the structural system, Δ_d is governed by the drift limit for code compliance, the strain limit of the materials, or the deflections of the connections used. The displacement shape vector, $\{\Delta_i\}$, can be obtained from plotting all displacements Δ_i along the height of the building, and reflects the system's first inelastic mode shape. In cases like tall buildings, where the influence of higher modes is not negligible, Δ_d can be scaled using an empirical reduction factor (ω_θ) to account for the deformation contribution provided by the structural members, as per Priestley et al. (2007) and as shown in Equation [12]:

$$\Delta_{d,\omega} = \omega_\theta \cdot \Delta_d \qquad [12]$$

where $\Delta_{d,\omega}$ is the reduced design displacement. For example, for reinforced concrete-frame systems, ω_θ is determined by Equation [13]:

$$\omega_\theta = 1.15 - 0.0034 \cdot H_n \qquad [13]$$

where H_n is the total height of the building. Equation [13] is valid for a drift less than 1%. For systems that are sensitive to torsion, separate expressions of Equation [13] are provided in Priestley et al. (2007). Since there are no equations for timber buildings, it is suggested that those for steel and concrete buildings be used. The effective mass (m_e) and height (H_e) of the substitute single-degree-of-freedom system are given by Equations [14] and [15], respectively:

$$m_e = \sum_{i=1}^{n} \frac{(m_i \cdot \Delta_i)}{\Delta_d} \qquad [14]$$

$$H_e = \frac{\sum_{i=1}^{n} m_i \cdot \Delta_i \cdot H_i}{\sum_{i=1}^{n} m_i \cdot \Delta_i} \qquad [15]$$

where H_i represents the height from the ground of the i-th storey. The equivalent single-degree-of-freedom response is modelled by assuming a bilinear elastic-plastic force-displacement curve (Figure 10e) that passes through the yield point Δ_y and the design displacement point Δ_d. The dissipated energy is accounted for by equivalent viscous damping, denoted as ξ_d. The equivalent viscous damping represents the dissipation capability of the structure (Figure 10f) and is governed by the hysteretic energy absorbed during inelastic deformation of the components of the system. More specifically, equivalent viscous damping includes an elastic term, ξ_{el}, related to the inherent damping of the structure, such as friction between structural and nonstructural components, and a hysteretic term, ξ_h, which is calibrated considering a single-degree-of-freedom system with an effective stiffness K_e at the design displacement Δ_d. Values for equivalent viscous damping are obtained from nonlinear dynamic analyses or by using empirical models (Figure 10g) expressed as a function of displacement ductility μ_Δ, as shown in Equation [16]:

$$\xi_d = \zeta_{el} + \zeta_h = 0.05 + C \cdot \left(\frac{\mu_\Delta - 1}{\mu_\Delta}\right) \quad [16]$$

where C is an empirical coefficient based on the construction system and material. A procedure to find C values is given by Priestley et al. (2007), based on other studies. Specifically, the hysteretic energy contribution was modelled following Jacobsen's area-based approach and adopting an equivalent damping and reducing that value by a correction factor R_h to account for the random nature of the ground motion induced by an earthquake, in order to maintain consistency with the nonlinear dynamic analysis results. The displacement ductility μ_Δ is determined as the ratio of design to yield displacements ($\mu_\Delta = \Delta_d/\Delta_y$).

To assess Δ_y, empirical equations are provided for construction types with different geometry and materials. For instance, the yield drift of a reinforced concrete frame θ_y can be expressed as a function of the steel bars' yield strain ε_y, the beam span L_b, and the cross-section depth of the beam h_b, according to Equation [17]:

$$\theta_y = 0.05 \cdot \varepsilon_y \cdot L_b/h_b \quad [17]$$

Since the yield displacement depends on the geometry of the system, the development of expressions like that in Equation [17] is relatively straightforward, starting from the yield curvature of the elements and, where relevant, the yield displacement of the connections. Direct displacement-based design adopts the design displacement spectra (see Figure 10h) scaled to the system's damping level to assess the effective period, T_e, of the single-degree-of-freedom system, which is used to evaluate the required effective stiffness K_e, according to Equation [18]:

$$K_e = 4 \cdot \pi^2 \cdot m_e/T^2 \quad [18]$$

Once the single-degree-of-freedom system is characterized, evaluation of the base shear V_b can be computed as shown in Equation [19]:

$$V_b = K_e \cdot \Delta_d \quad [19]$$

Finally, the lateral force F_i applied to the i-th storey on its centre of mass (Figure 10i) is computed as shown in Equation [20]:

$$F_e = \frac{V_b\, m_i\, \Delta_i}{\sum_{i=1}^{n} m_i \cdot \Delta_i} \quad [20]$$

Linear elastic analysis is then used to find the member stresses and design the sections and details.

Comprehensive reading on the *Displacement-Based Seismic Design of Structures* is presented in Priestley et al. (2007). An effort to introduce the procedure into the seismic design of wood-frame structures is provided in Filiatrault & Folz (2002) and Newcombe (2010). The basic steps of the procedure are as follows:

1. Definition of target displacement and seismic hazard: The first step in the design procedure is to define the target displacement that the building should not exceed under a given seismic hazard level. The seismic hazard associated with the target displacement must then be defined in terms of a design-relative displacement response spectrum that is obtained from the acceleration spectrum.

2. Selection of structural system: Once the design performance level and associated seismic hazard have been defined, the main wood-based lateral load-resisting system must be specified.

3. Determination of equivalent viscous damping, ξ_d: To capture the energy dissipation characteristics of the structure at the target displacement, an equivalent viscous damping ratio must be determined. For this purpose, a database of damping values must be established for the selected structural system, based on its hysteretic behaviour obtained from testing. The equivalent damping should account for the energy dissipation characteristic of structural and nonstructural elements in the building. For tall wood structures, damping contribution from nonstructural components, taken as 2% of the critical, is expected to yield reasonable results.

4. Determination of the equivalent elastic period, T_e: If the target displacement is known, as well as the equivalent viscous damping of the building at that target displacement, the equivalent elastic period of the building T_e may be obtained directly from the design displacement response spectrum (Step 1).

5. Determination of the required equivalent lateral stiffness, K_e: By representing the building as an equivalent linear single-degree-of-freedom system, the required equivalent lateral stiffness may be calculated based on the period, effective seismic weight acting on the building, and acceleration of gravity.

6. Determination of actual equivalent lateral stiffness, K_e: The actual equivalent lateral stiffness of the building at the target displacement may be determined from the results of a static pushover analysis.

7. Lateral stiffness verification: The actual equivalent lateral stiffness of the building must be compared to the required equivalent lateral stiffness. If these two stiffness values differ substantially, the lateral load-resisting system of the building must be modified by returning to Step 2.

Pang & Rosowsky (2007) and Pang et al. (2009, 2010) presented an improved procedure for the displacement-based design of wood buildings, which may be used instead of the one presented above. Finally, displacement-based design of CLT buildings is discussed in Hummel (2017).

The direct-displacement procedures have some advantages over the traditional forced-based design methods:

- No estimation of the elastic period of the building is required.
- Force modification factors R_d and R_o do not enter the design process.
- The displacements drive the entire design process.
- Relationships between the elastic and inelastic displacements are not required.

The direct-displacement design strategy, on the other hand, requires detailed knowledge of the global nonlinear, monotonic, load-displacement pushover behaviour of the main lateral load-resisting system, as well as the variation of the global equivalent viscous damping with displacement amplitude. If no information is available in the literature, connection, assembly, and seismic force-resisting system level testing is required in parallel with the development of nonlinear structural analysis models for the tall wood structure.

5.3.3.5.3 Performance-Based Design

Performance-based design is another approach that can be used when an Alternative Solution design path is chosen for a tall wood building. The concept of performance-based design for seismic started in the 1990s and evolved to its present form due to political, social, science, engineering, and technology changes and advancements. In 2001, the Applied Technology Council contracted with the Federal Emergency Management Agency to develop the Next-Generation Performance-Based Seismic Design Procedures for New and Existing Buildings. The work continued under various contracts with hundreds of contributors worldwide until 2018. It resulted in the production of many documents in the FEMA P-58 series, *Seismic Performance Assessment of Buildings, Methodology* (FEMA, 2018a) and *Implementation Guide* (FEMA, 2018b), as well as the electronic Performance Assessment Calculation Tool for performing probabilistic computations and accumulating losses. Figure 11 illustrates the framework of the performance-based design for seismic loads.

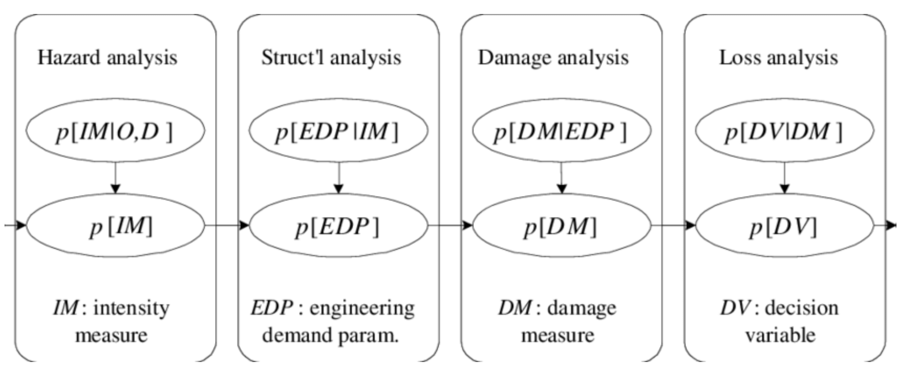


Figure 11. Performance-based seismic design framework.

The framework consists of four conditional analyses, starting with the hazard analysis of a project site, which is typically conducted by the geotechnical engineer. The structural analysis includes nonlinear dynamic time-history analysis to obtain peak structural responses or engineering demand parameters such as inter-storey drift ratio or total floor acceleration. Due to the required computation time and limited ground motion records that are applicable to a project site, correlated engineering demand parameters can be synthetically generated with the same statistical distribution as the seed engineering demand parameters from the nonlinear analysis. This is essential to the underlying probabilistic approach of performance-based seismic design. To carry out the damage analysis, major structural and nonstructural components, including contents of the building, are identified. The corresponding repair method, repair material quantity, and repair cost function are defined for each component. The components are further categorized based on the location and sensitivity to engineering demand parameters. Designers, contractors, and stakeholders should attempt to include all possible damageable components of a project. For a given engineering demand parameter, the damage state of a component is determined by a Monte-Carlo simulation. This is then used in the loss analysis to translate damage quantities into decision variables or performance metrics, which could be monetary, downtime, casualty, or carbon footprint.

Building codes and material standards provide guidelines on how to perform hazard and structural analyses within the performance-based seismic design framework. The analyses are intended to establish the minimum requirements for providing life safety from seismic hazards. The objectives of seismic design according to the NBC (NRC, 2020) are:

1. to resist minor earthquakes without damage;
2. to resist moderate earthquakes without structural damage but with some nonstructural damage; and
3. to resist major earthquakes with significant structural and nonstructural damage but without collapse.

These goals are implicitly accomplished through the specification of prescriptive criteria that regulate acceptable materials, approved structural and nonstructural systems, specified minimum strength and stiffness levels for elements and connections, and control of deflections of the building. Although these prescriptive criteria are intended to result in buildings that are capable of providing certain levels of performance, the actual performance of an individual building design is not assessed as part of the design process. As a result, the performance of buildings designed to the same prescriptive criteria can vary: some buildings may be better than the code standards, while others could be worse.

The performance-based seismic design framework explicitly evaluates how a building is likely to perform given the potential hazard it is likely to experience. It considers the uncertainties inherent in the quantification of potential hazard and the uncertainties in the assessment of the actual building response. Within the framework, identifying and assessing the performance capability of a building is an integral part of the design process that guides decision-making. Figure 12 shows the key steps in the performance-based design process. It is iterative, beginning with selection of performance objectives, followed by development of a preliminary design, assessment of whether the design meets the performance objectives, and lastly redesign and reassessment, if required, until the desired performance level is achieved.

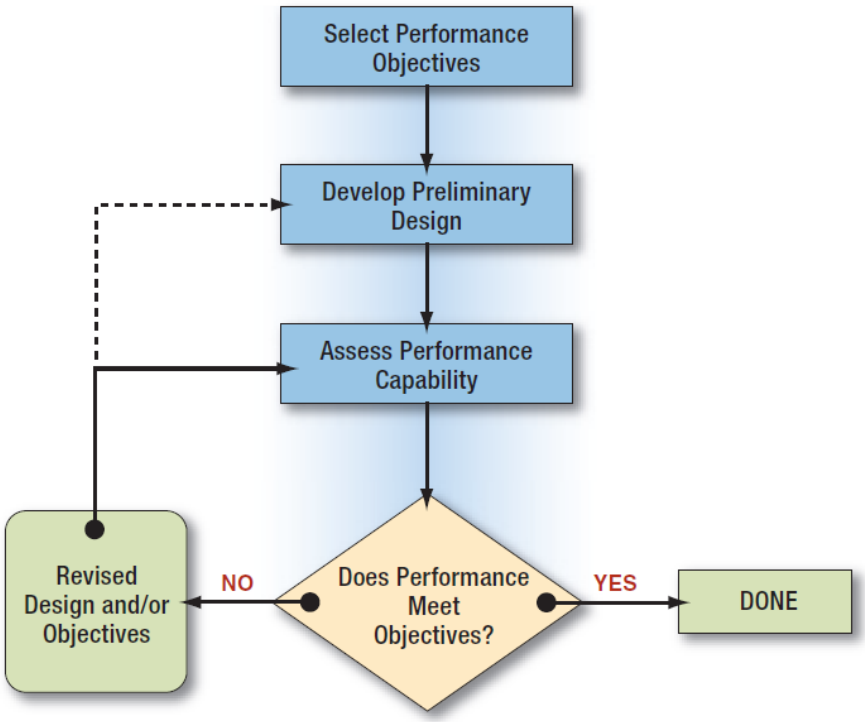


Figure 12. Simplified diagram of the performance-based seismic design procedure.

Three structural performance levels are defined, consistent with the performance most frequently sought by building owners: immediate occupancy, life safety, and collapse prevention.

The collapse prevention (structural stability) performance level is intended to represent a state of incipient collapse in which the lateral force-resisting system has experienced substantial stiffness and strength degradation. The gravity load-resisting system, while also potentially compromised, is anticipated to retain enough integrity to continue to support basic dead and live loads. Structures performing to the collapse prevention level are anticipated to be potentially complete economic losses. However, because collapse has not occurred, they present only a moderate level of risk to occupants during an earthquake. The life safety performance level is also a state in which significant damage has occurred to the seismic force-resisting system; however, this damage is reduced relative to the collapse prevention level. While structures responding to the collapse prevention level are expected to have little or no remaining margin against collapse (Figure 13), structures performing to the life safety level are expected to retain significant margin. Such structures are expected to be repairable, though perhaps not economically so. It is expected that they represent a very low level of risk to occupant safety during a design earthquake. The immediate occupancy performance level is a state of minor damage. Structures performing to this level are expected to experience limited stiffness degradation and no significant strength degradation. Such structures are expected to present a negligible risk to life safety, both during and after a design earthquake, and are therefore immediately available for post-earthquake reoccupancy, presuming that damage to nonstructural elements does not preclude this.

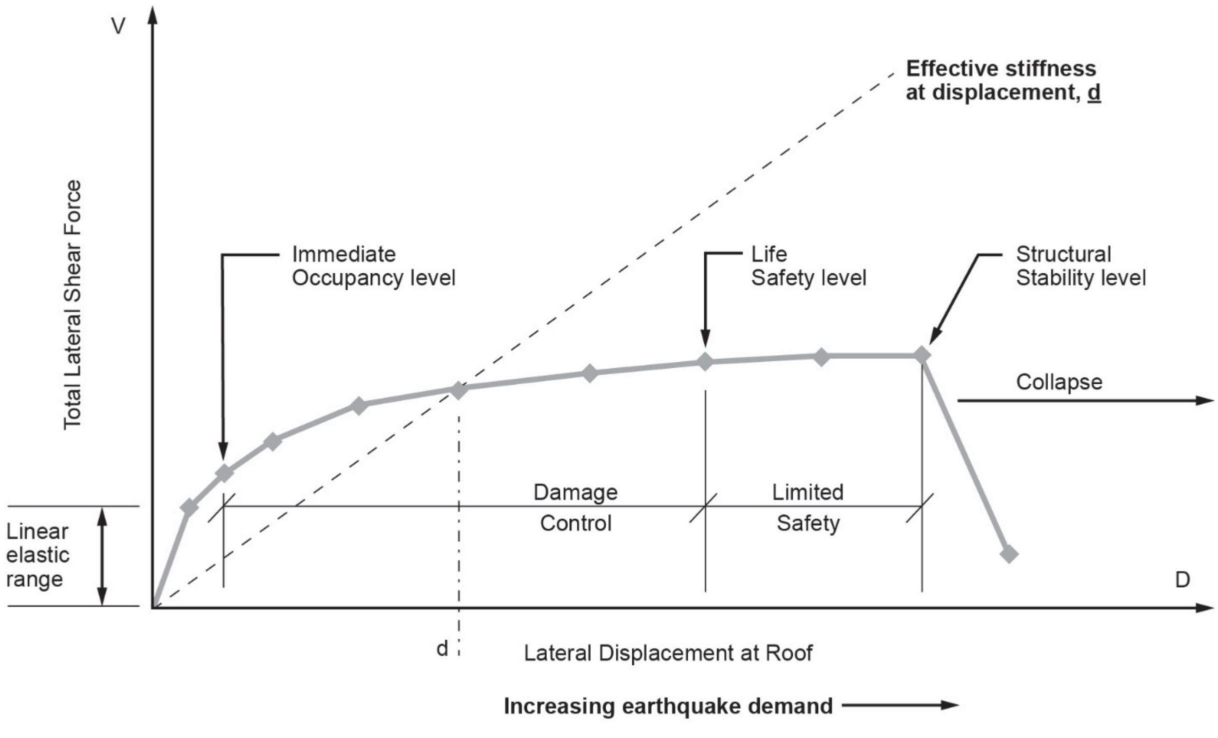


Figure 13. Typical pushover curve of seismic force-resisting system with the structural performance levels.

The performance levels in the 1997 National Earthquake Hazards Reduction Program provisions (FEMA, 1997) include, for the first time, performance criteria associated with different return periods of a design earthquake (Figure 14). The diagonal lines indicate the performance objectives expected for various types of buildings. Specifically, it is anticipated that regular buildings would meet the life safety performance level for design-level earthquakes in the United States (10% in 50 years), while the collapse prevention level for a maximum considered earthquake would have a 2% probability of being exceeded in 50 years. The immediate occupancy (operational) level for frequent earthquakes would have a 50% probability of being exceeded in 50 years.

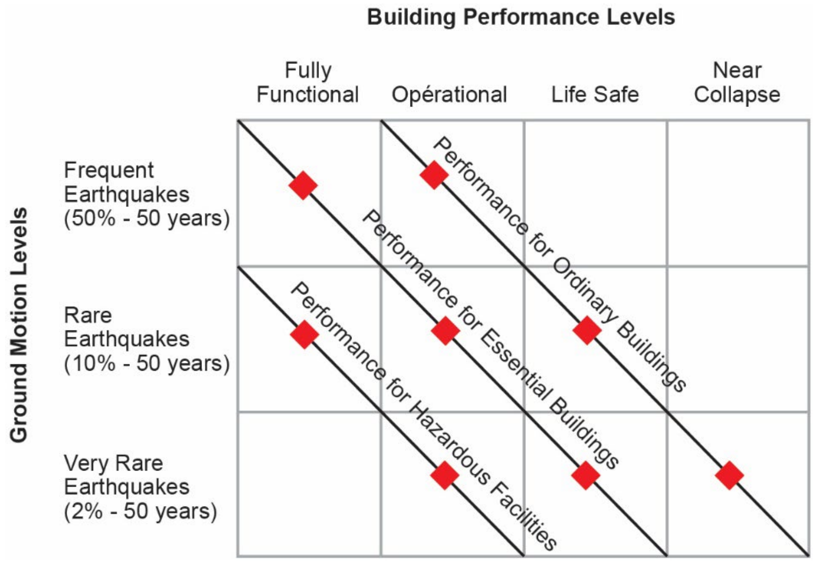


Figure 14. 1997 National Earthquake Hazards Reduction Program performance objectives (FEMA, 1997).

Later documents, such as ASCE 41-17 (ASCE 2017), define the current practice for performance-based seismic design in the United States. In ASCE 41-17, the building performance is expressed in six discrete structural performance levels (SPL) and two intermediate structural performance ranges. The discrete structural performance levels are immediate occupancy (S-1), damage control (S-2), life safety (S-3), limited safety (S-4), collapse prevention (S-5), and not considered (S-6). These performance levels are similar to those shown in Figure 13. The intermediate structural performance ranges are the enhanced safety range and reduced safety range. For each performance level, acceptance criteria are defined for various types of buildings.

Four types of analyses are mentioned in ASCE 41-17 (ASCE 2017), which give designers progressively detailed information about structural performance. The first two methods (linear static and linear dynamic) match the model code style of force-based design and cannot be used on buildings with long periods or significant irregularities. Some tall wood buildings may fit this category. The second two methods (nonlinear static and nonlinear dynamic) serve to directly determine the post-yield capability of a building. In addition to a set of general analysis requirements, each analysis method is defined in terms of specific modelling requirements and procedures. A common acceptance criterion is provided for the linear methods (force-based) and nonlinear methods (displacement-based). The criteria are extensive, organized by material type, and based on the amount of available information, including applicable test results.

Although performance-based seismic design of wood structures has been a topic of research and development since 2005, advancements have been slower than for other structures. Moreover, almost all the research has been related to wood-frame structures, the predominant system used in North America. The following short summary of the research may be useful to designers:

The shortcomings of using force-based design for wood structures were identified by Filiatrault & Folz (2002). The direct displacement-based design procedure that was first suggested by Priestley et al. (1999) was adopted and presented one possible displacement-based design procedure for wood structures. New steps toward defining a performance-based seismic design for wood-frame structures were discussed at a workshop in Colorado (van de Lindt, 2005). This design procedure was applied to a 2-storey wood-frame building (Filiatrault et al., 2006). An experimental study showed a strong correlation between displacement/drift and the level of damage that occurred during shake table tests of a wood structure (van de Lindt & Liu, 2006). A design procedure that focuses on limiting inter-storey drift as a rational approach for performance-based seismic design of engineered wood-frame buildings when damage limitation is one of the design objectives was developed by Rosowski (2002), Rosowski & Ellinwood (2002), and Pang & Rosowski (2007). It includes the fragility analysis for wood-frame shear walls (Kim & Rosowski, 2005). Also, efforts were made to develop damage-based seismic reliability concepts for wood-frame structures (van de Lindt & Gupta, 2006). The direct displacement-based design procedure was used in performance-based design and for determining the preliminary force modification factors for CLT structures in Canada and the United States (Pei et al. 2012, 2013a, 2013b).

Because discussions on performance-based codes are continuing in Canada, designers of tall wood buildings who are interested in using performance-based seismic design are advised to follow the latest FEMA and ASCE documents. As an alternative, the direct displacement-based design procedure for wood structures developed by Filiatrault & Folz (2002), presented in Section 5.3.3.5.2, may be used. The method requires nonlinear pushover analysis of the complete structure, and an estimate of equivalent viscous damping at a target drift limit.

If necessary, the performance of the designed building may be further verified using a series of time-history dynamic analyses of a nonlinear model of the building, as conducted in Pei et al. (2013a). A suite of records for the site, scaled to the 2% in 50 years hazard, should be chosen for the analyses. Based on the maximum drifts obtained from the analyses, fragility curves for the building performance can be obtained, and the performance of the building can be assessed in terms of the probability of exceeding a certain drift. A probability of failure of 10% for a 2% in 50 years seismic hazard is acceptable under the model codes in the United States, such as ASCE/SEI 7-16 (ASCE 2016), and other documents such as FEMA P-695 (FEMA, 2009a). Similar approach, although not explicitly stated in NBC (NRC, 2020), may be considered in the development of an Alternative Solution in Canada as well.

5.3.3.6 Capacity-Based Design Procedures

The concept of capacity-based design is of major importance in seismic design. Capacity-based design is widely used for the seismic design of concrete, steel, and masonry structures, and should be used in the seismic design of tall wood buildings. This design approach is based on the simple understanding of the way a structure sustains large deformations under severe earthquakes. By selecting certain modes of deformation of the seismic force-resisting system, certain parts of it are suitably designed and detailed for yielding and energy dissipation under the imposed severe deformations. These critical regions of the seismic force-resisting system, often termed as "plastic hinges" or "dissipative zones", act as energy dissipaters to control the force level in the structure. All other structural elements may be designed as non-yielding, and are protected against actions that could cause failure by providing them with strength greater than that corresponding to the development of probable strength in the potential plastic hinge regions. In other words, non-yielding elements, resisting actions originating from plastic hinges, must be designed for strength based on overstrength rather than on code-specified factored strength (resistance), which is used for determining required strengths of hinge regions. This "capacity" design procedure ensures that the chosen means of energy dissipation can be maintained. An example of desirable and undesirable hinge mechanisms is shown in Figure 15. In some cases, it is necessary to verify that the stiffness of the non-yielding element is sufficient to ensure the desirable mechanism; i.e., providing stiffness greater than that of the plastic hinge. This can be investigated by conducting pushover analysis.

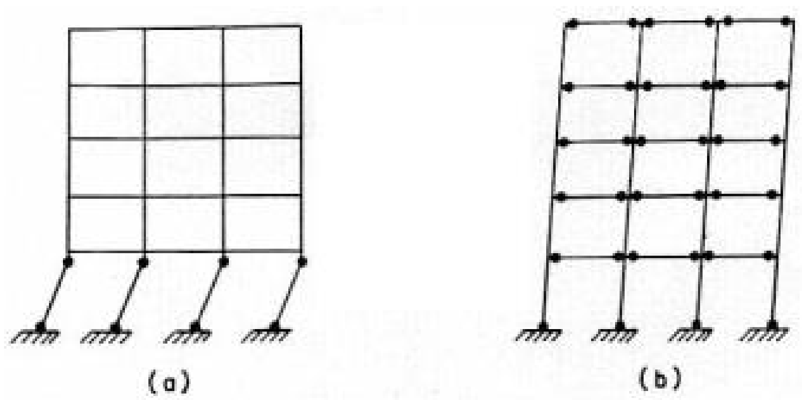


Figure 15. Potential choices for plastic hinges: (a) hinges in columns can lead to a soft storey mechanism; (b) hinges in beams can lead to desirable weak beam–strong column design.

In capacity-based design used in steel structures, the members are typically designed to yield before the connections, and beam failure mechanisms are preferred since they can provide sufficient structural ductility without creating an undesirable mechanism of collapse (Figure 15). In timber structures, however, the failure of wood members in tension or bending is not favourable because of wood's brittle characteristics; consequently, all nonlinear deformations and energy dissipation in wood structures should occur in the connections. Thus, the steel and timber approaches are completely the opposite.

The main steps in the capacity-based design procedure for wood structures are as follows:

1. A kinematically admissible plastic mechanism is chosen for the structure, in which plastic hinge connections within the structure are clearly defined. The mechanism should allow the necessary overall displacement ductility to develop with the inelastic behaviour in the plastic regions (hinges).

2. Connections that will act as plastic hinge regions within the structure are designed to have their strength (factored resistance) as close as practical to the required strength (demand). Subsequently, these connections are carefully detailed to fail in the fastener yielding mode and to ensure that estimated ductility demands can be reliably accommodated under reversible loading.

3. Undesirable failure modes within the wood members containing the connections (plastic hinges) are inhibited by ensuring that the strengths of these modes exceed the overstrength capacity of the plastic hinges.

4. Components of the structure that are not suited for stable energy dissipation are protected by ensuring that their strength exceeds the demands originating from the overstrength of the plastic hinges; therefore, these regions are designed to remain elastic irrespective of the intensity of ground shaking or the magnitude of inelastic deformations that may occur.

Using this approach, for braced timber-frame systems for example, the dissipative zones should be in the connections between the braces and the rest of the frame. They should be able to produce yielding through a combination of wood crushing and fastener yielding. All other connections should be designed to remain linear elastic, with a strength that is slightly higher than the force induced on each of them when neighbouring dissipative zones reach their overstrength. There should be a gap between the diagonal braces and the rest of the frame (in the corners). The presence of a gap allows for the brace connections (dissipative zones) to deform and reach their ductility capacity. When there is no gap between the end of the brace and the frame corners (a case of the brace having been tight fitted in the frame corners), the braced frame will be stiffer and would probably be able to carry larger lateral loads but may also be less ductile and induce significant bending deformation on the columns. Eccentricities in all connections of the braced frame, and especially in the dissipative zones, should be minimized. All wood members should be designed to remain linear elastic at all times. The columns should be continuous as much as possible over the height of the structure and should be able to carry the vertical load at all deflection levels, including the maximum allowable lateral drift. Diagonal timber braces should be designed not to buckle at any time. The structural integrity of the frame should be maintained at all times, while dissipative zones experience inelastic behaviour.

In the case of platform-type CLT structures, typically all nonlinear deformations and energy dissipation occur in the shear connections (brackets) between the wall and the floor panels and in the vertical half-lap or spline shear joints in the walls. All other connections should be designed to remain linear elastic with a strength that is higher than the force induced on each of them when neighbouring dissipative zones reach their overstrength resistance. All connections used for energy dissipation in CLT structures should be designed to fail in fastener yielding mode. No wood failure modes in these connections should be allowed. Sliding should also be minimized at every floor level.

Using this strategy, the connections in horizontal joints between floor panels (No. 2 in Figure 16) should have sufficient factored strength and adequate stiffness to allow for the diaphragm to act as a single unit. Similarly, connections tying the floor panels to the walls below (No. 3 in Figure 16) should be designed with a factored strength of the strongest connection element in the structure. If vertical half-lap or spline joints (No. 4 in Figure 16) are used to join several wall segments to form a larger wall, the joints should be designed as the yielding elements (dissipative zones) to yield simultaneously with the steel bracket connections in uplift. If the aspect ratio of the wall segments is between 2 and 4, such CLT structures can use seismic force modification factors of Rd = 2.0 and Ro = 1.5 according to CSA O86 (CSA, 2019a). CLT structures that have wall segments with aspect ratios lower than 2 should use the product of Rd Ro = 1.3 as per CSA O86, while those that have segments with aspect ratios higher than 4 should not be taken into account as part of the seismic force-resisting system.

Another design approach can always be used by over-designing the connections in the lap joints, which will result in the entire wall being able to act as a single panel. In this case, the seismic force-resisting system should be treated as non-dissipative and should use Rd Ro = 1.3, which means that the benefits of the vertical lap joints as energy dissipating zones will be lost. The vertical joints between perpendicular walls (No. 1 in Figure 16), may or may not be included as dissipative joints. The effect of perpendicular walls on the seismic performance of CLT walls has not been investigated in depth thus far. Until these effects are fully known and quantified, it is suggested that vertical joints between perpendicular walls be over-designed. This approach also slightly simplifies the seismic design procedure and gives the structure an additional degree of robustness and safety. Fasteners should be placed in the available space in the steel brackets and the hold-downs to achieve the maximum fastener spacing possible (i.e., not every hole in the bracket has to be filled with an fastener). Larger fastener spacing will help avoid load concentration in a small area of the CLT panel. Refer to CSA O86 (CSA, 2019a) Clause 11.9 for more information on capacity design of platform-type CLT structures.

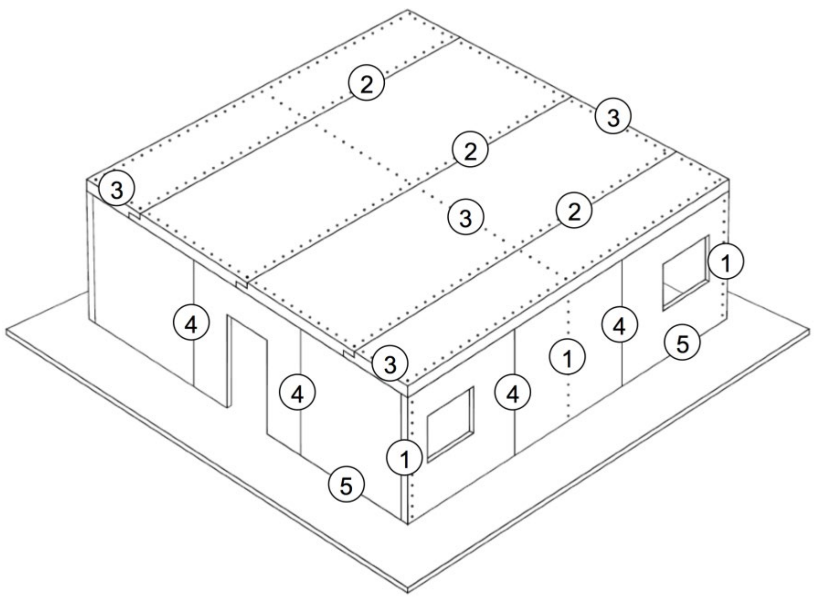


Figure 16. Typical storey of a multi-storey CLT structure with various connections between panels: connections 1, 2, and 3 to be elastic, 4 to be ductile.

It should be noted that capacity design is not an analysis technique (like the methods outlined earlier in this section) but a design philosophy. It enables the designer to "tell the structure what to do" and to desensitize it to the characteristics of an earthquake, which are, after all, unknown. Subsequent judicious detailing of all potential plastic regions will enable the structure to fulfill the designer's intentions. A capacity design approach is likely to ensure a more predictable and satisfactory inelastic response under variable earthquake conditions because the capacity-designed structure should not develop undesirable hinge mechanisms or modes of inelastic deformation that would result in collapse or prevent evacuation after a major seismic event. The approach is insensitive to earthquake characteristics, as far as the magnitude of inelastic deformations is concerned. When combined with appropriate detailing for ductility, capacity design will enable optimum energy dissipation by rationally selected plastic mechanisms. Section 5.2 provides more detailed information on testing and analytical data related to various timber connections that may be useful for implementing capacity design procedures for tall wood buildings.

5.3.3.7 Other Aspects of Seismic Analyses and Design

5.3.3.7.1 Diaphragm Flexibility

Floor diaphragms in buildings have two different functions: (a) to carry the vertical dead and live loads and (b) to transfer the lateral loads imposed by wind and seismic action to the vertical components of the lateral load-resisting system below. In the latter case, the diaphragms rely on their in-plane strength and stiffness to transfer the imposed loads. In multi-storey buildings, where the diaphragms are composed of reinforced concrete slabs or steel decks with structural concrete topping, the in-plane stiffness of the diaphragm is quite large, and it acts as a rigid body. In wood-frame structures, the situation is often the opposite because the in-plane stiffness of wood diaphragms is much lower. The in-plane stiffness of the diaphragms must be taken into account when determining the response of a tall wood building because diaphragm deformation alters how the loads are distributed to the vertical components of the lateral load-resisting system below. In the case of flexible diaphragms, the components of the vertical lateral load-resisting system carry lateral loads from the tributary area of the diaphragm that they support. In the case of rigid diaphragms, the lateral loads must be assigned to the components of the vertical lateral load-resisting system in proportion to their stiffness. In this case, the torsional response (including accidental torsion) has to be taken into account. It should be noted that the NBC (NRC, 2020) requires that even in the case of flexible diaphragms, accidental torsion should be considered.

Currently, there are no criteria in the NBC (NRC, 2020) or in CSA O86 (CSA, 2019a) for classifying diaphragms as rigid or flexible. There are some guidelines on the subject in Special Design Provisions for Wind and Seismic (ANSI/AWC, 2021), FEMA 356 (FEMA, 2000), and its successor ASCE 41-17 (ASCE, 2017). In these documents, it is recommended that a diaphragm be classified as flexible when the maximum horizontal deformation of the diaphragm along its length is more than twice the average inter-storey drift of the vertical lateral-force-resisting elements of the storey immediately below the diaphragm. On the other hand, the diaphragm may be considered rigid if the maximum diaphragm deformation is less than half the average inter-storey drift in the storey below. Diaphragms that are neither flexible nor rigid are classified as being stiff, and in such cases the response of the structure should be based on an analysis that takes into account both the in-plane stiffness of the diaphragm and the stiffness of the vertical seismic force-resisting system. ASCE/SEI 7-16 (ASCE, 2016) provides both prescriptive and calculation-based methods of classifying diaphragms. According to these specifications, diaphragms constructed of untopped steel decking or wood structural panels (plywood or oriented strand board) may be idealized as being flexible when the vertical lateral load-resisting elements are steel or composite steel and concrete-braced frames, or concrete, masonry, steel and composite shear walls, or light-wood-frame construction, where the nonstructural concrete topping is no greater than 38 mm. Although such diaphragms may not always meet deflection-based criteria, the provisions continue to be widely followed in traditional design practice. For regular light-framed wood diaphragm buildings, a force distribution based on a flexible diaphragm assumption generally leads to better performance.

In the case of tall wood buildings, it is proposed that an analysis of the diaphragm flexibility be carried out. Whether a diaphragm can be treated as flexible, rigid, or semi-rigid depends on the in-plane stiffness of the diaphragm relative to that of the vertical seismic force-resisting system. Diaphragms that consist of CLT panels with or without concrete topping, as well as diaphragms that consist of vertically laminated glulam or heavy timber decking attached as specified in CSA O86 (CSA, 2019a), are stiffer than light-wood-frame diaphragms (for NLT and DLT diaphragms [see Section 5.1]). If the designer is not sure that the diaphragm can be assumed to be flexible or rigid, an envelope approach such as the one provided in the International Building Code (ICC, 2021) may be used. In the envelope approach, the designer should analyze the structure twice, postulating the flexible and the rigid diaphragm assumption, and then taking the worst-case scenario. Although mass timber diaphragms can achieve the minimum stiffness requirements of other material codes such as ACI 318-19: Building Code Requirements for Structural Concrete and Commentary (ACI, 2019), this assumption may not be valid, especially in the case of long spans.

In many cases, the designer may need to take the diaphragm design a step further by modelling the diaphragm as a semi-rigid plate with the bending and shear stiffness properties of the membrane (EA/GA) and the stiffness of the splines using line spring elements. This would lead to a "tuned" semi-rigid membrane for use in actual software (e.g., ETABS). Further information on some of the semi-rigid options as well as line springs is provided in FPInnovations' *Modelling Guide for Timber Structures* (Chen et al., 2022), Special Design Provisions for Wind and Seismic (ANSI/AWC, 2021), and Breneman et al. (2016). In buildings where dual lateral load-resisting structural systems are used, the diaphragms may be highly stressed in some locations due to non-fully compatible deflection shapes of the systems (e.g., the lowest and highest floors in a core plus perimeter moment-frame system). More rigorous analyses should be performed when these types of systems are selected. The main force transfer elements of diaphragms, such as the chords, struts, and parts around any openings, should be capacity protected to properly collect and transfer forces. They should stay elastic under the force and displacement demands induced in them when the energy-dissipative connections that are connecting them to the seismic force-resisting system reach their overstrength.

5.3.3.7.2 Discontinuities in Plan and Elevation

In general, the seismic force-resisting system should carry the lateral load demand to the ground with no interruption. In many cases, however, architectural challenges are present and need to be overcome, such as open lobby spaces or changes in the pattern of openings in the core to accommodate changes in occupancies or uses. These all introduce structural discontinuities. The NBC (NRC, 2020) identifies nine types of irregularities associated with mass, stiffness, and geometry of the system.

In-plane and out-of-plane discontinuities in the seismic force-resisting system, except podiums, should be avoided for tall wood buildings as much as possible. If they are unavoidable, columns must be placed at the end of the walls to ensure that overturning associated with the wall panels is transferred to the columns. Because shear is transferred through the diaphragm to the adjacent walls, the connection of the walls to the diaphragm and the columns supporting the seismic force-resisting system should be designed to the capacity of the seismic force-resisting system or for full elastic response of the system.

Clauses 4.1.8.3 (6) and (7) of the NBC should also be taken into consideration when analyzing and designing a building or calculating its period. CLT elements that are not considered part of a seismic force-resisting system should either be separated from all structural elements of the seismic force-resisting system so that no interaction takes place as the building deforms due to earthquake effects, or be made part of the seismic force-resisting system and satisfy the system design requirements. According to Clause 4.1.8.3 (7) of the NBC, the stiffness imparted to the structure from elements that are not part of the seismic force-resisting system should not be used to resist earthquake deflections but should be accounted for when (a) calculating the period of the structure for determining forces if the added stiffness reduces the fundamental period by more than 15%; (b) determining the irregularity of the structure, except that the additional stiffness should not be used to make an irregular seismic force-resisting system regular or to reduce the effects of torsion; and (c) designing the seismic force-resisting system if inclusion of the elements that are not part of the seismic force-resisting system in the analysis have an adverse effect on the seismic force-resisting system.

Adverse effects may change the load path and cause some parts of the seismic force-resisting system to be subject to higher forces and/or deformations than would otherwise be the case. When mass timber is used as a floor diaphragm or roof in systems that use non-wood seismic force-resisting systems, they should be able to act as a diaphragm and should be able to transfer the seismic forces to the non-wood seismic force-resisting system. Various means of connecting wood-based diaphragms to non-wood-based seismic force-resisting systems have existed for centuries, and with only slight modifications, they can be used to connect modern mass timber floors to the supports below. These connections should be non-dissipative connections and should be designed to remain elastic under the force and displacement demands that are induced in them when transferring the seismic loads to the seismic force-resisting system.

5.3.3.7.3 Mass Timber as a Gravity System Used with Non-Wood Seismic Force-Resisting Systems

When mass timber systems are used in the gravity system only, and the lateral loads are resisted by a seismic force-resisting system of another material, the mass timber gravity system, like other gravity systems, must be able to “go along for the ride” with the seismic force-resisting system, as per Clause 4.1.8.3 (5) of the NBC (NRC, 2020). Unless the building is located in a low seismic hazard zone (SC1 and SC2) where $I_E F_a S_a(0.2)$ is less than or equal to 0.35, as defined in the NBC (NRC, 2020), all mass timber structural elements and their connections that are not considered part of the seismic force-resisting system should be designed to ensure they behave elastically or have sufficient nonlinear capacity to support their gravity loads while undergoing earthquake-induced deformations. In other words, the designer should ensure that the gravity load-carrying system in the building can accommodate lateral drifts associated with the seismic response of the building.

The building drifts also produce secondary forces and moments in the gravity system that have to be taken into account in the design. The larger and stiffer the gravity system is, the more it will interact with the seismic force-resisting system, especially in taller buildings. The entire structural system should also be designed to sustain anticipated P- δ effects during the seismic response.

5.3.3.7.4 Lateral Drifts

Lateral drifts can be determined by methods of analyses presented in this section. Lateral drifts associated with the response of the seismic force-resisting system and formation of plastic hinges in the system during a seismic event must be accommodated by all nonstructural elements that need to be functional during and after a seismic event, such as cladding, the sprinkler system, and the gravity load-carrying system.

The drift should be calculated in accordance with the formation of plastic hinges throughout the lateral load-resisting system, as the difference between the lateral deformations of consecutive floors. Following the philosophy of this guide, lateral drift should also be limited to the NBC criteria for tall buildings in general.

5.3.3.7.5 Testing Needed to Support Seismic Load Analyses and Design

If the design input formation is not available for the main strength, stiffness, and ductility properties of the connections, structural elements, assemblies, and sections of the seismic force-resisting system used, testing should be carried out to determine those properties. More details about testing requirements in general are provided in Section 5.2. The tests should involve full-scale specimens as much as possible. Types of tests to be considered include static and cyclic tests on structural elements and connections, as well as cyclic, pseudo-dynamic, or shake table tests on the main lateral load-resisting assemblies or main portions of the seismic force-resisting system. Important parameters to be extracted include, but are not limited to, initial and post-yield stiffness, yield and ultimate strength and defection, strength and stiffness degradation, ductility, drift capacity, and hysteresis loop properties, including energy absorption.

5.3.4 ANALYSIS AND DESIGN FOR WIND LOADS

It is generally recognized that as the height of a building increases, wind forces become the controlling design loads for both safety and serviceability limit states. Due to their lighter nature, tall mass timber buildings, similar to some steel buildings, could experience larger dynamic oscillations when excited by strong winds. In this regard, a recurring question among practitioners is to what height can tall wood buildings be built without undergoing wind-induced serviceability issues. The dynamic response of wind-excited tall buildings depends on wind speed and direction, immediate surroundings, upstream terrain conditions, building aerodynamics, and dynamic structural properties. Satisfactory performance evaluation and design of wind-excited tall mass timber buildings can be made using simple procedures found in building codes or in more elaborate wind tunnel testing. This section aims to elaborate on these procedures with case study examples, highlight the challenges, and introduce performance-based wind engineering approaches.

5.3.4.1 Design and Analysis Framework

5.3.4.1.1 Davenport's Wind Loading Chain

The wind loading process is a complex, interconnected, and multi-scale one. Davenport's Wind Loading Chain systematically outlines this process (Figure 17). It laid the foundation for modern wind engineering and provided a theoretical basis for many building codes and standards. This "cause and effect chain" links meteorology, microclimatology, building aerodynamics, structural response, and design criteria. The weakest link in the chain ultimately governs the final response and reliability of the system.

Figure 17. Alan G. Davenport Wind Loading Chain.

In the performance assessment and design of tall buildings, the use of the Wind Loading Chain starts by studying the wind climate of the location of interest. The structure of the synoptic wind in the atmosphere can be considered as the result of two processes. The first process entails the movement of large-scale pressure systems, which results in the reference wind (the first element in Figure 17). In the second process, closer to the ground, the airflow is influenced by the terrain, which gives rise to a chaotic flow, formally known as turbulent flow. The most characteristic feature of a turbulent flow is its randomness in time and space. Turbulent flow, at a given point, has a mean velocity and three fluctuating velocity components that are orthogonal to each other. The third element in the Wind Loading Chain is aerodynamic effects. Bluff body aerodynamics deals with the mechanisms by which a flow field induces surface pressures on it. The bluff body is a body that has a large region of separated flow. The main features of flow around a bluff body are flow separation and reattachment, and formation of strong vortices in the wake regions. In general, surface pressures depend on the flow field, geometry, and orientation of the bluff body with respect to the mean wind direction. Boundary layer wind tunnel tests are routinely used to estimate aerodynamic wind loads. Recently, with the growth of computational power, computational fluid dynamics has become a usual tool for studying bluff body aerodynamics. The dynamic wind load responses could be the result of buffeting by the oncoming turbulence, turbulence in the shear layers, wake turbulence, buffeting induced by the wake of upwind structures, and aeroelastic effects. These aerodynamic phenomena are illustrated in Figure 18, a photograph taken during a wind tunnel test of a 40-storey tall mass timber building.

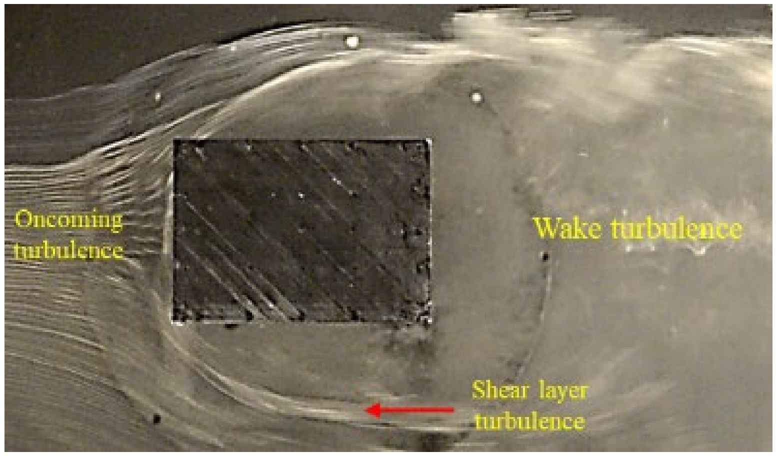
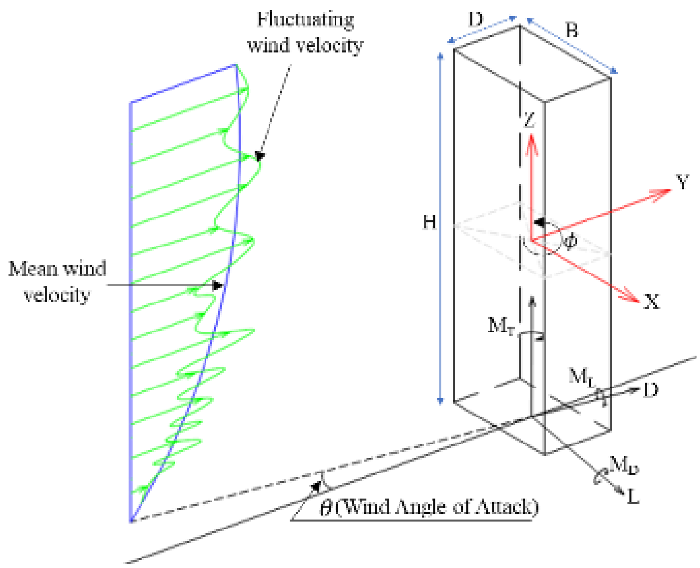


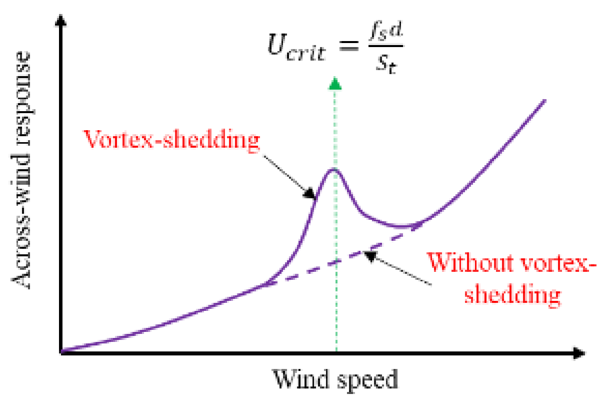
Figure 18. Flow around the aerodynamic model of a 40-storey tall mass timber building in turbulent boundary layer flow (photograph taken during wind tunnel testing).

Considering the wind angle of incidence, wind forces on a building consist of three components: along-wind, across-wind, and torsional (Figure 19a). The along-wind forces are parallel to the mean wind direction, and the associated dynamic excitation is caused mainly by the oncoming turbulence in the drag (D) direction. Along-wind excitations do not usually involve instabilities and can be predicted with reasonable accuracy using quasi-steady theory (Davenport 1967). Across-wind loads occur orthogonal to the mean wind load, in the lift (L) direction, and are the result of pressure fluctuations in the flow-separated region. The primary source of across-wind loads is the vortex-shedding phenomena, where vortices shed alternatively with a frequency (f) that can be defined by the shape-dependent Strouhal number (S_t). The frequency of vortex shedding is $f_s = S_t U/d$, where U is the mean wind velocity, and d is the across-wind width of the building. For very slender buildings (height to across-wind width ratio greater than 6), the spectrum of across-wind forces is narrow and roughly centred on f_s; hence, the across-wind forces are strongly dependent on the strength and frequency of vortex-shedding and weakly dependent on the oncoming turbulence.

As shown in Figure 19b, the effect of vortex excitation is to amplify the across-wind loads at wind speeds close to the critical wind speed (U_{crit}). For lightly damped and low-frequency buildings, once vortex excitation is initiated, a resonance phenomenon could lock the vortex shedding to the natural frequency of the building and cause the amplification by the vortex excitation to persist for a range of wind speeds. As a result, the building aerodynamic forces can be affected by the motion of the building and result in aeroelastic feedback. For buildings with a height to across-wind width ratio less than 6, the spectrum of the across-wind forces is relatively broader, in which the across-wind forces increase in proportion to wind speed and can be affected by the oncoming turbulence. In general, for tall mass timber buildings, the dynamic across-wind forces could exceed the along-wind forces (see the case studies in Section 5.3.4.2). Instantaneous pressure fluctuation over the surface of the buildings is a random phenomenon. This randomness induces asymmetries of pressure fluctuations in the wake regions, which results in dynamic torsional wind loads. Moreover, torsional building vibrations could be induced due to eccentricities between the resultant wind force and elastic centre of the buildings. For the design of tall buildings, buffeting in the drag direction and vortex shedding are critical.



(a)



(b)

Figure 19. (a) 3D schematic of a generic rectangular tall building with the definition of principal axes, mean wind angle of attack, and directions of drag (D), lift (L), and torsional moment; (b) effect of vortex-shedding on the across-wind response of tall buildings.

The last element in the Wind Loading Chain is the design criteria. In wind design, both strength and serviceability limit states should be considered. The serviceability limit states usually govern the design of lightweight, tall, slender, and very flexible buildings. The serviceability limit states of particular interest in the design of tall buildings are excessive deformation (deflections and drift) and occupant comfort (excessive accelerations). According to the NBC (NRC, 2020), under service level wind, the total storey level drift shall not exceed *h*/500, where *h* is the storey height. In addition, the code states that "limitation of 1/500 drift per storey may be exceeded if it can be established that the drift as calculated will not result in damage to non-structural elements." Clause 72 of Commentary I of the NBC (NRC, 2020) states that "unless precautions are taken to permit the movement of interior partitions without damage, a maximum lateral deflection limitation of 1/250 to 1/1000 of the building height should be observed." In line with the commentary, as an additional general rule, a global drift limit of *H*/500, where *H* is the total building height, can also be used. In addition, under a 1-in-10-year wind event, Clause 77 of Commentary I of the NBC limits the peak horizontal floor accelerations to 15 milli-g and 25 milli-g for residential and office buildings, respectively.

5.3.4.1.2 Estimation of Design Wind Loads Using the National Building Code

The NBC (NRC, 2020) permits the use of three analytical procedures for determining design wind loads: static, dynamic, and wind tunnel testing. The level of complexity and range of applicability differentiate the procedures. The following sections summarize the main features of each procedure and its applicability in the design of tall mass timber buildings.

5.3.4.1.2.1 Static and Dynamic Analytical Procedures

According to the NBC (NRC, 2020), the specified wind pressure acting on the surface of a building can be determined according to Equation [21]:

$$p = I_w q C_e C_t C_g C_p \qquad [21]$$

where I_w is the importance factor, q is the reference mean hourly reference velocity pressure, C_e is the exposure factor, C_t is the topographic factor, C_g is the gust effect factor, and C_p is the external pressure coefficient. The specified wind pressure, p, can have a positive or a negative sign when directed toward and away from the external surface of the building, respectively. Importance factors are provided in the NBC (NRC, 2020), depending on the building use and its occupancy. The 1-in-10- and 1-in-50-year reference wind velocity pressures for Canadian cities are also tabulated in the code. The variation of mean wind speed (wind pressure) with height is represented by C_e. The gust effect factor, C_g, is the ratio of mean peak response (load) to mean hourly response (load), which accounts for the effect of buffeting due to oncoming turbulence, turbulence in the shear layers, additional inertial forces due to wind excitations, and aeroelastic effects. Through the external pressure coefficient, C_p, building aerodynamics, the effect of building orientation, and wind speed profile are accounted for.

The NBC (NRC, 2020) permits the use of the static wind analysis procedure to design the lateral load-resisting system of rigid buildings and building envelopes such as the cladding. In the context of wind engineering, buildings with a frequency of vibration greater than 1 Hz are considered rigid. Hence, rigid mass timber buildings can be designed using this approach. When calculating the design wind loads using the NBC, there are three points to consider: (1) partial wind loading could be more critical than full loading; (2) torsion due to partial loadings; and (3) diagonal wind loading and sway in the across-wind direction. For taller structures, the latter is addressed by designing for 75% of the maximum wind pressure simultaneously applied in the two principal directions. The details of the static wind analysis procedure are provided in Commentary I of the NBC.

The NBC (NRC, 2020) requires the use of more elaborate dynamic or wind tunnel procedures to design buildings whose height is more than four times their minimum effective width, or which are taller than 60 m, or to design other buildings whose properties make them susceptible to wind-induced vibrations (if the lowest natural frequency is between 0.25 Hz and 1 Hz). The choice between using static or dynamic procedures in the design of mass timber buildings should be based on the dynamic properties of the buildings (vibration frequencies, generalized mass, and generalized stiffness) rather than height because the NBC recommendations based on height comply very well with buildings made from conventional construction materials. Studies by Bezabeh et al. (2018a, 2018b, 2020b) indicated that mass timber buildings shorter than 60 m could be excited by wind, which resulted in excessive dynamic oscillations. In the dynamic analysis procedure, which is recommended for lightweight, low-frequency, and low-damped buildings, both the background excitation and amplified resonant response arising from excitation by the wind at the vibration frequency of the building are included in C_g. The overall analysis format of both procedures is the same except for the determination of C_e and C_g. To calculate C_g, the NBC (NRC, 2020) presents a series of charts for the exposure factor, background turbulence factor, size reduction factor, and gust energy ratio at the vibration frequency of the structure.

As described earlier, the design of mass timber buildings for wind should consider excessive drift and occupant comfort (excessive accelerations) limit states. In the design of mass timber buildings, after proportioning for the strength limit state, the designs should be iterated until they satisfy the drift limit. Buildings that satisfy drift limits may not necessarily satisfy occupant comfort criteria because the former limit state is related to stiffness, and the latter depends on stiffness, mass, and damping. Usually, wind-induced deflections are higher in the along-wind directions, while peak floor accelerations are critical in the across-wind directions. The gust effect factor can also be used to estimate the along-wind peak floor acceleration demands of tall buildings. The NBC (NRC, 2020) provides equations for estimating the mean peak along-wind and across-wind accelerations of buildings. The estimation of the along-wind peak floor accelerations (a_D [m/s²]) is shown in Equation [22]. It includes the gust effect factor, C_g; the peak factor, g_p; the peak lateral deflection, Δ; the fundamental frequency in the along-wind direction, f_{nD}; the damping ratio as a percentage of critical damping in the along-wind direction, β_D; a surface roughness coefficient, K; a size reduction factor, s; an exposure factor, C_{eH} for a reference height H, and the gust energy ratio at the vibration frequency of the structure.

$$a_D = 4\pi^2 f_{nD}^2 g_p \left(\sqrt{\frac{KsF}{C_{eH}\beta_D}} \frac{\Delta}{C_g} \right) \qquad [22]$$

The across-wind acceleration (a_W [m/s²]) can be estimated using Equation [23], which includes the fundamental frequency in the across-wind direction, f_{nW}; across-wind effective width (m), w; along-wind effective depth (m), d; acceleration due to gravity, g; average building density, ρ_B; damping ratio as a percentage of critical damping in the across-wind direction, β_w; and wind speed at the top of the building, V_H, as shown in Equation [24]. It is important to note that Equations [22] and [23] are empirical.

$$a_w = f_{nW}^2 \, g_p \sqrt{wd} \left(\frac{a_r}{\rho_B \, g \sqrt{\beta_w}} \right) \quad [23]$$

where:

$$a_r = 0.0785 \left(\frac{V_H}{f_{nW} \sqrt{wd}} \right)^{3.3} \quad [24]$$

These equations were developed based on the results of wind tunnel tests that were conducted on steel and concrete buildings and which exhibited significant scatter. Hence, in the design of tall mass timber buildings, it is important to interpret the estimated peak across-wind accelerations from Equations 23 and 24 with due caution.

The NBC (NRC, 2020) provides design examples for wind vibration design checks. In applying the design check procedure to tall wood buildings, the building's natural frequencies and damping ratios need to be estimated. FPInnovations conducted field measurements on newly built mid-rise and tall wood buildings to determine their natural frequencies and damping ratios. It also collected data from the literature and created a database on measured frequencies and damping ratios of more than 35 wood buildings and structures across the world. The database was used to verify the NBC empirical equations for estimating building period. It was found that the estimated frequencies of those wood buildings matched well with the estimated frequencies from the NBC period equation for "shear walls and other structures". Based on FPInnovations' study, it is recommended that, in general, for wind design, the natural frequencies of a wood building can be estimated using any validated finite element method software package with proper assumptions and models for the connections. It is also possible to estimate the natural frequencies of wood buildings using Equations [25] and [26]:

$$f_1 = \frac{1}{0.035 \cdot h^{0.8}} \quad [25]$$

where f_1 = the first transverse vibration frequency of the wood building (Hz) and h = building height (m).

The second transverse vibration frequency of a wood building can be simply estimated from the first transverse vibration frequency, the geometry of the building, and its shape properties (if the building has a rectangular shape in elevation). By modelling the building as a cantilever beam, the second transverse natural frequency of the building can then be estimated approximately using Equation [26].

$$f_2 = \frac{D_L}{D_S} \sqrt{\frac{MOE_L}{MOE_S}} \, f_1 \quad [26]$$

where f_2 = the second transverse vibration frequency of the wood building (Hz), D_L = the longer dimension of the building cross-section (m), D_S = the shorter dimension of the building cross-section (m), MOE_L = the equivalent elastic modulus of the building in the longer axis of the building cross-section (N/m^2), and MOE_S = the equivalent elastic modulus of the building in shorter axis of the building cross-section (N/m^2).

The *Canadian CLT Handbook* (2019 edition) provides verifications for these two equations, and examples of how to use the equations (Karacabeyli & Gagnon, 2019). A damping ratio of 2% for a wood building without finish, and 3% for a wood building with finish is recommended.

It should be noted that using finite element method software that considers only structural elements can underestimate the frequency of a building by as much as 20–100% when compared to the formulae given above, which, based on field measurements, will include realistic amounts of damping and the contributions from nonstructural components. For example, Connolly et al. (2018) estimated that the fundamental frequency of the 18-storey Brock Commons building at the University of British Columbia (UBC) in Vancouver, B.C. would be 0.5 Hz, while the calculated one using Equation [25] would estimate the frequency at 1.2 Hz. Similarly, Chen & Chui (2017) estimated the fundamental frequency of the 20-storey mass timber CHECKER building at 0.53 Hz, whereas the frequency of that building calculated using Equation [25] would be 1.08 Hz. The equation based on the Rayleigh method in Clause 35 of Commentary I of the NBC (NRC, 2020) can also be used to calculate the period or frequency of a building.

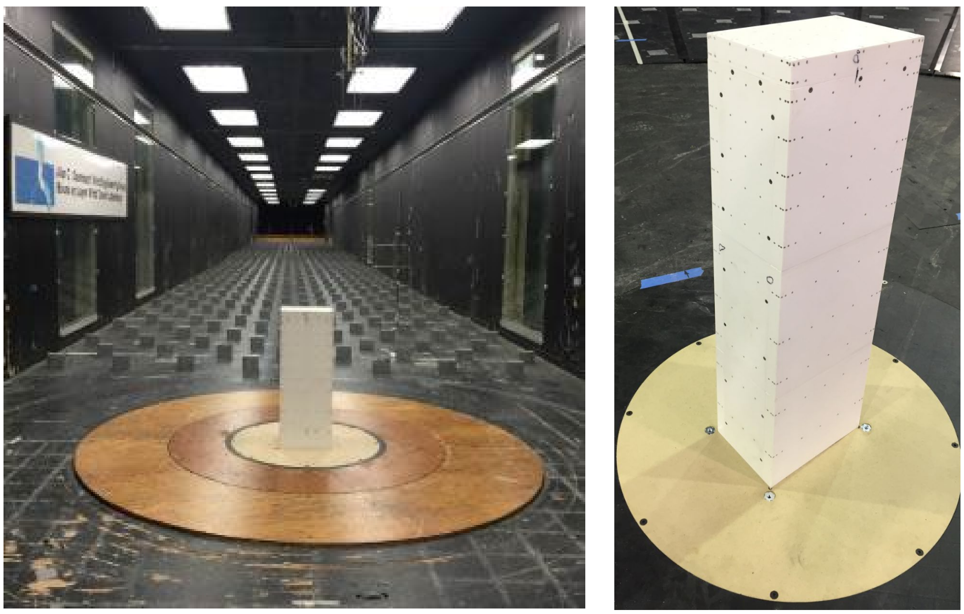
5.3.4.1.2.2 Wind Tunnel Techniques

Design wind loads and dynamic wind responses of buildings can be reliably assessed using wind tunnel techniques. The NBC (NRC, 2020) recommends conducting wind tunnel tests for buildings whose natural frequency is lower than 0.25 Hz or whose height-to-minimum-effective-width ratio is greater than 6. Moreover, the code recommends using wind tunnel testing for buildings subjected to wake buffeting from upwind buildings or channelling effects. In the design of tall mass timber buildings, the resonant response could be contributed by higher modes of vibrations such as torsion and coupled translation-torsion. For example, Bezabeh et al.'s (2020b) study, the first five modes of a 40-storey tall mass timber building had frequencies less than 1 Hz, and higher modes exhibited significant nonlinearity and coupling. The NBC provisions reasonably estimate the peak floor acceleration of buildings dominated by the first uncoupled sway modes of vibrations. Consequently, it is recommended that wind tunnel testing be used when designing tall mass timber buildings with significant higher mode contributions. In addition, directional effects of wind can adequately be included when synthesizing wind tunnel test results with the microclimate (Warsido & Bitsuamlak, 2015) of the construction site, which usually results in a significant cost saving.

A wind tunnel facility for structural engineering applications was first developed in the 1960s at the University of Western Ontario (currently Western University). Since then, similar facilities of varying size have been built in different parts of the world, and wind tunnel tests have been routinely used to estimate design wind loads. In general, atmospheric boundary layer wind tunnels have a long testing chamber, floor roughness elements, spires, and end barriers to allow for the development of a thick boundary layer that has similar characteristics to the natural wind flow over the terrain. The following are the three commonly used test methods for predicting design wind loads and responses of tall buildings:

- high-frequency-base-balance procedure
- high-frequency-pressure-integration procedure
- aeroelastic model procedure

In the high-frequency-base-balance test, a lightweight and stiff replica of the prototype building is mounted on a very sensitive force-balance device to measure the time histories (spectral densities) of the aerodynamic base shears and moments. The following are the main assumptions of the high-frequency-base-balance test: (1) the response of the prototype building is due mainly to the fundamental sway modes of vibration, (2) the fundamental sway modes of vibration vary linearly over the height of the building (linear sway mode shapes), and (3) the excitation of the building by the wind involves negligible aerodynamic damping. Amplification by the resonance is included analytically in post-test desktop analysis using random vibration theory. This testing technique is more widely used than the aeroelastic procedure due to its simplicity in building and testing the models. Moreover, as long as the building aerodynamics are the same, the test results can be reused if the structural properties are revised after the test.

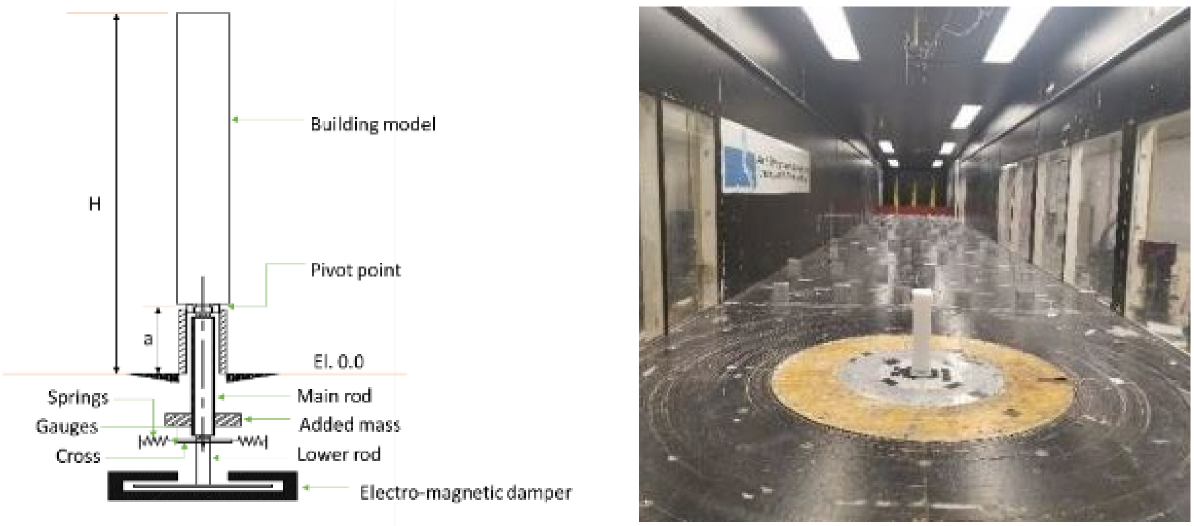


(a) (b)

Figure 20. Wind tunnel test of a 40-storey tall mass timber building model: (a) high-frequency-pressure-integration test setup; (b) closer view of the high-frequency-pressure-integration model.

The high-frequency-pressure-integration test uses hundreds of pressure taps installed on the surface of a rigid model to simultaneously measure the time histories of local aerodynamic forces. Figure 20 shows the typical test setup used during a high-frequency-pressure-integration wind tunnel test of a 40-storey tall mass timber building that was conducted at the Boundary Layer Wind Tunnel Laboratory at Western University. Synthesizing the measured local pressures requires assigning tributary areas for each tap. The storey-level and overall aerodynamic base forces can be computed by numerically integrating the time histories of measured pressures. The amplification by the resonance is included analytically in post-test computer analysis, using either random vibration theory or time domain analysis. The following are the main advantages of the high-frequency-pressure-integration test: (1) the test results can be used to design both the lateral load-resisting system and the cladding of the building; (2) the height-wise variation of aerodynamic loads, including torque, is relatively more accurate than high-frequency-base-balance test results (hence, with high-frequency-pressure-integration test data, both statistical and mechanical coupling of vibration modes can be incorporated into the estimation of the wind response of buildings); (3) as long as the building aerodynamics are the same, the high-frequency-pressure-integration test provides the flexibility of accommodating structural design changes without test repetition. The main limitation of this test procedure is the difficulty of installing pressure taps to capture pressure variations over porous cladding elements, very irregular cladding details, and structures with very small architectural features (such as lattice structures).

The aeroelastic model test is the final method reviewed in this section. Dynamic response evaluation of tall buildings based on both the high-frequency-base-balance and high-frequency-pressure-integration wind tunnel test involves several simplifying assumptions during the experimental phase and the post-test dynamic analysis. Inherently, both these models are rigid and do not include motion-dependent effects such as aerodynamic damping, which is related to the velocity of the wind-excited building. In the across-wind direction, aerodynamic damping can be positive or negative. Negative aerodynamic damping can significantly amplify dynamic across-wind responses. Galloping type instability can also be induced when negative aerodynamic damping overcomes inherent structural damping, and the wind speed reaches U_{crit}. Most tall buildings, however, operate below the U_{crit} in which aerodynamic damping is mostly positive. Compared to the high-frequency-base-balance and high-frequency-pressure-integration tests, aeroelastic procedures are more reliable and relatively accurate. Dynamic responses of study buildings, such as lateral drift, acceleration, and base bending moments can be measured directly from aeroelastic model tests. In aeroelastic tests, models sway and twist similar to the full-scale building under wind excitation; therefore, the dynamic properties of the building, such as mass, damping, and stiffness, should be modelled. In general, there are two categories of aeroelastic models: base-pivoted two-degrees-of-freedom aeroelastic model and multi-degree-of-freedom aeroelastic model. The choice of the aeroelastic model depends on the complexity of the structural system (such as higher mode effect, modal coupling, nonlinearity of mode shapes), the shape of the building, and the degree of accuracy sought.



(a) (b)

Figure 21. (a) Two-degrees-of-freedom aeroelastic model pivoted on a gimbal; (b) aeroelastic wind tunnel setup of a 40-storey mass timber building at the Boundary Layer Wind Tunnel Laboratory (Bezabeh et al., 2020b).

The two-degrees-of-freedom aeroelastic model is depicted in Figure 21a. The test setup inside the wind tunnel during the aeroelastic wind tunnel test of a 40-storey mass timber building model is shown in Figure 21b. Two-degrees-of-freedom aeroelastic tests are suitable for buildings dominated by uncoupled sway modes of vibration. Multi-degree-of-freedom aeroelastic models are suitable for buildings with complex 3D mode shapes, including torsion and coupled translation-torsion modes. In this procedure, it is customary to use a lightweight shell (such as balsawood or 3D printed parts) to model the building geometry and an aluminum spine to model the stiffness. During the test, the aeroelastic model is instrumented with accelerometers at the top occupied floor of the building model and a base balance to measure time histories of the overall moments and torsion.

5.3.4.2 Dynamic Response of Tall Mass Timber Buildings to Wind Excitations: Case Studies

Whereas the research on seismic response of mass timber buildings has progressed with reasonable success, little is known about the dynamic response and performance of tall timber-based buildings under wind excitations. In this regard, there has been a long-standing question among practising structural engineers and researchers about how high tall wood buildings can be built. To answer this question from a wind engineering perspective, the authors of this chapter launched a coordinated research program in 2016 between the University of British Columbia, Western University, and FPInnovations. It included several aerodynamic and aeroelastic wind tunnel tests at the Boundary Layer Wind Tunnel Laboratory. In total, 11 tall mass timber buildings were tested. The findings are reported in Bezabeh et al. (2018a, 2018b, 2018c, 2020a, 2020b). The following sections summarize the main findings of the research program, which focus on the parameters that affected the dynamic response of mass timber buildings excited by wind.

Two case studies on tall hybrid mass timber–concrete buildings are presented to illustrate some dynamic response concepts due to wind excitation. The 40-storey concrete jointed timber-frame concept by Skidmore, Owings, & Merril (SOM, 2013) is used to show the effect of height, turbulence, and structural damping; the 18-storey Brock Commons building at UBC is used to illustrate the effect of wake buffering and channelling. In the latter case study, the reinforced concrete (RC) core was replaced with a CLT core to help illustrate the result of more accurately determining buffeting effects from upstream structures.

5.3.4.2.1 Case Study 1: Effects of Building Height, Turbulence, and Structural Damping

The structural system of the mass timber building in this case study is shown in Figures 22 and 23. This structural system was first developed in 2013 by Skidmore, Owings, & Merril, LLP (SOM 2013) as part of the timber-tower concept development. The mass timber building consists of CLT floor, perimeter glulam columns, edge and link RC spandrel beams, and CLT shear and core walls. The CLT floor system is supported at the mid-span by the CLT walls and at the edge by the RC spandrel beams and perimeter glulam columns (Figure 23). In this structural system, the main elements of the lateral load-resisting system are the CLT core and shear walls, which resist both gravity and lateral wind loads. To increase the net uplift resistance when the wind is orthogonal to the broader face of the building, supplemental four shear walls are extended from the core walls to the perimeter spandrel beams. These shear walls are coupled using the RC link beams so that the whole lateral load-resisting system works as a unit. In addition to enhancing lateral stiffness, these link beams increase the dead weight of the building. The elements of the lateral load-resisting system are discontinued at each floor, similar to platform-type CLT construction. The elements of the lateral load-resisting system and gravity systems are connected using concrete joints at the interface of the CLT walls and CLT floor. The Holz-Stahl-Komposit connection modified by Zhang et al. (2018) is used.

Figure 22. 3D view of the 30-storey mass timber building (Bezabeh et al., 2020b).

The case study examined the dynamic response and serviceability performance of five isolated tall mass timber buildings of varying height (10-, 15-, 20-, 30-, and 40-storey). The floor-to-floor height and the plan dimensions of the buildings (the high-end condominium scheme in SOM [2013]) were 3.4 m and 42 m × 30 m, respectively. The buildings were structurally designed according to the 2015 National Building Code and CSA O86-14 standard. Eigenvalue analysis identified the fundamental frequencies of the 10-, 15-, 20-, 30-, and 40-storey buildings as 0.22 Hz, 0.33 Hz, 0.49 Hz, 0.67 Hz, and 0.82 Hz, respectively. It should be noted that the lowest 5 and 4 vibration of modes of the 40- and 30-storey buildings, respectively, were less than 1 Hz with significant coupling and nonlinearity. High-frequency-pressure integration wind tunnel tests were conducted to obtain floor-by-floor aerodynamic wind load time histories (see Figure 20 for the typical test setup). Dynamic structural analyses in the frequency domain were performed to calculate peak floor accelerations for various levels of critical damping ratio, wind direction, and exposure conditions.

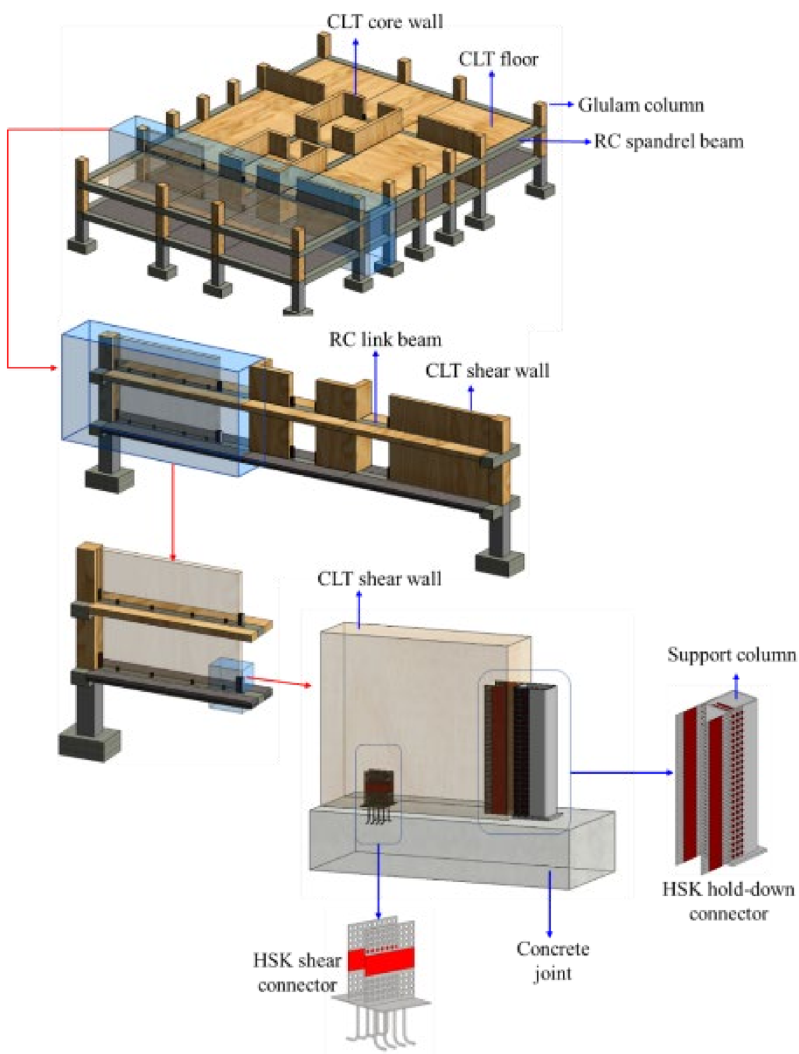


Figure 23. Structural system of the studied tall mass timber building (HSK = Holz-Stahl-Komposit) (Bezabeh et al., 2020b).

First, the effects of longitudinal turbulence were examined. The characteristics of the fluctuating aerodynamic wind loads can be adequately described using the spectral densities of the generalized forces. The spectral densities of the generalized along-, across-, and torsional-wind loads corresponding to the first three modal vibrations of the 40- and 10-storey mass timber buildings are presented in Figures 24 and 25, respectively. In the plots, the vertical axis is the normalized spectral density of the generalized forces, and the horizontal axis is the reduced frequency (fD/V_h), where *f*, *D*, V_h, $S_{FF}(f)$, and σ_f are the frequency, characteristic dimension of the building, wind speed at the building height, spectral density of the generalized force, and root-mean-square value of generalized wind force, respectively. In the figures, results are presented for the three exposure conditions defined in Figure 24 and zero wind angle of attack.

Figure 24 shows the normalized generalized force spectra of the 40-storey mass timber building under different wind exposure conditions. For all exposure conditions, the dynamic excitation of the building in the first mode is due to across-wind forces, which is characterized by a peak at the reduced frequency close to the Strouhal number of a rectangular prism. The effect of increasing the turbulence intensity (e.g., from open country to urban exposure) is to reduce the peak and slightly broaden the spectra. The generalized force spectra in the second mode follow the along-wind speed spectra. Hence, referring to the quasi-steady theory, wind excitations in the second mode are due to along-wind forces. Excitations in the third mode are the result of torsional moments. In all exposure conditions, the torsional moment spectrum has two peaks. The first spectral peak is due to the asymmetry in the vortex-shedding forces, and in an open country exposure, it occurs at fD/V_h ~ 0.1. The second peak in the torsional spectrum is the result of flow reattachment in the wake region. In all exposure conditions, the spectral characteristics of the first two modes of the 10-storey building are similar to the spectra of the wind gust, while the third mode generalized torsional spectra have a peak at fD/V_h ~ 0.1 (Figure 25). In general, vortex shedding in shorter tall mass timber buildings is less organized (nonperiodical) with broadened spectra. Hence, in the design of the 10-storey mass timber building, along-wind excitations dominated across-wind excitations.

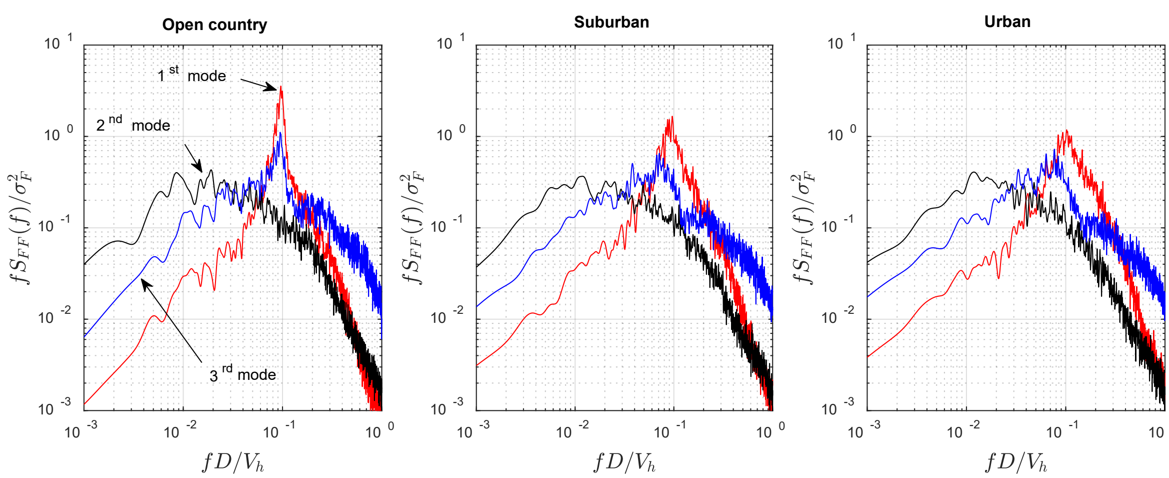


Figure 24. Spectra of the generalized forces of the 40-storey mass timber building (Bezabeh et al., 2020b).

The effect of longitudinal turbulence intensity on the dynamic response and serviceability performance was also studied. A parametric study on critical damping ratio and wind angle of attack was conducted. The results, in the form of resultant peak floor accelerations, are presented in Figures 26 and 27. In order not to lose generality, the influence of immediate surroundings was ignored, and directionality effects were included using the upper bound method. The resultant peak floor accelerations were calculated at the corner of the building floors, where the contribution from the torsional accelerations was included after transformation into translational components. To assess the habitability of the buildings, the comfort criteria of the NBC for residential (15 milli-g) and office buildings (25 milli-g) are included in the figures. As shown in Figure 26, for the 30- and 40-storey mass timber buildings, regardless of the critical damping ratio, the peak floor accelerations are reduced when the longitudinal intensity of turbulence increases (e.g., from open country to urban exposure). This is due mainly to the increase in local turbulence that deteriorates the periodicity vortex shedding in the wake regions. Another reason could be the increase in the reduced frequency of the buildings as exposures become rougher. In addition, peak floor accelerations are the highest for open country upstream exposure. Wind angle of attack = 0° and 90° are the most unfavourable wind directions. The acceleration response of buildings is inversely proportional to the square root of the critical damping ratio (ξ). Therefore, a small increase in damping could significantly reduce structural loads and accelerations. In all cases, doubling the damping reduces the peak floor accelerations by almost 30%.

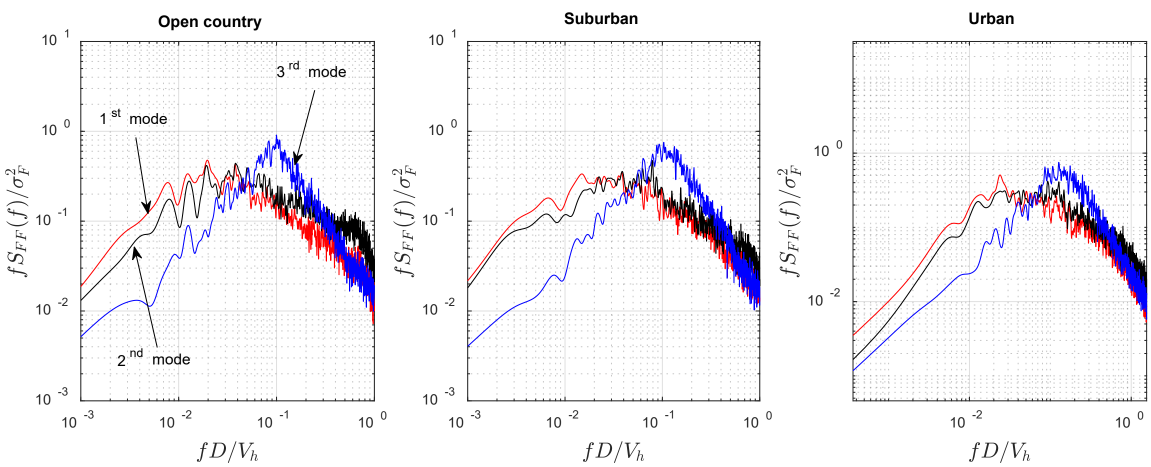
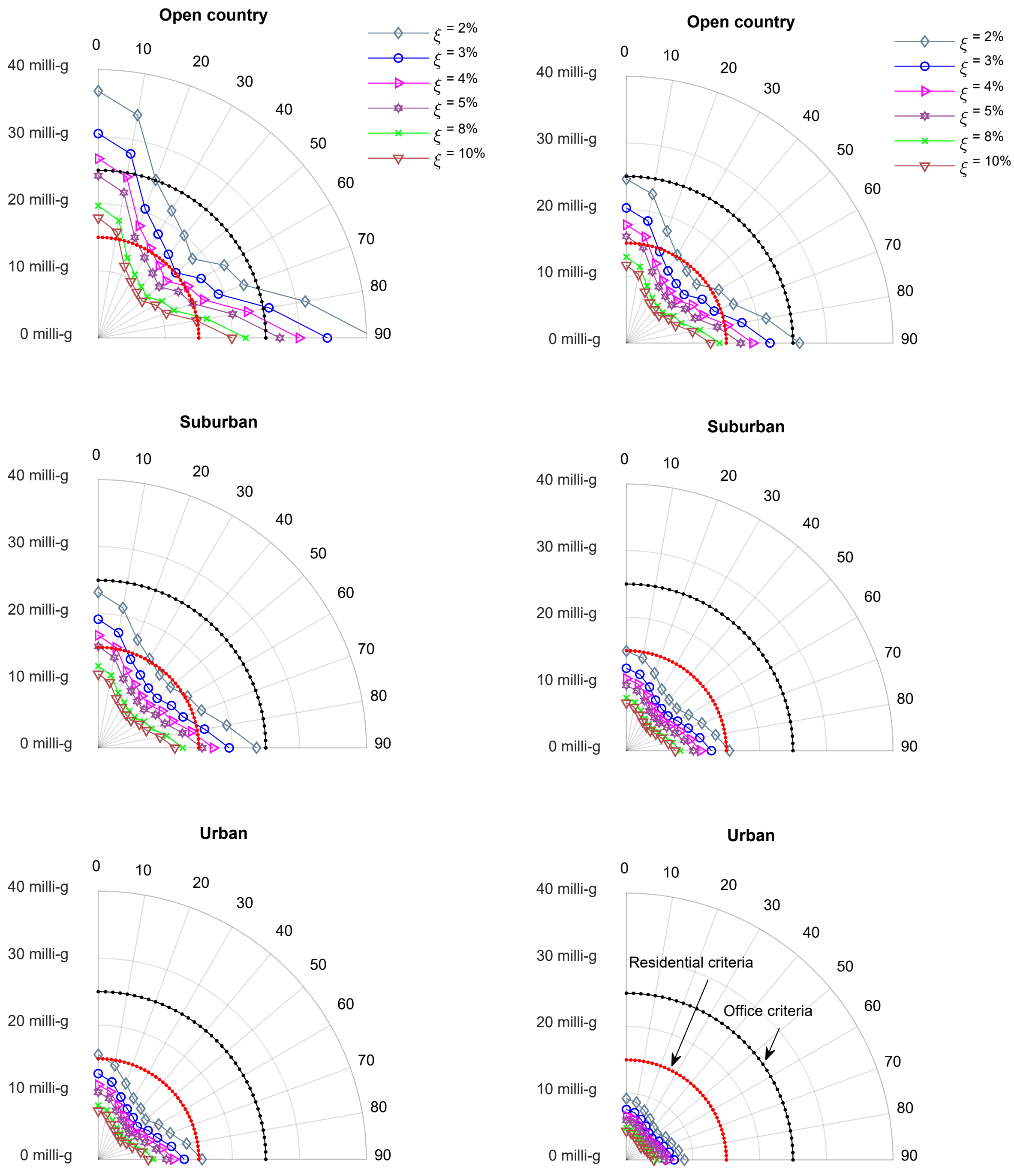


Figure 25. Spectra of the generalized forces of the 10-storey mass timber building (Bezabeh et al., 2020b).



(a) (b)

Figure 26. Effect of longitudinal turbulence intensity on the dynamic response of mass timber buildings: (a) 40-storey building; (b) 30-storey building.

The dynamic response of mass timber buildings under wind excitation is strongly dependent on the height of the building. Figure 26 compares the effect of building height on peak floor accelerations when the buildings are situated downstream of a suburban exposure condition. Under the suburban exposure condition, irrespective of the critical damping ratio, all buildings except the 40-storey mass timber building satisfy both the office and residential criteria of the NBC. As expected, as the building height increases, the peak floor accelerations increase significantly.

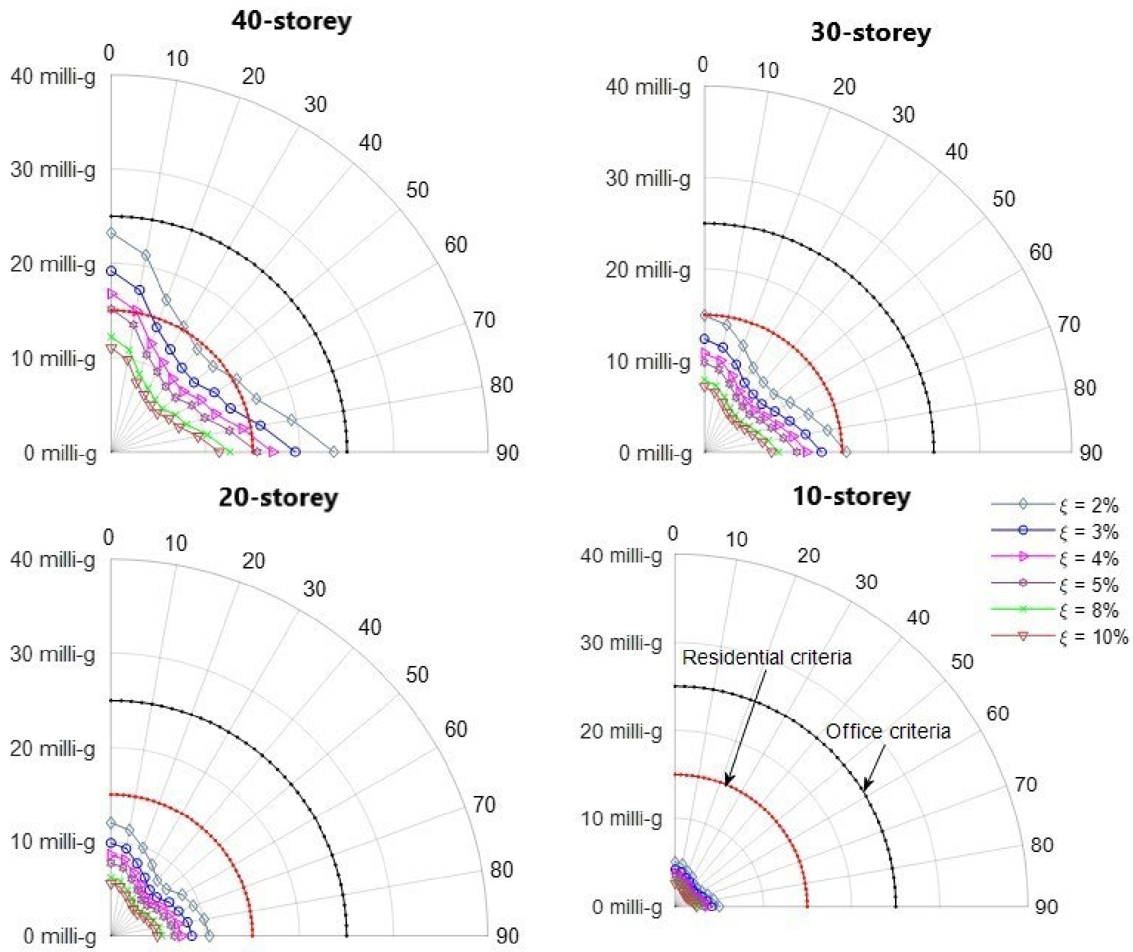
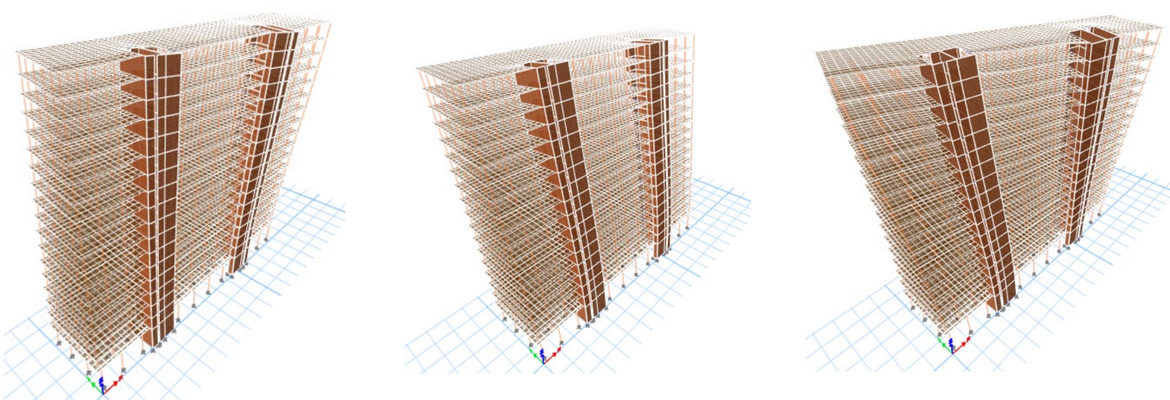


Figure 27. Effect of building height and structural damping on the dynamic response of mass timber buildings under a suburban exposure condition.

For suburban exposure and critical damping ratio greater than 5%, the 40-storey mass timber building satisfies both the residential and office criteria of the NBC. If the same mass timber building is situated downstream of a well-developed urban area, the building satisfies both criteria as long as the critical damping ratio is higher than 2%. If situated downstream of an open country area and a critical damping ratio greater than 2%, the 30-storey mass timber building can be used for office purposes (see Figure 26b). In order to use the same mass timber building as a residential building, the damping ratio should be more than 5%, but this can be achieved only if external damping devices are used. More results for various exposure conditions studied are provided in Bezabeh et al. (2020b).

5.3.4.2.2 Case Study 2: Effects of Wake Buffeting and Channelling

The characteristics and magnitude of aerodynamic loads on a building can be significantly affected by the building's immediate surroundings. The role of immediate surroundings cannot be described easily because they can reduce wind loads by sheltering or increase dynamic responses by strong buffeting effects from the wakes of upstream structures. To study the effect of wake buffeting and channelling, wind tunnel testing of the 18-storey Brock Commons mass timber building at UBC was conducted. The building has CLT panels for the floors and glulam for the columns, and two RC interior cores as the main lateral load-resisting system. Since the interest is the performance of tall mass timber buildings, the building was redesigned by replacing the RC core with a CLT core. Subsequently, modal analysis was carried out to identify the mode shapes, frequencies of vibration, and generalized mass (Figure 28). The first three frequencies of vibration of the building with CLT cores were 0.33 Hz, 0.43 Hz, and 0.44 Hz. An aerodynamic wind tunnel test of the building was conducted at a 1:200 geometric scale at the Boundary Layer Wind Tunnel Laboratory. To include the effect of the immediate surroundings, all important features up to a distance of approximately 500 m were included in the test (Figure 29). In order to include wind directionality effects, the wind tunnel tests were conducted for a wind angle of incidence between 0° and 360° at 10° increments. The 1-in-10-year wind speed at Vancouver, B.C. was predicted based on wind speed data recorded at Vancouver International Airport from 1965 to 2005. The sector-by-sector wind climate synthesis method was used to combine the aerodynamic data from the wind tunnel with the full-scale directional wind speeds. Dynamic analysis in the frequency domain was used to calculate the peak floor accelerations for the first three modes of vibrations, considering various levels of critical damping ratios (1.5%, 2%, 3%, 5%).



(a) (b) (c)

Figure 28. Mode shapes of the 18-storey Brock Commons mass timber building with CLT core walls: (a) first mode, (b) second mode, (c) third mode.

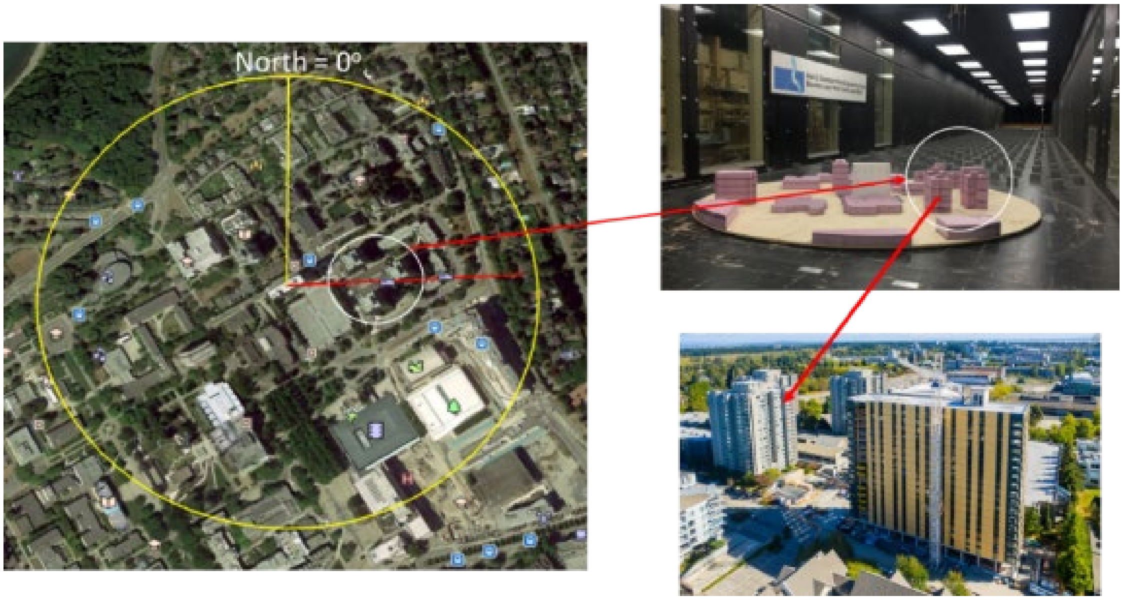
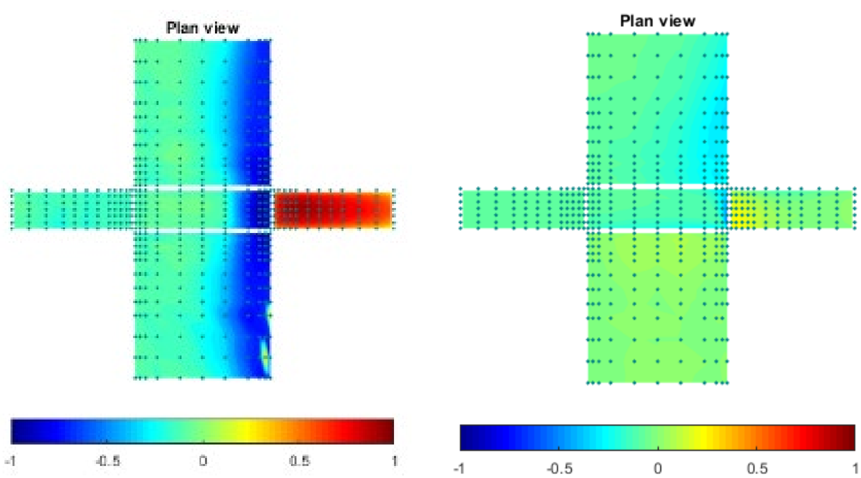


Figure 29. Wind tunnel test setup of the 18-storey Brock Commons mass timber building, including immediate surrounding structures, at the Boundary Layer Wind Tunnel Laboratory.

Figure 30 depicts the effect of the immediate surroundings on the aerodynamic pressure coefficients of a mass timber building. The figure compares the contours of the mean pressure coefficients of the isolated building and the building with the immediate surrounding when the wind angle of attack is 90° from true north in Vancouver. The building aerodynamics are significantly altered, due mainly to the presence of the adjacent three buildings, which are comparable in size to the building being studied.



(a) (b)

Figure 30. The role of immediate surroundings on building aerodynamics (angle of attack = 90°): (a) the mean Cp distribution over the surface of an isolated building; (b) the mean Cp distribution over the surface of the building with the immediate surroundings.

Figure 31 presents the peak floor acceleration responses of the case study mass timber building in the polar coordinates with the presence of the immediate surroundings. For the critical damping ratio of 1.5%, when the wind angle of incidence was 300° from true north in Vancouver, the mass timber building with the CLT core walls exceeded the residential requirement of the NBC. However, with a slight increase in the critical damping ratio (e.g., from 1.5% to 2%), the mass timber building with CLT core walls satisfied the criteria by a small margin. Overall, the results show the importance of the immediate surroundings and critical damping ratio. For project-specific studies, it is recommended that the influence of the immediate surroundings within a few kilometres of the mass timber building be included in the study.

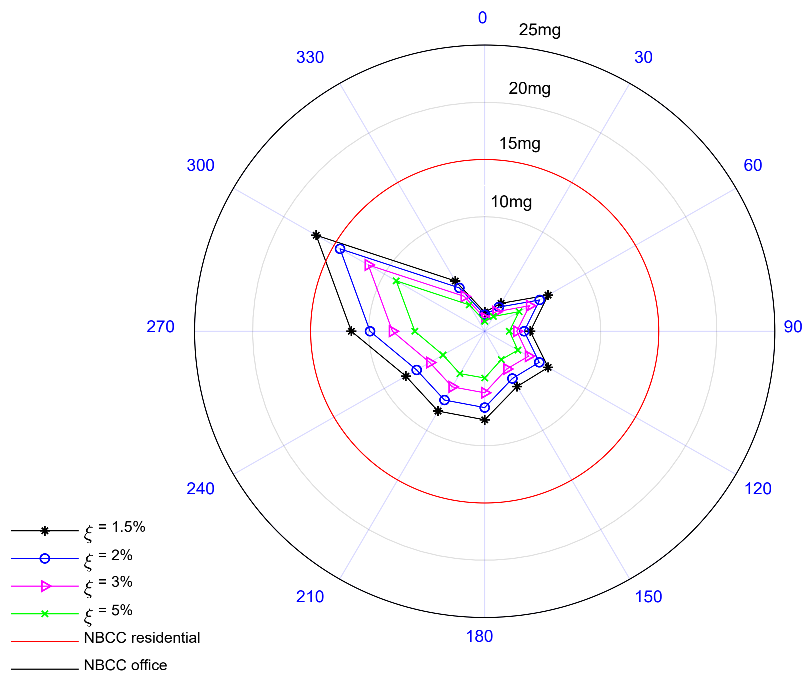


Figure 31. Resultant peak floor acceleration responses of the case study buildings in the polar coordinate (Bezabeh et al., 2020a).

5.3.4.3 Mitigation Strategies for Excessive Wind-Induced Motions in Tall Mass Timber Buildings

Under certain circumstances, the resultant peak floor accelerations of tall mass timber buildings could exceed the habitability criteria in the NBC. If the vibration frequency of a mass timber building is within the low-frequency tail of the wind spectrum (energy-containing region), the resonance component of the wind response contributes significantly to overall excessive wind-induced vibrations. In general, building motions can be reduced to some extent by changing the exterior geometry of the building. For a given shape, structural engineering solutions involve changing stiffness, mass, and structural damping. The following sections present mitigation strategies for excessive wind-induced motions in tall mass timber buildings.

5.3.4.3.1 Dynamic Wind Response Optimization

In many instances, changing the exterior geometry of buildings to reduce wind-induced responses involves the architect rather than the structural engineer. Hence, structural engineers usually end up altering the dynamic properties of the buildings, such as stiffness, mass, and damping (Warsido et al., 2009). To avoid this, the structural engineer should advise the architect at the beginning of the project to develop a more optimal geometry.

In this section, results from a parametric study on the effectiveness of these properties in reducing excessive wind-induced vibrations are discussed. The results are presented as a set of parametric maps that can guide structural engineers in altering a building's dynamic properties for optimal wind performance. For this purpose, the 40-storey tall mass timber building analyzed in Section 5.3.4.2 is considered as a benchmark. The generalized mass and stiffness of the building were varied from 50% to 300% at the increment of 10%. Two levels of critical damping ratio (ξ) were considered, including a very high $\xi = 5\%$ that can only be achieved through external damping systems. To vary the generalized mass and stiffness, two multipliers were considered: generalized stiffness multiplier ψ_K and generalized mass multiplier ψ_M. The parametric analysis was conducted for the most unfavourable aerodynamic direction when the wind blows orthogonal to the broader face of the building (angle of attack = 0°).

Figure 32 presents the parametric maps for the critical damping ratios of 2% and 5%, together with the habitability criteria of the NBC for office buildings (25 milli-g). As anticipated, increasing both the stiffness and mass of the building always reduced the peak floor accelerations. The rate at which the mass and stiffness reduced the peak floor accelerations was almost the same. For a given damping value, the parametric maps consistently show that excessive wind-induced vibrations can be controlled by (1) increasing the generalized mass while keeping the generalized stiffness at the benchmark value, or vice versa, and (2) simultaneously increasing both the generalized mass and stiffness.

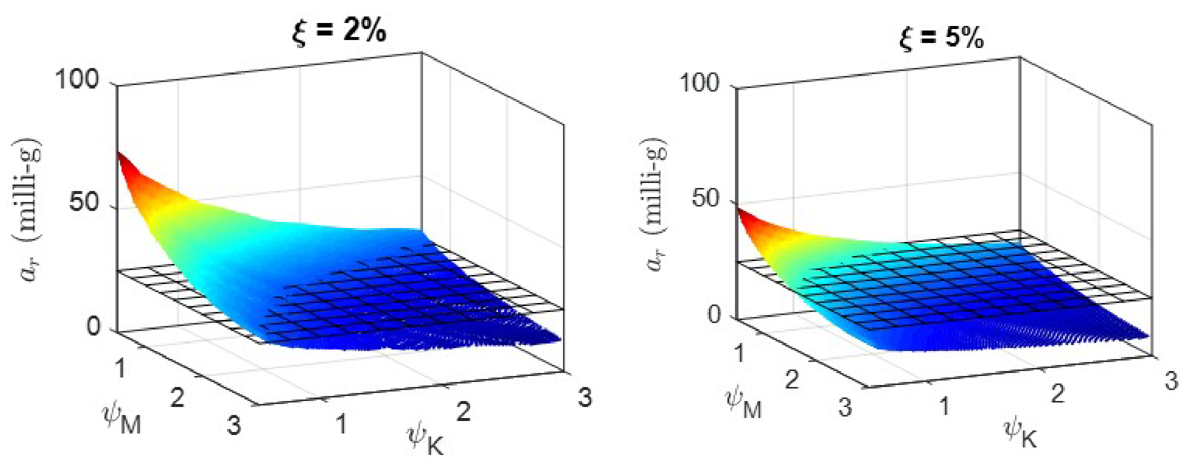


Figure 32. Parametric maps of peak floor accelerations of the 40-storey mass timber building.

A significant change in generalized stiffness may require changing the lateral load-resisting system of a mass timber building. In this regard, hybridizing the timber building with either steel or concrete will be a practical solution. For example the designers of two all-wood tall buildings in Norway used concrete slabs (power storeys in one building and number of upper storey slabs in the other one) to control wind-induced vibrations (Abrahamsen, 2015, 2017; Bjertnæs & Malo, 2014). More information on these buildings is provided in Section 5.1.

The construction of efficient hybrid mass timber structures has been reported in the literature; i.e., steel moment frames with CLT infill walls (Bezabeh et al., 2017), timber–steel core walls (Goertz et al., 2018), mass timber structures with concrete core walls (Tannert & Moudgil 2017), and steel–timber hybrid tall buildings (Chen & Chui, 2017; Green, 2012). Outrigger structures that connect CLT core walls and exterior columns can be used to reduce wind-induced vibrations of tall mass timber buildings. Typical layouts are depicted in Figure 33. Altering the stiffness and mass of a mass timber building makes it very effective at higher levels of critical damping. Overall, increasing the damping capacity is usually more efficient than increasing the stiffness and mass. Moreover, increasing the damping also reduces the susceptibility of mass timber buildings to vortex excitation. Enhancing damping capacity can be achieved through the use of passive and active supplemental damping systems, such as friction dampers, viscous dampers, yielding dampers, mass dampers, etc. Details on damping enhancement in tall buildings are provided in Irwin (2008), Kareem et al. (2013), and Vickery et al. (1983).

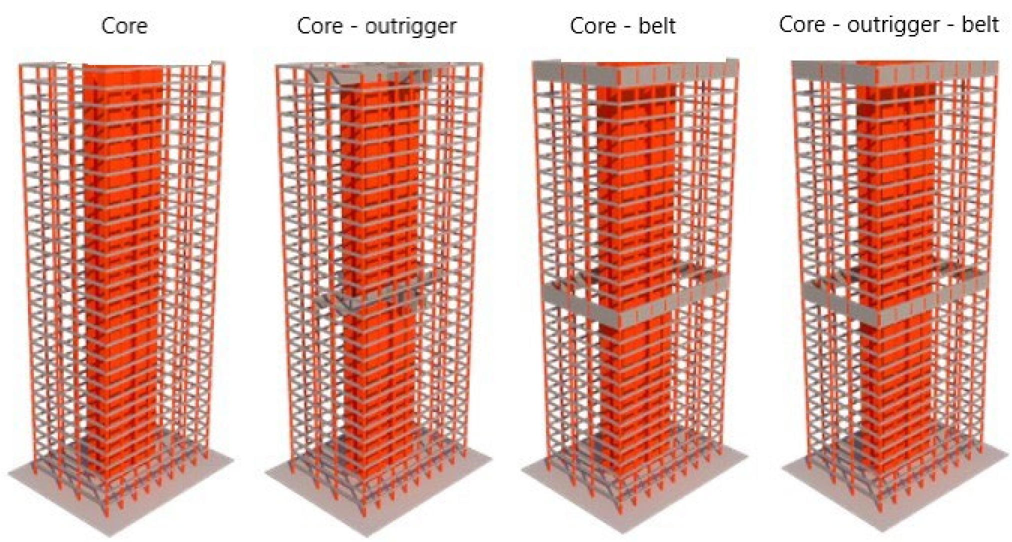
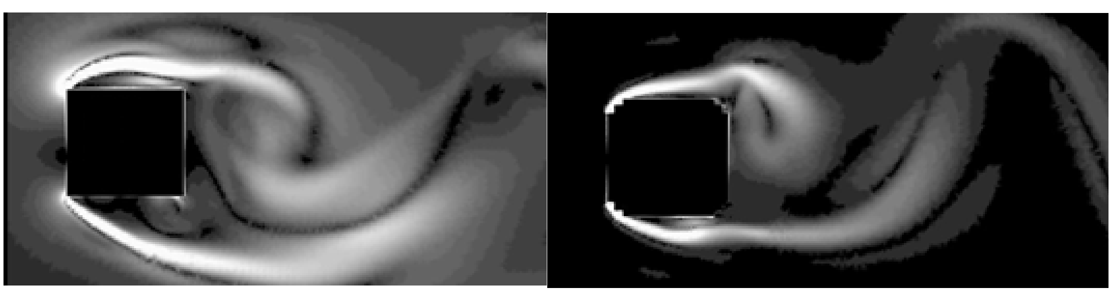


Figure 33. Application of outriggers for tall mass timber buildings: simple core, core and outrigger, core and belt, and core with outrigger and belt.

5.3.4.3.2 Aerodynamic Modifications

The results presented in the preceding sections and in the study by Bezabeh et al. (2020a) show that across-wind motions dominate the wind response of mass timber buildings that are taller than 10 storeys. It is generally recognized that vortex shedding in shorter buildings is less organized with broadened spectra, in which the across-wind responses are relatively small. Vortex excitation in taller mass timber buildings can be suppressed by increasing the stiffness, mass, and damping., as shown in Figure 32. At times, altering the dynamic properties of buildings could be a cost-prohibitive approach. On the other hand, aerodynamic measures have been routinely applied to reduce the vortex excitation in tall buildings, such as Taipei 101, the Burj Khalifa tower, and the Petronas Twin Towers (Irwin, 2008). The effect of shapes and the benefits of considering aerodynamic measures at the early design stage of tall buildings is illustrated in Merrick & Bitsuamlak (2009) and Elshaer et al. (2017). Typical aerodynamic measures include the softening of sharp corners by chamfering and rounding, the use of tapering and setbacks over the building height, and the use of spoilers and through-building openings. For square and rectangular buildings, chamfering of corners up to 10% of the building width can be beneficial in reducing the vortex excitation (Kwok, 2013; Tamura et al., 2010). Chamfering of corners alters the shear layer turbulence and the magnitude of wake energy around the shedding frequency. To illustrate this effect, a computational fluid dynamics approach was used to examine the aerodynamic characteristics of tall mass timber buildings with sharp and chamfered corners.

Figures 34a and 34b compare the pressure gradient of the flow field around the studied buildings. As expected, the chamfering of the corners affected the flow structure in the wake region and the reattachment points of the separated shear layers. The results indicate the possibility of reducing the overall along- and across-wind responses of taller mass timber buildings. Varying the shape of the cross-section over the height of the building through setbacks and tapering can also be effective in reducing the wind vibrations. This kind of aerodynamic mitigation reduces the coherence of the aerodynamic excitation (i.e., it confuses the wind). With the recent growth in computational capability, computational fluid dynamics has been used to perform aerodynamic optimization of tall buildings. For example, Elshaer & Bitsuamlak (2018) developed computational fluid dynamics based on automated shape optimization algorithms. Moreover, performance-based topology optimization algorithms, as reported in Spence (2018), can be used to perform both aerodynamic and structural optimizations of tall mass timber buildings.



(a) (b)

Figure 34. Comparison of aerodynamic characteristics of tall mass timber buildings with (a) sharp corners and (b) chamfered corners (courtesy of Tibebu Birhane and Girma Bitsuamlak).

5.3.4.4 Performance-Based Wind Design of Tall Mass Timber Buildings

In Davenport's Wind Loading Chain (Figure 17), the design of tall mass timber buildings for wind loads integrates the wind hazard, its turbulence, building aerodynamics, and structural properties to arrive at engineering demand parameters that should be compared with the performance criteria. However, each link within the Wind Loading Chain has its uncertainties, and the weakest link always dictates the design outcome. Consequently, the overall reliability of the design process is dominated by the link with the largest uncertainty. In the current design approaches used in building codes, uncertainties are accounted for by using safety coefficients; i.e., partial load and resistance factors. The underlying assumption behind this approach is the automatic propagation of uncertainties through the design process. The calibrated load factors in building codes may not account for additional uncertainties due to new construction materials such as mass timber (Bezabeh et al., 2018b). In general, the issue of damping uncertainty is significant in the design of tall mass timber buildings. As shown in Figures 26, 27, and 31, the dynamic response of tall mass timber buildings is highly dependent on the assumed critical damping ratio. The understanding and studies about the source and mechanism of structural damping in mass timber structures are not as mature as those regarding concrete or steel buildings. In the literature, full-scale data on damping in mass timber structures are very limited, scattered, and highly variable. Hence, for wind design and performance assessment of tall mass timber buildings, the most rational approach is to explicitly model and propagate uncertainties by using Davenport's Wind Loading Chain. In the study by Bezabeh et al. (2018b), a new probabilistic performance-based wind design framework was developed and used to design a 30-storey tall mass timber building. By using the framework, all uncertainties, including damping, could be directly modelled, and the habitability risk, including the cost of business interruption due to excessive motion, could be quantified so that the owners of the building could make an informed decision about the building's performance.

5.3.4.5 Design of Tall Mass Timber Buildings for Tornadic Wind Loads

A tornado, sometimes referred to as a twister, is a fast-spinning air column that stretches between the clouds and the Earth's surface (Gairola & Bitsuamlak, 2019). Tornadoes are often regarded as one of the most violent storms in nature. As indicated in the NBC (NRC, 2020), the probability of a building being hit by a tornado is extremely small; hence, designing for tornadic wind loads is generally uneconomical. The code also outlines key construction details to protect occupants' safety in tornado-prone areas. Because mass timber buildings are lightweight and have low lateral stiffness, when they are subjected to extreme windstorms like violent tornadoes, their drift-sensitive components could be susceptible to damage due to increased deflection. Bezabeh et al. (2018c) used experimentally simulated tornado-like wind fields to assess the structural performance of a 10-storey mass timber building that was designed according to NBC criteria. The study showed that strong tornadoes may cause significant damage to drift-sensitive nonstructural components of mass timber buildings. Proposed roadmaps for improving the design of mass timber buildings in tornado-prone areas are provided in Bezabeh et al. (2018c).

5.3.5 STRUCTURAL VIBRATION CONTROL AND LOW SEISMIC DAMAGE

5.3.5.1 Code Design Objectives

Building owners and the general public usually believe that if a building satisfies the code provisions related to seismic design, no damage to the building is to be expected during a seismic event. Experiences from earthquakes during the last few decades (e.g., the 1994 Northridge [Los Angeles], 1995 Kobe [Japan], and 2011 Christchurch [New Zealand] earthquakes) have forced recognition that damage, sometimes severe, can occur in buildings designed in accordance with building codes. For example, during the Christchurch earthquake, apart from two buildings that fully collapsed during the earthquake, most of the modern buildings met the code-specified goal of life safety. In most cases, however, this was accompanied by major structural and nonstructural damage. The extent of the structural damage in many buildings was so great that close to 1100 buildings that "performed adequately" according to the code objectives had to be fully or partially demolished (CERC, 2012). The number of demolitions, the cost of repairs, and insured losses related to structural and nonstructural damage and business disruption after a large earthquake have substantial financial and social impact.

5.3.5.2 Types of Seismic Isolation and Vibration Control

The structural and nonstructural damage observed in earthquakes has accelerated the development of new solutions and technologies for the seismic design of buildings that focus on reducing sustained damage during and after major earthquakes. These solutions ensure that the inflicted damage during a severe earthquake event is relatively small and can be easily repaired with minimal disruption and downtime for building users. Over the past three decades, numerous structural vibration control and low-damage technologies have been developed that can be cost-competitively incorporated into the structure. Although many of the vibration control and low-damage technologies are inter-related and not mutually exclusive, they can be grouped into three main categories of energy dissipation and vibration control: (a) passive control, (b) active control, and (c) hybrid control.

Methods of passive control include base isolation, use of various types of dampers or other energy-dissipation devices (also called fuses) at critical locations in the building that can be used either solely or with base isolation, and controlled rocking systems with or without energy dissipators. The concept of base isolation consists of a layer of elastomeric bearings with low horizontal stiffness that are placed between the ground and the building so that the bearings deform rather than the building. The low horizontal stiffness of the bearings results in a modified structure that has a fundamental period that is much longer than that of a building on a fixed base. The increase in the fundamental period of the building (to 2–3 seconds) significantly reduces the force demand during a seismic event. Similarly, fuses such as mechanical dampers, friction dampers, and viscous dampers isolate energy dissipation at designated locations to protect the structure and expedite recovery. The response of these systems needs to be evaluated using nonlinear dynamic analysis in which the excitation is consistent with the requirements in the latest NBC provisions (NRC, 2020). This approach would normally comprise ground motion time histories that have spectra that are compatible with the NBC Commentary J specified design spectral acceleration values for a particular location, including both site effects and the appropriate importance factor.

Detailed information on the seismic design of buildings using energy dissipation devices such as viscous dampers and base isolation, including both theory and examples of practical applications, are provided in in Section 4.1.8.20 of the NBC (NRC, 2020), Chapter 16 of ASCE/SEI 7-16 (ASCE, 2016), Chapter 12 of FEMA P-1050-1 (FEMA, 2015), and their commentaries.

Active control systems can adapt their properties based on differences in earthquake excitations, their frequency content, and the building response at any instant in time. To have such capabilities, active systems must be connected to a high-power computational source and have sophisticated computer algorithms, which makes them very expensive. Moreover, adding mechanical energy actively to the building during a seismic response may cause stability problems in the structure. These drawbacks can be remedied by using semi-active (hybrid) control systems, which can provide the proper amount of damping without causing stability problems.

The use of other active and passive systems, such as tuned mass dampers, may also be explored. For example, water tanks at the top of a tall wood building that serve as a backup supply for the fire sprinkler system, as discussed in Chapter 6, can be designed to act as mass dampers (e.g., tuned liquid column dampers) to alter how the building responds to seismic and wind loading.

5.3.5.2.1 Rocking Self-Centring Post-tensioned Systems

The rocking mechanism, as a method of resisting lateral earthquake forces, has been used in structures since ancient times. The principle is the same with modern structural rocking mechanisms, which use high-strength post-tensioned rods acting as a controller to ensure that the structure returns back to its original position after the shaking. Such a high-performance structural system was developed in the United States in the 1990s, as part of the Precast Seismic Structural Systems (PRESSS) research program (Priestley et al., 1999). The system was first used in precast reinforced concrete moment frames or interconnected concrete shear walls, then in steel moment frames (Christopoulos et al., 2008), and lastly, it has been introduced into wood structures (Palermo et al., 2006a). The wood solution of this system, named Pres-Lam™, was developed at the University of Canterbury with the support of the Structural Timber Innovation Company Ltd., a research consortium of the timber industry, universities, and the New Zealand government. The seismic forces and movements are accommodated through a controlled rocking mechanism of mass timber elements such as glulam beams, laminated veneer lumber, laminated strand lumber, and CLT panels used as walls (Figure 35). The structural elements are held together by long, unbonded, high-strength steel tendons that provide self-centring capabilities. The energy dissipation is provided by the yielding of replaceable mild steel axial fuses placed between the column and the beams or at the bottom of the walls, or U-shaped flexural plates between the walls, or by other energy dissipation devices, such as hysteretic or friction dampers.

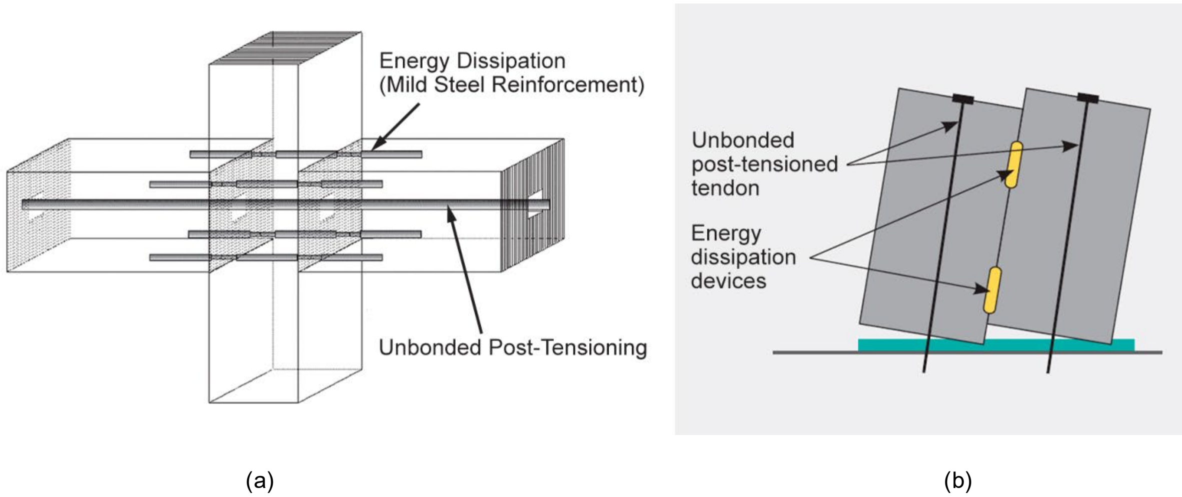


Figure 35. Post-tensioning details of (a) a beam–column frame structure, and (b) a wall system.

The system is sometimes called a "flag-shaped" hybrid system because of the way it self-centres and because of the shape of the cumulative (hybrid) hysteresis curve. The combined hysteresis curve of such a system is shown in Figure 36. Post-tensioning helps the frame or wall return to its original position, whereas supplemental damping devices dissipate seismic energy through ductile yielding in tension or bending.

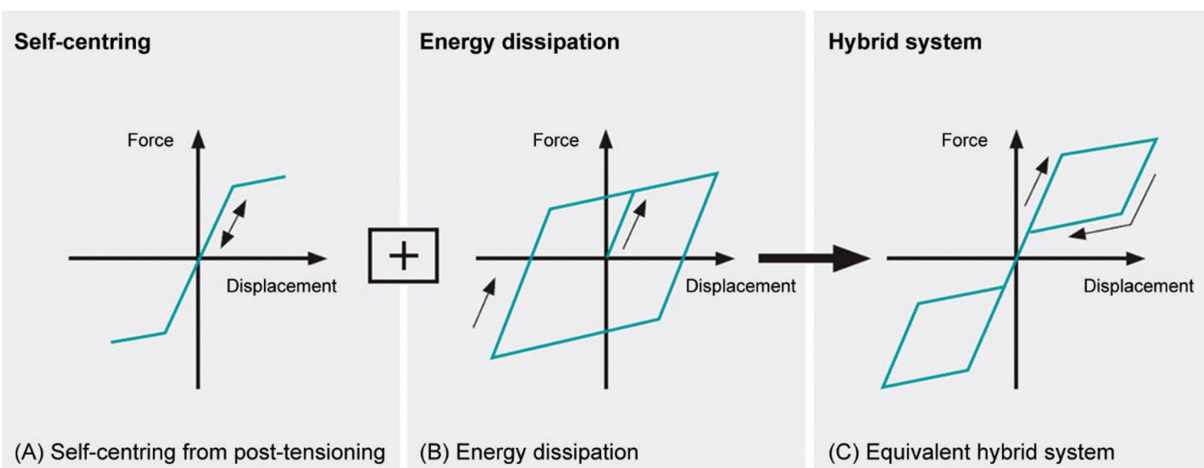


Figure 36. Self centring, energy dissipation and hybrid system hysteresis for the Pres-Lam system (CERC, 2012).

The system can be used for the construction of a wide range of residential and nonresidential buildings in low- to high-rise applications. From an economic standpoint, this system may have higher initial construction costs, but they may be offset by the fact that such a building will experience little or no structural damage after a strong seismic event, which will result in minimal repairs of the structural system and consequently lower insurance premiums. While some damage to the nonstructural components is to be expected, these buildings will still require less downtime for repairs following a strong earthquake compared to regular buildings. In addition, this system eliminates any potential demolition and reconstruction, which is significant not only from an economic standpoint but also from an environmental perspective. Special design detailing of the diaphragms is needed to allow for rocking of the walls.

Figure 37. Coupled mass timber walls with post-tensioning cables and axial energy dissipators in the Trimble Office building, Christchurch, New Zealand.

The system has been used in several single- and multi-storey buildings in New Zealand and the United States and one in Japan. The interior of one of the buildings in New Zealand, the Trimble Office which has coupled mass timber walls and energy dissipators at the bottom of the wall, as well as U-shaped flexural plates between the walls, is shown in Figure 37.

Figure 38. Erection of mass timber post-tensioned walls at the Peavy Hall building.

The first building of this type in the United States was the George W. Peavy Hall, a 3-storey mass timber structure located at the College of Forestry, Oregon State University in Corvallis, Oregon. The seismic force-resisting system is also made of post-tensioned CLT rocking shear walls with U-shaped flexural plates (Figure 38), while CLT–concrete composite floors take the gravity loads to the glulam beams and columns. Another building in the United States that was planned to include the Pres-Lam™ wall system as a seismic force-resisting system was the Framework building, which was to be built in Portland, Oregon but was cancelled due to financial issues. Framework would have been the first high-rise building in the United States made from wood and the first earthquake-resilient building of its kind (Figure 39).

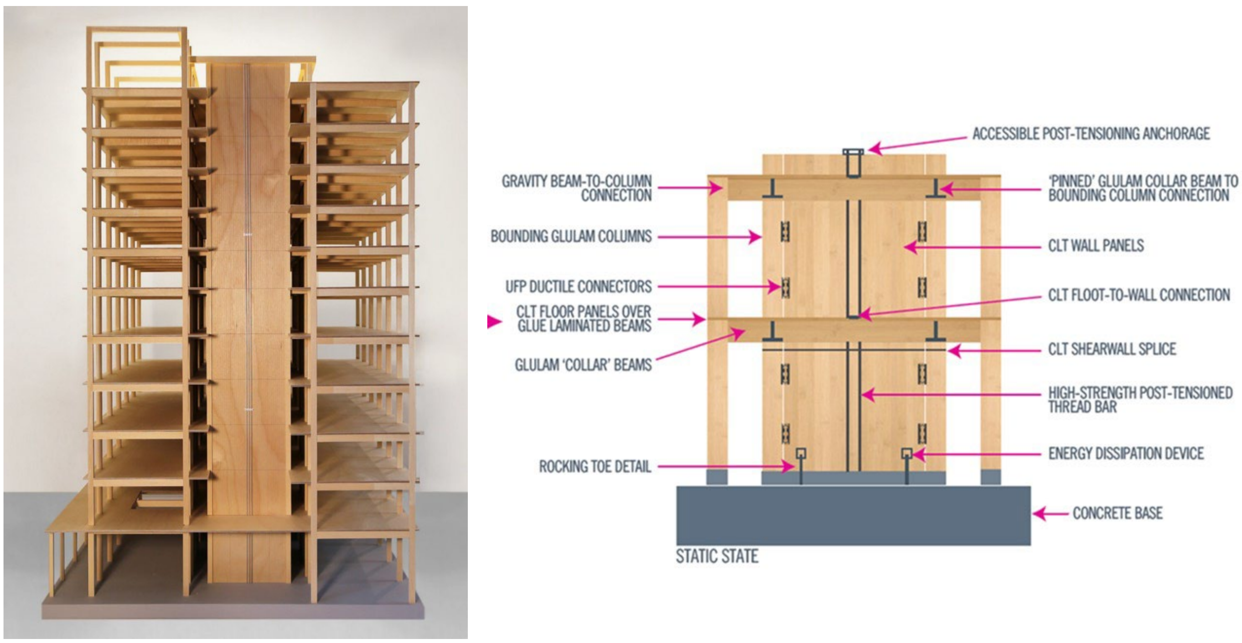


Figure 39. Rendering of the Framework building with a continuous Pre-Lam™ wall system (left) and detail of the Pres-Lam™ wall system (right) (courtesy of KPFF).

The Framework building project was awarded a prize of US$1.5 million to fund the research necessary to use the wood products in high-rise construction. Extensive testing was conducted at Oregon State University and Portland State University to generate performance data on many aspects of the lateral and the gravity load-resisting systems for the Framework building (OSU/PSU 2017).

In general, seismic design of Pres-Lam™ systems involves a careful balance of number of different parameters. The most important include the following: (i) the level of the post-tensioning force; (ii) the diameter of the steel cables and their yield strength; (iii) the recentring capability of the walls; (iv) the type of energy dissipators (fuses); (vi) the placement of the fuses, and their yield strength and ductility; and (vii) the material properties of the mass timber walls, particularly their compression strength and stiffness in the longitudinal direction. Post-tensioned timber under high compressive stresses experiences some axial shortening due to creep and relaxation in the "parallel-to-the-grain" direction.

The associated losses in post-tensioning have to be allowed for in the design. Because strength and stiffness perpendicular to grain of the column elements is much lower than those parallel to grain, and shrinkage is greater, columns in post-tensioned beam-column joints require reinforcement that takes into consideration wood shrinkage and the lower strength and stiffness of wood perpendicular to grain as compared to parallel to grain.

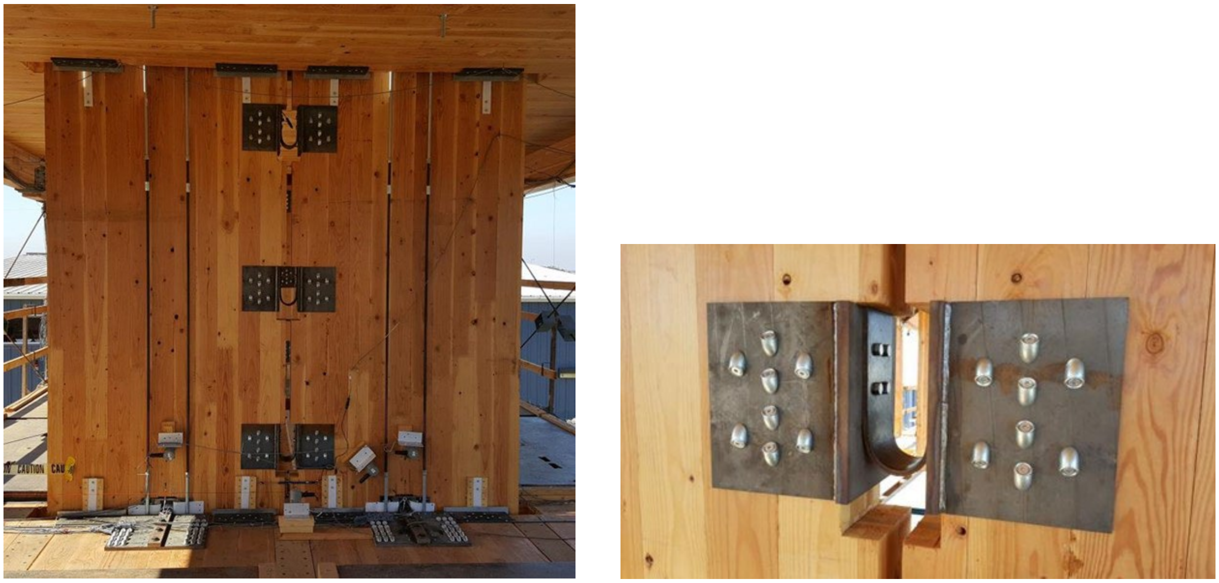
Currently, there are no design guidelines in Canada for this system. Some guidelines have been developed for other countries. Although they have not been developed for Canadian codes and standards, they can serve as a valuable resource for designers in Canada. Design guidelines for Pres-Lam™ systems were developed by the Structural Timber Innovation Company Ltd. in New Zealand for Australia and New Zealand (STIC, 2013). The design guidelines consist of three parts. Part 1 provides mainly background information on the Pres-Lam™ technology, and outlines general principles for design and construction, with examples from experimental testing at the University of Canterbury and details from recently completed buildings in New Zealand. Most of the principles in Part 1 apply equally in Australia and New Zealand. Part 2 gives the detailed design methodology and worked examples of seismic design for a 5-storey case study building in New Zealand that was designed in accordance with New Zealand Standards. Part 3 provides detailed design methodology and worked examples for gravity design of the same case study building. Design examples in Part 3 are intended for buildings where no seismic design is required, or where the lateral loads are resisted by structural elements that are designed separately.

A design guide for Pres-Lam™ wall systems in the United States is currently being developed by a team of designers from KPFF, Holmes Structures, researchers from the Colorado School of Mines and FPInnovations, and staff from the American Wood Council and WoodWorks US. Until a Canadian guide is developed, this guide will be very beneficial not only to designers in the United States but also to those in Canada.

In terms of research, a wide range of structural testing on the Pres-Lam™ system using laminated veneer lumber has been carried out over the last 15 years in New Zealand, the United States, and Canada. Some of the most important work is outlined below as a reference for designers. The influence of initial post-tensioning force level, and internal and external mild steel axial energy dissipators (also called fuses) on single post-tensioned walls was investigated by Marriott et al. (2008) and Palermo et al. (2005, 2006a, 2006b). The hybrid energy dissipation effect of coupled post-tensioned walls using U-shaped flexural plates (Iqbal et al., 2015) and nailed plywood panels (Iqbal 2011; Iqbal et al., 2017) was also studied. Sarti (2015) and Sarti et al. (2016a, 2016b) examined the structural performance of a column-wall-column system with fuses and U-shaped flexural plates. The entire building performance of a 2-storey Pres-Lam™ construction, including Pres-Lam™ frames and walls in different directions, was also studied by testing (Newcombe et al., 2010).

Figure 40. Full-scale 2-storey CLT building tested at the shaking table, University of California San Diego.

Five single walls with varying post-tensioning areas, initial tensioning force, CLT panel composition, and rocking surface, and one coupled wall with U-shaped flexural plates as coupling devices were tested by Ganey et al. (2017). The results showed that the CLT walls were able to recentre even after large drift cycles and that the crushing of the CLT material was the governing limit state for most specimens. Hybrid walls that combined post-tensioned CLT walls and light-frame wood shear walls were tested and numerically analyzed by Ho et al. (2017). The results indicated that such a hybrid system possesses high performance (recentring capacity and energy dissipation) during strong ground shaking. Pres-Lam™ CLT core walls with screws or U-shaped flexural plates were tested by Moroder et al. (2018). The Pres-Lam™ CLT lift shafts and stairwell core walls provided not only a strong and very stiff lateral load-resisting system but also a damage-limiting response in the case of a large seismic event. Pei et al. (2018, 2019) tested a full-scale 2-storey CLT building at the largest shake table in the United States (at the University of California San Diego) to study the dynamic behaviour of the building with a Pres-Lam™ wall system. The results showed that Pres-Lam™ CLT walls can be designed to be compatible with heavy timber gravity frames to provide an open floor plan building that will survive repeated earthquakes at design basis earthquake and maximum considered earthquake intensity levels without visible damage (Figures 40 and 41).



(a) (b)

Figure 41. (a) The Pres-Lam™ coupled wall part of the seismic force-resisting system of the 2-storey structure tested at the shaking table at the University of California San Diego; (b) detail of the U-shaped flexural plates between the walls.

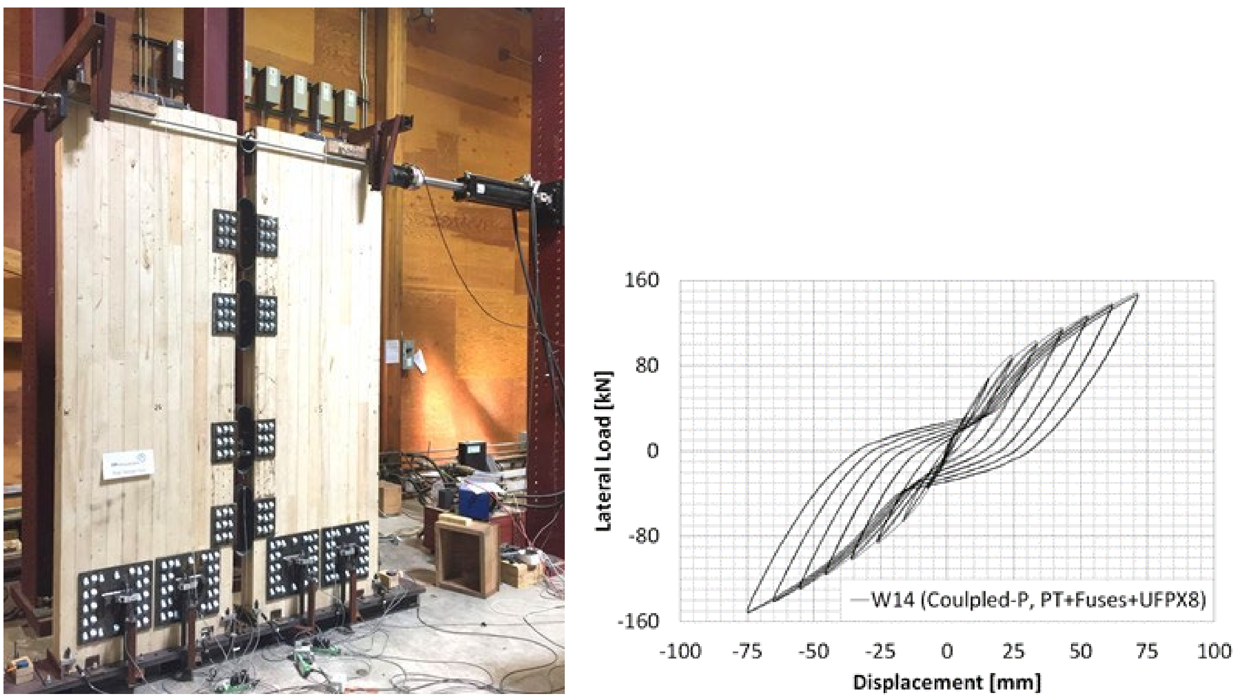
In Canada, the lateral-load response of post-tensioned only and Pres-Lam™ CLT shear walls was investigated by Chen & Popovski (2020a). In total, 14 different full-scale post-tensioning only or Pres-Lam™ walls with four configurations were tested under monotonic and reversed cyclic loading (Figure 42). The difference in performance among the wall configurations was investigated, and the influence of key parameters on the structural performance of the walls was discussed. An increase in the level of post-tensioning force resulted in an increase in (a) the rocking resistance of the walls, (b) the secant stiffness K_2, and (c) the load at the decompression point (when the wall starts to lift from the foundation) in walls with post-tensioned cables only. Even though the energy dissipation for these walls was low, it still increased with an increase in the post-tensioning force. In this case, the energy dissipation was caused by the crushing of wood at the bottom of the walls. The energy dissipation in the Pres-Lam™ walls was about 10 times that of post-tensioned only walls. The energy dissipation decreased with an increase in the post-tensioning force because a higher post-tensioning force causes a higher overturning resistance in the walls, which reduces the effect of energy dissipation in the fuses.

Increasing the distance between the two axial fuses from 333 mm to 500 mm resulted in an increase in energy dissipation of 59%, while the load at the decompression point increased by only 9.5%. Increased distance between the fuses had negligible influence on the initial stiffness (K_1) and resistance of the Pres-Lam™ walls. Coupled Pres-Lam™ walls with eight U-shaped flexural plates had a 19% increase in the load at the decompression point. The influence of the number of U-shaped flexural plates on the stiffness, resistance, and energy dissipation of coupled Pres-Lam™ CLT walls was not obvious because the fuses had a higher overturning resistance in each panel, which reduced the effect of the U-shaped flexural plates. The test results also showed that the behaviour of the Pres-

Lam™ CLT shear walls could be decoupled, and a superposition rule could be applied to obtain the stiffness, resistance, and energy dissipation of such systems. In other words, the properties of a coupled Pres-Lam™ CLT shear wall ($M_{Pres-lam}$) could be estimated using Equation [27], by using the mechanical properties of two single-panel Pres-Lam™ CLT walls ($M_{(PT+Fuse)}$), a coupled-panel post-tensioned CLT wall with U-shaped flexural plates $M_{(PT+UFP)}$, and two single-panel post-tensioned only CLT walls (M_{PT}).

$$M_{Pres-lam} = M_{(PT+Fuse)} + M_{(PT+UFP)} - M_{PT} \quad [27]$$

Yielding and buckling of the fuses occurred at the early stage of loading as designed, and localized crushing of wood at the end of the panels happened when the lateral drift was at or beyond 2.5%.



(a) (b)

Figure 42. (a) Coupled Pres-Lam™ walls tested at FPInnovations; (b) typical hysteretic curve of coupled Pres-Lam™ walls with axial fuses and U-shaped flexural plates obtained from the testing.

A consortium of U.S. universities and international partners, including FPInnovations, led by Dr. Pei from the Colorado School of Mines, is planning to test a 10-storey Press-Lam™ building at the shaking table at the University of California San Diego toward the end of 2021. At the time of writing this guide, the gravity design of the building had been completed and a significant amount of research on component level was underway at several U.S. universities. The seismic force-resisting system consists of four continuous post-tensioned rocking walls on each side of the building (Figure 43). There are different floor plans along the height of the building that are related to different types of usage, such as retail (storeys 1 and 2), office (storeys 3–6), and residential (storeys 7–10). This will be the tallest timber building ever tested on a shaking table. Information on the progress of all activities related to this project can be obtained at http://nheritallwood.mines.edu/task8.html.

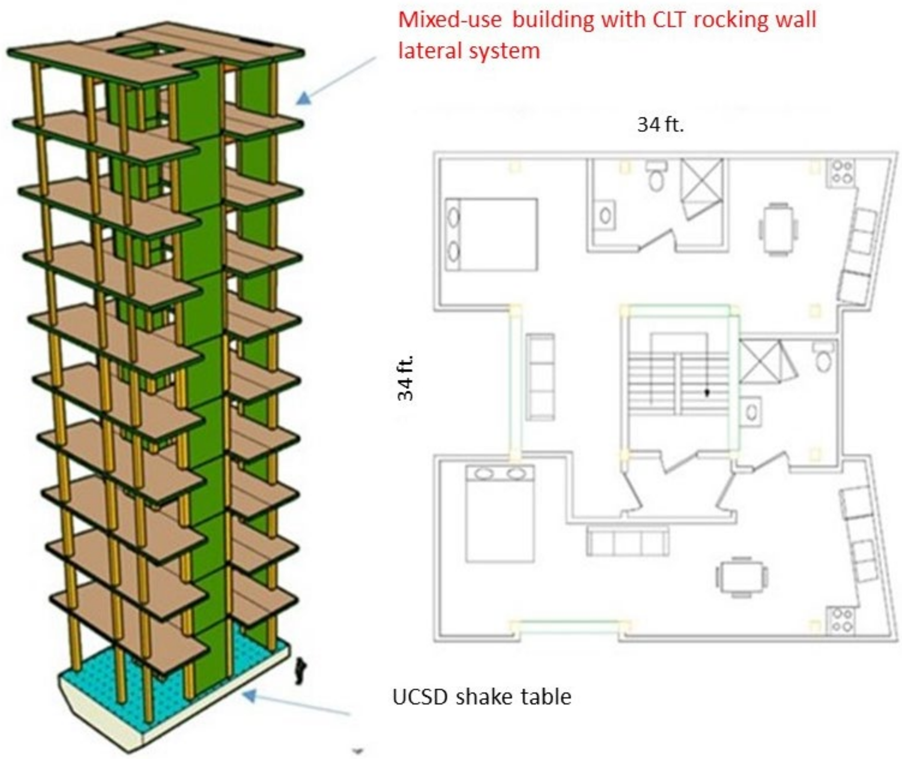


Figure 43. Structural system of the 10-storey building (left) and typical residential floor plan (right).

5.3.5.2.2 Systems with Friction Dampers

Because friction dampers are designed to slip before structural members yield, they act as a reusable fuse that dissipates seismic input energy without the need for replacement after an earthquake event. In doing so, the building can withstand an earthquake without sustaining significant damage to its structure. The inline friction damper dissipates energy as the elements of the damper slide relative to one another in both tension and compression, thereby converting an earthquake's kinetic energy directly into thermal energy in a nondestructive process. The benefits of friction dampers compared to other methods of dissipating energy include low cost and maintenance, ease of design and installation, and insensitivity to velocity and temperature. Some friction dampers have a rectangular hysteretic loop, which is the highest possible energy dissipation per cycle. They can be installed in parallel to resist large loads and can act as load-limiting devices (to prevent buckling or limit column and foundation loads).

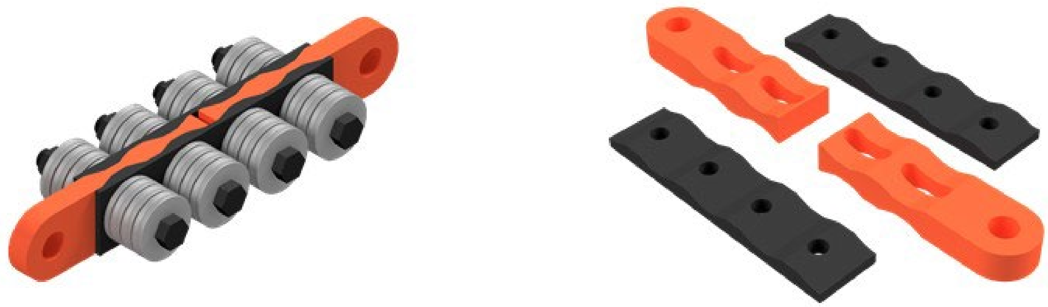


Figure 44. A typical Resilient Slip Friction Joint (left) and its profiled plates (right).

One such friction damper (connection) that was designed for timber structures to avoid damage during seismic events is the Resilient Slip Friction Joint (RSFJ) (Figure 44). The RSFJ, developed at the University of Auckland, New Zealand, can provide damping through friction and has self-centring capability. The combination of its friction damping capability and self-centring ability makes this device both an ideal ductile fuse and damage avoidant. In its normal operation, there is no yielding of any component. The fuse resets itself after an earthquake event, thereby, eliminating any loss of stiffness and restoring the building to its initial position, as shown by the hysteresis loop in Figure 45.

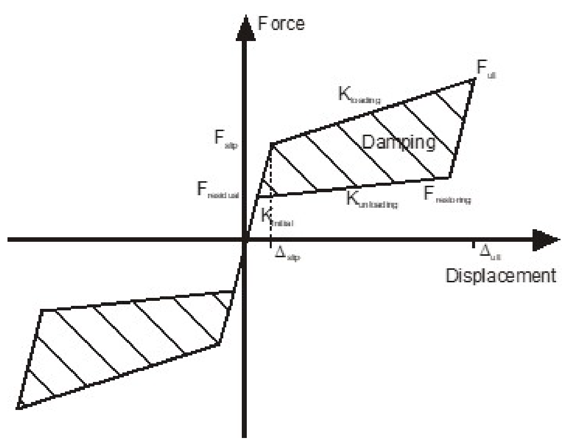


Figure 45. Flag-shaped load-deformation response of the Resilient Slip Friction Joint.

Its operation is simple. The RSFJ connects two structural timber members through its deformed middle plates. The bolts compress disc springs that press matching deformed cap plates onto the two middle plates to provide an initial rigidity to the device in order to prevent any movement under small load demands (wind or small earthquakes). When an earthquake of a certain magnitude strikes, it imposes a displacement demand on the device, and the middle plates are either pulled apart or pushed closer together. Because of the deformed shape of the plates, the two cap plates are pushed apart, and the outside disc springs are further compressed. The compressed disc springs provide a restoring force that brings the device back to its initial position following the earthquake loading. This can be repeated as many times as required as long as the force demand remains within the design load (deformation range) of the RSFJ.

The dimensions and configuration of the RSFJ can vary to provide different levels of resistance and damping. Typically, the device damping ranges between 15 and 20%, depending on the amount of displacement provided. The damping ratio provided by this technology is one of the highest compared to other self-centring systems. The number of bolts, the angle of the grooves, the level of prestress of the bolts/disc springs assembly, and the number of disc springs are all design variables that allow the device to be customized for a range of demands. This variability in configuration results in a multitude of potential flag-shaped load deformation relationships, which can accommodate different load and displacement levels.

The RSFJ can be used in all possible seismic force-resisting systems. As shown in Figure 46 (left), it can be part of a timber brace to offer the required ductility in a chevron-type mass timber braced frame. Two RSFJ units of 300 kN capacity each were used in this case, with each of the braces capable of resisting the load in compression and in tension. The RSFJ units were designed to offer a 50-mm displacement for a 2% in 50-year probability of an earthquake occurrence. In this application, it was also important to ensure that the brace retains its required out-of-plane stability, and within the portion of the damper, a male/female anti-buckling tube assembly was provided to ensure this. In similar projects that are under development, a brace with RSFJ capacity of 1800 kN is used. For this application, there are four RSFJs of 450 kN each that are capable of resisting both tension and compression forces.

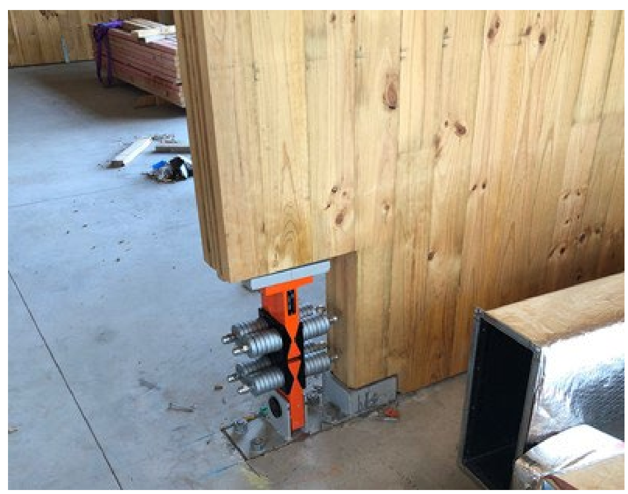



Figure 46. Tension/compression Resilient Slip Friction Joints in a braced bay (left), and a Resilient Slip Friction Joint used as a hold-down for a CLT wall (right) (courtesy of Tectonus).

Resilient Slip Friction Joints can also be used as hold-downs, as shown in Figure 46 (right), where the RSFJ provides the overturning resistance to a rocking CLT wall. The resistance of this hold-down is 300 kN. In other projects in development, two such RSFJs of 1350 kN each provide the overturning resistance to a mass timber shear wall in a multi-storey mass timber building. For such rocking shear walls, ductility is provided in the tension connection, not in the wall horizontal shear connections, which remain rigid. For such applications, since the wall deformation can occur in all directions, a pin connection is provided at the bottom of the wall, in combination with a swivel bearing, to eliminate internal bending moments, which provides true deformation compatibility.

The design philosophy for seismic-resistant timber structures with RSFJs is based on the principle that the ductility comes from the RSFJ units and other components, including the timber elements, remain linear elastic with minimum damage. This allows the structure to return to service following a quick inspection after a major seismic event. Both the traditional force-based design and the performance-based design can be used. For the performance-based design approach, the characteristics of the RSFJs are determined to provide the required resistance while capping the inter-storey drifts within the desired targeted values. It is also worth mentioning that the capacity spectrum method is a very efficient way to design a structural system with RSFJs. With the RSFJs acting as seismic fuses, the rest of the structural components are designed using an overstrength factor of 1.25 to ensure that they remain undamaged. The RSFJs can be modelled in commercially available design software such as ETABS or SAP2000. Both have a built-in link element that can accurately represent the load-deformation behaviour of the RSFJ. By implementing this modelling technique and using the design methods mentioned, the specifications for the RSFJs can be established and the design can be optimized.

5.3.6 NUMERICAL MODELLING

Experience from a number of tall wood building projects that have been completed or are underway (see Section 5.1) has show that numerical modelling plays a crucial role in analysis and design of these buildings. The use of advanced modelling in the design of tall wood buildings imposes a significant change in the role of the structural engineers, who have used primarily simplified methods to design low-rise timber residential buildings. In addition to having the knowledge of basic design principles and structural analysis methods for timber structures, an engineer will need a full understanding of numerical modelling techniques (Chen & Chui, 2017). The basics of the modelling principles, methodologies, and techniques used for tall wood buildings are introduced in this section. Information needed for modelling is also provided in the sections of this guide that deal with analysis and design. In addition, basic information related to modelling of timber systems will be provided in the Canadian Wood Council's *Advanced Wood Engineering Manual* (to be published in 2023), while more in-depth modelling and analysis technologies, methods, and solutions will be provided in the FPInnovations' *Modelling Guide for Timber Structures* (Chen et al., 2022).

5.3.6.1 Considerations in the Selection of Analysis Programs

Numerous commercially available software packages can help engineers develop linear and nonlinear finite element numerical models of buildings (Chen et al., 2017). Examples include ABAQUS, ADINA, Ansys, DRAIN 3DX, Dlubal, ETABS, NONLIN, NonlinPro, OpenSees, P-Frame, Perform-3D, RAM, RISA, S-Frame, SAFI, SAP2000, SeismoStruct, ST STRUDEL, STAAD, and many others. The key to choosing a suitable analysis program in the design practice is based on the uncertainties of the specific engineering problems related to a particular building, and whether the program can provide a suitable model to replicate the structure and its performance according to its use. This is especially important for tall wood buildings because certain software packages may be more suited to a particular application.

All software packages used in the design practice can be divided into two main categories: general purpose programs and design-orientated programs. General purpose programs such as ABAQUS and Ansys are suitable for more advanced analyses. For special engineering problems, such as blast and fire, general purpose programs are the right option because they have extensive material models, elements, and different solvers (e.g., explicit or implicit solvers). Many researchers have used the ABAQUS platform to develop user subroutines that can model the unique structural behaviour of wood-based components, connections, assemblies, and even entire building systems, which may not be as extensive as in other software packages. Some of these programs are now part of the engineering curriculum; consequently, many consulting companies have been using these types of software in their design practice in recent years. For a conventional structural analysis, design-orientated software packages such as SAP2000, ETABS, S-Frame, Dlubal, and SAFI are the best options. However, they usually have limited capacity for modelling certain types of structures and have limited types of finite elements compared to general purpose programs. Their advantage is their capacity to carry out design checks based on any codes and standards that have been pre-programmed. They can therefore quickly post-process the analysis results and design the structure according to codes of practice. More structural design programs, such as Dlubal, S-Frame, SAFI, and RISA, have been adding wood modules. These software programs provide a more user-friendly function for practising engineers to design tall timber buildings.

5.3.6.2 Modelling Principles

The structural behaviour of timber structures is different from that of other types of structures (e.g., steel or concrete), and the modelling is correspondingly different. Wood is an anisotropic material (Chen et al*.,* 2020b); therefore, a suitable material constitutive model should be chosen. Wood-based products and connections have various modes of failure, which needs to be considered when selecting a suitable element model and analysis method. Because computer modelling approximates practical problems rather than solving them in an exact way, it is important that the modelling follows certain principles for obtaining the best possible results when analyzing tall wood buildings:

- Start with a simple model and refine it step-by-step.
- More precise and complicated modelling should focus on the key structural components and connections, while simplifications can be made for the part of the building that is of secondary importance.
- Select a suitable type of model (1D, 2D, or 3D) based on the analysis problem and the characteristic of the system.
- Choose adequate elements for the structural components and connections.
- Choose adequate constitutive models for the structural components and connections.

- Choose right types of boundary conditions that are applied to the structural components and assemblies.
- Ensure that the models are sufficiently detailed and realistic but not overly complicated.

The results from the numerical model of the building (static and dynamic analyses) should be checked against simplified methods of calculation or test results. For example, the fundamental periods of tall wood buildings computed by modal analysis should be compared with available empirical formulas and similar test data to ensure the results are not biased. The numerical models for the components, connections, and assemblies must be verified against the available test result data. This is paramount in ensuring equivalent properties and model assumptions are used in the static and dynamic analyses, and the results are trustworthy. The verified models may then be extrapolated to develop more complex, robust models of tall wood buildings. When in doubt, the use of sensitivity analysis is highly recommended to bound a design problem and remain practically conservative. The following are several helpful checks of common modelling errors that may be useful to designers:

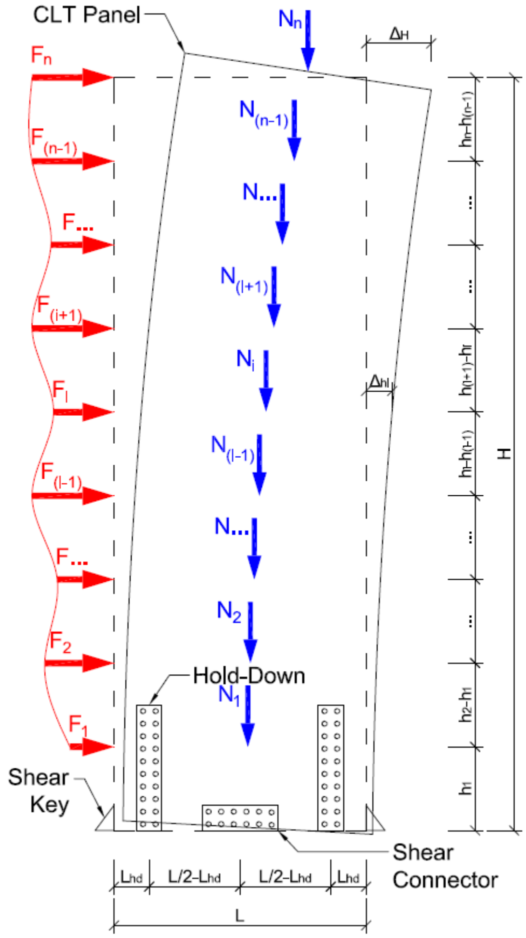
- Are the reactions equal to the total applied loads?
- Is the meshing too large or too small?
- Are the chosen meshing elements excessively large or small at some locations?
- Are there too many or not enough restraints applied?
- Are there over or under bending-moment-releasing structural components?
- Are there any inappropriate offsets?
- Are all loads present, or are some missing (e.g., torsion)? Are they applied correctly?
- Are the units used in dimensions, loads, and material properties correctly assigned?
- For nonlinear dynamic analysis, check mass and damping input to avoid inappropriate (insufficient or excessive) inertia and damping energy output.

5.3.6.3 Modelling Methodologies

A variety of numerical modelling methods are available for simulating the behaviour of structural systems under a variety of loading conditions. In this section, four types of modelling approaches are briefly introduced: analytical modelling, finite element modelling, hybrid simulation, and material-based finite element modelling. For more information on the input parameters for modelling of connections and assemblies, see Section 5.2.

5.3.6.3.1 Analytical Modelling

Analytical models (also called mechanics-based models) provide a typical method for understanding and predicting the structural performance of structures. These models are suitable for the initial conceptual designs and for verifying results obtained from complex finite element models. Examples of mechanics-based models for multi-storey balloon-type CLT shear walls are provided in Chen & Popovski (2020b) and are shown in Figure 47. Once such models are developed, the analysis of corresponding structural systems with various key parameters is straightforward. The drawback of these models is that users must solve the equilibrium equations, deformation coordination equations, and constitutive equations for the structural system. For structural systems where mechanics-based models do not exist or their development outweighs the benefit, finite element modelling is a more efficient approach.



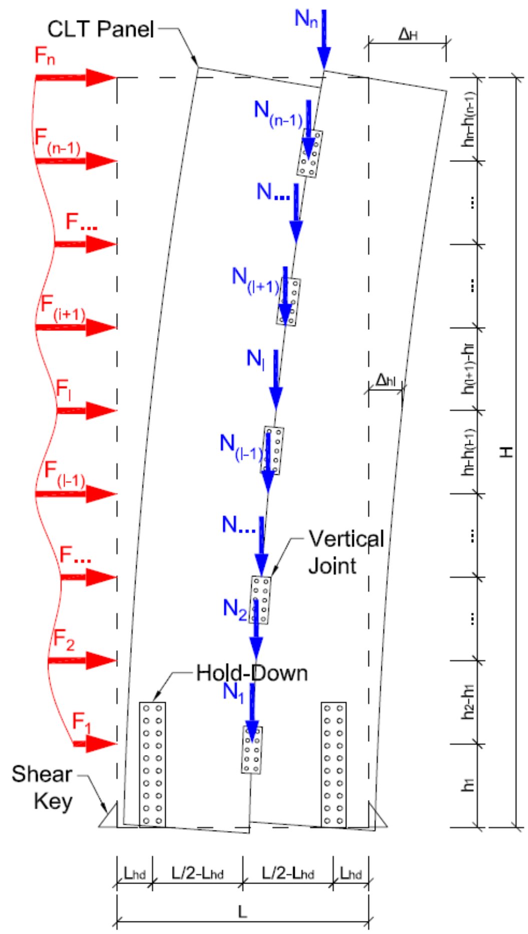
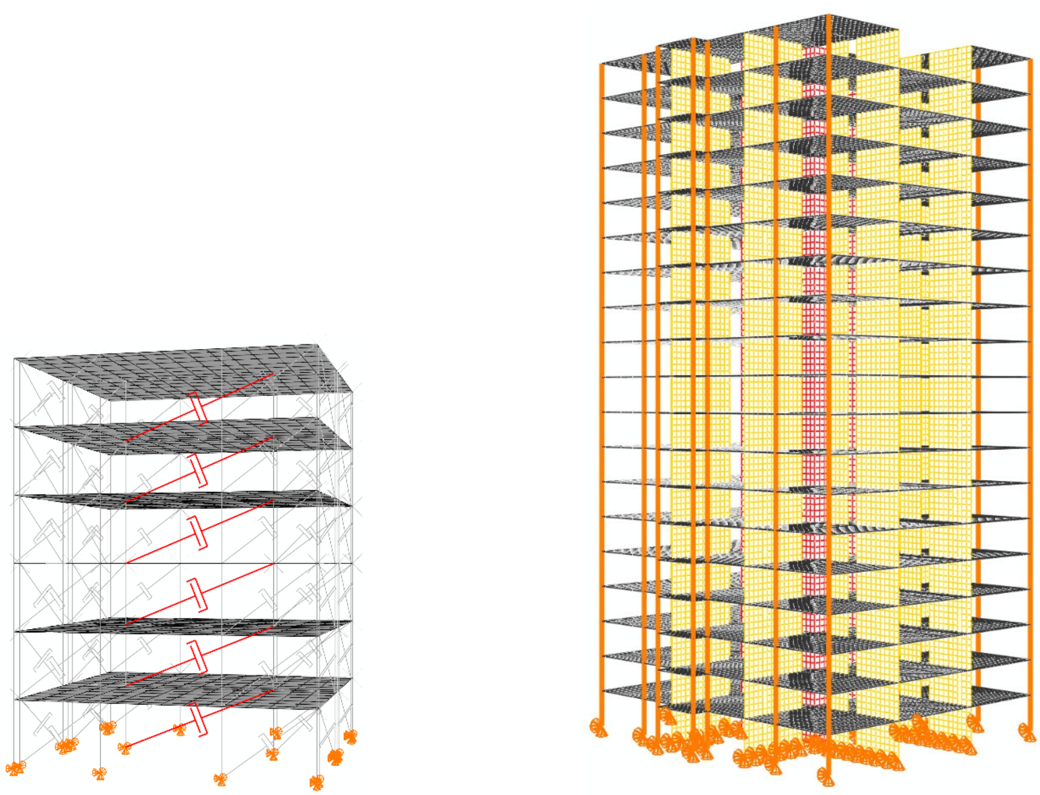


Figure 47. Mechanics-based models for single-panel (a) and coupled-panel (b) balloon-type CLT shear walls.

In Figure 47, F_i and N_i represent the lateral load and vertical load on the wall at a storey level i, respectively, while h_i represents the storey height (from the base) of the lateral and vertical load (F_i and N_i). The deflection of the wall at the top (level $h_n = H$) and at any level i is designated as Δ_H and Δ_{hi}, respectively, where n indicates the number of load levels.

5.3.6.3.2 Finite Element Modelling

In this modelling approach, the major structural components and connections are developed using any of the finite element type of software previously mentioned. In terms of the scale of the models, two main model types are available: micro-scale and macro-scale. Micro-scale models form a broad class of computational models that simulate fine-scale details. In contrast, macro-scale (super) models amalgamate the details into selected coarse-scale categories. The complexities of the problem determine which modelling approach will be used. In structural engineering, micro-scale models are commonly used in the analyses of structural components (Chen et al, 2011; Martínez-Martínez et al., 2018) and connections (Chen et al., 2020b), with testing results of materials as model input. These models focus on how the behaviour of the modelled object is influenced by its geometrical and material properties. In contrast, macro-scale models are widely used in the analyses of structural assemblies (Xu & Dolan 2009b; Zhu et al., 2010) and entire buildings (Chen & Ni 2020; Xu & Dolan 2009a). They require calibration against test results of connections and/or assemblies and are used to study how the structural response is affected by the structural design parameters. A 6-storey light-wood-frame building with portal frames that use macro-wall-elements (Chen et al., 2014c) is shown in Figure 48a; a 19-storey mass timber building that uses macro-connection elements on a concrete podium (Chen, Chui, & Popovski 2015; Chen, Li, et al., 2015) are shown in Figure 48b.



(a) (b)

Figure 48. Finite element models for timber structures: (a) 6-storey light-wood-frame building; and (b) 19-storey mass timber building (Checker) on a unshown concrete podium.

In the finite element modelling approach, the major structural components and connections are typically developed using the elements commonly available in commercial software (Chen et al., 2013). Beam elements should be used to model structural components in bending or under a combination of bending and axial loads; e.g., columns and beams. Truss or bar elements should be used to model axial structural components where it is deemed that bending can be ignored; e.g., webs in a truss structure. Shell elements should be used to model structural components with a thickness that is much smaller than the other two dimensions, such as floors and walls. Because of the anisotropic material characteristics of wood (Chen et al., 2011), orthotropic material properties are required for the model input for wood-based products.

Connections play a critical role in any timber structural models in terms of stiffness, and by providing ductility and energy dissipation at high load levels. Connections that experience semi-rigid behaviour can be modelled using linear springs or connection elements. For nonlinear analyses (pushover or nonlinear dynamic analysis), suitable backbone curve models that can represent the yielding and post-yield behaviour of the connections, and hysteretic models that can represent the energy dissipation and pinching effect of timber connections, have to be used. The floors and roofs distribute gravity and lateral loads to the lateral load-resisting assemblies. Diaphragm flexibility is a key factor that affects the lateral load distribution to the walls and other elements below (Chen et al., 2014a, 2014b). Diaphragms in the structural models should be modelled according to their stiffness and deformability characteristics, as described in Section 5.3.3.7.1. For example, light-wood-frame diaphragms should be modelled with a stiffness calculated according to the CSA O86 formula (CSA, 2019a). It must be noted that the nonstructural components, such as gypsum wallboard, provide considerable additional stiffness to lateral load-resisting light-wood systems (Chen et al., 2016; Lafontaine et al., 2017). Engineers must exercise judgement about whether the contribution of nonstructural components should be considered in the model.

For structures in which the storey shear deformation is the major component induced by lateral loads, mass-spring-damper models can be used to simulate the entire building or the main lateral load-resisting assemblies (Chen & Ni, 2020). If bending deformation cannot be ignored under lateral loads, the mass-spring-damper models would not be suitable, and the lateral load-resisting assemblies have to be modelled in a relatively more detailed approach. The connections in these assemblies, however, can be simulated using suitable nonlinear hysteretic springs (Xu & Dolan, 2009b; Zhu et al., 2010).

5.3.6.3.3 Hybrid Simulation

Dynamic response of a structure during an earthquake has traditionally been explored using either experimental or analytical methods. Full-scale testing is generally viewed as the most realistic method for evaluating structural components, assemblies, or even entire systems. However, this experimental method requires a full-scale or near-to-full-scale testing setup with strong floors and walls, or the use of a shaking table, which is only available at some universities and institutes. This method is time consuming and labour intensive; hence, it is impractical for designers. Furthermore, issues of structural size, equipment capacity, hydraulic control, and availability of research funding continue to limit the use of full-scale testing of structures. Analytical methods, while being readily available and economical, are limited to solving specific types of problems, and in many cases, cannot properly capture complex and generally unknown force-displacement behaviour or failure modes at the system or component levels. Combining both experimental and analytical methods in a single simulation to take advantage of what each method has to offer is referred to as hybrid simulation (Schellenberg et al., 2009).

In the hybrid simulation of a tall wood building, the entire structure is modelled using finite element software, but the structural components, connections, or assemblies of interest that cannot be confidently modelled are tested in a laboratory. At each time step of the numerical integration for the equation of motion, as shown in Figure 49, the trial displacement calculated by the software is applied to the specimen. The force feedback of the specimen is then used by the software to check equilibrium prior to proceeding to the next time step. This way, the dynamic response of the entire building can be obtained with real input from the tested components, connections, or assemblies. Hybrid simulation can have many significant advantages: (1) experimental costs can be reduced because only a portion of the structure is tested in a laboratory, (2) specimens can be tested in large scale because most of the structural components are modelled analytically, (3) the testing configuration can be complex because most of the loads are simulated, and (4) large and/or complex structures can be tested using geographically distributed laboratories, which means that resources such as lab space, testing equipment, and research personnel from different laboratories can be shared.

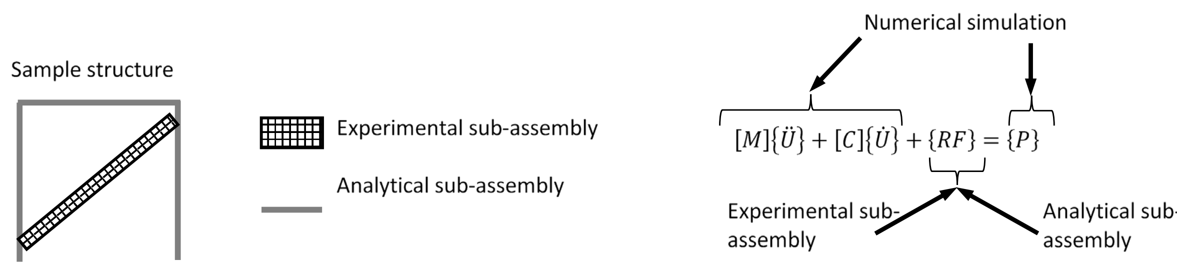


Figure 49. Illustration of hybrid simulation.

Note: $[M]$ and $[C]$ are the mass and damping matrices of the multi-degree-of-freedom (DOF) system, respectively; $\{\ddot{U}\}$ and $\{\dot{U}\}$ are the acceleration and velocity vectors at the free DOFs, respectively; $\{RF\}$ and $\{P\}$ are the resisting and applied forces at the free DOFs, respectively.

Hybrid simulation is suitable for tall wood buildings, particularly resilient building with structural fuses, because nonlinearity is typically concentrated at connections, which are complex to model but can be tested in a laboratory . The remaining structure, which is capacity designed to be elastic, can be easily modelled with confidence. Figure 50 shows the hybrid simulation for braced timber frames.

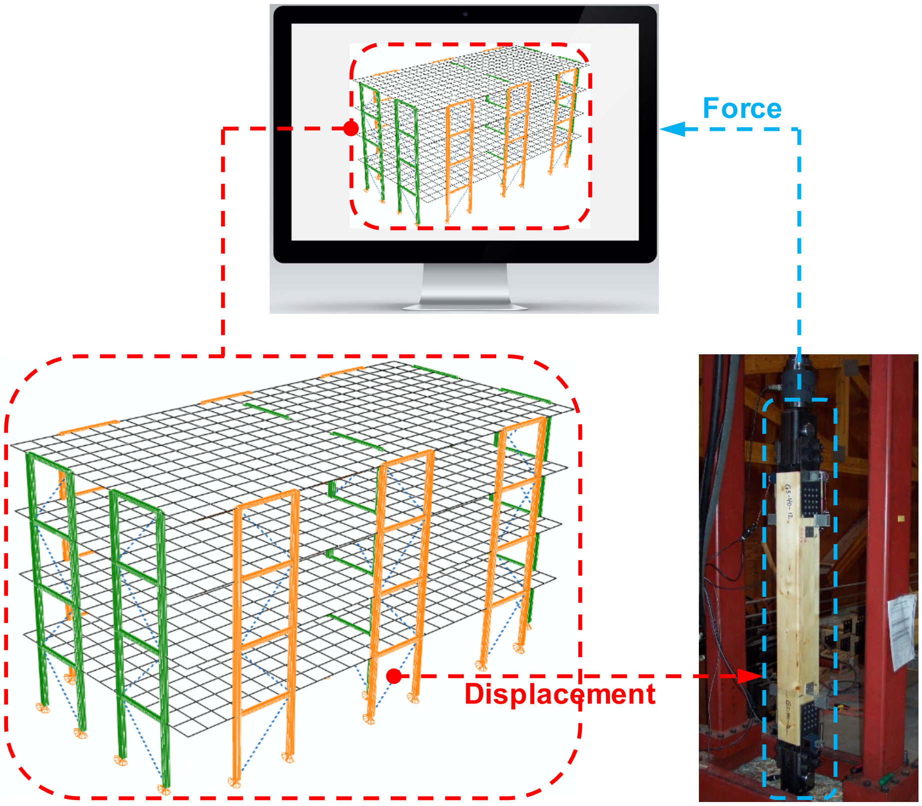


Figure 50. Schematic of hybrid simulation for braced timber frames.

5.3.6.3.4 Material-Based Finite Element Modelling

Over the past several decades, progress in digital technology has transformed the entire construction industry, ushering in a technological era now known as the fourth industrial revolution. New digital technologies, including building information modelling and artificial intelligence (e.g., machine learning), began to enter the industry and gradually changed how infrastructure and residential and nonresidential buildings are designed, constructed, operated, and maintained. More refined finite element models that are capable of exchanging construction details among different areas such as architecture, fabrication, and construction, and reducing or even eliminating the need for larger scale tests and calibrations, are anticipated for the design and analysis of structural assemblies or entire structural systems. Rapid development of high-performance computing (e.g., cloud computing), more comprehensive constitutive models for material behaviour (Chen et al., 2011; Sandhaas et al., 2012), and more accurate contact models has provided a solid foundation for the use of more refined system and building models. In order to fulfill the new demand for more sophisticated models by the construction industry, a material-based modelling method was developed (Chen & Popovski 2020a), where only the material (physical and mechanical) and geometrical properties of the components and connections are required as input.

The following are key points of the material-based modelling method:

Structural components

a) Structural components should be categorized as main or secondary components based on their structural contribution and influence. The main components should be modelled as detailed as possible, while the secondary components should be modelled with more strategic simplifications to reduce the unnecessary details.

b) Geometrical models of the structural components should be developed with the necessary design information.

c) Constitutive models that are capable of fully describing key material behaviour should be selected.

d) Structural components should be meshed using elements that are compatible with the geometrical and constitutive models. The mesh should be dense in key spots and can be looser in other locations.

Connections

a) Connections can be treated as either simple components or complex systems. Most connections can be modelled as structural components, while more complex connections have to be modelled using microscale models.

b) The development of geometrical and constitutive models, and element mesh for the connections should follow the same rules for the structural components mentioned above.

Contact zones (constraints and interactions)

a) Constraints can be grouped as rigid, semi-rigid, and pinned. While it is straightforward to model rigid or pinned constraints, attention should be paid to ensuring that no stress concentration is unrealistically developed in the components near the areas of interest. In the case of semi-rigid constraints, specific elements and modelling techniques should be used to properly simulate the stiffness and strength of the constraints.

b) Interactions between two components can be classified as either a “hard” or “soft” contact in the normal direction of the contact area, and with or without friction in the tangential direction. Appropriate interaction models should be selected for each specific case.

Figure 51 shows the material-based model for post-tensioned coupled CLT walls.

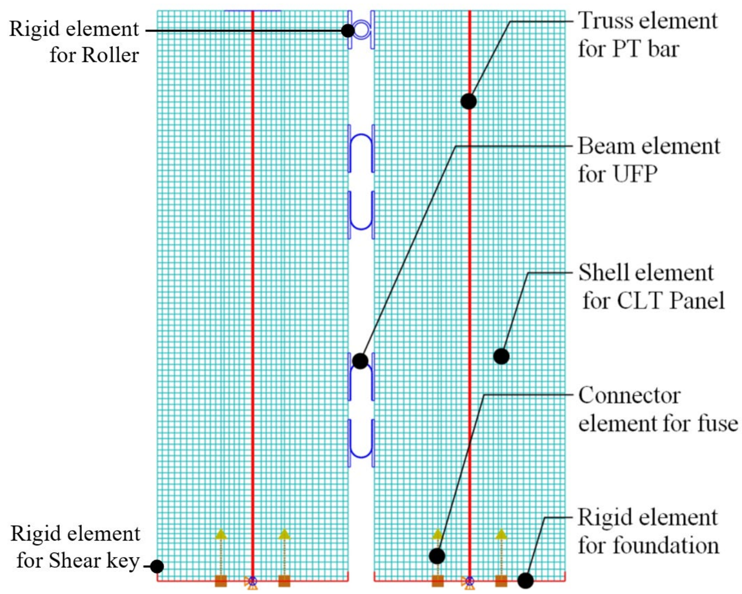


Figure 51. Material-based model for post-tensioned coupled CLT walls (PT = post-tensioning; UFP = U-shaped flexural plate).

In Figure 51, the CLT panels were modelled using shell elements with orthotropic elastic-plastic properties, while the steel post-tensioned cables were modelled using truss elements with isotropic elastic-plastic properties. Axial energy dissipators (fuses) and U-shaped flexural plates were modelled using connector elements and beam elements with orthotropic elastic-plastic properties, respectively. The foundation, shear keys, roller, and steel plates connected to the post-tensioned cable at the top were modelled using rigid elements. The gaps between the CLT panel and the foundation, the CLT panel and the steel plate, and the CLT panel and the shear key were simulated using "softened elements" connected with friction.

5.3.7 ALTERNATIVE DESIGN SOLUTIONS FOR TALL WOOD BUILDINGS

The primary regulations governing the construction of tall wood buildings at any location in Canada are the provincial building codes. The provincial codes are modelled on the National Building Code of Canada, which regulates the design and construction of new buildings, and substantial renovation of existing buildings. If the structural system or height of a planned building is not allowed in the provincial building code, approval of the building will have to be obtained by using the Alternative Solution path provided in the code. In such cases, the design team will have to work closely with the provincial authority and the local authorities having jurisdiction during the design and construction process. Examples of provincial authorities include the British Columbia Building and Safety Standards Branch and Régie du bâtiment du Québec; local authorities having jurisdiction are mainly cities or municipalities and their building code officials and representative bylaws. In some cases, such as the 18-storey Brock Commons building at UBC, the project team worked with the University's Chief Building Official and the British Columbia Building and Safety Standards Branch to draft site-specific design regulations that are applicable to a single building on a single site. The intention of such regulations is to ensure occupant health and safety protection that is equal to or better than that provided in the provincial codes. The resulting regulation is applicable only to the specific building site and does not serve as a precedent for future projects.

The design process usually begins with meetings among the various parties involved in the design and construction process in order to achieve a collaborative integrated design approach. Discussions should focus on determining the structural solution approach in terms of costs, constructability, and effects on the building's engineering systems. The discussions should involve structural designers; architects; mechanical, electrical, and plumbing engineers; the fire protection engineer; virtual modellers; and key design advisors and assistants, including the construction manager. In addition, some input from trades and contractors later in the process can provide valuable information on constructability, trade safety, cost estimates, and scheduling projections of the design solution. The structural engineers can look into different structural systems for carrying gravity and lateral loads and can conduct simplified preliminary analyses to evaluate those solutions not only from a structural performance standpoint but also from other aspects such as fire protection. Once consultations have concluded, the preferred structural system should be singled out and the detailed design process can begin. The main design steps, from a structural standpoint, for a structural system of a tall wood building located in high seismic hazard zones are as follows:

- It is recommended that a linear static (code-prescribed procedure) and dynamic response spectrum analysis be carried out to determine the overall seismic demand at various storeys.
- This may be followed by a nonlinear static analysis to gauge the sequence of yielding and formation of hinges at various levels. The information developed, including sensitivity analyses, will help establish the overall backbone curve of the lateral load-resisting system and therefore the global displacement ductility demand and local axial/rotation/curvature ductilities.

The development of Alternative Solutions or a site-specific regulation usually involves rigorous review processes. In some cases, the authority having jurisdiction may require that an Alternative Solution be evaluated by a peer review panel consisting of independent experts with in-depth knowledge. The purpose of the process is to confirm that all areas of uncertainty are identified and adequately addressed in the design process or resulting regulation. The project design team should develop the design concepts, propose strategies for mitigating key areas of technical risks, and obtain peer reviews by third-party structural engineers. In the development of Alternative Solutions, the design team may opt to use the performance-based design methodologies that are explained in this guide. The peer review panel should have expertise in local and provincial building codes and structural concepts and code issues, and should consider strategies for addressing gravity and lateral loads of individual elements and connections. The peer review panel should also validate designers' applications of the codes and reference standards, and provide recommendations for areas of further analysis. The City of Vancouver (2015) has developed *Guidelines for Alternative Solution Peer Reviews*, which include sections on the peer review panel, Terms of Reference, evaluation procedures, results of the panel's review, and payment for panel members. Some cities in the United States have also developed design guides for tall buildings in general, which may be used by the designers as viable references for the analysis and design of the Alternative Solutions (LATBSDC, 2011). Finally, the Pacific Earthquake Engineering Research Center (PEER, 2010) has developed seismic design guidelines for tall buildings, which are also very useful for designers.

5.3.8 REFERENCES

Abrahamsen, R. B. (2015). First 14-storey wood building in the world at Bergen in Norway. *5th Forum International Bois Construction FBC*.

Abrahamsen, R. B. (2017). Mjøstårnet – Construction of an 81 m tall timber building. *23 Internationales Holzbau-Forum IHF 2017.*

American Concrete Institute (ACI). (2019). *ACI CODE-318-19: Building code requirements for structural concrete and commentary*. Farmington Hills, MI: Author.

American National Standards Institute & American Wood Council (ANSI/AWC). (2021). *2021 Special design provisions for wind and seismic*. Leesburg, VA: American Wood Council.

American Society for Testing and Materials (ASTM). (2009). *ASTM E2126*: *Standard test methods for cyclic (reversed) load test for shear resistance of vertical elements of the lateral force resisting systems for buildings*. West Conshohocken, PA: Author.

American Society of Civil Engineers (ASCE). (2011). *ASCE/SEI 59-11*: *Blast protection of buildings*. Reston, VA: Author.

American Society of Civil Engineers (ASCE). (2016). *ASCE/SEI 7-16*: *Minimum design loads for buildings and other structures*. Reston, VA: Author.

American Society of Civil Engineers (ASCE). (2017). *ASCE 41-17*: *Seismic rehabilitation of existing buildings*. Reston, VA: Author.

Applied Technology Council (ATC). (1996). *ATC-40*: *Seismic evaluation and retrofit of concrete buildings.* Redwood City, CA: California Seismic Safety Commission.

Arup. (2011). *Review of international research on structural robustness and disproportionate collapse*. London, UK: Department for Communities and Local Government.

Bernasconi, A. (2016, August). Four residential towers as CLT timber construction in the city of Milan. World Conference on Timber Engineering 2016 (5771–5778), Vienna, Austria: TU Verlag.

Bezabeh, M. A., Bitsuamlak, G. T., Popovski, M., & Tesfamariam, S. (2018a). Probabilistic serviceability-performance assessment of tall mass-timber buildings subjected to stochastic wind loads: Part I: Structural design and wind tunnel testing. *Journal of Wind Engineering and Industrial Aerodynamics*, 181, 85-103.

Bezabeh, M. A., Bitsuamlak, G. T., Popovski, M., & Tesfamariam, S. (2018b). Probabilistic serviceability-performance assessment of tall mass-timber buildings subjected to stochastic wind loads. Part II: Structural reliability analysis. *Journal of Wind Engineering and Industrial Aerodynamics*, 181, 112-125.

Bezabeh, M. A., Bitsuamlak, G. T., & Tesfamariam, S. (2020a). Performance-based wind design of tall buildings: concepts, frameworks, and opportunities. *Wind and Structures*, 31(2), 103-142.

Bezabeh, M. A., Gairola, A., Bitsuamlak, G. T., Popovski, M., & Tesfamariam, S. (2018c). Structural performance of multi-storey mass-timber buildings under tornado-like wind field. *Engineering Structures*, 177, 519-539.

Bezabeh, M. A., Gairola, A., Bitsuamlak, G. T., Popovski, M., & Tesfamariam, S. (2020b). Dynamic response of tall mass-timber buildings to wind excitation. *Journal of Structural Engineering*, 146(10). doi:10.1061/%28ASCE%29ST.1943-541X.0002746

Bezabeh, M. A., Tesfamariam, S., Popovski, M., Goda, K., & Stiemer, S. F. (2017). Seismic base shear modification factors for timber-steel hybrid structure: collapse risk assessment approach. *Journal of Structural Engineering*, 143(10). doi:10.1061/(ASCE)ST.1943-541X.0001869

Biggs, J. M. (1964). *Introduction to structural dynamics*, McGraw-Hill, New York, NY.

Bjertnæs, M. A., & Malo, K. A. (2014). *Wind-induced motions of "Treet"- a 14-storey timber residential building in Norway*. Paper presented at the World Conference on Timber Engineering, Québec City, QC.

Breneman, S., McDonnel, E., & Zimmerman, R. (2016). *An approach to CLT diaphragm modeling for seismic design with an application to a US high-rise project*. Washington, D.C.: WoodWorks.

Brett, C., & Lu, Y. (2013). Assessment of robustness of structures: current state of research. *Frontiers of Structural and Civil Engineering*, 7(4), 356-368.

Byfield, M., Mudalige, W., Morison, C., & Stoddart, E. (2014). A review of progressive collapse research and regulations. *Proceedings of the Institution of Civil Engineers – Structures and Buildings*, 167(8), 447-756.

Canadian Construction Materials Centre (CCMC). (2021). Technical guide for evaluation of seismic force resisting systems and their force modification factors for use in the National Building Code of Canada with concepts illustrated using a cantilevered wood CLT shear wall example. Ottawa ON: National Research Council Canada.

Canadian Standards Association (CSA). (2012). *CSA S850: Design and assessment of buildings subjected to blast loads*. Mississauga, ON: Author.

Canadian Standards Association (CSA). (2019a). *CSA O86: Engineering design in wood*. Mississauga, ON: Author.

Canadian Standards Association (CSA). (2019b). *CSA A23.3: Design of concrete structures*. Mississauga, ON: Author.

Canadian Standards Association (CSA). (2019c). *CSA S16: Design of steel structures*. Mississauga, ON: Author.

Canterbury Earthquakes Royal Commission (CERC). (2012). *Low-damage building technologies*. *Final Report* (Vol. 3). Christchurch, New Zealand: Author.

Chen, Z., & Chui, Y. (2017). Lateral load-resisting system using mass timber panel for high-rise buildings. *Frontiers in Built Environment*, 3, 40. doi:10.3389/fbuil.2017.00040

Chen., Z., Chui, Y. H., Doudak, G., Nott, A. (2016). Contribution of Type-X gypsum wall board to the racking performance of light-frame wood shear walls. *Journal of Structural Engineering*, 142(5), 04016008.

Chen, Z., Chui, Y. H., Mohammad, M., Doudak, G., & Ni, C. (2014a). *Load distribution in lateral load resisting elements of timber structures*. Paper presented at the World Conference on Timber Engineering, Québec City.

Chen, Z., Chui, Y. H., Ni, C., Doudak, G., & Mohammad, M. (2014b). Load distribution in timber structures consisting of multiple lateral load resisting elements with different stiffness. *Journal of Performance of Constructed Facilities*, 28(6). doi:10.1061/(ASCE)CF.1943-5509.0000587

Chen, Z., Chui, Y. H., Ni, C., & Xu, J. (2014c). Seismic response of mid-rise light wood frame buildings with portal frame. *Journal of Structural Engineering*, 140(8). doi:10.1061/(ASCE)ST.1943-541X.0000882.

Chen, Z., Chui, Y. H., & Popovski, M. (2015). Development of lateral load resisting system. In Y. H. Chui (Ed.), *Application of analysis tools from NEWBuildS research network in design of a high-rise wood building* (15-36). Vancouver, BC: FPInnovations.

Chen, Z, & Ni, C. (2020). Criterion for applying two-step analysis procedure to seismic design of wood-frame buildings on concrete podium. *Journal of Structural Engineering*, 146(1). doi:10.1061/(ASCE)ST.1943-541X.0002405

Chen, Z, Ni, C, Dagenais, C, & Kuan, S. (2020). A temperature-dependent plastic-damage constitutive model used for numerical simulation of wood-based materials and connections. *Journal of Structural Engineering*, 146(3). doi:10.1061/(ASCE)ST.1943-541X.0002524

Chen, Z, & Popovski, M. (2020a). Material-based models for post-tensioned shear wall system with energy dissipators. *Engineering Structures*, 213, 110543.

Chen, Z, & Popovski, M. (2020b). Mechanics-based analytical models for balloon-type cross-laminated timber (CLT) shear walls under lateral loads. *Engineering Structures*, 208, 109916.

Chen, Z., Popovski, M., & Iqbal, A. (2020). Structural performance of post-tensioned CLT shear walls with energy dissipators. *Journal of Structural Engineering*. doi: 10.1061/(ASCE)ST.1943-541X.0002569.

Chen, Z., Tung, D., & Karacabeyli, E. [2022]. Modelling guide for timber structures. In preparation. Special Publication. Pointe-Claire, QC: FPInnovations. In prep.

Chen, Z., Zhu, E., & Pan, J. (2011). Numerical simulation of wood mechanical properties under complex state of stress. *Chinese Journal of Computational Mechanics*, 28(04), 629-634, 640.

Chen, Z., Zhu, E., & Pan, J. (2013). Lateral structural performance of Yingxian wood pagoda based on refined FE models. *Journal Of Building Structures*, 34(9), 150-158.

Chopra, A. K. (2017). *Dynamics of structures* (45th ed.). Upper Saddle River, NJ: Prentice Hall.

Christopoulos, C., Tremblay, R., Kim, H. J., & Lacerte, M. (2008). Self-centering energy dissipative bracing system for the seismic resistance of structures: development and validation. *Journal of Structural Engineering,* 134(1), 96-107.

City of Vancouver. (2015). Guidelines for Alternative Solution peer reviews (Bulletin 2002-007-BU). Vancouver, BC: Author. https://vancouver.ca/files/cov/2002-007-guidelines-for-alternative-solution-peer-reviews.pdf

Čizmar D., Kirkegaard, P. H., Sørensen, J. D., & Rajčić, V. (2011). Reliability-based robustness analysis for a Croatian sports hall. *Engineering Structures*, 33 (11), 3118–3124.

Clough, R. W., & Penzien, J. (1993). *Dynamics of structures* (2nd ed.). New York, NY: McGraw-Hill.

Connolly, T., Loss, C., Iqbal, A., & Tannert, T. (2018). Feasibility study of mass-timber cores for the UBC tall wood building. *Buildings,* 8(8), 98.

Côté, D., & Doudak, G. (2019). Experimental investigation of cross-laminated timber panels with realistic boundary conditions subjected to simulated blast loads. *Engineering Structures*, 187, 444-456.

Davenport, A. G. (1967). Gust loading factors. *Journal of the Structural Division*, 93(3), 11-34.

Dietsch, P. (2011). Robustness of large-span timber roof structures–structural aspects. *Engineering Structures*, 33(11), 3106–3112.

Ellingwood, B. R., & Dusenberry, D. O. (2005). Building design for abnormal loads and progressive collapse. *Computer-aided Civil and Infrastructure Engineering*, 20(3), 194-205.

Ellingwood, B. R., Smilowitz, R., Dusenberry, D.O., Duthinh, D, Lew, H.S., & Carino, N.J. (2007). *Best practices for reducing the potential for progressive collapse in buildings* (NISTIR 7396). Gaithersburg, MD: National Institute of Standards and Technology, United States Department of Commerce.

Elshaer, A., & Bitsuamlak, G. T. (2018). Multi-objective aerodynamic optimization through openings to reduce wind loads on of tall buildings. *Journal of Structural Engineering*, 140(10) http://dx.doi.org/10.1061/(ASCE)ST.1943-541X.0002199

Elshaer, A., Bitsuamlak, G., & El Damatty, A. (2017). Enhancing wind performance of tall buildings using corner aerodynamic optimization. *Engineering Structures*, 136, 133-148.

European Committee for Standardization (CEN). (2006). *EN 1991-1-7 (2006): Eurocode 1 – Actions on structures – Part 1-7: General actions – Accidental actions*. Brussels, Belgium: Author.

Federal Emergency Management Agency (FEMA). (1997) *NEHRP guidelines for the seismic rehabilitation of buildings* (FEMA 273). Washington, DC: Author.

Federal Emergency Management Agency (FEMA). (2000). *Pre standard and commentary for the seismic rehabilitation of buildings* (FEMA 356). Washington, DC: Author.

Federal Emergency Management Agency (FEMA). (2005). *Improvement of inelastic analysis procedures* (FEMA 440). Washington, DC: Author.

Federal Emergency Management Agency (FEMA). (2009a). *Quantification of building seismic performance factors* (FEMA P-695). Washington, DC: Author.

Federal Emergency Management Agency (FEMA). (2011). *Quantification of building system performance and response factors - component equivalency methodology* (FEMA P-795). Washington, DC: Author.

Federal Emergency Management Agency (FEMA). (2015). *NEHRP recommended seismic provisions for new buildings and other structures* (FEMA P-1050-1). Washington, DC: Author.

Federal Emergency Management Agency (FEMA). (2018a). *Seismic performance assessment of buildings. Volume 1 – Methodology* (2nd ed., FEMA P-58-1). Washington, DC: Author.

Federal Emergency Management Agency (FEMA). (2018b). *Seismic performance assessment of buildings. Volume 2 – Implementation Guide* (2nd ed., FEMA P-58-2). Washington, DC: Author.

Filiatrault, A., Christovasilis, I., Wanitkorkul, A., & Folz, B. (2006). *Displacement-based seismic design of light-frame wood buildings*. Paper presented at the 9th World Conference on Timber Engineering, Portland, OR.

Filiatrault, A., & Folz, B. (2002). Performance-based seismic design of wood framed buildings. *Journal of Structural Engineering,* 128(1), 39-47.

Gairola, A., & Bitsuamlak, G. T. (2019). Numerical tornado modeling for a common interpretation of experimental simulators. *Journal of Wind Engineering & Industrial Aerodynamics*, 186, 32-48.

Ganey, R., Berman, J., Akbas, T., Loftus, S., Dolan, D., Sause, R., Ricles, J., Pei, S., van de Lindt, J., & Blomgren, H. (2017). Experimental investigation of self-centering cross-laminated timber walls. *Journal of Structural Engineering*, 143(10).

General Services Administration (GSA). (2003). *Progressive collapse analysis and design guidelines for new federal office buildings and major modernization projects*.

General Services Administration (GSA). (2016). *General Service Administration alternate path analysis & design guidelines for progressive collapse resistance*. https://www.gsa.gov/cdnstatic/Progressive_Collapse_2016.pdf

Goel, R. K., & Chopra, A. K. (2004). Evaluation of modal and FEMA pushover analyses: SAC buildings. *Earthquake Spectra,* 20(1), 225-254.

Goertz, C., Mollaioli, F., & Tesfamariam, S. (2018). Energy based design of a novel timber-steel building. *Earthquakes and Structures*, 15(4), 351-360.

Green, M. C. (2012). *The case for tall wood buildings: How mass timber offers a safe, economical, and environmentally friendly alternative for tall building structures.* Vancouver, BC: Michael Green Architecture. https://cwc.ca/wp-content/uploads/publications-Tall-Wood.pdf

Gupta B., & Kunnath, S. K. (2000). Adaptive spectra-based pushover procedure for seismic evaluation of structures. *Earthquake Spectra,* 16(2), 367-391.

Hewson, N. (2016). *Robustness in structures*. Melbourne, Australia: Forest and Wood Products Australia Limited.

Ho, T., Dao, T., Aaleti, S., van de Lindt, J., & Rammer, D. (2017). Hybrid system of unbonded post-tensioned CLT panels and light-frame wood shear walls. *Journal of Structural Engineering*, 143(2), 04016171.

Huber, J., Ekevad, M., Girhammar, U. A., & Berg, S. (2019). Structural robustness and timber buildings – A review. *Wood Material Science & Engineering*, 14(2), 107-128.

Hummel, J. (2017). *Displacement-based seismic design for multi-storey cross-laminated buildings*. (Unpublished doctoral dissertation). University of Kassel, Kassel, Germany. doi: http://dx.medra.org/10.19211/KUP9783737602891

International Code Council (ICC). (2021). *International Building Code, 2018*. Country Club Hills, IL: Author.

Iqbal, A. (2011). *Seismic response and design of subassemblies for multi-storey prestressed timber buildings*. (Unpublished doctoral dissertation). University of Canterbury, Christchurch, New Zealand.

Iqbal, A., Fragiacomo, M., Pampanin, S., & Buchanan, A. (2017). Seismic resilience of plywood-coupled LVL wall panels. *Engineering Structures*, 167(15), 750-759.

Iqbal, A., Pampanin, S., Palermo, A., & Buchanan, A. (2015). Performance and design of LVL walls coupled with UFP dissipaters. *Journal of Earthquake Engineering*, 19(3), 383-409.

Irwin, P. A. (2008). Bluff body aerodynamics in wind engineering. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(6-7), 701-712.

IStructE. (2010). *Practical guide to structural robustness and disproportionate collapse in buildings*. Institution of Structural Engineers, London, UK.

Izzuddin, B., Vlassis, A., Elghazouli, A., & Nethercot, D. A. (2007). Assessment of progressive collapse in multi-storey buildings, structures and buildings. *Proceedings of the ICE – Structures and Buildings,* 160(4), 197-205.

Jacques, E., Lloyd, A., Braimah, A., Saatcioglu, M., Doudak, G., & Abdelalim, O. (2014). Influence of high strain-rates on the dynamic flexural material properties of spruce–pine–fir wood studs. *Canadian Journal of Civil Engineering*, 41(1), 56-64.

Jorissen, A., & Fragiacomo, M. (2011). General notes on ductility in timber structures. *Engineering Structures*, 33(11), 2987-2997.

Kalkan, E., & Kunnath, S. K. (2006). Adaptive modal combination procedure for nonlinear static analysis of building structures. *Journal of Structural Engineering*, 132(11), 1721–1731.

Karacabeyli, E., & Gagnon, S. (2019). *Canadian CLT handbook, 2019 edition*. (Special Publication SP-532E). Pointe-Claire, QC: FPInnovations.

Kareem, A., Bernardini, E., & Spence, S. M. (2013). Control of the wind induced response of structures. In Y. Tamura & A. Kareem (Eds.), *Advanced structural wind engineering* (377-410). Tokyo: Springer.

Kim, H. J., & Rosowski, D. V. (2005). Fragility analysis for performance-based seismic design of engineered wood shearwalls. *Journal of Structural Engineering*,131(11), 1764-1772.

Kwasniewski, L., Izzuddin B., Pereira, M., Bucur C., & Gizejowski, M. (2009, September). Modelling and analysis. *Joint Workshop of COST Actions TU0601 and E55*. Ljubljana, Slovenia.

Kwok, K. C. (2013). Wind-induced vibrations of structures: with special reference to tall building aerodynamics. In Y. Tamura & A. Kareem (Eds.), *Advanced structural wind engineering* (121-155). Tokyo: Springer.

Lacroix, D. N. (2017). *Investigating the behaviour of glulam beams and columns subjected to simulated blast loading*. (Unpublished doctoral dissertation). University of Ottawa, Ottawa, Canada.

Lacroix, D. N., & Doudak, G. (2015). Investigation of dynamic increase factors in light-frame wood stud walls subjected to out-of-plane blast loading. *Journal of Structural Engineering*, 141(6), 04014159.

Lacroix, D. N., & Doudak, G. (2018). Determining the dynamic increase factor for glued-laminated timber beams. *Journal of Structural Engineering*, 144(9), 04018160.

Lafontaine, A., Zhiyong C., Doudak, G., & Chui, Y. H. (2017). Lateral behavior of light wood-frame shear walls with gypsum wall board. *Journal of Structural Engineering*, 143(8). doi:10.1061/(ASCE)ST.1943-541X.0001798

Lawson, P. M., Byfield, M. P., Popo-Ola, S. O., & Grubb, P. J. (2008). Robustness of light steel frames and modular construction. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 161(1), 3–16.

Leach, H. (2018). *Interstorey drift performance of timber beam-hanger connections*. (Unpublished master's thesis). Queen’s University, Kingston, Canada.

Los Angeles Tall Buildings Structural Design Council (LATBSDC). (2011). *An alternative procedure for seismic analysis and design of tall buildings located in the Los Angeles region: A consensus document*. Los Angeles, CA: Author.

Loss, C., Tannert, T., & Tesfamariam, S. (2018). State-of-the-art review of displacement-based seismic design of timber buildings. *Construction and Building Materials*, 191(1), 481-497.

Marriott, D., Pampanin, S., Bull, D., & Palermo, A. (2008). Dynamic testing of precast, post-tensioned rocking wall systems with alternative dissipating solutions. *Bulletin of the New Zealand Society for Earthquake Engineering*, 41(2), 14.

Martínez-Martínez, J. E., Alonso-Martínez, M., Rabanal, F. P. Á., & Díaz, J. J. d. C. (2018, July). Finite element analysis of composite laminated timber (CLT). *Proceedings of the 2nd International Research Conference on Sustainable Energy, Engineering, Materials and Environment*, Mieres, Spain. https://doi.org/10.3390/proceedings2231454

Merrick, R., & Bitsuamlak, G. (2009). Shape effects on the wind-induced response of high-rise buildings. *Journal of Wind and Engineering*, 6(2), 1-18.

Mitchell, D., Tremblay, R., Karacabeyli, E., Paultre, P., Saatcioglu, M., & Anderson, D. L. (2003). Seismic force modification factors for the proposed 2005 edition of the National Building Code of Canada. *Canadian Journal of Civil Engineering*, 30(2), 308–327.

Moroder, D., Smith, T., Dunbar, A., Pampanin, S., & Buchanan, A. (2018). Seismic testing of post-tensioned Pres-Lam core walls using cross laminated timber. *Engineering Structures*, 167(15), 639-654.

Mpidi Bita H. (2019). *Disproportionate collapse prevention analyses for mid-rise cross-laminated timber platform-type buildings*. (Unpublished doctoral dissertation). University of British Columbia, Vancouver, Canada.

Munch-Andersen, J., & Dietsch, P. (2011). Robustness of large-span timber roof structures — Two examples. *Engineering Structures*, 33(11), 3113-3117.

Naeim, F. (2008). *The seismic design handbook* (2nd ed.). Norwell, MA: Kluwer Academic Publishers.

National Research Council (NRC). (2020). *National building code of Canada*. Ottawa, ON: Author.

Newcombe, M. P. (2010). *Multistorey timber buildings seismic design guide* (6th ed.). University of Canterbury. Canterbury, New Zealand.

Newcombe, M. P., Pampanin, S., & Buchanan, A. H. (2010). *Design, fabrication and assembly of a two-storey post-tensioned timber building*. Paper presented at the 11th World Conference on Timber Engineering, Riva del Garda, Italy.

Newmark, N. M., & Rosenblueth, E. (1971). *Fundamentals of earthquake engineering*. Englewood Cliffs, N.J.: Prentice-Hall.

Oregon State University & Portland State University (OSU/PSU) (2017). *Framework: An urban + rural ecology. Deliverable 18: Structural testing*. https://www.thinkwood.com/wp-content/uploads/2018/10/18-Framework-Structural-Testing.pdf

Pacific Earthquake Engineering Research Center (PEER). (2010). *Seismic design guidelines for tall buildings* (PEER Report 2010/05). Berkeley, CA: University of California.

Palermo, A., Pampanin, S., & Buchanan, A. (2006b, September). Experimental investigations on LVL seismic resistant wall and frame subassemblies. In *Proceedings of the First European Conference on Earthquake Engineering and Seismology* (Paper 983). Geneva, Switzerland.

Palermo, A., Pampanin, S., Buchanan, A., & Newcombe, M. (2005, March). Seismic design of multi-storey buildings using laminated veneer lumber (LVL). *Proceedings of the New Zealand Society Earthquake Engineering Conference*, Wairakei, New Zealand.

Palermo, A., Pampanin, S., Fragiacomo, M., Buchanan, A. H., & Deam, B. (2006a). *Innovative seismic solutions for multi-storey LVL timber buildings*. Paper presented at the 9th World Conference on Timber Engineering, Portland, OR.

Pang, W., & Rosowsky, D. V. (2007). *Direct displacement procedure for performance-based seismic design of multistorey woodframe structures* (NEESWood Report NW-02). College Station, TX: Texas A&M University.

Pang, W., Rosowsky, D. V., Pei, S., & van de Lindt, J. W. (2010). Simplified direct displacement design of six-storey woodframe building and pretest seismic performance assessment. *Journal of Structural Engineering,* 136(7), 813-825.

Pang, W., Rosowsky, D. V., van de Lindt, J. W., & Pei, S. (2009). *Simplified direct displacement design of six-storey NEESWood capstone building and pre-test seismic performance assessment* (NEESWood Report NW-05). Clemson, SC: Clemson University.

Pei, S., Popovski, M., & van de Lindt, J. W. (2012). *Seismic design of a multi-storey cross laminated timber building based on component level testing*. Paper presented at the 12th World Conference on Timber Engineering, Auckland, New Zealand.

Pei, S., Popovski, M., & van de Lindt, J. W. (2013a). Analytical study on seismic force modification factors for cross-laminated buildings. *Canadian Journal of Civil Engineering,* 40(9).

Pei, S., Popovski, M., & van de Lindt, J. W. (2013b). Approximate R-factor for cross laminated timber walls in multi-storey buildings. *Journal of Architectural Engineering,* 19(4), 245-255.

Pei, S., van de Lindt, J., Barbosa, A., Berman, J., Blomgren, H., Dolan, J., McDonnell, E., Zimmerman, R., Fragiacomo, M., & Rammer, D. (2018). Full-scale shake table test of a two-storey mass-timber building with resilient rocking walls. In *16th European Conference on Earthquake Engineering*, Thessalonki, Greece.

Pei, S., van de Lindt, J. W., Barbosa, A. R., Berman, J. W., McDonnell, E., Dolan, J. D., Wichman, S. (2019). Experimental seismic response of a resilient 2-storey mass-timber building with post-tensioned rocking walls. *Journal of Structural Engineering*,145(11), 04019120.

Poulin, M., Viau, C., Lacroix, D. N., & Doudak, G. (2018). Experimental and analytical investigation of cross-laminated timber panels subjected to out-of-plane blast loads. *Journal of Structural Engineering*, 144(2), 04017197.

Priestley, M. J. N., Calvi, G. M., & Kowalsky, M. J. (2007). *Displacement-based seismic design of structures*. Pavia, Italy: IUSS Press.

Priestley, M. J. N., & Kowalsky, M. J. (1998). Aspects of drift and ductility capacity of rectangular cantilever structural walls. *Bulletin of the New Zealand Society for Earthquake Engineering,* 31(2), 73-85.

Priestley, M. J. N., Sritharan S., Conley, J. R., & Pampanin, S. (1999). Preliminary results and conclusions from the PRESSS five-storey precast concrete test building. *PCI Journal,* 44(6), 42-67.

Rosowsky, D. V. (2002). Reliability-based seismic design of wood shear walls. *Journal of Structural Engineering,* 128(11), 1439-1453.

Rosowsky, D. V., & Ellingwood, B. (2002). Performance-based engineering of wood frame housing: fragility analysis methodology. *Journal of Structural Engineering*, 128(1), 32-38.

Sandhaas, G., Kuilen, J.-W. v. d., & Blass, H. J. (2012). *Constitutive model for wood based on continuum damage mechanics*. Paper presented at the World Conference on Timber Engineering, Auckland, New Zealand.

Sarti, F. (2015). *Seismic design of low-damage post-tensioned timber wall systems*. (Unpublished doctoral dissertation). University of Canterbury, Christchurch, New Zealand.

Sarti, F., Palermo, A., & Pampanin, S. (2016a). Development and testing of an alternative dissipative posttensioned rocking timber wall with boundary columns. *Journal of Structural Engineering*, 142(4), E4015011.

Sarti, F., Palermo, A., Pampanin, S., & Berman, J. (2016b). Determination of the seismic performance factors for post-tensioned rocking timber walls systems. *Earthquake Engineering and Structural Dynamics*, 46(2), 10.1002/eqe.2784.

Schellenberg, A. H., Mahin, S. A., & Fenves, G. L. (2009). *Advanced implementation of hybrid simulation*. Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA..

Skidmore, Owings & Merril LLPl. (SOM). (2013). *Timber tower research project*. New York, NY: Author.

Sørensen, J. D. (2011). Framework for robustness assessment of timber structures. *Engineering Structures*, 33(11), 3087–3092.

Spence, S. M. (2018). Optimization of uncertain and dynamic high-rise structures for occupant comfort: An adaptive kriging approach. *Structural Safety*, 75, 57-66.

Starossek, U. (2006). Progressive collapse of structures: nomenclature and procedures. *Structural Engineering International*, 16 (2),113–117.

Starossek, U., & Haberland, M. (2010). Disproportionate collapse: Terminology and procedures. *Journal of Performance of Constructed Facilities,* 24(6), 519–528.

Structural Timber Innovation Company (STIC). (2013). *Design guide Australia and New Zealand post-tensioned timber buildings – Parts 1 to 3*. Christchurch, NZ: Author.

Sullivan, T. J., Calvi, J. M., Priestley, M. J. N., & Kowalsky, M. J. (2003). The limitations and performances of different displacement based design methods. *Journal of Earthquake Engineering*, 7 (sup001), 201–241.

Tamura, Y., Tanaka, H., Ohtake, K., Nakai, M., & Kim, Y. (2010). Aerodynamic characteristics of tall building models with various unconventional configurations. In *Structures Congress 2010* (3104-3113).

Tannert, T., & Moudgil, M. (2017). Structural design, approval, and monitoring of a UBC tall wood building. In *Structures Congress 2010* (541-547).

UKBR Consultancy. (2004). Disproportionate collapse, Part A, Schedule 1: A3. In *The Building Regulations 2000*. London, UK: HMSO.

United States Department of Defense (2016). *Design of buildings to resist progressive collapse* (UFC 4-023-03). https://www.wbdg.org/FFC/DOD/UFC/ufc_4_023_03_2009_c3.pdf

van de Lindt, J. W. (2005). The next step for ASCE 16: Performance-based design for woodframe structures. In *Proceedings of the 1st Invitational Workshop on Performance-based Design of Woodframe Structures*, Appendix B.

van de Lindt, J. W., & Gupta R. (2006). Damage and damage prediction for wood shearwalls subjected to simulated earthquake loads. *Journal of Performance of Constructed Facilities*, 20(2).

van de Lindt, J. W., & Liu H. (2006). Correlation of observed damage and FEMA 356 drift limits: Results from one-story wood-frame house shake table tests. In *Structures Congress 2006*, St. Louis, MI.

Viau, C. (2020). *Investigation and optimization of connections in timber assemblies subjected to blast loading*. (Unpublished doctoral dissertation). University of Ottawa, Ottawa, Canada.

Viau, C., & Doudak, G. (2016). Investigating the behaviour of typical and designed wall-to-floor connections in light-frame wood stud wall structures subjected to blast loading. *Canadian Journal of Civil Engineering*, 43(6), 562-572.

Viau, C., & Doudak, G. (2019a). Behaviour and modelling of cross-laminated timber panels with boundary connections subjected to blast loads. *Engineering Structures*, 197(15), 109404.

Viau, C., & Doudak, G. (2019b). Analytical modelling of heavy timber assemblies with realistic boundary conditions subjected to blast loading. *CSCE 2019 Annual Conference*. Laval, QC.

Viau, C., Lacroix, D., & Doudak, G. (2018). Design considerations for cross-laminated timber panels subjected to simulated blast loads. *CSCE 2018 Annual Conference*. Fredericton, NB.

Vickery, B. J., Isyumov, N., & Davenport, A. G. (1983). The role of damping, mass and stiffness in the reduction of wind effects on structures. *Journal of Wind Engineering and Industrial Aerodynamics*, 11(1-3), 285-294.

Warsido, W., & Bitsuamlak, G. T. (2015). Synthesis of wind tunnel and climatological data for estimating design wind effects: A copula based approach. *Structural Safety*, 57, 8-17.

Warsido, W., Merrick, M., Bitsuamlak, G.T. (2009, June). Dynamic optimization for the wind-induced response of a tall building. *11th American Conference of Wind Engineering*. San Juan, Puerto Rico.

Wells, M. (2011). Tall timber buildings: Applications of solid timber construction in multistorey buildings. *CTBUH Research Paper*, 2011(1), 24–27.

WoodWorks. (2019). *Analysis guidance for cross-laminated timber construction exposed to airblast loading: Overview of the Protective Design Center Technical Report (PDC-TR) 18-02*. WW-WSP 15. 9. WoodWorks – Wood Products Council, USA.

Xu, J., & Dolan, D. (2009a). Development of a wood-frame shear wall model in ABAQUS. *Journal of Structural Engineering*, 135(8). doi:10.1061/(ASCE)ST.1943-541X.0000031

Xu, J., & Dolan, D. (2009b). Development of nailed wood joint element in ABAQUS. *Journal of Structural Engineering*, 135(8). doi:10.1061/(ASCE)ST.1943-541X.0000030

Zhang, X., Popovski, M., & Tannert, T. (2018). High-capacity hold-down for mass-timber buildings. *Construction and Building Materials*, 164(10), 688-703.

Zhu, E., Chen, Z., Pan, J., & Wang, L. (2010). *Finite element modelling of the structural performance of Dou-Gong brackets of Yingxian wood pagoda*. Paper presented at the 11th World Conference on Timber Engineering, Florence, Italy.

CHAPTER 5

SECTION 5.4

Building Sound Insulation and Floor Vibration Control

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ABSTRACT

Mitigating excessive sound transmission and vibration in multi-family or multi-party residences are important serviceability design considerations. While many of the methods for mitigating the two issues may be similar, the actual mechanisms may be different. This section presents an overview of each of these issues, and provides general guidance on methods that can be used to reduce or eliminate related occupant annoyance. Current best practices for implementing solutions to achieve the building's design goals and ensure the end users' satisfaction are also discussed.

The first part of this section addresses sound transmission and the design considerations associated with minimizing it. The requirements and recommendations of the National Building Code of Canada (NBC) and other codes for building sound insulation are provided, along with a discussion of the mechanisms available for wood construction to meet those requirements. General concepts of how connections, structural form, and material combinations can be adjusted to improve mitigation of sound transmission are discussed. Examples of systems with good performance are also provided, along with architectural and structural considerations that may conflict with noise mitigation measures and render them ineffective. The discussion illustrates that the overall building system has as large an effect on the final sound mitigation effort as the design of the individual components.

The second part of this section addresses excessive vibration and why vibration can be annoying, and presents design considerations for mitigating excessive vibration. Previously proposed design methods are presented, along with a discussion of the mechanisms of wood floor's response to footstep forces when occupants are walking on the floors. Procedures used in designing and evaluating floor systems to ensure they will perform in an acceptable manner are also discussed. This section provides examples of how different types of wood floor systems can be designed to meet the intent of the NBC with respect to floor vibration serviceability in an economical manner. How various structural configurations can affect vibration response and how simplifying assumptions can result in a conservative or nonconservative design are discussed.

The information in this guide aligns with the NBC's new requirements for airborne sound insulation in buildings (NRC, 2020) and CSA O86: Standard on Engineering Design in Wood (CSA, 2019) for vibration-controlled design methods for light-frame wood joisted and cross-laminated timber (CLT) floor systems. The information also aligns with ISO 18324: Timber Structures – Test Method – Floor Vibration Performance (ISO, 2016) and ISO/TR 21136: Timber Structures – Vibration Performance Criteria for Timber Floors (ISO, 2017) standards for field evaluation of floor vibration performance.

The updated "Building Sound Insulation" section (Section 5.4.1) includes the latest research on, and some new design examples of, mass timber floor and wall assemblies, with their ASTC/FSTC/STC and AIIC/FIIC/IIC ratings. It also addresses the equivalency of sound insulation performance for mass timber other than CLT. The updated "Floor Vibration Control" section (Section 5.4.2) gives more sophisticated design guidance for floors supported by vibration-controlled beams than that provided in the first edition of this guide. The design method suggested for timber–concrete composite floors is provided to align it with the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019). The design method also addresses the equivalency of vibration behaviour of mass timber floors other than CLT floors.

This chapter reflects state-of-the-art knowledge in building sound insulation and floor vibration control. As these fields continue to advance rapidly with ongoing research and with each new building project, it is expected that design information and guidance will continue to evolve.

5.4.1 BUILDING SOUND INSULATION

5.4.1.1 Scope

This section addresses the sound insulation of walls, partitions, and floor–ceiling assemblies between adjacent spaces in buildings of wood construction. These spaces can include dwelling units, as well as spaces between dwelling units and adjacent public venues, such as halls, corridors, stairs, or service areas.

5.4.1.2 Terms and Definitions

For the purposes of this section, the following terms and definitions apply:

Apparent Sound Transmission Class (ASTC): a single number rating of the apparent airborne sound insulation performance of walls and floors in buildings as perceived by the occupants. The apparent airborne sound insulation accounts for direct transmission through the demising element as well as flanking transmission. The ASTC is determined on the basis of ASTM E413: Classification for Rating Sound Insulation (ASTM 2016b) from data measured according to ASTM E336: Standard Test Method for Measurement of Airborne Sound Attenuation Between Rooms in Buildings (ASTM 2020). The higher the number rating, the better the performance. (See the Significance and Use sections of the above standards for a more detailed description of what is quantified by the ASTC.)

Dynamic stiffness: the ratio of dynamic force to dynamic displacement of a 1 m^2 piece of material ((N/m)/m^2)). It can be measured according to ISO 9052-1: Acoustics – Determination of Dynamic Stiffness – Part 1: Materials Used under Floating Floors in Dwellings (ISO, 1989).

Field Impact Insulation Class (FIIC): a single number rating of the field impact sound insulation performance of floors in buildings as perceived by the occupants. The field impact sound insulation accounts for direct transmission through the demising floor as well as flanking transmission. The FIIC is determined on the basis of ASTM E989: Standard Classification for Determination of Impact Insulation Class (ASTM, 2012) from data measured according to ASTM E1007: Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission through Floor-Ceiling Assemblies and Associated Support Structures (ASTM, 2021). The higher the number rating, the better the performance. (See the Significance and Use sections of the above standards for a more detailed description of what is quantified by the FIIC.)

Field Sound Transmission Class (FSTC): a single number rating of the field airborne sound insulation performance of walls and floors in buildings. The FSTC is determined on the basis of ASTM E413 from data measured according to ASTM E336. The higher the number rating, the better the performance. (See the Significance and Use sections of the above standards for a more detailed description of what is quantified by the FSTC.)

Flanking transmission: the sound transmission along paths other than the direct path through the common wall or floor-ceiling assembly.

Impact Insulation Class (IIC): a single number rating of the impact insulation performance of floors defined in the section on scope. The IIC is determined on the basis of ASTM E989 from data measured according to ASTM E492: Standard Test Method for Laboratory Measurement of Impact Sound Transmission through Floor-Ceiling Assembles Using the Tapping Machine (ASTM, 2016c) in an acoustic chamber where the flanking transmission is eliminated. The higher the number rating, the better the performance.

Normalized Impact Sound Rating (NISR): a single number rating of the impact sound insulation performance of floors in buildings. Similar to the NNIC discussed below, the NISR takes into account direct and flanking sound transmission and depends on the room volume. The NISR is determined on the basis of ASTM E989 from data measured according to ASTM E1007. The higher the number rating, the better the performance. (See the Significance and Use sections of the above standards for a more detailed description of what is quantified by the NISR.)

Normalized Noise Isolation Class (NNIC): a single number rating of the apparent airborne sound isolation performance of walls and floors in buildings. The NNIC is valid only for rooms of 150 m^3 and takes into account direct and flanking airborne sound transmission. Contrary to the ASTC, it depends on the room volume and area of the demising floor or wall. The NNIC is determined on the basis of ASTM E413 from data measured according to ASTM E336. The higher the number rating, the better the performance. (See the Significance and Use sections of the above standards for a more detailed description of what is quantified by the NNIC.)

Sound Transmission Class (STC): a single number rating of the airborne sound insulation performance of walls and floors defined in the scope of this section. The STC is determined on the basis of ASTM E413 from data measured according to ASTM E90: Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements (ASTM, 2016a) in an acoustic chamber where the flanking transmission is eliminated.

Static airflow resistivity: the differential sound pressure created across a sample of unit thickness per unit velocity of the airflow ((Pa/m)/(m/s)). It can be measured according to ISO 9053-1: Acoustics – Determination of Airflow Resistance – Part 1: Static Airflow Method (ISO, 2018).

5.4.1.3 Principles of Building Sound Insulation Design

Providing sufficient mass, decoupling building components, and discontinuing building components are the basic principles of building sound insulation design. Specifically, the main factors that affect the sound insulation of wall– and floor–ceiling assemblies are as follows (NRC, 2002):

a) **Total weight per unit area**: The greater the weight, the better the sound insulation, especially for low-frequency sound.

b) **Sound absorption**: The use of sound-absorbing material in the airspace or cavity between layers is beneficial. The higher the static airflow resistivity (sound resistance) of the material in the cavity, the better the ASTC/FSTC or STC performance of the wall and floor assembly.

c) **Stiffness**: In general, for "heavy" monolithic assemblies, such as CLT, concrete, etc., the stiffer the assembly, the better the sound insulation. However, this cannot be generalized for light-frame walls and floors. The use of short-span, very stiff, wood-joist floor–ceiling assemblies results in poor low-frequency impact sound insulation, and stiff stud walls with small stud spacing also have poor sound insulation. The lower the torsional rigidity of the wall studs, the higher the wall ASTC or STC.

d) **Contact between layers**: The softer the contact between layers, the better the sound insulation. The lower the dynamic stiffness of the resilient layer, the higher the impact insulation of a floor assembly. Currently, the Korean building code is the only code that requires the dynamic stiffness of the resilient materials to be no greater than 40 ((MN/m)/m^2) for floating floors.

e) **Material porosity**: A material with a low porosity has better sound insulation than a material with a high porosity.

f) **Multi-layers with airspace**: The larger the airspace, the better the sound insulation. The fewer number of airspaces, the better the sound insulation. A configuration with a large airspace is better than one with multiple small airspaces.

g) **Floor surface hardness**: The harder the surface, the poorer the impact sound insulation, especially for high-frequency impact sound.

However, the following are general design details that are effective in limiting sound transmission in wood floor systems: (a) breaking direct structural transmission of sound by separating the floor framing between occupancy areas, (b) providing a relatively high mass structure floor, or adding a high mass covering or topping, and (c) providing soft materials such as carpeting for floor covering, or a floating flooring; or between the structural assemblies, providing resilient materials at the wall-to-floor junctions to dampen sound transmission. See Figure 1 for examples.

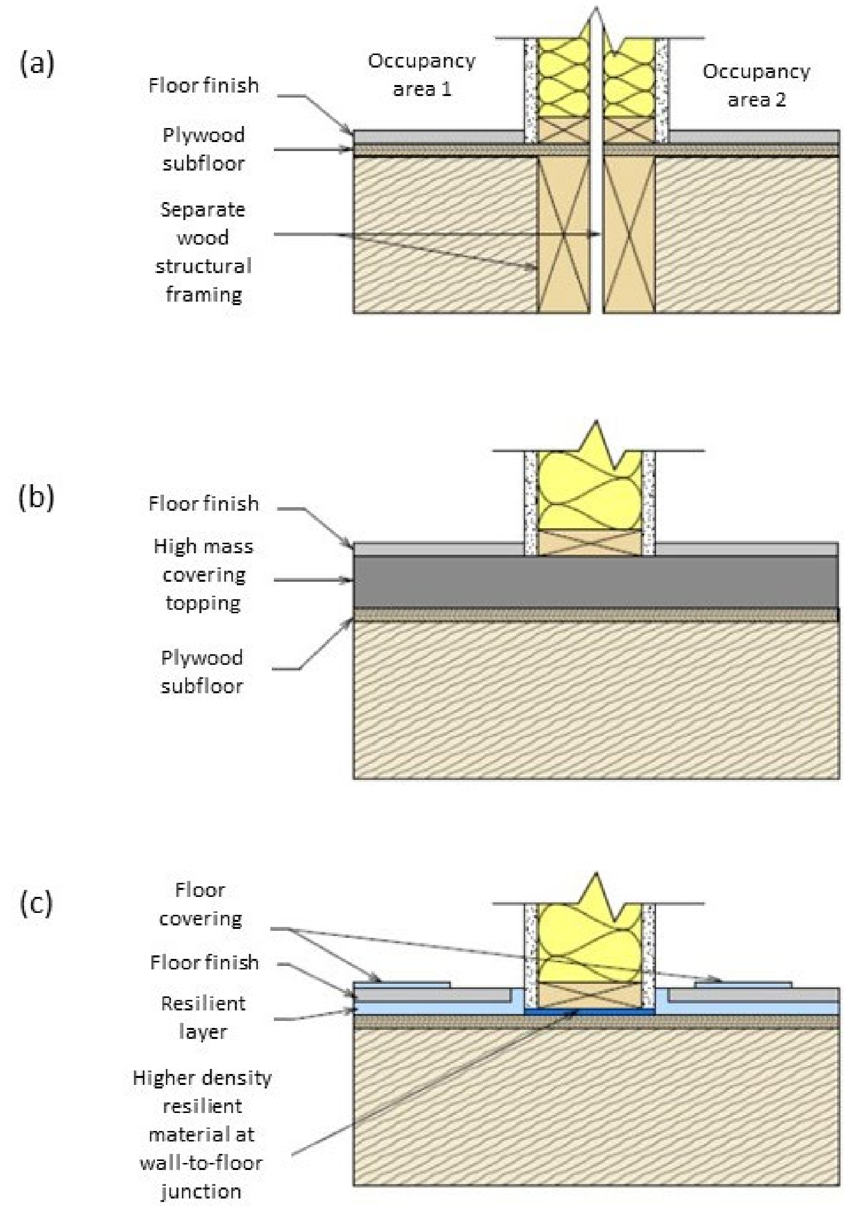


Figure 1. Some design details to limit sound transmission in wood floor systems.

In general, to ensure acceptable sound insulation performance: (a) sound should be contained in one room or occupancy area by designing traffic patterns and penetrations to avoid direct transmission to the adjoining occupants' area, (b) the sound transmission pathway should be disrupted by staggering studs or floor and ceiling joists, and (c) high mass materials that will either absorb or dampen sound between the occupancy areas should be used.

Marketability/profitability

There are solutions for exceeding acceptable code performance levels that may be demanded in certain market segments. DfMA considerations are important to ensure that lab performance is transferred to the field. In critical markets, mock-ups and prototype testing provide guidance on how to achieve the desired quality.

Simply addressing wall and floor construction details may not be sufficient for sound insolation. Openings are very effective in transmitting sound. For example, a well-designed wall might not transmit much sound, but if there are openings—such as doors—into a common hallway, or penetrations to allow plumbing, electrical, etc. to pass from one room or floor to the next, the sound barrier will be rendered ineffective. Penetrations and access patterns must be considered, and additional methods for insulating those locations must be employed.

Knowledge of human perception of noise is also important for developing a cost-effective sound insulation design or improving existing sound insulation strategies. Pope (2003) described how humans perceive changes in sound levels (Table 1): a change (reduction or increase) in sound level of less than 3 dB will likely not be perceived by a listener, but a change of 3 dB or greater will likely be perceived by most people.

Table 1. Perceptible change in loudness due to change in sound level (Pope, 2003)

Change in sound level (dB)	Change in perceived loudness
3	Just perceptible
6	Noticeable difference
10	Twice as loud, or reduced to half of the loudness
15	Large change
20	Four times as loud, or reduced to one-quarter of the loudness

5.4.1.4 National Building Code and Other Code Requirements

The 2020 National Building Code of Canada (NBC) requires that dwelling units be separated from building spaces that generate noise by using airborne sound insulated walls and floors that provide an ASTC rating of not less than 47 (NRC, 2020).

To achieve compliance with the ASTC requirement, the NBC provides three separate Acceptable Solution paths under Division B (NRC, 2020):

- in situ field measurement using the ASTM E336 procedure (ASTM, 2020) (and the ASTM E413 calculation procedure [ASTM, 2016b]), which can be applied only to completed buildings;

- a prescriptive "deemed-to-comply" procedure, using the existing list of STC-rated assemblies in the Part 9 Fire and Sound resistance tables for light-frame walls and floors (Tables 9.10.3.1.-A and -B), combined with certain joint configurations and other required details provided in Part 9; and
- a design procedure that is based on the calculation methodology of ISO 15712-1: Building Acoustics – Estimation of Acoustic Performance of Buildings from the Performance of Elements – Part 1: Airborne Sound Insulation between Rooms (ISO, 2005), described in the *Guide to Calculating Airborne Sound Transmission in Buildings* (Hoeller et al., 2017b).

The NBC also requires construction that separates a dwelling unit from an elevator hoist way or a refuse chute to have an STC rating of no less than 55 (NRC, 2020).

Regulatory Acceptance

Due to the subjectivity of an occupant's assessment of attributes such as vibration or noise isolation performance, code requirements are generally set at an acceptable minimum. Design teams can use the fast prototyping of mass timber construction to assess different solutions to not only achieve higher performance but also ensure buildability.

The NBC does not set a requirement for impact noise (structure-borne noise) protection, but it recommends that bare floors tested without a carpet should achieve an Impact Insulation Class (IIC) of no less than 55 (NRC, 2020).

The U.S. International Building Code (ICC, 2018) specifies a minimum sound insulation for demising walls and floor–ceiling assemblies between adjacent dwelling units or between dwelling units and public areas, such as halls, corridors, stairs, or service areas (Table 2).

Table 2. International Building Code minimum requirements for the sound insulation of demising walls and floor–ceiling assemblies (ICC, 2018)

	Airborne sound[a]		Structure-borne sound[b]	
Wall	STC	50	N.A.	
	FSTC	45 (field measured)		
Floor	STC	50	IIC	50
	FSTC	45 (field measured)	FIIC	45 (field measured)

Notes:
[a] When tested in accordance with ASTM E90 (ASTM, 2016a) for STC and ASTM E336 (ASTM, 2020) for FSTC
[b] When tested in accordance with ASTM E492 (ASTM, 2016a) for IIC and ASTM E1007 (ASTM, 2021) for FIIC

The International Code Council (ICC, 2010) recommends two grades of acoustic performance beyond the current code minimums: acceptable and preferred (Tables 3 and 4).

Table 3. International Code Council grades of acoustic performance recommendations based on field testing (ICC, 2010)

Field sound rating	Acceptable performance (Grade B)	Preferred performance (Grade A)
Airborne noise, NNIC	52	57
Impact noise, NISR	52	57

Table 4. International Code Council grades of acoustic performance recommendations based on laboratory testing (ICC, 2010)

Laboratory sound rating	Acceptable performance (Grade B)	Preferred performance (Grade A)
Airborne sound, STC	55	60
Impact sound, IIC	55	60

5.4.1.5 Wood-Based Wall Sound Insulation

5.4.1.5.1 *Light-Frame Wood Stud Walls*

Various light-frame wood stud walls and their STC ratings for typical low-rise buildings are listed in the NBC (NRC, 2020). Included in the fire and sound resistance tables of the NBC are 38 mm × 89 mm wood stud load-bearing or non-load-bearing walls of single row studs, two rows of staggered studs on a 38 mm × 140 mm plate, and walls with doubled studs on separate plates. The STC ratings measured on the walls vary from 32 to 62 depending on construction details such as stud spacing, wall sheathing panel type and thickness, finishing with gypsum boards and number of gypsum board layers, use of sound absorption materials in the wall cavity, and attachment detail of the gypsum boards to the structure walls. The latter includes directly attaching the boards to the walls, or attaching the boards to the walls through furring or resilient channels.

Hu (2014b) provides additional information on ASTC/FSTC ratings of some light-frame wood stud walls in wood-frame buildings, and the wall construction details. The report covers single-row and double-row 38 mm × 89 mm wood stud walls that have ASTC/FSTC ratings ranging from 50 to 56.

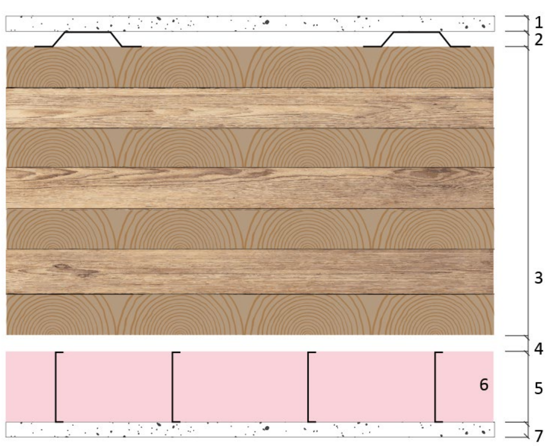
5.4.1.5.2 *CLT Walls*

Considerable research has been undertaken to measure STC or ASTC/FSTC of CLT walls with various construction details, including 3-ply of 78-mm to 7-ply of 245-mm thick single- and double-leaf CLT walls. The construction details include finishing with gypsum board, the number of gypsum board layers, the method of attachment of the gypsum boards to the CLT walls, and the sound absorption materials in the wall cavity.

The National Research Council (NRC) laboratory tested the STC ratings of many CLT walls with various construction details. Panels of 78-mm and 175-mm thick CLT were used for the wall assemblies, which included single-leaf and double-leaf walls with various degrees of coupling between gypsum board and the CLT. The STC ratings are provided in Sabourin (2015) and Schoenwald et al. (2014). Additional information on the STC ratings of various CLT wall assemblies is provided in *Acoustically-Tested Mass Timber Assemblies* (WoodWorks, 2020), which summarizes the STC ratings of almost all the tested CLT wall assemblies found in the literature.

Chapter 9 of the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019) provides examples of CLT wall assemblies, with their ASTC/FSTC ratings, which were measured on various CLT walls in CLT buildings and in laboratory mock-up (Hu, 2019). The ASTC/FSTC ratings of the CLT wall assemblies ranged from 45 to 65, depending on the construction details (Hu, 2019). An example of an ASTC/FSTC 65 single-leaf CLT wall is presented in Table 5.

Table 5. CLT wall assembly of ASTC/FSTC 65 (Hu, 2018b)

Top view of cross-section	Assembly description of drawing, from one side to the other side	ASTC/ FSTC
	1. 2 layers of 15.9-mm thick Type X gypsum board 2. 22-mm deep W-14 hat steel channels at 400-mm o.c. 3. 245-mm thick CLT 4. 19-mm wide air gap 5. 90-mm deep light gauge steel studs at 400-mm o.c. 6. 90-mm thick glass fibre insulation in cavity 7. 2 layers of 15.9-mm thick Type X gypsum board	65

Note: The ASTC/FSTC rating also depends on the building details; see FPI's report (Hu, 2014b) for the building details. The ASTC/FSTC is a reference value.

5.4.1.5.3 Other Wall Construction

Limited data on STC ratings of nail-laminated timber (NLT) wall assemblies that meet the minimum code requirement of 50 are provided in Mahn et al. (2018). The highest STC of an NLT wall assembly was 64. The wall was made of 235-mm thick NLT with 19-mm thick plywood on one side. Two layers of 12.5-mm thick Type X gypsum board was attached to a 64-mm wood frame at 600-mm o.c. The frame was decoupled from the NLT with a 13-mm air gap and 65-mm thick glass fibre in the frame cavity. The frame was placed on the plywood side (Mahn et al., 2018). The document *Acoustically-Tested Mass Timber Assemblies* summarizes all NLT wall assemblies tested by the NRC (WoodWorks, 2020).

The sound insulation designs of wall assemblies not addressed in the references cited above should be verified by measuring STC, FSTC, or ASTC ratings in accordance with ASTM E90 (ASTM, 2016a) for STC and ASTM E336 (ASTM, 2020) for FSTC/ASTC.

5.4.1.6 Wood-Based Floor Sound Insulation

Design details for wood-based floors in tall buildings are not expected to differ very much structurally from typical designs used in low-rise buildings because floor designs usually do not vary significantly between storeys or with building height. However, there may be differences due to other requirements, such as fire safety, changes in occupancy, or differences in construction type (e.g., mass timber post-and-beam construction, hybrid construction) that is employed for tall wood buildings.

5.4.1.6.1 *Light-Frame Wood Joisted Floors*

The NBC lists various light-frame wood joisted floors and their STC and IIC ratings, including solid sawn lumber joists, minimum 38 mm × 235 mm; and wood I-joists, minimum 38 mm × 38 mm flange with minimum 9.5-mm OSB or plywood web, and minimum 241 mm deep; and open-web wood trusses with wood-framing members no less than 38 mm × 89 mm and minimum 235 mm deep (NRC, 2020). The STC and IIC ratings of the floor–ceiling assemblies vary from 31 to 70, and 19 to 51, respectively, depending on the construction details, which include the topping material and thickness, and the construction details of the ceiling, such as the number of gypsum board layers, the thickness of the gypsum boards, the type of attachment of the gypsum boards to joists, and the type of material used to fill in the ceiling cavity. The topping material in the listed floor-ceiling assemblies is limited to 11-mm OSB or plywood, 25-mm gypsum–concrete, and 38-mm normal-weight concrete. The concrete should be poured directly on the subfloor but should not be floated. The floor–ceiling assemblies are assumed to have no finish. For light-frame joisted floors, higher IIC ratings than those listed in the NBC can be obtained if the cementitious topping has a cushioned or impact-reducing finish, or is floating on a resilient layer between the wood panel sheathing and the cementitious topping.

Some manufacturers of sound insulation materials, wood I-joists, and open-web trusses provide STC and IIC ratings for various light-frame wood joisted floors in their product brochures. To ensure results are comparable, designers should verify that the information in manufacturers' literature was obtained by following testing procedures that meet standards recognized by national and provincial codes.

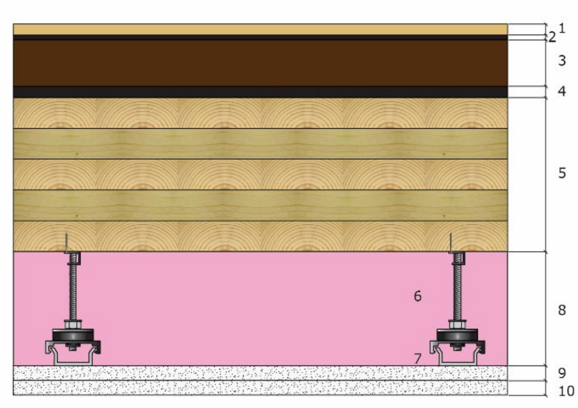
Hu (2014b) provides additional information on ASTC/FSTC and AIIC/FIIC ratings of some light-frame wood joisted floors measured in various wood-frame buildings in the field and in a mock-up of a 2-storey light-frame wood building. The floor–ceiling assemblies included finish, and a dry or wet floating topping on various resilient layers. The dry toppings consisted of a 20- to 30-mm thick gypsum board raft and cement-fibre board. The wet topping was 25- to 50-mm thick gypsum concrete, lightweight concrete, or normal-weight concrete. The measured ASTC/FSTC and AIIC/FIIC ratings were from 45 to 60. The report also includes a study of the effects of finish, underlayment, and topping on impact sound insulation of the light-frame wood floors.

5.4.1.6.2 *CLT Floors*

Significant efforts have been made to develop solutions for CLT floor sound insulation, and to measure their ASTC/FSTC/STC and AIIC/FIIC/IIC ratings. The STC and IIC ratings for 5-ply and 7-ply Canadian CLT floor assemblies with and without floating floor topping and gypsum board ceiling are published in Sabourin (2015) and Schoenwald et al. (2014). Those studies showed that similar to concrete floors, the sound insulation improvement of a floor topping or hung gypsum board ceiling measured on one CLT floor may be used under certain conditions to predict the sound insulation performance of other bare CLT floors with known airborne and impact sound insulation. Sabourin (2015) and Schoenwald et al. (2014) provide measured and predicted STC and IIC ratings for generic CLT floor assemblies with a variety of different floor and ceiling treatments. The CLT floor–ceiling assemblies did not have finishes. Other information on CLT floor assembly sound insulation ratings is provided in *Acoustically-Tested Mass Timber Assemblies* (WoodWorks, 2020), which summarizes sound insulation ratings of almost all the CLT floor assemblies found in the literature, especially those with the ceiling side exposed.

Chapter 9 of the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019) provides examples of CLT floor–ceiling assemblies, with the ASTC/FSTC and AIIC/FIIC ratings measured on various CLT floors in CLT buildings and in mock-up. The examples include 3-ply of 100-mm to 7-ply of 208-mm thick CLT floors with various construction details, with or without a dropped ceiling. The construction details include the finish, topping, resilient layer type, number of gypsum board layers in the ceiling, method of attachment of the gypsum boards to the CLT floors, and sound absorption materials in the floor cavity. The ASTC/FSTC and AIIC/FIIC ratings of the CLT floor assemblies ranged from 45 to 59, and from 44 to 61, respectively, depending on the construction details. Two examples of the CLT floors with and without a dropped ceiling are presented in Table 6.

Table 6. Sound insulation ratings of example CLT floors with and without a dropped ceiling

End view of cross-section	Assembly description from top to bottom	ASTC/ FSTC	AIIC/ FIIC
 (Hu, 2014b)	1. 10-mm thick laminated flooring 2. 3-mm thick rubber membrane (InsonoFloor) 3. 2-layer 16-mm thick Fibrerock® 4. 10-mm thick rubber mat (InsonoMat) 5. 175-mm thick CLT 6. 200-mm high sound isolation clip (RSIC-1ADM® Multi-Clip) 7. Metal hat channel 8. Rock fibre insulation (Roxul-AFB®) 9 and 10. 15.9-mm thick Type X gypsum board	59	61
 (Ramzi, 2017)	1. 10-mm thick laminated flooring 2. 2.4-mm thick felt (AcoustiTECH Premium™) 3. 2 layers of 18-mm thick OSB 4. 38-mm × 89-mm lumber sleepers at 1.2-m o.c., connected to the OSB 5. Rock fibre insulation (Roxul-AFB®) 6. 10-mm thick rubber pad of 38 mm x 38 mm under the lumber sleeper at 1.2-m o.c. along the length of each sleeper 7. 175-mm CLT	55	57

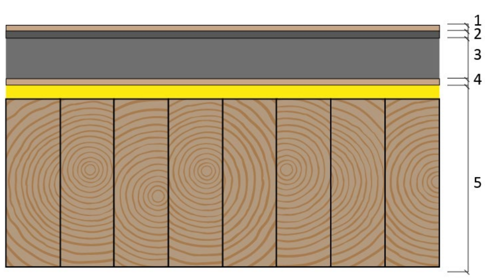
Note: The ASTC/FSTC and AIIC/FIIC ratings also depend on the building details; see FPI's report (Hu, 2014b; for the building details. The ASTC/FSTC and AIIC/FIIC are reference values.

5.4.1.6.3 *Mass Timber Floors Other than CLT*

Since 2014, when the first edition of the *Technical Guide for the Design and Construction of Tall Wood Buildings* was published (Karacabeyli, & Lum, 2014), "mass timber panels" other than CLT, especially glued-laminated timber (GLT), nail-laminated timber (NLT), and dowel-laminated timber (DLT), have attracted designers' interest and have been used extensively in various wood buildings. Research has been conducted to develop acoustics solutions for GLT, NLT, and DLT floor–celling assemblies that meet codes requirements and consumers' satisfaction (BSLC & FII, 2017; Hu, 2014b, 2019; Mahn et al., 2018; Sabourin, 2015). Additional information on the sound insulation ratings of NLT and GLT floors is provided in *Acoustically-Tested Mass Timber Assemblies* (WoodWorks, 2020).

Examples GLT and DLT floors with ASTC/FSTC and AIIC/FIIC ratings are presented in Table 7.

Table 7. ASTC/FSTC and AIIC/FIIC ratings of example GLT and DLT floors (Hu, 2019)

End view of cross-section	Assembly description from top to bottom	Airborne ASTC/FSTC	Impact AIIC/FIIC
	1. 12-mm thick laminate flooring 2. 2.2-mm thick felt (AcoustiTECH VP™) 3. 2layers of 18-mm thick OSB 4. 38-mm × 89-mm lumber sleepers at 1.2-m o.c., connected to the OSB 5. 10-mm thick rubber pad of 38 mm × 38 mm under the lumber sleeper at 1.2-m o.c. along the length of each sleeper 6. Rock fibre insulation (Roxul-AFB®) 7. 160-mm GLT with 15.5-mm thick plywood on top	58	57
	1. 6-mm thick floating flooring 2. 2.2-mm thick felt (AcoustiTECH VP™) 3. 38-mm thick normal-weight concrete 4. 6-mm thick felt (Therma-Son VB™) 5. 162.5-mm DLT with 12.5-mm thick plywood on top	N.A	53

Note: The ASTC/FSTC and AIIC/FIIC ratings also depend on the building details; see Hu (2019) for the building details. The ratings are reference values.

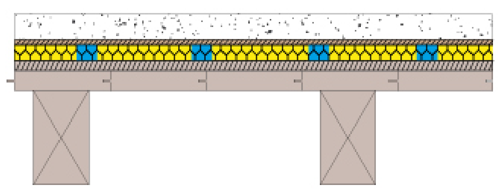
Hu (2019) reported that, in general, the orientation of lumber laminates, and the use or absence of glue to fill the gaps between the laminates affected the sound insulation performance of mass timber, especially bare mass timber floors. The addition of topping reduced those effects. In terms of impact sound insulation performance for a given panel thickness, the DLT floor with plywood nailed on the top was the best, and the GLT floor with plywood nailed on the top was better than the CLT floor. But in terms of airborne sound insulation performance, the trend was reversed: the CLT floor was the best, and with plywood nailed on the top, the GLT floor performed better than the DLT floor.

5.4.1.6.4 *Hollow Mass Timber Floors*

"Hollow mass timber" is mass timber engineered with mass timber slabs as flanges and beams as webs to form a T-, I-, or H-shaped cross-section. Because it is lighter weight and a more efficient use of wood than solid mass timber slabs, designers' interests are growing. The main advantage of hollow mass timber is demonstrated in its use in long-span floor construction. However, there currently is limited information on the sound insulation ratings of hollow mass timber floors.

Four hollow mass timber floors with the ceiling side exposed and highest STC and IIC of 54 and 52, respectively, are profiled in *Acoustically-Tested Mass Timber Assemblies* (WoodWorks, 2020). The field-measured airborne sound and impact sound ratings of a hollow mass timber floor are shown in Table 8.

Table 8. FSTC and FIIC of a hollow mass timber floor (NCBM, 2021)

End view of cross-section	Assembly description from top to bottom	FSTC	FIIC
	75-mm lightweight concrete (polished) 13-mm plywood 50-mm Kinetics® RIM (roll-out insulation material) L-2-16 89-mm wood deck subfloor Steel beam and glulam joist support	62 (NNIC)	54

Note: The ASTC/FSTC and AIIC/FIIC ratings also depend on the building details; see NCBM (2021) for the building details. The ratings are reference values.

Hu (2014b) includes information on ASTC/FSTC, and AIIC/FIIC ratings of hollow mass timber floor systems consisting of glulam beams and thick wood decks; the ratings were measured in a post-and-beam office building and a mock-up 2-storey wood building. The glulam floors spanned 9 m. The floors did not have a dropped ceiling (i.e., the wood was exposed on the ceiling side) but were covered with either a gypsum board dry topping or a cement-based topping. The ASTC/FSTC ratings were from 40 to 50, and the AIIC/FIIC ratings were from 33 to 49, depending on the underlayment for the topping and/or finishing. The system with the best field airborne sound insulation had a heavy topping of 78 kg/m², while the test floor with the best impact sound insulation had a carpet finish over the heavy topping. The report also describes the effects of various underlayment and toppings on the impact sound insulation of the glulam floors tested in the mock-up.

5.4.1.6.5 *Timber–Concrete Composite Floors*

North American information on the sound insulation of timber–concrete composite (TCC) floors is lacking in the literature. Although some information is available from Europe, where this construction has more applications, the sound insulation ratings are typically developed according to ISO standards (Churchhill & Hopkins, 2013). Hu (2014b) reports the results of a field study on the sound insulation of a timber–concrete composite floor in a post-and-beam building. The floor was built with 100-mm reinforced concrete connected to 89-mm laminated strand lumber, using shear connectors that protruded through a 25-mm thermal insulation layer. The wood on the ceiling side of the floor system was exposed, and its top was covered with a carpet. The span of the floor was 6.4 m. The measured ASTC/FSTC and AIIC/FIIC of the floor was 53 and 63, respectively. Note that the ASTC/FSTC and AIIC/FIIC ratings also depended on the building details.

5.4.1.6.6 *Other Floor Construction*

Sound insulation performance of other types of floor construction should be evaluated in accordance with ASTM E90 (ASTM, 2016a) for STC; ASTM E336 (ASTM, 2020) for FSTC/ASTC; ASTM E492 (ASTM, 2016c) for IIC; and ASTM E1007 (ASTM, 2021) for FIIC/AIIC.

5.4.1.7 Wood Building Sound Insulation System Performance

Apparent airborne and impact sound insulation performance of demising floor and wall elements in real buildings is generally worse than when tested in a wall or floor sound transmission test facility because flanking sound transmission is suppressed in the test facility. Flanking sound transmission occurs if building elements—either the demising element or others that are connected to it—are excited by airborne or impact sound. At the building junction, structure-borne sound is transmitted from the excited element to other connected building elements and radiated from the demising or flanking elements into the receiving room. The principle of flanking transmission at the floor wall junction between two horizontally adjacent rooms is depicted in Figure 2.

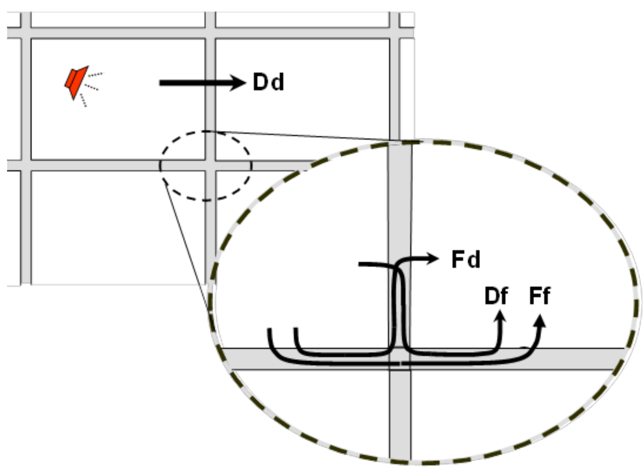


Figure 2. Direct and flanking sound transmission for the floor–wall junction between two side-by-side rooms (path naming convention according to ISO 15712: "D", "d": direct element; "F", "f": flanking element; Source room: Capital letter; Receiving room: lowercase).

Other flanking sound transmission paths could be leaks; e.g., due to building service installations that penetrate the demising element or duct work from one room to the other.

The sum of direct and flanking sound transmission between two rooms is the so-called apparent sound transmission that is rated using ASTC/FSTC, AIIC/FIIC, NNIC, and NISR.

5.4.1.7.1 *Wood-Frame Assemblies*

Where light-wood-frame assemblies are used for noise isolation, it is useful to draw on experience with testing wood-frame buildings. The NBC provides the procedure for estimating ASTC performance from measured STC and junction properties of light-frame and CLT wall and floor assemblies (NRC, 2020). However, due to the uncontrollable variations in flanking paths and because sound leaking in wood buildings is strongly influenced by workmanship, there currently is no established method for predicting ASTC and AIIC performance of wood-frame buildings made of wood construction and insulation materials that can account for all flanking paths and leakages. Therefore, it is better to measure apparent sound transmission in either a real building or a controlled laboratory environment in a special flanking sound transmission test facility (Estabrooks et al., 2009). In the latter, flanking sound transmission along a particular junction path can be isolated (King et al., 2009), which allows the effects of design modifications to be studied (NRC, 2006a) and data from different junctions to be combined in order to predict the apparent sound insulation between two rooms in a building. Flanking sound insulation data for typical junctions of wood-frame walls with 38 mm × 89 mm studs and wood joist floors are presented in the *Guide for Sound Insulation in Wood Frame Construction* (Quirt et al., 2006).

More recent data with specific design details for taller wood-frame buildings were published by Schoenwald, et al. (2014). The report includes, for example, wall designs with staggered, tripled 38 mm × 89 mm studs with and without shear bracing, and the effect of build-up columns that are necessary in tall wood buildings to support point loads or tie-downs. All the above-mentioned data are included in Hoeller et al. (2017a, 2017b) and the NRC’s soundPATHS software.

Apparent sound insulation can also be measured in the field, and the results obtained for an existing building can be used to demonstrate code compliance of another building with nominally the same design details. Sources for airborne and impact apparent sound insulation results from field tests are presented in Sections 5.4.1.5 and 5.4.1.6.

5.4.1.7.2 *CLT Buildings*

CLT wall and floor assemblies are acoustically similar to homogenous monolithic construction, such as concrete and masonry. Therefore, it is possible to approximately predict flanking sound insulation using the direct airborne and impact sound insulation data of the elements and data for coupling of structure-borne sound at the building junction. The standardized prediction method is well established for concrete and masonry buildings and has proven valid for predicting apparent sound transmission in CLT buildings (Schramm et al., 2010). ISO 15712 is technically identical to the European Standard EN 12354 that is usually referred to in publications abroad. The application of the method to CLT buildings is described in detail in the *Guide to Calculating Airborne Sound Transmission in Buildings* (Hoeller et al., 2017b). The guide also presents the necessary input data for element performance and junction coupling for some typical building junctions. However, the latter has to be measured at CLT junction mock-ups according to ISO 10848-5: Acoustics (ISO, 2020), since the equations for simple line connections in ISO 15712 are not valid for CLT construction because CLT elements are usually point connected with long wood screws or metal plates.

It is also possible to obtain apparent sound transmission data in field tests on an existing building, or in the laboratory using a flanking sound transmission suite similar to that described for wood-frame construction. However, greater effort is required for testing in a flanking sound transmission facility compared to using ISO 15712 methods. The apparent sound insulation measured in the field is applicable only to the particular combination of CLT wall and floor elements, and surface treatments (e.g., gypsum board wall and ceiling linings, and floor toppings and finishing). Sources for airborne and impact apparent sound insulation results from field tests are presented in Sections 5.4.1.5 and 5.4.1.6.

5.4.1.7.3 *Mass Timber and Timber-Hybrid Buildings*

For mass timber and timber-hybrid buildings, the methods suggested in Section 5.4.1.7.2 are valid. In some cases, for flanking transmission between generally monolithic building elements, such as TCC floors, the ISO 15712 methods are also applicable for obtaining estimates of apparent sound insulation.

The *Guide to Calculating Airborne Sound Transmission in Buildings* (Hoeller et al., 2017b) presents examples of apparent sound transmission in timber-hybrid buildings with concrete block walls and wood-framed floors. The examples are based on the results of a joint research project by the National Research Council and the Canadian Concrete Masonry Producers Association (Zeitler et al., 2015).

Further sources of apparent sound insulation data for mass timber floors and TCC floors obtained in field measurements are presented in Sections 5.4.1.6.3 and 5.4.1.6.4.

5.4.1.8 Best Practices for Ensuring End Users' Satisfaction – Step-by-Step Guide

This section guides the reader toward a satisfactory sound insulation solution for wood building projects.

5.4.1.8.1 *Step 1: Selecting Construction Solutions for ASTC/FSTC and AIIC/FIIC Ratings of No Less than 50*

Field surveys and investigations have shown that meeting even the minimum International Building Code requirements (i.e., FSTC and FIIC of 45) or the NBC requirement for ASTC 47 does not always eliminate complaints from occupants. While not always possible, it is recommended that building designs aim to achieve ASTC/FSTC and AIIC/FIIC ratings of at least 50, or that ICC recommendations be used, particularly in multiple residential dwelling units.

5.4.1.8.2 *Step 2: Eliminating Avoidable Flanking Paths*

To optimize the efficiency of the sound insulation solutions provided in codes and the literature, a quality-controlled installation protocol must be implemented in order to eliminate avoidable flanking paths.

Project Delivery

A mock-up or prototype may be used to assess achievable construction tolerances and build quality on performance attributes such as vibration and flanking noise transmission. Interpreting these preliminary results may be challenging, but it should help identify options for correcting issues identified during in-situ testing.

There are two types of flanking transmission: sound leaking through openings, and vibration transfer between coupled surfaces or through continuous structural elements. Flanking control involves sealing openings, decoupling surfaces, and discontinuing structural elements, provided doing so does not affect structural safety and serviceability. However, compromises are sometimes necessary. A checklist of flanking paths and treatments is provided in Table 9. The list includes the most obvious and crucial flanking paths that must be controlled or eliminated. If the flanking paths can be controlled, the recommended treatments should provide satisfactory sound insulation for wood buildings.

Table 9. Checklist of flanking paths and treatments

Flanking path	Treatment
Leaks around edges of partitions (ASTM E336 [ASTM, 2020])	Seal leaks with tape, gaskets, or caulking compound (ASTM E336). Plan traffic patterns so that doors do not open onto common areas where sound can easily be transmitted around the dividing wall, floor, etc.
Cracks at wall/floor junctions	Caulk joint between gypsum board and floor (NRC, 2002).
Debris between floor and wall sill plates	Clean floor and caulk sill plate (NRC, 2002).
Leaks through electrical outlets	Avoid back-to-back outlets by offsetting them 400 mm (16 in.) or at least one stud space from side to side (NRC, 2002).
If gypsum board is rigidly attached to studs or the wall framing, the wall could contribute to flanking (NRC, 2002).	Attach gypsum board on resilient channels (NRC, 2002).
Joint between the perimeter of the flooring or topping and the surrounding walls, especially if the flooring or topping is floating or not rigidly attached to the subfloor	Leave a gap around the entire perimeter of the flooring or topping assembly and the walls. Fill it with resilient perimeter isolation board or backer rod, and seal the joint with acoustical caulking.
Continuous subflooring, joists, and CLT elements between two adjacent units	Discontinue subflooring, joists, and CLT as much as possible. Add floating topping and floating flooring if continuity is not avoidable. Connect CLT sub-elements of the floor at junctions with a wall.

5.4.1.8.3 *Step 3: Measuring ASTC/FSTC and AIIC/FIIC Performance after Finishing*

To ensure proper airborne and impact sound insulation of finished wall and floor assemblies, it is advisable to measure the ASTC/FSTC, NNIC, AIIC/FIIC, and NISR performance to confirm that they meet or exceed target design values. In the worst-case scenario, if these expected performance ratings are not met, it may be possible to remedy this situation before the building is occupied.

5.4.1.8.4 *Step 4: Subjective Evaluation by Architects, Designers, Builders, and Contractors*

It is recommended that builders, developers, architects, designers, contractors, and/or product manufacturers conduct an informal subjective evaluation of a building's sound insulation performance once the building has been completed and before the occupants move in. If they are not satisfied with the sound insulation, additional measures can be taken. For critical applications, it may be useful during design to identify what mitigation measures can be used, and to carry out testing and inspections during construction to determine if the design details are being properly implemented. Alternatively, some assemblies may be assessed and installed as prefabricated units.

A subjective evaluation protocol is provided in Hu (2014b).

5.4.2 FLOOR VIBRATION CONTROL

5.4.2.1 Scope

This section addresses control of excessive transverse vibrations induced by footsteps from normal human walking or machines on wood-based floors in order to ensure occupants' comfort.

5.4.2.2 Terms and Definitions

For the purposes of this section, the following terms and definitions apply:

Damping: parameter related to the dissipation of energy or, more precisely, to the conversion of the mechanical energy associated with a vibration to another form of energy (sound and heat).

Fundamental natural frequency: the lowest frequency among the infinite number of natural frequencies of a system.

Floor vibration: the oscillation perpendicular to the floor plane and the vertical oscillation of a floor about its neutral plane.

Vibration: the oscillation of a system about its equilibrium position.

Vibration frequency: the number of oscillations per second (Hz). For a continuous system, such as a floor, its vibration response to an excitation theoretically contains an infinite number of frequency components.

5.4.2.3 Control of Floor Vibration Induced by Footsteps to Enhance Occupant Comfort

5.4.2.3.1 *Design Principles for Control of Floor Vibrations Induced by Footsteps*

Decades of floor research (Hu, 2007) has shown that for lightweight floors characterized by a fundamental natural frequency above 9 Hz, vibrations induced by footsteps can be controlled by using the proper combination of floor stiffness and mass. For heavy floors characterized by a fundamental natural frequency below 9 Hz, vibrations induced by footsteps can be managed similarly as wood-based floors are considered lightweight.

The general cause of occupant annoyance with floor vibration occurs when the vibration interferes with some part of the operation of the building, or the vibration fundamental frequency occurs within a range of frequencies that correspond to the natural frequencies of different parts of the human body. Therefore, the objective of the design is to determine the mass and stiffness of the floor system so it has a fundamental natural frequency that is significantly different from the equipment (such as a ceiling-hung projector) being affected (2–5 Hz), or the annoyance range for the human body (7–12 Hz).

The following are some general rules for achieving improved floor vibration:

a) Separate the floor framing system between occupancy areas to prevent vibration transmission. This may be accomplished by introducing a break at supports rather than using continuous multi-span floor framing between occupancy areas (the main mechanism for transmission of vibration is bending action); more discussion on supporting beams is provided in Section 5.4.2.5.1.

b) Plan the floor framing system so that the floor joists or floor panels are not supported on other bending framing members, or ensure that the supporting framing is very stiff. The interaction of the flexible support with the floor joists or floor panels often causes the vibrations to become annoying to occupants. More discussion on supporting beams is provided in Section 5.4.2.5.1.

c) Isolate sources of noise (such as China cabinets) associated with the vibration. The added sense of hearing exasperates the perception of the vibration.

5.4.2.3.2 *Light-Frame Joisted Floors*

Light-frame joisted floors are constructed of sawn lumber, wood I-joists, or open-web parallel chord trusses, and are sheathed with structural wood panels or lumber. They may be overlaid with nonstructural topping made of concrete or gypcrete. A number of research studies on this type of floor system have been conducted, all with the objective of developing suitable design approaches to prevent excessive human-induced floor vibration. Some of the design methods are summarized in Table 10.

Table 10. Summary of design methods for light-frame wood joisted floors

Design parameters	Performance criteria	Limitation	Method and reference
d_{pl} where d_{pl} = deflection under a 1 kN load	d_{pl} < 2 mm for span < 3 m d_{pl}< 8/span$^{1.3}$mm for span ≥ 3 m	Not suitable for floors with heavy topping, and not a dynamic-based criterion, which has limited its application; see further discussion below	National Building Code of Canada (NRC, 2020)
f_1 where f_1 = fundamental natural frequency	$f_1 > 14$ Hz	Appears quite restrictive, especially for long-span floors and floors with a heavy topping	Dolan et al. (1999)
f_1, d_{pl}, and V_{peak} where V_{peak} = peak velocity due to unit impulse	$d_{pl} > 1.5$ mm $f_1 > 8$ Hz $V_{peak} < 100^{(f1\ \xi\ -1)}$	Limited validation, and not validated against floors with a heavy topping	Swedish design guide (Ohlsson, 1988)
f_1, a_{rms} where a_{rms} = frequency-weighted root-mean-square acceleration	f_1 > 8 Hz $a_{rms} \leq 0.45$ m/s^2	Limited validation, and not intended for floors with a heavy topping	Smith & Chui (1988)

The NBC method of establishing vibration-controlled spans (NRC, 2020) is limited for lumber joisted floors with spans from 3.0 to 6.0 m and with bridging/strapping/blocking. A table of vibration-controlled spans for lumber joisted floors was derived from this method and is provided in the NBC. The method accounts for the effect on floor vibration of using glue, along with nails or screws, to attach the subfloor to joists. The method allows for an increase in floor span if a normal-weight concrete topping is poured directly on a wood floor; however, caution should be used in applying the method to light-frame joisted floors with concrete topping. Research has shown that the spans of light-frame wood floors should be reduced when heavy concrete topping is added (Hu & Gagnon, 2009).

The Canadian Construction Materials Centre (CCMC) published a method of determining vibration-controlled spans for engineered wood members; e.g., wood I-joists or wood trusses (CWC, 1997). The span range is from 3.0 to 10.0 m. The method was an extension of the original floor vibration design method for lumber joisted floors that was first included in the NBC in the early 1990s. The CCMC method also accounts for the effects of glue, topping, and bridging/blocking/strapping on floor vibration, but it differs from the original method in that it allows for the use of engineered wood floors without the use of bridging/strapping/blocking, and the use of continuous multi-span joists. However, the CCMC cautioned users that for concrete-topped floors and floors with bridging and/or blocking, this method may lead to overestimation of allowable spans (Di Lenardo, 2002). Caution should also be exercised when using this method to determine maximum spans for continuous multi-span floors because it overestimates the maximum spans of floors that use multi-span joists.

Options for enhancing the performance of floors that do not meet the NBC and CCMC method performance targets are limited because the targets recognize only floor system stiffness as a parameter that controls floor vibration.

To overcome the limitation of the NBC and CCMC methods, and other methods listed in Table 10 FPInnovations, in collaboration with the University of New Brunswick (UNB), developed a generalized design method to determine vibration-controlled spans for light-frame joisted floors that had spans from 3.0 to 13.0 m (Hu, 2007). The method controls floor vibrations by controlling floor stiffness and mass. This approach consists of three elements: the design criterion, a calculation method for determining the criterion variables, and the proposed design properties for floor component materials.

The design criterion was developed based on a field consumer survey and testing of more than 100 wood-framed floors across Canada. The design criterion is expressed in Equation [1]:

$$\frac{f}{d^{0.44}} > 18.7 \text{ or } d < \left(\frac{f}{18.7}\right)^{2.27} \quad [1]$$

where d and f are the calculated static deflection due to a 1 kN load applied at the floor centre (in mm), and the calculated fundamental natural frequency of the wood-based floor (in Hz), respectively. Equations [2] and [3] are used to compute *d* and *f* based on ribbed plate theory:

$$d = \frac{4000\mathrm{P}}{ab\pi^4} \sum_{m=1,3,5} \sum_{n=1,3,5..} \frac{1}{\left(\frac{m}{a}\right)^4 D_x + 4\left(\frac{mn}{ab}\right)^2 D_{xy} + \left(\frac{n}{b}\right)^4 D_y} \quad [2]$$

$$f = \frac{\pi}{\sqrt[2]{\rho}} \sqrt{D_x\left(\frac{1}{a}\right)^4 + 4D_{xy}\left(\frac{1}{ab}\right)^2 + D_y\left(\frac{1}{b}\right)^4} \quad [3]$$

where P = point load applied at the centre of the floor (1000 N); *a* = floor span (m); *b* = floor width (m); m = number of half sine waves in the x direction; n = number of half sine waves in the y direction; D_x = floor flexural rigidity in floor span direction (N-m²/m); D_y = floor flexural rigidity in across span direction (N-m²/m); D_{xy} = shear rigidity of multi-layered floor deck + torsion rigidity of joist (N-m²/m); and ρ = area density of the floor system (kg/m²).

See Chui (2002) for guidance on how these parameters are determined.

This design approach was validated using the database for in situ floor testing (Hu, 2007). The predicted floor vibration performance was well matched with the occupants' expectations. The detailed comparison is reported in Hu (2007).

This method accounts for all the construction details of light-frame wood floors and overcomes some of the problems in the NBC, CCMC, and other methods. The construction details include the use of glue at the connections between the subfloor and joists, bridging/strapping/blocking, topping, and continuous multi-span joists.

The application of Equations [1] to [3] is an iterative process, which may be cumbersome to apply in design. FPInnovations further simplified the method above to explicitly determine the vibration-controlled span. The design method was adopted and included in Clause A.5.4.5.1 of CSA O86 (CSA, 2019), as shown in Equation [4]:

$$l \leq \frac{0.122\,(EI_{eff})^{0.284}}{F_{tss}{}^{0.14} m_L{}^{0.15}} \qquad [4]$$

where l = vibration-controlled span (m); EI_{eff} = effective composite bending stiffness of the floor system in the joist span direction for a 1-m wide panel (N-m^2) (see Clause A.5.4.5.1.1 of CSA O86); F_{tss} = factor to account for the transverse system stiffness contribution in reducing floor defection (see Clause A.5.4.5.1.3 of CSA O86); and m_L = linear mass of the composite cross-section of the floor that accounts for the joist, subfloor, and topping (kg/m) (see Clause A.5.4.5.1.2 of CSA O86).

The simplified version of the original method has the same features as the reference method, and was verified. Additional background on the calculations and notes is provided in Hu (2014a) and Clause A.5.4.5.1 of CSA O86.

5.4.2.3.3 *Light-Frame Joisted Floors with Heavy Topping*

The design method presented in Clause A.5.4.5.1 of CSA O86 (CSA, 2019) includes light-frame joisted floors with heavy topping such as normal-weight concrete topping or other types of cement-based topping. Attention needs to be paid to the notes in Clause A.5.4.5.1 when using the design method for floors with a topping.

5.4.2.3.4 *CLT Floors*

Clause A.8.5.3 of CSA O86 (CSA, 2019) provides the method for determining vibration-controlled spans of CLT floors, as shown in Equation [5]:

$$L \leq 0.11 \frac{\left(\frac{EI_{eff}}{10^6}\right)^{0.29}}{(m)^{0.12}} \qquad [5]$$

where L = vibration-controlled span limit (m); m = linear mass of CLT for a 1-m wide panel (kg/m) (see producer's specification); and EI_{eff} = effective bending stiffness in the major strength direction for a 1-m wide panel (N-mm^2) (may be obtained from the producer's specification or product standard ANSI/APA PRG 320-2018: Standard for Performance-Rated Cross-Laminated Timber (ANSI/APA, 2018), or can be calculated in accordance with accepted mechanics methods such as specified in CSA O86 for CLT design guidance (CSA, 2019), or in Chapter 7 of the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019).

Equation [5] assumes that the vibration-controlled CLT floor is rigidly supported on simple supports across the full width of the panel (e.g., on load-bearing walls).

Additional background information on the calculations and notes for multi-span floors, concrete topping, etc. is provided in the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019) and commentary of CSA O86 (CSA, 2019).

5.4.2.3.5 *Hollow Mass Timber Floors*

As discussed in Section 5.4.1.6.4, hollow mass timber floors are lighter weight than solid mass timber slabs and make more efficient use of wood, and they can be used in longer span floor and roof systems. Currently, there is limited information on vibration-controlled design methods for hollow mass timber floors.

The FPInnovations and UNB generic design method originally developed for light-frame joisted floors, and Equations [1] to [3], can be applied to hollow mass timber floors but may be conservative because hollow mass timber floors are heavier than light-frame joisted floors; therefore, further verification is likely required before the method can be used with confidence.

5.4.2.3.6 *Hybrid Steel Truss and Thick Wood Deck Floors*

Although the generic design method created by FPInnovations and UNB was originally developed for light-frame joisted floors, Equations [1] to [3] also have the potential to be applied to hybrid steel truss and thick wood deck floors. If the method is used for the design of these floors, further review and verification is required. (See Chapter 9 of this guide for direction on field-collecting information for model verification.)

Hu & Gagnon (2010) conducted a study on the vibration performance of a 9-m span, steel truss–glulam deck hybrid floor system. It showed that for occupants' satisfaction, a hybrid steel–wood floor should have a fundamental natural frequency above 10 Hz.

For a heavy concrete deck supported by steel beams or floor trusses, a limit on peak acceleration is recommended to control floor vibrations due to walking (Murray et al., 1997). Equation [6] shows the method for calculating peak acceleration:

$$\frac{a_p}{g} = \frac{P_0\ \mathrm{e}^{-0.35 f_1}}{\beta W} \qquad [6]$$

where a_p = peak acceleration of a floor, g; g = acceleration due to gravity (9.81 m/s^2); P_0 = a constant force equal to 0.29 kN (65 lb.); f_1 = fundamental natural frequency of the floor structure (Hz); β = modal damping ratio; and W = effective weight of a floor (kN).

(See Murray et al. [1997] for information on the acceleration limit and modal damping ratio, and the method for calculating the effective weight of a floor.)

Heavy steel–concrete floors typically have fundamental natural frequencies below 8 Hz, and the vibration induced by human walking on these floors is mainly resonance-based. Applying this method to hybrid steel truss and thick wood deck floors requires caution, especially in assigning the damping values and calculating the effective weights of steel–wood floors. A review and verification of the floor design, with a mock-up of the floor, is recommended. Hu & Gagnon (2010) reviewed the application of the American Institute of Steel Construction method to hybrid steel truss and thick wood deck floors.

5.4.2.3.7 *Timber–Concrete Composite Floors*

Timber-concrete composite floors are composed of a thick, reinforced, concrete slab that is mechanically connected to a thick wood deck using shear connectors. Different types of proprietary shear connectors are available on the market (such as inclined screws, or HBV or SFS intec shear connectors). Technical information on these connectors is available from the manufacturers; however, there are currently no standardized design methods or test procedures in Canada for evaluating these products.

Cuerrier-Auclair et al. (2018) proposed a tentative design method for determining the vibration-controlled spans for TCC floors with both ends simply supported, based on Equation [7]:

$$L \leq 0.329\frac{\left(EI_{eff}\right)^{0.264}}{m^{0.206}} \qquad [7]$$

where *L* = vibration-controlled span limit of a TCC floor (m); EI_{eff} = effective bending stiffness in the major strength direction for a 1-m wide panel of TCC (N-m^2); and *m* = linear mass of TCC for a 1-m wide panel (kg/m).

Detailed calculations of the parameters in Equation [7] are provided in Chapter 7 of the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019) and in Cuerrier-Auclair et al. (2018).

This design method should be further evaluated by testing. Guidance on measuring the performance of timber floor systems is included in Chapter 9 of this guide and in ISO 18324 (ISO, 2016). A subjective evaluation should also be performed according to ISO/TR 21136 (ISO, 2017).

5.4.2.3.8 *Mass Timber Slab Other than CLT Floors*

DLT may have higher bending stiffness in the major strength direction than CLT of the same thickness and species but much lower bending stiffness in the minor strength direction (Hu, 2020). The CLT floor design method may be used to determine the vibration-controlled spans for GLT, DLT, and NLT floors, provided the values for EI_{eff} and *m* are accurately established. Further investigation of the application of the CLT design method to those mass timber panel floors is desirable to gain more confidence in the method. Performance and subjective evaluation tests described in Chapter 9 of this guide can be used for that purpose.

5.4.2.3.9 *Other Innovative Wood-Based Floors*

Where the vibration behaviour of innovative wood-based floors has not been assessed by laboratory or field testing, existing design methods may not be applicable. Testing of field and laboratory-fabricated assemblies may be the only option for evaluating the vibration performance of those floor systems. Performance and subjective evaluation tests described in Chapter 9 of this guide can be used for that purpose.

Additional information on mass timber floor vibration-controlled designs is provided in the *U.S. Mass Timber Floor Vibration Design Guide* (Breneman et al., 2021).

5.4.2.4 Control of Floor Vibration Induced by Machines to Enhance Occupant Comfort

The NBC recommends that the undesirable effects of continuous vibration caused by machines be minimized by special design provisions such as locating machinery away from sensitive occupancies, providing vibration isolation, or altering the natural frequencies of the structure (NRC, 2020).

Altering the natural frequencies of a floor is generally conducted to ensure that the first few natural frequencies do not coincide with the vibrating frequency of the machinery. Relevant information on the operation frequency of the machinery can be obtained from its manufacturers and its specifications. Equation [8] can be used to calculate the natural frequencies of most floor systems, including light-frame joisted wood floor systems, hollow mass timber floors, hybrid steel truss and thick wood deck floors, and mass timber slab and TCC floors with four edges simply supported. For an orthotropic plate with only two edges simply supported, there is no closed-form formula for calculating natural frequency. However, for the floor in a building, Equation [8] can be used if it is assumed that the floor width is the building width, which is usually greater than the span. In effect, the supports at the other two edges are assumed to have little effect on the calculated frequency.

The effect of topping may also be incorporated into the appropriate input properties, as discussed by Hu (2007).

Equation [8] shows the method for calculating the natural frequencies, f_{mn} (in Hz) of most floor systems:

$$f_{mn} = \frac{\pi}{2a^2\sqrt{\rho}}\sqrt{D_x^{floor} m^4 + 2D_{xy}^{floor} m^2 n^2 \left(\frac{a}{b}\right)^2 + D_y^{floor} n^4 \left(\frac{a}{b}\right)^4} \qquad [8]$$

where m = number of half sine waves in the x direction; n = number of half sine waves in the y direction; a = floor span (m); ρ = area density of the floor system (kg/m^2); D_x^{floor} = floor flexural rigidity in floor span direction (N-m^2/m); D_{xy}^{floor} = floor shear rigidity (N-m^2/m); b = floor width (m); and D_y^{floor} = floor flexural rigidity in across-span direction (N-m^2/m).

Currently, the input values for some of the rigidities of mass timber such as GLT, DLT, NLT, hollow mass timber, or TCC floors are not available. Therefore, those properties should be determined through laboratory testing and/or the use of analytical models that appropriately model the anisotropic and nonhomogeneous behaviour of mass timber panels and the imperfect connectivity between the floor panels and supporting beams or ribs. Designers should validate any models used by conducting tests on the components and assemblies.

5.4.2.5 Best Practices

5.4.2.5.1 *Proper Supports*

Support conditions for floor joists, beams, and plates influence the stiffness properties of floor systems, and therefore their response to dynamic excitation. The support conditions also determine whether the floor vibration will be transmitted to other areas of the building. The bending action of the beams is the primary mechanism by which annoying vibration is transmitted. In platform construction, where the joists or plates rest on a supporting wall below, the support condition approaches that of a simple support, which is the underlying assumption for all vibration-controlled design methods proposed to date. Deviation from the simple support condition may occur in several ways. For example, where floor components are supported on nonrigid supports (such as joist hangers, secondary floor beams, or steel angle brackets), or are resting on an elastic foundation, the actual natural frequencies will be significantly lower and the actual deflection under an applied load will be higher than the respective model predictions. This could lead to the acceptance of an unsatisfactory floor. When this is suspected, a more in-depth analysis of the influence of the support condition is necessary. The design guide *Floor Vibrations Due to Human Activity* (Murray et al., 1997) provides an approach for calculating the fundamental natural frequency of a floor system with one end supported on a secondary beam, as shown in Equation [9]:

$$f_{system} = \sqrt{\frac{{f^2}_{floor}}{\left(\frac{f_{floor}}{f_{beam}}\right)^2 + 1}} \qquad [9]$$

where, f_{floor} can be determined using Equation [8]. The frequency of the supporting beam, f_{beam} (Hz), may be determined using Equation [10], assuming that the supporting beam is simply supported:

$$f_{beam} = \frac{\pi}{2l^2}\sqrt{\frac{EI}{m_l}} \qquad [10]$$

where l = span of the supporting beam (m); EI = apparent bending stiffness, including shear effect of the beam (N-m²); and m_l = mass of the beam per unit length (kg/m).

Hu (2018a) proposed a tentative supporting beam stiffness requirement for floor vibration control. The assumption underpinning the proposed requirement is that the ends of the supporting beams should at least be supported on load-bearing walls or columns. The supporting beam should be made of wood, engineered wood, composite wood, or other wood-based material.

Under the above conditions, the vibration-controlled supporting beam's apparent bending stiffness should meet the requirement shown in Equation [11] to ensure the supporting beam is solid as a simple support:

$$(EI)_{beam} \geq 132.17\, F_{span}\, l_{beam}^{6.55} \qquad [11]$$

where *(EI)**beam*** = supporting beam apparent bending stiffness (N-m²) provided by the beam producers or calculated using Equation [12]; F_{span} = 1.0 for simple span beam and ≈ 0.7 for multi-span continuous beam; and l_{beam} = clear span of supporting beam (m):

$$l_{beam} = \frac{Eb\,h^3}{12} \qquad [12]$$

where E = apparent modulus of elasticity (N/m²) (for wood, see CSA O86 [CSA, 2019]; for other materials, see the appropriate material standards); b = beam width (m); and h = beam depth (m).

The proposed requirement for vibration-controlled supporting beams is well matched to the test results for appropriate floor systems in post-and-beam wood buildings, especially in new mid-rise and tall wood buildings (Hu, 2018b). However, besides meeting the proposed minimum requirement for vibration-controlled floor supporting beams, the supporting beams should also meet the other code requirements, including strength, deflection, and creep.

In contrast, when floor joists span an intermediate support or the ends of floor joists, or CLT plates are "clamped" between upper and lower stories, an end fixity condition is created (Hernadez & Chui, 2014). In this situation, the assumption of simple support leads to a conservative prediction of floor performance, which should be acceptable. Zhang et al. (2019) provide an approach for considering the influence of end fixity on natural frequency and static deflection under a point load. However, this does provide a flanking path for sound transmissions, which may be problematic.

5.4.2.5.2 Subjective Evaluation of Floors by Architects, Designers, Builders, and Contractors

Where there is little field experience with a particular system, an informal subjective evaluation by builders, developers, architects, designers, contractors, and/or product manufacturers should be conducted before the building is occupied. However, if this is not expected to be feasible, some evaluation may be performed on mock-ups and on the floor system as construction progresses so that possible adjustments to details can be made.

Nevertheless, valuable data can be obtained from existing structures based on an informal subjective evaluation conducted by builders, developers, architects, designers, contractors, and/or product manufacturers.

Building Performance

Measures for providing good vibration and sound isolation performance may be sensitive to the quality of the build. Because structural, sound control, and fire details often conflict, they should be designed together. Testing of a representative prototype may help refine design assumptions and address design conflicts.

Designers and builders are encouraged to record their observations using the subjective evaluation protocols and evaluation questionnaire developed by FPInnovations and provided in ISO/TR 21136 (ISO, 2017). See also Chapter 9 of this guide.

5.4.2.5.3 *Field Measurement Before and After Finishing*

Field tests are used to measure maximum floor deflection under a concentrated load applied at the floor centre, and to measure the floor acceleration or velocity response and the floor natural frequencies. Conducting field measurements on floor systems, before and after finishing, provides useful information on floor stiffness, indicated by the deflection under a concentrated load, and on the floor's natural frequencies. Test protocols for field measurements are provided in ISO 18324 (ISO, 2016). See also Chapter 9 of this guide.

5.4.3 REFERENCES

American National Standards Institute/The Engineered Wood Association (ANSI/APA). (2018). *ANSI/APA PRG 320-2018: Standard for performance-rated cross-laminated timber*. New York, NY: Author.

ASTM International (ASTM). (2021. *ASTM E989-21: Standard classification for determination of impact insulation class (IIC)*. West Conshohocken, PA: Author. https://www.astm.org/DATABASE.CART/HISTORICAL/E989-06R12.htm

ASTM International (ASTM). (2016a). *ASTM E90-09: Standard test method for laboratory measurement of airborne sound transmission loss of building partitions and elements*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E90.htm

ASTM International (ASTM). (2016b). *ASTM E413-16: Classification for rating sound insulation*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E413.htm

ASTM International (ASTM). (2016c). *ASTM E492-09(2016)e1: Standard test method for laboratory measurement of impact sound transmission through floor-ceiling assembles using the tapping machine*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E492.htm

ASTM International (ASTM). (2020). *ASTM E336-20: Standard test method for measurement of airborne sound attenuation in buildings*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E336.htm

ASTM International (ASTM). (2021). *ASTM E1007: Standard test method for field measurement of tapping machine impact sound transmission through floor-ceiling assemblies and associated support structures.* West Conshohocken, PA: Author. https://www.astm.org/Standards/E1007.htm

Binational Softwood Lumber & Forest Innovation Investment Ltd. (BSLC & FII). (2017). *Nail-laminated timber: Canadian design & construction guide v.1.1*. http://www.naturallywood.com/NLT

Breneman, S., Zimmerman, R., Gerber, A., Epp, L., Dickof, C., Taylor, A.,...Visscher, R. (2021). *U.S. mass timber floor vibration design guide*. WoodWorks – Wood Products Council. https://www.woodworks.org/wp-content/uploads/wood_solution_paper-Mass-Timber-Floor-Vibration.pdf

Canadian Standards Association (CSA). (2019). *CSA O86-19: Engineering design in wood*. Mississauga, ON: Author.

Canadian Wood Council (CWC), DMO Associates, Quaile Engineering Ltd., & Forintek Canada Corp. (1997*). Development of design procedures for vibration-controlled spans using engineered wood members*. Ottawa, ON: Canadian Construction Materials Centre and Consortium of Manufactures of Engineered Wood Products Used in Repetitive Member Floor Systems.

Chui, Y. H. (2002, August). Application of ribbed-plate theory to predict vibrational serviceability of timber floor systems. In *Timber construction in the new millennium: the Proceedings of 7th World Conference on Timber Engineering* (Paper No. 9.3.1, Vol. 4, 87-93). Shah Alam, Malaysia.

Churchill. C., & Hopkins, C. (2013). *Development of SEA models of composite heavyweight-lightweight floors by incorporating measured stiffness data for suspended ceiling hangers*. Paper presented at Internoise 2013, Innsbruck, Austria.

Cuerrier-Auclair, S., Hu, L., and Ramzi, R. (2018). *Design method for vibration control of timber-concrete composite floor*. Sainte-Foy, QC: FPInnovations.

Di Lenardo, B. (2002). Industry update: CCMC involved in efforts to make engineered wood joists easier to use. *NRC-IRC: Construction Innovation*, 7(4), 4-5.

Dolan, J., Murray, T., Johnson, J., Runte, D., & Shue, B. (1999). Preventing annoying wood floor vibrations. *Journal of Structural Engineering*, 125(1), 19-24.

Hernandez, S., & Chui, Y. H. (2014, August). Effect of end support conditions on the vibrational performance of cross-laminated timber floors. *Proceedings of World Conference in Timber Engineering* (Paper No. 571). Québec City, QC.

Hoeller, C., Mahn, J., Quirt, J. D., Schoenwald, S., & Zeitler, B. (2017a). *Apparent sound insulation in cross-laminated timber buildings* (Research Report 335). Ottawa, ON: National Research Council Canada. Institute for Research in Construction.

Hoeller, C., Quirt, J. D., & Man, J. (2017b). *Guide to calculating airborne sound transmission in buildings* (3rd ed., Research Report 331). Ottawa, ON: National Research Council Canada. Institute for Research in Construction. https://nrc-publications.canada.ca/eng/view/object/?id=1252c2f5-23a2-4e9f-8c6a-2c1135a26ef5

Hu, L. J. (2007). *Design guide for wood-framed floor systems*. Québec, QC: FPInnovations.

Hu, L. J. (2014a). *New design method for determining vibration controlled spans of wood joisted floors*. Québec, QC: FPInnovations.

Hu, L. J. (2014b). *Serviceability of next generation wood buildings: Sound insulation performance of wood buildings*. Québec, QC: FPInnovations.

Hu, L. J. (2018a). *Advanced wood-based solutions for mid-rise and high-rise construction: Proposed vibration-controlled design criterion for supporting beams*. Sainte-Foy, QC: FPInnovations.

Hu, L. J. (2018b). *Advanced wood-based solutions for mid-rise and high-rise constructions: In-situ testing of the Origine 13-storey building for vibration and acoustics performance*. Québec City, QC: FPInnovations.

Hu. L. J. (2019). *Solutions for upper mid-rise and high-rise mass timber construction: Solutions for noise control of mass timber floors and walls*. Sainte-Foy, QC: FPInnovations.

Hu, L. J. (2020). *Expending wood use towards 2024: Vibration performance of mass timber other than CLT floors*. Sainte-Foy, QC: FPInnovations.

Hu, L. J., & Gagnon, S. (2009). *Verification of 2005 NBCC maximum spans for concrete-topped lumber joist floors*. Sainte-Foy, QC: FPInnovations.

Hu, L. J., & Gagnon, S. (2010). *Construction solutions for wood-based floors in hybrid building systems*. Sainte-Foy, QC: FPInnovations.

International Code Council (ICC). (2010). *Guideline for acoustics, ICC G2-2010*. Washington, DC: Author.

International Code Council (ICC). (2018). *International Building Code. Section 1207: Sound transmission*. Washington, DC: Author.

International Organization for Standardization (ISO). (1989). *ISO 9052-1: Acoustics – Determination of dynamic stiffness – Part 1: Materials used under floating floors in dwellings*. Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2005). *ISO 15712-1: Building acoustics – Estimation of acoustic performance of buildings from the performance of elements – Part 1: Airborne sound insulation between rooms* (1st ed.). Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2016). *ISO 18324: Timber structures – Test method – Floor vibration performance* (1st ed.). Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2017). *ISO/TR: 21136: Timber structures – Vibration performance criteria for timber floors* (1st ed.). Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2018). *ISO 9053-1: Acoustics – Determination of airflow resistance – Part 1: static airflow method*. Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2020). *ISO 10848-5: Acoustics — Laboratory and field measurement of the flanking transmission for airborne, impact and building service equipment sound between adjoining rooms — Part 5: Radiation efficiencies of building elements*. Geneva, Switzerland: Author.

Karacabeyli, E., & Gagnon, S. (2019). *Canadian CLT handbook, 2019 edition* (Special Publication SP-532E). Pointe-Claire, QC: FPInnovations.

Karacabeyli, E., & Lum, C. (Eds.). (2014). *Technical guide for the design and construction of tall wood buildings in Canada* (1st ed.). (Special Publication SP-55E). Pointe-Claire, QC: FPInnovations.

Mahn, J., Quirt, J. D., Hoeller, C., and Mueller-Trapet, M. (2018). *Addendum to RR-335: Sound transmission through nail-laminated timber (NLT) assemblies*. Ottawa, ON: National Research Council Canada. Institute for Research in Construction.

Murray, T. M., Allen, D. E., & Ungar, E. E. (1997). *Floor vibrations due to human activity*. Steel Design Guide Series No. 11. Chicago, IL: American Institute of Steel Construction.

National Research Council (NRC). (2002). *Leaks and flanking sound transmission*. Presented at Sound Isolation and Fire Containment – Details that Work: Building Science Insight Seminar 2002. Ottawa, ON: Institute for Research in Construction, National Research Council.

National Research Council (NRC). (2010). *National building code of Canada*. Ottawa, ON: Author.

National Research Council (NRC). (2020). *National building code of Canada*. Ottawa, ON: Author

Noise Control Building Materials (NCBM). (2021). *Kinetics noise control: STC/IIC sound test data, all wood-framed construction*. https://kineticsnoise.com/arch/tests/wood-framed.html

Ohlsson, S. (1988). *Springiness and human induced floor vibration – A design guide* (Document D12). Stockholm, Sweden: Swedish Council for Building Research.

Pope, J. (2003, April). *Principles of acoustics and the measurement of sound*. Presented at B&K (Brüel and Kjær) Seminar, Norcross, GA.

Quirt, J. D., Nightingale, T. R. T., & King, F. (2006). *Guide for sound insulation in wood frame construction* (Research Report). Ottawa, ON: National Research Council of Canada. Institute for Research in Construction. https://nrc-publications.canada.ca/eng/view/ft/?id=6ff33ad9-2d98-4438-87e2-fa386d61cdb0

Ramzi, R. (2017). *Acoustic solutions for mass timber floor with apparent ceiling*. Sainte-Foy, QC: FPInnovations.

Sabourin, I. (2015). *Measurement of airborne sound insulation of 8 wall assemblies, measurement of airborne and impact sound insulation of 29 floor assemblies* (Report No. A1-006070.10). Ottawa, ON: National Research Council Canada.

Schoenwald, S., Zeitler, B., King, F., and Sabourin, I. (2014). *Acoustics – Sound insulation in mid-rise wood buildings: Report to Research Consortium for Wood and Wood-hybrid Mid-Rise Buildings*. Ottawa, ON: National Research Council Canada. Institute for Research in Construction.

Schramm, M., Dolezal, F., Rabold, A., & Schanda, U. (2010). *Stoßstellen im Holzbau – Planung Prognose und Ausführung*. Paper presented at DAGA 2010, Berlin, Germany.

Smith, I., & Chui, Y. H. (1988). Design of lightweight wooden floors to avoid human discomfort. *Canadian Journal of Civil Engineering*, 15(2), 254-262.

WoodWorks. (2020). *Acoustically-tested mass timber assemblies*. https://www.woodworks.org/wp-content/uploads/Acoustically-Tested-Mass-Timber-Assemblies-WoodWorks.pdf

Zeitler, B., Quirt, D., Schoenwald, S., & Mahn, J. (2015). *Apparent sound insulation in concrete block buildings* (Construction. Report No. RR-334). Ottawa, ON: National Research Council Canada.

Zhang, S., Zhou, J., Niederwestberg, J., & Chui, Y. H. (2019). Effect of end support restraints on vibration performance of cross laminated timber floors: An analytical approach. *Engineering Structures*, 189,186-194.

Fire Safety and Protection

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ABSTRACT

Concerns about fire safety are often considered impediments to the use of wood elements in buildings. This chapter discusses Acceptable Solutions for mass timber in tall wood buildings that are included in the National Building Code of Canada (NBC) (NRC, 2020a), and provides guidelines for developing an Alternative Solution to demonstrate that a tall mass timber building can meet—or even surpass—the level of fire performance currently stipulated in the NBC's Acceptable Solutions for tall buildings of noncombustible construction. The development of sound Alternative Solutions for tall timber buildings is both feasible and practical, given current knowledge of mass timber buildings and building elements, as well as fire safety engineering.

In recent decades, the NBC has restricted the use of combustible construction to 4 storeys due, in part, to fire safety concerns. These provisions traditionally anticipate construction with the lowest level of fire performance within the single category of combustible construction; consequently, the current acceptable prescriptive solutions for wood construction do not fully reflect the state of the art of fire engineering design methodologies and the many engineered structural wood products available today. As a result, current technical provisions are often conservative.

The acceptable fire safety solution for a tall building can be quite complex. It is assumed that the proposed tall wood building would comply with the prescriptive provisions in Division B of the NBC. The most significant alternative is that the structural elements will be of mass timber construction as opposed to noncombustible construction with a similar fire-resistance rating. For tall buildings, a 2-hr fire-resistance rating is prescribed for structural elements. Methods for calculating the structural fire-resistance of mass timber elements, including connections, are provided in detail in this chapter. In addition, the fire-resistance integrity of fire separations is given much attention. This includes discussion of the methods for protecting service penetrations and joints between mass wood panels.

In order to limit the severity of a fire, it can be demonstrated that complete encapsulation of all mass timber elements can result in an equal or better level of fire performance than that provided by buildings of noncombustible construction. A lesser level of encapsulation, and exposure of certain mass timber elements, can be demonstrated to provide an equivalent level of safety when compared to that of noncombustible construction. The pros and cons of three levels of encapsulation are considered: complete, limited, and no encapsulation (fully exposed). The potential for using enhanced fire protection systems—including enhanced sprinkler systems and smoke control systems to compensate for the additional risk of exposed timber—is also explored.

This chapter addresses other concerns, such as flame spread of mass timber construction, the effect of combustible construction on building exposure and spatial separation, performance concerns during a fire following an earthquake, and the treatment of void spaces.

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6.1 INTRODUCTION

This chapter discusses Acceptable Solutions for the use of mass timber in tall wood buildings included in Division B of the National Building Code of Canada (NBC) 2020 (NRC, 2020a), and provides guidelines on developing Alternative Solutions to demonstrate that a tall mass timber building designed beyond the prescriptive provisions anticipated by the NBC 2020 can meet the level of fire safety anticipated by the NBC's Acceptable Solutions for taller buildings. The term tall mass timber building is commonly applied to mass timber buildings exceeding 6 storeys in height.

Koo (2013) confirmed that a substantial number of historical tall wood buildings built in Toronto and Vancouver at the beginning of the 20th century continue to provide excellent service. These buildings are up to 9 storeys and 30 m in height, with a total floor space of up to 29 000 m². Similar buildings have also been identified in Montreal. These building have not only been in service for more than 100 years, but many have also been renovated and redeveloped, including vertical additions, and are the foundation of some of the most popular entertainment, office, and residential districts of Vancouver's Gastown and Yaletown, Montreal's Vieux Port, and Toronto's downtown core. Experience with the redevelopment of these buildings confirms that a tall mass timber building can be designed to meet the level of safety expected in tall buildings considered in the current NBC.

6.1.1 Acceptable Solutions for Fire Safety

The Acceptable Solutions for fire protection in buildings are provided in Part 3 of Division B of the NBC. These prescribed solutions are deemed by the building code to provide an acceptable level of safety. The NBC has traditionally restricted the use of combustible construction to 2-, 3-, or 4-storey buildings, due in part to fire safety concerns. With recent developments in fire safety, the 2015 NBC expanded wood-frame combustible construction up to 6 storeys. Heavy timber construction, as defined in the NBC, has inherently better fire performance than more common types of lighter wood construction. Nevertheless, it was categorized the same way as combustible construction in most cases. While the benefits of heavy timber were in some ways recognized with the allowance of unprotected steel or iron connections in interconnected floor spaces and in roofs of 2-storey buildings, which would otherwise be required to be of noncombustible construction, there was generally minimal recognition of the advantages of heavy timber components and construction in Division B up to the 2015 version of the NBC. However, steady advancements in fire testing and the development of state-of-the-art fire engineering design methodologies, as well as the wide availability of engineered structural wood products in recent years have led to greater allowances for the use of combustible elements in building construction, and the NBC 2020 includes provisions for a new category of construction—encapsulated mass timber construction (EMTC)—for buildings up to 12 storeys. Mass timber elements in EMTC buildings are protected on most surfaces inside the building by at least two layers of 12.7-mm thick Type X gypsum board, or other equivalent membrane protection. There are provisions for allowing a small amount of timber to be exposed. Further information on the new provisions for EMTC in the NBC 2020 are provided in Section 6.2 of this chapter.

It is important to note that the provisions for Acceptable Solutions in Division B of the NBC are simply a set of solutions that have been reviewed through the Canadian code change process and accepted as providing an acceptable level of performance. Other solutions are not prohibited. In many cases, other solutions are not included in the NBC simply because they have not yet been analyzed and accepted through the code change process. An example would be a 12-storey mass timber building of assembly occupancy. Its absence from the NBC does not prohibit its construction through the Alternative Solution compliance path. The building code permits the development of Alternative Solutions in recognition of the fact that it does not and cannot include all possible solutions.

6.1.2 Alternative Solutions for Fire Safety

The objective-based NBC is structured in such a way that a designer can use an Acceptable Solution explicitly spelled out in Division B or implement Alternative Solutions that achieve at least the minimum level of performance required by Division B in the areas defined by the objectives and functional statements attributed to the applicable Acceptable Solutions. Figure 1 demonstrates the equivalency of these two compliance paths.

Marketability/Profitability

Alternative Solutions will allow mass timber construction to continue to evolve and support innovation. British Columbia is seeing the benefits of fire engineering that began in 1994 (UBC [n.d.]). Practitioners from that program are now contributors to the code changes and Alternative Solutions.

Prescriptive codes specify how a building is required to be built rather than how it will actually perform (Buchanan et al., 2006). The main advantage, to some extent, of complying with prescriptive provisions is that it is easier and faster for designers and authorities having jurisdiction to develop, review, approve, and apply a design. However, it also gives the impression that there is only one method of construction, with few options to meet the required level of fire safety in a building (Hadjisophocleous et al., 1998).

Performance-based codes, on the other hand, establish or express explicit performance levels to be achieved, such as for fire safety, and permit the designer to develop solutions to meet the required performance levels. Unlike performance-based codes, the objective-based NBC provides objectives that explain the intent behind the prescriptive provisions. Under this framework, the Acceptable Solutions in Division B establish the minimum acceptable level of performance for the specific objectives relating to the Acceptable Solutions.

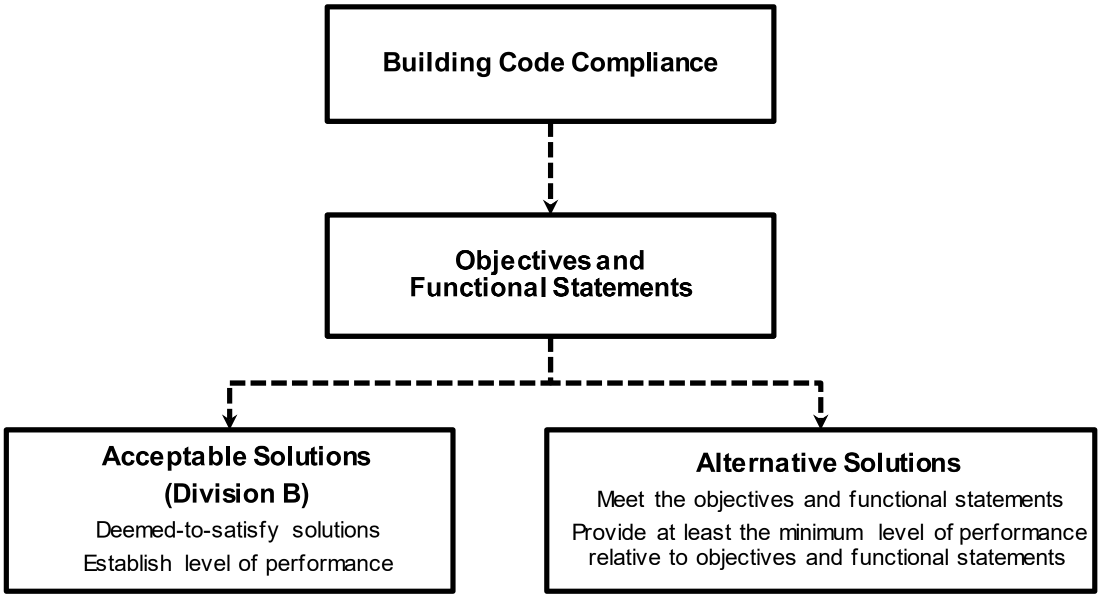


Figure 1. Summary of the two compliance paths in the National Building Code.

To demonstrate compliance with the fire safety provisions of the NBC using an Alternative Solution, a qualitative or quantitative fire risk assessment may be needed to establish the level of fire risk associated with the Acceptable Solution, and then the same assessment should then be done for the Alternative Solution, so that the level of performance between the two designs can be compared. If this comparative risk analysis shows that the Alternative Solution provides at least the same level of fire performance as the Division B Acceptable Solution, then the Alternative Solution can be accepted as complying with the building code. Guidance on conducting a fire risk assessment is provided in Appendix 6A of this chapter. Fire risk assessments range from very simple to very complex and cannot be taken as the sole method for demonstrating the compliance of an Alternative Solution. In most situations, this analysis is a very simple comparison of levels of performance, but it may include much more complex risk analysis, modelling, or fire testing. Section 6.3 of this chapter provides guidelines on developing an Alternative Solution for a tall mass timber building; it demonstrates that tall mass timber buildings can meet—or even surpass—the level of fire performance currently provided by the NBC.

In a performance-based design, an Alternative Solution may not necessarily need to demonstrate a level of performance that is at least equivalent to a prescriptive Acceptable Solution (i.e., a comparative approach). Several prescriptive requirements in Division B of the NBC are determined qualitatively through a technical consensus of different stakeholders and building experts, and thus are difficult/impossible to quantify. As such, an absolute approach may be more suitable, where an Alternative Solution demonstrates that it fulfills the objectives, functional statements, and required performance criteria based on engineering analyses, which were agreed upon as suitable, reasonable, and reliable to ensure a safe and satisfactory design (Dagenais et al., 2017).

6.1.3 Acceptance by Authority

The authority having jurisdiction (AHJ) must agree that an Alternative Solution provides the requisite level of performance, although the process for review and approval varies depending on the authority. The AHJ typically requires documentation to demonstrate that the level of performance provided by the Alternative Solution meets or exceeds that established by the building code. Section 2.3 of Division C of the NBC provides guidance on developing such documentation and outlines the criteria for acceptance of an Alternative Solution by the AHJ.

> **Regulatory Acceptance**
>
> Alternative Solutions are project specific and need to be discussed early in the project. In most cases, a variation of the Alternative Solution may have been accepted in an earlier project; this should provide a sense of the likelihood of obtaining approval. Eventually, common Alternative Solutions may be proposed to be Acceptable Solutions in the NBC.

The inclusion of mass timber construction in the NBC 2020 has made it substantially easier for the development and acceptance of Alternative Solutions for tall mass timber buildings. Notwithstanding this, an Alternative Solution for tall mass timber buildings designed beyond the parameters of the Acceptable Solutions in the NBC 2020 can still be inherently complex and, depending on the level of complexity of the Alternative Solution, it may be appropriate for the applicant and the authority to agree to delegate the review process to third parties or peer reviewers with qualifications in timber engineering and fire science. It is recommended that the review process and selection of peer reviewers be agreed upon early in the process and that reviewers and proponents establish a good dialogue on the project. Furthermore, for the process to be effective, peer reviewers should be given the task of providing assistance in finding solutions rather than just identifying errors and omissions. Further advice with respect to peer review is provided in guides published by the Society of Fire Protection Engineers (SFPE) (SFPE, 2000, 2004, 2020).

Experience has shown that for complex Alternative Solutions, it is imperative for the applicant and the authority to agree on the review process early in the preparation of the Alternative Solution. It is important that all parties, the applicant, authorities having jurisdiction (typically both fire and building departments), and peer reviewers meet early and often to maintain an effective dialogue so that they are satisfied with the outcome.

6.1.4 Objectives and Functional Statements

The objectives and functional statements attributed to a particular Acceptable Solution identify the risk areas that the NBC is addressing in that provision. Risks that are not addressed by the objectives/functional statement pairs directly attributed to the Acceptable Solution are outside the NBC framework and therefore are not considered. For example, the risk of failure due to a terrorist attack is currently not a risk area recognized by the NBC.

The fire safety, health, accessibility, and environmental provisions set forth in the NBC interrelate with five main objectives. They describe, in very broad and qualitative terms, the overall goals that the NBC's provisions are intended to achieve, namely:

1. OS – Safety
2. OH – Health
3. OA – Accessibility for the disabled
4. OP – Fire and structural protection of buildings
5. OE - Environmental

The objectives describe undesirable situations and their consequences. The NBC aims to limit the probability of occurrence of these situations and consequences in buildings. Each objective is further refined through the establishment of sub-objectives, which are listed in Part 2 of Division A of the NBC. It is acknowledged that the provisions of the NBC cannot entirely prevent all undesirable events from happening or eliminate all risks; therefore, the objectives are intended to "limit the probability" of "unacceptable risk" of injury or damage caused by exposure to various hazards. It is assumed that an undesirable situation is possible and that strategies will need to be provided to reduce the probability of these occurrences and their consequences to below an “acceptable risk” level. It is understood that an "acceptable risk" is the level of risk remaining once compliance with the NBC prescriptive (Acceptable) Solutions has been achieved (NRC, 2020a).

Each provision (i.e., Acceptable Solution) prescribed in Division B of the NBC is linked to one or more objectives and sub-objectives, and to one or more functional statements. An example of a sub-objective is OP1.3, which aims to limit the probability that because of its design or construction, the building will be exposed to an unacceptable risk of damage resulting from the collapse of physical elements due to a fire or explosion. This particular sub-objective is directly linked to structural fire-resistance requirements for load-bearing elements. A functional statement describes a function of the building, or part of the building, that a particular requirement helps achieve. They are more detailed than the objectives and, similarly, are entirely qualitative. Examples of functional statements related to fire safety provisions in Part 3 of Division B of the NBC include:

- F01 – to minimize the risk of accidental ignition
- F02 – to limit the severity and effects of fire or explosions
- F03 – to retard the effects of fire on areas beyond its point of origin
- F04 – to retard failure or collapse due to the effects of fire
- F05 – to retard the effects of fire on emergency egress facilities
- F10 – to facilitate the timely movement of persons to a safe place in an emergency

Objectives and functional statements are always tied together (i.e., in pairs); such twinning helps define what needs to be done (function) and why it should be done (objective). In other words, a building must provide this (function) in order to meet that (objective).

Additional information on objectives and functional statements is provided in Parts 2 and 3, respectively, of Division A of the NBC.

6.1.5 Level of Performance

In the objective-based NBC, the performance targets for the Acceptable Solutions are implicit in the provisions themselves; the performance attained by the Acceptable Solutions in Division B constitutes the minimum anticipated level of performance. For example, Sentence 3.4.2.5.(1) sets 45 m as the maximum travel distance to an exit in a sprinklered office (Group D) floor area. The objective and functional statement attributed to Sentence 3.4.2.5.(1) is [F10-OS3.7], which is to facilitate the timely movement of persons to a safe place in an emergency in order to limit the risk of injury due to persons being delayed in, or impeded from, moving to a safe place during an emergency. The performance target is the measure of time for occupants to reach an exit within the 45-m maximum distance relative to the onset of unsafe conditions (i.e., untenability conditions for occupants). If an Alternative Solution is proposed, one would need to demonstrate that the resultant travel distance to an exit meets or surpasses the performance attained by the 45-m travel distance scenario with respect to [F10-OS3.7], assuming all other factors remain unchanged.

As mentioned previously, an Alternative Solution may not necessarily need to demonstrate a level of performance that is at least equivalent to a prescriptive Acceptable Solution (i.e., a comparative approach) when an absolute approach is more suitable.

6.1.6 Fire Dynamics and Engineering Design

Wood is a combustible material. In wood buildings, wood elements may be exposed to a fire and subsequently support the growth and/or spread of the fire; therefore, not only could the structural integrity of the combustible construction be affected by fire, but the construction material itself may also become the fuel. To scientifically understand and discuss both the inherent and explicit risk of combustible construction in fire, it is important to discuss some basic physics concepts related to compartment fires and the general strategies that have traditionally been implemented in the NBC to address the risks posed by compartment fires. This would allow for a more systematic approach to examining the relevant fire risks.

Fire is the exothermic chemical reaction of a fuel with oxygen in air. Common solid combustibles in buildings must first be heated to their ignition temperatures before they become involved in a fire. The most significant combustion products released during a fire include substantial heat, soot (smoke), carbon dioxide, and carbon monoxide (Drysdale, 1998). In buildings, compartment fires are generally the fire of concern (although exterior fires can also be a concern). The walls, floors, and ceilings in a building can be designed to create physical and thermal boundaries that confine the fire to an enclosure (i.e., the fire compartment or room of fire origin). Accordingly, the behaviour of the fire can be understood in terms of a set of unique physics commonly referred to as compartment fire dynamics. The progression of a compartment fire can generally be depicted by the temperature (or sometimes the heat release rate) versus the time curve shown in Figure 2.

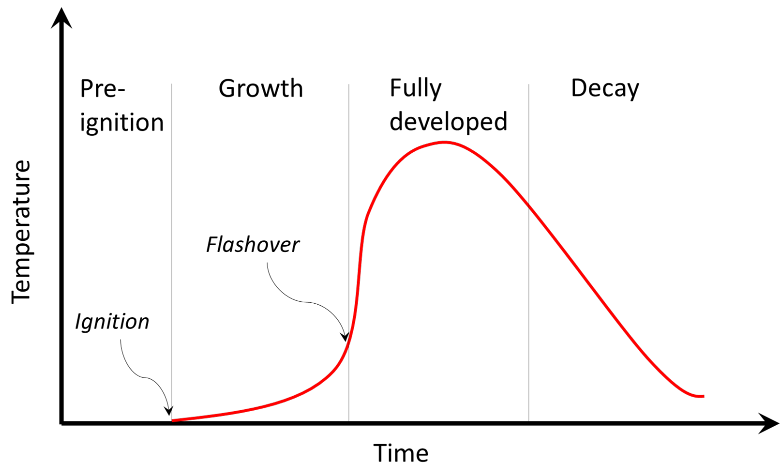


Figure 2. Typical stages of fire development.

During the ignition and growth stages, a fire is a localized phenomenon. Heated gas and products of combustion rise and form a hot upper smoke layer under the ceiling. As the fire progresses, the smoke layer thickens and begins to descend along the walls. The temperature of the smoke layer also steadily increases. During this stage, the building's construction materials may have a significant effect on the advancement of the fire. This includes interior finishes and any exposed construction material of the building. Combustible construction materials, particularly on the ceiling or walls, may ignite and thereby contribute to the temperature and rate of descent of the smoke layer. If the temperature of the smoke layer reaches approximately 600°C, the radiant heat emitted by the smoke layer causes the temperatures of all combustibles below the smoke layer to reach their ignition temperatures almost simultaneously, and flames will engulf the entire compartment. This transition from a localized fire involving a few combustibles to full room involvement is referred to as "flashover". An important fire safety objective is to prevent, or at least delay, the time to flashover.

The general strategy employed to address the life safety and property protection risks during the pre-flashover stage is to limit the growth and spread of fire, initiate and foster the timely evacuation of occupants for life safety, and facilitate firefighting and/or automatic suppression for life safety and property protection. This strategy generally includes (a) providing automatic fire detection through heat (e.g., sprinklers) and smoke detectors to alert occupants about a fire and notify emergency responders; (b) limiting flame spread ratings of interior finishes in certain parts/assemblies of the building to limit fire spread and growth; (c) providing automatic sprinklers to limit and control fire growth and smoke spread; (d) using fire-rated separations (i.e., walls and floors) to control the spread of fire and its effects beyond the room of fire origin, which are mainly heat and smoke; and (e) using fire-resistance rated and/or noncombustible materials to limit the involvement of building materials.

In a scenario where a fire reaches flashover and becomes fully developed, which is a rare event in buildings entirely protected by automatic sprinklers, the fire protection strategy shifts to preventing fire spread outside the fire compartment (room of fire origin) and preventing partial failure or collapse of the building's structural and separating elements within a given time frame. Although occupant survival within the fire compartment is not possible in a post-flashover environment (at temperatures above

600°C), the building's fire resistance is important because it provides time for occupants to move/evacuate outside the compartment of fire origin (e.g., in public corridors, on different floors, or in exits) and time for firefighters to carry out their operations.

Structural fire-resistance in a fully developed fire is generally achieved by requiring a minimum fire-resistance rating (FRR) for the building's key assemblies, including all floors and those walls and structural members that carry gravity loads. It is important to note that when a fire in a room or compartment reaches the fully developed stage, the heat release rate of the fire is typically governed by the available ventilation to the room or space (i.e., amount of oxygen available). When moving from the pre-flashover to post-flashover stage, the fire typically transitions from being fuel-controlled to being ventilation-controlled; consequently, the post-flashover burning rate is governed by the amount of oxygen available, not the fuel load itself. As such, the temperature within the compartment increases very slowly during the post-flashover stage until the decay phase is initiated, provided that fire-rated boundary elements enclosing the fire compartment are still performing efficiently. The NBC currently does not address the decay phase; however, the decay phase is implicitly addressed by the correlation between fuel load and fire-resistance rating. While this correlation is intended to address complete post-flashover burning, it also addresses decay in terms of allowing complete burnout of a compartment.

By understanding compartment fire dynamics, buildings can be strategically designed to perform in an acceptable manner during the different stages of a fire. In the context of designing mass timber buildings outside the parameters currently prescribed in the NBC 2020, the following key questions need to be considered:

1. Are mass timber buildings designed to sufficiently limit the involvement of structural wood elements during the pre-flashover stage?
2. Are mass timber buildings designed to limit the spread of fire and smoke beyond the room or compartment of fire origin?
3. Are mass timber buildings designed to provide an acceptable environment for emergency responders to conduct their operations both within and outside the compartment of fire origin during the fully developed stage?
4. Are mass timber buildings designed to remain structurally and thermally sound if a compartment fire becomes fully developed?
5. Are mass timber buildings designed to limit the spread of fire to neighbouring buildings if a compartment fire reaches flashover?

With an objective-based code, it is not always clear how to identify the required minimum level of performance that the fire engineering design strategy (such as outlined by the five questions above) needs to achieve. What level of performance is acceptable to building officials and designers, and thereby, presumably tolerable to building occupants? However, based on the various provisions in Division B of the NBC, it is possible to interpret the required minimum performance level. As mentioned in Section 6.1.4 of this chapter, the objectives and functional statements of the NBC aim to "limit the probability" of "unacceptable risk" of injury or damage caused by exposure to various hazards, which is a qualitative statement for the most part. In order to develop an "acceptable"

Alternative Solution to the prescriptive fire safety provisions, an understanding of risk assessment is needed. Guidance on undertaking a fire risk assessment is provided in Appendix 6A of this chapter.

6.2 ENCAPSULATED MASS TIMBER CONSTRUCTION

6.2.1 New National Building Code Provisions for Encapsulated Mass Timber Construction

The NBC 2020 includes a new type of construction—encapsulated mass timber construction (EMTC)—which is defined as ”that type of construction in which a degree of fire safety is attained by the use of encapsulated mass timber elements with an encapsulation rating and minimum dimensions for structural members and other building assemblies”. In EMTC, “encapsulation rating” can be defined as the time in minutes that a material or assembly of materials will delay the ignition and combustion of encapsulated mass timber elements when it is exposed to fire under specified conditions of test and performance criteria. EMTC is permitted to be used for buildings of Group C (residential) and Group D (office) occupancies up to 12 storeys in height with provisions for Group A-2 (assembly), Group E (retail), and certain types of industrial occupancies and storage garages on the lower storeys.

Historically, the NBC has addressed the growth and spread of fire by prescribing the use of noncombustible construction in buildings that exceed specified building heights and/or building areas. The intent of the requirement for noncombustible construction has been to limit the contribution of the structure to fire growth and spread, and thereby limit the potential size and spread of a fire within a storey. The NBC’s (2020) introduction of EMTC as a new type of construction follows similar principles: the prescribed encapsulation is intended to “cover” most of the timber structure in order to limit its contribution to a fire. Only limited portions of the load-bearing mass timber elements within the structure are permitted to be exposed per the prescribed solutions in the NBC 2020. Based on results from recent (2019–2021) fire tests and research on the characteristics of mass timber in fire and fire dynamics in buildings of EMTC, it is likely that proposals for future code change will be submitted for consideration, which may result in increases in the allowable percentage of exposed mass timber.

An outline of the EMTC provisions from the NBC 2020 is provided herein. This is not intended to be a reproduction of the provisions but rather a summary of the most pertinent requirements.

- Building area – A maximum building area (e.g., building footprint) of 6000 m^2 and 7200 m^2 is permitted for Group C residential and Group D office buildings, respectively.
- Building height – Up to 12 storeys and a maximum height of 42 m is permitted, measured between the floor of the first storey and the uppermost floor level.
- Minimum dimensions of mass timber elements – In order to obtain the fire performance attributed to mass timber construction, the NBC 2020 prescribes minimum member sizes for wall (1- or 2-sided fire exposure), floor, and roof assemblies and beams, columns, and arches (2- to 4-sided fire exposure), as shown in Table 1. The NBC also requires that structural mass

timber elements be "arranged in heavy solid masses without concealed spaces and with smooth flat surfaces"; however, there are some exceptions for "protected" concealed spaces.

Table 1. Minimum dimensions of structural mass timber elements in encapsulated mass timber construction, as proposed in the National Building Code 2020 (NRC, 2020a)

Structural wood elements	Minimum thickness (mm)	Minimum Width x Depth (mm × mm)
Walls that are fire separations or exterior walls (1-sided exposure)	96	–
Walls that require fire-resistance rating but are not fire separations (2-sided exposure)	192	–
Floors and roofs (1-sided exposure)	96	–
Beams, columns, and arches (2- or 3-sided exposure)	–	192 × 192
Beams, columns, and arches (4-sided exposure)	–	224 × 224

- Encapsulation – Unless otherwise exempted (see "Exposed timber" below), the NBC 2020 prescribes encapsulation of all mass timber elements within an EMTC building, with a prescribed encapsulation rating of not less than 50 min as determined by CAN/ULC-S146: Standard Method of Test for the Evaluation of Encapsulation Materials and Assemblies of Materials for the Protection of Structural Timber Elements (ULC, 2019). This level of encapsulation can be provided by two layers of Type X gypsum board, each not less than 12.7 mm thick, not less than 38-mm thick gypsum–concrete or concrete topping, or any noncombustible material or assembly or materials that maintain the temperature increase between the interface of the encapsulation and the timber to less than 250°C on average or 270°C at any point for a period of 50 min when exposed to the standard time–temperature curve given in CAN/ULC-S101: Standard Methods of Fire Endurance Tests of Building Construction and Materials (ULC, 2014a).
- Fire-resistance ratings – Floor assemblies require a 2-hr fire-resistance rating, and mezzanines require a 1-hr fire-resistance rating. Load-bearing walls, columns, and arches require a fire-resistance rating not less than that required for the supported assembly. Fire-resistance is permitted to be calculated in accordance with Annex B of CSA O86 Engineering Design in Wood (CSA, 2019), as discussed in Section 6.6 of this chapter. As a supplement to the use of Annex B of CSA O86, additional information is provided in Appendix D of the NBC 2020 regarding the requirements and generic solutions for protection of the assembly to

address integrity and thermal insulation properties, as well as detailing of acceptable cross-laminated timber (CLT) panel-to-panel joints.

> Note: The encapsulation rating and fire-resistance rating are not the same; each must be considered separately. While two layers of 12.7-mm thick Type X gypsum board are deemed to provide the prescribed 50-min encapsulation rating, the same two layers of 12.7-mm thick Type X gypsum board are considered per Annex B of CSA O86 (CSA, 2019) to contribute 60 min to the fire-resistance rating of CLT elements, with the remainder of the structural fire resistance provided by the residual timber portion beneath the protective char layer. This is logical because there will be a period after the heat has penetrated the gypsum board when the timber exceeds the temperature increase for encapsulation, when the gypsum wallboard is likely still in place and limiting the rate of heat transfer and direct flame impingement on the underlying timber.

- Exposed timber – Limited amounts of exposed timber are permitted: (1) wall surfaces within a suite equal to an area not exceeding 35% of the wall area of the perimeter of the suite where their surfaces face the same direction; (2) surfaces of beams, columns, or arches with an area not exceeding 10% of the wall area of the perimeter of the suite or fire compartment; and (3) up to 25% of the ceiling area, depending on whether any walls are exposed. For any of these unprotected elements, the entire fire-resistance rating has to be provided by the timber alone. Because exposed timber has deeper char after fire exposure (thereby reducing the effective cross-section), the thickness of timber required for structural design is often more than the thickness required for encapsulated members.
- Mixed occupancies – The EMTC provisions apply separately to residential (Group C) and office (Group D) buildings of up to 12 storeys in height, with limits for the lower levels of other occupancies: retail occupancies (Group E) on the first 2 storeys; assembly occupancies (Group A, Division 2) on the first 3 storeys; and storage garages on the first 4 storeys. Low- and medium-hazard industrial occupancies (Group F, Division 2 and 3) are permitted on the first 2 storeys of an office building only.
- Cross-laminated timber – Adhesives used in CLT structural mass timber elements must conform to the elevated temperature performance requirements in the 2018 edition of ANSI/APA PRG 320: Standard for Performance-Rated Cross-Laminated Timber (ANSI/APA, 2018).
- Other provisions – The building code includes other prescribed provisions for EMTC, including provisions for concealed spaces, roofing materials, combustible elements in partitions, exterior cladding, etc.
- Fire Code provisions – The National Fire Code 2020 (NRC, 2020b) also includes specific provisions for construction fire safety, discussed in Section 6.15 of this chapter.

Additional information and guidance on the design of mass timber buildings up to 12 storeys as prescribed by the NBC 2020 and Alternative Solutions are provided in the *Joint Professional Practice Guidelines: Encapsulated Mass Timber Construction up to 12 Storeys* (AIBC/EGBC, 2020), *Mass Timber Buildings up to 12 Storeys: Directives and Explanatory Guide* (RBQ, 2015), and *Ontario's Tall Wood Building Reference* (OMNRF/OMMA, 2017).

6.2.2 New Provisions for Mass Timber Construction in the United States

The 2021 International Codes (I-Codes) recognize three new construction types—IV-A, IV-B, and IV-C—which marks the first time in the history of modern U.S. building codes that significantly new construction types have been added. These new tall mass timber construction types allow for the use of large cross-section wood structural members (i.e., mass timber). Their height and area limits are significantly greater than previous limits for wood structures. Type IV-A, for example, allows up to 18 storeys for certain occupancies, whereas traditional Type IV construction (now designated as Type IV-HT) allows only 6 storeys. All three new construction types allow for the use of mass timber in floors, walls, roofs, and other building elements as permitted by Table 601 of the International Building Code (ICC, 2021). Combustible light-framing members are not permitted to be used as building elements.

Concealed spaces are permitted in all three construction types, provided they do not contain combustibles (with the exception of mechanical, electrical, or plumbing materials permitted in plenums based on the International Mechanical Code). Any mass timber within such spaces must therefore be covered with noncombustible protection (e.g., gypsum board). Other areas where mass timber is required to be covered by noncombustible protection include both sides of shaft walls (such as elevator hoistways and interior exit stairway enclosures) and the outside surface of mass timber used in exterior walls. In Types IV-A and IV-B, all mass timber surfaces on the building interior are required to be protected with noncombustible material (e.g., gypsum board on the walls and ceilings, gypsum concrete on the floors). However, Type IV-B permits some exposed mass timber on walls and ceiling.

Additional provisions include a redundant sprinkler water supply for buildings exceeding 36 m (120 ft.) in height, noncombustible exit shaft enclosures for buildings exceeding 12 storeys, fire-resistant protection of connections, and special inspections and specific precautions for fire safety during construction.

Types IV-A, IV-B, and IV-C construction are distinguished primarily by differences in requirements regarding noncombustible protection of combustible elements and fire-resistance ratings, and by corresponding differences in building size, as summarized in Table 2. Refer to the appropriate I-Code for the defined terms, such as the determination of building heights and allowable areas, because there are fundamental differences in some fire safety design concepts between Canada and the United States.

Table 2. Fire design provisions in the 2021 International Building Code

	Type IV-A	Type IV-B	Type IV-C
Noncombustible protection requirements			
Where is it required?	All mass timber surfaces, including walls, ceilings, and floors	All mass timber surfaces, except for limited amounts of exposed areas permitted for walls and/or ceilings	Required only for mass timber shaft walls, the exterior side of mass timber in exterior walls, and on mass timber in concealed spaces
How much is required?	Enough to make up $^{2}/_{3}$ of the required fire-resistance rating on walls and ceilings; minimum 25-mm (1 in.) thick noncombustible covering on floors	Enough to make up $^{2}/_{3}$ of the required fire-resistance rating on walls and ceilings; minimum 25-mm (1 in.) thick noncombustible covering on floors	At least 40 min of protection where required
Fire-resistance rating requirements			
Primary structural frame	3 hr	2 hr	2 hr
Load-bearing walls (interior and exterior)	3 hr	2 hr	2 hr
Floor construction	2 hr	2 hr	2 hr
Roof construction	1.5 hr	1 hr	1 hr
Height and area limits for Group B (business occupancy—other occupancies vary)			
Height (storeys)	18	12	9
Height (distance)	82 m (270 ft.)	55 m (180 ft.)	26 m (85 ft.)
Allowable area factor[a]	30 100 m² (324 000 ft.²)	20 050 m² (216 000 ft.²)	12 500 m² (135 000 ft.²)
Height and area limits for Group R-1 and R-2 (residential occupancy—other occupancies vary)			
Height (storeys)	18	12	8
Height (distance)	82 m (270 ft.)	55 m (180 ft.)	26 m (85 ft.)
Allowable area factor[a]	30 100 m² (324 000 ft.²)	20 050 m² (216 000 ft.²)	12 500 m² (135 000 ft.²)

[a] Factors shown reflect allowable area per storey, up to 3 storeys, for a single-occupancy Group B building when sprinklered with an NFPA 13 system. For buildings taller than 3 storeys, total building area is limited to three times the allowable area factor. Factors shown do not include increases for open frontage (a maximum increase of 25% of the factor shown).

6.2.3 Compartment Fire Testing

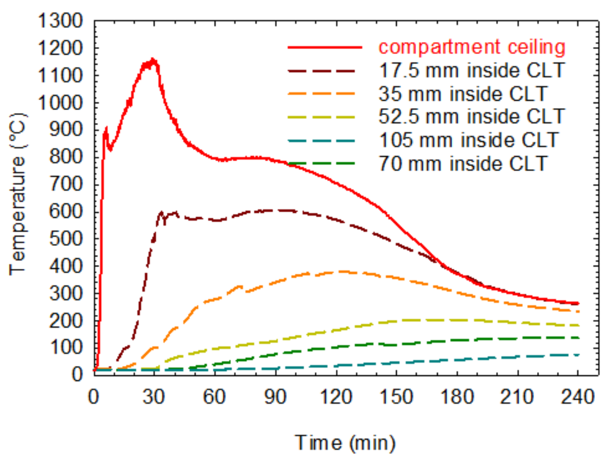
Several fire experiment programs were conducted over the last decade to study the potential contribution of mass timber structural elements to compartment fires (Brandon et al, 2021; Janssens, 2015; McGregor, 2013; Medina, 2014; Su et al., 2018a, 2018b, 2019; Taber et al., 2014; Zelinka et al., 2018). Most of the programs simulated nonstandard residential fires without sprinklers or firefighting intervention in order to determine whether the mass timber structure would eventually cease combustion after the movable fuel contents had been consumed in the compartment.

Encapsulation materials (such as gypsum board, cement board, or gypsum concrete) can be used as a protective cover for mass timber structural elements to keep the timber below the charring temperature for a period of time or even avoid ignition of the timber. A considerable amount of performance data on fully encapsulated mass timber structures, including CLT, nail-laminated timber (NLT), and glue-laminated timber (glulam), was produced from the experimental programs. The large-scale compartment fire experiments demonstrated that complete encapsulation can limit the contribution of the timber structural elements to fires, which can lead to fire decay after the movable fuel content has been consumed.

Recent architectural trends demand more visible timber surfaces, which adds further complexity to designing for fire safety since exposed timber may add fuel to the fire. Partially encapsulated (i.e., partially exposed) mass timber structures were studied in some compartment fire tests (Brandon et al., 2021; McGregor, 2013; Medina, 2014; Su et al., 2018a, 2018b, 2019; Zelinka et al., 2018); their contribution to the fire depended on the amount of exposed timber involved in the fire, the adhesives used in making the mass timber elements, and the sufficiency of encapsulation on the protected portion of the timber structure, in addition to other enclosure and fuel variables.

Because CLT is fabricated using multiple lumber lamellae bonded with structural adhesives, the thermomechanical performance of the adhesive is critical to maintaining the char layer in place and the thermal insulation. Several compartment fire experiments highlighted the performance issue of a low-melting-point (< 220°C) adhesive with various exposed CLT surfaces (McGregor, 2013; Medina, 2014; Su et al., 2018a). The adhesive melted before the char front (the zone separating the charred and uncharred wood) reached the bond line. This caused the charred CLT lamella to delaminate and the fresh surface of the next lamella to be exposed to the fire, which led to fire regrowth rather than decay of the fire. This prompted the development of a new edition of the North American CLT manufacturing standard, ANSI/APA PRG 320 (ANSI/APA, 2018), which requires that the adhesives used in CLT be thermal resistive. This is done by evaluating the adhesives in a small-scale flame test and a room-scale fire test to eliminate those adhesives that cannot prevent premature fall off of the CLT lamella as the lamella chars.

A recent series of compartment fire experiments were conducted (Su et al., 2018b) to investigate the performance of CLT bonded with a thermal resistive adhesive that had met the small-scale flame test requirements (Brandon & Dagenais, 2018; Klippel et al., 2017). The compartment was constructed of 175-mm thick CLT panels with five lamellae (5 × 35 mm thick). One of the experiments had a fully exposed CLT ceiling, while the CLT walls were encapsulated using two layers of 12.7-mm thick Type X gypsum board. A fully exposed glulam beam and column were included in the CLT compartment; the exposed glulam surface was equivalent to 19% of the total area of the perimeter walls. Figure 3(a) shows temperatures measured in the compartment and in the exposed CLT ceiling assembly during the experiment. The compartment temperature reached a peak of 1170°C during the fully developed fire stage, then started to decrease after 35 min. As char formed on the exposed CLT ceiling and glulam beam and column, flames on the exposed timber surfaces reduced significantly. The temperatures measured at various depths of the CLT ceiling indicated that the char front (assessed based on a temperature of 300°C) reached 35 mm deep (the first bond line) after 60 min. The temperatures at the 70 mm and 105 mm depths (the second and third bond lines) were below 150°C and 95°C, respectively. Visual observation and temperature measurements at the bond lines indicated that the charred lamella largely remained on the ceiling until the end of the experiment to shield the inner CLT lamellae from the fire. It is worthwhile to note that the compartment temperature briefly increased at approximately 60 min because the protected CLT wall panels started to char behind the gypsum board, which contributed heat to the compartment. Nevertheless, the compartment temperature continued to decline. By 150 min, the flames ceased on the exposed CLT ceiling and glulam beam and column. The compartment fire was completely self-extinguished at 170 min (Figure 3[b]). At the end of the experiment (240 min), the compartment temperature had declined to less than 270°C. This experiment showed that exposed CLT with a thermally resistant adhesive improved fire performance by enabling the charred CLT lamella to stay in place to insulate the inner lamellae so that the fire could continue to decay until a full burnout.



(a) Temperatures in the CLT compartment and exposed CLT ceiling assembly

(b) Fire burnt out in compartment with exposed CLT ceiling, glulam beam, and column

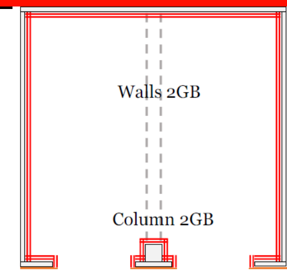
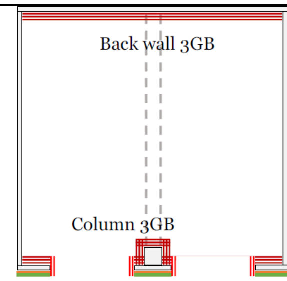
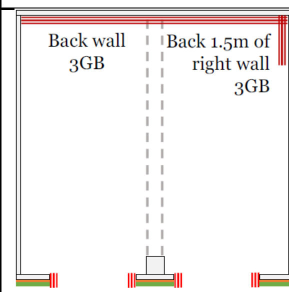
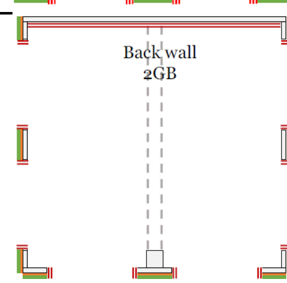
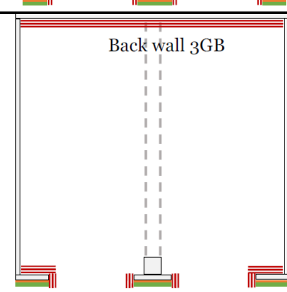
Figure 3. Temperature profiles and residual elements, per Su et al. (2018b).

Another test configuration in the CLT compartment fire experiments involved a fully exposed ceiling and two fully exposed opposing walls 4.5 m apart (Su et al., 2018b). The two exposed walls represented 35% of the total perimeter wall area, and gypsum board was used to protect the other two walls. This same configuration was used in the NLT compartment fire experiments (Su et al., 2019). When two layers of 12.7-mm thick Type X gypsum board were used to protect the other two walls, neither the CLT nor the NLT compartment experiment reached a complete burnout in this configuration. These experiments showed that the encapsulation on the protected walls was inadequate in this configuration since the protected CLT and NLT panels started to char shortly after 40 min and evolved to significant burning behind the gypsum board, which provided progressive fuel load to sustain the fire, particularly when the gypsum board fell off. The experiment was reconfigured for the NLT compartment to protect the other two walls using three layers of 12.7-mm thick Type X gypsum board. In this configuration, following the initial fire growth and fully developed stages, the fire started to decay after 40 min. Flames on the exposed ceiling and the two exposed opposing walls self-extinguished by 90 min. The compartment temperature decreased to below 300°C by 130 min and stayed below 300°C until the end of the experiment (> 240 min). The results showed that with the same amount of exposed timber surface but enhanced encapsulation on the two protected walls, the contribution of the timber to the fire was greatly reduced such that the compartment fire reached a continuous decay and self-extinguishment. The NLT panels had small gaps between laminations (these gaps could provide passages for the flame and hot pyrolysis gas to travel) and were not as tightly fitted as the CLT panels. It is reasonable to expect that with enhanced encapsulation on the two protected walls, the CLT (with the thermally resistive adhesive) would likely perform significantly better than NLT in this configuration to reach full decay of the fire.

More recently, compartment fire testing funded by the U.S Forest Service, managed by the American Wood Council, and performed at RISE in Sweden, demonstrated that, compared to the 2021 provisions in the IBC (refer to Section 6.2.2), larger exposed areas are possible while providing the requisite level of fire safety (Brandon et al., 2021). The adhesive used for face-bonding the CLT elements used in this research was compliant with the 2018 edition of ANSI/APA PRG 320; thus, the adhesive did not exhibit heat delamination characteristics. Five compartments with internal dimensions of 7.0 m × 6.85 m × 2.73 m (23 ft. × 22.5 ft. × 9 ft.) with varying ventilation factors and amount of exposed mass timber were evaluated (Table 3). Tests 1, 2, 3, and 5 were intended to replicate a residential suite, while Test 4 with large openings was intended to replicate an open-space concept.

The performance criteria used during these tests were the same as those used to develop the 2021 IBC provisions: a compartment fire should exhibit continual decay without significant fire re-growth during the decay phase for 4 hours following fire initiation. Additional criteria were used and are provided by Brandon et al. (2021).

Table 3. Test configuration conducted by RISE for AWC (Brandon et al., 2021)

Test	Window opening size	Gypsum board protection	Exposed mass timber surfaces	Schematic
Test 1	8 m²	All walls and columns protected with 2 layers of 15.9-mm Type X	100% ceiling 100% beam 0% walls (53.8 m²)	
Test 2	8 m²	Back and front walls protected with 3 layers of 15.9-mm Type X	100% ceiling 100% beam 100% left wall 100% right wall (91.2 m²)	
Test 3	8 m²	Back wall and the back 1.5 m length of right wall protected by 3 layers of 15.9-mm Type X	100% ceiling 100% beam 100% left wall 78% right wall 100% front wall 100% column (96.2 m²)	
Test 4	31.2 m²	Back wall protected by 2 layers of 15.9-mm Type X	100% ceiling 100% beam 100% left wall 100% right wall 100% front wall 100% column (77.9 m²)	
Test 5	8 m²	Back wall and 0.7 m on the left- and right-side edges of front wall protected by 3 layers of 15.9-mm Type X	100% ceiling 100% beam 100% left wall 100% right wall 60% front wall 100% column (97.2 m²)	

In summary, tests of CLT with a thermally resistive adhesive significantly improved the retention of charred CLT lamellae, which allowed compartment fires to burnout and self-extinguishment without the use of sprinklers or other firefighting measures. Research also demonstrated that to maintain the same level of fire performance, increasing the amount of exposed timber surfaces requires that timber elements intended to be protected must have an enhanced encapsulation rating such that they will not become a progressive fuel load at a later stage of the compartment fire.

6.3 DEVELOPMENT OF A FIRE-SAFE ALTERNATIVE SOLUTION

6.3.1 Approach to an Alternative Solution for Fire-Safe Tall Wood Buildings

In theory, the development of an Alternative Solution related to fire safety is a matter of developing a method of assessing the relative fire risks of the proposed building (in this case, one containing mass timber elements designed beyond the parameters prescribed by the NBC 2020) and a building that conforms to the traditional construction methodology reflected in the NBC Division B's Acceptable Solutions.

The prescriptive Acceptable Solutions in Division B of the NBC have historically restricted the use of wood in building construction to 2, 3, and 4 storeys above grade, and more recently in 2015 to 6 storeys above grade. As building size increases, the occupant load and the cost of construction and repairs generally increase proportionally. Commensurate with this, the provisions for fire safety in the NBC become more stringent to reflect the higher risk (higher probability of injury/loss of life due to fire and/or greater financial loss due to failure of the building). In larger and taller buildings, Division B of the NBC generally prescribes more restrictive flame spread ratings for the interior finishes and the use of higher fire-resistance rated and noncombustible or EMTC materials. The Acceptable Solutions in the NBC 2020 now permit the use of EMTC for buildings up to 12 storeys that contain residential and office occupancies, and have assembly, mercantile, and medium- and low-hazard industrial occupancies permitted below the fifth storey. For taller and larger buildings and buildings of other occupancies (depending on occupancy type), noncombustible construction is prescribed. The intent is to minimize the probability of combustible materials contributing to pre-flashover fire growth (i.e., limiting the duration of post-flashover burning), thereby increasing the chances of the fire protection strategy being successful. It is significant that the NBC does not, and cannot, regulate building contents, which usually pose a much larger fire load and greater fire hazard than combustible interior finishes or structural elements.

Although the NBC does not explicitly outline fundamental fire protection strategies, the limitation regarding use of combustible construction materials is noted in its intent statements. An intent statement explains the basic rationale behind each NBC provision in Division B. For example, the objectives and functional statements attributed to the requirement for noncombustible construction within a storey are [F02-OS1.2, OP1.2], and the intent statement reads as follows (NRC, 2020a):

> To limit the probability that combustible construction materials within a storey of a building will be involved in a fire, which could lead to the growth of fire, which could lead to the spread of fire within the storey during the

time required to achieve occupant safety and for emergency responders to perform their duties, which could lead to harm to persons and damage to the building.

The intent of this chapter is to provide guidelines for developing a fire-safe Alternative Solution that will demonstrate that mass timber structural systems in a tall building which do not conform directly to the NBC 2020 prescriptive solutions can still meet at least the same level of performance provided by EMTC and noncombustible construction. However, it is not suggested that the approach presented in this guide is the only suitable one; the development of other approaches is encouraged. This guide does however highlight issues and concerns that other approaches may need to address.

There are a number of approaches for developing a fire-safe Alternative Solution for a tall wood building. The complexity of these approaches depends on the extent of variance from the Acceptable Solutions being addressed. One approach would be to identify and analyze the risks that need to be addressed or mitigated, using a risk assessment methodology, as an example. Then an assessment needs to be developed to demonstrate that the overall level of safety (level of risks) is equivalent to, or better than, that provided by the deemed-to-satisfy Acceptable Solutions permitted in Division B for the same building scenario.

Where the NBC 2020 prescribes noncombustible construction for a tall building (that is, where the building is more than 12 storeys high and/or contains occupancies other than those permitted in a building of combustible construction or EMTC), it may be necessary to start from the premise that the building will conform to the provisions for noncombustible construction and to assess the effect on the level of risk arising from the introduction of structural combustible components. That is, as mass timber components are introduced in the building, the performance of those components, complete with their protection methodology, must be compared to the performance of traditional components and their representative protection methodology. However, because the NBC now permits EMTC where noncombustible construction was originally prescribed, minimal analysis would likely be required to demonstrate that the use of EMTC in lieu of noncombustible construction is able to provide an acceptable level of performance. For Alternative Solutions where it is desired to expose a greater percentage of the wood structure than permitted by the NBC 2020, an analysis from first principles and/or reliance on fire tests may be necessary to demonstrate an acceptable level of performance. For Alternative Solutions that involve other aspects related to the use of combustible elements in high buildings, the EMTC provisions set the baseline for the acceptable level of performance against which the Alternative Solution must be compared.

The approach for developing an Alternative Solution for tall wood buildings is essentially iterative. The steps that need to be taken are as follows:

1. Review the specific code provisions—in this case, the requirement for EMTC as described in the NBC 2020, or noncombustible construction.
2. Assume that the fire protection elements/features of the building, other than the additional combustible elements proposed, conform to the NBC's Acceptable Solutions (to be reviewed after the development of the risk analysis).

3. Perform the risk analysis on the direct risks associated with the objectives and functional statements, and demonstrate that based on the comparative findings, the level of risk of the proposed solution is equal to, or lower than, the Acceptable Solution, or if not of lower risk, what compensating measures are available to lower the risk to an acceptable level.
4. Review other critical elements of the building that are compliant with Division B in order to determine whether the Alternative Solution would negatively impact the effectiveness of these provisions.
5. Review the effect of the specific Alternative Solution on other Alternative Solutions contemplated for the building as well as the effect of these other Alternative Solutions on the specific Alternative Solution.
6. If more refined Alternative Solutions to Division B solutions are required, perform the risk analysis on those Alternative Solutions and determine whether compensating measures are required.
7. Repeat the review of the critical elements, if any, and specifically note that some Alternative Solutions may have effects on other Alternative Solutions.

Depending on the scope of the proposed Alternative Solution, it may be appropriate to review and address basic fundamentals of building fire protection; measures for high buildings, including measures for firefighting, automatic sprinklers, and fire alarm provisions; and measures to protect from fire spread on the exterior of the building.

Common Alternative Solutions anticipated in relation to the use of mass timber construction may include those to address:

- the use of encapsulated mass timber for buildings higher than 12 storeys;
- buildings containing occupancies other than currently prescribed;
- exterior wall construction with respect to spatial separation provisions;
- an increase in the percentage of exposed structural wood surfaces; or
- an approach to fire blocking and protection of concealed spaces.

6.3.1.1 Other Fire Safety Objectives

The objective-based NBC provides objectives and functional statements for most of the technical provisions in Division B; however, the NBC does not address all fire risks, nor can the attribution of objectives and functional statements for each provision in the Acceptable Solutions necessarily be considered comprehensive and complete. In practice, the state of knowledge in fire science is not at a point where a pure quantitative fire risk analysis can be performed; in essence, it is not possible to predict all the events and failures that might occur. It is also important to be aware of "unknown unknowns"; that is, potential concerns that do not occur with conventional construction and are beyond the areas of performance identified for the applicable Division B provisions.

On the other hand, it is important to note that the prescriptive solutions in Division B do not address all possible events and failures that may occur. There are many known risks in existing buildings of noncombustible construction, as well as "unknown unknowns". It is the intent of this guide, by involving a wide range of experts with varied experience, to resolve most of these issues and identify enough of the "unknown unknowns" to provide confidence that in its entirety, a tall timber building of any height and area can be designed to provide the level of performance that is expected in modern noncombustible construction.

6.3.2 Level of Performance in the Areas Defined by Objectives and Functional Statements

The minimum level of performance anticipated by the NBC for high buildings is noncombustible construction with a 2-hr fire-resistance rating. EMTC is permitted in limited application for residential and office buildings up to 12 storeys high. Section 6.6 of this chapter details how to design mass timber structural elements to provide the specified 2-hr fire-resistance rating.

6.3.2.1 Objectives and Functional Statements Related to Noncombustible Construction and Encapsulated Mass Timber Construction

The objectives and functional statements of the NBC that are attributed to the requirement for noncombustible construction are [F02-OS1.2] and [F02-OP1.2], which are reproduced as follows:

- [F02-OS1.2]: "to minimize the severity and effects of fire or explosions so as to limit the probability that, as a result of the design or construction, a person in, or adjacent to, the building will be exposed to an unacceptable risk of injury due to fire or explosion impacting areas beyond its point of origin", and
- [F02-OP1.2]: "to minimize the severity and effects of fire or explosions so as to limit the probability that, as a result of the design or construction, a building will be exposed to an unacceptable risk of damage due to fire or explosion impacting areas beyond its point of origin".

As noted, similar objectives and functional statements will most likely be attributed to EMTC.

In summary, the potential for the building's combustible structural elements to contribute to the intensity, severity, or spread of fire (including products of combustion) beyond its point of origin (i.e., the room of fire origin) needs to be addressed. Therefore, in developing an Alternative Solution, it is necessary to either (1) limit the involvement of wood in contributing to the intensity, severity, and spread of fire and smoke to the levels anticipated in a building of noncombustible construction at the minimum depending on what the minimum level of performance is established as, or (2) provide features that compensate for the potential increased intensity, severity, and spread of fire and smoke.

The intent statement also notes a time frame during which these objectives and functional statements must be satisfied; namely, "during the time required to achieve occupant safety and for emergency responders to perform their duties".

6.3.2.2 Scope of Proposed Alternative Solution

For a complex or an Alternative Solution that cannot be easily compared to an Acceptable Solution, a detailed analysis of life safety of the whole building may be necessary, given that many other aspects of the solution in Division B are predicated on the assumption of noncombustible construction or EMTC with limited exposed structural elements. This is the case for a tall wood building.

To simplify the analysis in this guide, it is assumed that floor-to-floor heights are relatively standard, and that contents (quantities of combustibles, such as furniture, etc.) are evenly distributed, similar to the fire loads in typical residential or office occupancies. Where fire loads of contents are expected to be unusually high, it may be appropriate to perform a fire modelling study based on appropriately sized design fires to establish that the increased fire loads will not lead to potential collapse of the building. Information on developing design fires and design fire scenarios is provided in various fire engineering publications, including ISO 16733-1 (ISO, 2015), ISO/CD TS 16733-2 (ISO, 2019), and *The SFPE Handbook of Fire Protection Engineering* (SFPE, 2016). These comments apply equally to any type of construction; however, given that a tall mass timber building may undergo increased scrutiny and is frequently perceived to be of a higher risk, such an analysis will be more critical for Alternative Solutions for early tall mass timber buildings. The proponents of the Alternative Solution will need to establish that their assumptions are consistent with the occupancy and characteristics of the proposed building.

The analysis presented assumes that the proposed building is defined as a "high building", per the NBC definition. However, there may be cases where a proposed mass timber building is of lesser height yet sufficient area that the Acceptable Solutions in Division B prescribe noncombustible construction but require structural assemblies to have only a 1-hr fire-resistance rating. In such scenarios, recommendations in this guide should be appropriately modified.

6.3.2.3 Combustible Components Explicitly Permitted in Division B of the National Building Code 2020

Within a conventional building prescriptively permitted to be of EMTC or noncombustible construction, numerous nonstructural elements, both minor and in some cases more significant, are permitted to consist of combustible materials.

Subsection 3.1.5. of Division B and the 2020 NBC provide an outline of nonstructural combustible components permitted in a building that is required to be of noncombustible construction or EMTC, respectively.

Subsection 3.1.5. notes the advantages of sprinkler protection. When a building is entirely sprinklered, substantial additional combustible components, including combustible partitions and combustible wall finishes, are permitted. Essentially, any interior partition or fire separation, except for vertical shafts, that has a prescribed fire-resistance rating less than the floor rating is permitted to be of combustible construction, either mass timber or wood-frame. Elements such as gypsum board or millwork are also acceptable in a building of noncombustible or EMTC. Of specific note is the case of gypsum board: the paper covering gypsum board is combustible; however, gypsum board is specifically permitted under Article 3.1.5.1. of Division B of the NBC. Provisions for combustible cladding and roofs are discussed in Section 6.11 of this chapter.

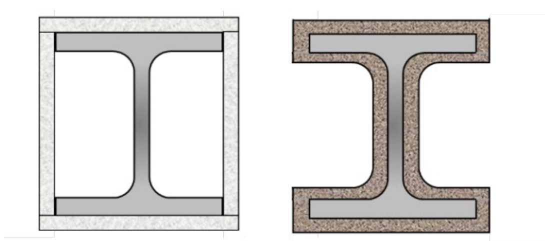
6.4 ASSESSMENT OF PERFORMANCE LEVEL OF AN ALTERNATIVE SOLUTION

An Alternative Solution must limit the probability that combustible construction materials within a storey of a building will be involved in a fire that could spread within the storey during the time required to achieve occupant safety and for emergency responders to perform their duties in order to prevent harm to persons and damage to the building. An efficient, well-known method of addressing this technicality involves protecting the combustible structural elements in order to delay their ignition and limit their potential contribution to a fire. This is the method employed by the NBC 2020 for EMTC.

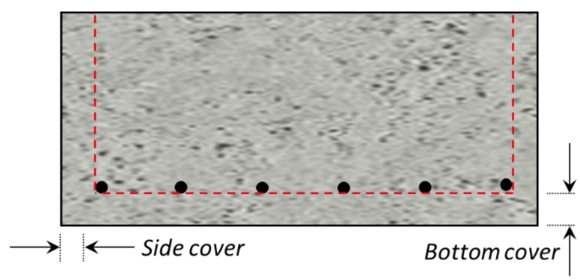
6.4.1 What is Encapsulation?

Encapsulation is a fundamental approach to fire protection of all structural materials. In large buildings, steel is traditionally protected by fibrous or cementitious coatings, board-type materials such as gypsum board, or special paints. Reinforced concrete is a composite material of steel and concrete, and is usually protected by a non-load-bearing layer of concrete, referred to as "cover", of a given thickness that protects the load-bearing composite structure from reaching a specific critical temperature threshold (Figure 4). Consistent with the NBC 2020, the following definition of encapsulation is used in this guide:

> Encapsulation relates to the use of materials for protecting the structural elements to mitigate the effects of the fire on the structural elements, in such way that any effects of the combustible structural elements on the fire severity can be delayed.



(a) Encapsulation of steel components



(b) Encapsulation of steel rebars in concrete components

Figure 4. Examples of encapsulation methods for structural steel and concrete components.

Encapsulation delays the effects of a contents fire on the structural elements of traditional noncombustible construction, thereby prolonging the time to loss of strength and potential failure. With mass timber construction, encapsulation delays the time it takes for the combustible structural elements to ignite and begin contributing to fire severity and potential failure. In the NBC 2020 provisions for EMTC, encapsulation of mass timber can be achieved using a material or assembly of materials consisting of gypsum board, gypsum concrete, noncombustible materials, materials that conform to Sentences 3.1.5.1.(2) to (4), or any combination of these materials that are able to remain in place and prevent initiation of charring for the required encapsulation duration.

The default encapsulation rating required for mass timber in the NBC 2020 is generally based on two layers of 12.7-mm thick Type X gypsum board, which delays the onset of charring for approximately 50 min under the standard fire exposure of CAN/ULC-S101 (ULC, 2014a). However, any material or assembly of materials that provides a 50-min encapsulation rating when tested in accordance with CAN/ULC-S146 (ULC, 2019) is permitted. In the NBC 2020, two layers of 12.7-mm thick Type X gypsum board and 38 mm of concrete or gypsum-concrete topping are defined as generic acceptable encapsulation solutions that are deemed to have an encapsulation rating of 50 min.

Four levels of encapsulation are discussed in this guide: complete, limited, suspended, and fully exposed (no encapsulation).

6.4.1.1 Complete Encapsulation

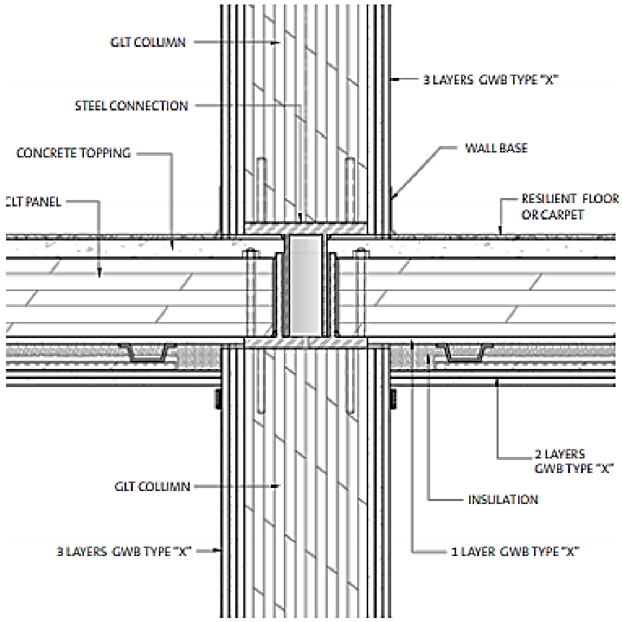
Conservatively, a 2-hr fire-resistance rating may be used for encapsulation; this is the prescribed rating within the Acceptable Solutions of the NBC for a tall building of noncombustible construction.

The prescribed minimum fire-resistance ratings in the NBC are used to meet two objectives: (1) structural performance, and (2) fire separation requirements. Basing encapsulation on the 2 hours required for structural fire-resistance provides a conservative means of protecting combustible structural elements. This method is referred to as "complete encapsulation".

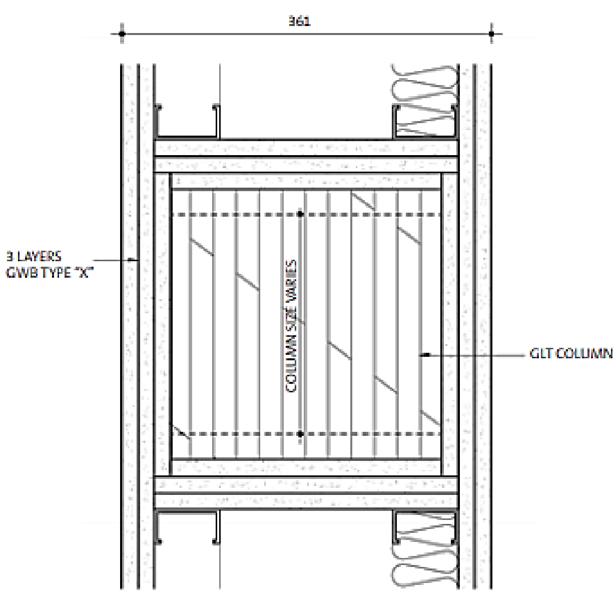
Protecting all beams, columns, and structural floor and roof panels with multiple layers of Type X gypsum board can provide "complete" protection (Figure 5). During a 2-hr standard fire exposure, the mass timber elements would likely not be significantly affected, nor would the timber elements ignite and contribute significantly to the fire’s intensity or to the severity or spread of fire or smoke. This approach is based on the premise of achieving burnout without he structural mass timber elements contributing to the fire (OMNRF/OMMA, 2017). CSA S408: Guidelines for the Development of Limit States Design Standards (CSA, 2011b) recommends that for “high buildings”, structural integrity should be ensured for complete burnout of the moveable combustible contents in any fire compartment. Therefore, a building with mass timber structural elements that are fully encapsulated could be deemed to provide a level of fire performance equivalent to that of noncombustible construction.

Encapsulation materials can provide most or all of the required fire-resistance rating and may provide other advantages such as reduced cross-section of structural mass timber elements and improved sound transmission performance (OMNRF/OMMA, 2017).

To achieve complete encapsulation for 2-hr fire resistance, such that the underlying timber is not charred or affected by heat in a standard fire test, at least four layers of 12.7-mm thick Type X gypsum board would most likely be required. Complete encapsulation was used for Tallwood House at Brock Commons on the University of British Columbia campus in Vancouver. Initial calculations indicated that slightly more than three layers of 15.9-mm thick gypsum wallboard were required to protect the timber for 2 hr. The panel of experts tasked with reviewing the project agreed that three layers were sufficient (Figure 6), as confirmed by the final Site Specific Regulation (Ministerial order M307) on September 28, 2015, also known as UBC Tall Wood Building Regulation (BC Reg 182/2015). Intermediate-scale encapsulation tests performed by Hasburgh et al. (2016) also demonstrated that three layers of 15.9-mm thick Type X gypsum board provide an encapsulation rating of 130 min when directly attached to mass timber elements.



(a) Detail of typical column and floor intersection and encapsulation, by Fast + Epp project Structural Engineers



(b) GLT and PSL columns are encapsulated by multiple layers of Type X gypsum board (detail by Acton Ostry, project Architects)

Figure 5. Complete encapsulation details for Tallwood House at Brock Commons, floor connection and column.

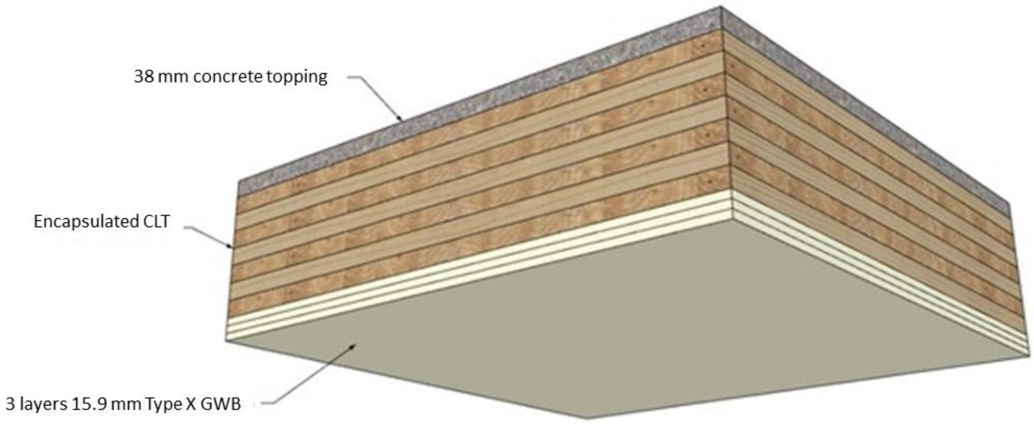


Figure 6. Complete encapsulation of CLT (2 hr of fire protection using three layers of 15.9-mm thick Type X gypsum board).

6.4.1.2 Limited Encapsulation

In principle, a more economic approach to complete encapsulation can be developed with a significantly reduced level of encapsulation. As discussed in Section 6.1.6, there are two fundamental stages to a fire: ignition and growth (i.e., pre-flashover) and fully developed (i.e., post-flashover). During the post-flashover stage, the fire is controlled primarily by ventilation factors, so the presence of mass timber elements or additional combustibles will not significantly increase the temperature, although they may increase the duration of the fire until burnout. A reasonable approach is to limit the involvement of the mass timber elements during fire growth and for some portion of the fully developed stage (Figure 7).

Providing sufficient encapsulation to delay the involvement of the wood to the point at which a compartment fire in a noncombustible structure would achieve burnout can provide equivalent performance to that of a steel or concrete building because the burning rate at flashover is ventilation controlled (i.e., limited by the available oxygen and contents, along with combustible finishes permitted in a noncombustible structure). When a single layer of 15.9-mm thick Type X gypsum board is directly attached to mass timber elements, the contribution of the timber to the fire, and the effect of the fire on the mass timber may be delayed, as discussed in Section 6.6.7 of this chapter. This delay can also be compared, for example, to the time it takes for occupants of the fire compartment and adjacent compartments to evacuate. This approach is in agreement with the intent statement detailed in Section 6.3.1 of this chapter.

Another measure in the NBC used to limit fire spread within floor areas is the use of walls as fire separations. For most occupancies, the NBC requires up to a 1-hr fire-resistance rating for fire separations between suites (see Division B, Section 3.3 of NBC). As indicated in Section 6.1.6, a primary concern regarding the use of combustible structural elements is the potential for increased fire spread within the storey of fire origin. An analysis of fire statistics in residential and multi-level residential buildings (using either combustible or noncombustible construction) showed that fires were contained to the room of origin nearly 94% of the time; for the most part, the fire was limited to the object of origin or the part of the room where the fire had started (Garis et al., 2019). The analysis also showed that fire spread was more prominent in buildings that did not have sprinklers installed.

Providing encapsulation to delay the involvement of combustible structural elements would limit the effect of a fire involving the structural elements on the fire separations and therefore on fire spread within the storey of fire origin.

While it is generally agreed that a single layer of gypsum board directly applied to the mass timber elements can provide the level of performance specified, it is likely prudent to use two layers of either 12.7-mm or 15.9-mm thick Type X gypsum board to achieve the expected level of fire performance and provide better reliability due to the ability to stagger the gypsum board joints. This is the approach adopted by the NBC 2020, which deems that two layers of 12.7-mm thick Type X gypsum board provide an appropriate level of encapsulation.

If a limited encapsulation approach is used as part of an Alternative Solution for a building designed beyond the parameters of the NBC 2020, it may be necessary to address the potential for an extended fire duration. This may require the use of enhanced fire protection systems, such as improving the reliability of automatic sprinklers by using an on-site or gravity-fed water supply, and improving provisions for firefighter salvage operations (which relates to limiting damage to a structure after a fire and suppression). These items are addressed further in Section 6.4.3 of this chapter.

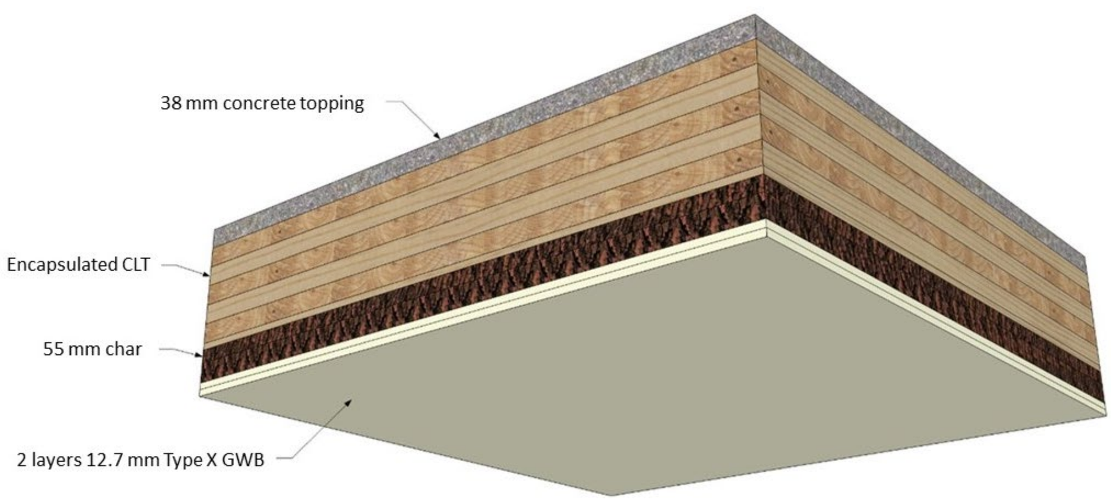


Figure 7. Limited encapsulation of CLT (two layers of 12.7-mm thick Type X gypsum board provides an FRR of 120 min with 55 mm of char (2@30 min + 60 min × 0.80 mm/min + 7 mm, per methodology of CSA O86 [CSA, 2019]).

6.4.1.3 Suspended Membrane-Type Encapsulation

Instead of applying the encapsulation directly to the structural members, a technique commonly used in steel buildings involves providing a membrane fire separation at the ceiling, with unprotected steel members supporting a steel deck ceiling. A similar approach can be used to protect mass timber; that is, a membrane ceiling can be suspended below a ceiling cavity. In this case, it will be necessary to demonstrate two things:

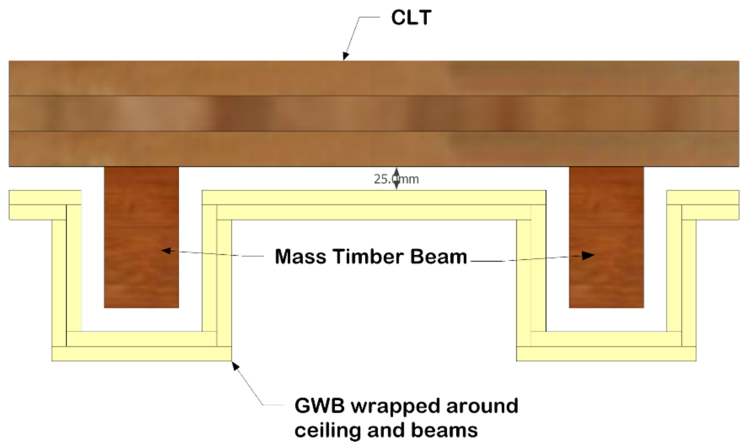
- the assembly provides the requisite encapsulation and fire-resistance ratings, and
- a fire in the cavity will not spread excessively or affect the structural performance of the assembly.

However, further research is required to establish how the level of performance provided in a noncombustible structure can be ensured in combustible construction with exposed mass timber in large void spaces. As an initial approach, it is recommended that all exposed timber in concealed spaces be protected by direct encapsulation that is sufficient to protect it from a fire that might occur in the concealed space. Again, this is the approach taken from the NBC 2020, which limits the distance between the encapsulation material and the mass timber elements being encapsulated to no more than 25 mm, and the space should be fire blocked.

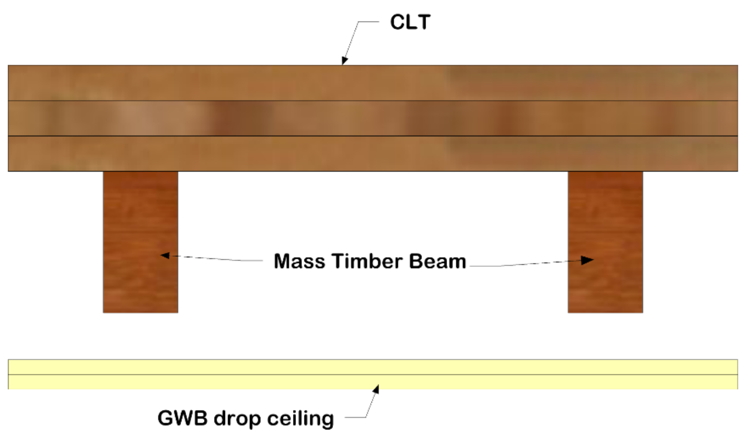
It may be feasible to demonstrate that sprinklers can provide an appropriate level of protection in deep void spaces with exposed combustibles. If such an approach is taken, research may be necessary to demonstrate that the level of sprinkler protection is appropriate. Specifically, it cannot be assumed that the exemptions in NFPA 13: Standard for the Installation of Sprinkler Systems (NFPA, 2013a) for omitting sprinklers from concealed spaces are appropriate. Moreover, the NBC 2020 prescribes the fire blocking of concealed spaces in EMTC regardless of whether NFPA 13 (NFPA, 2013a) prescribes sprinklers for concealed spaces.

Alternatively, a higher level of fire blocking may provide an acceptable level of protection for void spaces, especially fire blocking that may be inherent in the design of the assembly or that is provided by mass timber elements, and that results in only limited void volumes or areas that are not used for services or are connected to other voids. The degree to which such fire blocking is acceptable must be assessed and demonstrated by the individual designer.

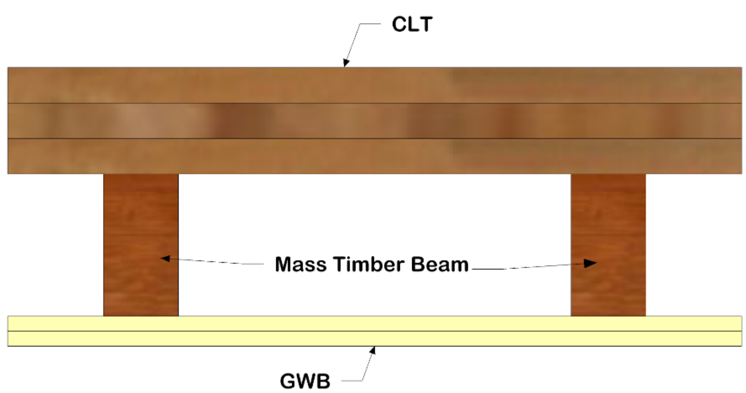
Some examples of suitable approaches are shown in Figure 8.



(a) Encapsulation permitted by the NBC 2020, with a gap up to 25 mm permitted between the encapsulation membrane and mass timber.



(b) Alternative approach to encapsulation: may need to be addressed as an Alternative Solution, and void space must be addressed.



(c) Alternative approach to encapsulation: may need to be addressed as an Alternative Solution, and void space must be addressed.

Figure 8. Approaches to encapsulation that create concealed spaces.

Figure 8a illustrates the encapsulation approach permitted by the NBC 2020, which requires the encapsulation materials to be attached to the mass timber members. Any concealed spaces created by the attachment of the membrane must not exceed 25 mm. Frequently, the encapsulation membrane provides the fire protection of the steel connectors. Careful review of the encapsulation membrane around connectors is required because it may be difficult to limit the void space to 25 mm where fasteners or plates are required. In such cases, it may be appropriate to fill the void space with noncombustible insulation.

The approaches illustrated in Figures 8b and 8c are not directly addressed by the NBC 2020; however, they are discussed and permitted in the RBQ (2015) guide and are referred to as "suspended encapsulation". In the RBQ guide, an encapsulation rating of 1 hr is prescribed, and the concealed spaces created must be filled with noncombustible insulation. These approaches could be proposed as part of an Alternative Solution, with adequate risk analysis and design measures used to demonstrate that an acceptable level of performance is provided.

In many cases, conformance with the NFPA 13 standard (NFPA, 2013a) requires that sprinklers be installed in a cavity, or alternatively, that the flame spread rating of exposed elements within cavities be no more than 25, employing a method acceptable to the standard.

Consideration may be given to treating the surface of void spaces with a paint that is formulated to reduce flame spread. However, it is not certain whether the current method for testing surfaces treated with such products adequately proves their effectiveness in addressing fire spread within narrow or small void spaces. Additional testing is needed to validate the use of these surface treatments and demonstrate their long-term durability (i.e., whether the surfaces need to be recoated after a given number of years in service).

Furthermore, it will be necessary to examine the effect of exposed timber in cavities on the development of smoke and on smoke movement within the building. Use of paint or other treatments to reduce flame spread in concealed spaces may increase smoke production and toxicity. Additional discussion on concealed spaces is presented in Section 6.10 of this chapter.

6.4.1.4 Fully Exposed

If mass timber members are to be fully exposed, fire-resistance can be achieved by protecting the structural cross-section of timber elements with a sacrificial layer of timber that could be permitted to char (Figure 9). Char formed from the sacrificial layer would protect all structural members, as described in Section 6.6 of this chapter. Within this approach, exposed timber in the occupied space, service spaces, and other cavities may contribute to the intensity of a fire and the production of smoke; therefore, the use of compensating measures to control the spread of fire and smoke may be appropriate.

Development of an Alternative Solution for a fully exposed timber building was beyond the resources and time available during the writing of this guide; however, there are examples of fully exposed buildings that, through an Alternative Solution and qualified peer review, can provide the required level of performance. As an example and as detailed in Section 6.2.2 of this chapter, the 2021 edition of the

International Building Code in the United States allows Type IV-C construction up to 9 storeys using fully exposed mass timber, provided mass timber structural elements have a 2-hr fire-resistance rating.

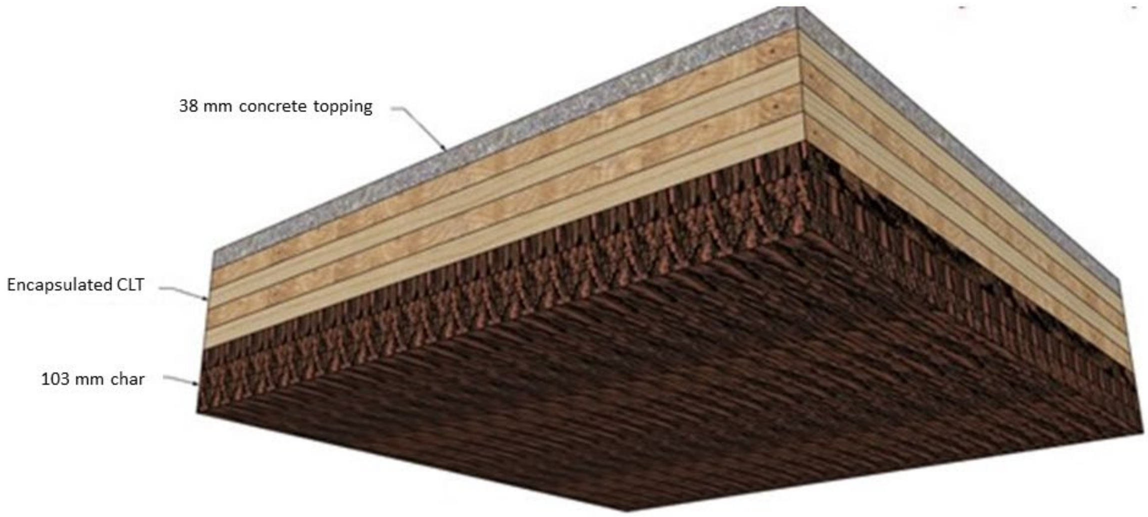


Figure 9. Fully exposed CLT floor assembly(103 mm of char provides 120 min FRR [0.8 mm/min x 120 min + 7 mm]).

In conclusion, complete encapsulation—where the mass timber elements are fire protected for a period of 2 hr is a conservative approach that can provide a fire performance comparable to or better than that of a prescribed noncombustible construction with the same fire-resistance rating. A lesser level of encapsulation can likely also provide the level of performance required. Furthermore, the levels of encapsulation discussed are based on compartment fires. Fire modelling and analysis could be used in some cases to demonstrate that less encapsulation may be sufficient for areas with limited fire loads, such as concealed spaces, exit and elevator shafts, service spaces, and exterior walls. As discussed, an encapsulation rating of 50 min is considered sufficient for some mass timber buildings up to 12 storeys. It is the responsibility of the designers of the Alternative Solution to determine the level of encapsulation that achieves the necessary level of protection.

6.4.2 Exposed Mass Timber within Occupied Spaces

As discussed in Section 6.7 of this chapter, mass timber has a low flame spread rating, and it will contribute less to the growth of fire than permitted wood finishes, which typically have higher flame spread ratings. The Acceptable Solutions of the NBC 2020 allow for significant use of combustible finishes within the interior of a building that is otherwise required to be of noncombustible construction or EMTC, including:

- wall and ceiling finishes up to 25 mm in thickness
- flooring elements
- wood convenience stairs in dwelling units in a building of EMTC (wood exit stairs are required to be encapsulated)

- solid wood partitions that are not part of floor-to-floor separations, exit separations, or vertical service spaces (protection with a layer of gypsum board or fire-retardant treated wood is prescribed for partition in a building of encapsulated mass timber)
- wood-framing in partitions that are not part of floor-to-floor separations, exit separations, or vertical service spaces (protection with a layer of gypsum board or fire-retardant treated wood is prescribed for partition in a building of encapsulated mass timber)

The provisions in the NBC 2020 for encapsulated mass timber also permit a small percentage of exposed structural mass timber. These provisions may provide a basis for allowing additional exposed mass timber. However, exposed mass timber may contribute to longer fire durations and more challenging firefighting operations. Therefore, appropriate measures for addressing any increase in risk should be considered.

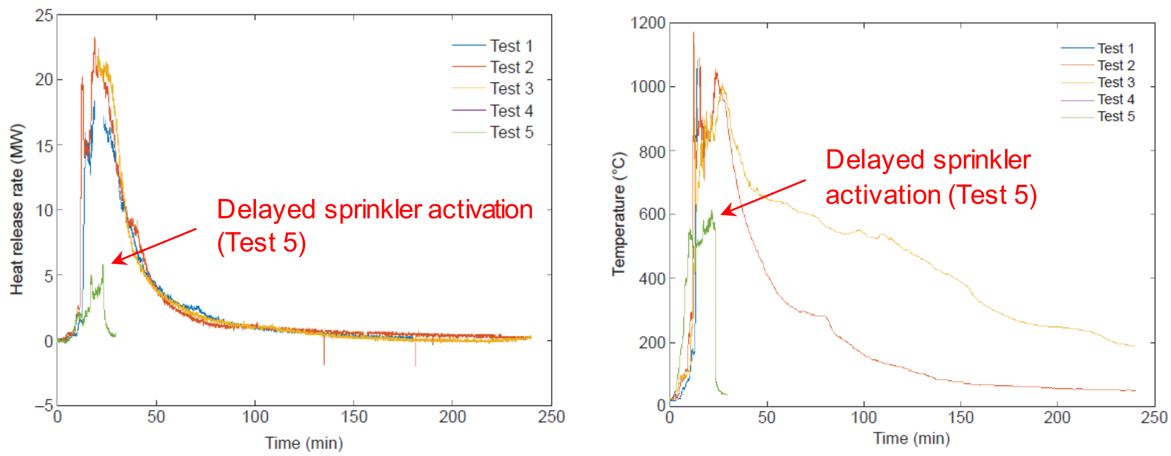
Floors are a special case. The involvement of floor finishes in a fire compartment is usually minimal because they are located below the hot upper smoke layer. Exposed mass timber floors can reasonably be considered to be acceptable, given that the NBC 2020 permits wood floors of any thickness, and it is unlikely that a greater depth of wood floor would be involved in a compartment fire when exposed to a fire above it. However, due to buoyancy of hot gases and combustion products, ceilings are typically more of a concern because they will heat up and potentially ignite faster than floor finishes. This may be one of the reasons why Division B of the NBC requires ceilings to exhibit a flame spread rating of not more than 25 when used in noncombustible construction or EMTC.

It is incumbent upon the proponent of the Alternative Solution to assess each area where exposure of mass timber is proposed and to establish, through fire dynamics and comparative risk analysis with directly permitted timber finishes, that acceptable performance is provided. In many cases, the NBC permits wood finishes based on a reliance on sprinklers, and this may be equally applicable to exposed mass timber elements.

6.4.3 Automatic Sprinklers

Sprinklers are highly effective in controlling fires. The Acceptable Solutions in Division B of the NBC specify that all buildings taller than 6 storeys must be provided with sprinkler protection in accordance with NFPA 13 (NFPA 2013a). The solutions in Division B attribute several benefits to sprinkler systems, such as reducing limiting distances and significantly increasing allowable building areas, but they may not recognize the full value of sprinkler systems. While it is not within the scope of this document to debate measures of "reliability" (to operate when needed) or specifics of sprinkler systems, various sources rate the "effectiveness" of sprinkler systems in preventing major fires at between 90 and 99%. Studies that report the lower end of this range have usually involved high fire risk occupancies, older sprinkler systems, and systems that did not have a modern fire alarm system equipped with automatic signals that were sent to the fire department. The state of sprinkler systems is perhaps best described by Richardson (1985), and is supported by more recent data. Richardson (1985) indicated that systems in use in Canada at that time had 96% reliability but could reasonably be improved to 99% if certain measures were used.

A series of five tests were conducted by the USDA Forest Service's Forest Product Laboratory (Zelinka et al., 2018) in cooperation with the American Wood Council; the Bureau of Alcohol, Tobacco, Firearms, and Explosives; and the Forest Service's State and Private Forestry in Beltsville, Maryland. The tests involved 2-storey, 175-mm thick, 5-ply CLT structures with compartments measuring 9.2 m × 9.2 m (30 ft. × 30 ft.) that were fully furnished and had a fuel load density of 412 MJ/m² in the living room and 807 MJ/m² in the kitchen. Tests 4 and 5 were equipped with automatic sprinklers, of which one activation was intentionally delayed. Both tests demonstrated that sprinklers were effective at reducing heat release rates and temperatures within a few minutes and preventing flashover from occurring (Figure 10). Sprinklers activated 2 min, 37 sec after ignition in Test 4, and were manually activated after 23 min in Test 5. The results were used to support the 2021 International Building Code change provisions detailed in Section 6.2.2.



(a) Heat release rates

(b) Hot layer temperatures in living room

Figure 10. Heat release rates and temperatures in CLT compartments (Zelinka et al., 2018).

As discussed elsewhere in this chapter, depending on the level of encapsulation used, in consideration of the possible extended duration of fires, or in areas with limited firefighting capability or with seismic risk, an on-site water supply may be needed for a tall timber building to improve reliability of the fire protection strategy. The size of the supply should be based on an analysis of a number of factors such as fire department response times, evacuation times, and the presence of mobility-impaired people. Other considerations for enhancing the reliability of sprinkler systems include the provision of redundant features such as:

- fire pumps and/or power sources
- risers or piping systems to the floor area, and
- fire safety systems

6.4.4 Nonstandard Fire Exposure

The preceding discussion relates to elements that may be subjected to standard fire exposure (i.e., CAN/ULC-S101 [ULC, 2014a]). There are many elements of a building that may have a lesser, or greater, fire exposure. For example, in shafts and concealed spaces and exterior faces of the building, fire exposure may be significantly reduced. Some of these conditions are discussed elsewhere in this chapter, including Section 6.11.2 on exterior cladding.

For buildings with greater fire hazards, such as high-piled storage, large retail occupancies, or industrial occupancies, it may be necessary to perform a fire modelling exercise to establish fire exposure and design the encapsulation or adjust charring rates accordingly.

6.4.5 Protection in Depth

For a traditional building of noncombustible construction or EMTC permitted by the NBC 2020, the fire safety approach includes a combination of active and passive fire protection systems, such as detection, construction type, compartmentation, sprinkler protection, and smoke control systems, that when combined, provide an appropriate redundant fire safety design. An Alternative Solution should therefore have redundancy in fire safety systems as a key feature. For example, sprinklers will inherently control the movement of smoke by limiting its production; however, a mechanical smoke control system may also be relied upon to control the spread of smoke if the sprinklers do not adequately control the fire.

Depending on the extent of variance from the Acceptable Solution or the complexity of the Alternative Solution, it may be necessary to provide additional protection with other systems, which could include one or more of the following measures: improving the effectiveness, coverage, or reliability of sprinkler systems and smoke control systems, or upgrading fire alarm detection and notification systems and improving exit systems.

One concern about encapsulating mass timber is the potential for damage to the encapsulation. While the encapsulation used for noncombustible construction materials is also subject to damage, both before and during a fire event, those materials, even if exposed, do not add fuel to a fire but may be subjected to other detrimental thermal effects. Direct encapsulation of mass timber elements by multiple layers of directly applied gypsum board would restrict the mass timber's contribution to a fire for the period that the protective membrane remains intact, which is likely to be less than that of the minor combustible components, such as 25-mm thick wood panelling, that are currently permitted in a building of noncombustible construction.

6.4.6 Practical Considerations

Adoption of practical approaches for common building features can simplify an Alternative Solution and facilitate development of the technical rationale needed to support it:

- Integrity of exits – Consideration should be given to increasing the level of protection in protected exit stairwells and elevator shafts. Maintaining the continuity of the fire separations and limiting the path of fire travel and smoke movement are important for a successful design.
- Service shafts – Service shafts also require appropriate attention to limit penetration, address wall and ceiling interfaces, and limit discontinuities in the design that may result in increased fire exposure to the wood structure.
- Concealed spaces – Protection of all large concealed spaces by sprinklers, encapsulation with gypsum board, or filling with noncombustible insulation will limit the probability of fire ignitions and fire spread within concealed space that could progress and spread substantially before being detected.

6.5 PROVISIONS FOR HIGH BUILDINGS (PART 3 OF DIVISION B)

The Acceptable Solutions in Division B of the NBC contain prescriptive and some performance-based solutions for high buildings. The main concerns for high buildings are (1) movement of smoke in tall shafts due to the effects of stack action, and (2) more challenging firefighting conditions due to the limitation of exterior firefighting capabilities. Based on the occupancy classification and physical height of the building, Division B of the NBC provides the criteria to determine when a building is considered to be a high building. The proponent of an Alternative Solution should be aware of, and consider the fundamentals of, these requirements.

The following high-building prescriptive provisions in the NBC are intended to provide smoke control and/or facilitate firefighting operations:

- limits to smoke movement between, below-, and above-grade storeys via stairways, elevator shafts, and service shafts
- limits to smoke movement between storeys via air handling systems
- limits to smoke movement between connected buildings of which at least one is a high building
- emergency operation and design of elevators for firefighters
- venting to aid firefighting
- central alarm and control facility
- voice communication system

6.5.1 What is "Stack Effect"?

Within building shafts, such as stair, elevator, and service shafts, and mail, garbage, and linen chutes, airflow is driven by the difference in temperature between the exterior and interior of the building. In winter, air flows upward shafts due to the buoyancy of warm air inside the building relative to the cold air outdoors. This is similar to the upward flow in smokestacks, and is known as normal stack effect. In air-conditioned buildings in the summer, temperatures can be lower inside the building than outside, which produces a downward airflow within the shaft, known as "reverse stack effect".

Figure 11 shows the general airflow in a building during a normal stack effect. Air flows into the building below the neutral plane, up the shafts, and out of the building above the neutral plane. The neutral plane is a horizontal plane where the air pressure inside the shaft equals the outdoor pressure.

The severity of stack effect depends on the height of the building and the temperature gradient between the indoor and outdoor temperatures. In Canada, winter temperatures can be very low, which can produce a significant stack effect. For fire safety engineering design in Canada, it is generally assumed that reverse stack effect in summer is minimal and may be ignored in most cases.

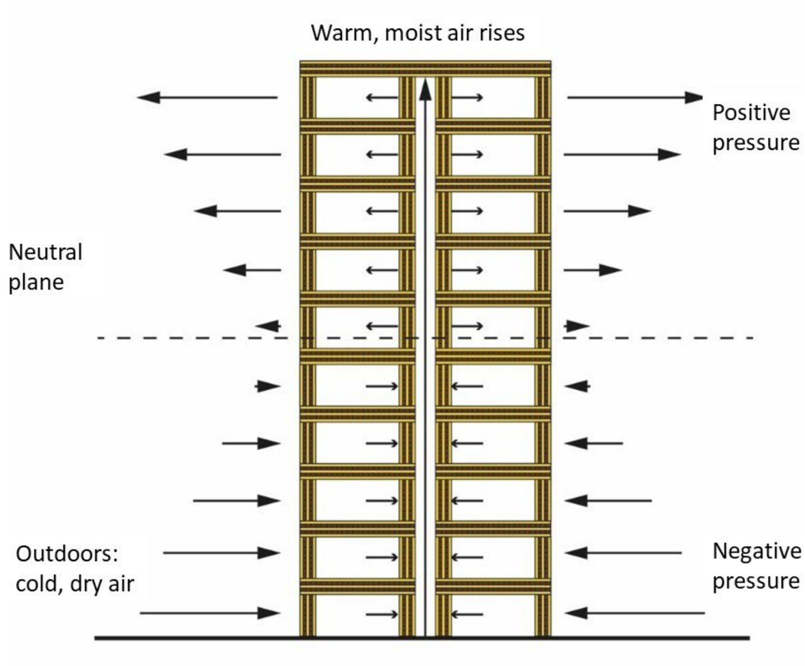


Figure 11. Normal stack effect in high buildings.

6.5.2 Design of Tall Shafts to Resist Movement of Smoke to an Acceptable Level

Naturally, there may be a desire to leave some elements of the wood construction exposed. However, when designing tall shafts, such as stair, elevator, and service shafts, and chutes for mail, garbage, and linen, it is recommended that the wood construction be encapsulated. The goal is twofold. First, modern mass timber construction typically consists of large wood panels (such as CLT) which may be fairly airtight, but the joints may not be as tight as other framed assemblies. As a result, shafts constructed of exposed wood panels may be subject to greater risk of smoke migration. Secondly, exposed wood panels in a tall shaft could be subject to flame spread within the shaft. Therefore, unless further analysis, testing, or modelling demonstrates otherwise, shafts should be lined with noncombustible material, such as sheet stee, or at least one layer of gypsum board.

With respect to the level of encapsulation, the NBC 2020 prescribes a minimum of two layers of 12.7-mm thick Type X gypsum board. However, with proper analysis as part of an Alternative Solution approach, and if all mass timber surfaces in the shaft are covered with sheet steel or a single layer of gypsum board to prevent a significant-sized fire from initiating, no further encapsulation may be required.

Garbage and linen chutes may require special consideration because they can contain combustible loads. However, the solutions in Division B of the NBC require these shafts to be lined with steel and to be provided with additional protection in the form of sprinklers at alternate floors, and protection of the shaft openings.

Short shafts in tall wood buildings may not be subject to the same risk; however, the fire protection engineer must use sound engineering judgment in determining whether certain shafts can have exposed wood.

Stair shafts of mass timber construction require particular consideration because they may contain additional combustible loads in the form of wood stairs and the shaft construction, and they need to be kept free of fire and smoke. Stair shafts are also likely to be subject to damage that may go unrepaired; therefore, it is recommended that stair shafts be lined with gypsum board. Furthermore, where stair shafts occur back-to-back, or in the case of scissor stair configurations, special attention to maintaining the fire and smoke separations between the stair shafts is required.

When designing a tall wood building, it is expected that the measures required in Division B of the NBC will be met either directly or through Alternative Solutions to limit smoke movement through shafts to an acceptable level. Additional smoke control methods are provided in NFPA 92 (NFPA, 2012) and Klote et al. (2012), and in the Canadian-developed methods for unsprinklered buildings in the Supplement to the 1990 NBC (NRC, 1990).

6.6 FIRE-RESISTANCE OF ASSEMBLIES AND COMPONENTS

Building regulations require that key building assemblies exhibit sufficient fire-resistance to allow time for occupants to evacuate, to minimize property losses, and to allow emergency responders to carry out their duties. The strategy is to limit the possibility of structural collapse and to subdivide a building into fire-resistance-rated compartments (see Section 6.8.1). The goal of compartmentalization is to limit fire spread beyond its point of origin by using boundary elements (e.g., walls, ceilings, floors, partitions) that have a fire-resistance rating not less than the minimum ratings prescribed by the NBC. Fire-resistance ratings are usually assigned in whole hours (e.g., 1 and 2 hr) or parts of hours (e.g., 1/2 hr or 30 min; 3/4 hr or 45 min). In the case of tall buildings, a 2-hr fire-resistance rating is typically the minimum required for structural elements. Moreover, each suite in occupancies other than business and personal service (Group D) are to be separated from adjoining suites by a fire separation that has a fire-resistance rating of not less than 1 hr.

6.6.1 What is Fire Resistance?

The fire-resistance of building assemblies is typically assessed by conducting standard fire-resistance tests in accordance with CAN/ULC-S101 (ULC, 2014a). However, there are other sources for deriving what are considered generic fire-resistance ratings, such as those contained in Appendix D of the NBC. For mass timber construction, fire-resistance may also be calculated using methods in Annex B of CSA O86 (CSA, 2019), as described in Section 6.6.8 of this chapter. The CAN/ULC-S101 fire test method is essentially a means of comparing the fire performance (such as restriction of fire spread and structural response capabilities) of one building component or assembly with another, in relation to its performance to a standard fire exposure. CAN/ULC-S101 is a performance-based fire endurance test method with particular performance criteria that are used to assign fire-resistance ratings. Such testing is not related to standard fire testing for the noncombustibility of materials, which is conducted in accordance with CAN/ULC-S114: Standard Method of Test for Determination of Non-combustibility in Building Materials (ULC, 2018). When assigning a fire-resistance rating to floor, roof, or ceiling assemblies, the assemblies must be fire-resistance rated for exposure to fire from the underside. Firewalls and interior vertical fire separations must be fire-resistance rated for exposure to fire from either side, while exterior walls must be fire-resistance rated for exposure to fire from inside the building.

The standard fire-resistance test method uses three performance criteria to establish the fire-resistance ratings (Figure 12) for both fire separations and structural fire-resistance. The time at which the assembly can no longer satisfy any one of the following three criteria establishes the fire endurance period, which is then used to define the assembly's fire-resistance rating:

- Insulation: The assembly must prevent the rise in temperature (above the initial temperature) on the unexposed surface from being greater than 180°C at any location or an average of 140°C measured at nine locations.
- Integrity: The assembly must prevent the passage of flames or gases that are hot enough to ignite a cotton pad.

- Structural resistance: The assembly must support the applied load, if any, for the duration of the test.

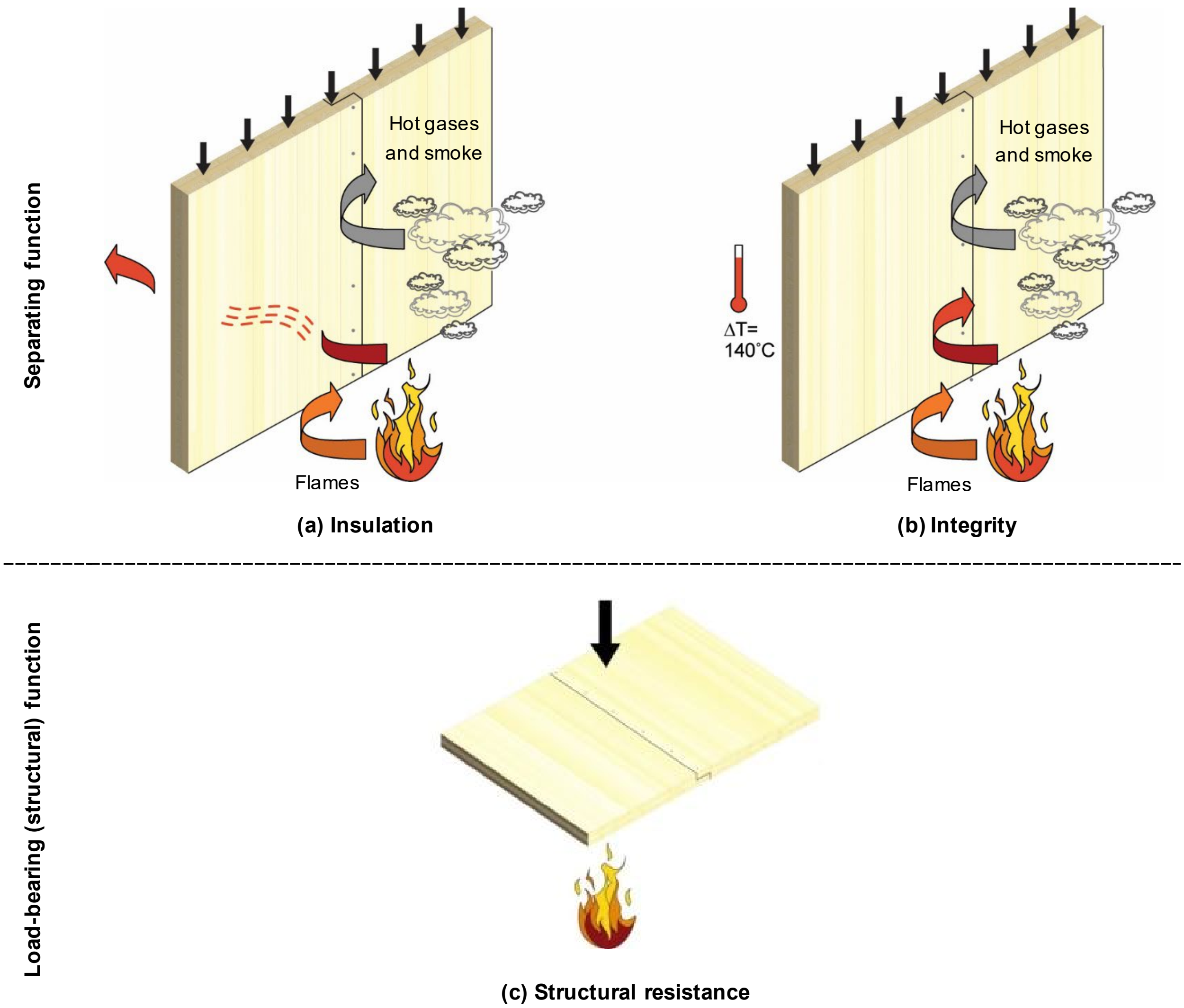


Figure 12. Fire-resistance criteria per CAN/ULC-S101 (ULC, 2014a).

The structural fire-resistance criterion applies to the load-bearing function of assemblies and components (floors/ceilings, load-bearing walls, beams, and columns), while integrity and insulation criteria relate to the separating function of assemblies, such as partitions, doors, walls, roofs, and floors/ceilings. In the case where an assembly is acting as a load-bearing and a separating element (e.g., roofs, floors, and many walls), all three criteria need to be fulfilled.

6.6.2 Standard Fire versus Design Fire Scenarios

The CAN/ULC-S101 (ULC, 2014a) fire test method requires a wall, floor, or roof assembly, or a structural element such as a column or beam to be exposed to a post-flashover fire in which the temperature of the fire gases increases over time, following a standardized time–temperature curve (Figure 13). As mentioned previously, the standard fire test allows the performance of one building component or assembly to be compared with another in relation to its performance in a fire. Although the standard time–temperature curve does not represent "real" fire scenarios, it has been developed in an attempt to replicate the post-flashover conditions of real fires with a standard (nominal) time–temperature curve, which is the stage of a fire that challenges a building structural system the most. However, it does not consider the potential decay phase or change in fire regime (i.e., a fire would most likely be ventilation controlled during the fully developed phase, and fuel controlled during the growth and decay phases).

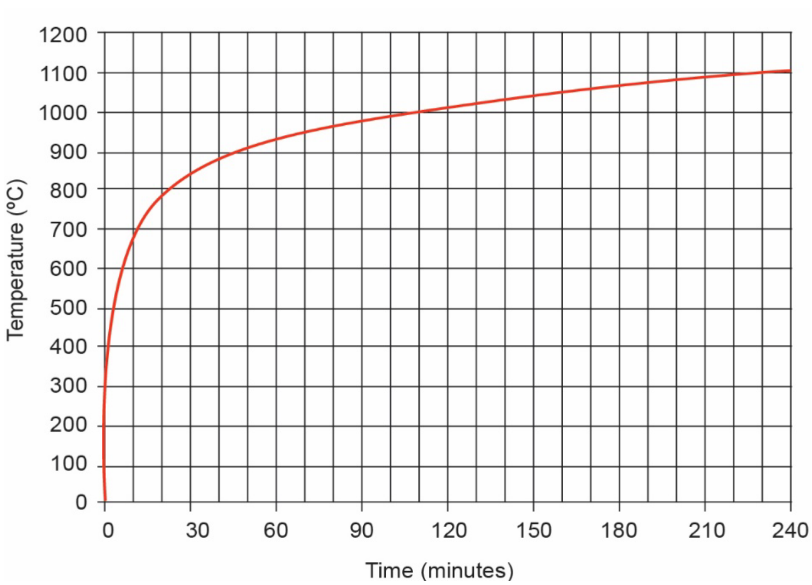


Figure 13. CAN/ULC-S101 standard time–temperature curve (ULC, 2014a).

As noted, the CAN/ULC-S101 (ULC, 2014a) standard time–temperature curve may not represent a real or natural fire, as shown in Figure 14. Therefore, in some cases, it may be necessary, as part of an Alternative Solution, to use a design fire curve that more appropriately represents the profile expected in a specific compartment based on the compartment configuration, expected boundary conditions (including their thermal inertia), compartment geometry, available ventilation conditions (oxygen to sustain combustion), fuel load (furniture and contents) arrangement, and effects from automatic sprinklers on the heat release rate and temperature. Depending on the characteristics, this design fire could be either more intense or less intense than the standard fire.

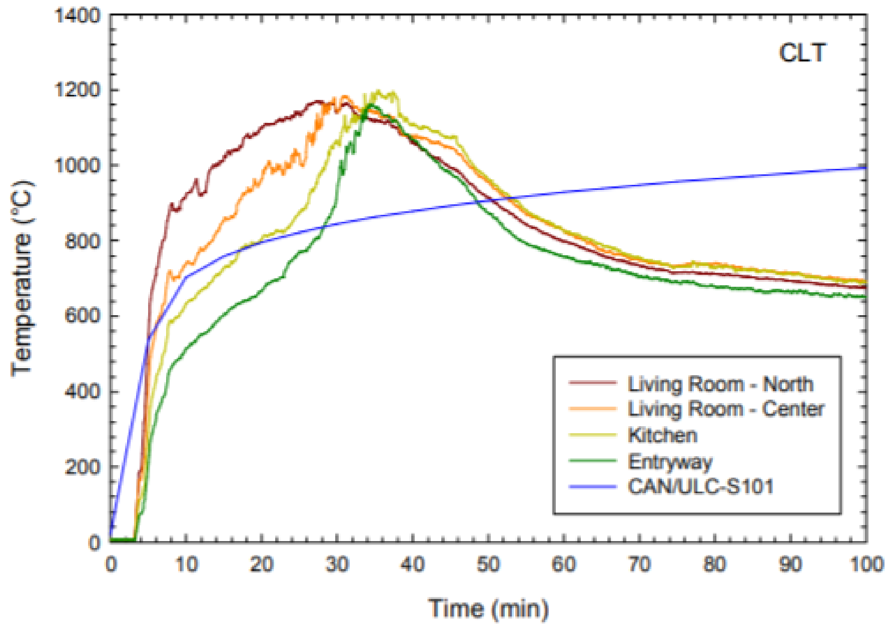


Figure 14. Example fire time–temperature curves in a CLT compartment fire experiment compared to the CAN/ULC-S101 (ULC, 2014a) standard temperature curve (Taber et al., 2013).

6.6.3 Behaviour of Wood at High Temperatures (Charring)

Under elevated temperature conditions, such as those associated with building fires, the behaviour of a structural component depends primarily on the thermal, mechanical, and chemical properties of the material of which the component is composed.

When exposed to elevated temperatures, wood undergoes thermal degradation that affects its performance. This material-specific property, called pyrolysis, begins at approximately 200°C, while the remaining wood subsequently converts to char at temperatures ranging from 280 to 300°C (Figure 15). Charring is influenced by various factors, such as wood density, moisture content, contraction, and exposure conditions (fire severity). White (2016) found that the charring rate is proportional to the ratio of external heat flux over wood density. In experiments conducted on spruce specimens, charring rates were 0.56, 0.80, and 1.02 mm/min when exposed to heat fluxes of 25, 50, and 75 kW/m², respectively. Oxygen concentration also influences charring rate. Cone calorimeter experiments that used white pine specimens exposed to a constant heat flux and oxygen concentrations of 21%, 10.5%, and 0% showed that the mass loss rate decreased by 20% and 50% when the oxygen concentration decreased from 21% to 10.5% and 0%, respectively (Mikkola, 1990). This suggests that as a fire grows within a compartment and the oxygen concentration declines, the charring rate is expected to decrease. Piloted ignition of wood occurs at temperatures ranging from 350 to 365°C (for softwoods) and 300 to 310°C (for hardwoods) (Janssens & Douglas, 2004). Charring can also occur when wood is subjected to a constant heat flux between 10 and 13 kW/m², with a commonly accepted value of 12.5 kW/m²

(White & Dietenberger, 2010), which is also the assumption used in the NBC for setting the minimum spatial separation between buildings.

When structural wood elements are encapsulated with a single or multiple layer of fire-rated gypsum board, the heat transfer at the wood and gypsum board interface is effectively delayed so that the wood elements do not reach their critical heat flux or ignition temperature for a certain period. If the gypsum board protection remains in place when the critical heat flux or ignition temperature is reached, charring will occur at a slower rate than shown in Table 4 until the protective membranes fail.

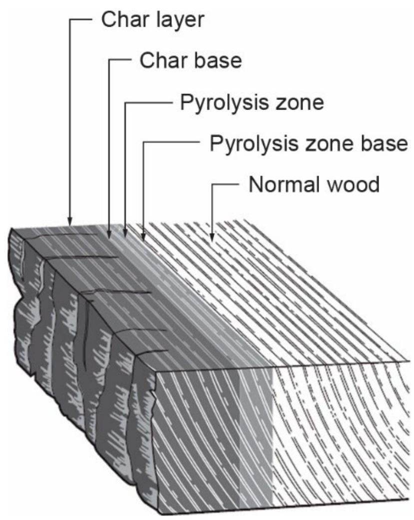


Figure 15. Char layer formed during a small-scale flame test (CSA O177-06 [CSA, 2011a]).

The charred layer formed around the exposed surface of the wood acts as thermal protection to the inner core, thereby reducing and stabilizing the rate of burning. The charred layer protects the inner core from thermal and strength degradation, as shown in Figure 16 and Figure 17. The temperature at the base of the char layer is approximately 300°C, and there is a heated layer about 35 mm thick below the char front, as assumed in Annex B of CSA O86 (CSA, 2019). The effective thermal protection (preventing strength-degrading levels of temperature rise in the wood) provided by the char layer has a depth of approximately 25 mm (CEN, 2004) from the top of the char layer.

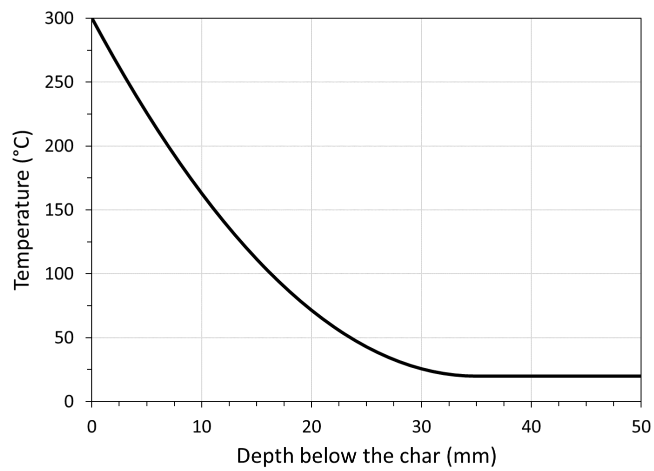
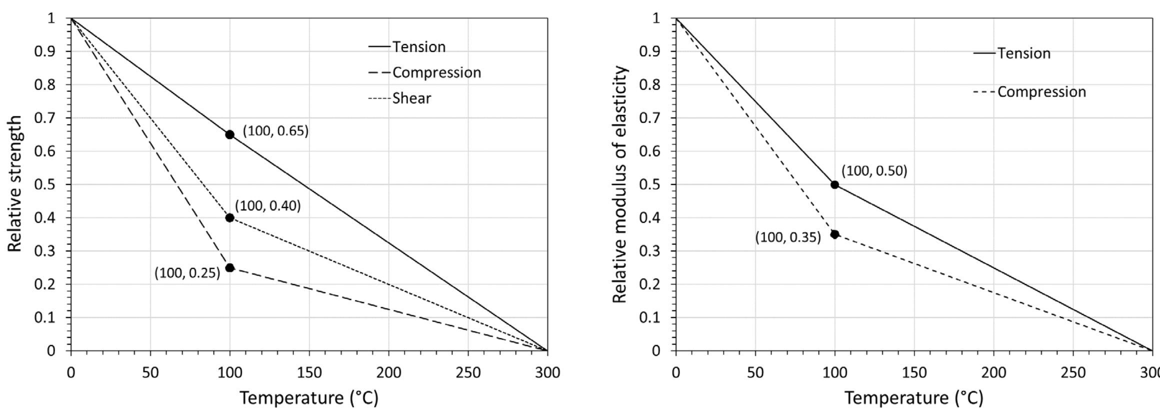


Figure 16. Temperature profile beyond the char layer.



(a) Strength (b) Modulus of elasticity

Figure 17. Effect of temperature on wood strength and modulus of elasticity (CEN, 2004).

Most design codes assume a constant charring rate throughout a standard fire exposure, which may differ depending on wood density. Charring rates for some solid wood and wood-based products, as specified in Annex B of CSA O86 (CSA, 2019), are shown in Table 4.

The one-dimensional charring rate, β_o, for standard fire exposure represents the rate expected for thermally thick slabs of wood (i.e., residual thickness of at least 35 mm, as depicted in Figure 16) that are exposed to fire on only one side, such as a floor assembly. Where there is fire exposure from more than one side, β_n is the notional charring rate, which is increased to offset the loss of cross-section at corners. These char rates apply to wood products for which the minimum residual cross-section is greater than 70 mm when heated on opposite parallel sides. Charring rates for other wood products are provided in the Eurocode 5: Part 1-2 (CEN, 2004) and could be applicable to Canadian timber, provided the characteristic densities are similar. Char rates for other mass timber products such as nail-laminated timber, dowel-laminated timber, and structural composite lumber may be determined from manufacturers' technical literature or test reports.

Table 4. Design charring rates of timber, as specified in CSA O86 (CSA, 2019)

Timber	β_o mm/min	β_n mm/min
Timber and plank decking	0.65	0.80
Glued-laminated timber	0.65	0.70
Structural composite lumber	0.65[a]	0.70[a]
Cross-laminated timber	0.65	0.80

[a] Applicable to wood-based structural composite lumber products only.

The most critical information for determining the fire-resistance of an assembly and its components is its response to temperature in the room or compartment and the heat flux impinging on the assemblies or components. Both can be assessed on the basis of exposure to either a standard or a design fire.

Figure 18 shows the typical steps for determining the fire-resistance of structural elements using advanced calculation methods such as those employed in a performance-based design. Three fundamental models may be required:

- Fire model: used to determine exposure from either a standard, real, or design fire
- Heat transfer model: used to evaluate the rise in temperature within the element or assembly
- Structural model: used to determine the structural resistance of a component/assembly at elevated temperatures using simple or advanced calculation models

Various models are available for calculating the temperature profile of standard and design fire scenarios (Buchanan & Abu, 2017; Drysdale, 1998; Lennon, 2011; SFPE, 2016; SP Trätek, 2010).

Building Performance

For simplicity, all approved mass timber components are fabricated to meet the same fire resistance as heavy timber. Because mass timber components, either solid sawn, glued, or composites, have the same char rates, they will provide some degree of fire separation but may not be detailed to meet code requirements. Mass timber components not originally design for fire resistance do not need to be removed; they can easily be upgraded during a building renovation.

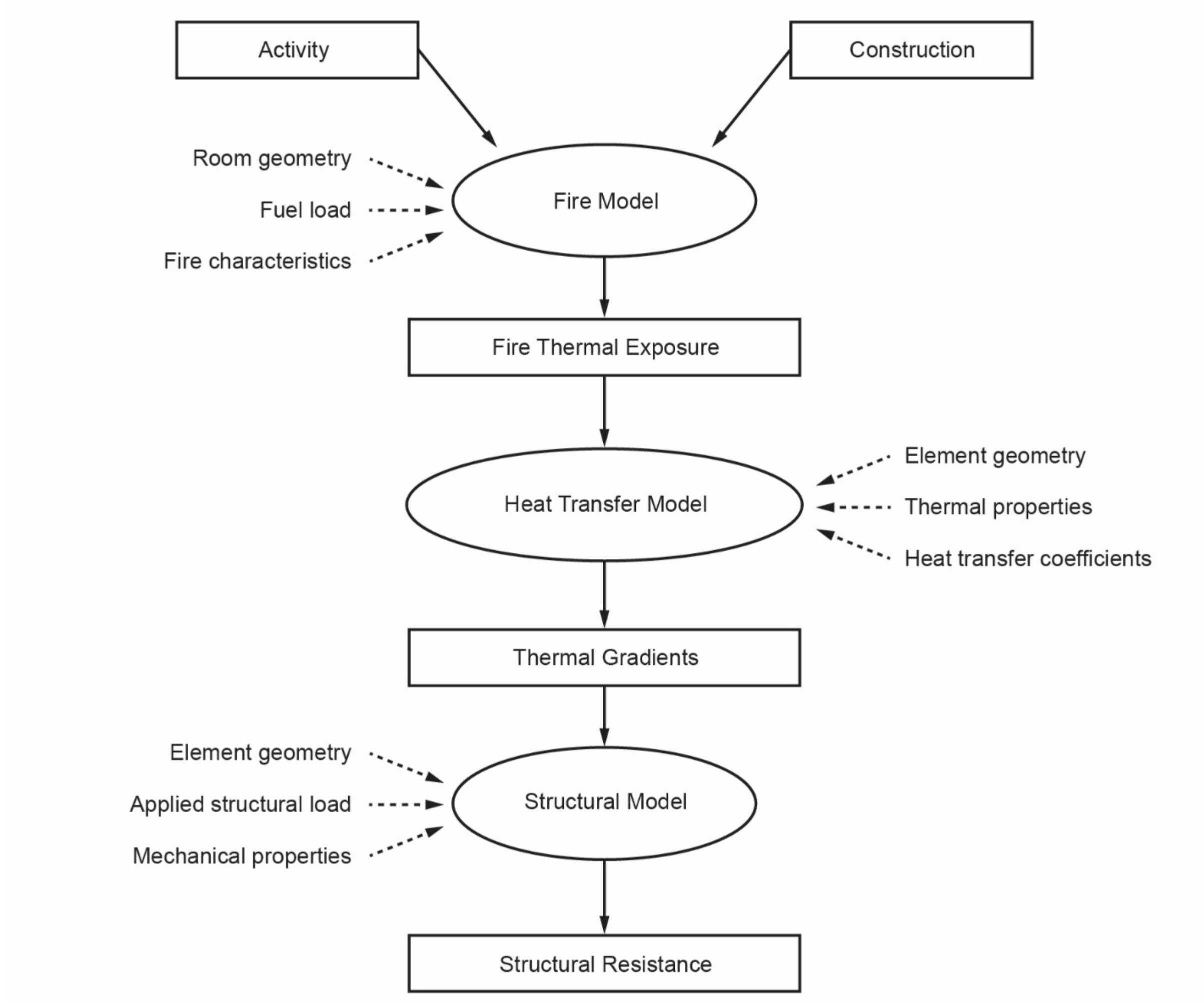


Figure 18. Flow chart for advanced calculations for structural fire-resistance of elements.

Heat transfer occurs from regions of high temperature to regions of cooler temperature within solids (e.g., from the room of fire origin to adjacent compartments, through a wall or floor assembly). Heat transfer in solid materials is called conduction and is a well-known mechanism that satisfies Fourier's law of conduction, as shown in the partial differential Equation [1] for transient heat transfer:

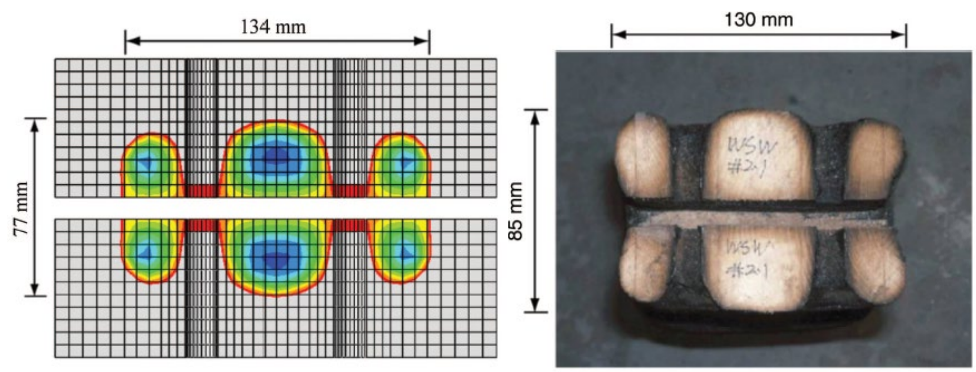
$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right)+\dot{Q}=\rho c \frac{\partial T}{\partial t}$$

where T is the temperature (K), $k_{x,y,z}$ are thermal conductivities in x, y, z directions (W/m·K), $\dot{Q}$ is the heat internally generated by the rate of heat absorption (heat of reaction) per unit volume due to chemical reaction (i.e., pyrolysis of wood) and the rate of heat absorption per unit volume due to evaporation of water (W/m³), ρ is the density (kg/m³), c is the specific heat (J/kg·K), and t is the time (sec).

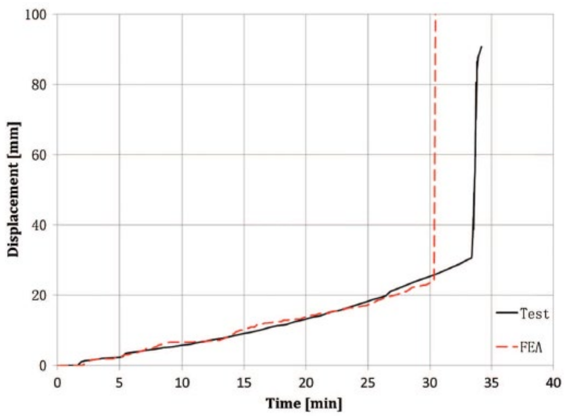
Heat transfer through a material that exhibits charring behaviour is slightly more complicated than through other materials such as steel and concrete (assuming the concrete is not spalling). The rate of heat absorption per unit volume due to a chemical reaction consists of two parts: (1) the pyrolysis of the wood ($\dot{Q}'''_{pw}$) expressed by an Arrhenius function, and (2) the rate of heat absorption per unit volume due to evaporation of water ($\dot{Q}'''_{w}$). More information on the rate of heat transfer, pyrolysis of wood, and heat of evaporation of water is provided in a number of publications (Craft, 2009; Lu, 2012; SFPE, 2016).

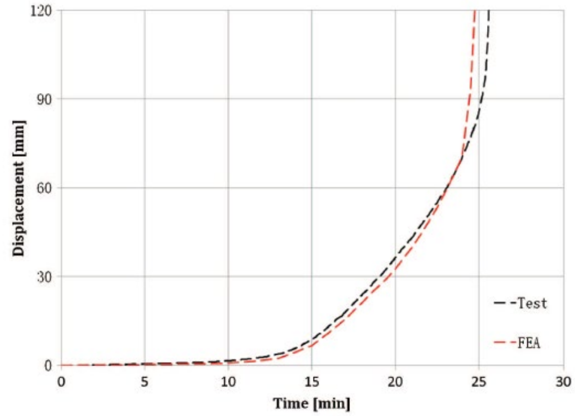
Wood charring is a complex process, and defining thermal properties for every stage of pyrolysis can be onerous. Therefore, commercially available, finite-element software packages are normally used for solving the differential equations. Heat transfer and structural capacity can also be modelled. However, the use of such software packages can be challenging for designers because they require expertise in how to use them (and understand the results), considerable effort in entering required data, and long computational time. Instead, there is broad acceptance of simplified fire-resistance calculation models that reduce the model development and computational time so that different design options can easily be assessed.

To evaluate the structural fire behavior of wood components and connections exposed to a standard fire (ASTM E119 [ASTM, 2020] and CAN/ULC-S101 [ULC, 2014a]), a temperature-dependent plastic-damage constitutive model called WoodST was developed (Chen et al., 2020). The model has been validated against actual test data, and accurately simulates thermal and mechanical behaviour in terms of temperature field, displacement, load-carrying capacity, failure mode(s), and failure time. Figure 19 shows some of the results generated from the model.



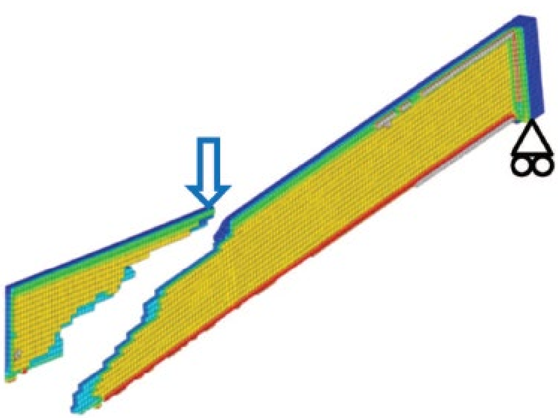
(a) Temperature profile of a bolted connection (grey indicates char)

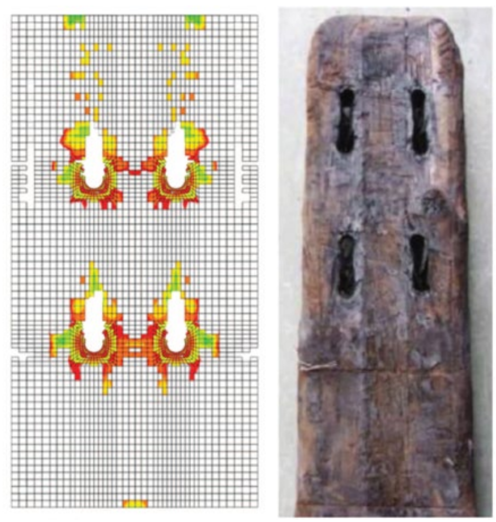




(b) Displacement curve of an LVL beam

(c) Displacement curve of a bolted connection





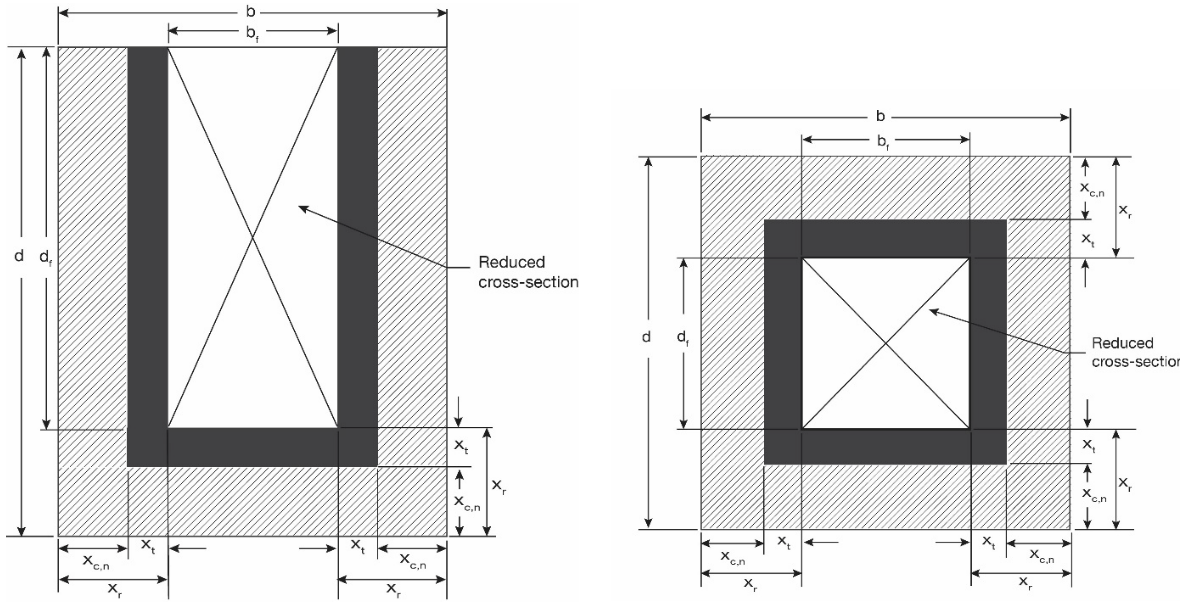
(d) Failure mode of an LVL beam

(e) Failure mode of a bolted connection

Figure 19. Numerical modelling using WoodST.

6.6.4 Fire-Resistance of Timber Structure – Structural Criteria

The inherent fire-resistance of mass timber may, in many cases, be comparable to that of other building materials; e.g., concrete, masonry, and steel. Calculating the fire-resistance of timber structures can be relatively simple due to the constant rate of charring during fire exposure. Figure 20 shows a cross-section of a timber component exposed to fire, as presented in the *Wood Design Manual* (CWC, 2020). For any given fire exposure duration (t), the reduced cross-section can easily be calculated based on the charring rate (β), by subtracting the char layer ($x_c = \beta \cdot t$) and zero-strength layer (x_t) from the initial dimensions (b and d). Charred wood is assumed to provide no strength and no rigidity; therefore, the remaining (reduced) cross-section must be capable of carrying the applied design load in the fire design to fulfil the structural resistance criterion. CSA O86 (CSA, 2019) details the methods for calculating the structural resistance of residual cross-sections.



(a) 3-sided exposure **(b) 4-sided exposure**

Figure 20. Charred timber cross-section exposed to fire from three sides (a) and four sides (b), as presented in CWC (2017).

6.6.4.1 Solid Sawn Timber and Glued-Laminated Timber

The NBC's Acceptable Solutions enable the fire-resistance of solid sawn timber to be determined on the basis of full-scale fire-resistance tests that conform to CAN/ULC-S101 (ULC, 2014a) or are assigned on the basis of Appendix D of the NBC. Provisions for assigning a fire-resistance rating to massive (solid) wood walls, floors, and roofs are provided in Section D-2.4. Other approaches are permitted under the Alternative Solution process of the NBC. The fire-resistance of glued-laminated timber beams and columns can be determined from equations in Section D-2.11. of Appendix D in the NBC. Section D-2.11., originally introduced in 1977, provides design equations for beams and columns based on their stress ratio and column slenderness. The stress ratio should be determined from factored load effects in normal conditions, as provided, for example, in load case no. 2 of Table 4.1.3.2.-A in Division B of the NBC. The factored resistance is determined from relevant sections of CSA O86 (CSA, 2019).

Annex B of CSA O86 (CSA, 2019) will be recognized as an Acceptable Solution in the NBC 2020 Section D-2.11 of Appendix D for calculating fire-resistance of solid-sawn timber and glue-laminated timber. It also applies to structural composite lumber and cross-laminated timber, as discussed below.

6.6.4.2 Structural Composite Lumber

Structural composite lumber (SCL) are proprietary engineered wood products that are manufactured and tested in accordance with ASTM D5456: Standard Specification for Evaluation of Structural Composite Lumber Products (ASTM, 2019) and are evaluated for conformance by the Canadian Construction Materials Centre (CCMC). Parallel strand lumber (PSL), laminated veneer lumber (LVL), and laminated strand lumber (LSL) are the most commercially available SCL products in North America.

CSA O86 (CSA, 2019) provides a char rate for SCL (Table 4). It may be used for SCL generally, unless the manufacturers have specific data for some other applicable charring rate. Tests conducted by O'Neil et al. (2001) showed that SCL elements that are built up using mechanical fasteners (nailed, screwed, and bolted) do not exhibit the same fire behaviour as that of a single SCL element of similar initial dimensions. Glued built-up SCL members may also not behave the same as a solid single SCL element exposed to fire, unless proven otherwise.

Guidance on some SCL products is provided in the CCMC's product evaluation reports for verifying whether the equations for glued-laminated timber in the current Section D-2.11. of the NBC are applicable to these proprietary products.

6.6.4.3 Cross-Laminated Timber

The fire-resistance of cross-laminated timber (CLT) elements may be determined from Annex B of CSA O86 (CSA, 2019) . The wood and adhesive used in manufacturing CLT need to conform to the 2018 edition of ANSI/APA PRG 320. Full-scale fire-resistance tests on CLT assemblies demonstrated that fire-resistance of nearly 3 hr can be achieved with unprotected CLT floor elements tested under full loading conditions (Dagenais et al., 2019a). Fire-resistance ratings greater than 3 hr can easily be achieved under actual specified loading conditions, given that they are typically less than those of the test series.

Similar to the equations in Section D-2.11. of the NBC, the fire-resistance calculation method for CLT is influenced largely by the induced stress ratio. The structural capacity of the residual (reduced) cross-section of a CLT assembly exposed to fire must be determined from the classical laminated wood composites theory, whereas the cross plies (i.e., minor strength axis) are not taken into account in the calculation of the design-resistive moment for floors or the resisting wall compression capacity (i.e., $E_{90} = G_0 = G_{90} = 0$). Also, the effective one-dimensional charring rate of CLT (β_0) is dependent on fire exposure duration and whether the char front passes the first glue line (Dagenais, 2016). If the char layer is not expected to pass the first bond line, a charring rate of 0.65 mm/min may be used. Otherwise, a charring rate of 0.80 mm/min should be used. Figure 21 illustrates the two scenarios. Further information is provided in Chapter 8 of the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019), in Annex B of CSA O86 (CSA, 2019), and in the *Wood Design Manual* (CWC, 2020).

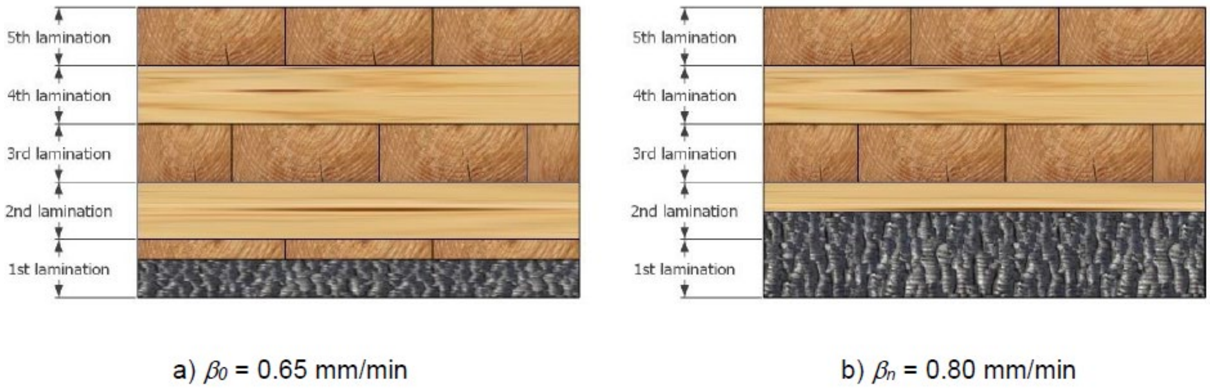


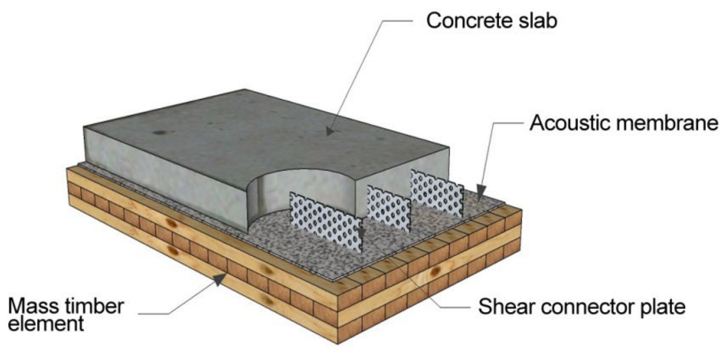
Figure 21. Charring rate for CLT.

Lastly, as opposed to a beam or column, CLT assemblies are used not only as load-bearing but typically also as fire separating elements. Therefore, integrity and insulation criteria, as set forth in CAN/ULC-S101 (ULC, 2014a), need to be evaluated in addition to the structural fire-resistance described herein. Sections 6.6.5 and 6.6.6 of this chapter address the integrity and insulation criteria of mass timber used as separating elements.

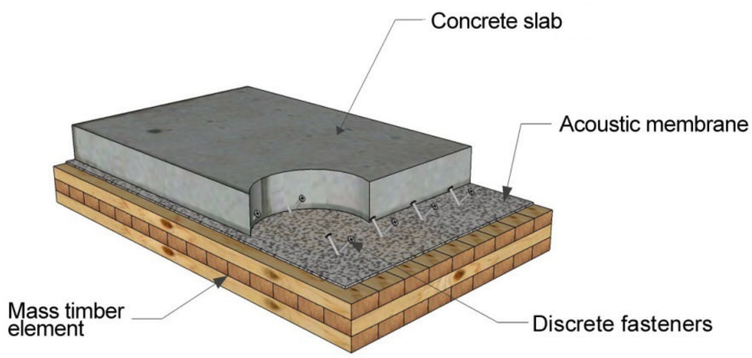
6.6.4.4 Timber–Concrete Composite Structure

Composite structures made from timber–concrete are gaining popularity, especially for long-span floor systems, because they provide enhanced serviceability and acoustic performance. Traditionally, the concrete would be stressed mainly in compression, while the timber would be subjected to tension. The composite structure can be either a concrete slab connected to a massive timber slab (an open-faced "sandwich" assembly) or a concrete slab connected to timber beams (e.g., a T-shaped cross-section). Typically, the composite action between the materials is provided by shear connector plates or discrete fasteners, such as bolts and screws (Figure 22).

Full-scale experiments on such composite assemblies (Fontana & Frangi, 1999; O'Neil et al., 2001; Osborne, 2015; and Ranger et al., 2016) have shown that their structural fire-resistance can easily be calculated using the reduced cross-section of the timber slabs or beams, as shown in Figure 23, provided that the concrete slab is fire-resistance rated accordingly for the entire duration required by the NBC. Because the benefits of a composite timber–concrete structure are achieved by the shear connection between the materials, it is also fundamental that heat transfer through the assembly be sufficiently limited so as not to affect the shear connectors (including adhesive, if used). Following similar structural design principles as those used under normal conditions, calculations of new sectional properties (due to an upward shift of the neutral axis) and applied stress are required. Further information on the design of timber–concrete composite floors is provided in Cuerrier-Auclair (2020).



(a) Shear connector plates



(b) Discrete fasteners at a 45° angle

Figure 22. Examples of timber–concrete composite systems.

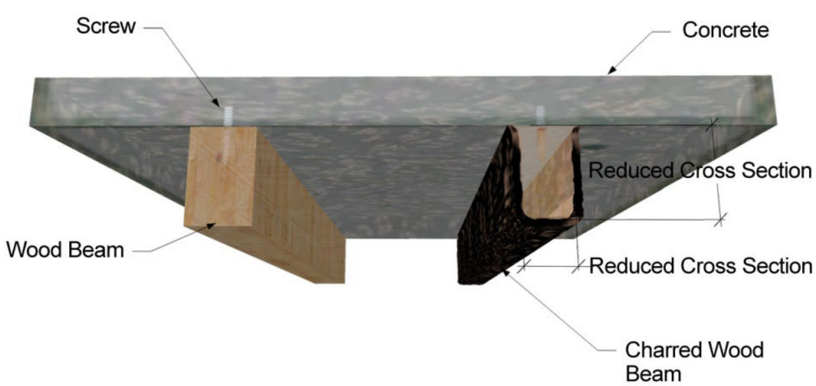


Figure 23. Reduced cross-section of a timber–concrete composite structure.

6.6.4.5 Fasteners and Connections

Connections in mass timber construction play an essential role in providing strength, stiffness, stability, ductility, and structural fire-resistance. Moreover, connections that use metallic fasteners, such as bolts, dowels, and steel plates or brackets, are widely used to assemble mass timber components or CLT panels, and to provide an adequate load path for gravity and/or lateral loads. Connections require careful design so as to limit the probability that they will be the weak link in the event of a fire.

The performance of mass timber connections that are exposed to fire can be quite complex due to the influence of numerous parameters such as the type of fasteners used, the geometry of the connection, different failure modes, and different thermal conductivity properties of steel, wood, and char layer components. Due to the high thermal conductivity of steel, metallic fasteners and plates that are directly or indirectly exposed to fire may heat up and not only lose strength but also conduct heat into the wood members. The wood components may then experience charring on the exposed surface and around the fastener. Large-diameter fasteners (e.g., bolts) and metal plates (e.g., seated hangers) are more likely to conduct heat within a timber element than are small-diameter fasteners (e.g., self-tapping screws), which are less conductive. Because structural connections form an integral part of the structural system, and recent research has revealed the importance of their role in assembled frameworks during a fire, the use of good fire protection engineering practices is important to ensure connections are designed for, or protected from, exposure to fire. Typically, a connection in which the steel is located within the reduced cross-section of the wood element is considered to be properly protected from thermomechanical degradation. Protecting steel connections within the reduced cross-sections accomplishes two goals: (1) it prevents the steel from reaching a temperature of 550^{o}C, considered to be the temperature at which steel loses half its strength, and (2) it prevents the steel from heating up and causing accelerated charring around it, which could lead to loosening and failure of the connection. Proprietary test systems are available, and designers must rely on information provided by the manufacturers regarding the use of such systems (OMNRF/OMMA, 2017).

Caution must be used with respect to intumescent and spray-applied coatings. Testing has indicated that intumescent coatings may not always perform as well as expected when used to protect steel components in mass timber connections (Peng, 2010). Further research is required to assess the appropriate fire-resistance durability of intumescent coatings used on exposed metallic fasteners.

Also, good fire performance of unprotected steel or cast-iron connections in historical heavy timber buildings may not be applicable to modern connections because the historical connections were more massive than modern connections, and generally consisted of column caps that provided load distribution rather than connections that relied on tensile and/or shear strength. Figure 24 shows a connection in the 100-year-old, 9-storey Leckie building in Vancouver. It is an effective design of a connection which, although unprotected, would most likely not be a weak structural link in the event of a fire.

Figure 24. Connection in historical Leckie Building, Vancouver, B.C.

Some connections are not vulnerable to the damaging effects of fire. For example, wall-to-floor connections in platform-framed CLT construction that are used to resist wind or seismic load would most likely not be significantly affected by fire because the steel components would be protected by wood. However, some special considerations may be needed for connections that are used to resist gravity loads in order to increase their fire-resistance to exposure from underneath. Examples of such connections in mass timber construction are provided in Dagenais et al. (2019a).

To improve aesthetics, designers often prefer to conceal connection systems (Figure 25 and Figure 26). Hidden metal plates may be used, but machining is required to produce grooves in the timber elements to conceal the metal plates. When connections are used in chemically treated wood (fire-retardant or preservative), recommendations regarding the types of metal fasteners and fastener coatings need to be obtained from the chemical treatment manufacturer because some treatments may accelerate corrosion of certain metals.

(a) Fire-resistance test conducted on concealed plate (courtesy of L. Peng, 2010)

(b) Connection covered with wood panelling

Figure 25. Protected connections for enhanced fire performance.

(a) Internal steel plate

(b) Internal plate and concealed fasteners

Figure 26. Concealed connections for enhanced fire performance.

It is advisable to review the recommendations provided in Section 5.2 of this guide regarding proper detailing of connections in timber construction.

6.6.4.6 Structural Adhesive

Various structural engineered wood products are manufactured with adhesives. When exposed to fire, the adhesive needs to perform in such a way that the glued product behaves similarly to a solid wood element. Moreover, an adhesive used in a glued structural product should maintain the bond between wood members when exposed to high temperature in order to prevent failure at the bond line and to ensure that the char layer continues to provide thermal protection to the remaining unheated wood. Traditionally, thermosetting adhesives, such as phenolic-based adhesives, have performed well in fire conditions. Phenolic-based adhesives need to be evaluated in accordance with

CSA O112.6: Phenol and Phenol-Resorcinol Resin Adhesives for Wood (High-Temperature Curing) (CSA, 2006a) or CSA O112.7: Resorcinol and Phenol-Resorcinol Resin Adhesives for Wood (Room and Intermediate Temperature Curing) (CSA, 2006b).

Relatively new adhesives, in particular polyurethane and isocyanate-based adhesives, which can be distinguished by their clear or white colour, are now widely used. These new adhesives need to be evaluated in accordance with CSA O112.9 Evaluation of Adhesives for Structural Wood Products (Exterior Exposure) (CSA, 2010) or CSA O112.10: Evaluation of Adhesives for Structural Wood Products (Limited Moisture Exposure) (CSA, 2008), depending on the type of adhesive and its intended use (wet- and/or dry-service conditions). These standards provide an elevated temperature creep test—the condition B_2 creep test—which is intended to simulate temperatures that framing members in a fire-protected assembly can be exposed to during fire exposure. The B_2 test is used to provide information to determine whether fire-resistance ratings obtained from assemblies framed with solid wood can be maintained for assemblies framed with glued wood members (e.g., finger-joined lumber). However, the results of the tests in the standards are not intended to be used as the sole basis for replacing full-scale fire-resistance tests.

Research conducted on the reduction (and ultimately, elimination) of heat delamination characteristics of CLT elements that are exposed to fire led to improved performance requirements in the 2018 edition of ANSI/APA PRG 320 (Dagenais, 2017; Dagenais & Grandmont, 2017a, 2017b). ANSI/APA PRG 320-2018 now requires a small-scale flame test to be conducted on CLT specimens made of 20-mm thick laminations. The test is successful if the total delamination length is 3 mm or less, when determined from digital imagery analysis. Moreover, Annex B of ANSI/APA PRG 320 states that in a 4-hr room fire test, adhesives delamination of the CLT test specimen is not permitted because it could result in fire regrowth and secondary flashover during the cooling phase. These requirements have significantly raised the level of performance of CLT elements. Recent standard fire-resistance tests showed that a constant one-dimensional charring rate could be used throughout a CLT element (versus an increased rate of 0.80 mm/min) and that achieving burnout of fuel content is now feasible (Dagenais et al., 2019b; Su et al., 2018b). CLT elements not manufactured to ANSI/APA PRG 320-2018 may perform differently, namely with respect to heat delamination during fire; therefore, design provisions detailed herein may not be applicable.

6.6.5 Fire-Resistance of Timber Structures – Integrity Criteria

As described in Section 6.6.1, integrity related to flame penetration or temperature rise is one of the two nonstructural fire performance characteristics that are relevant to the fire-separating function of building assemblies. The time at which an assembly can no longer prevent the passage of flame or gases that are hot enough to ignite a cotton pad defines the integrity fire-resistance. This requirement is essential in limiting the risk of fire spread to other fire compartments beyond the fire compartment of fire origin.

The joint details between components within a timber assembly can affect the integrity performance of the assembly. The sides of individual components (e.g., planks, decking, CLT) are shielded from full fire exposure by adjacent panels collectively acting as a joint. Partial exposure may occur as panels shrink and joints between panels open. Traditionally, floor integrity performance was deemed to be mitigated in heavy timber construction by requiring the use of tongue-and-groove flooring not less than 19 mm thick, laid crosswise or diagonally, or tongue-and-groove phenolic-bonded plywood, strandboard, or waferboard not less than 12.5 mm thick.

Extensive fire-resistance testing of mass timber wall and floor assemblies (Osborne et al., 2012) demonstrated that meeting integrity criteria is dependent on preventing the flow of hot gases through joints and openings in panels. This can be accomplished with protection methods such as the generic solutions prescribed in Appendix D-2.11.4. Method B of the NBC. For mass timber floor and roof assemblies, protection material of OSB, plywood, concrete topping, or gypsum-concrete topping should be applied on the unexposed (upper) surface of the assemblies. For interior mass timber wall assemblies, protective material of OSB, plywood, or gypsum board should be used on at least one side of the assembly. Similarly, for exterior mass timber wall assemblies, the protective material should be provided on at least one side of the assembly, and can consist of OSB, plywood, gypsum board, gypsum sheathing, or rock or slag insulation sheathing. For CLT wall, floor, and roof assemblies, the joints do not need to be protected with any of these generic protective materials, provided the panel joints are either lapped or splined (Figure 27), as detailed in Appendix D-2.11.4. Method B of the NBC 2020. Further, it is recommended that the CLT joints be sealed using construction adhesive or caulking.

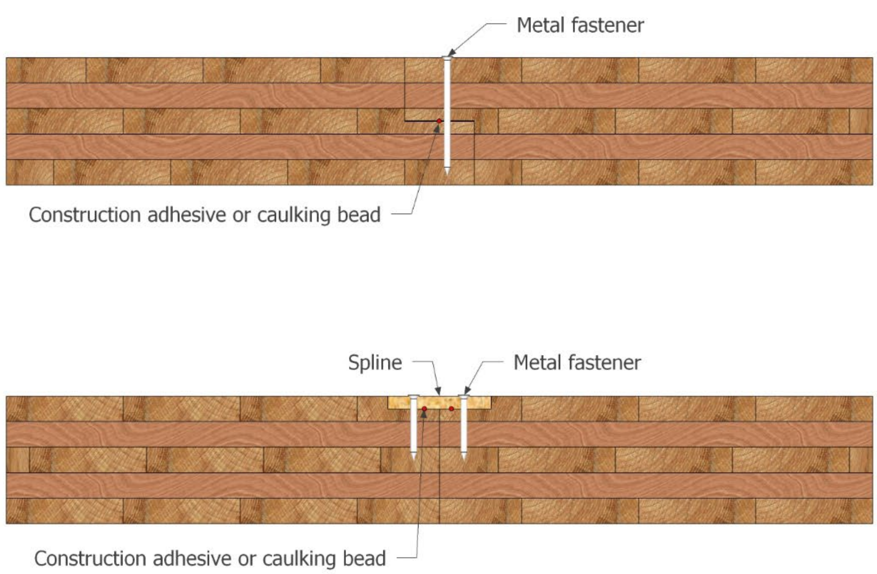


Figure 27. CLT joint details, per National Building Code 2020 provisions.

The integrity of separating building assemblies is also regulated in the NBC by the provisions that through-penetrations (i.e., service penetrations) in assemblies be fire-rated (see Section 6.9 of this chapter for more details). Additional guidance on evaluating the integrity performance of timber assemblies is also provided in the Eurocode 5: Part 1-2 (CEN, 2004) and in Chapter 8 of the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019).

6.6.6 Fire-Resistance of Timber Structure – Insulation Criteria

Insulation is the second performance expectation of the separating function of building assemblies. The time at which an assembly can no longer prevent the temperature on the unexposed surface from rising above the initial temperature by 180°C at any location, or by an average of 140°C measured at nine locations, defines the insulation fire-resistance. This requirement is essential in limiting the risk of fire spread to fire compartments beyond the fire compartment of fire origin, and in allowing safe egress within the space located on the side of the assembly away from the fire (unexposed side).

When a wood member is charring, the temperature gradient is steep in the remaining uncharred wood section (White, 2016). The temperature at the innermost zone of the char layer is assumed to be 300°C. Because wood has a low thermal conductivity, the temperature 6 mm inward from the base of the char layer is about 180°C once a quasi-steady-state charring rate has been obtained. Equation [2] is used to determine the temperature gradient within the remaining uncharred wood section:

$$T = T_i + \left(T_p - T_i\right)\left(1 - \frac{x}{a}\right)^2 \qquad [2]$$

where T is the temperature (°C), T_i is the initial temperature (°C), T_p is the char front temperature (usually considered to be 300°C), x is the distance from the char front (mm), and a is the thermal penetration depth (mm). Based on tests conducted on eight species (White, 1992), the best fit values for the thermal penetration depth were 34 mm for spruce, 33 mm for western redcedar and southern pine, and 35 mm for redwood. Using this equation, no temperature increase on the unexposed surface is calculated to occur until the residual timber thickness is reduced to 35 mm. This correlates with the temperature profile shown in Figure 16 and the requirement of CSA O86 (CSA, 2019) that the char rates in Annex B apply only to cross-sections of wood products with residual minimum dimensions greater than 70 mm when the wood member is heated from opposite sides.

6.6.7 Additional Fire-Resistance of Gypsum Board Membranes

The char layer provides effective thermal protection against heat effects. If the timber components are protected by additional protective membranes (e.g., gypsum board or wood-based sheathings), the start of charring (ignition) is delayed, and where the protective membrane remains in place after the charring is initiated, the charring rate is reduced compared to that of initially unprotected timber components.

In some areas, the use of gypsum boards may be required to address other fire-related performance attributes such as flame spread rating or encapsulation ratings. If Type X gypsum board is applied on the fire-exposed sides of mass timber assemblies, the unprotected member failure time calculated from the models presented in Section 6.6.4 of this guide can be increased by the following durations:

- 25 min when one layer of 12.7-mm (½ in.) Type X gypsum board is used
- 40 min when one layer of 15.9-mm (⅝ in.) Type X gypsum board is used

- 60 min when two layers of 12.7-mm (½ in.) Type X gypsum board are used
- 80 min when two layers of 15.9-mm (⅝ in.) Type X gypsum board are used
- 120 min when three layers of 15.9-mm (⅝ in.) Type X gypsum board are used

The additional times of 25–60 min are based on experiments completed on beams in tension (White, 2009) and on CLT assemblies protected by Type X gypsum boards (Osborne et al., 2012). The additional times of 80 and 120 min are extrapolated from testing conducted by the American Wood Council (AWC, 2017), are based on Harmathy's (1965) *Ten Rules of Fire Endurance Rating*, and are believed to be conservative.

These additional times are based on the following attachment methods. Gypsum board protective membranes should be attached directly to the mass timber elements using Type S drywall screws that penetrate at least 25 mm into mass timber and are spaced at 305 mm on the centre, along the perimeter and throughout. Screws must be kept at least 38 mm from the edges of the gypsum boards. When a single thermal protective membrane is used, the gypsum board joints should be covered with tape and coated with joint compound. End joints should be staggered from end joints of adjacent gypsum boards. When multiple layers of thermal protective membranes are used, the face layer joints should be covered with tape and coated with joint compound. End joints of the face layer must be staggered from end joints of adjacent gypsum boards and end joints of the base (first) layer. In all cases, the screw heads of the exposed layer should be covered with joint compound.

The five additional times above are simple additive components that provide conservative values. However, advanced calculations using finite element modelling, for example, may help expand these thermal protection times of gypsum boards. Heat transfer models can usually be adapted to various material thermal properties (specific heat, density, and thermal conductivity) at elevated temperatures, provided that the thermal properties are available and validated from tests or literature. It can also be demonstrated from such models that encapsulation by multiple Type X gypsum boards can maintain the temperature at the gypsum board–timber interface below 300°C. This type of encapsulation would make it possible, as one of many other Alternative Solutions, to be in line with the NBC objectives, functional statements, and related levels of performance by limiting structural combustible materials from being involved in a fire and by limiting their contribution to fire growth beyond the required time period. Membrane protection using materials other than gypsum board is feasible; however, no test data are readily available at this time.

6.6.8 Fire-Resistance Using CSA O86 ANNEX B

Annex B of CSA O86 (CSA, 2019) provides a calculation method for determining the fire-resistance of mass timber elements. The wood products currently addressed are solid-sawn timber and plank decking, glued-laminated timber, structural composite lumber, and cross-laminated timber, with char rates as listed in Table 4. As noted in Reference B.1.3. of CSA O86 (CSA, 2019), the methodology can be used to predict the structural fire-resistance that would be obtained if the mass timber element were exposed to the standard fire test, CAN/ULC-S101 (ULC, 2014a).

Annex B of CSA O86 (CSA, 2019) is intended to replicate the testing of fire-resistance-rated assemblies under load. The unfactored or actual specified gravity loads (1.0 × dead load + 1.0 × live load) are required to be used in calculating the fire-resistance of the mass timber elements. The structural fire-resistance is confirmed when the reduced structural resistance of the element expected to remain after the required duration of fire exposure is greater than the specified gravity loads. The residual cross-section for a specified duration can be calculated by subtracting the char depth and a zero-strength layer calculated based on the formulae in Annex B and as discussed in Section 6.6.3 of this chapter.

Because Annex B can be used only to calculate the structural component of the fire-resistance, other methods are required to demonstrate that a mass timber assembly meets the insulation and integrity criteria where the assembly is intended as a fire separation such as a wall or floor assembly. Mass timber panels generally provide inherent fire separation functions due to the continuity of the elements, provided gaps and joints are sealed at the interface between panels and within the panels themselves. As discussed in Section 6.6.5 of this chapter, there are various generic methods for maintaining the integrity component of the calculated fire-resistance rating and, by extension, the insulation criteria.

6.7 FLAME SPREAD RATING OF TIMBER

The NBC limits the allowable flame spread rating (FSR) and smoke development class of interior finishes based on the location, building occupancy, and availability of an automatic fire suppression system. The prescriptive provisions for interior finishes in noncombustible construction and EMTC are set forth in several sections of Division B of the NBC, including Subsection 3.1.13. (for all buildings), Article 3.1.13.7. (for high buildings), Articles 3.1.5.12. and 3.1.13.8. (for noncombustible construction), and Article 3.1.6.12. (for EMTC). These provisions are intended to limit the spread of fire through a building in a manner that allows safe egress of the occupants and limits damage to the building in which the fire originated.

In Canada, the FSR of a material, assembly, or structural member is determined on the basis of no less than three standard fire tests conducted in conformance with CAN/ULC-S102: Standard Method of Test for Surface Burning Characteristics of Building Materials and Assemblies (ULC, 2010). Some construction materials that can be assigned in generic terms, such as gypsum board and most softwood lumber species, have been assigned FSRs based on historical data, which are specified in Section D-3 of the NBC. Results of FSR testing on proprietary materials are usually available from product manufacturers or accredited fire testing laboratories.

6.7.1 What is Flame Spread?

Surface flame spread is a process of a flame moving in the surroundings of a pyrolyzing region on the surface of a solid (or liquid) that acts as a fuel source (Hasemi, 2016). In the case of mass timber, the spread of flame occurs when flames from the burning timber heat the surface ahead of the flame by direct or indirect flame impingement. Flame spread may also occur in different configurations, which are governed by the orientation of the fuel and the direction of the main flow of gases relative to that of flame spread (White & Dietenberger, 2010).

The growth of a fire depends on the time it takes a flame to spread from the point of origin (i.e., ignition) to an increasingly large area of combustible material (Drysdale, 1998). However, the material's thermal conductivity, heat capacity, thickness, and blackbody surface reflectivity influence the material's thermal response; an increase in the values of these properties corresponds to a decrease in the rate of flame spread (White & Dietenberger, 2010).

The primary purpose of the CAN/ULC-S102 (ULC, 2010) test is to determine the comparative burning characteristics of a material or an assembly by evaluating the flame spread over its surface when exposed to a standardized test flame. The test method attempts to establish a basis on which surface burning characteristics of different materials or assemblies can be compared, without specific consideration of all the end-use parameters that might affect those characteristics. It also does not provide insight on a product's or assembly's fire hazard or potential contribution to a fire (i.e., heat release rate, yields of fire effluents, etc.). Flame spread rating and smoke development classification are recorded as dimensionless numbers in this test, with the understanding that there is not necessarily a relationship between the two measurements. A lower FSR is indicative of a lower propensity to flame spread, while a higher FSR is indicative of a greater (faster) potential to flame spread.

6.7.2 Fire Safety Strategies in a Pre-flashover Compartment

In general, the NBC requires that interior wall and ceiling finishes have an FSR no greater than 150, which can easily be met by most wood products. In public corridors of unsprinklered buildings, the maximum FSR is set to 25 for ceilings and 75 for walls, but the NBC allows for materials with an FSR up to 150 in the lower half of corridor walls, provided the top half has an FSR of no more than 25. In sprinklered buildings, the FSR for wall and ceiling finishes in public corridors is allowed to be 150.

Moreover, when a building is classified as a high building (as per Subsection 3.2.6. of Division B in the NBC 2020), combustible interior wall and ceiling finishes are generally required to have an FSR of no more than 150 and 25, respectively, and should not be more than 25 mm in thickness. The NBC also allows ceilings to have materials with an FSR of 150 or less, provided that they do not cover more than 10% of the ceiling area within a fire compartment and are not more than 25 mm thick. Exposed mass timber elements are also permitted in an EMTC building; the amount of exposed surfaces permitted depends on the elements being exposed.

Traditionally, combustible interior wall and ceiling finishes have been evaluated for flame spread using lumber specimens of 19 mm in thickness or less. In order to evaluate the surface burning characteristics of mass timber assemblies, such as CLT, NLT, SCL and glued-laminated timber decking, flame spread tests on mass timber assemblies have been conducted in accordance with CAN/ULC-S102 (ULC, 2010). CLT (99 and 105 mm thick), NLT (140 mm, flat surfaced), SCL specimens (of 89 mm and greater thicknesses), and glue-laminated timber decking (64 mm thick) exhibited very low flame spread ratings (35–75) compared to similar thinner products, which generally had a flame spread rating in the 100 range (Table 5).

Table 5. Flame spread rating and smoke development classifications of wood and wood-based products

Wood and wood-based products		Flame spread rating	Smoke development classification
Lumber, not less than 19 mm in thickness[a]			
Cedar	Western red Pacific Coast yellow	60 50	100 90
Fir	Amabilis (Pacific silver)	69	58
Hemlock	Eastern Western	40 75	110 25
Oak	Red or white	100	100
Pine	Eastern white Lodgepole Ponderosa (yellow) Red Western white	85 60 105–230 180 75	100 115 n.d. 70 n.d.
Poplar	–	180	55
Spruce	Eastern red Sitka (Coast Sitka) White (Western white)	65 74 50	175 74 70
Other solid wood products[a]			
Shakes	Western redcedar	69	n.d.
Shingles	Western redcedar	49	n.d.
Maple	Flooring	104	n.d.
Structural composite lumber[b]			
PSL	PSL (min. 89 mm, on flat)	35	25
LVL	LVL (min. 140 mm, on edge)	35	30
LSL	LSL (min. 89 mm, on flat)	75	85
Cross-laminated timber			
CLT[b,c]	3-ply SPF E1 stress grade (min. 105 mm)	35	40
	3-ply SPF V2 stress grade (min. 99 mm)	40	30
Glue-laminated timber decking			
Glulam[d]	SPF glulam decking (64 mm)	40	55
Nail-laminated timber			
NLT[e]	SPF flat-surfaced (140 mm)	50	55

Wood and wood-based products		Flame spread rating	Smoke development classification
Structural sheathing			
Plywood[f]	Douglas-fir, 11 mm thickness Poplar plywood, 11 mm thickness Spruce face veneer plywood, 11 mm thickness	150	300

n.d. = not determined due to insufficient test information

[a] *Fact Sheet – Surface Flammability and Flame-spread Ratings* (CWC, 2020)

[b] Dagenais (2013a)

[c] Dagenais (2013b)

[d] Dagenais (2014)

[e] Ranger & Dagenais (2019)

[f] Table D-3.1.1.A, National Building Code of Canada (NRC, 2020a)

6.7.3 Effect of Exposed Timber on Traditional Fire Safety Strategies

Previous studies presented in White et al. (1999) suggest that there may be a relationship between the time to reach flashover conditions in an ISO 9705: Fire Tests – Full-Scale Room Test for Surface Products (ISO, 2016) room/corner fire test and the ASTM E84: Standard Test Method for Surface Burning Characteristics of Building Materials (ASTM, 2020) flame spread indexes of materials (similar to FSR evaluated by CAN/ULC-S102 [ULC, 2010]). Materials with a low FSR provide are associated with a longer time before flashover conditions are reached. It should be noted that while both ASTM E84 and CAN/ULC-S102 methods generate flame spread and smoke developed data, their sample mounting procedures and test sampling are different. Therefore, the results are usually not exactly the same, but similar flame spread values, within a 10% range, are generally obtained (Mehaffey, 2006).

The use of materials that exhibit lower flame spread ratings than typical combustible interior finish materials could result in a reduced risk of ignition and potentially increase the time to flashover conditions, depending on the configuration and ventilation of the room of fire origin. This reduced risk may make it possible to be in line with NBC objectives and functional statements when developing an Alternative Solution, although further work on this approach is likely required.

If the wood becomes ignited, exposed mass timber assemblies can have a significant effect on fire growth. Studies have shown an increase in fire growth rate in unprotected (fully exposed) CLT room fires, which led to flashover conditions being reached sooner than when CLT was initially protected by gypsum board (McGregor, 2013). In rooms with initially protected CLT (using directly applied gypsum board), the fires self-extinguished when all combustibles had been consumed and the CLT remained unaffected by the fire, with no noticeable contribution to fire growth, duration, or intensity. This research highlights the fire hazards associated with construction that uses exposed mass timber in situations where no active fire protection is provided and where a fire is burns for extended periods without response. However, as required for buildings taller than 6 storeys and tall buildings in the NBC, automatic sprinklers would provide active protection against fire growth because they are expected to be activated before significant fire growth and fire involvement of exposed CLT panels.

The NBC's Acceptable Solutions permit significant additional combustible content, including extensive combustible wall finishes, where sprinklers are present, and provide the proponent with a baseline for judging where reliance on sprinklers to limit fire growth and flashover is appropriate.

Hakkarainen (2002) conducted similar room fire studies to evaluate temperature development and charring behaviour in compartments built from light and heavy timber construction. The results showed that the temperature rise and peak temperature in the compartment constructed with unprotected timber were lower than those in the protected timber rooms (which used directly applied gypsum board). Based on visual observations and energy balance considerations, it was concluded that a larger part of the pyrolysis gases burned outside the fire compartment in the case of the unprotected timber rooms compared to the protected rooms.

Even with a combustible material such as timber, a change in the boundary conditions of a compartment (i.e., thermal inertia and flame spread rating of exposed surfaces) influences fire development and dynamics. Such change may also reduce the safe evacuation time if flashover conditions occur faster; therefore, installation of additional fire safety measures may be required.

6.8 FIRE COMPARTMENTS AND FIRE SEPARATIONS

6.8.1 What is a Fire Compartment?

The NBC generally requires buildings to be subdivided into compartments that are fire-resistance rated (i.e., fire compartments) to limit the risk of fire spread beyond the compartment of origin. To effectively provide fire-resistance-rated boundaries to a compartment, the elements (walls and ceilings) constructed as boundaries need to be built as fire separations. The Acceptable Solutions in Division B permit the use of wood-framing and solid wood walls in some fire separations within floor areas in buildings that are otherwise prescribed to be of noncombustible construction and EMTC.

Internal fire compartmentation using fire separations can also limit the area of a burning building façade when determining the percentage of unprotected openings and type of construction of exterior walls under the relevant spatial separation provisions of the NBC.

6.8.2 Integrity of Fire Separations

Walls, partitions, and floors that are required to be designed as fire separations need to be constructed to create a continuous barrier and, often, to have a prescribed fire-resistance rating. However, service penetrations and gaps in fire separations are inevitable. To maintain the continuity and integrity of fire separations that contain service penetrations and gaps, these details must be sealed to maintain the separations' integrity and fire-resistance. Also, except for framing systems protected by gypsum board, firestops must be provided at joints where fire separations abut or intersect a floor, wall, or roof, and at joints in a horizontal plane between a floor and an exterior wall. Subsections 3.1.8. and 3.1.9. of Division B of the NBC list the specific provisions for enclosures and penetrations in fire-resistance-rated assemblies and fire separations.

6.9 FIRE PROTECTION OF SERVICE PENETRATIONS AND CONSTRUCTION JOINTS

6.9.1 Fire Stopping

Firestops are intended to ensure the continuity and integrity of a fire separation that encloses a fire compartment, and the integrity of a membrane that forms part of an assembly that is required to have a fire-resistance rating by maintaining the fire-resistance rating of the floor and/or wall assemblies at any penetrating items or at construction joints between different elements. Subsection 3.1.9. of Division B of the NBC prescribes when and where different types of penetrations of a fire separation or a membrane forming part of an assembly that is required to have a fire-resistance rating are to be either cast in place or sealed by a firestop that has been tested in accordance with CAN/ULC-S115: Standard Method of Fire Tests of Firestop Systems (ULC, 2011). In the NBC 2020, the provisions for F-ratings of firestops were significantly revised. Instead of being based on the "fire protection rating" of closures in fire separations, the required F-ratings for firestops are now equal to the fire-resistance rating of the fire separation that is being penetrated. An F-rating can be defined as the period where the through penetration firestop system limits the spread of fire (flaming) through the opening around a penetrating item. FT-ratings (based on temperature rise and flaming on the unexposed side of the penetration) are prescribed for firewalls and other separations between buildings, and for around outlet boxes and in joints abutting a fire separation.

6.9.2 Availability of Firestops for Mass Timber Assemblies

Firestop system designs tested in accordance with CAN/ULC S115 (ULC, 2011) for sealing penetrations of mass timber elements are currently not readily available. However, various test programs have demonstrated that a number of the firestop systems that have been approved for use with concrete and/or light-frame wood construction may be used for mass timber, provided that the firestop is not located in the potential char layer during fire exposure and that metal penetrating items are not in contact with the wood. Protecting wood from a metal penetrant is essential to prevent additional charring within the penetration due to heat transfer from the hot metal; this may be achieved by installing mineral wool between the penetrant and the wood (Harmsworth, 2016).

Dagenais et al. (2018) tested a series of assemblies with firestops. Various fire-rated joint fillers (caulking) and sealing tapes that are commercially available and approved for 2-hr fire ratings for concrete assemblies were evaluated (Figure 28). The results showed that 90 min and 120 min can be achieved even with mass timber elements, provided that the charred layer does not interfere with the firestop system.

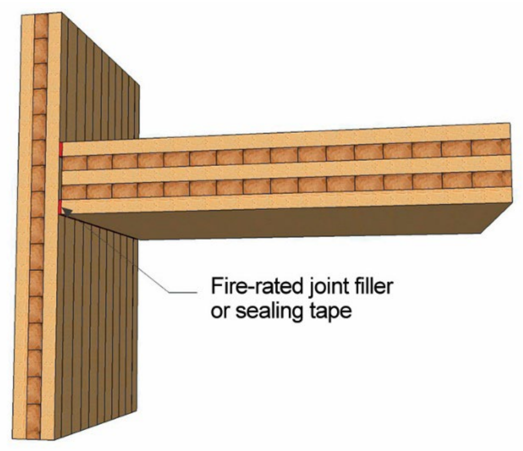


Figure 28. Example of fire stop system evaluated for CLT assemblies.

Additional information on firestops, service installations, and detailing in timber structures is provided in Chapter 8 of *Fire Safety in Timber Buildings – Technical Guideline for Europe* (SP Trätek, 2010) and in the *Literature Review: Fire Stop Requirements as Related to Massive Wood Wall and Floor Assemblies* (Dagenais, 2013c), which covers research conducted in Europe.

Special fire-stopping practices may be required for CLT construction joints because potential gaps between the boards can create channels around the firestops and allow smoke to bypass them (Figure 29). Further research is needed to adequately investigate the fire performance of firestops in mass timber construction, including potential smoke leakage. Engineering judgment from firestop manufacturers can also be requested on a project-by-project basis but should be reviewed by a Professional Engineer, and the AHJ may require the engineering reports to be sealed.

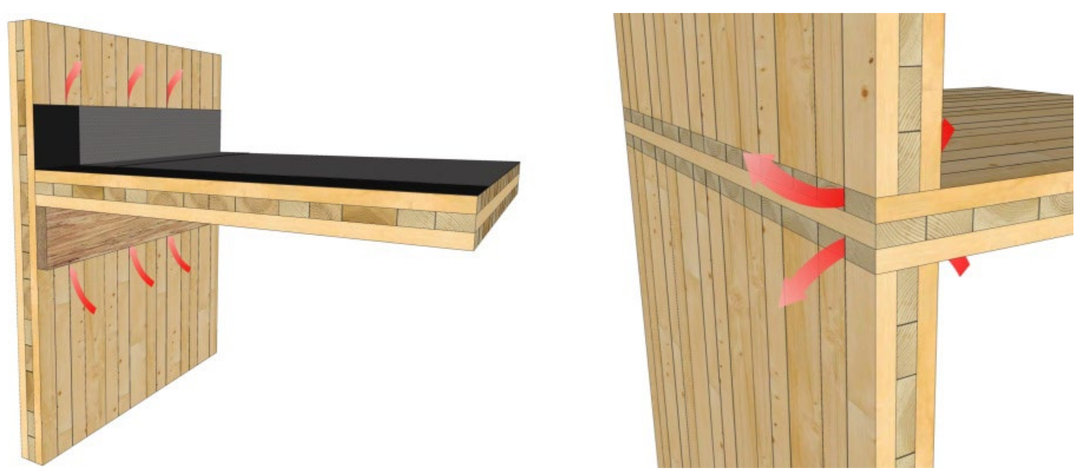


Figure 29. CLT potential smoke leakage paths (courtesy of RDH Consulting).

6.10 CONCEALED SPACES

6.10.1 What are Concealed Spaces?

Inherent in any building are concealed spaces: some are used for specific purposes, such as service spaces to facilitate the installation of building services; others are simply part of the building construction. Concealed spaces may be large, such as above a ceiling suspended a certain distance below the structural elements, or small, formed merely by the attachment of protective membranes or as part of a wall or floor assembly. In developing an Alternative Solution, it is essential to acknowledge that some void spaces will occur, and there may be a need to establish a methodology to address the fire risk, where acceptable forms of protection are not otherwise prescribed/available. Unprotected concealed spaces may allow for fire growth or may contribute to fire spread through a building by bypassing fire separations. Such fires may spread without being detected by fire alarm systems and may be difficult to extinguish.

The NBC 2020 includes provisions for addressing the protection of concealed spaces in EMTC. Additionally, all exposed timber within concealed spaces must be covered, unless it is shown that protection is not required in the Acceptable or Alternative Solution.

The method of encapsulation will often lead to some concealed spaces having exposed combustibles within. For example, when connections or uneven profiles are enclosed, small cavities will exist and should be acceptable; however, the effect of these concealed spaces should be addressed in the Alternative Solution for combustible construction. This is discussed in Section 6.4.1.3 of this chapter.

6.10.2 Performance of Combustible Concealed Spaces of Mass Timber

The traditional concern with combustible concealed spaces in wood-frame structures is not applicable to mass timber due to the inherent fire performance of mass timber elements. If an Alternative Solution is developed to include large or numerous void spaces within encapsulation methodology, it should be based on the understanding that fire spread in mass timber in a void space may have limited consequences, unlike that in wood-frame construction.

In wood-framing, fire spread through concealed spaces can lead to premature, sudden, and unexpected collapse of structures, such as floors, that are located away from the fire incident. This is particularly prevalent in some older (pre 1970) structures that do not have appropriate fire blocking. However, this is unlikely to happen with mass timber members because of their inherent fire performance, so a fire in a small void space is unlikely to cause significant damage to the building structure or metal fasteners. Ranger & Dagenais (2020) conducted a series of tests in which flame spread in concealed spaces that were permitted by NFPA 13 to have exposed combustible materials and did not require sprinkler protection was compared to that in concealed spaces with exposed mass timber. In general, the assemblies with exposed mass timber performed better than the NFPA 13 sprinkler-exempt assemblies: flame spread was slower, ignition times were longer, and temperatures along the length of the tunnel increased more slowly.

6.10.3 Building Code and NFPA 13 Provisions for Concealed Spaces

Within a noncombustible structure, void spaces are generally not expected to contain significant exposed combustible construction materials, and void spaces in EMTC are expected to be limited. Subsections 3.1.5. and 3.1.6. of Division B of the NBC list small quantities of combustible materials that are permitted to be used within noncombustible construction and EMTC, respectively. Subsection 3.1.11. of Division B describes specific provisions for fire blocking in concealed spaces, including those in buildings required to be of EMTC and noncombustible construction. Those provisions do not permit large amounts of exposed timber unless the space is within otherwise permitted wood elements.

The standard on automatic sprinklers referenced in the NBC—NFPA 13—provides guidance on the protection of concealed spaces within buildings of both noncombustible and combustible construction, and identifies areas where sprinkler protection may be omitted. These provisions are intended to facilitate an acceptable level of protection within existing conventional buildings. Sprinkler protection of void spaces may be appropriate for addressing concerns regarding exposed combustible elements in void spaces. However, an assessment would be required to determine whether the NFPA 13 provisions for the omission of sprinklers in some void spaces remain applicable, and whether additional measures to enhance sprinkler system reliability are appropriate, as discussed in Section 6.4.3 of this chapter.

6.10.4 Methods of Protecting Concealed Spaces

Complete or partial encapsulation is used to protect mass timber structures from fire. When developing an Alternative Solution, it must be acknowledged that some void spaces will occur and a strategy may be needed to address concerns about them.

It may be appropriate to rely on sprinkler protection of void spaces, especially in cases where the sprinkler system has enhanced reliability, as discussed in Section 6.4.3 of this chapter. However, this may not always be practical or necessary.

The NBC 2020 provides Acceptable Solutions for protecting void spaces in EMTC, including providing fire blocks to limit the size of the spaces and filling the spaces with noncombustible insulation. Another approach that may be employed as part of an Alternative Solution involves applying a spray or other form-fitting protection to all exposed timber. Spray-applied, fire-resistant materials that are typically used for providing fire-resistance to structural steel elements may be appropriate for this purpose if material compatibility and adhesion are acceptable. However, this approach is likely not necessary for all void spaces, and some smaller void spaces within the structure may not pose any additional fire risks.

Fire is limited by available oxygen. Therefore, if a void space is sealed and small enough (or is fireblocked to be small enough) to preclude significant air circulation within the space, it should not have a substantial effect on the EMTC component. If void spaces are sealed and the effect of fire within them is unlikely to threaten the integrity of either steel connections or mass timber elements, unprotected void spaces can be considered to be acceptable.

Alternative approaches to protecting void spaces with exposed heavy timber include coating all surfaces within the void space. Readily available products such as paint could be used to reduce the surface burning characteristics of materials (flame spread rating). However, test conditions used in the surface testing of such products to encourage flame spread may not be possible in narrow or small void spaces; additional testing aimed at narrow void spaces is needed.

Unless addressed otherwise in an Alternative Solution or as permitted by the Acceptable Solutions for EMTC in Division B of the NBC, permission for outlet boxes or combustible services to penetrate membranes should not be applied to encapsulation membranes unless the effects are specifically considered, given that air circulation could increase within void spaces and therefore aid combustion.

6.11 EXTERIOR FINISHES AND EXTERIOR FIRE EXPOSURE

6.11.1 Assumptions Underlying the Current Spatial Separation Provisions

A fire in a building can pose a threat to neighbouring buildings. Flames issuing through windows or other unprotected openings in the exterior wall can cause combustible materials on a nearby building to ignite by either direct flame impingement or through excessive thermal radiation. The potential for fire spread from building to building was studied by the National Research Council in 1958, during experiments called the "St. Lawrence Burns". Before the town of Aultsville was removed for the construction of the St. Lawrence Seaway, the National Research Council conducted a number of experiments using the abandoned wood buildings to establish the nature of flame extension through openings and the intensity of thermal radiation emitted by those flames.

When a typical combustible material, such as wood, is exposed to a radiant heat flux that is sufficient to raise the surface temperature of the material to a high level, a small pilot (spark or flame) will cause the material to ignite. Using the values of thermal radiation emitted by flames measured during the St. Lawrence Burns and some geometrical analyses, it was possible to predict appropriate distances from openings of an arbitrary size at which the radiant heat flux received at a neighbouring building would remain lower than 12.5 kW/m². Such analyses form the basis of the fire separation and exposure protection requirements in Subsection 3.2.3. of Division B of the NBC and in similar codes in the UK and United States, where radiant heat fluxes of 180 kW/m² and 360 kW/m² are assumed to be emitted from openings of normal and severe hazards, respectively (Torvi et al., 2005).

The following measures listed in Subsection 3.2.3. of the NBC refer to limiting the risk of fire spread from one building to another:

a) The size of unprotected openings in an exposing building face (i.e., the exterior wall of a fire compartment) is limited, thereby reducing the surface area and consequently, the overall intensity of the radiating flames;

b) A minimum permitted distance from the exposing building face to the property line is prescribed. This ensures there is no direct impingement, but also limits the radiant heat flux on the face of the neighbouring building, since the radiant heat flux significantly decreases as a function of the distance from the radiating surface; and

c) The combustibility and fire-resistance of the exposing building face and the combustibility of its cladding are regulated. This ensures that the size of the radiating surface does not increase during a fire due to burn through of the exterior wall or to flame spread along the surface of the cladding.

The precise nature of these measures depends on the occupancy of the exposing building (which affects the potential fire severity) and whether or not the exposing building is sprinklered (which also affects the potential fire severity). The tall wood buildings considered in this guide must be entirely protected by automatic sprinklers; therefore, fire severity can be expected to be limited. The NBC assumption is that the radiant heat fluxes of 180 kW/m² and 360 kW/m² emitted by flames issuing from openings are reduced by half when a building is protected by automatic sprinklers.

Sprinklered tall wood buildings in which the "complete encapsulation" strategy has been employed will perform as well as a sprinklered building of noncombustible construction in terms of all fire protection considerations, including those related to the spatial separation and exposure protection requirements of Section 3.2.3 of the NBC. In this case, the provision of automatic sprinklers provides another layer of redundancy to reduce fire risk.

If a "partial encapsulation" method is employed, fire intensity will likely not be significantly greater than in a noncombustible structure, but fire duration could be longer; therefore, the duration of water supply for controlling exposures should be increased accordingly. A properly designed automatic sprinkler system will mitigate this concern.

In suburban or rural areas where rapid firefighter response is not available (defined in Subsection 3.2.3. of the NBC as less than 10 min from the time the alarm is received by the fire department), consideration should be given to further increasing the reliability of the sprinkler system, including ensuring on-site water supplies have sufficient volume to maintain the sprinkler operation until firefighting forces can respond and reinforce the water supply and initiate suppression activity.

And lastly, as discussed in Section 6.11.2 of this chapter, cladding systems for tall wood buildings need to comply with the same performance standard as that for a structure of EMTC permitted by the NBC 2020: that is, noncombustible cladding, exterior wall and cladding systems that conform to Article 3.1.5.5. of Division B, or limited amounts of combustible cladding that meet the criteria described in the NBC (2020). The cladding and exterior wall system will not increase the exposure of adjacent buildings to fire, nor will it have a tendency to ignite from an adjacent fire more than that considered in the prescriptive provisions in Division B of the NBC.

6.11.2 Exterior Cladding

For exterior cladding on buildings of EMTC, the NBC 2020 permits combustible cladding and cladding systems that contain combustible components, provided they conform to the specific performance criteria in Clause 3.1.5.5.(1)(b) when tested to CAN/ULC-S134: Standard Method of Fire Test of Exterior Wall Assemblies (ULC, 2013) or the prescriptive criteria in the 2020 NBC provisions. CAN/ULC-S134 is a standard fire test with a fire plume extending from a window (Figure 30). It is considered to represent an appropriate design fire for exposure to a window fire plume and to be conservative relative to exterior fire impingement. It is essentially a test to confirm that a cladding system containing combustible components will not support unacceptable flame propagation up the face of a building any more than would likely occur after 15 min of steady-state fire exposure when using noncombustible cladding.

Figure 30. CAN/ULC-S134 full-scale test of exterior wall assembly (Su & Lougheed, 2014).

Exposed wood cladding that is not fire-retardant treated and is installed over spans greater than those permitted in the NBC 2020 provisions (NRC, 2020a), and is therefore subject to the CAN/ULC-S134 (ULC, 2013) test, will not meet the performance criteria established by the NBC. Any wood cladding treatment used to limit ignition and fire spread would also have to be permanent and not subject to degradation due to weathering, as identified in Article 3.1.5.5 of the NBC. At this time, the availability of a suitable fire-retardant treatment is limited and may be costly. Therefore, mass timber exterior walls need to be protected from exposure to fire from the exterior by noncombustible cladding. A level of encapsulation based on CAN/ULC-S146 (ULC, 2019) fire tests, as discussed earlier for interior spaces, would be acceptable but is not explicitly required by the NBC 2020 for the exterior face of exterior components in EMTC buildings. Protection of the exterior face by a single layer of 15.9-mm thick exterior gypsum board or Type X gypsum board can provide conformance with Article 3.1.5.5. of the NBC, as confirmed by NRC-IRC testing in the 1990s (Oleszkiewicz, 1990).

It is expected that various forms of noncombustible exterior cladding systems and cladding systems in combination with noncombustible exterior insulation can conform to Article 3.1.5.5. when installed over mass timber wall elements; however, this will require testing or analysis to demonstrate conformance. While full-scale testing may be expensive and time-consuming, it is possible, in some cases, to develop hand-based calculations and computer models to demonstrate conformance.

Similarly, the use of combustible components in exterior walls can be demonstrated to be acceptable, based on testing or analysis to show conformance with Clause 3.1.5.5.(1)(b) of the NBC. Examples of such systems deemed to satisfy the criteria of Clause 3.1.5.5.(1)(b) when tested in accordance with CAN/ULC-S134 (ULC, 2013) are provided in Table D-6.1.1 of Appendix D of the NBC 2020, and are reproduced in Table 6.

Table 6. Construction specifications for exterior wall assemblies deemed to satisfy the criteria of Clause 3.1.5.5.(1)(b) when tested in accordance with CAN/ULC-S134 (ULC, 2013), as presented in the National Building Code 2020

Wall number	Structural members	Absorptive material	Sheathing	Cladding	Design
EXTW-1	38 × 89 mm wood studs spaced at 400 mm o.c.[a,b]	89-mm thick rock or slag fibre in cavities formed by studs[c,d]	–	12.7-mm thick fire-retardant treated plywood siding[e]	
EXTW-2	38 × 140 mm wood studs spaced at 400 mm o.c.[a,b]	140-mm thick rock or slag fibre in cavities formed by studs[c,d]	Gypsum sheathing ≥ 12.7 mm thick	Noncombustible exterior cladding	
EXTW-3	38 × 140 mm wood studs spaced at 400 mm o.c.[a,b]	140-mm thick rock or slag fibre in cavities formed by studs[c,d]	15.9-mm fire-retardant treated plywood[f]	Noncombustible exterior cladding	
EXTW-4	38 × 140 mm wood studs spaced at 600 mm o.c. attached to CLT wall panels ≥ 38 mm thick[a,g,h]	140-mm thick glass, rock or slag fibre in cavities formed by studs[c]	Gypsum sheathing ≥ 12.7 mm thick	Noncombustible exterior cladding	

Wall number	Structural members	Absorptive material	Sheathing	Cladding	Design
EXTW-5	89 mm horizontal Z-bars spaced at 600 mm o.c. attached to CLT wall panels ≥ 105 mm thick[h]	89-mm thick rock or slag fibre in cavities formed by Z-bars[c,d]	–	Noncombustible exterior cladding attached to 19-mm vertical hat channels spaced at 600 mm o.c.	

Notes:

[a] The stated stud dimensions are maximum values. Where wood studs with a smaller depth are used, the thickness of absorptive material in the cavities formed by the studs must be reduced accordingly.

[b] Horizontal blocking between the vertical studs or horizontal stud plates must be installed at vertical intervals of at most 2324 mm, such that the maximum clear length between the horizontal blocking or stud plates is 2286 mm.

[c] The absorptive material must conform to CAN/ULC-S702: Standard for Mineral Fibre Thermal Insulation for Buildings (ULC, 2014b).

[d] The absorptive material must have a density not less than 32 kg/m³.

[e] The fire-retardant-treated plywood siding must conform to the requirements of Article 3.1.4.5. of the NBC and must have been conditioned in conformance with ASTM D2898-10: Standard Practice for Accelerated Weathering of Fire-Retardant-Treated Wood for Fire Testing (ASTM, 2017) before being tested in accordance with CAN/ULC-S102: Standard Method of Test for Surface Burning Characteristics of Building Materials and Assemblies (ULC, 2010).

[f] The fire-retardant-treated plywood must conform to the requirements of Article 3.1.4.5. of the NBC.

[g] Horizontal blocking between the vertical studs or horizontal stud plates must be installed at vertical intervals of at most 2438 mm, such that the maximum clear length between the horizontal blocking or stud plates is 2400 mm.

[h] A water-resistant barrier may be attached to the face of the CLT wall panels.

6.11.3 Wildfire

Most tall buildings are expected to be in urban or suburban environments where wildfires are not a significant hazard. Because the exterior cladding of a tall wood building would conform to the exterior cladding provisions for a building of EMTC, the risk of the building being affected by wildfire or wooded areas would be no different than that associated with a conventional building designed and constructed in compliance with the NBC. However, wildfire considerations are outside the scope of the NBC. NRC/Codes Canada is developing a guide that addresses the risk of fire spread to buildings from wildfires. Factors that affect wildfire hazard include topography, environmental conditions, and fuel sources. A building's exposure to wildfire occurs through ember transport, radiation, and/or convection and direct flame contact. Addressing wildfire risks can include using fire-resistant construction on the exterior (e.g., cladding and roofs), and appropriate landscaping and maintenance within the proximity of the building.

Tall wood buildings in high-hazard wildfire zones may be susceptible to exposure from wildfires during construction due to exposed wood surfaces. An appropriate analysis of the risk should be undertaken, and measures commensurate with the risk level should be taken. During construction this may include erecting temporary barriers around the building, using an exterior water supply and fire hose to provide protection, or establishing construction sequencing that prioritizes completion of the building face(s) that have the highest exposure risk.

6.11.4 Roof Construction

The Acceptable Solutions in the NBC (Subsection 3.1.5) permit the use of significant combustible elements (e.g., roof framing and sheathing) in the roof of a noncombustible structure of unlimited height when built above a concrete roof deck with exterior parapets or an encapsulated mass timber deck. The NBC also permits conventional heavy timber roofs of unlimited area in larger buildings that do not exceed 2 storeys in height. The design of the roof system should address not only firefighter safety, but also the tendency of the construction to contribute to flying brands during a fire. The use of appropriate roof covering materials in conjunction with mass timber elements that have an inherent fire-resistance rating can address this issue.

6.12 FIREFIGHTING ASSUMPTIONS

6.12.1 Firefighting Considerations in Tall Wood Buildings

The safety of firefighters and other emergency responders is addressed in the objectives and functional statements of the NBC because those individuals are treated as occupants of the building. This is directly tied to NBC requirements that specifically call for either passive fire protection through fire-resistance-rated construction or active fire protection through automatic sprinkler protection.

Traditionally, unsprinklered construction relied on exterior firefighting operations. With the advent of buildings being protected with monitored and supervised sprinkler systems and related firefighting practices, the NBC shifted to reliance on sprinkler systems and interior firefighting access.

In buildings that are entirely protected by sprinklers, firefighting operations can be conducted from the interior of the building because the internal fire risk is reduced compared to that of an unsprinklered building. Sprinkler systems have shown to be reliable and effective, and typically operate automatically well before firefighters arrive at the fire scene. In multi-level residential buildings, sprinkler use has resulted in a reduction in death and injury; significantly less frequent involvement and effort by the fire service than in unsprinklered buildings; a high incidence of fire containment to the room of origin; and in many cases, full extinguishment of a fire (Garis & Clare, 2012). There have been few known major fires in fully sprinklered high buildings, except where a specific event (terrorism, explosion, or poor maintenance) has disabled the sprinkler system.

The shift to a reliance on sprinkler systems and interior firefighting access implies that the NBC considers sprinkler protection to be an important asset and considerably more beneficial than other fire risk reduction measures, such as locating a building so it faces multiple streets. The NBC allows a building that is entirely sprinklered to be of larger area than an unsprinklered building that faces one or two streets. Also, a sprinklered building is required to face only one street, and access openings for firefighting in exterior walls are not required because interior firefighting is possible.

In principle, firefighters' safety in a completed building of combustible construction or EMTC that has all required active and passive fire protection systems can be expected to be similar to that in a noncombustible construction that has been designed with minimum active and passive fire protection systems. However, a building of combustible construction or exposed mass timber is more likely than an EMTC to become involved in a fire.

The safety of both firefighters and occupants in a tall wood building depends primarily on the reliability of the fire suppression system and the fire-rated compartments within the building. All tall wood buildings will be sprinklered, and as in noncombustible construction, the sprinkler system will be relied upon to control or extinguish a fire. However, some Alternative Solutions recommend having an independent backup water supply for tall wood buildings to mitigate the risk of failure of the municipal water supply. This will typically require on-site water storage and a fire pump.

Historically, the greatest operational factor that has contributed to firefighter deaths or injuries has been incomplete situational awareness (IAFC, 2012). Lack of knowledge of the building and its contents, and of the fire location and characteristics, is the major factor in increased risk for individual firefighters. Most tall wood buildings are expected to be in urban environments where there are professional fire departments with the capability of preplanning fire responses, and the buildings are expected to have fire safety plans. The fire safety plan can be developed by involving the local fire department in the design stages of a project, both to ensure that firefighters are aware of any special characteristics of a tall wood building and to address the fire department's concerns at an early stage in the design process.

A critical risk to firefighters in wood-frame construction is the potential for fire to spread within the combustible surfaces of voids and attack lightweight structural elements, which can result in the premature and unexpected collapse of floor assemblies. Because mass timber has inherent fire-resistance, this level of risk is significantly mitigated, provided that connections are suitably designed for fire protection. As noted in Section 6.6.1 of this chapter, the probability of fire spread within void spaces of mass timber buildings is significantly less than that within light-frame combustible assemblies. Furthermore, a fire that challenges the fire-resistance of a building or that spreads within its void spaces can cause structural collapse in a wood-frame building but rarely in a mass timber building.

Many tall wood buildings will meet the definition of a high building in the NBC. However, Alternative Solutions will still be required for wood buildings of a lower height, particularly nonresidential buildings. To facilitate the approval of an Alternative Solution for those buildings, the provision of firefighter communication features that are required for high buildings should be considered, including firefighters' telephones at each exit stairway on each floor and voice communication throughout the floor areas. These systems can assist communication between firefighters and allow firefighters to provide instructions to occupants and thereby improve the efficiency of fire department operations.

6.13 MEANS OF EGRESS

Means of egress, including provisions for the safety and evacuation of mobility-impaired occupants, in tall timber buildings are no different than those in conventional buildings because the buildings are designed to perform in a manner that is equal, if not superior, to noncombustible construction.

Provisions for fire separations and smoke control systems, along with emergency communication systems, will protect occupants from a fire event and provide information to occupants who are unable to evacuate the building on their own. There should be no need to provide additional features for a mass timber building because the building will be designed to provide the same level of safety as noncombustible construction, but firefighters' telephones or panic buttons could be provided at elevators to enable disabled occupants to call for assistance.

In the unlikely event that a wood building is designed to house a large number of mobility-impaired occupants, it would be appropriate to undertake evacuation modelling to confirm that the occupants can be evacuated prior to being affected by untenable conditions. This may be earlier than 2 hr, and is implicit in the NBC requirements. However, this is equally applicable to a building of noncombustible construction that would house a large number of mobility-impaired occupants.

Alternatively, and over and above the level of performance expected in permitted noncombustible construction, it is possible in Canada to design elevator systems as egress elevators, subject to an Alternative Solution. Guidance is provided in the International Building Code (ICC, 2018), which permits unsprinklered high-rise buildings (not permitted in Canada) and requires that these buildings have elevator systems for egress for persons with disabilities.

6.14 CONSIDERATIONS FOR MAJOR NATURAL DISASTERS

While Part 4 of the NBC (Structural Design) specifically addresses natural disasters such as earthquakes and windstorms, Part 3 of the NBC does not. For a tall wood building, it may be necessary to address disasters that could affect emergency response and infrastructure. This should, however, also be applicable to tall buildings of noncombustible construction. In terms of risk, natural disasters are low-probability events but have potentially high consequences.

If the structure of a tall wood building is protected by complete encapsulation, it can perform the same as a structure of noncombustible construction. However, if the structure of a tall wood building is protected by partial encapsulation or has significant exposed mass timber elements, it might continue to char/smoulder following a fire, and could eventually collapse if inherent fire-resistance is limited and firefighting operations are not available to extinguish the fire.

In a major disaster, such as an earthquake, emergency response may be overwhelmed and unavailable, and municipal water supplies may be cut off; furthermore, the disruption of a building and its systems and contents significantly increases the probability of a fire incident following an earthquake. However, the NBC addresses a "rare event", such as a fire or an earthquake, as a single and distinct event (i.e., not combining rare events). Robertson (1998) and Harmsworth (2000) provide further guidance on fire concerns following an earthquake. At the time, Robertson was the Chief

Building Official for the City of Vancouver; his report notes the following with regard to the City of Vancouver's water supply:

> An internal report of the City of Vancouver concludes that, at present, an M-7 earthquake would render the Greater Vancouver Water District supply system completely dysfunctional with 1000 water main breaks and 1000 service breaks.

The NBC requires an emergency power supply of 2 hr. Therefore, tall wood buildings may also need to have a secondary water supply so that the sprinkler system can remain operational and assist firefighters or civilians in performing firefighting duties to control or extinguish the fire.

Guidance on design requirements is provided in NFPA 13 and the International Building Code; the latter requires that all high buildings have a 30-min water supply on-site for sprinkler systems. Based on this requirement, an operating sprinkler system can maintain tenable conditions and facilitate nonprofessional fire response (sprinklers are designed to control a fire, not necessarily fully extinguish it); therefore, if occupants are alerted by a seismic event and the building's fire alarms, it is reasonable to assume that in the absence of firefighters, the occupants can respond to small fire incidents within a reasonable time frame if they are alerted during the initial stages of the fire. The provision of a 30-min or 60-min water supply should therefore be sufficient.

6.15 FIRE SAFETY DURING CONSTRUCTION

6.15.1 Fire Risk Factors and the Fire Problem during Construction

Buildings that use combustible elements have the highest risk of fire occurring during construction due to hazards and conditions at construction sites that are different from those for completed buildings. These include:

- incomplete fire separations;
- lack of functional fire suppression and fire alarm systems;
- inadequate water supply for manual firefighting;
- fire department response inefficiencies due to the state of construction;
- hazardous operations on construction sites, such as hot work (e.g., cutting, grinding, welding, soldering, and torch-applied roofing);
- significant on-site stored and erected unprotected combustible materials; and
- arson and other intentional fires when the site is unoccupied.

Fire exposure to or from adjacent buildings may also differ from that of a completed building because the NBC's spatial separation provisions are based on completed buildings that have protective systems and fire separations that are not available to partially constructed buildings. A combustible structure under construction can expose existing adjacent buildings to the effects of fire. The analysis of fire risks during construction, which is applicable to any building, should not only take into account the location and size of existing buildings and structures, along with any other exterior items that may spread fire, such as adjacent trees or shrubs, but should also consider appropriate mitigation features. These may include using exterior fire barriers, restricting combustibles from being stored adjacent to other buildings, using temporary exterior fire suppression or standpipe systems, and prioritizing the completion of building faces adjacent to other buildings.

Section 5.6 of the NFCC 2020 has been updated to address fire safety during construction of buildings of EMTC. Provisions include:

- minimum clearance to combustible refuse materials
- adequate water supply for firefighting
- a minimum of two fire-separated exit stairs
- standpipe installation
- protective encapsulation of both interior and exterior assemblies

Other considerations for mass timber buildings include providing adequate firefighting access to the building, installing site security and surveillance, and having a detailed site risk management protocol.

6.15.2 Fire Safety during Renovations

Renovations cannot easily be categorized because the scope of work for various types of renovations can differ widely. Renovations are assumed to be carried out in a building that was previously completed; consequently, the various fire safety systems and features of the building should be in a completed condition prior to commencement of the renovations. Some or all of the risk factors noted above for a building under construction may also be applicable to renovations, depending on their scope.

In addition, renovations may be carried out in a portion of a building while the remainder of the building is occupied. In that situation, fire safety planning for the renovations should take into account the safety of occupants in adjacent areas of the building. Fire safety planning during renovations should also consider the safety of the workers, the importance of fire detection, and alarm system coordination and communication between renovation and occupied areas.

6.15.3 Fire Safety Considerations during Construction and Renovations

Fire safety on a construction site is primarily the responsibility of the contractor(s) and possibly the owner or developer, but everyone involved plays an important role. For major projects, the approach to construction fire safety should involve several members of the project team, including the general contractor, trades contractors, owner or developer, project consultants, and possibly a specialty consultant who deals with fire protection issues, and the local fire department. The NFCC 2020, the Canadian Wood Council (CWC, 2012a, 2012b), and the NFPA 241 (2013b) provide additional guidance.

A fire safety approach for construction sites should include a construction fire safety plan and coordinator, a preconstruction meeting, the establishment of a fire watch during off-hours, the creation of a firefighting water supply, the use of fire compartmentalization, and implementation of functional sprinkler systems, as soon as practical during construction.

6.15.3.1 Construction Fire Safety Plan

A construction fire safety plan should include the designation and organization of site personnel who are responsible for carrying out fire safety duties, and should identify emergency procedures, measures for controlling fire hazards, and maintenance procedures for on-site firefighting facilities. Development of the plan should include an analysis of fire risk, including any unique hazards associated with the construction site, and proposed actions to mitigate the risk. The type and severity of risk will vary depending on factors such as project size, type of construction, scheduling, complexity, and proximity to other buildings. The construction fire safety plan should also be updated at regular intervals to address hazards associated with particular construction phases. Because mass timber elements are generally prefabricated and their delivery can be coordinated, fewer combustibles have to be stored at the construction site compared to other forms of construction (see Chapters 3 and 8 for the benefits of prefabrication).

> **Construction Moisture**
>
> Some steps in the construction fire mitigation plan need to be implemented when the building is not fully enclosed and is potentially exposed to inclement weather; therefore, they need to take into account the effect and management of construction moisture.

The construction fire safety plan should be developed in consultation with the responding fire department, and the completed plan should be submitted to the fire department for its review and comment prior to commencing construction. The NFCC 2020 provides further guidance on construction fire safety plans.

6.15.3.2 Construction Fire Safety Coordinator

The contractor on a tall building project should assign a construction fire safety coordinator who is responsible for the overall coordination of fire protection and risk mitigating measures from the commencement of construction through to building occupancy. The coordinator should keep workers up to date on emergency procedures, monitor the site in relation to ongoing fire hazards and the construction fire safety plan, be the main contact with the local fire department, and be trained to identify and respond to fire hazards. The coordinator should also implement and manage a system for the control of hot works.

6.15.3.3 Preconstruction Meeting

A preconstruction site meeting that includes the general contractor, key members of the project team, and the local fire department should be held to provide all participants with an opportunity to clarify their expectations and review the fire risks for the project.

6.15.3.4 Fire Watch during Off-Hours

Construction sites face a risk of incendiary fire, primarily during nonworking hours; therefore, consideration should be given to establishing a fire watch system during off-hours. This could be a staffed fire watch system with regular surveillance of all areas of the site, an active detection system, or a combination thereof, and may include other features such as security cameras.

6.15.3.5 Firefighting Water Supply and Sprinklers

In many projects, connection to the municipal water supply is not completed until fairly late in the construction process; therefore, on-site firefighting capacity is limited during most of the construction stages.

Tall buildings typically require a standpipe system with hose connections for use by the fire department. To allow for manual firefighting during construction, installation of the standpipe system must progress with the construction. The NFCC 2020 requires the standpipe to be not more than one floor below the highest forms, staging, and similar combustible elements at all times, and the fire department pumper connection must be accessible from the street. Early coordination between the local municipality, project consultants, and applicable contractors is required to provide a water supply for firefighting as soon as significant quantities of combustible material arrive on-site.

Where practical, the building's sprinkler system should be charged and operational. This will vary depending on the stage of construction. The partially completed system may be operational during off-hours but temporarily deactivated for specific zones while work is in progress in that area.

Construction Fire

The construction fire risk mitigation plan should anticipate different wetting events, such as water from fire suppression. These events may occur in areas that are not expected to be exposed to the weather. As with weather-exposed areas, short-term wetting can be addressed by vacuuming water trapped in mass timber gaps and maintaining good drying conditions. Particular attention should be paid to exposed end-grain surfaces.

6.15.3.6 Fire Compartmentalization

Without completed fire separations within the floor area or enclosed exit stairs, there may be few, if any, physical barriers to fire spread within a building, and no safe routes out of the building. The completion of an unobstructed (with respect to fire separations) exit stairway to each floor level that discharges at ground level would help address this risk. Construction sequencing should give priority to construction of fire compartments, firewalls, and closures in fire separations, and closures should be kept closed when practical.

"Top-down" interior completion of low-rise and mid-rise buildings has become common in some areas, particularly in multi-unit residential buildings, where interiors of the uppermost levels are completed first, followed progressively by the lower levels. This approach can expose the entire building to the effects of a fire at a lower level because the structure at the lower levels supports the upper levels, and makes it more difficult to progressively install fire protection systems. For a tall wood building, it will be necessary to limit fire risk by providing temporary fire protection systems on lower floors, at a minimum, as construction progresses. The NFCC 2020 includes minimum requirements for protective encapsulation during construction of EMTC buildings. Consideration should therefore be given to "bottom-up" interior completion of the building in order to allow fire protection systems to be progressively installed.

6.16 CONCLUSION

The construction of tall wood buildings can follow the Acceptable Solutions in Division B of the NBC 2020; however, where the design deviates from the Acceptable Solutions, Alternative Solutions will need to be employed. An Alternative Solution for a tall wood building is, as presented in this chapter, both feasible and practical given the current state of knowledge about mass timber buildings and building elements, and is subject to agreement by the AHJ.

In this chapter, it is assumed that the proposed Alternative Solution for a tall wood building complies with most of the prescriptive provisions in Division B of the NBC for a building of noncombustible construction or EMTC. The most significant alternative is that the structural elements consist of mass timber construction as opposed to noncombustible construction with a similar fire-resistance rating. The basis for the calculation of the structural fire-resistance of mass timber elements, including connections, is also reviewed. The importance of maintaining the integrity fire-resistance of fire separations at service penetrations and joints between mass wood panels is also discussed.

Limiting the severity of a fire through complete encapsulation of all mass timber elements will result in an equal and possibly better level of fire performance than that provided by buildings of noncombustible construction. A lesser level of encapsulation and exposure of certain mass timber elements can, when combined with other fire risk mitigation measures, provide a level of safety equivalent to that afforded by noncombustible construction. The pros and cons of three levels of encapsulation are discussed: complete, limited (partial), and no encapsulation (fully exposed).

The recommended design approach is essentially iterative: encapsulating all mass timber elements in sufficient gypsum board is considered first, such that they are not affected by a fire and do not contribute to a fire for a 2-hr duration (i.e., complete encapsulation); then, by analyzing various fire protection scenarios, the level of encapsulation can be reduced to the point where a fire analysis demonstrates that it continues to provide the level of fire safety that is expected in modern tall buildings.

6.17 REFERENCES

American National Standards Institute/The Engineered Wood Association (ANSI/APA). (2018). *ANSI/APA PRG 320-2018: Standard for performance-rated cross-laminated timber*. New York, NY: Author.

American Wood Council (AWC). (2017). *Fire resistance testing of CLT floor/ceiling assemblies to establish contribution of gypsum protection* (WFCi Report #17091r1). Leesburg, VA: Author.

Architectural Institute of British Columbia & Engineers and Geoscientists British Columbia (AIBC/EGBC). (2020). *Joint professional practice guidelines: encapsulated mass timber construction up to 12 storeys.* Draft version 1.0. Vancouver, BC: Author.

ASTM International (ASTM). (2017). *ASTM D2898-10: Standard practice for accelerated weathering of fire-retardant-treated wood for fire testing*. West Conshohocken, PA: Author.

ASTM International (ASTM). (2019). *ASTM D5456-19: Standard specification for evaluation of structural composite lumber products*. West Conshohocken, PA: Author.

ASTM International (ASTM). (2020). *ASTM E84-20: Standard test method for surface burning characteristics of building materials*. West Conshohocken, PA: Author.

ASTM International (ASTM). (2020). *ASTM E119-20: Standard test methods for fire tests of building construction and materials*. West Conshohocken, PA: Author.

Brandon, D., & Dagenais, C. (2018*). Fire safety challenges of tall wood buildings—Phase 2: Task 5—Experimental study of delamination of cross laminated timber (CLT) in fire*. RISE Research Institutes of Sweden, Stockholm, Sweden.

Brandon, D., Sjöström, J., Temple, A., Hallberg, E. & Kahl, F. (2021). *Fire safe implementation of visible mass timber in tall buildings – compartment fire testing (RISE report 2021:40).* RISE Research Institutes of Sweden, Stockholm, Sweden.

Buchanan, A. H., & Abu, A. K. (2017). *Structural design for fire safety* (2nd ed.). United Kingdom: John Wiley & Sons.

Buchanan, A. H., Deam, B. L., Fragiacomo, M., Gibson, T., & Morris, H. (2006, August). Fifteen years of performance-based design in New Zealand. In *Proceedings of the 9th World Conference on Timber Engineering* (WCTE 2006). Portland, OR: Oregon State University.

Canadian Standards Association (CSA). (2006a). *CSA O112.6-06: Phenol and phenol-resorcinol resin adhesives for wood (high-temperature curing)*. Mississauga, ON: Author.

Canadian Standards Association (CSA). (2006b). *CSA O112.7-06: Resorcinol and phenol-resorcinol resin adhesives for wood (room and intermediate temperature curing).* Mississauga, ON: Author.

Canadian Standards Association (CSA). (2008). *CSA O112.10-08: Evaluation of adhesives for structural wood products (limited moisture exposure)*. Mississauga, ON: Author.

Canadian Standards Association (CSA). (2010). *CSA O112.9-10: Evaluation of adhesives for structural wood products (exterior exposure)*. Mississauga, ON: Author.

Canadian Standards Association (CSA). (2011a). *CSA O177-06: Qualification code for manufacturers of structural glued-laminated timber*. Mississauga, ON: Author.

Canadian Standards Association (CSA). (2011b). *CSA S408-11: Guidelines for the development of limit states design standards*. Mississauga, ON: Author.

Canadian Standards Association (CSA). (2019). *CSA O86-19: Engineering design in wood*. Mississauga, ON: Author.

Canadian Wood Council (CWC). (2012a). *Fire safety and security: a technical note on fire safety and security on construction sites in British-Columbia*. Ottawa, ON: Author.

Canadian Wood Council (CWC). (2012b). *Fire safety and security: A technical note on fire safety and security on construction sites in Ontario*. Ottawa, ON: Author.

Canadian Wood Council (CWC). (2020). *Wood design manual*. Ottawa, ON: Author. https://webstore.cwc.ca/product/wood-design-manual-2020/

Canadian Wood Council (CWC). (2020). *Fact sheet – surface flammability and flame-spread ratings*. Ottawa, ON: Author.

Chen, Z., Ni, C., Dagenais, C., & Kuan. S. (2020). WoodST: A temperature-dependent plastic-damage constitutive model used for numerical simulation of wood-based materials and connections. *Journal of Structural Engineering,* 146(3). doi: 10.1061/(ASCE)ST.1943-541X.0002524

Craft, S. (2009). *CUWoodFrame – A heat and mass transfer model for light-frame wood floors exposed to fire*. (Unpublished doctoral dissertation). Carleton University, Ottawa, ON.

Cuerrier-Auclair S. (2020). *Design guide for timber-concrete composite floors in Canada* (1st ed.) (Special Publication SP-540E). Pointe-Claire, QC: FPInnovations.

Dagenais, C. (2013a). *Surface burning characteristics of massive timber assemblies*. Pointe-Claire, QC: FPInnovations.

Dagenais, C. (2013b). *Surface burning characteristics of V2 stress grade cross-laminated timber.* Pointe-Claire, QC: FPInnovations.

Dagenais, C. (2013c). *Literature review: fire stop requirements as related to massive wood wall and floor assemblies.* Pointe-Claire, QC: FPInnovations.

Dagenais, C. (2014). *Surface burning characteristics of glulam decking*. Pointe-Claire, QC: FPInnovations.

Dagenais, C. (2016). *Investigation of fire performance of CLT manufactured with thin laminates*. Pointe-Claire, QC: FPInnovations.

Dagenais, C. (2017). *Glulam and CLT innovative manufacturing processes and product development: fire performance of adhesives in CLT – Part 2 – Cone calorimeter test*. Pointe-Claire, QC: FPInnovations.

Dagenais, C., Chen, Z., & Popovski, M. (2017). *Performance-based approach to support tall and large wood buildings: Fire and seismic performance*. Pointe-Claire, QC: FPInnovations.

Dagenais, C., & Grandmont, J.-F. (2017a). *Glulam and CLT innovative manufacturing processes and product development: fire performance of novel adhesives in glulam beams – small-scale flame test*. Pointe-Claire, QC: FPInnovations.

Dagenais, C. & Grandmont, J.-F. (2017b). *Glulam and CLT innovative manufacturing processes and product development: Fire performance of adhesives in CLT – Part 1 – Small-scale flame test*. Pointe-Claire, QC: FPInnovations.

Dagenais, C., Ranger, L., & Benichou, N. (2019a). Chapter 8: Fire performance of cross-laminated timber assemblies. In *Canadian CLT handbook* (2nd ed.). (Special Publication SP-532E). Pointe-Claire, QC: FPInnovations.

Dagenais, C., Ranger, L., & Benichou, N. (2019b). *Solutions for upper mid-rise and high-rise mass timber construction: fire performance of cross-laminated timber with adhesives conforming to 2018 edition of ANSI/APA PRG 320*. Pointe-Claire, QC: FPInnovations.

Dagenais, C., Ranger, L., Lum, C., & Thomas, T. (2018). Fire performance of firestops, penetrations and fire doors in mass timber assemblies. *Proceedings of the 2018 World Conference on Timber Engineering*. Seoul, Republic of Korea.

Drysdale, D. (1998). *An introduction to fire dynamics* (2nd ed.). New York, NY: John Wiley & Sons.

European Committee for Standardization (CEN). (2004). *Eurocode 5: Design of timber structures – Part 1–2: General – Structural fire design*. Brussels, Belgium: Author.

Fontana, M., & Frangi, A. (1999). Fire behaviour of timber-concrete composite slabs. In *Proceedings of the Sixth International Symposium on Fire Safety Science*. Poitiers, France.

Garis, L., & Clare, J. (2012). *Sprinkler systems and fire outcomes in multi-level residential buildings*. University of the Fraser Valley, Abbotsford, BC.

Garis, L, Singh, A., & Plecas, D. (2019). *Fire protection system(s) performance in the residential building environment*: *Examining the relationship between civilian and firefighter injuries: A retrospective evaluation of residential and residential apartment fires, 2005 to 2015*. University of the Fraser Valley, Abbotsford, BC.

Hadjisophocleous, G. V., Benichou, N., & Tamin, A. S. (1998). Literature review of performance-based fire codes and design environment. *Journal of Fire Protection Engineering,* 9(1),12-40.

Hakkarainen, T. (2002). Post-flashover fires in light and heavy timber construction compartments. *Journal of Fire Sciences*, 20, 133-175.

Harmathy, T. Z. (1965). Ten rules of fire endurance rating. *Fire Technology*, 1(2), 93-102.

Harmsworth, A. (2016). *Firestopping test witness report for Nordic Structures* (GHL File NEW-4830.01). Vancouver, BC: GHL Consultants.

Harmsworth, A. (2000). *An economical approach to maintaining protection of fire sprinkler systems with respect to post earthquake fires*. Vancouver, BC: University of British Columbia.

Hasburgh, L. E., Bourne, K. J., Dagenais, C., Osborne, L. & Roy-Poirier, A. (2016). Fire performance of mass-timber encapsulation methods and the effect of encapsulation on char rate of cross-laminated timber. In *World Conference on Timber Engineering*, Vienna, Austria.

Hasemi, Y. (2016) Chapter 23: Surface flame spread. In *The SFPE handbook of fire protection Engineering* (5th ed.). Quincy, MA: Society of Fire Protection Engineers.

International Association of Fire Chiefs (IAFC). (2012). *Rules of engagement for structural firefighting - increasing firefighter survival.* Fairfax, VA: Author.

International Code Council (ICC). (2021). *International building code*. Washington, DC: Author.

International Organization for Standardization (ISO). (2016). *ISO 9705: Fire tests – full-scale room test for surface products*. Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2015). *ISO 16733-1: Fire safety engineering — Selection of design fire scenarios and design fires — Part 1: Selection of design fire scenarios*. Geneva, Switzerland: Author.

International Organization for Standardization (ISO). (2019). *ISO/CD TS 16733-2: Fire safety engineering — Selection of design fire scenarios and design fires — Part 2: Design fires*. Geneva, Switzerland: Author.

Janssens, M. (2015). *Full-scale tests in a furnished living room to evaluate the fire performance of protected cross-laminated and nail laminated timber construction*. San Antonio, TX: Southwest Research Institute.

Janssens, M., & Douglas, B. (2004). Chapter 7: Wood and wood products. In *Handbook of building materials for fire protection*. McGraw-Hill.

Karacabeyli, E., and Gagnon, S. (2019). *Canadian CLT handbook*. (2nd ed.). (Special Publication SP-532E). Pointe-Claire, QC: FPInnovations.

Klippel, D., Schmid, J., & Frangi, A. (2017). *Fire tests on cross-laminated timber panels glued with HB X and HB E adhesive*. Zurich, Switzerland: ETH Zurich.

Klote, J. H., Milke, J. A., Turnbull, P. G., Kashef, A., & Ferreira, M. J. (2012). *Handbook of smoke control engineering*. Atlanta, GA: ASHRAE.

Koo, K. (2013). *A study on historical tall-wood buildings in Toronto and Vancouver*. Pointe-Claire, QC: FPInnovations.

Lennon, T. (2011). *Structural fire engineering*. London, UK: Institution of Civil Engineers Publishing.

Lu, L. (2012). *Fire modelling heat transfer computer model of a 3-ply cross-laminated timber board under standard fire exposure using ANSYS* (CFS Final Report 3.22). Pointe-Claire, QC: FPInnovations.

McGregor, C. (2013). *Contribution of cross-laminated timber panels to room fires* (Unpublished master's thesis). Carleton University, Ottawa, ON.

Medina, H. A. R. (2014). *Fire resistance of partially protected cross-laminated timber rooms*. (Unpublished master's thesis). Carleton University, Ottawa, ON.

Mehaffey, J. R. (2006). *Fire performance of interior finishes, room linings and structural panel products* (Project Report No. 3638). Ottawa, ON: Forintek Canada Corp.

Mikkola, E. (1990). *Charring of wood* (Research Report 689). Espoo, Finland: Technical Research Center of Finland.

National Fire Protection Association (NFPA). (2012). *NFPA 92: Standard for smoke control systems*. Quincy, MA: Author.

National Fire Protection Association (NFPA). (2013a). *NFPA 13: Standard for the installation of sprinkler systems*. Quincy, MA: Author.

National Fire Protection Association (NFPA). (2013b). *NFPA 241: Standard for safeguarding construction, alteration, and demolition operations*. Quincy, MA: Author.

National Fire Protection Association (NFPA). (2013c). *NFPA 551: Guide for the evaluation of fire risk assessments*. Quincy, MA: Author(?).

National Research Council of Canada (NRC). (1990). *Supplement to the National Building Code of Canada*. Ottawa, ON: Author.

National Research Council of Canada (NRC). (2020a). *National Building Code of Canada*. Ottawa, ON: Author.

National Research Council of Canada (NRC). (2020b). *National Fire Code of Canada*. Ottawa, ON: Author.

Oleszkiewicz, I. (1990). Fire exposure to exterior walls and flame spread on combustible cladding. *Fire Technology,* 26, 357-375.

O'Neil, J., Carradine, D., Moss, P. J., Fragiacomo, M., Dhakal, R., & Buchanan, A. H. (2001). Design of timber-concrete composite floors for fire resistance. *Journal of Structural Fire Engineering*, 2(3), 231-242.

Ontario Ministry of Natural Resources and Forestry/Ontario Ministry of Municipal Affairs (OMNRF/OMMA). (2017). *Ontario's tall wood building reference: A technical resource for developing Alternative Solutions under Ontario's Building Code*. Toronto, ON: Author.

Osborne, L. (2015). *Fire resistance of long span composite wood-concrete floor systems*. Pointe-Claire, QC: FPInnovations.

Osborne, L., Dagenais, C., & Bénichou, N. (2012). *Preliminary CLT fire resistance testing report*. Pointe-Claire, QC: FPInnovations.

Peng, L. (2010). *Performance of heavy timber connections in fire*. Ottawa, ON: Carleton University.

Ranger, L., & Dagenais, C. (2019). *Evaluating fire performance of nail-laminated timber: Surface flammability*. Pointe-Claire, QC: FPInnovations.

Ranger, L. & Dagenais, C. (2020). *Flame spread in concealed mass timber spaces*. Pointe-Claire, QC: FPInnovations.

Ranger, L., Dagenais, C., & Cuerrier-Auclair, S. (2016). *Fire-resistance of timber-concrete composite floor using laminated veneer lumber*. Pointe-Claire, QC: FPInnovations.

Régie du bâtiment du Québec (RBQ). (2015). *Bâtiments de construction massive en bois d'au plus 12 étages: Directives et guide explicatif*. Montréal, QC: Author.

Richardson, J. K. (1985). *The reliability of automatic sprinkler systems*. Ottawa, ON: National Research Council Canada.

Robertson, J. R. (1998). *Accounting for fire following earthquakes in the development of performance-based building codes*. Vancouver, BC: University of British Columbia.

Society of Fire Protection Engineers (SFPE). (2000). *SFPE engineering guide to performance-based fire protection analysis and design of buildings*. Bethesda, MD: Author.

Society of Fire Protection Engineers (SFPE). (2004). The SFPE *code official's guide to performance-based design review*. Bethesda, MD: Author.

Society of Fire Protection Engineers (SFPE). (2016). *The SFPE handbook of fire protection engineering* (5th ed.). Quincy, MA: Author.

Society of Fire Protection Engineers (SFPE). (2020). *Guidelines for peer review in the fire protection design process*. Bethesda, MD: Author.

SP Trätek. (2010). *Fire safety in timber buildings - technical guideline for Europe* (SP Report 2010:19). Stockholm, Sweden: Swedish Institute for Wood Technology Research.

Su, J., Lafrance, P.-S., Hoehler, M., & Bundy, M. (2018a). *Cross laminated timber compartment fire tests for research on fire safety challenges of tall wood buildings—Phase 2*. Quincy, MA: Fire Protection Research Foundation.

Su, J. Z., Leroux, P., Lafrance, P.-S., Berzins, R., Gratton, K., Gibbs, E., & Weinfurter, M. (2018b). *Fire testing of rooms with exposed wood surfaces in encapsulated mass timber construction.* Ottawa, ON: National Research Council of Canada.

Su, J., Leroux, P., Lafrance, P.-S., Berzins, R., Gratton, K., Gibbs, E., & Weinfurter, M. (2019). *Nail laminated timber compartment fire tests*. Ottawa, ON: National Research Council of Canada.

Su, J. Z. & Lougheed, G. D. (2014). *Fire safety summary: Fire research conducted for the project on midrise wood construction: Report to Research Consortium for Wood and Wood-Hybrid Mid-Rise Buildings* (Client Report A1-004377.1). Ottawa, ON: National Research Council of Canada.

Taber, B., Lougheed, G. D., Su, J. Z., & Bénichou, N. (2013). *Alternative Solution for mid-rise wood construction: Full-scale apartment fire test with encapsulated cross laminated timber construction*. Ottawa, ON: National Research Council of Canada.

Torvi, D., Kashef, A., & Benichou, N. (2005). *FIERAsystem radiation to adjacent buildings model (RABM): Theory report*. (Research Report No. 189). Ottawa, ON: National Research Council of Canada.

Underwriters Laboratories of Canada (ULC). (2010). *CAN/ULC S102: Standard method of test for surface burning characteristics of building materials and assemblies*. Toronto, ON: Author.

Underwriters Laboratories of Canada (ULC). (2011). *CAN/ULC S115: Standard method of fire tests of firestop systems*. Toronto, ON: Author.

Underwriters Laboratories of Canada (ULC). (2013). *CAN/ULC S134: Standard method of fire test of exterior wall assemblies*. Toronto, ON: Author.

Underwriters Laboratories of Canada (ULC). (2014a). *CAN/ULC S101: Standard methods of fire endurance tests of building construction and materials*. Toronto, ON: Author.

Underwriters Laboratories of Canada (ULC). (2014b). *CAN/ULC S702: Standard for mineral fibre thermal insulation for buildings*. Toronto, ON: Author.

Underwriters Laboratories of Canada (ULC). (2018). *CAN/ULC S114: Standard method of test for determination of noncombustibility in building materials*. Toronto, ON: Author.

Underwriters Laboratories of Canada (ULC). (2019). *CAN/ULC S146: Standard method of test for the evaluation of encapsulation materials and assemblies of materials for the protection of structural timber elements*. Toronto, ON: Author.

University of British Columbia (UBC). (n.d.). Vancouver to benefit from UBC fire protection expertise. *UBC News*. https://news.ubc.ca/1997/09/17/archive-media-releases-1997-mr-97-89/

White, R. H. (1992). Charring rate of wood for ASTM E119 exposure. *Fire Technology*, 28(1), 5-30.

White, R. H. (2009, January). Fire resistance of wood members with directly applied protection. In *Fire & Materials Conference*, San Francisco, CA.

White, R. H. (2016). Chapter 55: Analytical methods for determining fire resistance of timber members. In *The SFPE handbook of fire protection engineering* (5th ed.). Quincy, MA: Society of Fire Protection Engineers.

White R. H., & Dietenberger, M. A. (2010). Chapter 18: Fire safety of wood construction. In *Wood handbook: Wood as an engineering material* (FPL-GTR-190). Madison, WI: USDA Forest Service .

White, R. H., Dietenberger, M. A., Tran, H., Grexa, O., Richardons, L., Sumathipala, K., & Janssens, M. (1999). Comparison of test protocols for the standard room/corner test. *Fire and Materials*, 23,139-146.

Zelinka, S. L., Hasburgh, L. E., Bourne, K. J., Tucholski, D. R., & Ouellette, J. P. (2018). *Compartment fire testing of a two-story cross-laminated timber building* (General Technical Report FPL-GTR-247). Madison, WI: USDA Forest Service.

APPENDIX 6A

Fire Risk Assessment

6A.1 What is Risk?

In the most basic terms, risk is the product of the probability (or likelihood) and consequence of an undesirable event occurring. For fire engineering, the risks considered are generally fire-related and therefore are referred to as fire risks.

In conducting a fire risk assessment, the designer uses available fire risk assessment methods to determine both the likelihood and consequence of fire events occurring. A fire risk analysis is a detailed examination that is conducted to determine the threat of fire to human life and property, and it includes fire risk assessment and management of alternatives.

6A.2 Fire Risk Assessment Methods

A number of methods can be used to assess fire risks. They can generally be categorized as qualitative, semi-quantitative, and quantitative methods. A class of risk assessment methods called "risk indexing" has also emerged as a useful tool for assessing nonspecific fire risks.

6A.2.1 Qualitative Methods

Qualitative methods do not assess risk in any quantitative way; they are generally limited to identifying what the risks are. Qualitative methods include what-if analysis, checklists, and logic-tree analysis. An example of qualitative risk assessment is an engineering judgment on "what if the fire plume spills out the window?"

6A.2.2 Semi-quantitative Methods

Semi-quantitative methods quantitatively assess either the likelihood or consequence of the risk. They can be further classified into semi-quantitative likelihood methods and semi-quantitative consequence methods. Semi-quantitative likelihood methods, such as an event tree analysis, quantitatively assess the likelihood of a fire event and subsequent events occurring but assess the consequences qualitatively or not at all. An example would be "based on statistics, there is a 5% chance that sprinklers do not operate as expected in a fire", but the consequences of this particular fire scenario would not be assessed. While this type of assessment is useful for ruling out low-probability events, it could miss certain low-probability but high-consequence events, such as the failure of the sprinkler system during a major disaster, when other resources such as the fire department and exit paths may also be disrupted.

Semi-quantitative consequence methods, on the other hand, focus on the consequences of a fire event and give little or no consideration to the likelihood of the event occurring. In fire engineering, they are typically deterministic fire models, such as zone and computational fluid dynamics models and evacuation models. For example, a fire modelling assessment may be used to show that a steel column in a shopping mall could fail when the surface temperature reaches 600°C; however, this assessment provides no indication of the likelihood of the event occurring. While an engineering assessment of this nature generally produces conservative answers, it could result in overly onerous provisions when the event in question is very rare.

6A.2.3 Quantitative Methods

Quantitative methods quantitatively estimate the likelihood and consequences of an event. They can be a combination of semi-quantitative likelihood and semi-quantitative consequence methods, as illustrated in Figure 6A.1. In this hypothetical example, three potential events are identified as A, B, and C, with likelihoods of X, Y, and Z, respectively. A fire modelling assessment was carried out to determine that the sprinkler activation times were 2 min, 1 min, and 8 min for Events A, B, and C, respectively. As a result, following Event A, fire damage would be limited to nearby objects; following Event B, fire damage would be limited to the object of fire origin; and following Event C, there would be extensive fire damage within the room. The same assessment would be carried out for both the Division B Acceptable Solution and Alternative Solution so that the engineer could make a decision about whether the events and their likelihoods met the level of performance required by the NBC. This can be extended to assess the effect on property protection and life safety as well.

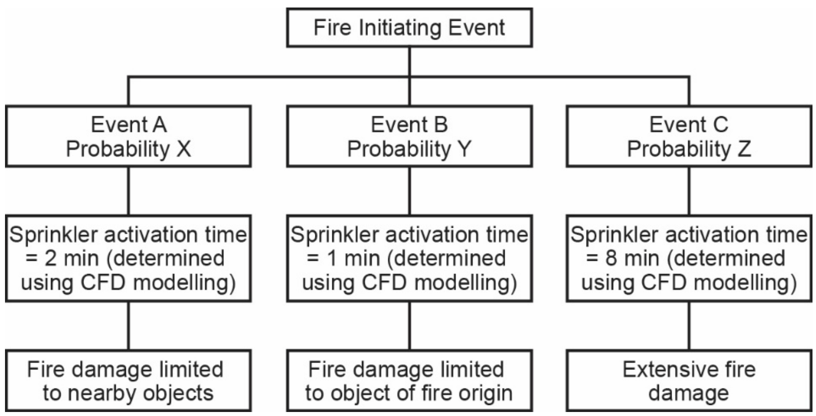


Figure 6A.1. Example of an event tree assessment (CFD = computational fluid dynamics).

Quantitative risk assessment software packages have been created, including CESARE-Risk from Australia; FiRECAM, FIERAsystem, and CURisk from Canada; CRISP from the UK; and QRA from Sweden. The designer should be fully familiar with the fire risk assessment principles and assumptions made during development of the software so that an informed engineering judgment can be made regarding the results.

6A.2.4 Indexing Method and the Delphi Panel

A class of fire risk assessment methods known as "fire risk indexing" has been used in recent years to study risks related to the more fundamental fire safety issues of a building, such as compartment area, compartment height, and construction provisions. The indexing approach examines risk in a more implicit manner given that it is not based on any specific fire event. It determines how well a building might perform in a fire event as a whole, based on its design features (or parameters), such as the type of construction, the number of exits, firefighting response time, and occupancy classification. Indexing involves a scoring system that assigns points to the relevant parameters, which are weighted based on the importance of each parameter:

$$Index = \sum_{i=1}^{n} s_i w_i$$

where s_i is the score for parameter i and w_i is the weighting for parameter i. When the performance of two building designs are compared (e.g., a Division B-compliant design and an Alternative Solution design), the design with the greater overall index score would be regarded as having a superior level of performance. It is important to note that the parameters and available scores are generally predetermined by a decision-making body such as a committee of experts. However, depending on the makeup of the committee and its culture and background, the index system developed may prove to be subjective.

Further detailed discussion on fire risk assessment methods is provided in generally accepted fire engineering literature in Canada and the United States (NFPA, 2013c; SFPE, 2000, 2016).

6A.3 Comparative Risk Assessment for Alternative Solutions

The fundamental requirement of an Alternative Solution is that it must perform "as well as" the Acceptable Solutions in Division B of the NBC for which a variance is being sought. An assessment that simply shows that an Alternative Solution is "good enough" based on anecdotal evidence will not meet that requirement. To demonstrate that an Alternative Solution complies with the provisions of the objective-based NBC, a comparative risk assessment should be conducted to assess the level of performance for each provision in Division B and the corresponding Alternative Solution with respect to the risk areas identified by the objectives and functional statements.

CHAPTER 7

Building Enclosure Design

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ABSTRACT

The building enclosure system physically separates the exterior environment from the interior environment(s). Chapter 7 of this guide focuses on the control of heat, air, and moisture transfer through the building enclosure. Noise and fire control are also discussed, along with wood durability and moisture protection of wood components during construction. Together with the heating, cooling, and ventilation systems, the building enclosure maintains controlled and healthy indoor spaces. The building enclosure is also a key passive design element for an energy-efficient building and is the most important system for ensuring the durability of a tall wood building.

Elements of the building enclosure include roofs, above- and below-grade walls and floors, windows, doors, skylights, and all the interfaces and details in between. Because the focus of this guide is on tall wood buildings, the unique considerations for the wood-based, above-grade wall and roof assemblies that are different from other high-rise structures are addressed in this chapter. Environmental loads (primarily wind, rain, temperature differentials, moisture differentials) and structural loads (primarily wind and snow, as well as seismic and related lateral movements) act on the building enclosure, just like on tall buildings constructed of steel or concrete. The structural loads for tall wood buildings are generally greater than those to which low-rise light-wood-frame buildings are subjected. Design considerations for taller wood buildings, such as cumulative vertical wood movement (e.g., shrinkage, compression, gap closure, and creep) of the structure, are emphasized and need to be accommodated by the building enclosure.

The structural system has a significant effect on the location of insulation, as well as the details. This chapter addresses predominant wood-based structural systems and associated exterior wall assemblies, including platform (and balloon) framing; post-and-beam or mass timber structure with curtain wall, light-wood-frame, or mass timber infill walls; and poured-in-place concrete frames with wood-based infill walls. The information provided applies to the design and construction of prefabricated exterior wall panels.

High rain exposure conditions associated with tall wood buildings dictate that a rainscreen water penetration control strategy be adopted for all exterior wall assemblies and details. In addition, the energy-efficiency requirements and the best practice for hygrothermal durability favour exterior-insulated mass timber or split-insulated light-wood-frame walls as the assemblies of choice. Various air barrier strategies may be considered; however, an exterior air barrier system often provides the best solution for implementation and quality assurance if there is exterior access. Attention to vapour diffusion control must be considered, with allowances made for both wood drying and limiting wetting in service, given that mass timber typically has low vapour permeance.

Roof assemblies considered include both conventional and protected membrane systems on mass timber roof structures. In either case, a durable membrane system, such as a two-ply, modified bituminous membrane, is recommended over single-ply membranes because the wood substrate and structure are more susceptible to deterioration than are other substrates when exposed to moisture. Construction moisture management is critically important for mass timber roof construction; temporary waterproofing remains a practical solution for most cases.

The key to ensuring durable wood construction is to first prevent excessive moisture accumulation and to allow wood to dry if it gets wet during construction and in service.

7.1 INTRODUCTION

This chapter addresses building enclosure (building envelope) and durability design considerations for tall wood buildings in Canada.

> **Marketability/Profitability**
>
> The low thermal conductivity of wood and the ease with which fenestrations are accommodated or cladding is attached makes mass timber the ideal material for highly energy-efficient building enclosures. With the automated fabrication of mass timber panels, fenestrations in each exterior panel may be unique.

Wood structures, and specifically light-wood-frame building enclosures, have a long history of successful performance throughout Canada and abroad. The environmental loads (primarily wind, rain, and temperature and moisture differentials) and structural loads (primarily wind, seismic, and snow) acting on the building enclosure of a tall building constructed of wood are the same as those acting on an equivalent-sized building constructed of steel or concrete, but they are greater than those acting on a low-rise light-wood-frame building. Design parameters, such as vertical differential movement resulting from wood dimensional changes and loads, are taken from the vast experience gained from designing and monitoring multi-storey light-wood-frame building enclosures. The intent of this chapter, therefore, is to generally define the loads and effects of loads that act on taller buildings and to consider them in the context of tall wood buildings.

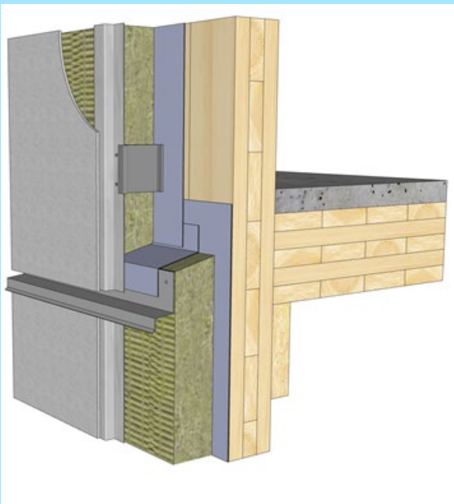
The following building enclosure design guidelines and building science references are available in Canada and provide design and construction guidance for durable and energy-efficient, wood-based building enclosures (see Section 7.9: References for additional documents):

- *Building Enclosure Design Guide* (BC Housing, 2020)
- *Building Envelope Thermal Bridging Guide* (Version 1.5, BC Hydro et al., 2020)
- *CLT Handbooks* (Canadian version: Karacabeyli & Gagnon, 2019; American version: Karacabeyli & Douglas, 2013)
- *Guide for Designing Energy-Efficient Building Enclosures* (Finch et al., 2013)
- *Nail-Laminated Timber: Canadian Design and Construction Guide* (Binational Softwood Lumber Council and Forestry Innovation Investment, 2017)
- *Building Science for Building Enclosures* (Straube and Burnett, 2005)
- *Builder's Guide for North American Climates* (Lstiburek 2004–2009)

The building enclosure design fundamentals described in these publications may be applied to tall wood buildings, but because most recommendations for wood building construction and design are applicable only to buildings up to 6 storeys high (the current maximum building height in some jurisdictions), caution is urged when considering the design of buildings surpassing such heights. Many assemblies, details, or materials that are appropriate for use in low-rise light-wood-frame buildings may not be suitable for taller buildings due to the increased environmental loads, increased durability expectations, and greater sensitivity to enclosure failures.

This chapter provides key building enclosure design considerations specific to tall buildings—and particularly, the aspects of design for tall wood buildings that differ from those for low- and mid-rise buildings, within the various climate zones of Canada. The chapter is organized to take the reader from an understanding of the key building enclosure loads and building and energy-related code requirements through to a summary of the fundamentals of building enclosure design, building enclosure assemblies, and detailing strategies; it then concludes with a discussion of wood protection and durability, including on-site moisture management and use of wood for exterior applications.

7.2 BUILDING ENCLOSURE SYSTEMS



Three-dimensional cutaway of a typical rainscreen cladding design at a CLT wall/floor line.

The building enclosure is a system of materials, components, and assemblies that physically separate the exterior environment from the interior environment(s). The building enclosure primarily manages heat, air, and moisture transfer, and with the heating and ventilation systems, helps maintain a controlled and healthy indoor environment. It also forms a key passive design element of an energy-efficient building and is the most important system for ensuring the durability of a tall wood building.

The elements of the building enclosure include roofs, above- and below-grade walls, windows, doors, skylights, exposed floors, the basement/slab-on-grade floor, and all the interfaces and details in between. Because the focus of this guide is on tall wood buildings, only considerations for wood-based, above-grade wall and roof assemblies that are different from other high-rise structures are addressed. Detailing considerations for fenestration, such as punched windows or curtain wall assemblies, and other components or penetrations through these wood assemblies are also discussed, where appropriate. Below-grade concrete and other non-wood assemblies are not within the scope of this chapter.

The structural system of a tall wood building has a significant effect on the selection and design of building enclosure assemblies. Several wood-based structural/enclosure wall and roof systems that could be used in a tall wood structure are considered (Figure 1):

- traditional light-wood-frame construction (either platform or balloon framed);
- light-wood-frame or mass timber infill/panel enclosure on non-wood structures;
- post-and-beam or mass timber framing with non-load-bearing enclosure; and
- wood roofs: light-wood-frame or mass timber.

Mass timber includes products and systems, such as glued-laminated timber, cross-laminated timber (CLT), nail-laminated timber (NLT), dowel-laminated timber (DLT), and mass plywood panel (MPP), and structural composite lumber products, such as laminated strand lumber (LSL), laminated veneer lumber (LVL), oriented strand lumber (OSL), and parallel strand lumber (PSL). Alternate systems, such as aluminum or wood curtain wall assemblies, are also discussed.

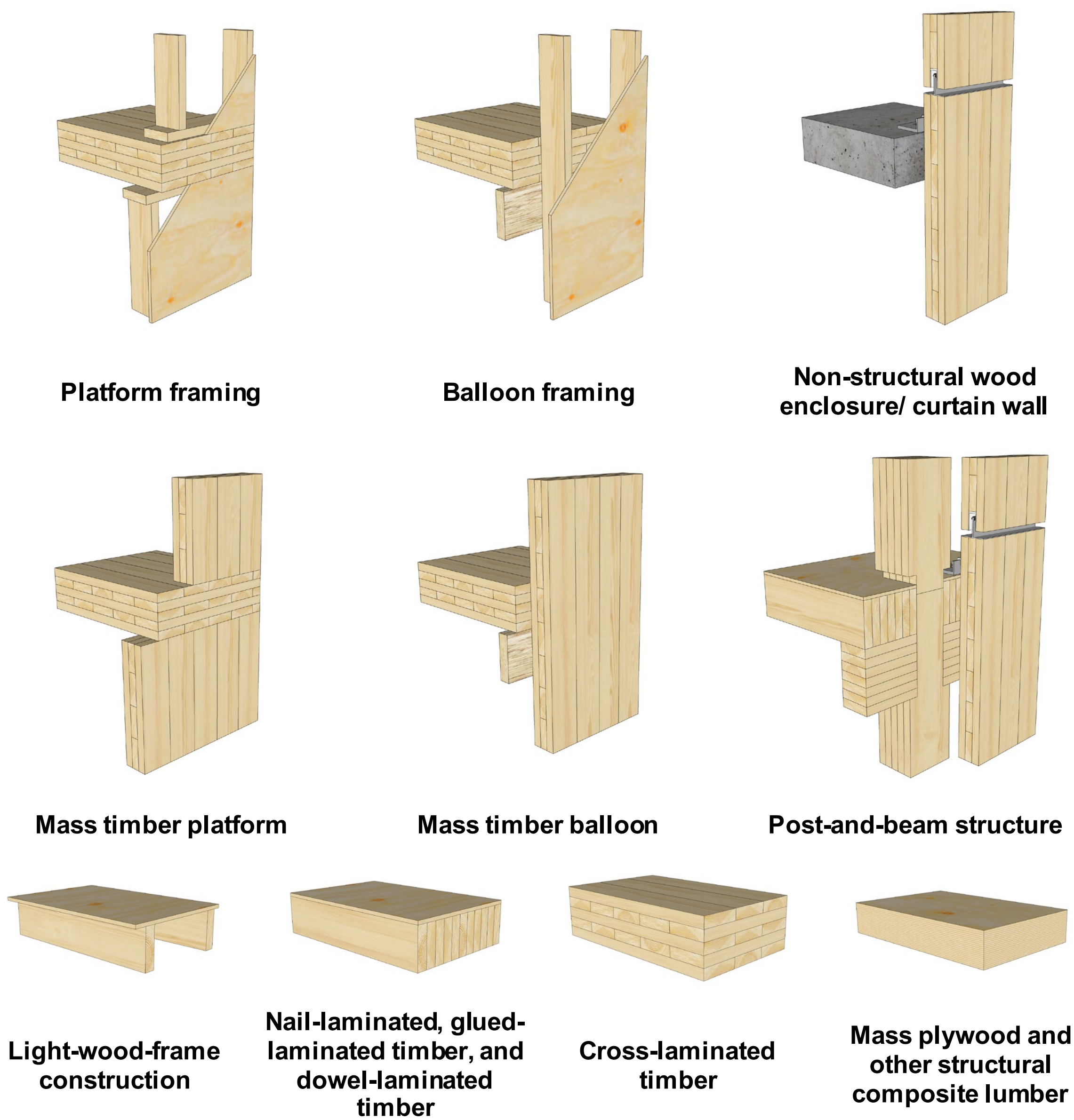


Figure 1. Examples of structural and exterior wall and roof systems that use wood components.

The structural system typically dictates the location and properties of thermal insulation that is used in the exterior wall or roof assemblies. The insulation used affects the appropriate location and materials used for the control of air and vapour transfer and may also affect fire safety and acoustic performance. The structural system also affects thermal bridging considerations and the thickness of exterior walls, which may have implications with regard to usable floor space and building setback restrictions. Structural movement between load-bearing and non-load-bearing assemblies must be detailed so that non-load-bearing components are not unintentionally loaded, and air and water seals between these interfaces are maintained over the life of the building.

> **Regulatory Acceptance**
>
> Due to greater interest in highly energy-efficient building envelopes, many innovative products and building techniques are being developed to improve performance or simplify construction. It is important that such product or designs do not negatively affect the drying capacity of an exterior wood assembly (see Sections 7.5 and 7.6).

7.2.1 Traditional Framing

Most modern, low-rise light-wood-frame structures (up to 6 storeys high) are constructed of solid sawn or engineered wood in dimension lumber sizes and wood-based panels (i.e., plywood, oriented strand board [OSB]) where the wood roof trusses, floor joists, and load-bearing stud walls carry all the structural loads (i.e., gravity, wind, and seismic) of the building. The components that manage heat, air, and moisture transfer (for example, the insulation between and outboard of the wall studs, which manages heat transfer) are constructed within and around the light-wood-frame structure and protect the structural components from the exterior environment. The design and construction of such light-wood-frame building enclosure assemblies are well understood across Canada, but there are limits to the structural capacity of light-wood-frame construction. The structural loads beyond 6 storeys require larger and heavier structural wood components for most parts of the building; thus, traditional light-wood-frame enclosure assemblies may need to be adapted to one of the alternate systems discussed below.

7.2.2 Non-load-bearing Light-Wood-Frame Exterior Walls

Six-storey heavy timber office building (Bullitt Center in Seattle, Wash.) using timber columns and steel framing for lateral loads. Building enclosure components consist of non-load-bearing infill walls and aluminum curtain wall components placed outboard of the structure.

Light-wood-frame components still have an important place in taller buildings, though: for example, non-load-bearing light-wood-frame interior walls within a mass timber, steel, or concrete building, where traditionally steel stud, masonry, or concrete infill walls may have been used. Light-wood-frame may also be used in non-load-bearing applications in exterior walls to improve thermal performance and provide economic and other benefits. Traditionally, this type of structure has not been widely used in Canada. Fire and building code requirements are being updated to allow the use of wood enclosures on larger buildings (see Chapter 6).

Although non-load-bearing exterior walls do not carry the gravity load of the structure, they need to be designed to accommodate and transfer wind loads to the primary structure. Also, the movement and deflection of the primary structure, as caused by the environmental loading, needs to be considered in enclosure detailing.

Just as with traditional load-bearing framing, non-load-bearing light-wood-frame building enclosure components protect the structural components from the exterior environment and wetting from interior sources (e.g., condensation due to vapour diffusion or air leakage).

7.2.3 Post-and-Beam

Post-and-beam framing has been used in many buildings where larger spans or exposure to heavy timber framing is desired. Infill spaces between large wood beams and columns are typically filled with non-load-bearing light-wood-frame walls, mass timber panels, or even non-wood enclosure assemblies. Mass timber panel floors and roofs are commonly used with this structure. The structural interaction of the non-load-bearing components with the load-bearing components is a consideration in the enclosure assembly design.

7.2.4 Mass Timber

Mass timber construction using CLT panels (Origine, 13-storey building in Québec City, Que.). Insulation and critical control barriers are placed outboard of the CLT panels. This is ideal for the long-term durability of the wood structure. Further information about recommended wall assemblies for CLT buildings is provided in this guide and several referenced industry guidelines.

Mass timber construction uses CLT or other engineered timber products, such as glulam, NLT, DLT, LSL, LVL, OSL, and PSL. Mass timber construction may consist of solid wood shear walls, cross-bracing, columns, beams, roof, and floors, part of which also forms the building enclosure. Interior load-bearing walls and posts may also be used as part of the structure. Light-wood-frame infill walls—whether load-bearing or non-load-bearing—may also be used within mass timber structures where mass timber components are not needed. Insulation and other components of the building enclosure are typically constructed on the exterior of the solid timber components but may also be designed with interior applications.

Other building enclosure systems, such as light-steel-framing, may also be used in a mass timber structure. Further guidance on enclosure assemblies that use mass timber (e.g., CLT) walls and roofs is provided in the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019), the *Mass Timber Building Enclosure Best Practice Design Guide* (Finch & Brown, 2020a), and the *Guide for Designing Energy-Efficient Building Enclosures* (Finch et al., 2013).

7.3 BUILDING ENCLOSURE LOADS

7.3.1 Climate Considerations and Environmental Loads

Over the life span of a building, the building enclosure is subjected to a wide range of exterior environmental elements, including solar radiation, precipitation (rain, snow, ice, hail), high or low relative humidity (RH), and wind. Interior environmental factors include temperature, RH, and water vapour condensation, as well as liquid water from human activities and potential defects in appliances, sprinklers, and interior plumbing. Rain on, and flow over, the exterior surface of the building, as well as differences in temperature, air water vapour content, and air pressures between the exterior and interior environments create critical loads that the enclosure must resist without deteriorating prematurely. Other functions of the enclosure such as fire, smoke, and noise separation must also be maintained.

The location or the climate zone in which the building is constructed dictates the magnitude, direction, and duration of exterior environmental factors on the building enclosure. The National Building Code of Canada (NBC) and provincial building codes provide basic climatic design data (e.g., average temperatures, heating and cooling degree days, design wind pressures, rainfall, and snow loads) for locations across Canada. Every climate zone requires unique design, construction, and maintenance considerations. In general, colder climate zones have more stringent requirements for insulation and condensation control (greater control of vapour and air leakage) than warmer climate zones. In addition, a low indoor RH during winter can cause issues with excessive wood shrinkage, surface checking, and human occupant discomfort. Rainy marine climates pose a challenge to wood buildings in terms of keeping the wood dry during construction (see Section 7.7.1: On-site Moisture Management) and in service (see Sections 7.4 and 7.5 for appropriate rainwater management). Construction in the Far North and Arctic is subject to unique challenges, given that buildings are exposed to extreme cold and permafrost.

In addition, potential climate change scenarios and their effect on a building's environmental loads may need to be considered in building enclosure designs, both from a durability perspective and for energy performance. Potential effects on the durability of buildings due to climate change are covered in the CSA standard *CSA S478: Durability in Buildings*. For example, typically drier areas may require more robust rain protection measures than previously used if the frequency and/or intensity of rainfall events increases. Areas with warming temperatures should consider the potential increased cooling load and increased need for solar shading. Greater wind gusts, fire frequency, and flood risks may also be new considerations, depending on location.

Climate maps provide information on standard climate zone and rainfall classifications (Figure 2), and are useful for determining key design factors across Canada as they are currently understood.

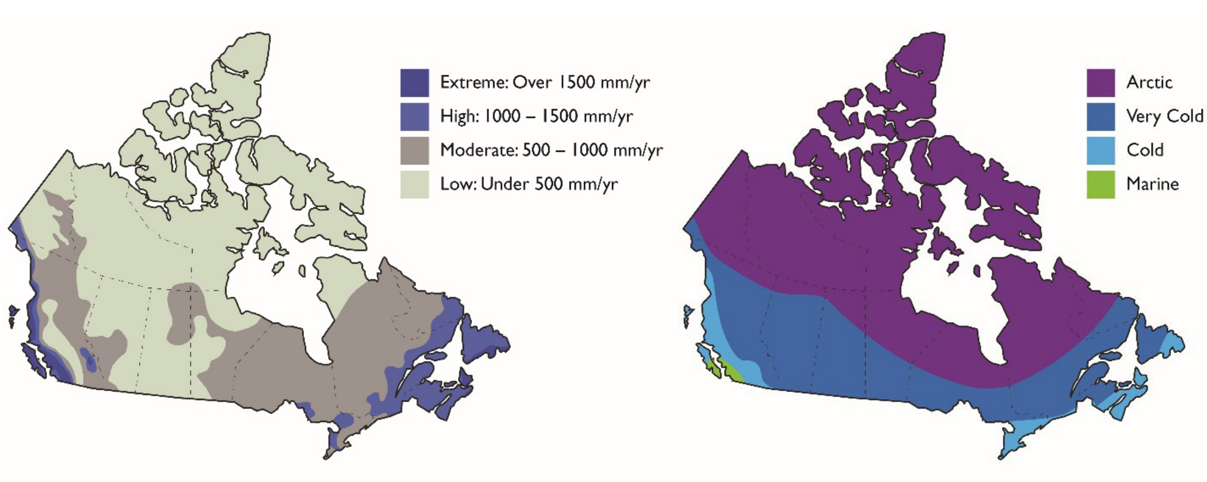


Figure 2. Climate maps of Canada showing annual rainfall (left) and general climate zone classifications (right).

7.3.2 Building Movement and Structural Considerations

The building enclosure must safely accommodate the structural loads acting on it (e.g., dead load, live load, wind, and seismic) and transfer those loads to the primary structure. This is particularly relevant for the attachment of claddings, curtain wall systems, windows, and exterior doors, as well as air barrier materials subjected to wind and seismic loads in taller buildings. Structural attachments that penetrate thermal insulation are a source of thermal bridging and heat loss, and optimization of structural connections is an important design consideration for an energy-efficient building enclosure.

> In tall wood buildings, extra attention should be paid to the enclosure design. Potential high inter-storey lateral drift and vertical differential movement over the height of the building could occur due to wind and seismic loads and wood moisture content changes over time. Tolerances will depend primarily on the structural design and the materials used, and will be provided by the structural engineer for incorporation into the building enclosure design. Tolerances of other integrated materials, such as concrete slabs, should also be considered.

The movement of the primary structural system—resulting from settlement, wood shrinkage and swelling, and structural loads (e.g., compression, deflection, creep, and lateral drift) relative to the building enclosure—is another factor that must be considered in the design of building enclosure assemblies and details. Settlement occurs during and after construction, and load-induced movement, such as compression and deflection, should be within a safe limit for a structurally sound design. Movement caused by wood dimensional changes also warrants careful consideration in design.

Wood dimensional changes due primarily to moisture content (MC) changes from the construction stage (resulting from exposures to high RH levels or construction wetting) to service become more significant in taller wood buildings. It is well documented that dimensional changes affect traditional light-wood-platform-framed buildings as low as 2 storeys high, and that mid-rise wood buildings, which have greater susceptibility, require adoption of details that can accommodate differential movement of wood. Wood dimensional changes also affect buildings that incorporate CLT and glulam beams.

Wood exchanges moisture with its surroundings, and the amount of moisture gain or loss depends on the ambient RH and temperature and the existing MC level in the wood. Adjacent materials (e.g., fresh concrete or recently mudded drywall) may influence the local environment and consequently the wood MC. Wood achieves equilibrium moisture content (EMC) under nominally constant environmental conditions (Figure 3); for example, the MC of wood converges to 12% at an RH of approximately 65% and a temperature of 20°C. The seasonal MC increases and decreases that occur in service are often much smaller than those from initial construction to service; however, in some Canadian climates and building types, it is possible for wintertime RH levels to be as low as 10–20% and summertime RH levels to be as high as 60–70%, which causes several percent MC changes over seasons.

Wood shrinks when losing moisture and swells when gaining moisture up to a MC corresponding to the fibre saturation point, which typically occurs when the MC is between 26 and 30%, depending on the wood species and where within the tree the wood was extracted (e.g., heartwood versus sapwood). The amount of shrinkage or swelling is somewhat wood-species dependent and can be computed from the wood's shrinkage coefficient and the percentage change in MC below the fibre saturation point. The shrinkage or swelling of solid wood (such as dimensional lumber and solid wood timbers) occurs primarily across the grain and is generally negligible in the longitudinal direction or along the grain. Figure 4 shows the approximate relationship between MC change and dimension change (i.e., shrinkage) for typical wood species. The calculation method for wood shrinkage/swelling can be found in relevant standards and design publications (e.g., CSA 2019). Most wood design publications recommend using an average shrinkage coefficient of 0.20% or 0.25% for each percent change in MC for cross-sections (perpendicular to the grain) of softwood lumber.

End splits within a CLT panel due to liquid water exposure and subsequent drying, and the longitudinal wood restricting shrinkage/movement.

Engineered wood products, such as CLT and glulam, usually have significantly reduced shrinkage compared to "S-Dry" dimensional lumber (which is typically produced with an MC below 19%), primarily because the MC of lumber used for CLT and glulam (typically between 12 and 14% MC) is much closer to the EMC in service, and therefore reduces the MC change from the time of installation to in service. The hygrothermal properties of wood also ensure that short timescale fluctuations in ambient humidity and temperature (e.g., hours and days) do not appreciably affect the MC in the core of the wood member; therefore, the wood largely maintains its dimensions. Another benefit of engineered wood is that it can be designed to control unwanted expansion or contraction (e.g., cross-laminated timber bonds tangential wood to longitudinal wood with adhesive, which restricts undesired movement).

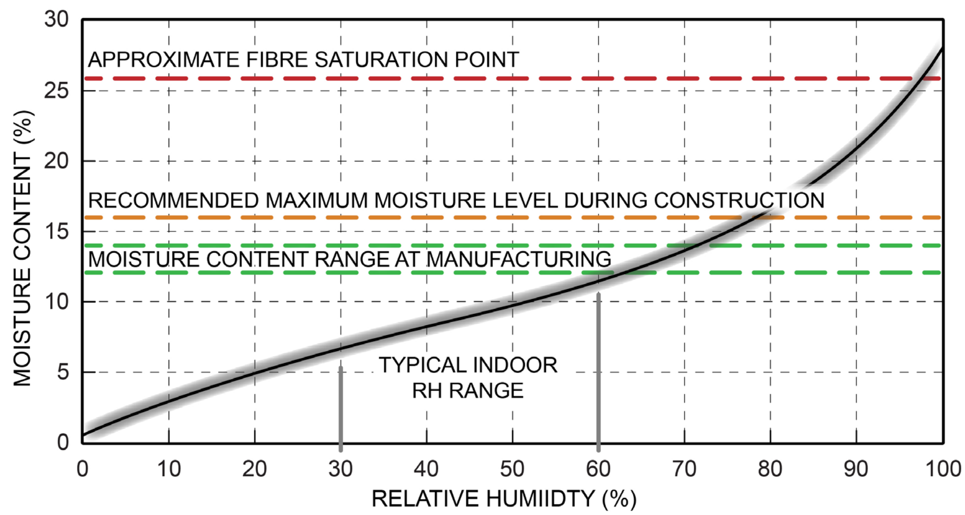


Figure 3. Relative humidity versus moisture content for typical softwood species, and typical range of moisture content for mass timber and relative humidity (adapted from BC Housing, 2020).

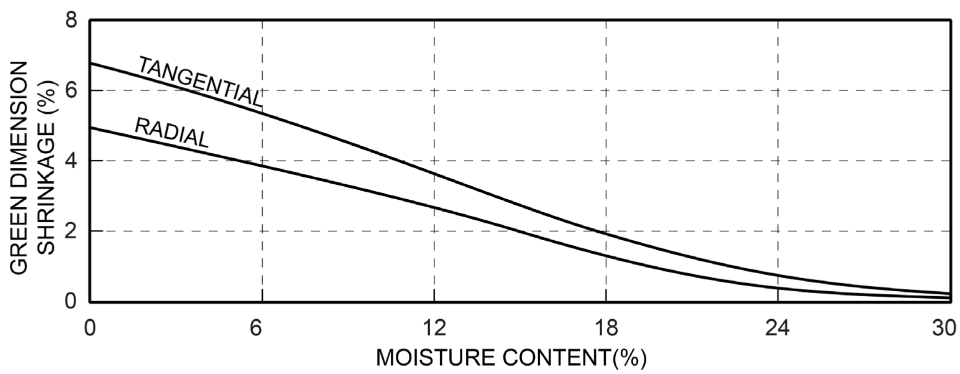


Figure 4. Typical moisture content-shrinkage curves (adapted from USDA, 2010).

For buildings, it is the differential movement that occurs between connected parts and components that matters. Differential movement may occur between wood and other materials, such as steel, concrete, glass, and masonry. For those materials, thermal expansion or contraction rather than MC changes may govern dimensional changes. Differential movement may also occur between different wood components due to different products, grain orientations, or exposure to different environments (exterior and interior). For example, differential shrinkage may be noticeable across floors that are supported on conventional platform-framed walls at one end and on wood columns or CLT panels at the other end.

Several field monitoring studies have been conducted in Canada to measure and document vertical movement in both light-wood-frame construction and mass timber buildings from 4 to 18 storeys high (Munoz et al., 2012; Mustapha et al., 2017; Wang, 2016b; Wang and Ni, 2014; Wang et al., 2013, Wang et al., 2016). FPInnovations has provided guidance on estimating differential movement based on long-term field monitoring and laboratory testing. In summary, the two main methods for reducing potential building/differential movement are:

- avoiding/minimizing cross-sections of wood in the gravity load path (i.e., loading perpendicular to the grain), such as by using a balloon-type structure or connecting columns without horizontal wood members between them; and
- using wood that is below 15% MC and kept below that level through the entire construction phase, and adopting construction moisture management strategies to achieve this (see Section 7.7.1).

Building Performance

Understanding how wood dimensions change with moisture content will help the design detailing process. When possible, have the wood moisture content as close to what is expected in-service. If this is not possible, having a lower initial moisture content is generally not problematic, provided some allowance is made for swelling from exposure to moisture.

7.4 BUILDING AND ENERGY CODE CONSIDERATIONS

In Canada, two national model codes specify building enclosure and energy-efficiency design provisions for buildings: the National Building Code of Canada (NBC) (NRC, 2020) and the National Energy Code for Buildings (NECB) (NRC, 2017). These national codes are adopted with or without modifications by each of the provinces and territories; those adopted provincially are identified as provincial building codes. In addition to the provincial codes, some local jurisdictions, including the City of Vancouver, have a modified version of the provincial building code written into their municipal building bylaws. In addition to these codes, provinces and municipalities may reference external standards or other energy performance requirements.

7.4.1 Canadian Building Code Considerations

The design of the building enclosure of a tall wood building is addressed in Part 5: Environmental Separation of the NBC, or in the relevant provincial building codes. NBC Part 5 is concerned primarily with controlling moisture accumulation, excessive heat loss or gain, interior temperatures, deterioration, health and safety, biological growth, transfer of gas from the ground, and sound transmission. The application of NBC Part 5 to a tall wood building is similar to the application to other high-rise buildings. Fundamentals of building enclosure design that meet the objectives of Part 5 are addressed in this chapter.

The 2020 NBC (NRC, 2020) includes requirements for encapsulated mass timber construction (EMTC) buildings up to 12 storeys high. Currently, the Québec Construction Code and the British Columbia Building Code have amendments to include the NBC EMTC allowances. The related fire regulations and design recommendations are provided in Chapter 6.

7.4.2 Canadian Energy Code Considerations

The NECB (NRC, 2017) and ASHRAE Standard 90.1 (ASHRAE, 2019) specify minimum energy performance requirements. The adoption of either or both of these energy standards (and the edition of the standard) as the minimum energy-efficiency requirements varies by province.

> The BC Energy Step Code (BCBC 9.36.6) is a compliance option in the BC Building Code that provides an incremental and consistent performance-based approach to achieving more energy-efficient buildings that go beyond the requirements of the base BC Building Code. The BC Energy Step Code does not prescribe how to construct an energy-efficient building, but it identifies an overall energy-efficiency target that must be met.

Additional energy-efficiency requirements beyond these standards can also be implemented by the provinces. For example, British Columbia references ASHRAE 90.1-2019, NECB 2017, and a compliance pathway under the BC Energy Step Code, where four steps are provided for large buildings to achieve net-zero-energy-ready performance by 2032. In Ontario, the Supplementary Standard SB-10 (SB-10) adds additional building enclosure requirements to both the NECB and ASHRAE 90.1, and references ASHRAE Standard 189.1-2014: Standard for the Design of High-Performance Green Buildings except Low-Rise Residential Buildings as an energy performance compliance option.

In all these energy standards and codes, the building enclosure, along with the mechanical and electrical systems and components, must all meet minimum criteria and work together to reach an overall minimum energy-efficiency target outlined by one of the various compliance paths.

Compliance with the building enclosure provisions of the NECB or ASHRAE Standard 90.1 requires meeting some minimum prescriptive and mandatory requirements as well as one of the three alternate building enclosure compliance pathways. In order of lowest to highest complexity and level of effort required to demonstrate building project compliance, the three pathways are as follows: Building Envelope Prescriptive Path, Trade-off Path (Option in ASHRAE), and Building Energy Performance Path (Energy Cost Budget Method in ASHRAE). There are some slight differences between ASHRAE 90.1 and the NECB within the Building Energy Performance Path: notably, ASHRAE 90.1 is energy cost based and NECB is energy consumption based. Future simulation requirements may include greenhouse gas emissions.

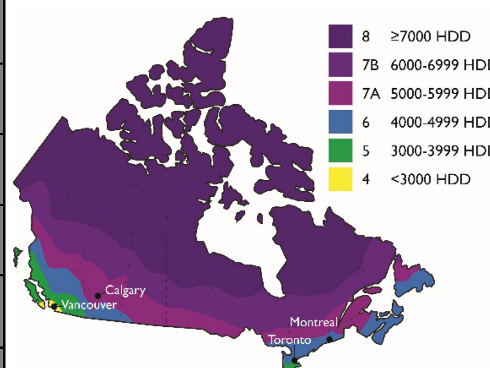
With regard to the selection and design of building enclosure assemblies and components, in both the ASHRAE and NECB energy standards and all the compliance paths, the effective R-value or U-value of each building enclosure assembly needs to be determined and implemented, or some minimum nominal prescriptive insulation level needs to be installed.

Nominal insulation R-values are the rated R-value of the insulation product, as determined under standard testing conditions and not taking into account energy losses due to thermal bridging or differing temperature conditions. Effective R-values are a truer representation of thermal resistance of an insulated assembly and account for thermal bridging. Thermal bridging occurs mostly through structural elements (e.g., framing, fasteners), penetrations through the installed insulation (e.g., window-to-wall interface), and other interfaces (e.g., roof-to-wall interface). Within the opaque enclosure parts of a tall wood building, thermal bridging occurs primarily through wood framing (e.g., studs, columns, floor slabs, solid shear walls) as well as through cladding attachments through exterior insulation. While the degree of thermal bridging within a tall wood building is typically less than that of a steel or concrete frame building due to the much higher thermal resistance of wood than steel or concrete, it still needs to be considered in design (BC Hydro et al., 2020).

Continuous insulation, defined in ASHRAE 90.1 as "continuous across all structural members without thermal bridges other than fasteners and service openings", is required in the ASHRAE and NECB standards. This continuous insulation requirement is commonly addressed with exterior rigid or semi-rigid insulation installed on the exterior of the structure. Continuous insulation could also be installed in the interior or within the middle (sandwich construction) of some assemblies, although it would be difficult to maintain continuity across floor levels in multi-storey buildings. Most wall and roof assemblies for tall wood buildings that are recommended in this guide incorporate continuous insulation on the exterior of the wood structure.

Figure 5 summarizes the minimum prescriptive thermal insulation requirements in the NECB 2017 and ASHRAE 90.1-2019 for above-grade light-wood-frame walls and roofs (flat roofs) in climate zones across Canada. Requirements for other building enclosure assemblies, including windows, doors, skylights, below-grade assemblies, and floors, are provided in both standards. These minimum effective R-values are good baseline targets for building enclosure assemblies in tall wood buildings. However, most of these prescriptive effective R-value targets are higher than the current standard for light-wood-frame construction (i.e., batts within 2x6 studs) in many jurisdictions of Canada, which will eventually require more highly insulated assemblies. Several options for wood-based wall assemblies that can meet these higher targets are outlined in Section 7.6.1. For reference, the approximate R-value ranges likely needed to reach Step 2 through 4 of the BC Energy Step Code are also included in Figure 5.

Climate zone	NECB 2017 above-grade wall and roof minimum effective R-values (RSI)	ASHRAE 90.1-2019 above-grade wall and roof minimum effective R-values (RSI)	Potential BC Energy Step Code Steps 2–4 target effective R-values (RSI)
Zone 4	Walls: 18.0 (3.17) Roofs: 25.0 (4.41)	Walls: 15.6 (2.75) Roofs: 30.9 (5.43)	Walls: 20–30 (3.5–5.3) Roofs: 25+ (4.4+)
Zone 5	Walls: 20.4 (3.60) Roofs: 31.0 (5.46)	Walls: 19.5 (3.44) Roofs: 30.9 (5.43)	Walls: 20–30 (3.5–5.3) Roofs: 30+ (5.3+)
Zone 6	Walls: 23.0 (4.05) Roofs: 31.0 (5.46)	Walls: 19.5 (3.44) Roofs: 30.9 (5.43)	Walls: 20–30 (3.5–5.3) Roofs: 30+ (5.3+)
Zone 7A	Walls: 27.0 (4.76) Roofs: 35.0 (6.17)	Walls: 19.5 (3.44) Roofs: 30.9 (5.43)	Walls: 20–30 (3.5–5.3) Roofs: 40+ (7.0+)
Zone 7B	Walls: 27.0 (4.76) Roofs: 35.0 (6.17)		Walls: 20–30 (3.5–5.3) Roofs: 50+ (8.8+)
Zone 8	Walls: 31.0 (5.46) Roofs: 40.0 (7.04)	Walls: 31.2 (5.49) Roofs: 35.9 (6.33)	Walls: 30–40 (5.3–8.8) Roofs: 50+ (8.8+)



NECB climate zone HDDs

Figure 5. Minimum effective R-value requirements for above-grade wall and roof assemblies in NECB 2017 and ASHRAE 90.1-2019, target effective R-values for Step 2 of the BC Energy Step Code, and NECB and ASHRAE 90.1 climate zones (HDD = heating degree days).

Where the minimum effective R-values cannot be prescriptively met, one of the two alternate trade-off paths (Trade-off Path [Option in ASHRAE] and Building Energy Performance Path [Energy Cost Budget Method in ASHRAE]) must be followed. In these paths, addressing the largest source of heat loss, such as windows, and choosing products with higher-than-code-minimum R-values can be used to offset the heat loss at walls or roofs that do not meet these criteria.

Recent trends in Canadian construction have made high-performance energy-efficient buildings a viable option for many new projects, especially residential and commercial tall buildings where government regulations and incentives may support better-than-code-minimum buildings. Passive House and Net Zero Energy buildings employ highly insulated and airtight assemblies, among other energy-efficiency measures, to achieve very low levels of energy use for heating and cooling. These buildings are usually designed, constructed, and certified based on third-party programs and go well beyond current prescriptive code minimums.

7.5 BUILDING ENCLOSURE DESIGN FUNDAMENTALS

7.5.1 Moisture Management and Control

Appropriate moisture management is critically important for achieving long-term durable performance of tall wood buildings. The major moisture sources for building enclosures are rain, snow and ice, ground moisture, construction moisture, and water vapour. The frequency and intensity of wind-driven rain is a prime factor in determining the amount of water likely to be delivered to the enclosure from the environment. Snow and ice (i.e., snow loads) are also contributors to the risk of water penetration and material damage. Ground moisture is the determining factor for the design of wood members and assemblies that come in contact with or are adjacent to grade. The use of detailing and/or preservative treatment to protect structural wood components near grade, in contact with grade, or potentially near contact with grade in the future is very important for maintaining the durability of a tall wood building.

Occupants also generate a significant amount of indoor moisture, which should be taken into consideration in design. In larger buildings, there are often other significant moisture sources, including recreational areas with pools, hot tubs, kitchen areas, and rooms with higher humidity levels, which call for special attention to moisture management in the enclosure. The relationship between the interior environment and building enclosure is influenced by many factors: assembly details; airtightness; design and operation of the heating, ventilation, and air conditioning (HVAC) system; interior space layout; and type of usage and occupancy of the space. Because of the nature of occupancy and the typical ventilation systems used, residential buildings tend to have higher indoor moisture levels than commercial or institutional buildings; therefore, some residential building enclosure assemblies sometimes have a higher moisture risk from interior sources.

7.5.1.1 Wetting and Drying Potential

The design and construction of a building enclosure for the purpose of moisture management is a process of balancing moisture-entry mechanisms (wetting) and moisture-removal mechanisms (drying). Wetting can occur as a result of exterior moisture (rain, groundwater, snow, vapour) and interior moisture during building operation, as well as construction moisture. Drying mechanisms include drainage, airflow, and vapour diffusion. Unlike non-hygroscopic materials, wood materials have an inherent capacity to safely store moisture or act as a moisture buffer. Provided safe moisture levels are not exceeded, this moisture storage capacity will allow for seasonal or short-term storage of moisture until drying occurs.

An imbalance in wetting, drying, and safe storage from moisture may result in moisture accumulation and deterioration of less moisture-tolerant materials. Heat flow through building enclosure assemblies plays an important role in determining the balance of these mechanisms. Thermally efficient building enclosure assemblies are potentially more sensitive to moisture accumulation than less insulated assemblies due to reduced heat flow through the assembly, lower temperatures of the exterior components, and associated lower drying potential. To improve the balance in favour of drying, strategies such as placing insulation on the exterior side of the wood structure are used because the insulation helps keep the wood warmer and consequently drier because of greater evaporation/diffusion potential. Other strategies discussed in this guide include the recommended use of vapour-permeable membranes and insulation materials to facilitate drying of mass timber components, which themselves are relatively vapour impermeable.

Wood and wood-based materials always contain some moisture; the amount varies over time with exposure to humidity and water. Fortunately, the EMC of wood exposed to humidity alone is generally below levels conducive to the growth of decay fungi. As a general rule, liquid water needs to be present for some time to create decay conditions (i.e., sufficient exposure for the wood MC to be kept well above the fibre saturation MC of 26%). Sustained high-humidity conditions, coupled with moderate temperatures, may be an exception to this rule; under these conditions, the likely presence of liquid water on the surface of wood can be sufficient to initiate fungal growth. Designing wood assemblies to keep members away from liquid water and high humidity is essential for avoiding decay.

Large wood members such as CLT, NLT, LVL, mass plywood panel, and glulam have a much higher wood mass on a cross-sectional basis than conventional wood stud or plywood sheathing, and therefore have a higher moisture storage capability. The corollary is that moisture that is absorbed into the mass timber assembly may dry at a much slower rate than in a conventional wood framing and sheathing assembly. For further guidance on moisture management for mass timber components, see Table 2 in Section 7.7.1.

Note that while a well-designed and constructed building enclosure system will protect the wood components once fully constructed, the moisture exposure and wetting of the wood when exposed during construction can be significant if not managed, and can have long-term effects on the performance of the assembly after construction. Therefore, construction-phase moisture protection is an important consideration for wood building projects. See Section 7.7 for the potential consequences of excessive wetting, and additional wood protection and durability solutions for different mass timber products and assemblies.

7.5.1.2 Control Layers and Critical Barriers – Assembly Design and Detailing

A primary function of the building enclosure is to control or appropriately manage environmental loads. Various materials are used within enclosure assemblies and details to perform different control functions depending on their material properties and placement. The notion of control functions, and more specifically **control layers**, may help explain the function of different materials (or material layers) within building enclosures and aid designers in the selection of appropriate materials. The following control functions are typically considered: water (precipitation, ground), water vapour, air, heat, sound, fire, light, and contaminants.

In applying the concept of control functions and control layers, the term **critical barrier** is used to describe layers and components that must be essentially continuous for the enclosure to perform as designed. Specific critical barriers, such as a **vapour retarder/barrier** or **air barrier**, are also defined within an enclosure assembly. This chapter also refers to a **water-shedding surface (WSS)** (first plane of protection, in the terminology of the NBC and provincial building codes) and a **water-resistive barrier (WRB)** (second plane of protection) to facilitate discussion of water penetration control strategies. In addition to the vapour retarder/barrier, air barrier, and primary moisture control layers, the thermal insulation and building form and features may be evaluated in this context. Noise and fire control layers could also be evaluated in a similar manner.

To establish the link between the concept of control functions and the associated critical barrier, Figure 6 shows the related primary and secondary relationships. The use of building form and features such as canopies is discussed in Sections 7.5.1.2.6 and 7.5.1.3.

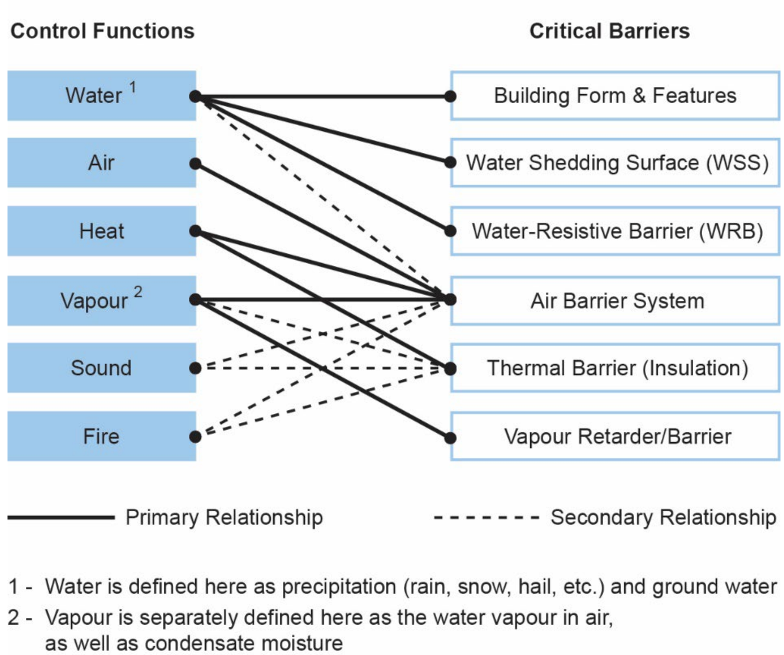


Figure 6. Primary building enclosure control layers and associated critical barrier functions.

In tall wood buildings, many assemblies and details will be new or unfamiliar to design teams and contractors. The application of the critical barrier concept can help all parties better understand the role and importance or functions of certain materials and details. The following sections further discuss each critical barrier and associated control functions. Additional guidance on the selection of critical barriers and the detailing of connections is provided in existing building enclosure guides (BC Housing, 2020; Finch et al., 2013).

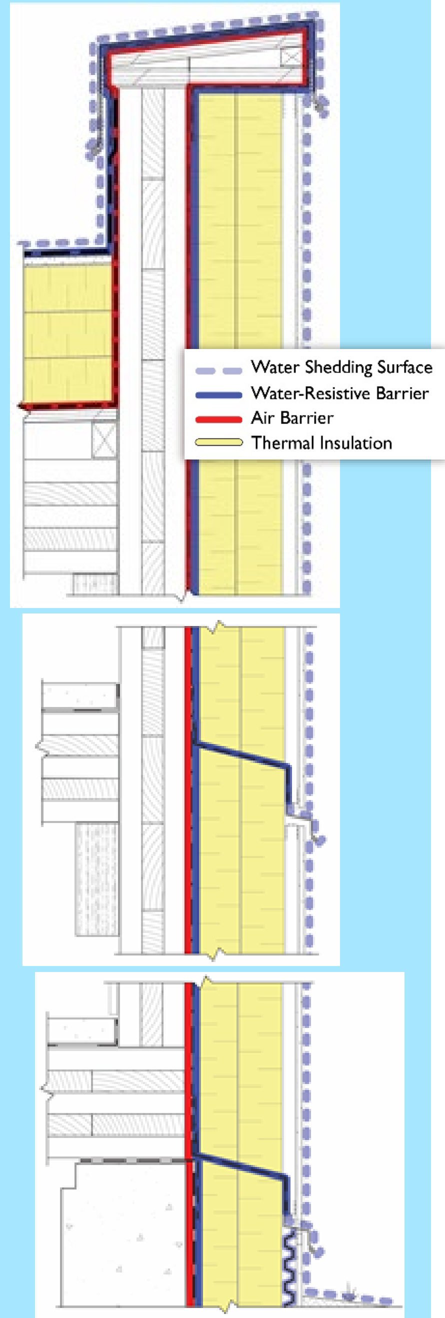
7.5.1.2.1 Water-Shedding Surface

In general, the water-shedding surface (WSS) is the outer surface of assemblies, interfaces, and details that deflect and/or drain most of the exterior water from the assembly. In simple terms, it is the exterior surface of the building enclosure and part of the water control function. Some WSSs also perform as a water-resistive barrier function. The WSS reduces the rain load on the underlying elements of the assembly. For wall assemblies, the WSS is the cladding surface; for conventional roofs, it is the roofing membrane; and for protected membrane roofs, it is the top surface of the insulation. The WSS concept may be used to encourage designers to consider the differences between various types of claddings, such as fibre-cement, brick, open-jointed panels, etc. For example, open-jointed rainscreen claddings, and porous claddings, such as brick veneer, allow a significant amount of water past the WSS. It becomes particularly important for the walls with these claddings to drain moisture out of the wall, typically with a more robust WRB. The exterior surface of the building enclosure is also exposed to solar and UV radiation and serves a solar control function.

7.5.1.2.2 Water-Resistive Barrier

The water-resistive barrier (WRB), also called the moisture barrier, has the following characteristics:

- It is the surface or layer farthest from the exterior that can safely manage moisture exposure and prevent liquid water from travelling further into the assembly. It has an integral water control function and is often relied upon to maintain watertight assemblies.
- For many standard wall assemblies, the WRB consists of a water-resistive membrane (e.g., sheet, self-adhesive), in combination with flashing and sealants at penetrations, that sheds any incidental moisture back out of the assembly. It may also be the surface of the exterior insulation if it is taped and sealed to prevent water entry. Where the WRB is also part of the air barrier system, it is made airtight by tapes, sealants, gaskets, and other airtight components.
- WRB materials may be vapour permeable or impermeable depending on the location and other functions the WRB may be performing within the wall. In most wood wall



Example of critical barrier analysis for an exterior-insulated CLT wall detail from low- slope roof parapet to grade. Note: The wall air barrier and WRB are the same material (in this case, a self-adhered sheet-applied membrane) applied to the outside of the CLT panel.

assemblies, the WRB is vapour permeable to facilitate drying toward the exterior; but it may be vapour impermeable if the assembly (e.g., roof) can safely dry toward the interior under any circumstances (e.g., integration of interior ventilation). In all cases, the materials selected for the WRB must be durable and remain in service for the life of the assembly.

7.5.1.2.3 Air Barrier

The air barrier is a system of materials that controls the flow of air through the building enclosure, either inward or outward. Airflow has a significant effect on heat flow (space conditioning), interstitial vapour condensation (water vapour transported by bulk airflow), and rain penetration control. Good airflow control is particularly important for thermally efficient wood-based building enclosure assemblies. Detailed air barrier strategies that are appropriate for taller wood buildings are discussed in Section 7.5.4.

7.5.1.2.4 Thermal Insulation

The placement and continuity of thermal insulation is an important component of a thermally efficient building enclosure. This layer consists of insulation and other low-conductivity materials within an assembly or detail. Evaluating the placement of low-conductivity materials throughout the building enclosure helps identify thermal bridges or any thermal discontinuities that should be addressed by design. Within a wood building, the primary resistance to heat flow is provided by thermal insulation; however, wood components such as CLT panels provide some insulating value and are often installed in a continuous manner. Wood components instead of metal may also be used within details to reduce thermal bridging effects.

7.5.1.2.5 Vapour Diffusion Control

The vapour diffusion control layer consists of a material that retards or stops (barrier function) the flow of water vapour due to vapour pressure differences across enclosure assemblies. In cold climates, which include all of Canada, a vapour barrier (sometimes a vapour retarder) is typically placed inboard of the insulation layer (on the warm or high vapour pressure side) to control outward vapour diffusion into and through enclosure assemblies during the predominant heating seasons. Note that air conditioning (cooling) may reverse the directionality of vapour flow during the summer in many locations in Canada. Continuity of the vapour control layer is not necessary to adequately control vapour diffusion in most cases (i.e., small holes, gaps or tears are not critical, unlike with the air barrier). Vapour diffusion control is not to be confused with bulk airflow control (air barrier), where continuity and sealing of air barrier details are very important; therefore, if the same material is being used to control both vapour diffusion and airflow, it must be tightly sealed as an air barrier. Per part 5 of the NBC, vapour diffusion control layers are not required in assemblies, provided the uncontrolled vapour diffusion will not adversely affect the health or safety of building occupants, the intended use of the building, or the operation of the building's services.

7.5.1.2.6 Building Form and Features

Building form and features are typically less relevant to a tall structure but may be applicable to local assemblies, such as balconies and windows. Features such as canopies can play an important "enclosure" function by deflecting rain, providing sun shade, and buffering wind. The protection they provide may allow for alternate water control strategies to be used at protected areas. For this reason, elements like canopies and large overhangs may be considered to be part of the critical barrier analysis. Conversely, balconies and other exterior architectural elements can also act as water-trapping features unless carefully designed to prevent this. The criticality of building form also depends on climate characteristics, especially rainfall.

7.5.1.3 Control of Rainwater – Assembly and Detail Design

Rain is usually the greatest moisture source for building enclosures, and the control of rainwater penetration is essential across Canada, particularly in coastal climates. While climate zone is an important consideration in the design of building enclosures, the building shape, surface details, height, and exposure are often just as important; for example, a 5-storey building on an open site near Calgary can be exposed to more rain than a suburban house in Vancouver. Tall wood buildings are typically exposed to much greater rain deposition than low-rise buildings, which much of the wood industry has vast experience designing. However, important steps can be taken in the design of a tall wood building to reduce the enclosure's exposure to wind-driven rain and to minimize potential rain moisture loads.

The basic principles of water-penetration control have been well understood for many years. Good summaries are provided by the 4 Ds principles: deflection, drainage, drying, and durable material (Hazleden and Morris 1999). These principles aim to (1) limit, through the use of overhangs, canopies, eyebrows, balconies, drip edges, etc., the amount of water that can come in contact with the building enclosure; (2) facilitate drainage and drying if some moisture does penetrate the enclosure; and (3) use more durable materials to minimize deterioration, particularly when the use of details to deflect rain and the timely inspection and repair of those details and the building enclosure is not possible.

The classification of possible rain control strategies for enclosures is covered by Straube and Burnett (2005). The three strategies applied to wall assemblies are perfect barrier (also referred to as face-seal or concealed barrier), mass wall, and imperfect barrier "rainscreen" (drained and vented, drained and ventilated, and pressure moderated). In general, multiple lines of defence should be provided to control water penetration, and a rainscreen approach should be used for any tall wood structure.

7.5.1.3.1 Rainscreen

A drained or screened approach (often termed a rainscreen) acknowledges that some water will penetrate the outer surface of wall assemblies, and provides surfaces and a cavity (drainage space) behind it to help control rain penetration. A rainscreen strategy for controlling water penetration of wood-based walls has the following characteristics:

- a WSS (the "screen" of the rainscreen);
- an airspace behind the cladding that is large enough, vented/ventilated, and drained to the outside;
- a WRB (drainage plane), such as a sheathing membrane, inside the drainage space (WSS and WRB are separated); and
- drain holes or gaps through the WSS so the water can leave the cavity, with flashing at penetrations and transitions (e.g., base of wall, doors, and windows) to direct draining water to the outside away from the surface of the WSS.

The use of open rainscreen claddings (perforated water- shedding surface) is becoming common in many building designs. The open joints in many of these cladding systems allow more water to pass through the WSS and therefore increase the moisture load on the drainage system and WRB. These systems may also allow UV radiation to reach the WRB (which is often subject to UV degradation). The use of these claddings requires careful consideration and detailing on more exposed buildings.

A better approach, especially for tall wood buildings, is to use details and materials that provide the appearance of an open rainscreen cladding (e.g., black painted metal hat-tracks, black synthetic membranes behind the joints) and that prevent penetration past the WSS.

In addition, many rainscreen wall assemblies also have a continuous air barrier system at the WRB (i.e., one membrane that serves both functions) to improve the control of rainwater penetration.

The drainage space also creates a capillary break to prevent liquid water and water vapour from migrating further into the assembly, and provides an opportunity for air movement to facilitate drying. Common practice in high-rise buildings is to form a 10- to 25-mm cavity using intermittent cladding attachments such as metal hat-tracks, clips, or masonry ties. An air cavity is also often included in cladding designs to accommodate dimensional variations. A large gap allows for easier detailing at interfaces, and absorbs tolerances in structural elements (slabs, columns) often seen in taller buildings, without obstructing drainage or drying ability.

A rainscreen can achieve three basic levels of performance:

- If the drainage space behind the cladding allows for movement of air, a vented system that enables lateral diffusion and mixing of cavity and outdoor air can be created.
- If the drainage space allows easy airflow, with vent holes large enough and arranged to facilitate airflow through the cavity, the assembly may be considered to be ventilated and has a much-improved drying capability (i.e., drained and ventilated rainscreen).
- If some attention is paid to the details of cavity size, the compartmentalization and stiffness of the cladding, and the air barrier, some degree of pressure moderation (reduction of the wind-induced pressure drop across the cladding) can be achieved; therefore, less water will penetrate past the cladding surface (i.e., a drained and ventilated and pressure-moderated rainscreen).

Compartmentalizing the cavity in rainscreen wall assemblies can help moderate the pressure drops over the cladding or stop high-speed wind around corners. For tall wood buildings, some compartmentalization may be warranted. This can be accomplished by vertically blocking the cavity (resisting horizontal flow) at building corners and possibly at some intermediate locations. Note that efforts to compartmentalize should never compromise the capacity for drainage and ventilation.

The presence of multiple lines of defence (e.g., WSS and WRB) separated by a drained cavity provides enormous benefits. Unplanned holes in the inner and outer surface are generally not aligned so that direct rain passage by momentum is prevented. Water that passes through the WSS is driven either by gravity or air pressure differences. It tends to run down the back side of the cladding where it can be intercepted and drained back to the outside at a cross-cavity flashing location.

Exterior insulation within rainscreen cavities may also act as a secondary drainage plane for incidental water that penetrates the WSS and rainscreen cavity. With these features, the amount of water that reaches the inner surface of the cavity and remains in contact with potentially moisture-sensitive materials is greatly reduced. This kind of detail incorporating multiple lines of defence provides redundancy that is important for the durable performance of tall wood buildings.

For a tall building in Canada, drained and ventilated assemblies are recommended regardless of climate zone (Figure 7). This applies to the walls, windows, curtain walls, joints, and other interfaces exposed to rainwater. Drained enclosure approaches are already common in most high-rise construction in many parts of the country, and are increasingly used for low-rise light-wood-frame buildings. To address combustibility concerns of possible flame spread through rainscreen cavities during a fire, the air gap width must typically be less than 25 mm and should be compartmentalized at every floor level.

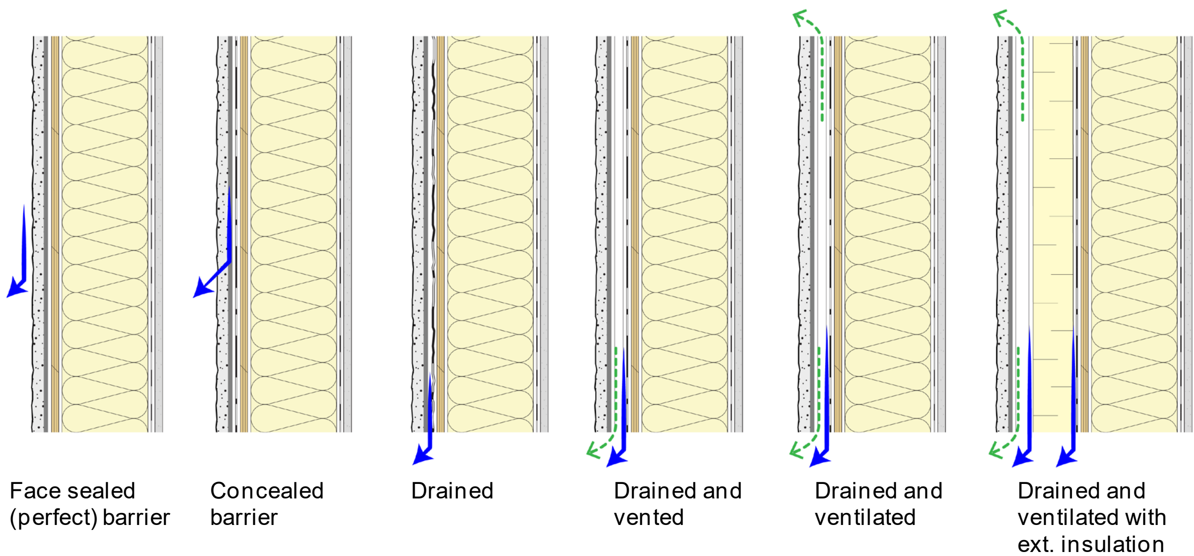


Figure 7. Section views of moisture management strategies in above-grade walls, from face-sealed to rainscreen approaches (left to right). Note: Only drained and vented/ventilated systems are recommended for a tall wood structure in any climate.

It is important to note that the use of rainscreen wall assemblies that exhibit good resistance to water penetration and are fundamentally less sensitive to moisture ingress does not eliminate the need for implementing proper details and ensuring acceptable construction practices are used. Improper details are frequently sources of water entry, and as such, critically affect the moisture performance of the assembly. A recommended design strategy is to understand the control functions and identify and label the critical barriers of all building enclosure assemblies and details, as covered in Section 7.5.1.2, such that errors of omission are minimized prior to construction.

7.5.1.4 Accidental Interior Sources of Moisture

Other sources of moisture within a high-rise building include accidental leakage of water from sprinklers, from defects in plumbing, or from water-containing appliances (e.g., dishwashers, washing machines, ice makers, refrigerators, water coolers). Water leakages from these sources can cause major damage to wood and other materials if they are not dried quickly and thoroughly. Therefore, in the design stages, consideration should be given to limiting the spread of water if a leak occurs and to facilitating drying and ease of repair. The design of building enclosure assemblies that have the ability to dry out in the event of a leak or flood is recommended wherever possible. This is discussed further in Section 7.7.2.

7.5.2 Control of Heat Flow and Thermal Bridging

Reducing space-heating energy use is a primary function of the building enclosure. While heat flow through the building enclosure can never be entirely stopped, it can be controlled to reduce total energy consumption and improve comfort. This is achieved by constructing a thermally insulated and airtight building enclosure, which is a fundamental strategy in achieving an energy-efficient building.

There are three primary components in controlling the heat flow in wood building enclosures:

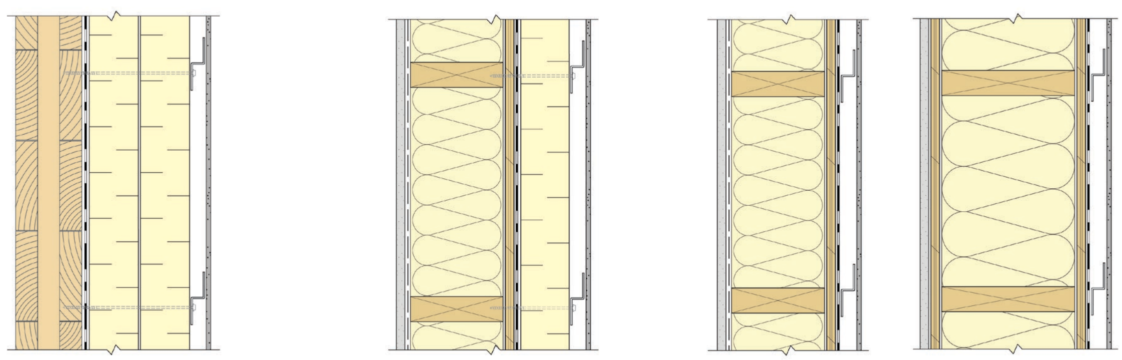
- Solar gain through glazing: Consider the use of the site, the features of the building, and the glazing properties (such as low-E glass) to reduce solar gains in the summer while collecting useful solar gains in the winter.
- Conductive heat flow: Form a continuous thermal control layer by using thermally efficient window frames and glazing, minimizing conductive heat flow through opaque enclosures by using insulating materials, and avoiding thermal bridging (such as at cladding attachments, floor slabs, structural columns, and other interfaces).
- Airtightness: Limit unintentional air leakage through the building enclosure by constructing airtight assemblies (a continuous air barrier system that functions as the air control layer).

Most energy conservation-related regulations target greater thermal insulation levels in opaque building enclosures as being the key strategy for reducing energy use in buildings. In order to achieve effective heat flow control, the continuity of thermal insulation should be maintained through assemblies, and details should be provided to reduce thermal bridging. Because of the modest thermal conductivity of wood (about 400 times less than steel and 20 times less than concrete), tall wood buildings have major advantages in controlling thermal bridging through structural framing as compared to steel or concrete buildings. This is also relevant to mass timber (e.g., CLT, NLT) wall and roof assemblies, where the continuous wood structure contributes to the overall assembly thermal resistance (approximately R-1.2/in.). Effective R-value targets are outlined in Canadian energy codes and in Figure 5.

The placement of insulation plays a key role in the thermal efficiency and hygrothermal performance of a building enclosure assembly. Within a typical wood-based assembly, insulation is placed between the wall studs (interior-insulated) or is divided between the stud cavity and the exterior of the structure (split-insulated) for light-wood-framing, and typically is placed to the exterior of the structure (exterior-insulated) for a mass timber system.

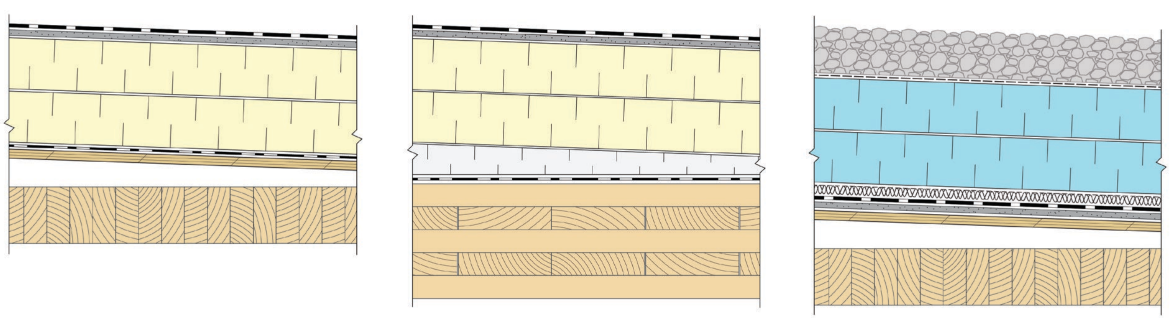
The higher the proportion of the total insulation located outside the structure, the warmer and drier the structure is and, typically, the higher the effective R-value (since there is less thermal bridging through the structural framing). This means that in general, exterior-insulated assemblies are more durable than interior-insulated assemblies, although the latter has a long history of satisfactory performance in Canada. The split-insulated approach may be a good compromise in terms of cost (cavity insulation is cheaper than exterior insulation) and wall thickness; however, such an assembly requires careful design. The hygrothermal performance of a split-insulated wall depends on the thickness and type of exterior insulation, climate, and interior conditions. The design of split–insulated light-wood-frame walls is covered in many of the referenced documents, including the *Guide for Designing Energy-Efficient Building Enclosures* (Finch et al., 2013) and *High Performance Enclosures* (Straube, 2013).

Figure 8 and Figure 9 show various insulation strategies for wood-based wall and roof assemblies, respectively, that are likely to be used within a tall wood building. Other roof assemblies that are more common in low-rise light-wood-frame construction, such as interior-insulated vented or unvented and pitched roofs, would not be common in a tall wood building due to structural requirements for heavier timber components. Other possible enclosure assemblies, such as interior-insulated mass timber walls or roofs, are generally not durable assemblies; therefore, they are not recommended, and so are not discussed in this guide.



Exterior insulated (long screws) | Split insulated | Interior insulated (conventional and deep stud)

Figure 8. Options for placement of thermal insulation within light-wood-frame and mass timber wall assemblies.



Conventional (sloped framing) | Conventional (tapered insulation) | Inverted/protected membrane (sloped framing)

Figure 9. Options for exterior-insulated low-slope roof assemblies.

7.5.3 Condensation Control

Condensation occurs when water vapour in air changes phase to a liquid form. The variables that affect condensation potential include surface temperatures, air temperature, and amount of vapour in the air. Warmer air can hold more moisture. The dew point temperature is a measure of the temperature at which air can hold no additional moisture. Condensation occurs on surfaces that are colder than the dew point temperature of the air to which they are exposed.

Condensation, if not effectively controlled, can lead to damage of finishes, structural components, and other materials of the building enclosure, and it may affect indoor air quality and occupant comfort. Condensation may become an even more important issue for highly insulated building enclosure assemblies, and is a critical issue for cold climate buildings with high interior RH.

In heating-dominated climates (i.e., regions in which heating is required during the winter), there are strategies for controlling condensation:

- Reduce indoor humidity: Control indoor humidity levels by providing sufficient ventilation year-round or using mechanical dehumidification during the summer in more humid climates, such as in many areas of central and eastern Canada.
- Keep wood surfaces warm (thermal insulation): Place insulation so that wood surfaces are on the warm side, and avoid using thermally conductive materials to ensure that heat is not conducted away from critical areas. Strategies include placing insulation on the exterior of moisture-sensitive materials, minimizing or blunting thermal bridges, and improving interior air circulation with HVAC systems directed at exterior walls with windows.
- Manage air leakage through the enclosure (air barrier): Control air movement within and through assemblies by means of continuous air barrier systems across the field of the assemblies and at all interfaces.
- Control of vapour diffusion (vapour barrier): Use low-vapour-permeance materials where appropriate; a vapour retarder on the warm (high vapour pressure) side of the insulation may also work provided it is considered appropriate for both the summer and winter months (i.e., a space that is not air conditioned in the summer and heated in the winter).

While these condensation control strategies seem simple, they can become complicated because materials used to keep water vapour from moving into an assembly can also restrict water vapour from moving out of it. This is a problem in situations where some drying is necessary, particularly to facilitate the initial drying of wet building materials (such as wet wood or concrete) or accidental wetting in service, or because of reversal in the primary direction of moisture drive (e.g., the inward drive due to heated moisture in absorptive claddings). For example, exterior foam insulation (e.g., low-permeance foil-faced polyisocyanurate or XPS) in wood-frame assemblies should not be installed over wet sheathing, wet CLT, or other wet wood components, nor should water be allowed to penetrate behind such insulation during construction or in service due to the difficulty of drying.

In addition, the vapour permeability of mass timber, such as CLT wall and roof panels, is low enough in most constructions that additional interior vapour diffusion control layers (such as polyethylene or vapour barrier paint) are not necessary and could in fact increase risk in many assemblies. Table 1 lists the vapour permeance of CLT at different thicknesses and RH levels. At typical interior wintertime conditions where the RH is low, the permeance of most mass timber panel products is low enough (i.e., less than the often prescribed 60 ng/Pa·s·m^2) that an interior vapour control layer is not needed. The low vapour permeance of mass timber products (e.g., CLT) also makes it very difficult for drying to occur toward the interior when moisture is trapped on the timber product's exterior, such as between mass timber and low-permeance exterior insulation.

Table 1. Vapour permeance of CLT at various thicknesses and relative humidity levels (Alsayegh et al., 2013)

Relative humidity	Vapour permeance ng/Pa·s·m^2 (US perms)		
	100 mm (4 in.)	150 mm (6 in.)	200 mm (8 in.)
20	3.4 (0.06)	2.3 (0.04)	1.7 (0.03)
50	18.0 (0.31)	12.0 (0.21)	9.0 (0.15)
80	59.0 (1.00)	39.0 (0.68)	30.0 (0.51)

Vapour permeance of materials in assemblies must therefore be carefully selected in the context of the permeability of the other layers within the assembly and the given climate zone. The control of vapour diffusion is particularly important in highly thermally efficient assemblies.

7.5.4 Air Leakage Control

The control of airflow through the use of air barrier systems is important to minimize rain penetration, interstitial vapour condensation, and loss of conditioned air from building enclosures.

Air barrier systems are required for buildings in all Canadian climate zones. Air sealing measures are prescriptively called for in the NBC, NECB, and ASHRAE 90.1, along with airtightness requirements for materials and assemblies; however, a whole building airtightness target is currently not required. Overall building airtightness is included in a number of other building codes and programs in Canada and abroad. Typical building airtightness targets are less than 2.0 L/s·m^2 (0.40 cfm/ft.^{2}) of enclosure area (at 75 pascals [Pa] testing pressure). More stringent requirements of less than 1.27 L/s·m^2 (0.25 cfm/ft.^{2}) of enclosure area at 75 Pa, such as that set by the U.S. Army Corps of Engineers, are recommended for a large building target and are an appropriate performance measure for a tall wood building. More stringent energy performance programs such as Passive House, SB-10, and the BC Energy Step Code all include the requirement for a highly airtight enclosure and the completion of building airtightness testing to confirm airtightness levels. The report *Air Leakage Control in Multi-unit Residential Buildings* (RDH 2013), prepared for CMHC, summarizes air leakage control strategies and testing measures, and provides a database for large buildings in Canada and the United States.

In order to function properly, the air barrier system must comply with five basic design requirements (Figure 10):

- **All the components (materials)** of the air barrier system must be adequately air **impermeable**. They must each have an air permeability of less than 0.02 L/s·m^2 at 75 Pa, based on definitions in the NBC. Alternatively, air barrier materials must conform to CAN/ULC-S741: Standard for Air Barrier Materials–Specification. Many materials, such as membranes (polyethylene, exterior sheathing membrane), drywall, and wood-based sheathing (e.g., plywood and OSB) can meet the requirements. **Air barrier assemblies** should have an air permeability of less than 0.2 L/s·m^2 at 75 Pa (10 times higher than material standard), as recommended in the Appendix of the NBC and by several industry organizations, including ASTM (see also CAN/ULC-S742: Standard for Air Barrier Assemblies–Specification).
- The air barrier system must be **continuous** throughout the building enclosure. It must span dissimilar materials and joints, and must be sealed between assemblies and components (e.g., from wall to roof, and wall to window) and around penetrations such as ducts and pipes.
- The air barrier system must be **structurally adequate** or be supported to resist air pressure forces due to peak wind loads, sustained stack effect, or fans, and to accommodate cyclic movement due to thermal and moisture changes and inter-storey drift, etc.
- The air barrier system must be sufficiently **rigid** or be supported so that displacement under pressure does not compromise its performance or that of other assembly components.
- The air barrier system should have a service life as long as that of the wall and roof assembly components; alternatively, it must be easily accessible for repair or replacement (and therefore, must be **durable**).

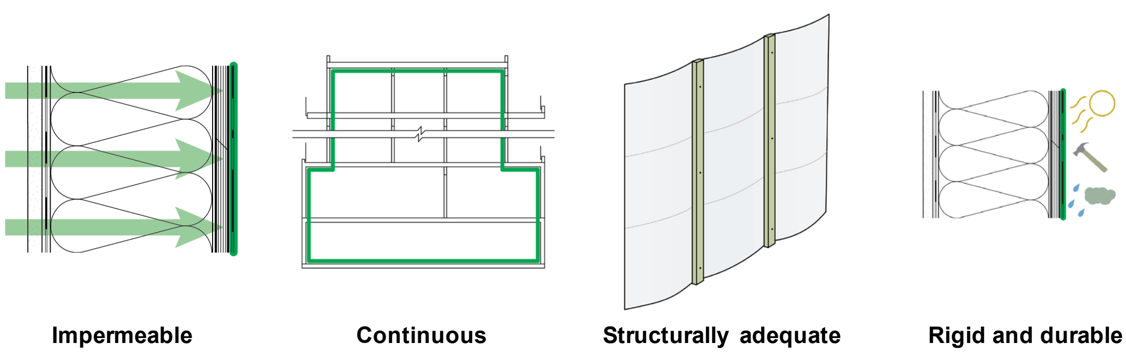


Figure 10. Air barrier design requirements.

Air leakage in a building occurs through unintentional defects, joints, and interfaces in the building enclosure, but also through open windows and mechanical penetrations. In tall buildings, air leakage may account for a significant portion of the space heat loss, depending on, for example, the air-leakage rate, building height and wind exposure, occupant behaviour, and mechanical penetrations. Air leakage in a tall wood building is typically greater than in a low-rise building due to the increased wind exposure, increased stack effect, and mechanical systems, all of which contribute to higher and more sustained differential pressures across the building enclosure.

Air barriers are generally located on either the interior (e.g., polyethylene sheeting, drywall) or the exterior side (e.g., sheathing membrane, exterior insulation) of the wall or roof assembly. The most ideal location for installing the air barrier may depend on ease of detailing, materials, and other factors related to the construction schedule and sequencing. In light-wood-framing assemblies in cold climates, the air barrier is generally installed on the interior side of the insulation (e.g., use of interior polyethylene sheet membranes or airtight drywall) to limit air exfiltration into the assembly, limit convective looping within fibrous insulations, and help prevent moist indoor air from contacting cold exterior sheathing surfaces. Air barrier systems on the exterior side of insulated light-wood-frame walls may be more sensitive to imperfections than interior side air barrier systems, so choice of details and application becomes critical. In cold climates, an air barrier material may also be installed on the exterior side of the wall to prevent wind washing or wind infiltration (e.g., the use of an airtight sheathing membrane or sealed rigid sheathing). Unlike vapour barriers, there is no downside to multiple air barrier assemblies, provided that the materials used for the air barrier do not negatively affect drying via vapour diffusion and a clearly defined primary air barrier system is identified to ensure continuity across all enclosure elements and air barrier systems. Various air barrier systems are discussed in Section 7.6.1.3.

Mass timber construction using CLT panels with self-adhered air barrier membrane installed on the exterior surface.

The air barrier system in building enclosure assemblies, particularly for tall wood buildings, must accommodate the imposed wind load and transfer it to the building structure. In many cases, a combination of materials comprise the air barrier system; however, usually one or two materials play a dominant role in any particular air barrier strategy. For example, vapour-permeable sheathing membranes and tapes are often the key materials in an exterior air barrier strategy, while the exterior sheathing or interior gypsum boards are the key materials in more rigid air barrier systems. The materials and their joints, tapes, and sealant must be capable of staying airtight under applicable wind and air pressure loads. This can be a challenge in a tall wood building, and attention must be paid in design and construction to ensure airtightness.

7.5.5 Noise Control

The building enclosure controls the transmission of undesirable outdoor noise pollution into indoor spaces. Urban noise from vehicle traffic, rail, aircraft, industry, neighbours, etc. is undesirable indoors and interferes with many activities, including conversation, sleep, and concentrated thinking. The components that make up the building enclosure in terms of acoustic mass, sound resistance, and dampening properties, as well as air tightness, affect noise transmission from outdoors. The selection of appropriate windows, wall and roof assemblies, and building enclosure interface details all need to be considered in controlling noise transmission.

In North America, the most widely used rating for sound insulation of building enclosure components is the sound transmission class (STC), which rates airborne sound reduction in the middle- to high-frequency ranges. The STC rating does not properly rate low-frequency noise sources. The STC rating for many common building enclosure components, based on laboratory testing, is provided in several industry sources. STC ratings for windows and glazing are well documented in product literature, as are some common residential building enclosure assemblies (e.g., 2x4, 2x6 stud insulated walls) (Bradley & Birta, 2000). Ratings for less common exterior-insulated and heavy timber wall and roof assemblies that use CLT panels and other engineered lumber products are not readily available at this time.

Currently, there are no noise control/acoustic requirements for the exterior building enclosure in Canadian building codes. The only requirements in codes are for addressing noise control within the building and, more specifically, between units/spaces. This is covered in Section 5.4. While the provincial and national building codes in Canada do not have specific requirements for acoustics in building enclosure design, many municipal planning/building departments have included noise control requirements in municipal bylaws which must be followed. These requirements are often based on NRC/CMHC industry guidelines and frequently contain minimum STC ratings or design requirements, depending on the type of building, site, and proximity to roads, railways, airports, or other industries.

For example, planning departments may require certain STC ratings for glazing or glazing treatments (i.e., use of laminated glass or dissimilar glass pane sizes) for certain building sites (e.g., along busy streets). In some instances, depending on the cladding and wall assembly construction, additional layers of gypsum wall board on resilient channels at the interior of stud-framed walls may be required to achieve the desired performance referenced by the municipal bylaw.

Tall wood buildings will often be constructed in noisier urban areas. The assessment of more traditional light-wood-frame wall and roof assemblies and windows should be relatively straightforward, based on existing performance data; however, the lack of performance data for some of the heavy timber wall and roof assemblies that are used in tall wood buildings makes acoustic design more difficult. Fortunately, mass timber panels, insulation materials, and gypsum drywall generally have good acoustic properties (mass and dampening), and these assemblies typically meet municipal requirements. Most often, windows have the lowest STC rating compared to walls or roofs, and therefore are often the limiting component.

Additional guidance on noise control for building enclosures is provided in the *City of Vancouver Noise Control Manual* (Wakefield Acoustics, 2005) and in some older references, including

Controlling Sound Transmission into Buildings (Quirt, 1985), *Road and Rail Noise: Effects on Housing* (CMHC, 1981), and *Laboratory Measurements of the Sound Insulation of Building Façade Elements* (Bradley and Birta, 2000).

7.5.6 Fire Control

The building enclosure can also play a key role in controlling the spread of fire and smoke. In a fire scenario, the building enclosure must remain intact for a certain period of time to limit flame spread on the exterior or limit flames from entering the building, primarily to allow occupants to safely escape, which includes limiting their exposure to fire and preventing structural collapse. Within a tall wood building, which uses wood structural elements and light-wood-framed building enclosure assemblies, this presents some challenges for designers, as discussed in Chapter 6. In general, the building enclosure components must be protected from fire, and the cladding and cladding system should be designed so that they do not contribute to the spread of fire up the exterior of the building. This generally means using noncombustible claddings, cladding supports, and insulation (mineral wool), and providing protection of wood components (similar to other high-rise buildings). But there are exceptions for encapsulated mass timber construction (EMTC).

The use of foam plastic insulation (XPS, EPS, polyisocyanurate, spray foam) within wall cavities could contribute to fire load and smoke production, and is therefore discouraged for most applications. To address combustibility concerns of possible flame spread through rainscreen wall cavities, the air gap width must typically be less than 25 mm and void spaces must be compartmentalized, such as with fire blocking, at every floor level.

The basic premise of the approach to fire protection in tall wood buildings is addressed in Chapter 6, which states that all structural timber components must be fully encapsulated to prevent them from contributing to a fire, except as allowed by the EMTC provisions or where it is specifically demonstrated that reduced—or no—protection is permitted. In general, mass timber panels that form exterior walls also require protection from fire on the inside, as discussed in Chapter 6.

The 2020 NBC (NRC, 2020) includes requirements for EMTC buildings up to 12 storeys high. For exterior cladding, the building code permits the use of combustible wood cladding and cladding systems containing combustible components (i.e., foam plastic exterior insulation, membranes, and cladding supports), provided that the system conforms to specific performance criteria outlined in NBC Article 3.1.5.5, when tested to a full-scale exterior fire, as prescribed by CAN/ULC-S134: Standard Method of Fire Test of Exterior Wall Assemblies. This test is intended to represent an appropriate design fire for exposure to both a window plume and exterior fire impingement. The test assesses whether a cladding system (in this case containing combustible components) will support unacceptable flame propagation up the face of a building. Unfortunately, these full-scale wall fire tests can be quite expensive and time-consuming, and there are few facilities capable to performing such tests. Therefore, most cladding systems and combinations have not been tested, nor will they likely be tested over mass timber substrates; this leads to a reliance on analysis or modelling to demonstrate conformance, which may or may not be considered an acceptable alternative by the authority having jurisdiction. Section 6.11 in Chapter 6 provides additional information on the use of combustible materials in exterior walls, and on new construction specifications for exterior wall assemblies that are deemed to satisfy the performance requirements outlined in NBC Article 3.1.5.5 (NRC, 2020).

Exposed wood that is not fire-retardant-treated does not meet NBC Article 3.1.5.5. This Article also stipulates that any combustible cladding that includes fire-retardant-treated wood needs to be exposed to ASTM D2898: Standard Practice for Accelerated Weathering of Fire-Retardant-Treated Wood for Fire Testing (ASTM 2017) prior to testing to CAN/ULC S134; this ensures that the treatment is not subject to degradation due to weathering. At this time, the availability of suitable treatment is limited and costly; therefore, any mass timber exterior walls need to be suitably encapsulated on the exterior face. This could be done by means of exterior gypsum drywall, as confirmed through testing by NRC/IRC in the 1990s (Oleszkiewicz, 1990). However, various forms of noncombustible exterior cladding systems and noncombustible exterior insulation (i.e., mineral wool) would also suffice.

Protection of the building structure and building enclosure is also critical during the construction of a tall wood building. In some cases, encapsulation of the components at various intervals prior to building completion is required (see EMTC requirements). Further information about fire protection during construction is provided in Chapter 6.

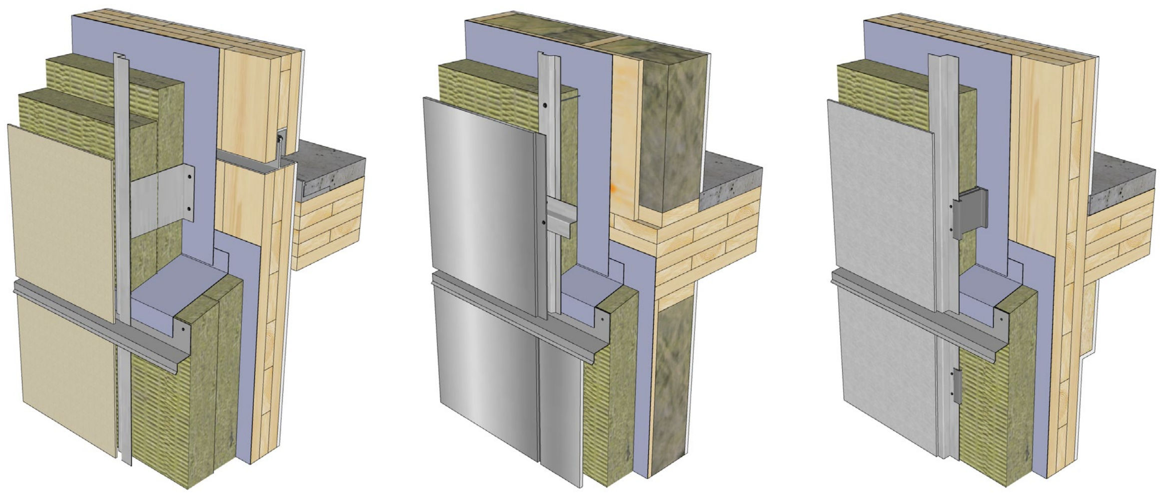
7.6 BUILDING ENCLOSURE ASSEMBLIES AND DETAILS

7.6.1 Wall Assemblies

7.6.1.1 Structure and Insulation

Suitable wall assemblies for a tall wood building generally include a rainscreen cavity (as described in Section 7.5.1) and are either exterior-insulated or split-insulated (as described in Section 7.5.2) to comply with the minimum requirements for thermal performance and for meeting durability objectives (to keep the wood structure warm and dry). Insulated stud-cavity, light-wood-frame walls with drained and ventilated cladding systems may be used within infill panel wall applications; however, in climate zones 5 and higher, a 2x6 wall with glass or mineral fibre insulation (up to effective R-17) does not meet the prescriptive R-value targets in either the 2017 NECB (R-20.4) or ASHRAE 90.1-2019 (R-19.6). Deeper 2x8 or 2x10 walls could be considered, and may be required, for high-rise buildings exposed to greater wind loads. Split-insulated and exterior-insulated assemblies readily meet or surpass the minimum energy standard requirements. Examples of split-insulated light-wood-frame and exterior-insulated CLT wall assemblies with alternate cladding support strategies are shown in Figure 11.

Intermittent metal clip supports | Screws through insulation with continuous metal furring | Proprietary low-conductivity clip and rail system



Exterior (Intermittent metal clip supports)

- Cladding (WSS)
- Airspace (ventilated)
- Steel hat-track/furring and intermittent metal clips
- Semi-rigid mineral fibre insulation (thickness to meet R-value requirements)
- Adhered vapour-permeable sheathing membrane (WRB/air barrier)
- CLT panel (vapour barrier)
- Interior finish

Interior

Exterior (Screws through insulation with continuous metal furring)

- Cladding (WSS)
- Airspace (ventilated)
- Steel hat-track/furring and long screws through insulation
- Rigid mineral fibre insulation (thickness to meet R-value requirements)
- Adhered vapour-permeable sheathing membrane (WRB/air barrier)
- Exterior sheathing
- 2x wood framing with batt insulation
- Polyethylene sheet (vapour control where needed)
- Interior finish

Interior

Exterior (Proprietary low-conductivity clip and rail system)

- Cladding (WSS)
- Airspace (ventilated)
- Steel furring and intermittent clips
- Semi-rigid mineral fibre insulation (thickness to meet R-value requirements)
- Adhered vapour-permeable sheathing membrane (WRB/air barrier)
- CLT panel (vapour barrier)
- Interior finish

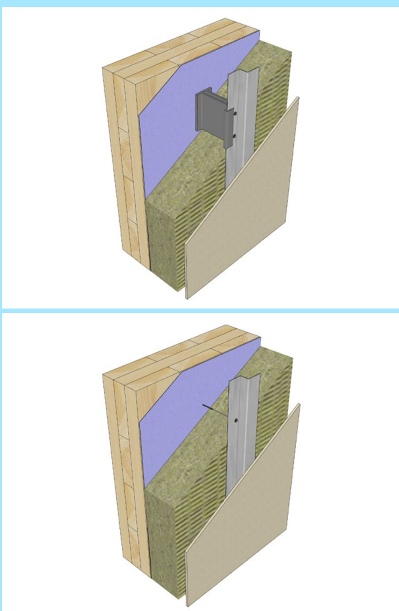
Interior

Figure 11. Examples of exterior-insulated CLT wall assemblies (left, right) and split-insulated light-wood-frame wall assemblies (middle).

The design and selection of appropriate wall assemblies involves controlling exterior moisture (through WSS and WRB, etc.), developing an appropriate air barrier strategy, ensuring insulation with the required properties is selected and correctly placed, attaching and supporting cladding through exterior insulation, and maintaining the correct vapour flow. Effective R-values are dictated by the amount and placement of insulation and the presence of thermal bridges within the assembly. The *Guide for Designing Energy-Efficient Building Enclosures* (Finch et al., 2013) provides an in-depth account of appropriate light-wood-frame and CLT wall assemblies, in addition to calculated effective R-values and typical details. While that guide is generally intended for wood buildings up to 6 storeys high, the design analysis for a taller building is similar, except that the use of more robust and adhered WRB/air barrier membranes and sealants and more durable cladding and fastening systems is recommended. Gypsum sheathing, mineral fibre insulation, and other fire protection measures may also be required for some building types, which would limit the design options for applicable wall assemblies.

The Effective R Calculator web tool (http://www.EffectiveR.ca/) provides the effective thermal resistance for more than 16,000 wall combinations with CLT and light-wood-frame assemblies (Canadian Wood Council, 2020). It also includes a durability assessment for each assembly. Designers can use this tool to demonstrate code compliance or to compare durability options prior to modelling the wall assembly for a performance path solution.

7.6.1.2 Claddings and Cladding Attachment



Intermittent clips and long screws through exterior insulation can minimize thermal bridging from cladding attachment and maximize the thermal efficiency of the insulation layer(s) compared to continuous girts that penetrate the full thickness of the insulation.

Claddings used on high-rise buildings are typically noncombustible and are manufactured from durable and low-maintenance, pre-finished materials, such as aluminum or galvanized steel panels or composites, fibre cement, glass fibre composites, concrete, brick masonry, terracotta, and glass. Curtain wall assemblies made of glass and aluminum, and a range of spandrel panel claddings, are also common. Where rigid claddings are used, appropriate joints must be provided to accommodate potential vertical differential movement and lateral drift of the tall wood structure, which may be greater than that of a comparable concrete or steel structure. Claddings are typically separated at floor levels to accommodate such movement and improve moisture management. Attachments for these cladding are similar to those of other noncombustible buildings but take into account the potentially greater movement tolerances.

While potentially desirable from an architectural perspective, the use of fire-resistant wood claddings on a tall wood building should be carefully considered in terms of fire safety, durability, and life span. Very few fire retardants on the market can meet rigorous fire testing requirements (e.g., weathering before fire testing). The use of wood-based cladding, except on lower accessible floors, may also create challenges for building maintenance, as described in Chapter 9.

Cladding attachment can be a source of significant thermal bridging in exterior- and split-insulated wall assemblies. Optimizing structural cladding attachments is important for improving the thermal efficiency of wall assemblies while minimizing exterior insulation and overall wall thicknesses. It is also critically important to adequately consider gravity, wind, and seismic loads so that the claddings perform in service without excessively deflecting, cracking, or detaching from the structure. Many strategies, products, and techniques, some of which have proven to work structurally and thermally, have been developed over the years to meet this challenge. Several of these strategies are presented in existing guides (BC Housing, 2017, 2020; Finch et al., 2013); detailed thermal bridging analysis is provided in the *Building Envelope Thermal Bridging Guide* (BC Hydro et al., 2020).

7.6.1.3 Appropriate Air and Water Barrier Systems for Tall Wood Buildings

Efforts to achieve airtight assemblies in light-wood-frame construction in the early 1980s focused on the use of polyethylene sheet membranes on the interior side of the enclosure, which served a dual function of air barrier and vapour barrier. The polyethylene sheet was stapled to the wood framing but was better secured once the interior gypsum board was installed, which sandwiched the polyethylene between the insulation and the gypsum. This interior air barrier approach is still successfully employed in low-rise light-wood-frame buildings. A variation of this approach—the airtight drywall approach—relies on the interior gypsum board as the primary air barrier, and is also effective for low-rise buildings.

> While the interior air barrier approaches are good solutions for compartmentalization within tall buildings, a more robust exterior air barrier approach can typically better accommodate the high air pressures that the exterior building enclosure resists.

While these two approaches are excellent for achieving interior compartmentalization (i.e., airflow control between suites/areas of the building), they are often unreliable for the exterior building enclosures because tall wood buildings are subjected to significantly higher air pressures than those of low-rise buildings.

In general, if there is exterior access, an exterior air barrier approach can be simpler to implement than an interior approach because it does not interface with numerous interior elements such as framing or service penetrations for electrical and plumbing. Also, because the components of the exterior air barrier are often also used as the water-resistive barrier, the effort and care required to achieve a continuous layer to resist moisture intrusion also contributes to the overall continuity of the air barrier.

Based on experience with high-rise steel and concrete buildings and 4- to 6-storey light-wood-frame construction, there are several possible approaches for achieving good airtightness in tall wood buildings, as described below. More details are provided in existing guides (BC Housing, 2017, 2020; Finch et al., 2013).

7.6.1.3.1 Exterior Air Barrier Approach

The exterior air barrier approach requires a robust membrane to be installed over the exterior face of the building structure and made into a continuous air barrier assembly with tape, additional membrane, and sealant over joints, transitions, and penetrations. While mechanically fastened systems are commonly used on low-rise light-wood-frame construction, this approach is not appropriate for taller buildings because significantly higher design wind loads on upper storeys may cause tearing of the membrane. Self-adhered membranes, on the other hand, rely on adhesion to the substrate and at membrane laps, and therefore are far more robust than mechanically fastened membranes. The membrane must be sufficiently flexible to accommodate potential vertical and horizontal building movement, especially when used with CLT.

The exterior membrane used on wood-based walls should be vapour permeable in most cases to allow drying toward the exterior. When a vapour-impermeable membrane (e.g., modified asphalt peel-and-stick or torch-applied roofing membrane) must be used (e.g., within a roof assembly), measures should be taken to ensure that the assembly can safely dry toward the interior within an acceptable period.

7.6.1.3.2 Liquid-Applied Membrane

Exterior liquid-applied membranes share many of the advantages of self-adhered membranes and are especially useful for complex detailing. Liquid-applied membranes rely on a supporting substrate to provide a continuous backing to achieve an airtight barrier. Joints in liquid-applied systems typically require specific detailing considerations and often incorporate membrane reinforcement. Liquid-applied membranes are generally used as the water-resistive barrier, and therefore must be installed and detailed as such. The substrate and weather conditions can have a significant effect on curing time and adhesion. In general, CLT panel is not a suitable substrate for a liquid-applied membrane because joints and gaps between boards may widen when the wood becomes drier.

7.6.1.3.3 Other Approaches

Panelized systems, such as unitized curtain or prefabricated façade systems, use proprietary air sealing methods, such as internal gaskets, or rely on sealant applied once they are installed. Prefabricated conventional wall panels, using an exterior air barrier system applied in the factory, are also becoming more common in residential construction. The panels are installed on-site with a gasket or sealant air seal at the perimeter joints between panels and at interfaces. The primary challenge with panelized systems is maintaining an air-tight seal at the joints between components, especially where concealed gaskets are used.

Mass timber building enclosure details can pose unique challenges to air barrier detailing practices. CLT panels could be airtight if all wood edges are glued, but gaps between the lumber within each ply and at the panel interfaces will open in service, creating numerous air leakage pathways around and through the edges of the panels. In addition, CLT structural connections, including angles and clips, can interfere with and puncture air barrier membranes. For this reason, it is not recommended that CLT panels serve as the air-barrier; a dedicated air barrier membrane should be used. Figure 12 shows some examples of common air barrier details that require special consideration, and Figure 13 shows possible air leakage pathways for parapet and floor level/shear wall conditions if no dedicated air barrier membrane is used.

The installation of robust air barrier membranes, use of construction site mock-ups, and air barrier commissioning will help improve air barrier installation and performance with CLT construction.

Figure 12. Some of the unique air barrier detail considerations required for CLT panel assemblies when used within tall wood buildings: gaps between lumber plies and connections (left), structural anchors interfering with installation of the air barrier membrane (centre), and protruding structural elements (right).

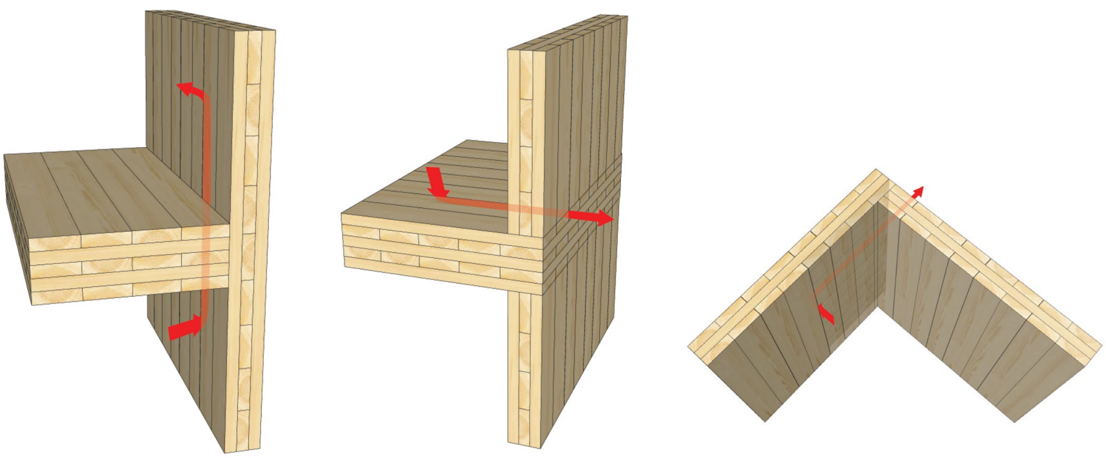
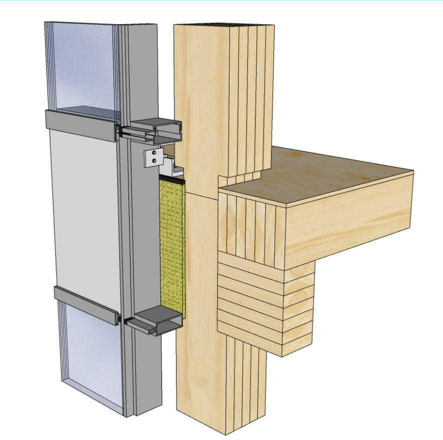


Figure 13. Potential air leakage pathways that need continuous (adhered) air barrier membranes and transitions for CLT wall and roof details.

7.6.1.4 Fenestration Selection and Installation Considerations



Curtain wall assembly integrated into a building using a heavy timber structural system with standard aluminum curtain wall components and anchors bolted into the NLT floor panel. Pay attention to sealing floors at the perimeter when curtain wall is used.

Thermally broken aluminum is commonly used in punched windows, window wall, and curtain wall applications in high-rise buildings. The use of fibreglass, uPVC (vinyl), or wood-hybrid (where properly water-managed) window frames may also be considered in a tall wood building to improve overall building thermal efficiency. Exterior exposed wood window frames are not recommended for use in a tall wood building due to the need for frequent painting and maintenance. However, interior exposed wood frames, such as those in wood curtain wall systems, could function adequately.

The selection of window assemblies that meet appropriate air, wind, and water resistance ratings is critical for a tall wood building to achieve weather tightness of the assembly. For example, the minimum appropriate window for a 10- to 20-storey tall wood building has an AAMA/WDMA/CSA 101/I.S.2/A440-11, NAFS – North American Fenestration Standard/Specification for Windows, Doors, and Skylights performance grade of PG 60 and higher, a water penetration resistance of 510–720 Pa, and a performance class of CW or AW.

The integration of window systems into a tall wood building is straightforward, provided that best practices for installation details are followed. This involves the incorporation of rainscreen details in which the critical barriers of the wall (WSS, WRB, and air barrier, in particular) tie into the window assemblies. The key differences between a wood-based and a concrete or steel-frame tall building are structural connections, as well as potentially larger deflection tolerances. In most cases, standard window anchor components designed for concrete and steel buildings may be used "as is" or with slight modifications to accommodate alternate wood fasteners.

7.6.1.5 Balconies and Horizontal Projections

Balconies are a design feature often incorporated into residential high-rise building designs to provide outdoor living space for occupants. Balcony interface details may increase the risk associated with moisture intrusion and durability, and degrade thermal performance in any type of structure, although at the same time, balcony and other horizontal projections such as eyebrows may provide beneficial rainwater protection and shading of walls below.

Balconies have a history of moisture-related problems in light-wood-frame buildings when poorly executed details and deferred maintenance have allowed water intrusion at the interface between the balcony structure and adjacent wall framing. From the perspective of water management detailing, a balcony is similar to a low-slope roof or deck that intersects the exterior wall, although in practice it may lack the same durable waterproofing membrane as a roof. When properly detailed, this waterproofing membrane is incorporated into the wall assemblies' water control layers, and positive drainage is provided so that water is diverted to drain away from the exterior walls.

Within a tall wood building, there may be a desire to use mass timber elements, such as solid CLT panels, to form the structure of balconies or other horizontal projections, such as eyebrows or canopies. However, any time structural members protrude through the insulated building enclosure, moisture problems are likely to occur from an enclosure detailing and durability standpoint; therefore, their use is not recommended, especially in tall wood buildings, unless exceptional care is taken in detailing and selecting materials.

CLT panels and other types of mass timber products are typically made with wood that is not preservative treated and is vulnerable to decay if it stays sufficiently wet (above fibre saturation of the wood) for an extended duration. If wood decay were to occur in the deck of a balcony, particularly one that is integrated with the floor structure, repairing the structure would be difficult and costly.

Where balconies are incorporated into a tall wood building design using a mass timber (e.g., CLT) structure, it is suggested that they be attached to the structure using discrete bolted connections in lieu of integrated balconies which use the structure's floor slabs projected to the exterior (Figure 14). This approach allows for continuity of the building's critical barriers to be maintained past the slab edge, and for water management details of the balcony to remain isolated from the primary building structure. In addition, this method allows for the balconies to be installed as prefabricated elements with a durable waterproofing membrane, guard railings, and other finishes already in place, and to potentially be made of other structural systems such as metal frame. This method also allows for the balconies to be replaced, if required, with minimal disruption of the weather-protected structural frame.

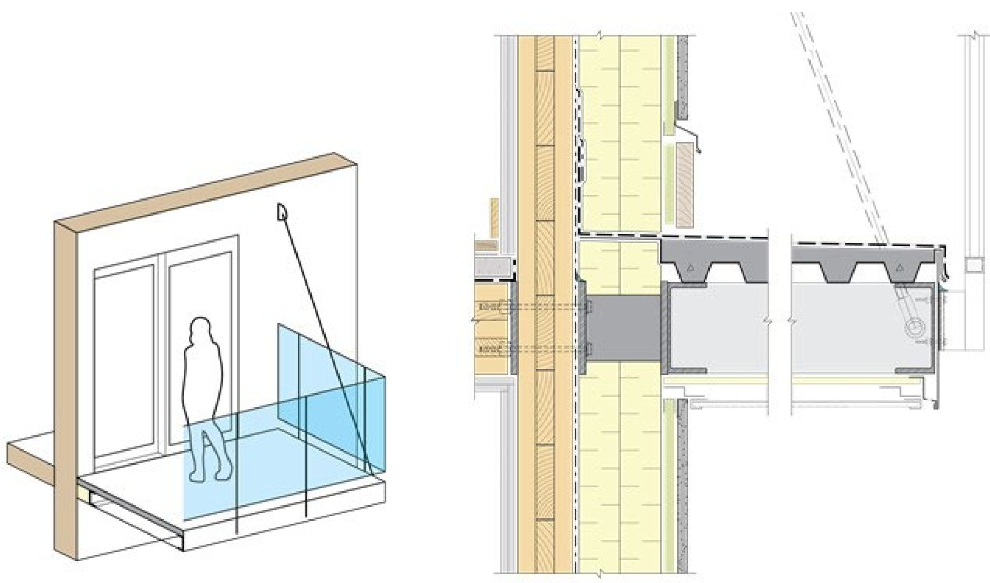


Figure 14. Schematic and detail of the face-mounted balcony approach for mass timber buildings.

7.6.2 Roof Assemblies

7.6.2.1 Structure and Insulation

Tall buildings typically use low-slope roof and roof-deck assemblies. Roof tops are often used for placement of mechanical equipment to provide access for maintenance of exterior walls and for additional outdoor space (roof decks or common amenity space). Pitched roofs may be incorporated as a feature roof but are less common in a tall wood building. In many structural designs, the wood roofing structure behaves as a lateral load-resisting diaphragm element consisting of heavy timber framing or panels. This use of heavier framing, rather than light-wood joists and wood sheathing used in low-rise light-wood-frame construction, dictates certain approaches for a tall wood building.

Insulation is typically placed on the exterior of the wood structure, and either a conventional or protected membrane roofing assembly (also referred to as an "inverted" roof) is recommended for roofs and roof decks. Protected membrane roofs provide greater protection of the roofing membrane and are recommended for roof decks or roofs that receive high traffic.

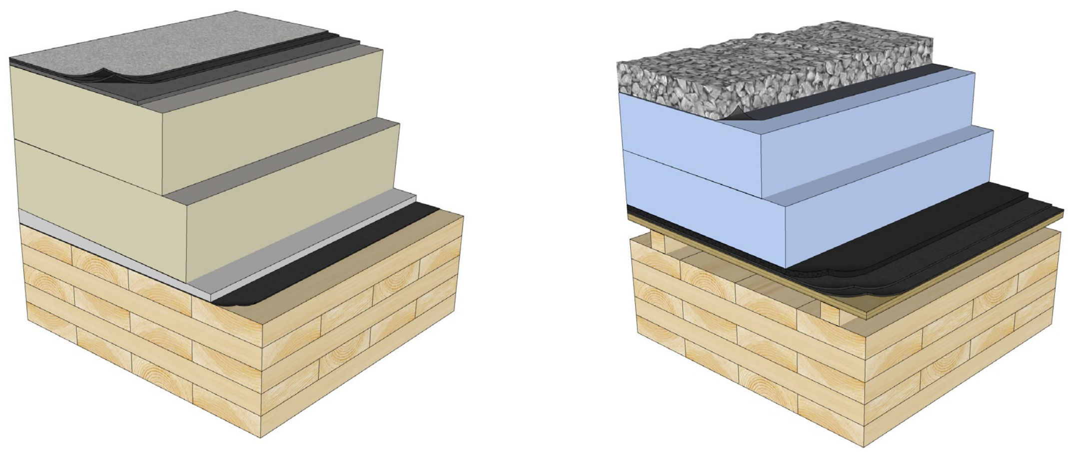
7.6.2.2 Green Roofs

Whether selecting an intensive green roof with deep soil to accommodate large plants and an irrigation system, or an extensive green roof system with shallow soil and no irrigation system, the roof enclosure should be very carefully considered in terms of life span, maintenance needs, and costs in order to mitigate the risk of leaks and resulting damage to the underlying wood structure. A protected membrane roof assembly forms the basis of most intensive and extensive green roofs, with modifications to the design to accommodate specific needs such as a robust root barrier, a drainage layer, a water retention medium, and other aspects related to soil and planting of vegetation. Green roofs can also be established over conventional membrane roofing assemblies by using roof trays or planters. This approach decouples the roof assembly from the vegetation system/growing medium and allows for easier access to the roof membrane for maintenance and repair.

7.6.2.3 Roof Membrane and Drainage

Conventional and protected membrane roof assemblies are designed to control all moisture at the waterproof membrane above the structure/insulation. The waterproof membrane surface and primary drainage surface are coincident, unlike in a wall assembly. The assembly is sensitive to exterior moisture that penetrates at a roof membrane leak location since water can migrate within the structure/insulation and even saturate the roof over prolonged time if undetected. Flat roofs on mass timber buildings require robust roofing systems and detailing, and adequate consistent slopes to drains. Typically, a two-ply modified bitumen membrane system is used as the roof membrane. This may include adhered and/or torch-applied systems. Where torch-applied roofing membranes are used against wood, a protection layer (mechanically attached asphalt underlay board, adhered fire-resistant membranes, or gypsum board) is required to protect the wood from burning, in addition to other measures used to prevent fire when roofing a wood building. Additionally, since all low-slope roofing materials are vapour impermeable, they should be applied only if the wood is dry and the ability to dry to the interior is facilitated in the roof design.

In a mass timber roof deck assembly without built-in slope, the slope to drains (a minimum of 2% is recommended) may be achieved by using either a tapered insulation package or a tapered secondary sheathing substrate above the wood deck. Figure 15 shows both a conventional and a protected membrane roof assembly over a mass timber CLT roof structure and alternate roof membrane slope options where the heavy timber roof structure is not sloped itself (preferred approach where possible). In case wetting occurs before a leak is repaired, the protected membrane roof assembly shown in Figure 15 provides an interior vent/ventilation function to dry the roof by providing a gap between the mass timber and the roof sheathing above. Note that void spaces inside mass timber assemblies (both for sloping and for services) must be appropriately protected for fire safety purposes as required by the applicable codes (including EMTC provisions in the NBC and others). Alternatively, in some building designs, the roofing structure itself could be sloped to drain.



Exterior

- Torch-applied or mechanically fastened roofing membrane
- Protection board
- Rigid roof insulation board (polyisocyanurate, mineral fibre, or EPS) ≥ 2 layers with staggered joints and thickness to meet R-value target
- Tapered insulation sloped to drain
- Adhered or torch-applied membrane (air barrier/vapour barrier)
- Mass timber panel
- Interior finish

Interior

Exterior

- Ballast (concrete pavers or gravel)
- Filter fabric
- XPS insulation, ≥ 2 layers with staggered joints and thickness to meet R-value target
- Drain mat/drainage composite
- Torch-applied or adhered roofing membrane
- Protection board
- Wood framing sloped to drain
- Mass timber panel
- Interior finish

Interior

Figure 15. Low-slope conventional roof (left) and protected membrane roof (right).

To provide real-time ability to detect and isolate leaks before major deterioration of the wood structure occurs, moisture monitoring and leak detection systems can be installed under the roof membrane or into the wood structure. Water leaks are a higher risk in mass timber roofs than in concrete slab or light-wood-frame structures because the leaks may not be immediately observed. Furthermore, the time needed for drying may prolong the repairs.

The *Guide for Designing Energy-Efficient Building Enclosures* (Finch et al., 2013) and the *Mass Timber Building Enclosure Best Practice Design Guide* (Finch & Brown, 2020a) provide in-depth reviews of appropriate roof assemblies and recommended materials, as well as calculated effective R-values and typical details.

As discussed in Section 7.7, constructing heavy timber roof assemblies requires excellent planning and on-site protection in wet climates. Heavy timber roof components, such as structural composite beams and NLT or CLT roof panels, can absorb a considerable amount of water if exposed to rain for a prolonged period during transport or construction. Depending on the time of year, it could take a long time for the wet wood to dry, or drying may need to be assisted by space heating; in either case, the roofing and overall building construction may be delayed. Therefore, on-site protection is important, and the assembly design should allow adequate drying. Aesthetically, staining is also likely to occur on the wood surfaces if the wood (or installed metal connectors) are exposed to rain during construction.

Providing protection by using factory-applied roofing or adhered roof vapour barrier membrane on mass timber roof panels and other exposed components is strongly recommended, with appropriate tape used to seal joints immediately upon installation. These pre-installed membranes, when properly detailed (for example, the joints are accessible to tape), can later serve as the air and vapour barrier in most roof assembly designs. For severe wetting risks, exposed wood elements can be protected with a temporary roof; that is, keeping the wood elements dry avoids delays in installing the vapour impermeable layers. Further information is provided in Section 7.7.1.

7.7 WOOD DURABILITY AND PROTECTION

Wood has proven long-lasting performance in properly designed and constructed buildings all over the world. In Canada, the major threat to long-term durability comes from decay fungi and mould growth. The key to achieving durability is to prevent excessive moisture accumulation and to allow wood to dry if it gets wet during construction and in service (Wang, 2016a). The risks are greater in a tall wood building due to greater exposure to rain and snow/ice (as a result of the greater building height and exterior surface area), and potentially longer construction schedules that span damp or icy seasons.

The main conditions that allow for fungi to grow in wood are favourable moisture and temperature. Wood and wood-based materials always contain some moisture; the amount varies over time depending on the wood's wetting and drying history, changes in RH and temperature, and liquid water in the environment. The MC of wood exposed to ambient humidity alone is generally below the levels conducive to the growth of decay fungi. As a general rule, liquid water (e.g., rain, vapour condensation) needs to be present to lead to wood decay. Research has shown that at a temperature of approximately 20°C, decay fungi can colonize kiln-dried wood products when the MC rises to a threshold of 26%, which can be considered the low end of the fibre saturation point (Wang et al., 2010). Under such marginal moisture conditions, it takes months or even years for detectable structural damage to occur when all other conditions are favourable for decay. But, higher MC can dramatically speed up decay, measured in weeks.

Sustained high humidity (i.e., surface RH of approximately 80% or higher, either from an external moisture source or due to the liquid moisture within the wood), coupled with warm temperatures (e.g., 20–30°C) may cause mould growth (Nielsen et al., 2004; Viitanen & Paajanen, 1988). The summary of mould and decay models in *Biodeterioration Models for Building Materials: Critical Review* (Lepage et al., 2019) may be useful for evaluating the risks to a building.

Wood species vary widely in natural durability. Sapwood of all wood species has low natural durability. Heartwood is generally more durable than sapwood. The heartwood of Spruce-Pine-Fir and Hem-Fir is considered to be "slightly durable". Douglas-fir and western larch heartwoods are moderately durable. The heartwoods of species such as western redcedar and yellow cedar are durable against decay. Engineered wood products, such as plywood, OSB, OSL, PSL, LVL, LSL, NLT, glulam, and CLT, have the same level of durability as the wood from which they were made unless they have been subjected to treatment with a preservative during the manufacturing process. However, mass timber products have unique moisture management issues due to their larger sizes compared to typical light-wood-frame components. The following section provides guidance on moisture protection strategies for wood assemblies, with a specific focus on mass timber horizontal and vertical assemblies.

7.7.1 On-site Moisture Management

Protection of wood during construction is of paramount importance; ideally, wood moisture content should be kept below 16%. The control of construction moisture can be difficult in a taller building under construction since it may be highly exposed and subject to a cascade of water accumulated from upper storeys.

A robust **moisture management plan** that includes factory-installed moisture protection, on-site moisture control, and fast building enclosure is needed to maintain acceptable moisture content levels in the wood assemblies. A plan allows for construction in inclement weather and helps avoid the need for potential remediation.

It is important to limit the amount of wetting that wood assemblies are subjected to. This is especially critical where mass timber products are used because they may absorb and store more moisture than dimensional lumber. Depending on the product type, they may also swell more when wetted and dry slowly; consequently, it can be difficult for assemblies to dry out after the insulation is installed. An ideal target is to keep the wood MC below 16% during storage and construction in order to provide a good margin of safety for durability performance (i.e., to ensure the MC never exceeds 19%) and reduce differential building movement after installation.

In addition to outdoor humidity, the sources that expose wood to liquid water include rain, snow, ground moisture, and vapour condensation. Wood absorbs water most rapidly through end grain, which can be exposed by end cuts, and through knots and drilled holes. Splits due to drying or “checking” on surfaces exposed to rain or condensation can trap moisture and increase water uptake. Compared to solid wood products, many engineered wood products have numerous exposed end grains, as well as small pores for capillary absorption, depending on the manufacturing.

Moisture can be properly managed with the right design, planning, and construction techniques. A lack of proper care can affect the aesthetics, dimensional tolerances, and even structural capacity and indoor air quality of the building. Figure 16 shows several examples of the results of poor moisture management during construction. Retroactive attempts to fix these problems can be costly and delay the construction schedule.

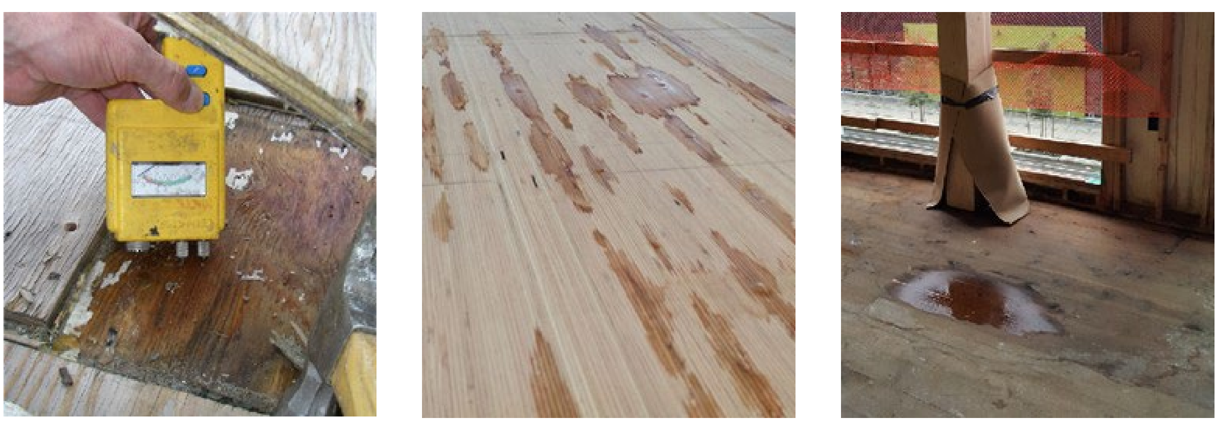


Figure 16. Various results of poor construction moisture management, including wetted and stained plywood (left) and LVL (centre), and ponding water and staining on a CLT floor panel (right).

7.7.1.1 Moisture Management Plan

Successful moisture management for the wood enclosure assemblies begins early in the design phase of the project and continues throughout the construction phase. A best practice approach to moisture management is to prepare a moisture management plan. The plan should identify the sources and amount of moisture that the building might experience, incorporate measures in the design to prevent moisture exposure where possible, and outline ways to address moisture exposure when it occurs during construction. These steps are summarized as follows:

- Step 1: Planning – Start planning for moisture management early in the design phase and begin with the enclosure assemblies and intermediate floor assemblies. Most projects benefit from beginning moisture management planning during the design development phase. Assembly design planning offers opportunities to consider the use of construction moisture protection materials that later may function as part of the building enclosure system (i.e., the air barrier, vapor control membrane, or acoustic separation). Once the assemblies have been determined, other moisture management items such as panel joint treatments and drain locations can be identified.
- Step 2: Risk Evaluation – A risk evaluation considers all aspects that may contribute to moisture exposure over the construction and occupancy of the project, including rainfall and snow/ice melt, the construction schedule, length of exposure, type of mass timber to be used, drain locations, assembly slopes, and plans for tenting and diverting water. Table 2 outlines considerations for exposure, wetting, drying, and protection of various mass timber products based on their typical applications and composition. See Section 7.7.1.2 for further guidance on assessing exposure risk.
- Step 3: Construction Phase Moisture Management Plan – Establish the construction phase moisture management plan during design to prepare the design and construction teams for managing moisture and unexpected exposure risks. The plan may include employing an active, on-site water control team and using tarps, squeegees, vacuums, whole-building protection systems, and/or environmental or mechanical drying tools.
- Step 4: Execution of Plan – Execute the plan during construction. If Steps 1 through 3 have been followed, the project team will be well prepared to execute the plan effectively.
- Step 5: Monitoring – Throughout the construction phase, monitor and evaluate the effectiveness of the moisture management plan by conducting regular checks using wood moisture measurement tools and qualitative assessments.

This type of moisture management plan is especially important for mass timber products that may absorb significant amounts of moisture.

Construction Moisture

Construction moisture risk mitigation plans should be part of initial planning. Allowing for drying is critical. Some details may be sensitive to moisture. Dimensional changes may be detrimental (e.g., moisture-induced swelling may be sufficient to stretch and break self-tapping screws).

Table 2. Mass timber product moisture-related risk and protection

Component	Wetting and drying potential	Protection methods	Other considerations

NLT
Nail-laminated timber
 	
DLT
Dowel-laminated timber
	• High susceptibility to damage caused by wetting and swelling given grain orientation and pathways for water entry and entrapment
	• Each lamination joint is a potential moisture pathway
	• Sheathing may be added to one face, which could protect from wetting if joints are sealed, but may also trap moisture
		• Used primarily in roof/floor applications
		• Use high-risk wetting protection:
		  ○ factory-installed water-resistive membrane on top face
		  ○ taped/sealed joints on-site
		• Manage water buildup and runoff on-site
			• Not typically made from preservative-treated lumber
			• Can be made from preservative-treated lumber or naturally durable wood (e.g., yellow cedar)
			• Often intended to have "show side", so rapid wetting and drying may lead to unsightly gaps/cracks
			• Moisture remediation and cleaning to original design intent is challenging
			• Nails within NLT should be corrosion protected to minimize staining if wetted

CLT
Cross-laminated timber
	• Low to moderate susceptibility to damage due to wetting
	• Glued laminations may help limit moisture transfer
	• Solid wood with glue layers can limit drying potential
	• Exposed end grain on all edges can absorb more moisture
		• Used in floor/roof assemblies and in wall assemblies
		• Use moderate-risk wetting protection (for exposed components):
		  ○ factory-installed protective coating or membrane
		  ○ taped/sealed joints
		• Manage water buildup and runoff on-site; protect top edge of exposed walls from wetting
			• Not typically made from preservative-treated lumber
			• Can be made from naturally durable wood or preservative-treated lumber
			• Dimensionally stable due to cross-laminations; however, excessive repetitive wetting and drying poses risk to appearance and structural capacity (delamination of plies)
			• Glue on lamination edges can significantly reduce moisture transfer and reduce potential cracks/gaps

GLT Glue-laminated (glulam) timber	• Low to moderate susceptibility to damage due to wetting • Glued laminations help limit moisture transfer • Typically manufactured with high-quality seal at face	• Typically used as columns, beams, and headers • Use moderate-risk wetting protection (for exposed components): ○ factory-installed protective coating or membrane on all sides • Manage water buildup and runoff on-site; protect top edge of exposed members from wetting	• Not typically made from preservative-treated lumber • Can be made from naturally durable wood or can be preservative treated • Dimensional movement primarily in the depth • Often used in exposed applications; most glulam is fabricated with tight moisture control and wood selection, and is coated in the factory to reduce moisture sensitivity

Component	Wetting and drying potential	Protection methods	Other considerations
SCL Structural composite lumber (e.g., LSL, OSL, LVL, PSL, MPP)	• Moderate to high susceptibility to damage due to wetting • Made from strands or veneers, laminated with significant amounts of glue • Often manufactured with water repellent on surfaces	• Typically used as columns, beams, headers, and floor/roof assemblies • Use high-risk wetting protection (for exposed components): o factory-installed protective coating or membrane on all sides • Manage water buildup and runoff on-site; protect top edge of exposed members from wetting	• Not typically made from preservative-treated lumber • Some products can be preservative treated • Typically dimensionally stable (for LVL, rapid wetting/drying may cause bowing/curling) • Not typically used in exposed applications

7.7.1.2 Exposure Risk

The exposure risk of wood assemblies depends on the following factors:

- Climate and season: Local climate and seasonal considerations include rainfall and snowfall amounts and frequency, wind, temperature, and conditions that lead to drying events versus wetting events. Sustained exposure to rainfall and snowfall (if left unprotected), significant wind-driven rain events, and minimal opportunities for drying contribute to higher risk exposures.
- Water management strategies during construction: Sloped horizontal assemblies, water diversion/deflection, and drains affect exposure risk. A sloped mass timber panel that can encourage water to shed away toward drains and roof or floor edges is ideal, but it can also increase the risk of concentrated runoff or pools of water forming if not properly drained.
- Occupancy phase exposure: Moisture “events” during occupancy can also affect mass timber. Plumbing leaks, appliance leaks, and food preparation activities can all lead to exposure risk. The exposure of mass timber to moisture as a result of these events can be difficult to discover due to the presence of floor coverings, which can compound the risk of moisture-related movement and potential decay.
- Exposure duration: The duration for which panels are exposed to moisture is influenced by overhead protection, speed of construction for subsequent levels, and construction delays.
- Shipping and storage: Shipping protection, travel distance from the manufacturing facility and transit time, and site storage can all increase exposure to moisture prior to panel installation.
- Encapsulation: The use of mass timber elements encapsulated with gypsum or other moisture-sensitive materials requires a higher level of water protection than outlined above.

When determining the assembly exposure to moisture, all the above factors need to be considered collectively.

7.7.1.3 On-site Moisture Protection Measures

Good moisture protection principles and practices should be applied to all mass timber projects. To reduce time of exposure to wetness, timber installation should be scheduled during a relatively dry season, if possible. Off-site prefabrication, including precutting and drilling for connections and various service openings, can be used to minimize site work and save time. Ideally, materials should be delivered just prior to installation to eliminate site storage needs. Timber products should be stored off the ground and under shelter or in a well-drained and ventilated area. The wraps should be kept on the wood products until they are ready to use. The products should be re-covered with waterproof tarps if the original wrapping is damaged. However, plastic wraps and tarps may trap moisture and slow down drying if water gets under them and is unable to drain; therefore, the wrapping may be cut open at the bottom or partially removed upon installation.

Minimizing the time of water exposure for horizontal elements, such as floors and roofs that allow water to pool, is particularly important. Installing exterior walls quickly following erection of the main structure is an effective solution for protecting floors. Pre-installing temporary waterproofing for roof panels should be seriously considered in most projects. Vertical assemblies may be less prone to moisture accumulation but may still benefit from robust moisture protection measures. An example of measures taken is shown in Figure 17.

The wood should be dry before encapsulation. Components that include rigid mineral wool insulation and drywall are reasonably vapour permeable enough to allow drying but at greatly reduced rates (Wang, 2018).

Table 3 provides some examples of moisture protection measures for mass timber assemblies, and focuses on factory-applied water repellents and membranes. Water repellent has been found to be most effective for end grain, which is more water-absorptive than face grain, while a self-adhesive, vapour-permeable membrane often provides more robust protection and also makes it easier to maintain the continuity of the protection at various joints and interfaces (Wang, 2018).

The intent of any moisture management approach is to keep the MC low, ideally below 16%. Temporary or permanent membranes should not be applied unless the MC of the mass timber laminations, inclusive of any plywood or OSB sheathing layer, is dry enough, ideally with a maximum MC of 16%.

Table 3. Examples of mass timber assembly moisture protection measures

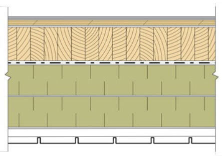
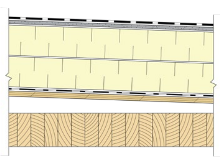
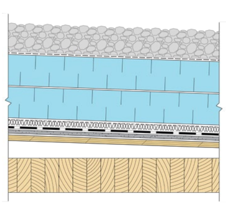
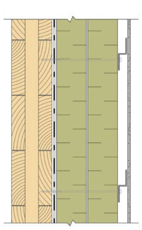
Assembly	Moisture protection approach		
	Low exposure	Moderate exposure	High exposure
 Floor	• Factory-applied hydrophobic face sealer or moisture-resistant sheathing, and high-build paraffin edge sealer • Panel joints taped/sealed upon installation	• High-build paraffin edge sealer • Factory-installed permeable membrane with laps and joints sealed • If used, factory-installed impermeable acoustic mat with laps and joints sealed	• High-build paraffin edge sealer • Factory-installed fully adhered waterproof membrane with laps and joints sealed • If used, factory-installed adhered impermeable acoustic mat with laps and joints sealed
 Conventional roof	• Factory-applied hydrophobic face sealer or moisture-resistant sheathing, and high-build paraffin edge sealer • Panel joints taped/sealed upon installation	• High-build paraffin edge sealer • Factory-installed fully adhered impermeable sheathing/structure membrane with laps and joints sealed	• High-build paraffin edge sealer • Factory-installed fully adhered/welded impermeable sheathing/structure membrane with laps and joints sealed/welded • Consider venting/drying ability of completed assembly
 Inverted roof	• Factory-applied hydrophobic face sealer or moisture-resistant sheathing, and high-build paraffin edge sealer • Panel joints taped/sealed upon installation	• High-build paraffin edge sealer • Factory-installed fully adhered impermeable sheathing/structure membrane with laps and joints sealed • Consider factory-installed permanent roofing membrane instead	• High-build paraffin edge sealer • Factory-installed fully adhered/welded impermeable roofing membrane with laps and joints sealed/welded • Consider venting/drying ability of completed assembly
 Wall	• Factory-applied hydrophobic face sealer • Panel joints taped/sealed upon installation	• High-build paraffin edge sealer • Factory-installed permeable sheathing/structure membrane with laps and joints sealed	• High-build paraffin edge sealer • Factory-installed permeable fully adhered sheathing/structure membrane with laps and joints sealed • Consider prefabrication of wall assembly; ensure top edge of exposed walls is covered

Figure 17. Vapor-permeable WRB over CLT floor panels is draped over the wall system below to shed water away from the lower levels of the building.

For further detailed guidance on on-site moisture management and planning, see general protection guidance for wood construction (Wang, 2016b), specific guidelines for CLT and NLT construction (Wang 2020a, 2020b), and the *Moisture Risk Management Strategies for Mass Timber Buildings* guide (Finch & Brown, 2020b).

7.7.1.4 Protection in a Dry Climate

On-site protection needs can be very different in a dry climate compared to construction under wet weather conditions. Excessive checking, cupping, or warping resulting from rapid drying or cyclic wetting and drying, which causes aesthetical and dimensional instability issues, usually becomes the major concern (Wang, 2016b). An effective measure is to avoid extremes in the environment through humidity control, typically by providing humidification when ambient conditions are too dry. Humidity should be measured during construction, and a relatively closed space needs to be created to ensure the humidification is efficient and effective. In addition to on-site moisture management, humidity control is typically required for in-service mass timber buildings in a dry climate, especially in the first few years, to avoid rapid drying and to allow the wood to slowly adjust to the service conditions.

Post-Occupancy Damage

Drying cracks in mass timber may form when the initial moisture content is higher than the in-service content. Cracks relieve internal drying stresses but should not affect the performance of mass timber panels and columns. In deep beams, large cracks may need to be assessed. Occupants may occasionally hear exposed mass timber cracking until drying stresses have been relieved.

7.7.2 Management of Interior Water Leaks

Interior water leaks may occur during building operation due to, for example, leaks from water pipes and activation of sprinkler systems. Although floors and interior walls are relatively well protected from ingress of rainwater during the building's service life, they are typically the most affected when there is a plumbing failure or an accidental activation of the sprinkler system. Dealing with an interior water leak does not differ significantly among CLT, other mass timber, light-wood-frame, or even light steel-frame assemblies. Most floors in large buildings have concrete topping covering the structural floor panels (e.g., CLT, plywood, OSB), with finishing materials (e.g., flooring, carpet) on the top. Most interior walls are covered with drywall, except for exposed bare CLT, where permitted. When a leak occurs, bulk water should be removed (e.g., by vacuum) as quickly as possible to minimize the exposure time to wetting. Remaining small amounts of moisture may be removed by heating and ventilation, such as by blowing hot air directly toward the wet areas to accelerate moisture evaporation. Non-structural components, such as drywall, batt insulation inside framed walls or floors, carpet, and wood or vinyl flooring, may need to be removed to accelerate drying of the wood members.

Many interior components, such as drywall, carpet, and wood may develop mould under damp conditions, which may thereafter affect indoor air quality. Warm and damp environments enhance the growth of fungi, and prolonged wetting may even allow decay to start in wood members. This may compromise the structural integrity of the structure and make rehabilitation a more complicated and challenging process. For the floors and walls of indoor damp spaces, such as those that may occur in a bathroom, special measures should be taken to manage the higher indoor moisture loads. For example, when CLT is used for floors, an adhesive-backed, vapour-permeable, water-proof membrane and a means of slope and drainage could be installed, where possible, to provide extra protection against water uptake. The installation of an additional interior vapour-retarding layer may become necessary to reduce vapour diffusion into CLT walls. See Section 9.5 for more detailed information on wood-related maintenance and repair.

7.7.3 Exterior Wood and Preservative Treatment

In mild and rainy coastal climates, in particular, exterior exposed wood is subject to a high risk of decay and other climate-related damage; therefore, the materials must be selected based on exposure conditions. In general, structural wood members, such as CLT panels and glulam beams, should not be exposed in most exterior environments where they can be wetted; however, wood claddings and other non-structural wood elements that use preservative-treated wood and naturally durable wood may be incorporated into the building enclosure of tall wood buildings.

Wood pressure treated with preservatives must be used for all ground contact applications. Any above-ground wood framing or cladding should be separated from the ground, with a minimum clearance of 200 mm. The bottom of the wood must be allowed to drain and dry, if wetted. When wood is used in an exterior application, whether it is preservative treated or untreated, coated or uncoated, it is best to protect it from the exterior climate using design features such as overhangs and canopies. For exposed above-ground applications, pressure-preservative-treated wood or naturally durable wood species such as cedar should be used. This is required by building codes for coastal areas of Canada. Building enclosure assemblies and details should always be carefully designed to prevent moisture entrapment and facilitate drainage and drying, as discussed in this chapter. Grade and soil levels should be maintained so they do not encroach on the wood structure.

Like many other materials, wood used in exterior applications without any coating weathers naturally. It is a slow surface deterioration process but is fast in terms of appearance change due to exposure to environmental agents such as ultraviolet light, visible light, water, oxygen, heat, windblown particulate matter, atmospheric pollutants, and micro-organisms. Light woods typically darken slightly and dark woods lighten, but all woods eventually end up a silvery-grey colour. The surface also roughens, checks, and erodes, and has a "rustic" look. The use of coatings is the most common way of reducing such deterioration and improving aesthetic appearance. However, all coatings have a limited service life, and coating maintenance is critical to preserving the wood's aesthetic appearance and functions. Typically, an opaque coating with a high amount of pigment is better at protecting the base material from damage caused by sunlight and moisture, and therefore tends to last long—up to several years or longer. Conversely, a transparent or semi-transparent finish can better expose the grain and texture of the base material, but it tends to fail quickly and requires more frequent recoating. The type of coatings selected affects maintenance needs and costs, particularly for less accessible locations, and must be taken into consideration in both the design and the maintenance plan (covered in Chapter 9).

When the wood is not naturally durable enough to prevent attack by decay fungi or insects, it can be treated with preservatives to meet CSA O80 standards and improve long-term durability.[1] Even for some mass timber products, preservative treatment can be very beneficial to the durability of the buildings, especially for areas that have a potentially high moisture risk but are not accessible for inspections or repairs. For mass timbers such as CLT and glulam, manufacturers should ensure that any water-based preservatives used before laminating do not adversely affect glue bonds, or that appropriate resin modifiers are added as needed. The use of non-swelling oil-based treatments for industrial glulam post manufacture is not a preferred approach for buildings due to VOC emissions; most of these treatments are not registered for interior use. Non-penetrating surface treatments are not likely to be effective against decay in the long term, but they may be effective against surface mould. Where moisture ingress is highly localized and predictable, boron or boron/copper rods can be relied upon for local protection until the source of moisture ingress is resolved. In most cases, boron rods should be used in combination with a borate/glycol surface treatment and a film-forming coating to prevent leaching if it should occur. The compatibility of wood treatments with building enclosure membranes, adhesives, and sealants needs to be tested where these elements will be in contact with treated wood.

More information on wood durability is provided at www.durable-wood.com (CWC & FPI, 2020), and the maintenance of tall wood structures is covered in Chapter 9.

7.8 CONCLUSION

This chapter provides guidance to practitioners on designing building enclosures for tall wood buildings in Canada. It emphasizes moisture, heat, and air control strategies and details to achieve durability and energy performance of building enclosures, and to accommodate increased environmental and structural loads given the height of the building. Properly designed enclosures can

[1] Not all wood species can be effectively preservative treated. Check with the mass timber supplier.

meet current and higher building energy code requirements, such as the BC Energy Step Code, without compromising other aspects of the building enclosure's long-term performance.

The guidance in this chapter is provided in the context of the wider use of mass timber components and assemblies, including the allowance for up to 12-storey encapsulated mass timber buildings in building codes across the country, and the unique design and construction challenges they present. Guidance on on-site moisture management and the use of exterior wood is provided in the context of taller wood buildings with higher exposure and longer construction schedules. Planning is required to effectively address the risk of moisture exposure of wood elements during construction, risks that conventional light-wood-frame and non-wood buildings are less likely to experience. Some guidance on managing moisture risk to a wood building post occupancy is also provided.

7.9 REFERENCES

Alsayegh, G., Mukhopadhyaya, P., Wang, J. Y., Zalok, E., & van Reenen, D. (2013). Preliminary characterization of physical properties of cross-laminated timber (CLT) panels for hygrothermal modelling. *Advances in Civil Engineering Materials* 2(1), 20120048. doi: 10.1520/ACEM20120048

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2019). *Energy standard for buildings except low-rise residential buildings*. (Standard 90.1). Atlanta, GA: Author. https://www.usailighting.com/stuff/contentmgr/files/1/b90ce247855d0f17438484c003877338/misc/ashrae_90_1_2010.pdf

ASTM International (ASTM). (2017). *ASTM D 2898: accelerated weathering of fire-retardant-treated wood*. West Conshohocken, PA: Author.

BC Housing. (2017). *Illustrated guide – R22+ effective walls in residential construction in B.C*. Vancouver, BC: Author. https://www.bchousing.org/research-centre/library/residential-design-construction/ig-R22-effective-walls-residential-construction

BC Housing. (2020). *Building enclosure design guide – wood-frame multi-unit residential buildings*. Burnaby, BC: Author. https://www.bchousing.org/research-centre/library/residential-design-construction/building-enclosure-design-guide

BC Hydro, BC Housing, Canadian Wood Council, Fortis BC, FPInnovations, & Morrison Hershfield. (2020). *Building envelope thermal bridging guide* (Version 1.5). https://www.bchousing.org/research-centre/library/residential-design-construction/building-envelope-thermal-bridging-guide

Binational Softwood Lumber Council and Forestry Innovation Investment Ltd. (2017). *Nail-laminated timber: Canadian design and construction guide.* https://info.thinkwood.com/nlt-design-and-construction-guide-canadian-version

Bradley, J. S., & Birta, J. A. (2000). *Laboratory measurements of the sound insulation of building façade elements*. (IRC Internal Report, IRC IR-818). Ottawa, ON: NRC Institute for Research in Construction. https://nrc-publications.canada.ca/eng/view/ft/?id=b516cfdd-0170-4427-9532-77daf90974d5

Canada Mortgage and Housing Corporation (CMHC). (1981). *Road and rail noise: effects on housing*. Ottawa, ON: Author. Available at: https://nrc-publications.canada.ca/eng/view/ft/?id=48a42a3e-a7c4-4df2-8f5a-9fd2b2e51687

Canadian Standards Association (CSA). (2019). *CSA O86: engineering design in wood*. Toronto, ON: Author.

Canadian Wood Council (CWC). (2020). *Effective R calculator*. Ottawa, ON: Author. https://cwc.ca/design-tools/effective-r-calculator/

Canadian Wood Council and FPInnovations (CWC & FPI). (2020). *Durable-wood.com*. Ottawa, ON: Author. Montreal, QC: Author. https://cwc.ca/why-build-with-wood/durability/

Finch, G., & Brown, B. (2020a). *Mass timber building enclosure best practice design guide*. Seattle, WA: RDH Building Science Inc. https://learnbuildingscience.com/products/mass-timber-building-enclosure-best-practice-design-guide

Finch, G., & Brown, B. (2020b). *Moisture risk management strategies for mass timber buildings*. Seattle, WA: RDH Building Science Inc. https://learnbuildingscience.com/products/moisture-risk-management-strategies-for-mass-timber-buildings

Finch, G., Wang, J. Y., & Ricketts, D. (2013). *Guide for designing energy-efficient building enclosures for wood-frame multi-unit residential buildings in marine to cold climate zones in North America*. (Special Publication SP-53). Vancouver, BC: FPInnovations. https://www.rdh.com/wp-content/uploads/2017/07/Guide-for-Designing-Energy-Efficient-Building-Enclosures-Web.pdf

Hazleden, D. G., & Morris, P. I. (1999). Designing for durable wood construction: the 4 Ds. In M. A. Lacasse, & D. J. Vanieer (Eds). *Proceedings, 8th International Conference on Durability of Building Materials and Components* (734-745). Ottawa, ON: NRC Research Press.

Karacabeyli, E., & Douglas, B. (Eds). (2013). *CLT handbook: cross-laminated timber*. U.S. ed. (Special Publication SP-529E). Pointe-Claire, QC: FPInnovations.

Karacabeyli, E., & Gagnon, S. (2019). *Canadian CLT handbook, 2019 edition*. (Special Publication SP-532E). Pointe-Claire, QC: FPInnovations. https://web.fpinnovations.ca/clt/

Lepage, R., Glass, S. V., Knowles, W., & Mukhopadhyaya, P. (2019). Biodeterioration models for building materials: critical review. Journal of Architectural Engineering 25(4), 04019021.

Lstiburek, J. (2004-2009). *Builder's guide*. Somerville, MA: Building Science Corporation. www.buildingscience.com

Munoz, W., Mohammad, M., & Gagnon, S. (2012). In-situ monitoring of a 6-storey hybrid wood-concrete office building in Québec, Canada. *Proceedings of the World Conference on Timber Engineering, Auckland, New Zealand*.

Mustapha, G., Khondoker, K., & Higgins, J. (2017). Vertical movement and moisture performance monitoring of pre-fabricated cross laminated timber – featured case study: UBC tall wood house. *Proceedings of 15th Canadian Conference on Building Science and Technology*, Vancouver, BC.

National Research Council of Canada (NRC). (2017). *National Energy Code for Buildings (NECB)*. Ottawa, ON: Author. https://nrc.canada.ca/en/search?keys=National+Energy+Code+for+buildings

National Research Council of Canada (NRC). (2020). *National Building Code of Canada (NBC)*. Ottawa, ON: Author. www.nationalcodes.nrc.gc.ca

Nielsen, K. F., Holm, G., Uttrup, L. P., & Nielsen, P. A. (2004). Mould growth on building materials under low water activities. Influence of humidity and temperature on fungal growth and secondary metabolism. *International Biodeterioration & Biodegradation* 54(4), 325-336.

Oleszkiewicz, I. (1990). Fire exposure to exterior walls and flame spread on combustible cladding. *Fire Technology* 26(4), 357-375.

Quirt, J. D. (1985). *Controlling sound transmission into buildings*. Ottawa, ON: National Research Council Canada. https://nrc-publications.canada.ca/eng/view/ft/?id=9a6fe2f1-4d4e-4973-bc32-d62cabc92be0

RDH Building Engineering Ltd. (RDH) (2013). *Air leakage control in multi-unit residential buildings – development of testing and measurement strategies to quantify air leakage in MURBS*. Vancouver, BC: Author. https://retrotec.com/pub/media/mageworx/downloads/attachment/file/a/r/article-_air_leakage_control_in_large_res._buildings.pdf

Straube, J. (2013). *High performance enclosures: design guide for institutional, commercial and industrial buildings in cold climates*. Somerville, MA: Building Science Press. www.buildingscience.com

Straube, J., & Burnett, E. (2005). *Building science for building enclosures*. Somerville, MA: Building Science Press.

United States Department of Agriculture (USDA). (2010). *Wood handbook—wood as an engineering material*. (General Technical Report FPL-GTR-190). Madison, WI: Author. https://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr190.pdf

Viitanen, H., & Paajanen, L. (1988). The critical moisture and temperature conditions for the growth of some mould fungi and the brown rot fungus *Coniophora puteana* on wood. (Document No. IRG/WP 1369). International Research Group on Wood Protection.

Wakefield Acoustics Ltd. (2005). *City of Vancouver noise control manual*. Vancouver, BC: City of Vancouver, Engineering Services. https://vancouver.ca/files/cov/noise-control-manual.pdf

Wang, J. Y. (2016a). *Potential impacts of wetting on performance of mass timber buildings.* Vancouver, BC: FPInnovations.

Wang, J. Y. (2016b). *A guide for on-site moisture management of wood construction.* Vancouver, BC: FPInnovations.

Wang, J. Y. (2018). *Wetting and drying performance related to on-site moisture management of cross-laminated timber.* Vancouver, BC: FPInnovations.

Wang, J. Y. (2020a). *Construction moisture management – cross laminated timber.* Vancouver, BC: FPInnovations.

Wang, J. Y. (2020b). *Construction moisture management – nail laminated timber.* Vancouver, BC: FPInnovations.

Wang, J. Y., Clark, J., Symons, P., & Morris, P. (2010). Time to initiation of decay in plywood, OSB and solid wood under critical moisture conditions. In A. Baskaran (Ed.), *Proceedings of International Conference on Building Envelope Systems and Technologies, ICBEST 2010*,. Vol. 2, 159-166. Ottawa, ON: National Research Council Canada, Institute for Research in Construction.

Wang, J. Y., Karsh, E., Finch, G., & Chen, M. (2016). Field measurement of vertical movement and roof moisture performance of the Wood Innovation and Design Centre. *Proceedings of the World Conference on Timber Engineering*, Vienna, Austria.

Wang, J. Y., & Ni, C. (2014). Monitoring of vertical movement in a 5-storey wood frame building in coastal British Columbia. *World Conference on Timber Engineering*, Québec City, QC.

Wang, J. Y., Ni, C., & Mustapha, G. (2013). Monitoring of vertical movement in a 4-story wood frame building in coastal British Columbia. *Journal of Testing and Evaluation* 41(3), 611-618.

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Project Execution – Design, Prefabrication, and Construction Considerations

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ABSTRACT

Once a tall wood building project is given the go-ahead, it is the responsibility of the collective team to successfully execute and deliver it. Mass timber prefabrication provides many opportunities and benefits to a project, but they need to be carefully planned and considered throughout the project's life cycle.

Fully realizing the benefits of prefabrication requires a different philosophical approach to construction that is underpinned by a greater emphasis on up-front planning, a strong reliance on the use of digital tools, and a “manufacturing mindset”, which can be quite different from the traditional craft-based “analog” approach to building.

Starting at the design stage, a solid understanding (by both designers and contractors) of the chosen materials’ parametric properties is required if the project is to be cost-effective. Selecting and having the input of a mass timber manufacturer will be beneficial to the whole project team.

With an experienced, collaborative team on board, building information modelling (BIM) can be a very powerful tool for all stakeholders. Because mass timber manufacturing and processing is heavily automated, it fits well with a Design for Manufacture and Assembly (DfMA) approach. An overview of both BIM and DfMA is provided to show how they can contribute to successful project delivery.

Project costing is an ongoing exercise through preconstruction and into the construction phase. The use of prefabricated mass timber products has implications beyond the straightforward change in the structural system costs, and those responsible for pricing projects need to be able to recognize and account for the benefits of mass timber prefabrication within budgets. There are also a number of items that can affect contractors' cost control during construction; the intent of identifying them in this chapter is to help contractors manage those risks more proactively.

Costing is closely tied to scheduling. The prefabrication of mass timber components can provide significant on-site time savings compared with other more conventional structural systems. This chapter examines the nature of those savings, where they are found, and how to plan for them so that other trade contractors are not "surprised" by (and therefore unprepared for) the speed of progress on a tall wood building. Additional details related to cost and value are provided in Chapter 3.

Mass timber elements are highly precise construction components and are delivered to site from a quality-controlled factory environment. This advantage can be quickly undone if the product is not properly managed during shipping and site handling. Some insights into the risks and mitigation tactics needed are provided in this chapter.

The key to all of the above is good, solid planning; this underlies the successful delivery of any construction project but is especially true for a tall wood building.

8.1 INTRODUCTION

The prefabrication of mass timber structures affects both the design and construction planning approaches. Fully realizing the benefits of prefabrication requires a different philosophical approach to construction that is underpinned by a greater emphasis on up-front planning, a strong reliance on the use of digital tools, and a "manufacturing mindset", which can be quite different from the traditional craft-based "analog" approach to building.

Using a prefabricated approach to building is a highly precise endeavour; therefore, costs can be incurred if changes are made during or after fabrication. These cost implications will potentially affect who should (ideally) be involved during the early stages of the process and the flow of information between them. The design team needs to adopt a different approach working with prefabricated elements: Design for Manufacture and Assembly. The prefabricated approach will also alter a number of the usual construction operating procedures once work on-site starts. However, a greater emphasis on planning and execution will have positive effects on the safety, schedule, and cost of building tall wood structures and the quality of the buildings.

The successful completion of any tall or large building, regardless of structure type, requires substantial planning, right from the start of design. A mass timber structure is no different, although the planning considerations vary from those for a steel- or concrete-framed project. What this means in terms of design and construction is reviewed, along with some of the associated costing implications.

Marketability/Profitability

Prefabrication imposes discipline on the project team and results in higher up-front efforts. If it is considered in the planning and design, higher quality and reduced on-site time compared to traditional approaches can be achieved, even for complex design needed for market differentiation.

The methodology used to build tall wood structures can open up other possibilities for improving the overall construction process. The use of precise, factory-made components can create dimensional stability in a building that cannot be achieved with site-built structures. This in turn increases the value that mass timber can bring to other trade contractors, all of which can have a positive effect on the timing and costing of a project.

The U.S. WoodWorks (2019) report *Mass Timber Cost and Design Optimization Checklists* is a valuable tool for all stakeholders in designing, costing, planning, and then executing a tall wood building.

8.2 PRECONSTRUCTION

8.2.1 Considerations When Designing for Prefabrication

Successfully integrating prefabrication into a project needs to start at the design stage. Recognizing the opportunities and limitations that prefabrication can bring, and how this needs to be represented within the project drawings (or better still, the building information model) and specifications will lead to a more seamless and predictable process for all concerned.

Some of the factors that should be considered when designing for mass timber prefabrication, discussed in detail below, include the following:

- the effect prefabrication will have on the design process
- optimizing the cost-effectiveness of the mass timber system
- integrating mass timber trades into the design phase
- creating and meeting design completion milestones
- increasing the overall amount of prefabrication on a project

8.2.1.1 Effect on the Design Process

The mass timber structural system to be used (e.g., post, beam and platform, post and platform) needs to be selected early in the design process, and the consultant team needs to have an understanding of the various mass timber systems available in order to optimize the layout and structural grid to suit the materials sizes available. The supply chain options include full-service/proprietary systems and suppliers who provide standard units ("blanks") to specialist fabricators. The mass timber manufacturer (and potentially the installer) will be best able to guide the design team to maximize the number of typical member or panel sizes to create cost efficiencies. In a conventional setting, the timeline and sequence of completing the design can be quite linear, with the design development of the various disciplines progressing in sequence. With a manufactured structure, however, the process often needs to take more of an iterative fast-track approach, more commonly associated with industrial design, where the design is completed in terms of elements of the project rather than by discipline.

> For the Tallwood 1 project in Langford, B.C., the grid was set to 2.95 m rather than 3 m to suit the panel manufacturing limit.

Production planning therefore needs to be integrated into and inform the design process. A lead time of often 4–6 months or more is required to produce and ship the engineered wood elements to the building site. Mechanical and electrical routing has to be scheduled earlier so that the necessary openings can be cut in the mass timber factory.

One of the benefits of prefabrication is the ability to complete work away from the site in parallel with the ongoing on-site work. For example, on the Brock Commons project at the University of British Columbia, Structurlam fabricated the mass timber elements in its factory while the concrete work was being conducted on-site. This can further necessitate finalizing the mass timber portion earlier in the design process.

8.2.1.2 Optimizing the Cost-Effectiveness of Mass Timber Design

As noted in Chapter 3 (Section 3.3.2.2), selecting the correct structural system is key to cost-effective mass timber design. However, a number of other considerations will further help project finances.

Using consistent panel sizes, optimized for the maximum capacity of the manufacturer's equipment, reduces material waste and accelerates the production timeline. The time it takes to manufacture a 3.0 m × 3.0 m cross-laminated timber (CLT) panel is not substantially less than the time required to produce a 10.0 m × 3.0 m panel of the same thickness. Fewer pieces also reduce the overall amount of changeover time between components at the factory CNC station.

Fewer pieces also translate to the installation of panels on-site. Hoisting effort and time is dictated more by the number of panels than the panel size, so the use of larger panels reduces the on-site time required for installation and the associated labour. It also reduces crane hook time, which is often the bottleneck on any tall building project. Components still need to be manageable for the installation crew: the more complex the connection detail, the longer it will take, so having this input during design will help arrive at the optimum panel configuration. The Brock Commons team successfully managed this by integrating the mass timber stakeholders into the design and construction planning process. They used virtual tools (Figure 1) to sequence and detail components, along with mock-ups, discussed in Section 8.2.2.

> Woodworks (2019) published checklists for achieving cost optimization on mass timber projects at the design stage; they provide helpful information for project teams.

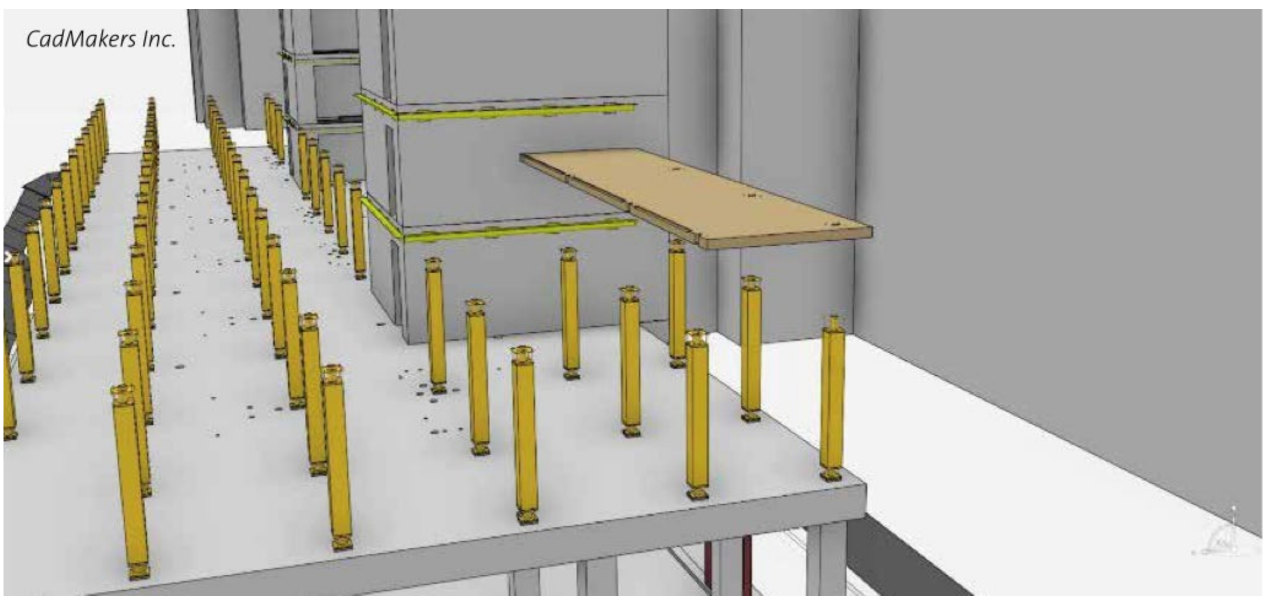

Figure 1. Brock Commons preplanning of erection sequence (naturally:wood, n.d.a.) (courtesy of CadMakers Inc.).

8.2.1.3 Integrating Mass Timber Trades into the Design Phase

Mass timber component pieces become a significant portion of the overall project, which leads to the need for greater communication and collaboration among the stakeholders. Designers have to understand not only the materials properties, but also the manufacturing and logistics limitations. The general contractor/construction manager (GC/CM) will also have to implement rigorous and robust coordination to ensure the on-site handling, placement, and protection of materials is properly managed.

A greater degree of prefabrication requires more communication and coordination up-front because the opportunity to “let the site guys figure it out” is removed. Mass timber panels are highly precise and engineered elements (Figure 2), and trades may need to be educated about how to work with and around the panels to avoid damaging them. The mass timber supplier will be able to identify key design parameters and flag any potential fabrication or installation issues so they can be solved ahead of time.

The time between a mass timber manufacturer getting involved in a project and the fabricated components arriving on-site is frequently 4 months or more. As the demand for tall wood buildings increases, early engagement of manufacturers in a project will become even more critical to obtaining a production capacity commitment.

Figure 2. Precisely processed CLT panel, Hoisko CLT Finland Oy (courtesy of Mark Taylor).

8.2.1.4 Creating and Meeting Design Completion Milestones

Prefabrication can create construction time advantages but only if the off-site work happens in parallel with the ongoing on-site tasks. To realize the benefits of accelerated schedules afforded by prefabrication, the design must be finalized earlier to allow manufacturing to begin. This is a significant cultural shift for the industry as a whole, which has become accustomed to (and possibly even reliant on) being able to make changes right up to the last minute. Project teams need to lock in their slot in the manufacturer's production schedule. Last minute changes can result in them losing their spot and going to the back of the line.

The consequences of making changes after fabrication has begun can be significant; in the worst case, it could stop the production line, which can have very real schedule and cost implications.

8.2.1.5 Increasing the Overall Amount of Prefabrication on a Project

With a manufactured product as the base, it makes sense for design teams to leverage other prefabricated solutions for the project.

This can be facilitated by two things: the use of building information modelling (BIM) (see Section 8.2.2) to properly coordinate these systems, and the tight tolerances with which mass timber elements are fabricated. This predictability is extremely valuable to other trades, and allows them to consider prefabricating more work ahead of time. The *Mass Timber Cost and Design Optimization Checklists* (WoodWorks, 2019) highlights this:

> With early engagement/design-assist, it is possible to prefabricate many openings and interface points that are much less costly and less prone to risk (damage, error, debris etc.) than when completed in the field. Seek MEP contractors skilled in prefabrication of their respective areas (piping, units, duct, etc.).
>
> Compare a completely prefabricated approach for incorporating MEP and fire protection systems to field accommodation techniques and decide on the best approach for your project.

In summary, designing to allow for prefabrication requires good planning and increased communication among team members, and the project team needs to embrace a shift in conventional construction thinking. Successfully executed, however, this can further improve the safety, quality, cost, and timeline of a project.

8.2.2 Building Information Modelling and Design for Manufacture and Assembly

Prefabrication applies industrial and manufacturing technology and philosophies to the construction process. The two major areas that apply to mass timber are:

- building information modelling—a technology; and
- Design for Manufacture and Assembly—a philosophy.

8.2.2.1 Building Information Modelling

Building information modelling (BIM) is a process for creating and managing information on a construction project for use across the project's life cycle from conceptual design to operation and maintenance (Figure 3). The building information model itself is the digital description of every aspect of the project beyond the spatial. A 4D building information model integrates time into the model, showing how the project will look at any particular time during construction based on the planned schedule. A 5D building information model integrates other data elements such as component cost. Each construction component has a digital twin within the model that is assigned parametric data. This can then be used for a variety of purposes, including:

- to review the interaction of the various components in terms of clashes or connections
- to determine overall material quantities
- to rationalize a project schedule and sequence of work
- to interface with manufacturers of the components
- to calculate weights of components
- to capture maintenance and care information for a building owner
- to model or monitor building performance

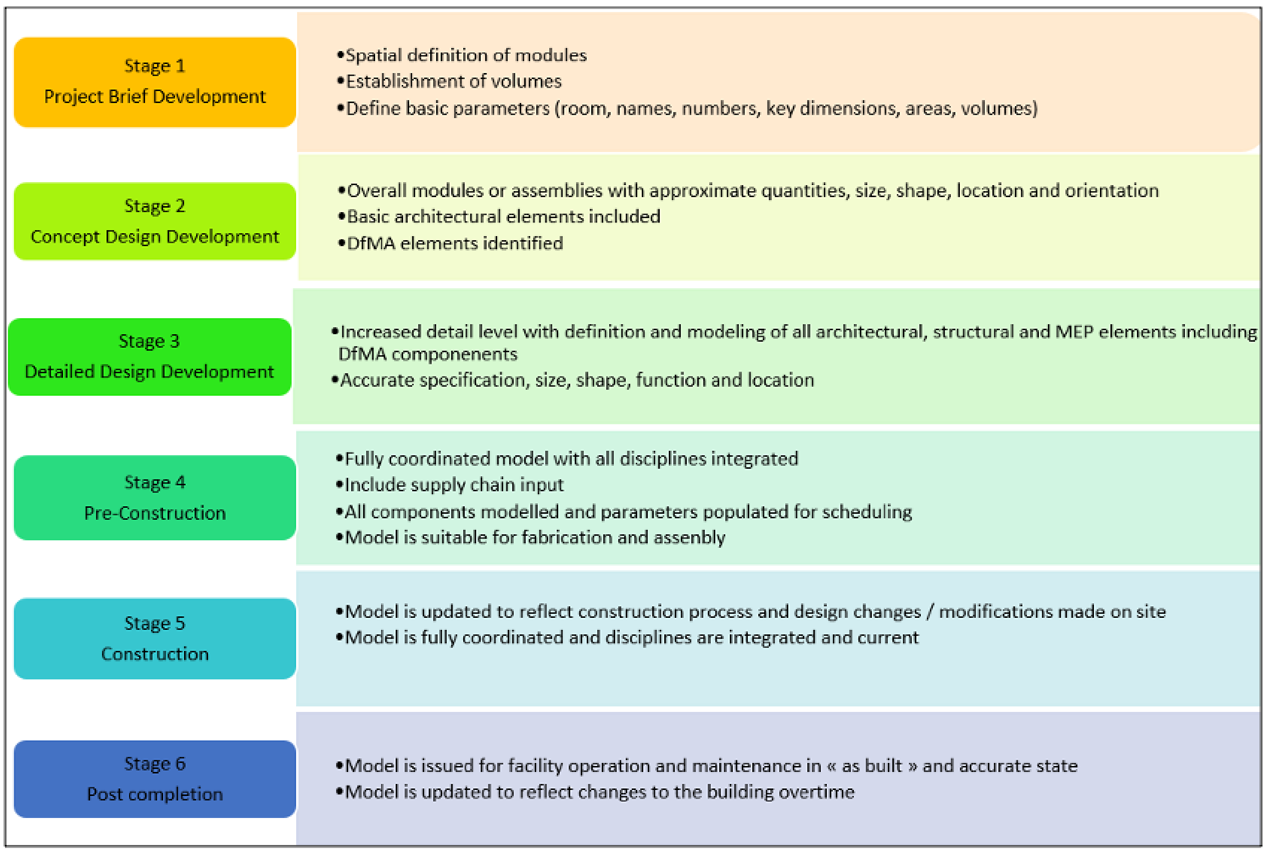

Figure 3. Building information model development and data required at various stages (Staub-French et al., 2018).

Being a common shared project asset that all stakeholders can provide input to and draw information from, the digital model can greatly benefit communication and coordination among team members. Because BIM enables a project to be planned with a high degree of detail, it is frequently referred to as “virtual construction”. By using it to this extent, the time and cost savings that can be realized during construction will more than offset the investment in its use up front.

BIM is not new to the construction industry: it has been widely accepted and used within the design community. However, the analog to digital shift has only recently started to take hold within the project execution phase, where adoption has been led by trade contractors rather than general contractors. Often this adoption was to facilitate greater off-site fabrication.

However, a project’s BIM is still rarely used to its full potential long term, often because the stakeholder who could make the most use of it—the client—is not informed of this possibility. To make the most of BIM’s potential for lifespan asset management, this conversation should start at the conceptual stages of the project.

Further discussions among team members about where and how they can best implement BIM on their project is encouraged. While BIM is gaining greater acceptance across the architecture, engineering, construction, and owner-operated (AECO) community, the level of adoption ranges across the full spectrum. Some companies have yet to adopt any form of BIM within their respective workflow. By highlighting BIM’s potential, it is hoped that stakeholders will seek to implement a wider use of the technology across their project’s stages.

8.2.2.2 Design for Manufacture and Assembly (DfMA)

DfMA is a philosophy that embeds the simplification of the manufacturing, delivery, and assembly of a product into the design. This requires the involvement of a broader range of project stakeholders early in the process and is a significant departure from traditional project delivery. It does, however, align well with the multidisciplinary and collaborative nature of BIM.

Involving a mass timber manufacturer will bring the DfMA approach to a project; the manufacturer’s ability to influence the design to optimize the manufacture and assembly of products is a key to their own success on the project. They will be able to provide input on details such as the connection points, edge details, and other trade interfaces to simplify both the production and installation of elements. This translates into greater efficiency on-site, which reduces both cost and schedule risk.

DfMA may also extend to incorporating work traditionally completed by other trades on-site into factory finished products. Performing those tasks in a controlled manufacturing environment can increase the level of quality control and improve worker efficiency and safety.

Considerable research has demonstrated the value of successfully applying DfMA approaches in the AECO industry. DfMA provides four main benefits (Buildoffsite, n.d.):

- improved quality
- reduced life cycle costs
- improved environmental performance
- improved site safety

Further details on DfMA and particularly its interface and interoperability with BIM on projects is well documented by Staub-French et al. (2018). The topic of designing for deconstruction and zero waste is covered in Chapter 4 (Section 4.3.3.3).

Consider a steel angle mounted to the panel edge as the connection detail between a CLT floor panel and a panelized exterior wall system. When installed on-site, each angle needs to be moved to its final installation location, which exposes tradespeople to a fall risk, and they will be less productive. However, if the angle were installed at the factory prior to shipping, all work could be done in one location, at ground level, and where the finished connection could be viewed more easily. This would improve worker productivity, quality, and safety, and it would be one less task that would have to be conducted on-site.

8.2.3 Preplanning Considerations

The planning process for the construction of a tall wood building encompasses all the same elements that a steel- or concrete-framed building would require and should happen in parallel with design progression. In order to optimize the cost-effectiveness of the structure, the construction planning will likely influence some design decisions.

BIM can be a powerful asset for creating a comprehensive construction plan for any tall building. Site layout, power requirements, safety, quality of construction, work sequencing and schedule, security, fire prevention/protection, and weather protection all need to be considered, along with:

- material shipping and handling
- crew sizes and requirements
- prefabrication opportunities for other trades

8.2.3.1 Building Information Modelling as a Construction Planning Tool

BIM provides some significant benefits to construction preparations. If a common building information model has been developed using input from all the stakeholders, it can be a powerful planning and communication tool for the construction team, and can even extend to the tendering of the work. By “virtually constructing” the building, the project team can address any technical or logistical issues, identify any conflicts or information gaps, and even pinpoint and address potential safety concerns. This will help communicate to the trades the many benefits that mass timber structures have, which in turn can reduce the fear about attempting to build something innovative and new.

General contractors and construction managers can use a common building information model tied to their schedules to create visuals that better communicate the plan for a project. The model can also help identify logic errors in the planning process.

The common building information model can also be used as a clash detection tool. This enables the designers, GC/CM, and trades to identify where different components are competing for physical space, and provides the following benefits:

- allows the routing of services to be optimized
- allows precutting of required openings in mass timber components
- allows preinstallation of connectors and other attachments to mass timber elements

The team on the Brock Commons project used the common building information model extensively in their planning, even down to the component level. The team was able to accurately sequence the panel and post installation for maximum efficiency before there was a worker on-site or the material was manufactured. This helped in determining the correct loading sequence for trucks in the factory to prevent double handling of material once it arrived on-site, which increased the workforce and crane efficiency and productivity (naturally:wood, n.d.b).

Problems on construction projects nearly always occur at interfaces between the work of different trades. Having a building information model allows the GC/CM to identify the most challenging areas ahead of time, and work with the affected trades to resolve the issues (Figure 4) by clarifying the scope of work, deciding on an optimum sequence, and mitigating tolerance or connection issues.

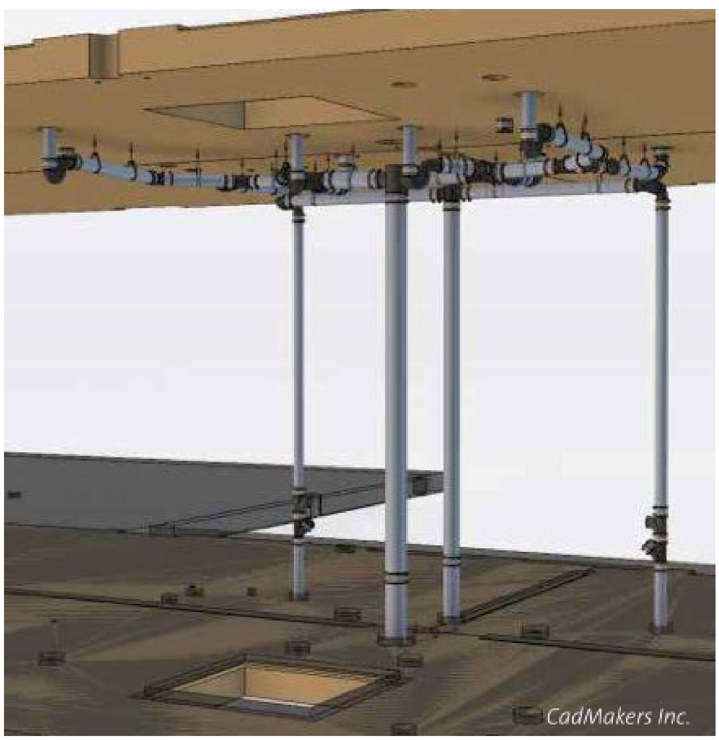

Figure 4. Brock Commons preplanning coordination between mass timber elements and plumbing system (naturally:wood, n.d.b.).

8.2.3.2 Integrating the Mass Timber Trades into Construction Planning

Tall wood building projects require coordination by the GC/CM to ensure that the on-site handling, placement, and protection of mass timber elements is properly managed. Greater communication among the mass timber manufacturer and other trades will be needed.

While the design team may be involved in some of this communication, unless a specific item has been designed/specified as prefabricated, most of the early interaction will be between the GC/CM and the various trades. This is another area where BIM can be an asset to a project.

If the mass timber supplier is "supply only", the GC/CM will require a separate contract for installation of the products. The GC/CM may undertake the installation with their own forces, or by a third-party trade contractor. This will necessitate further communication regarding their respective scopes—who is responsible for what, where the hand off occurs, how damage is monitored/attributed, etc.

Using mass timber also introduces some refinements into the work of the on-site trades. Different physical connection points between the manufactured and on-site work may be introduced. This requires clarity on how connections are made, and who is responsible for which parts.

Often there will be a requirement for an engineered erection sequence for a mass timber structure. This is similar to requirements for steel-framed buildings, and sometimes for concrete. Erection sequence planning is a critical element of the mass timber scope and for the GC/CM and other trades; therefore, it needs to be a key element of the overall construction planning. During erection, a mass timber frame needs to remain stable until all the final connections and fastening are completed. Some bracing of at least the columns will be required, which may affect the movement of workers around the floor, until they are safe to remove. Similarly, a certain percentage of fasteners may need to be in place before the next structural elements can be added. All these factors will affect the speed of erection and how soon other work can happen after the structure has been erected.

8.2.3.3 Materials Shipping and Handling

In planning for materials handling on a tall wood project, the GC/CM needs to understand how the materials are handled, and how they flow from a sequencing and cost perspective. Using the 4D capabilities of BIM can be helpful for this purpose.

Far fewer crane hours are required for building mass timber structures than concrete structures. This frees up more hook time for other trades, which often rely on the crane working overtime to do their hoisting, but their needs are more easily accommodated within the standard work week when building mass timber structures (Figure 5).

> Information about lifting and handling of CLT elements is provided in the *Canadian CLT Handbook* (Karacabeyli & Gagnon, 2019). A wide range of lifting systems and techniques that are inspired by systems in precast concrete construction are presented.

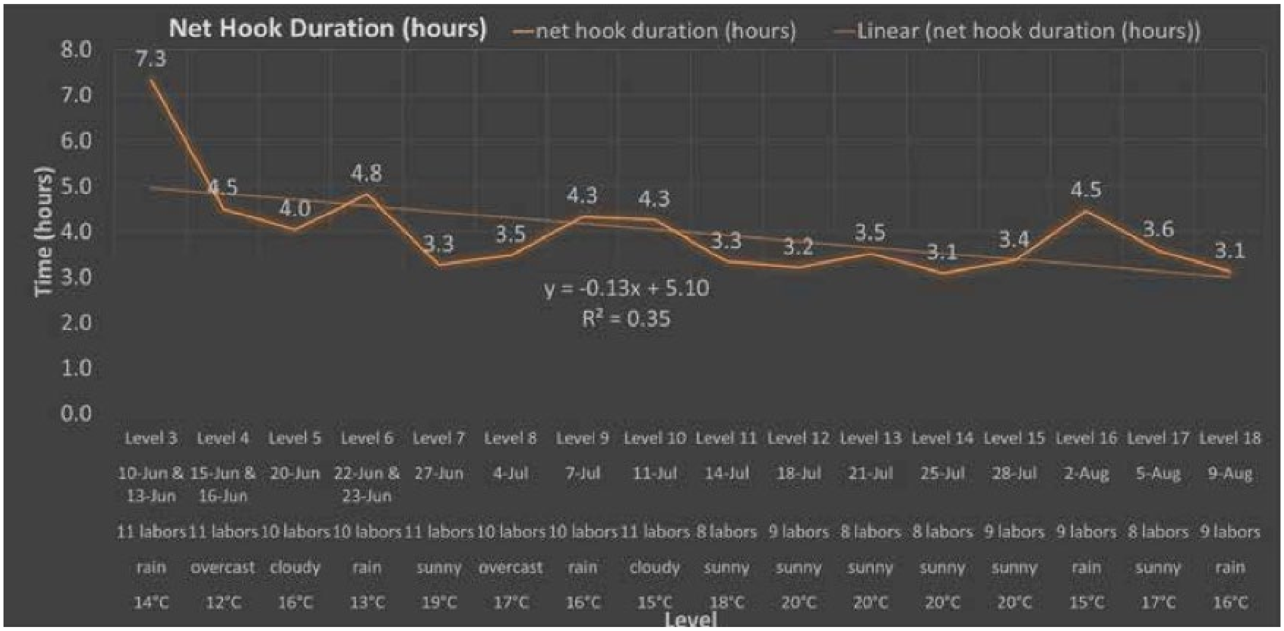

Figure 5. Analysis of on-site productivity by measuring hook time (naturally:wood, n.d.b.).

Ideally, once mass timber elements arrive on-site, they should be moved only once. They should go straight from the truck to their installation location with no double handling. Thus, the CM/GC should preplan sequencing with the installation contractor and involve the supplier to allow them to load delivery trucks accordingly. An accurate estimate of the erection timeline for each truck will help manage the flow of materials to the site. The correct number of trucks sent to the site each day will keep the installation crew working without creating a backlog of trucks waiting to unload. This is no different than the supply of concrete leaving a supplier's batching plant: a concrete works contractor will have a good understanding of how much concrete can be placed in an hour.

The type and size of crane selected may be influenced by the mass timber structure. Crane selection is driven by:

- the location of the crane and pick points
- the maximum weight of any individual lift, and
- the crane's load capacity at a given radius.

Both mobile and tower cranes provide benefits and have drawbacks, and each project will have its own site-specific influences that will dictate which type of crane is best. However, it may be possible to use a smaller capacity crane (all other things being equal) than would be needed for a concrete building, but not necessarily a steel one. The selection of the type of crane may then be driven by the weights of the mechanical or electrical equipment.

Project Delivery

Crane pick points are a key part of the site layout; they are the locations from which the crane can unload delivery vehicles. Mass timber delivery trucks may be the longest vehicles used on a project, so the pick point locations need to accommodate the area and sweep path that the trucks require.

From a weather protection perspective, storage of mass timber elements on-site is not desirable. Components should leave the factory wrapped in a moisture-resistant protective cover. At the factory, this wrap remains secure and intact. Trucking increases the risk of damage to the cover. If loads are subsequently stored on-site, waiting for installation, the chance of moisture-related damage increases.

Storage on-site also creates additional fire hazards that need to be controlled. See Chapter 6 for additional information.

8.2.3.4 Crew Sizes/Requirements

Prefabrication of mass timber elements provides advantages in terms of crew requirements for building projects. Finished panels allow for faster construction and a significant reduction in the amount of labour needed on-site. Building with mass timber requires only 25% of the on-site labour needed for building a comparable concrete structure (Kasbar, 2017). This has knock-on effects in terms of the site infrastructure required during the construction phase (e.g., washrooms, lunchrooms).

Reducing the amount of labour on- site also has positive effects on other trades: fewer people moving around the site creates fewer bottlenecks that reduce worker productivity rates (a good example is the reduced amount of time workers need to spend waiting for personnel hoists to access higher floors in a building).

8.2.3.5 Planning for Effects on Other Trade Systems

The building of mass timber structures can affect the materials and systems selected by other trades. The GC/CM needs to be aware of this and plan for it, from both a logistics and costing perspective. The following are just a few potential areas that need to be considered:

- Selection of plumbing and electrical trade materials/systems: In a concrete structure, much of the plumbing and electrical distribution can be achieved using cost-effective (labour and material) flexible plastic systems cast into the concrete. Mass timber arrives as finished, solid units; therefore, the mechanical and electrical systems need to be surface mounted. As a result, more costly and labour-intensive systems are needed. For example, in the Brock Commons building, compared to a concrete building, more copper plumbing pipe was required and the electrical wiring had to be mounted in metal conduit.
- When the construction of a concrete core is completed ahead of erection of the mass timber structure, fire risers need to advance in parallel. This is required as part of the fire risk mitigation plan (see Chapter 6), but it creates an extra (more challenging) step in the process, and there is limited access to install the pipes.
- Removal of spray-applied textured finish for ceilings: The soffits of mass timber floor panels are either covered with drywall as part of the encapsulation process or are left exposed (where allowed by code). When left exposed, contractors should pay attention to the material grade of wood used because a better finished look will be required. Care will also be needed to prevent moisture and physical damage to exposed wood finishes.

8.2.4 Scheduling Considerations

As discussed in Chapter 3 (Section 3.4), using mass timber can provide a number of scheduling benefits during the construction phase of a project; however, some factors need to be considered in order to realize those benefits.

Schedules for tall wood building projects need to factor in lead times for the manufacture of the mass timber materials. Early engagement with the manufacturer and installer allows more of the preparatory work to be done in parallel with the design. However, the fabricator may not be able to release the work to the shop floor until the design is finalized and coordinated.

The GC/CM should understand the mass timber fabricator's shop schedule—how long production will take, and what other projects are ahead of it on the production line and how that may influence when the material is ready to leave the factory.

Currently, there are relatively few mass timber fabrication facilities in North America, and they tend to be concentrated in specific geographic areas close to the wood sources; therefore, it is unlikely that the materials will arrive on-site the same day as they leave the factory. If the materials are coming from an offshore fabricator, the shipping time could be considerable. Therefore, the delivery of materials is a variable that the GC/CM needs to factor into the construction schedule.

Tall wood structures can be erected faster than concrete ones. Depending on the floor plate area, the cycle time for a typical high-rise concrete-frame residential building will be between 4 and 7 working days per storey, but that would be achieved only after 4–5 slower initial cycles as the crew got into a rhythm and their productivity improved.

The building of the structural system for Brock Commons was very efficient. The site crew routinely achieved a 3-day cycle and had a much shorter learning period. The project had two concrete cores that had been advanced and completed ahead of the mass timber installation, so that portion of work was not factored into the cycle time. A concrete core advanced in parallel with the mass timber structure, or better still a mass timber core, could potentially generate time savings of half a week per storey.

The erection of Origine (Figure 6 and Figure 7) took 3 months to complete the first 7 storeys but only 1 month to finish the remaining 5 storeys. This averaged out to 3 storeys per month, factoring in an extended learning curve due to the more complex site assembly method used. This timeline also included the erection of the exterior wall panels. However, because the Origine structural system was the first of its kind to be used, it can be expected that any subsequent projects will have learned from its construction and will be significantly faster. Even with the novel approach used, the architect noted that the project's overall timeline was 4–6 months shorter than what would be expected for a concrete building.

The delay between constructing the envelope and the structure is also reduced for a mass timber building. In a concrete building, construction of the envelope typically lags 6–7 storeys behind the construction of the structure due to the falsework and reshore infrastructure required. This delay is not required for mass timber structures, so immediately, these "inactive" storeys disappear from the equation.

Figure 6. Lifting the last panels to complete the Origine structure (Cecobois, 2018) (courtesy of Stephane Groleau).

Less crane hook time is required for erection of mass timber structures than erection of concrete structures. Prefabricating larger panels for the exterior wall (as in both Origine and Brock Commons) allows additional crane time to be available for installing the panels. The installation of the envelope can then potentially be 2 storeys or less below the currently completed structure. With larger prefabricated panels, the Brock Commons team could install the exterior wall in the same 3-day cycle as the floor. In some instances, CLT is being used as part of a panelized envelope system. While this approach is more common on low-rise projects, it would have definite benefits for tall wood buildings.

Creating a weathertight building sooner in the construction process allows subsequent finishing trades to start a number of weeks earlier in the process, which further contributes to a shortened schedule. The Origine project used CLT panels for the exterior walls, which resulted in no lag between the floor and wall installations, and permitted window installation to follow close behind. While the decision about creating a weathertight building quicker was driven primarily by the project's goal of being the world's first all mass timber tall wood building, Nordic Structures, the design and manufacturing company, noted that the accelerated enclosing of the building had a positive effect on subsequent trades being able to begin their work.

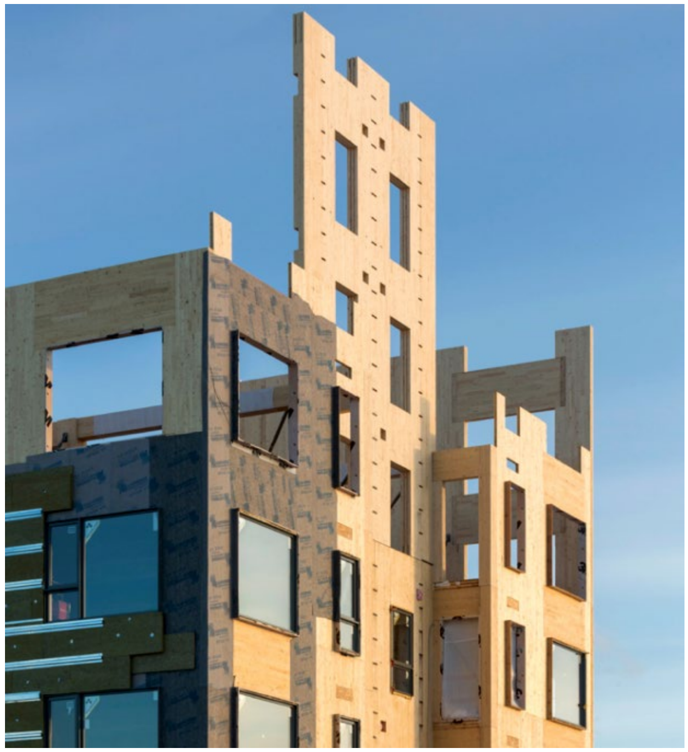

Figure 7. CLT panels used as exterior wall structure on the Origine building (Cecobois, 2018) (courtesy of Stephane Groleau).

The CM/GC needs to plan for this accelerated timeline. If other trades have not been involved in a mass timber building project before, they may not recognize (or even believe!) they can start their work earlier. This needs to be clearly mapped out and demonstrated ahead of time; otherwise, the trades may not be prepared to do their work when scheduled.

Work sequencing also changes with a tall wood building project. For example, the first layer of encapsulating drywall may need to be installed to within a certain number of levels below the live structure floor, which will have an effect on which trades are required when and the order in which they do their work.

8.3 CONSTRUCTION

Once a project moves into the construction phase, the team's focus shifts from design and planning to the execution and delivery of the physical project. This is when the benefits of strong preplanning come to fruition. Once into construction, the risks associated with any project become far more tangible, and the need to monitor and respond to them becomes more critical.

This section addresses further considerations regarding construction with mass timber, including:

- fabrication
- risk mitigation and management strategies

8.3.1 Fabrication Considerations

In the construction phase, the focus of the mass timber manufacturer and installer moves away from design and on to production. Discussion of the overall mass timber schedule (design to installation) should occur during the preconstruction phase. Clear timeline expectations should be agreed upon and should be used by the GC/CM to monitor the manufacturer's ongoing progress.

> **Construction Moisture**
>
> Once production has started, material will have to be kept in storage if delays occur. On-site weather-protected areas are always limited, so arrangements for storage, and how best to confirm when components can be shipped, should be discussed in advance with the manufacturing facility.

During the construction phase, the manufacturer must produce their own shop drawings for the consultants' review and to provide the basis for the data the factory equipment uses to process the mass timber. This is another area where a coordinated, shared BIM digital twin can be used to achieve time and effort efficiency. The manufacturer does not need to recreate the whole design, merely isolate their components and add to the level of detail for those parts. If this is done within the shared model, other users will be able to see those details, which will facilitate coordination with other trades. Devoting sufficient time to reviewing/coordinating these submittals with those of other trades becomes simpler and reduces the potential for problems once materials arrive on-site.

All stakeholders should recognize that mass timber manufacturing uses a production line methodology. Once under contract, a project is allocated a production time slot. If other stakeholders miss deadlines, the factory often has no option but to "bump" the project's production slot and move other projects up in the queue. Staying on top of design and site construction deliverables during this critical period is vital to maintaining the overall project schedule.

The GC/M should proactively check-in with the factory to obtain updates on the status of such things as:

- new questions or coordination issues that may have surfaced
- shop drawings
- factory workload
- materials availability

Once production starts, the GC/CM and design team should visit the factory to see the products and manufacturing progress for themselves.

A factory visit early in the production sequence can be valuable for reviewing mock-ups of particular details or finishes. This allows any required adjustments to be made easily at the source with minimal time and cost implications. If any of the mock-ups can be done during the preconstruction phase, that is even better. Factory visits as production begins can be used to confirm decisions made based on the mock-ups or will allow them to be fine-tuned.

On the Brock Commons project, a 2-storey mock-up was built early during design to try different connection methods and details (Figure 8). The team also used the mock-up to decide on the final panelized envelope system that would be used. This allowed them to investigate and solve potential constructability issues ahead of time, which in turn shortened the length of the on-site work and made it considerably more efficient.

Figure 8. Brock Commons structure mock-up (naturally:wood, n.d.b.) (courtesy of Urban One Builders).

Early factory visits and mock-ups can also be useful for informing the regulatory process. Allowing the local officials of the authority having jurisdiction to review the mock-ups, and in particular code-related details (e.g., fire separations, envelope details), can give them a preview of the project from which they can gain an early comfort level. In turn, this should limit the potential for regulatory issues later in the project.

> **Building Performance**
>
> Some attributes, such as noise isolation, depend on the quality of the build. To ensure successful final validation of building performance, awareness of sensitive details is required, and adequate supervision and interim validation must be provided during construction.

The manufacturer should provide copies of, or make available for review, any quality documentation or material certifications noted in the specifications. This could include ongoing product dimensional checks, equipment calibration logs, lumber moisture readings, and glue bond test results, in addition to any certification required for the lumber and glue materials. Prefabricated components may appear to be identical but could be engineered for a use in a specific location and orientation. Crews should be familiar with the component labelling system, particularly for exposed components, where the labelling may not be conspicuous.

There are some timing items that should be part of the original contract negotiations with the mass timber supplier/installer. A key point for both parties is the effect of any schedule delays ahead of the mass timber delivery and installation. If site work gets delayed for any reason, the mass timber product will need to be held in a dry storage environment. The contract should clarify who is responsible for the cost of this storage, and if the material is to be paid for while in storage. Storing the material in the controlled factory environment is always preferable to storing it on-site, as noted in Section 8.2.3.3.

8.3.2 Risk Mitigation and Management Strategies

Every project, regardless of structure type, has its own risk profile that will affect decisions made about the project. Tall wood building projects have their own risks and opportunities; a few key ones are:

- labour-to-material cost ratios
- quality assurance and control
- moisture protection
- improved safety
- opportunities due to tighter fabrication tolerances
- risks associated with tolerance differences between site and prefabricated components

8.3.2.1 Labour-to-Material Ratios

Compared to concrete-framed structures, the overall price of mass timber structures is more heavily weighted to the materials cost than to the labour cost (approximately 20/80 labour/material compared with 50/50 in concrete-frame construction). Project schedules highly depend on the availability of skilled labour. There has been a decline in both the size of the workforce and its skill level. Experienced, long-term tradespeople are retiring and leaving the industry, and are being replaced with fewer, less experienced workers.

A higher ratio of materials cost can help mitigate this labour risk. Although material pricing can have a degree of volatility, the price risk is removed once the mass timber supplier has committed to a price. The reduced number of workers required on-site to build a mass timber structure will also be easier to secure and retain for the shorter on-site timeline compared to the building of a concrete-framed structure.

8.3.2.2 Quality Assurance and Control

The factory production of mass timber provides greater control over the quality of the end product compared to cast-in concrete applications. Work done in a controlled environment is subject to fewer variables than that done on-site.

The building information model can be an asset for quality assurance and quality control. By using the model to accurately coordinate trade scope interfaces ahead of time, the chance of openings or connections being mislocated can largely be removed. If the model is used to assist with factory cutting and preparation of mass timber members, far tighter tolerances will be achieved, which will reduce the amount of rework required on-site to “make things fit”.

During the preconstruction/design phase of the project, the quality requirements should be defined and agreed upon. Project teams can then do much of their quality control checking at the manufacturing facility regarding:

- the level of finish
- any pre-applied coatings
- the addition of any connection pieces or other trades’ work
- the allowable dimensional tolerances of the mass timber, both as individual elements and as a completed structure

8.3.2.3 Moisture Protection

Moisture protection of the wood components is a key item for contractors to consider. Exposure to moisture can cause damage or marking of the wood, so the contractor needs a good plan to address this.

There are a number of ways the contractor can manage moisture protection, including:

- rapidly installing the building envelope using prefabricated curtain wall panels, as was done at Brock Commons
- using factory application of removable, non-marking, peel-and-stick protection to any exposed surfaces (e.g., top surfaces of CLT floor plates)
- prioritizing water management within the building

The key is to first understand when and where there is moisture risk. Because preventative moisture measures are likely more cost-effective, it is important to use multiple measures, whether that is through scheduling or shielding. Understanding what conditions need to be achieved and the steps to be taken is also vital. The moisture risk plan should also address periods when poor weather is anticipated and when crew are not able to respond to moisture-related issues at the construction site. See Chapter 7 for further details about minimizing moisture risk.

Construction Fire

The approach to construction fire and construction moisture risk follow the same concepts as addressing personnel health and safety. This starts with identifying the hazards and risk mitigation methods. These are discussed in this guide. With this information, the construction and risk mitigation plans can be jointly developed.

8.3.2.4 Safety

Falls are one of the most common sources of injuries and deaths on construction sites. Beyond the personal cost, they have implications for a project's schedule and costing. Prefabricated mass timber systems provide options to do more construction work at ground level. For example:

- perimeter guard rails can be installed prior to hoisting elements rather than along an open edge at height; and
- floor openings can easily be covered at ground level, or even in the factory.

These kinds of action can mitigate the risk of falls, and they provide more efficient ways of executing project tasks. BIM could be used to identify potential hazards ahead of time, although this is not (yet) widely practiced.

8.3.2.5 Opportunities Created by Tighter Fabrication Tolerances

Once on-site, the trades will require the same time as on other tall building projects. This is unlikely to change without wider adoption of prefabrication across the construction industry. The precision and tight tolerances that are achieved in a tall wood building, coupled with the use of BIM to create a digital model, creates opportunities for other trades, either individually or in collaboration with others. Thus, further cost and schedule savings are possible if they are identified and pursued during the design phase.

All the considerations above, many of which provide benefits if properly realized ahead of time, should be included when planning a tall wood building project.

Tighter tolerances also reduce the amount of waste generated both in the factory and on-site. Reducing the waste from construction, renovation, and demolition is a focus of many governmental authorities, as noted in Chapter 3 (Section 3.6). Construction is a notoriously wasteful industry. According to Statistics Canada, in 2016, 3.2 million tons of waste was generated from construction, renovation, and demolition, and was sent to landfill (Environment and Climate Change Canada, 2020). In addition, considerable effort, and therefore cost, is involved in cleaning up and disposing of construction waste. Conversely, prefabrication reduces the amount of waste generated on-site, and thus the effort required to maintain site cleanliness. Because most of the prefabrication work is done away from the construction site, less dust and noise are generated on-site; therefore, less time is spent sweeping the site, and the risk of fires and safety incidents is reduced. Prefabricating mass timber in a factory also allows for better reuse of offcuts or can optimize cut patterns to reduce waste.

8.3.2.6 Risks Associated with Tolerance Differences between Site and Prefabricated Components

Mass timber is a precise system, and the GC/CM needs to factor this into their planning. The accuracy and tolerance of the site-built work can have a significant effect on the installation of prefabricated elements. For example, factory CNC equipment can cut materials extremely precisely and create components that have a tolerance of ± 2 mm. Typical concrete specifications allow for tolerances that can be in excess of ± 10 mm in any given plane.

If site tolerances are too loose, they can cause significant cost, schedule, and quality problems when mass timber components are installed. If a CLT panel does not fit where it is supposed to because a site-built element is too far out of the designed location, there are a number of immediate cost and time effects:

- The panel stays on the crane hook longer while workers initially “try to make it fit”.
- When this does not work, the panel may need to be set down somewhere else temporarily while an alternative fix is found.
- The erection sequence may dictate that no further work can happen until the panel is installed and secured, so all mass timber erection work has to be halted, with the crane and crew standing idle.
- Often the fix will involve an on-site modification of the panel, which will require the crane to pick it up again, place it somewhere where the necessary adjustments can be made, wait until that work is done, and then hoist it back to its original location, where (hopefully) it now fits.

All these factors create both time and cost effects. However, on-site modifications can also cause quality risks. In the factory, holes and cuts in mass timber elements are made by CNC equipment that processes the wood with very precise tools. Modifications made on-site do not have that precision and are often made with the tools at hand. In addition to poor fit, which may affect fire resistance or acoustic performance, finished surfaces can be damaged.

Therefore, in planning a project, the team needs to consider these differences and develop connection and interface details that will account for them. This should ensure that prefabricated elements can be set and secured quickly in one operation, and avoid time, cost, and quality effects.

8.4 CONCLUSION

The design, planning, and construction of a tall wood building need not present any greater risk or challenge than any other project. With the proper planning and management, a mass timber structure, because of the necessity to use the prefabricated construction approach, can provide many excellent project risk mitigation strategies that are not available to other structural systems. The planning and management skills needed for building tall wood structures are fundamentally like those needed to plan a concrete- or steel-frame building. With a mass timber structure, however, the project stakeholders are required to appreciate the various forms of mass timber components that are available—beams, columns, and panels—and that each of them can be machined to very tight tolerances and can be connected in many ways to facilitate assembly and disassembly.

The building of mass timber structures can have fewer labour and schedule risks than many mid- and high-rise projects, and the challenges associated with quality and safety can be mitigated. This risk mitigation results from the fabrication of mass timber in a controlled factory environment ahead of when it is actually needed on-site.

Realizing the full benefit of mass timber’s advantages requires a change in some conventional design and procurement methods. Having the construction manager, mass timber supplier, and erector at the table with the consultants as the design is developed makes for more efficient use of the mass timber produced for the project, the space available on-site, and the construction schedule. This not only adds value to the project, as noted in Chapter 3, or results in a more environmentally-friendly project, as noted in Chapter 4, but construction is less disruptive to the local neighbourhood because less noise, waste, and runoff is generated.

The benefits of using BIM as a tool for team member integration and communications cannot be understated: it provides a common, shared information venue that all stakeholders can contribute to and draw information from. The building information model can help with project design, planning, and execution, and even ongoing operation of the building. Along the way, it will contribute to a greater use of a Design for Manufacture and Assembly approach, which will identify and remove more problems at the virtual stage rather than on-site, where they will have cost and time effects. All of these factors can positively affect worker safety (Duncheva et al., 2016), the quality of construction, the project schedule, and ultimately, the cost for the project owner (Autodesk, 2014).

8.5 REFERENCES

Autodesk. (2014). *The value of BIM for owners: Save time and money during building lifecycle*. https://damassets.autodesk.net/content/dam/autodesk/www/solutions/bim/BIM_for_Owners.pdf

Buildoffsite. (n.d.). *BIM and DFMA*. London, UK: Author.

Cecobois. (2018). *Origine Point-aux-Lievres Ecocondos, Quebec City.* https://cwc.ca/wp-content/uploads/2019/03/Origine-Case-Study.pdf

Duncheva, T., BuHamdan, S., Hairstans, R., & Al-Hussein, M. (2016). BIM-enabled health and safety analysis of cross laminated timber onsite assembly process. In A. G. Bruzzone, F. de Felice, C. Frydman, F. Longo, M. Massei, & A. Solis (Eds.), *Proceedings of the 17th International Conference on Modeling and Applied Simulation* (136–145). Budapest, Hungary. https://www.napier.ac.uk/~/media/worktribe/output-1303256/bim-enabled-health--safety-analysis-of-cross-laminated-timber-onsite-assembly-process.pdf

Environment and Climate Change Canada. (2020). *National waste characterization report: The composition of Canadian residual municipal solid waste.* Gatineau, QC: Author. https://publications.gc.ca/collections/collection_2020/eccc/en14/En14-405-2020-eng.pdf

Karacabeyli, E., & Gagnon, S. (Eds.). (2019). *Canadian CLT handbook.* (2nd ed.). Pointe-Claire, QC: FPInnovations. https://web.fpinnovations.ca/clt/

Kasbar, M. (2017). *Investigating the performance of the construction process of an 18-storey mass timber hybrid building*. (Unpublished master's thesis). University of British Columbia, Vancouver, BC. https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0347252

naturally:wood. (n.d.a.). *Brock Commons Tallwood House: design and preconstruction overview case study*. Vancouver, BC: Author. https://www.naturallywood.com/resource/brock-commons-tallwood-house-design-pre-construction-case-study/

naturally:wood. (n.d.b.). *Brock Commons Tallwood House: construction modelling case study*. Vancouver, BC: Author. https://www.naturallywood.com/resource/brock-commons-construction-modelling-case-study/

naturally:wood. (n.d.c.). *Brock Commons Tallwood House: construction overview case study*. Vancouver, BC: Author. https://www.naturallywood.com/resource/brock-commons-tallwood-house-construction-overview-case-study/

Staub-French, S., Poirier, E. A., Calderon, F., Chikhi, I., Zadeh, P., Chudasma, D., & Huang, S. (2018). *Building information modeling (BIM) and design for manufacturing and assembly (DfMA) for mass timber construction*. Vancouver, BC: University of British Columbia, BIM Topics Research Lab.

WoodWorks Wood Products Council. (2019). *Mass timber cost and design optimization checklists*. Washington, DC: Author. https://www.woodworks.org/wp-content/uploads/wood_solution_paper-Mass-Timber-Design-Cost-Optimization-Checklists.pdf

Monitoring and Maintenance

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ABSTRACT

Tall wood buildings are a new form of construction. It is prudent to design tall wood buildings with some redundancy and to be relatively conservative regarding assumptions related to design parameters. Testing and monitoring initial and in-service performance is critical to confirming actual performance and refining designs to be more cost-effective for future buildings.

This chapter presents short-term measures for testing airtightness of building enclosures, localized assemblies (e.g., fenestration), and enclosures (e.g., elevator shaft); building ambient vibration; sound insulation of walls and floors; floor vibration; water tightness of localized assemblies (e.g., fenestration and doors); and thermal resistance of enclosure assemblies. The evaluation of sound insulation is aligned with the new requirements in the National Building Code of Canada for airborne sound insulation of ASTC 47, and the evaluation of floor vibration is aligned with the ISO standards, ISO 18342:2016 for field timber floor vibration testing and ISO/TR 21136:2017 for subjective evaluation of timber floor vibration performance. This chapter also includes long-term measures for monitoring service conditions that affect durability; indoor environment elements (e.g., thermal, air quality) that affect comfort; building energy efficiency; vertical movement within and differential movement between load-bearing members; and wind-induced lateral vibrations. Recommendations address planning for performance testing and monitoring in coordination with construction schedules and building operations, as well as associated costing.

This chapter also provides guidance on building maintenance by focusing on design considerations to achieve durable performance (by referencing Chapter 7, *Building Enclosure Design*) and considerations to facilitate maintenance of tall buildings, such as cladding system access, fenestration, location of vents, and material selection. The detailed guidelines emphasize that building maintenance and renewal should be based on a proactive maintenance plan. Routine inspection, repair, and renewal should be conducted to achieve satisfactory long-term performance. In addition, this chapter provides guidance on the assessment and repair of timber members when their structural integrity is compromised due to moisture- or fire-related damage.

9.1 INTRODUCTION

Tall wood buildings are a new form of construction. It is prudent to design them with some redundancy and to be relatively conservative regarding assumptions about design parameters. Furthermore, testing and monitoring of initial and in-service performance is critical to confirming actual performance and refining designs to be more cost-effective in future buildings.

This chapter provides recommendations for in situ testing and monitoring of tall wood buildings, which design teams may need to better understand design assumptions. The recommendations address planning for performance testing and monitoring in coordination with construction schedules and building operations, as well as associated costing. Such testing and monitoring, however, does not aim to address requirements related to commissioning or warranties for performance. In addition, this chapter provides general guidance on building maintenance and repair to help maximize long-term performance and service life and avoid unexpected costly repairs and replacement during building operation.

All performance testing, monitoring, building maintenance, and repairs should be undertaken by knowledgeable, experienced professionals according to appropriate methods available. Building testing and monitoring is typically led by researchers, in cooperation with the design and construction team, with funding that is separate from the construction project. Instrumentation and devices used for testing and monitoring should be properly selected and calibrated. Appropriate locations for measurement should be identified in order to obtain relevant performance data that will meet the objectives of the testing and monitoring program. Replication of measurements should be provided whenever possible to overcome variations that occur in wood products, other materials, and construction.

Marketability/Profitability

Monitoring building assembly performance (especially vibration and acoustics that include the impacts of build tolerances) may help optimize the next build. Monitoring should be coordinated with the design team so that design assumptions are documented. Consideration should be given to measuring the performance of the mock-up or actual structure.

9.2 SHORT-TERM PERFORMANCE TESTS

This section outlines performance tests that can be completed within relatively short periods (typically hours) during or after completion of construction or off-site to verify performance of key building assemblies. These tests do not require installing and keeping instrumentation in the building for long periods. The cost depends on the time and complexity of the testing, as well as travel and equipment shipping needs. Table 1 summarizes the major performance tests, methods, instrumentation, and equipment used, and the testing timelines.

Table 1. Short-term building performance tests, methods, instrumentation, and testing timelines

Test/performance attributes	Method	Typical instrumentation/ equipment	Typical timelines/ coordination with design and construction
Airtightness of the entire building	Measuring airflow at a given pressure differential	Fan door (blower door)	Completion of construction Periodically during construction to monitor and measure the effect of construction procedures
Airtightness of localized assemblies (e.g., fenestration) or enclosures	Observing airflow by using smoke or based on thermography	Tracer gas, smoke tracers, test chambers with portable smoke machine, or infrared camera with a certified operator	Typically conducted during installation, such as installation of fenestration, to identify air leakage paths. Supplementary testing can also be performed following completion of the project. Infrared analysis (thermography) can be carried out following completion of the air barrier system or completion of overall construction, but ideally prior to final delivery of the project.
Water tightness of localized assemblies (e.g., fenestration and doors)	Measuring water penetration under a given pressure	Testing installed assemblies (e.g., windows and doors) using test chambers, a calibrated spray rack, portable ventilators, a pump, and gauges	Typically, testing is conducted on a mock-up assembly during design and construction to evaluate and improve water tightness of the installation method.
Thermal resistance of enclosure assemblies	Laboratory testing: measuring heat flux under steady-state conditions Thermography for identifying thermal resistance deficiencies in the final assembly	Laboratory testing of specimens representing those used in building enclosures Infrared camera and a certified operator	Before or at the design phase of opaque assemblies or fenestration Thermography can be performed following construction or assembly (prior to delivery, if possible)

Test/performance attributes	Method	Typical instrumentation/ equipment	Typical timelines/ coordination with design and construction
Building natural frequencies, mode shapes, and damping ratios	Ambient vibration testing to determine natural frequencies, mode shapes, and damping ratios	The test typically acquires time signals of vibrations induced by ambient driving forces, such as ground movement resulting from traffic, etc., by using accelerometers and data acquisition systems.	Completion of the structure, but without interior or exterior finishing (bare structure), and after completion of the entire building
Floor vibration	ISO 18324:2016 method: measuring fundamental natural frequency and maximum deflection under a point load of 1 kN, and FPInnovations protocols. Informal subjective evaluation by using ISO/TR 21136:2017 may also be conducted	A typical impact modal test system includes 7 accelerometers, an instrumented hammer, and an 8-channel analyzer.	Upon completion of floors, and before and after a concrete topping is added, if a concrete topping is used
Sound insulation performance of floors and walls	Following appropriate standards to measure field sound transmission class/apparent sound transmission class (FSTC/ASTC) of walls and floors, and field impact insulation class of floors. Informal subjective evaluation by using FPInnovations protocol may also be conducted.	A typical acoustic testing system includes a loudspeaker, a sound level meter, and software for remotely controlling the test, and post data analysis to determine a single-number rating, such as ASTC and FSTC, etc.	Completion of construction and floors with finishing

9.2.1 Airtightness

Minimizing air leakage from building enclosures is one of the most effective means of reducing energy loss, improving energy efficiency, and reducing the risk of interstitial condensation, particularly in heating-dominated climates. Good airtightness is also important for reducing rain ingress and improving sound insulation and smoke and fire separation performance. See Section 7.5.4: Air Leakage Control for more information. The requirements for air leakage control to limit water vapour condensation have been specified in the National Building Code (NBC) of Canada since 1985. This was mandated through the requirement that every building be equipped with an air barrier system—a designated element within wall and roof assemblies to control air leakage across the building enclosure. Since the NBC's main mandate was limited to health and safety, the initial requirements for an air barrier system and air leakage limits were set to limit the risk of condensation within the insulated portions of opaque walls, where uncontrolled air leakage would lead to condensation and degradation of the building enclosure elements, including the structure.

More recently, requirements for air barrier systems have been introduced into the National Energy Code for Buildings (NRC, 2017) and NBC Section 9.36: Energy Efficiency (NRC, 2020b). The BC Energy Step Code (Government of British Columbia, 2019) requires airtightness testing to meet those requirements. The City of Vancouver requires 3.5 air changes per hour (ACH) @ Δ50 Pa of pressure difference for single-family houses, and 2.0 L/s/m^2 @ Δ75 Pa[1] for residential 4- to 6-storey multi-family buildings (City of Vancouver, 2018). Among voluntary energy programs, the Passive House standard requires 0.6 ACH @ Δ50 Pa for building enclosure airtightness (Passive House Institute, 2018).

The design and testing of air barrier systems were extensively studied by the National Research Council's former Division of Building Research. Strategies and methods for whole-building airtightness testing were established and published for many categories of buildings, including high-rise residential and commercial buildings. The methods have been used not only to control condensation but also to limit uncontrolled air leakage in order to establish ventilation rates for health and energy-saving targets. Other organizations and practitioners have also conducted extensive research and testing on both new construction and existing buildings, and have developed best practice guides (BC Housing, 2017; CMHC, 2018). Testing may be conducted for the whole building (or individual units in the building) upon completion of construction in order to assess airtightness of the enclosure. Fan door tests have long been used by building enclosure engineers and energy advisors certified by Natural Resources Canada (NRCan) under the EnerGuide Program to measure airtightness of houses under controlled pressurization or depressurization (Figure 1). Detailed tests can follow the ASTM E779 standard (2019) or equivalent test methods, such as CAN/CGSB 149.10 (SCC, 2019).

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[1] For air barrier system qualification in a laboratory setting, the air leakage rate is measured at several pressure differences between 50 Pa and 300 Pa, and is plotted on a log-log graph to develop a regression line. The regression line characterizes the air leakage rates of the air barrier system across a range of pressure differences, and the relationship between air leakage rates and range of pressures is identified by reporting the air leakage rate at 75Pa ΔP as the “reference pressure”, which defines the slope of the regression line going through zero.

Air leakage testing is more complicated and expensive for a large multi-storey building than for a single-family house. The on-site test may take several hours or longer depending on the size and complexity of the building, and it typically requires the use of multiple fan doors running simultaneously. During testing, interior doors should be open and other measures should be taken to ensure uniform pressure between adjacent zones. The test measures airflow (infiltration or exfiltration) at a given pressure difference, and the pressure difference between the interior and exterior is induced within a range during testing, typically from 25 to 75 Pa, with an increment ranging from 5 to 10 Pa. The air leakage rates and effective leakage areas can be calculated for the conditions tested based on the method followed. Airtightness tests can also involve the use of a tracer gas, smoke tracers, and other methods to visually identify the paths of air leakage via localized assemblies and small enclosures, in particular, such as windows, doors, ceilings, and elevator shafts (ASTM E1186, 2017; ASTM E741, 2017). Measures can then be taken to seal any identified leakage and improve airtightness. Localized air leakage may also be identified using infrared scanning techniques, sometimes coupled with smoke testing, when the building or the individual compartment is pressurized or depressurized (ASTM E783-02, 2018).

Figure 1. Air leakage testing of a single suite in a wood-frame multi-unit residential building (courtesy of RDH Building Science).

9.2.2 Thermal Resistance

Good thermal resistance of a building enclosure is important for reducing energy loss associated with space heating or cooling. Building energy-efficiency requirements have been rapidly upgraded across Canada in recent years. In general, energy codes and standards tend to focus on requirements for thermal transmittance or resistance (taking into consideration thermal bridging in the newer codes and standards) of opaque assemblies and fenestration in different climate zones. Depending on the jurisdiction, provisions regarding energy efficiency for Part 3 buildings in Canada are based mainly on the National Energy Code for Buildings (NRC, 2017) and ASHRAE standards (ANSI/ASHRAE/IES Standard 90.1, 2019 or previous versions), as summarized in the *Guide for Designing Energy-Efficient Building Enclosures for Wood-Frame Multi-Unit Residential Buildings* (Finch et al., 2013). Detailed requirements should be checked before the building design stage; specific recommendations are also provided in Chapter 7.

Wood has high thermal resistance compared to other structural materials, such as steel and concrete, and the thermal conductivity of a typical wood species is usually only 2–4 times that of commonly used insulation materials, such as fibreglass insulation (NRC, 2020b). Thermal bridging caused by wood elements in a building enclosure is much less of a concern than that caused by metal elements; therefore, the thermal resistance of a wood-based enclosure assembly is relatively easy to calculate or predict using energy models. The effective thermal resistance of a number of above-grade walls and below-grade walls and roofs representative of those used in platform wood-frame construction, cross-laminated timber construction, and infill wall applications is listed in the *Guide for Designing Energy-Efficient Building Enclosures for Wood-Frame Multi-Unit Residential Buildings* (Finch et al., 2013), based on thermal modelling. Thermal bridging of building enclosure details used in mid-rise and high-rise buildings, including a few typical wood-based assemblies, have been extensively evaluated and documented (Morrison Hershfield, 2011, 2014) (Figure 2).

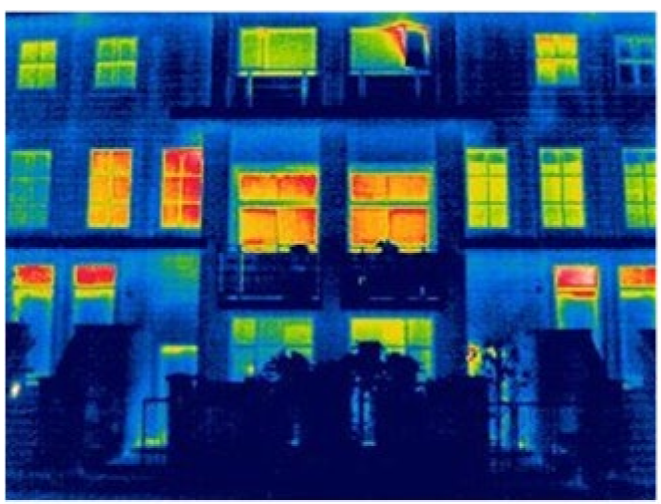

Figure 2. Infrared image of typically well-insulated wood-frame walls and less insulated windows with higher thermal bridging (courtesy of RDH Building Science).

It is not easy to precisely measure the thermal resistance of an in situ assembly in a building. Qualitative assessment of the thermal performance of a building enclosure can be conducted during operation using infrared imaging technologies, mainly for identifying thermal bridging, framed cavities with inadequate or missing insulation, or air leakage (ASTM E1186, 2017; ASTM C1060, 2015). If it is of interest to precisely quantify the thermal resistance of the materials, an opaque assembly, or the fenestrations, laboratory testing of the specimens representing those used in the building enclosures could be conducted. This can be used mainly to validate thermal modelling results and can be conducted by measuring the heat flux under steady-state conditions. Test standards are available for using a guarded hot box, a guarded hot plate, or other apparatuses (ASTM C177, 2019; ASTM C1060, 2015; ASTM C1199, 2014; ASTM C1363, 2019). Many of these apparatuses and ASTM methods have been developed by the National Research Council of Canada (NRC) thermal labs. Tests must be conducted by a qualified thermal laboratory that is audited by the NRC for accreditation by the Standards Council of Canada. For research purposes, long-term heat flow performance can be monitored by installing in situ heat flux and temperature measurement sensors in a building assembly, together with a data acquisition system (ASTM C1046, 2013), to determine the thermal resistance of the part of the assembly being monitored (ASTM C1155, 2013). Such monitoring typically requires additional funding and time, and care is needed in selecting reliable measurement systems.

9.2.3 Building Natural Frequencies, Mode Shapes, and Damping Ratios

The objective of measuring natural frequencies and damping ratios of a tall building is to understand its dynamic behaviours, which are determined primarily by natural frequencies and damping ratios, and are affected by non-structural components. The measured natural frequencies are needed to verify the predicted frequencies based on the dynamic analysis, following the requirements in the NBC (NRC, 2020b). The measured damping ratios are used as input for the dynamic analysis. The mode shapes are a key parameter used to ensure the measured natural frequencies are the frequencies associated with the vibration modes that are of interest. Sections 5.3 and 5.4 provide information on the analytical determination of natural frequencies and dynamic response of structures.

Ideally, building natural frequencies, mode shapes, and damping ratios should be measured once the structure is built but before interior and exterior finishing is conducted, and following completion of the entire building, due to the effects of non-structural components; they should also be measured after years of service to investigate potential changes over time. Ambient vibration testing is a simple, economical, and easy method of measuring building vibration. The test acquires data using sensors. The sensors record the measured time signals of the building vibration induced by ambient driving forces, such as wind and ground movement resulting from traffic (Figure 3). Then the signals are post-analyzed to obtain the building's natural frequencies, modal shapes, and damping ratios. Operational modal analysis software extracts the required natural frequencies, modal shapes, and damping ratios from the measured time signals. Various measurement systems are available. FPInnovations developed an ambient vibration testing measurement system by using accelerometers, a data acquisition device, and operational modal analysis software (Hu, 2012); McGill University developed a system that uses velocity transducers (Gilles & McClure, 2008).

Figure 3. Vibration testing being conducted in a building (left: indoor setup; right: accelerometer sensors).

9.2.4 Floor Vibration Performance

Measuring floor vibration performance provides designers with data that can be used to achieve a satisfactory performance for the building's occupants, and to develop a better understanding of the effects of non-structural components on dynamic behaviours. Collecting performance data and comparing design and test results for new and innovative floor assemblies is valuable for developing good design and construction methods to control floor vibration (Figure 4).

Figure 4. Vibration testing of a mass timber floor at FPInnovations.

The performance of residential floor vibration induced by normal walking can be assessed using ISO 18324 (ISO, 2016) for field floor vibration test methods and ISO/TR 21136 (ISO, 2017) for subjective evaluation protocols and the ISO/TR 21136 questionnaire. After testing and subjectively rating hundreds of residential wood-joisted floors across Canada, a criterion was developed for lumber-based floors, which was included in the 1995 NBC lumber floor span charts. In subsequent years, FPInnovations developed a performance criterion for evaluating the vibration performance of residential light-frame wood floors in field (Hu, 2000), which was included in ISO/TR 21136 (see Section 5.4.2 for more details). This performance criterion has been widely used for wood-joist floor assemblies, but caution should be exercised when it is used to evaluate wood-composite floors and floors constructed with other materials.

For vibration induced by rhythmic activities such as dancing, concerts, and sports, the NBC recommends acceleration limits for controlling the vibrations in various buildings (Table 2).

Table 2. NBC-recommended acceleration limits for vibrations caused by rhythmic activities (NRC, 2020a)

Occupancies affected by the vibration	Acceleration limit, % gravity (9.8 m/s^2)
Office and residential	0.4–0.7
Dining and weight lifting	1.5–2.5
Rhythmic activity area	
in an office or residential building	4–7
in a stadium or arena	10–18

9.2.5 Sound Insulation Performance of Floors and Walls

Good sound insulation performance is very important to the occupants of a building. The objectives of measuring the sound insulation performance of floors and walls after the completion of a building are to assess the actual sound insulation performance and determine the acoustic performance ratings based on various codes and standards. Although it can be estimated in advance, the actual sound insulation performance of floors and walls remains unknown until in situ measurements are taken, which include flanking transmission. Flanking transmission is caused by sound leakage through (1) assembly openings, many of which are not in place during the standard qualification tests for fire and sound, and (2) vibration transmission between coupled surfaces or through continuous structure elements that are required to maintain the structural integrity of the building. A structural engineer should be aware of decoupling requirements for reducing the risk of flanking transmission from the onset of design.

The final sound insulation performance within the constructed building could be unpredictable and is highly dependent on the design and how the installation details are implemented by the contractor. The NBC (NRC, 2020b) requires that a dwelling unit be separated from other spaces of the building where noise may be generated, with its walls and floors providing an apparent sound transmission class (ASTC) rating of not less than 47. Field measurements of the ASTC of a finished building[2] is very important for confirming whether the building sound insulation performance meets the code requirement, given how highly dependent the creation of flanking transmission paths is on workmanship.

Section 5.4.1.2 provides relevant sound insulation requirements for floors and walls based on various building codes and standards. Airborne sound transmission through floor or wall assemblies and impact insulation performance (tapping machine impact sound transmission) of floors can be measured and rated following ASTM standard test methods, such as ASTM E413 (2016), ASTM E336 (2020), ASTM E1007 (2021), and ASTM E2235 (2020), or other appropriate methods (Figure 5). Complementary to technical testing, the field sound insulation performance of floors and walls can also be assessed using informal subjective evaluation methods. The report *Vibration Performance of Wood Floors and Staircases, and Sound Insulation Performance of Wood/Ceiling and Wall Assemblies* (Hu, 2014) provides a detailed description of a protocol for testing the sound insulation performance of buildings.

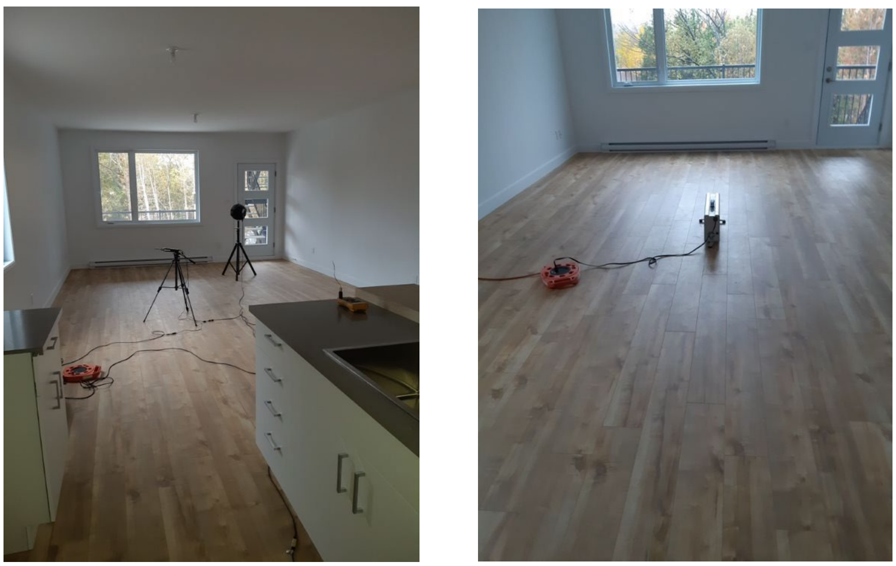

Figure 5. Testing airborne sound transmission through walls (left) and impact sound transmission through floors (right photo showing a tapping machine) in a residential suite.

9.3 LONG-TERM PERFORMANCE MONITORING STUDIES

Long-term performance monitoring typically involves installing instrumentation during construction, or sometimes once in service, and then measuring continuously for a long time or even for the life of the building. Such a study requires careful planning; support from the developer, owner, and design team; coordination with design and construction; and a budget to cover the entire monitoring period. Suitable sensors and compatible data acquisition systems

[2] If testing a finished wall or finished floor results in a sound rating deficiency, it may be very difficult to make repairs where the breach may have occurred within the structure (e.g., decoupling compromised, continuous structure/connection). Therefore, it is critical that the sound insulation details are inspected during construction before the final finishing is installed.

(including wiring for power and data transmission), locations and timing for installing the instrumentation, and access to data collected should all be carefully planned. The selected instrumentation systems must be reliable and durable for the planned monitoring period. After installation and when the building is occupied, it may become impossible or too expensive to access the systems for maintenance and repair. Mock-up tests may be needed to test and select products and develop installation details and procedures that are appropriate for the project and construction schedule. A secure space in the building should be identified to accommodate the sensors and data acquisition systems and run the wires. While the sensors usually have to be at specific locations for monitoring, the data acquisition systems should be located in an area with easy access, such as in the electrical or mechanical room of a building, for such purposes as making repairs or changing batteries. Data can be stored using an in situ dedicated logger and then downloaded at a convenient time or transmitted periodically using an Internet connection.

Regulatory Acceptance

Monitoring results from similar past projects can be used to support design assumptions in an Alternative Solution. This provides confidence in the outcomes of field measurements and confirms performance to the authority having jurisdiction. Sensitivity studies should be conducted to account for possible project-to-project variations.

Most instrumentation requires protection from the weather, particularly precipitation, high humidity, and extreme temperatures, or other potential harm, such as mechanical damage which could occur during construction or once the building is occupied. The timing of installation should be carefully determined to minimize potential damage while capturing the performance of interest, particularly when construction sequencing or building age matters. The monitoring system should be designed so that it can easily be checked periodically to confirm that readings are being recorded and are correct.

The budget for long-term performance monitoring should cover the cost of instrumentation, typically including sensors and data acquisition (logging) systems, installation of instrumentation, data collection and transmission, analysis and reporting, potential troubleshooting when problems occur, and removal of the instrumentation from the building should there be such a need. Modern systems—advanced data acquisition systems, in particular—can be expensive and should be investigated in advance. The frequency of data collection should also be determined. High frequency provides more data points but may require considerably more resources for downloading, storing, and processing data. Automatic data transmission requires dedicated connections, such as Internet service, and needs to be arranged in advance. Depending on the monitoring purposes, products selected, and measurement scale, such instrumentation is typically costly. Table 3 summarizes the major monitoring studies outlined in Sections 9.3.1–9.3.5, methods used, instrumentation, and timelines for coordination with design and construction.

Table 3. Long-term building performance monitoring, methods, instrumentation, and timelines for coordination with design and construction

Monitoring/ performance attributes	Method	Typical instrumentation	Typical timelines/ coordination with design and construction
Service environmental conditions that are affecting **durability performance**	Measuring wood moisture content (MC), relative humidity (RH), and temperature in the service environment	MC sensors, RH/T sensors, data acquisition systems, and Internet for remote monitoring	Sensors to be installed during construction or building operation
Indoor environment for assessing indoor thermal comfort and air quality (related to ventilation needs)	Measuring temperature, RH, CO_2, etc. in the living space	RH and temperature, or combined RH/T sensors, CO_2 sensors, data acquisition systems, and Internet for remote monitoring	Sensors to be installed upon completion of construction or during building operation
Energy consumption	Monitoring consumption of electricity, natural gas, and other energy sources in the building	Collecting utility bills; submetering for individual units or individual components	Utility bills can be collected during operation; submetering can be installed during construction or operation
Differential and vertical movement between load-bearing members/walls	Measuring vertical movement at representative interior and exterior columns/walls, together with monitoring the service environment of the major members Wood compression and settlement/shrinkage between floors, exterior wall settlement telegraphed in cladding attachment movement	Displacement sensors, RH/T sensors, MC sensors, data acquisition systems, and Internet for remote monitoring	Sensors to be installed before interior finishing. Typically, 1-in. to 2-in. holes to pass conduit through floors to accommodate sensors

Monitoring/ performance attributes	Method	Typical instrumentation	Typical timelines/ coordination with design and construction
Wind-induced **lateral vibrations**	Monitoring the time history of accelerations of wind-induced lateral vibrations and investigating the responses of a tall wood building in wind. FPInnovations has established a protocol for such monitoring.	A typical monitoring system includes 4 accelerometers, 1 anemometer (wind meter), a remote controller, and an 8-channel data acquisition system (based on a proven system used by FPInnovations).	Ideally, the wind meter should be installed before the roof membrane is installed, and should be taken into consideration during design and construction. Accelerometers can be installed once construction is completed.

9.3.1 Durability Performance

Chapter 7 and Sections 9.4 and 9.5 provide guidelines on building design, construction, and maintenance to ensure durable performance of tall wood buildings. In Canadian climates, most durability-related issues, such as mould growth, excessive dimensional change (sufficient to fail connectors), and decay result from prolonged wetting that causes wood moisture content (MC) to exceed 19% (Morris, 1998; USDA 2010a). Decay fungi can colonize kiln-dried wood products when the MC rises to a threshold of approximately 26% (Wang et al., 2010). To assess durability performance, the MC of wood can be measured using portable devices at critical locations during periodic inspection of the building (Figure 6). Any staining caused by water penetration and growth of mould and decay should be recorded. Small moisture meters are available, mostly for solid wood, and are based on electrical resistance or dielectric properties (capacitance). They typically have a working range from 6% to 25%. Some of these devices have built-in compensation capacities for wood species and temperature. Further investigation should be conducted when MC readings are higher than a desired level, such as 30%, and identified moisture sources should be eliminated as soon as possible.

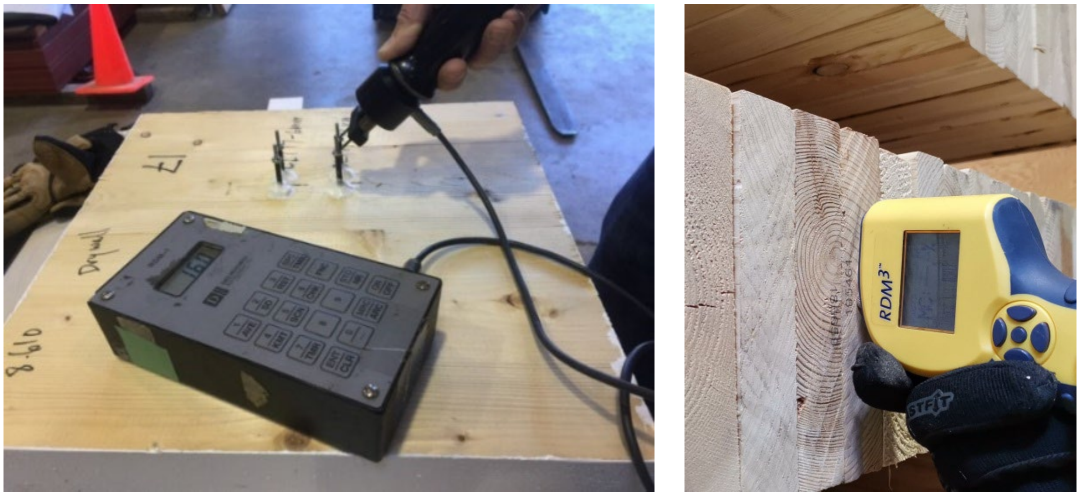

Figure 6. Measuring wood moisture content using pre-installed moisture pins (left) and a portable pin meter (right) in mass timber.

Wood MC sensors, together with data acquisition systems, can be installed at specific locations for detecting excessive moisture and for continuous monitoring of localized conditions that may lead to durability performance issues. The sensors can be installed and partially wired during construction, at locations that are not easily accessible after completion of construction, such as inside timber roof and wall assemblies. Resistance-based electrodes (moisture pins) are typically used for measuring wood MC (Figure 6; Figure 7). The pins should be inserted into wood, perpendicular to the grain, with the two pins aligned parallel to the grain and away from defects such as knots. Insulated pins (coated with a non-conducting material, except at the tips) measure the MC between the two tips, while non-insulated pins estimate the upper level of the MC between the embedded length of the two pins. Because resistance-based moisture measurements are temperature sensitive, thermocouples or thermistors may also be installed to measure in situ temperature. The MC collection procedures or systems should include compensating for the effects of wood species and temperature based on available information (e.g., Garrahan, 1988; James, 1988; Onysko et al., 2010; Pfaff & Garrahan, 1984; USDA, 2010b, 2010c). Special calibration and corrections are needed for wood composites such as OSB and plywood, or preservative- or fire-retardant-treated wood (Boardman et al., 2011, 2017; Maref et al., 2009; Onysko et al., 2010). For example, MC readings from damp plywood may overestimate the actual MC by more than 10% due to the adhesive and associated chemicals present.

Sensors are also available for detecting liquid water, and can be used for identifying leaks during building operation. If the in-service relative humidity (RH) is reasonably constant, the measurement of RH and temperature may also provide good estimates of the moisture content of the wood in service (USDA, 2010c) (Figure 7). Small in situ cameras can be installed to monitor local changes in appearances. Other techniques, such as infrared imaging (thermography), can also be used to detect localized water leakage during routine inspections; for example, to detect wet insulation in conventional roofing systems (ASTM C1153, 2015).

Figure 7. Small sensors installed to measure the service environment and performance of wood-frame construction (left: a relative humidity/temperature (RH/T) and moisture pin sensor installed on the interior side of plywood sheathing; right: an RH/T sensor installed in the rainscreen cavity to measure the exterior environment).

From a cost standpoint, moisture meters or moisture pins with a portable reading device are relatively inexpensive. More advanced sensors and data acquisition/logging systems may cost hundreds or thousands of dollars but provide better accuracy, resolution, and/or convenience of data access and transmission.

9.3.2 Indoor Environment

The indoor environment is important because people spend nearly 90% of their time indoors, on average, with most of that time spent in homes. Therefore, the indoor environment can have a significant effect on the well-being and productivity of occupants. A common standard index for the indoor environment does not exist since it can include a number of factors, such as air pollution, indoor air quality, and thermal comfort. The indoor environment is typically assessed with sensors for measuring temperature, humidity, CO_2, etc. In recent years, this has often been conducted in energy-efficient buildings to assess indoor thermal comfort and the adequacy of heat-recovery ventilators, particularly in regard to overheating (RDH, 2018; Wang, 2019a, 2019b) (Figure 8).

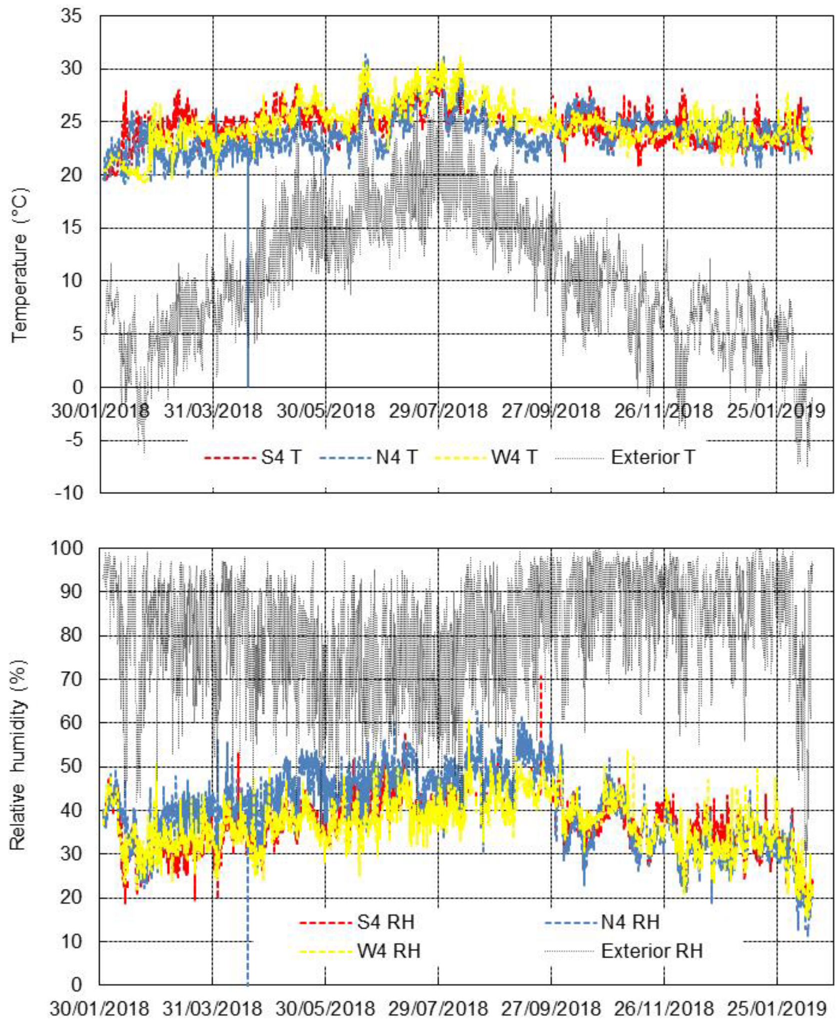

Figure 8. Indoor temperature (T, top) and relative humidity (RH, bottom) in three suites (S4 [south facing], N4 [north facing], and W4 [west facing]) on the 4th floor of an energy-efficient building in Vancouver, B.C., and exterior temperature and relative humidity (Wang, 2019b).

Introducing outdoor air into a building remains one of the most important measures for achieving good air quality by diluting indoor pollutants. In a typical building, outdoor air can enter and leave the building by unintentional infiltration and exfiltration (i.e., through small holes in the building enclosure), natural ventilation (i.e., opening windows and doors), and mechanical ventilation. Mechanical ventilation in a contemporary building is commonly used to remove indoor pollutants and provide fresh air for occupants, as regulated by building codes and standards (ANSI/ASHRAE, 2019a, 2019b). This becomes more important for buildings with airtight building enclosures. In a highly energy-efficient building, infiltration and exfiltration through the building enclosure are markedly reduced by improved airtightness, and opening windows/doors is not encouraged when the indoor environment is conditioned (heated or cooled) to save energy. Consequently, the use of heat-recovery ventilators is essential for an energy-efficient building to minimize the energy loss associated with mechanical ventilation. An energy-efficient building practically eliminates uncontrollable air leakage; thus, the controlling of fresh and exhaust air through mechanical systems is required to maintain good indoor air quality.

Indoor pollutants can be site-specific, complex, and difficult to measure. For simplicity, the concentration of CO_2 (in ppm) is often used as an indicator for both indoor air quality and ventilation rates because it is relatively easy to measure (Figure 9) (Wang, 2019a, 2019b). The CO_2 level is one of the main factors of indoor air quality, primarily because it is correlated to bioeffluents that cause odors that are unacceptable to people. High CO_2 concentration has an effect on a person's physiology and can lead to abnormal blood pressure changes (Kim et al., 2018). A commonly acceptable indoor CO_2 level is approximately 1000 ppm[3] (ANSI/ASHRAE, 2019a, 2019b). In Europe, indoor air quality is categorized (e.g., very low polluting building, low polluting building, and non-low polluting building) based on a prediction that a certain percentage of visitors will find the air quality unacceptable (CEN, 2007). The highest upper CO_2 limit, with 30% of people feeling dissatisfied about the air quality in a non-residential building, is slightly more than 1100 ppm (800 ppm above outdoor level) based on the recommendations provided. Higher CO_2 concentration indicates poor ventilation and thus poor air quality; low concentration indicates sufficient ventilation and thus good air quality. The topic of indoor air quality is also addressed in Section 4.4.1, with emphasis placed on structural adhesives, formaldehyde, and treatments for wood-destroying organisms and wood rot.

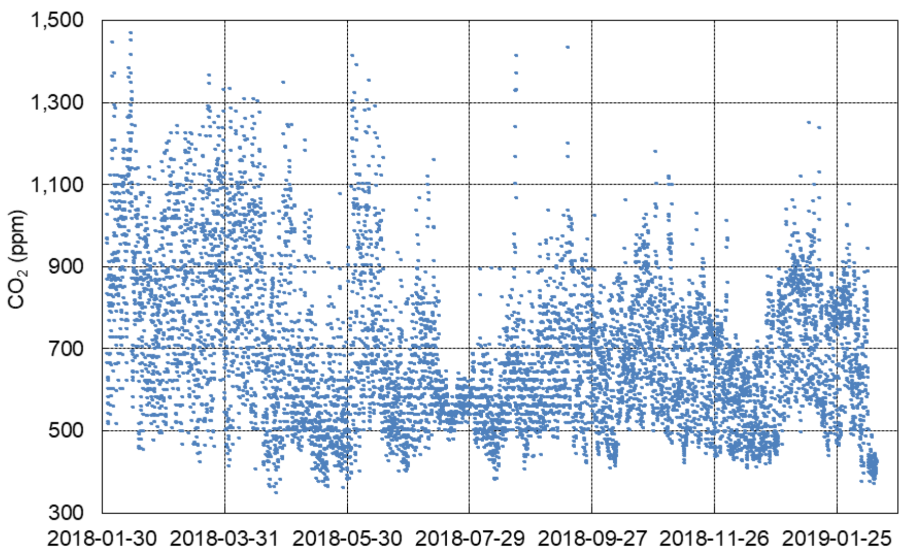

Figure 9. CO_2 concentrations in a suite in an energy-efficient building in Vancouver, B.C. (Wang, 2019b).

Thermal comfort is another important parameter for evaluating the indoor environment. Given that comfort is subjective and can vary greatly from person to person, the most accurate way of assessing the thermal comfort level of an indoor environment is by surveying occupants. Using

[3] This is calculated based on the assumption that the CO_2 level in the outdoor air is 350 ppm and the indoor CO_2 generation rate through breathing of occupants is 0.31 L/min per person (ANSI/ASHRAE, 2016a, 2016b).

the acceptable levels for most people (i.e., 80% of the occupants), the standard ANSI/ASHRAE 55 (2020) provides guidance on quantifying the effects of environmental factors, including temperature, thermal radiation, humidity, and air speed, and personal factors such as activity (metabolic rate) and clothing insulation.

Overheating can occur in highly energy-efficient buildings when the use of airtight and thermally insulated building enclosures to reduce the amount of energy needed for heating during the winter results in heat being trapped. Overheating is generally understood to be the accumulation of warmth within a building to an extent that it causes discomfort to occupants (NHBC Foundation, 2012). Overall, most people begin to feel “warm” at 25°C and “hot” at 28°C. The Passive House standard has stringent requirements for avoiding overheating by requiring that no more than 10% of the total hours in a given year exceed 25°C (Passive House Institute, 2018). External heat sources (i.e., mostly solar gains through windows) and internal sources, such as lighting, appliances, occupants, and building services (e.g., mechanical ventilation, hot water pipes), along with inappropriate or ineffective ventilation can all contribute to overheating. Factors such as window orientation, size, and properties (e.g., solar gain coefficient); use of overhangs and exterior shading; thermal mass effect; and ventilation and cooling systems all need to be considered in design to prevent overheating. Climate change is expected to result in more extreme weather conditions, with potentially hotter and drier summers. Designing for and assessing indoor thermal comfort has therefore become increasingly important.

9.3.3 Energy Consumption

Energy consumption of buildings varies greatly depending on building design, operation, occupant behaviour, and climate. The Natural Resources Canada Office of Energy Efficiency conducted a survey on household energy use to assess the changing characteristics of household energy consumption across Canada; statistical results from the latest survey are available (NRCan, 2007). Other organizations, including Canada Mortgage and Housing Corporation, BC Housing, and utility companies, have conducted large studies on energy consumption of existing buildings and have created measures for improving performance of new construction (Finch et al., 2010; Hanam et al., 2013; RDH, 2017). The energy consumption of many high-performance buildings is tracked to assess whether actual performance meets the target criteria (Kennedy & Wang, 2019; RDH, 2018). In terms of regulation, a growing number of energy-related labelling/rating programs, codes, and standards have requirements regarding energy intensity (typically based on heated indoor areas). For example, the Passive House standard has strict requirements that the space heating energy demand not exceed 15 kWh per square metre of net living space per year (Passive House Institute, 2018). The BC Energy Step Code provides specific requirements for total energy use intensity, enclosure-specific thermal energy demand intensity, and mechanical energy use intensity for a given building type and the target energy step (Government of British Columbia, 2019).

In general, the energy consumption of a building is recorded on utility bills, based on the amounts of electricity and natural gas used. Natural gas can be used for forced-air heating, hydronic heating, fireplaces, and domestic hot water; electricity can be used for electric forced-air heating, electric baseboard heating, domestic hot water, air conditioning, mechanical ventilation, lighting, and appliances. There may be only one meter for measuring gas or electricity usage in an entire building, but more new buildings have individual meters, particularly for measuring electricity use. Also, primarily for research purposes, submetering could be installed for individual components, such as a baseboard heater, a boiler, ventilators, and electric appliances, to better track energy usage and identify ways to reduce energy consumption. This could also help raise awareness among building occupants about how to further reduce energy consumption.

9.3.4 Differential and Vertical Movement

Differential movement between connected parts of a building or between different materials, such as between a masonry elevator shaft and the surrounding wood framing, is an important consideration for designing a tall building due to the cumulative effect of vertical movement. Special attention to detailing in order to reduce and accommodate differential movement is required to prevent its potential adverse effect on structural integrity, serviceability, and building enclosure durability.

Vertical movement of wood is caused primarily by dimensional changes due to MC variations below the fibre saturation point of the wood. Shrinkage and vertical building movement are discussed in Section 5.2, and briefly in Section 5.1. Most timber design textbooks in North America provide methods only for estimating vertical movement of platform-frame construction by considering shrinkage of horizontal dimension lumber in a load path (Breyer et al., 2006; CWC, 2005). Such methods have not been validated for use in the design of a tall building; therefore, field monitoring of vertical movement in taller buildings is very important for validating prediction methods and improving future building design. In recent years, a number of monitoring studies have been conducted to measure vertical movement in taller (e.g., mid-rise) platform-frame buildings and mass timber buildings (Munoz et al., 2012; Mustapha et al., 2017; Wang, 2018; Wang & King, 2015; Wang et al., 2013, 2016).

> **Construction Moisture**
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> Wood components intended for interior use must be protected from excessive moisture exposure during construction. If they become exposed, they must be sufficiently dried before allowing other steps that might impede drying, such as covering with gypsum. Understanding the exposure conditions that result in excessive absorbed moisture and what actions to take is important. Monitoring provides information to confirm assumptions about mitigation measures for the current and future projects. See Section 7.7 for guidance on managing moisture risk.

Displacement sensors (potentiometers) are the key instruments used for conducting continuous measurements of vertical movement (Figure 10). Movement occurs at different rates through the course of construction to building occupancy and until wood members equilibrate to a moisture content that is typical of the season and occupancy type. To detect changes with sufficient accuracy to inform, for example, design detailing, construction practices, and installation sequences, sensors must have proper resolutions and ranges, and be reliable and durable for the test conditions. It is important to note that instantaneous and time-dependent deformation when wood is stressed in compression, and building settlement resulting from simply closing the gaps between building elements, may all contribute to vertical movement (Wang, 2018; Wang & Ni, 2012). Depending on the type of sensors used, an additional cable or a rigid rod may be needed to measure movement over a certain distance; a suitable and dimensionally stable wire or rod should be selected. Once installed, sensors and cables (or rods) must be protected from external forces that may affect the readings. Draw-wire displacement sensors, overall, provide better flexibility for measuring movement over the height of a building.

Downward movement, resulting from shrinkage and loading, is typically predominant in wood structures, but wood members—engineered wood products, in particular, since they usually have a low MC after manufacturing—may expand if they gain moisture during construction or in service; therefore, the installation of sensors should allow displacement in both upward and downward directions to be measured. Different locations in a building also vary slightly in vertical movement, depending on the design, loading, construction stage, and sequencing, as well as in situ moisture and temperature conditions. The locations should be carefully determined based on the purpose of monitoring. For framed assemblies, the displacement sensors can be installed in the cavities so they remain invisible during building operation. For post-and-beam and solid wood panel construction, the sensor lines may need to be covered by conduits or enveloped in decorative covers to provide both protection and aesthetics.

Figure 10. A displacement sensor (left: the sensor box, which is adjacent to the column base; right: its metal conduit for protecting the wire) installed for measuring the vertical movement of a glulam column (Wang, 2018).

9.3.5 Time History of Accelerations of Wind-Induced Lateral Vibrations

The objective of measuring the time history of accelerations of wind-induced lateral vibrations is to investigate the responses of a building to wind. The measured peak accelerations are compared to the acceleration limits in the building code for controlling wind-induced vibration that may be uncomfortable for building occupants (NRC, 2020a). The measured accelerations are also needed to verify the building structural loads that are based on dynamic analysis, as outlined in Section 5.3.3.2. Case studies of the dynamic response of tall mass timber buildings to wind excitations are provided in Section 5.3.4.2.

The accelerations of a building, at both the top and ground levels, in both across-wind and along-wind directions, can be recorded by installing accelerometers. The measured accelerations at the ground level are used to subtract the ground movement-induced vibration signals from the total vibration measured at the top of the building. The wind speed over the top of the building should also be measured during the process by using anemometers (wind meters). In addition to providing background wind information, the anemometers can initiate the collection of accelerations during strong wind events, and thus reduce the amount of data that needs to be stored and processed. Five years of data are desirable for determining peak accelerations, as recommended by the building code (NRC, 2020a). FPInnovations installed a monitoring system in its laboratory building in Quebec City by using four accelerometers and two wind meters together with a data acquisition system (Hu, 2012).

9.4 BUILDING MAINTENANCE

Gradual aging of the elements that comprise a building is inevitable. However, the rate at which aging proceeds can be controlled through decisions made and actions taken during design and construction of the building, and through ongoing maintenance activities. In particular, elements and materials within joints between elements of the building enclosure will age over time as a result of exposure to the weather (sun, rain, wind, snow, or ice), and wear and tear (by the building occupants). Without adequate consideration of maintenance, elements will deteriorate prematurely, and the service life may be diminished.

Extensive guidelines regarding maintenance of buildings have been developed by Canada Mortgage and Housing Corporation and BC Housing (previously the Homeowner Protection Office) under the Maintenance Matters program.

Building operation, maintenance, repair, and renewals typically account for 70% of the life cycle cost of a residential building, while design/construction and disposal cost about 26% and 4%, respectively (BC Housing, 2013). Proactive maintenance, repair, and renewal reduces the overall cost of a building over its life span. In addition to the costs of normal activities, building maintenance should take into consideration any risk of accelerated wear and premature failure caused by user abuse. It is suggested that a cost consultant undertake a life cycle cost analysis at an early stage to forecast long-term cost implications. The life cycle cost analysis should follow the format of an elemental analysis; that is, divide the building into elements to be maintained or replaced.

9.4.1 Design Considerations

Planning for building maintenance and renewal should start at the design phase of a project and not be left as an afterthought for the current owner/developer and/or future owners to address once the building is handed over from the design and construction team.[4] The quality of the design and construction has a significant effect on the life expectancy of the building and its components, as well as on maintenance and renewal needs and costs. For example, structural components are generally difficult to repair and replace. Most of them are hidden inside interior/exterior assemblies and are expensive to access; therefore, they should not require repair or replacement during the life of the building. It is critically important that all products intended only for interior use (i.e., under dry conditions) be protected from all interior and exterior

> **Building Performance**
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> Comparison of measurements taken on mock-ups at various stages of completion compared to results from the actual structure provides the design/construction team with insights into where to focus attention during the build. Building a mock-up may also help prioritize or identify missed opportunities to optimize the Design for Manufacture and Assembly.

[4] To improve building durability and service life, the building design, construction quality assurance, operation, and maintenance can generally follow the CSA S478-19 standard (CSA, 2019).

moisture sources. Extensive guidelines for achieving durable building enclosures are provided in Chapter 7. In addition, good design will allow the building to easily be adapted to the occupants' evolving needs, and will address evolving legislative requirements, such as accommodating fire safety measures (e.g., sprinklers) or installing solar systems to further improve energy efficiency. General design considerations for maintenance of taller wood buildings are discussed below. Considerations specifically related to wood components are provided in Section 9.5.

9.4.1.1 Material Selection

More durable materials should be selected for locations that cannot readily be accessed for maintenance, and should take into consideration local hazards. For example, below-grade waterproofing is difficult to access; therefore, the selected membrane should be robust, and the drainage provisions should ensure that the membrane is not subjected to hydrostatic forces.

Exterior sealants and coatings used on the building enclosure require the most frequent maintenance and renewal; therefore, the use of more durable materials can considerably reduce overall costs. Higher quality paints and silicone sealants are usually only marginally more expensive than the minimum acceptable solutions but can add a lot of value over the life of the building. Where resistance to deterioration is important, the selection of materials should be based on long-term experience, field testing, or data from appropriate accelerated tests. Performance claims based on assumed inherent properties of the materials should be treated with skepticism since not all potential agents of degradation may have been identified and tested.

The relative service life of materials and components used within the building enclosure also needs to be considered. Designs should ensure that materials and components that require more maintenance and renewal are located closer to the surface of an assembly. For example, the selection of a flanged mounted window assembly that is likely to require replacement in 20 years is a poor choice when the flange will be installed behind a 50-year brick veneer cladding, since the brick will have to be removed prematurely when the window needs to be replaced. It may be more appropriate to use a box frame window (without a flange) or provide window perimeter detailing that incorporates removable trim so that the window can be removed without disrupting the brick veneer.

9.4.1.2 Access for Maintenance

There are key differences between low-rise wood-frame and taller mass timber buildings when designing to accommodate maintenance and renewal activities. Tall wood buildings preclude the use of ladders for most exterior maintenance activities; therefore, access methods that are more common for high-rise concrete buildings, such as the use of suspended access equipment (swing stages and bosun chairs), should be considered. Appropriate roof access and roof anchoring systems must be designed and installed. Roof anchoring points must be incorporated into the design of the primary structure, and measures must be taken during design, construction, and maintenance to prevent rain penetration from those points. Highly articulated building features (such as roof overhangs, balconies, and setbacks) can dictate the use of complex roof anchoring patterns. Consideration should also be given to selecting components that do not need to be maintained at a height, such as self-cleaning glazing, or smart window systems that can be cleaned from the interior of the building.

9.4.1.3 Fenestration

Given the wood structure's sensitivity to moisture, the design and installation of all fenestrations must meet required performance standards regarding water ingress, air leakage, and associated vapour condensation. Operable units or casement windows,[5] in particular, should be thoroughly tested, both in the laboratory during the design phase and on-site during the construction phase, to ensure that the fenestration (and its perimeter/installation) can effectively resist water ingress and air leakage over the long term. The tests can be conducted using standard test methods, such as ASTM E783 (2018), ASTM E1105 (2015), and AAMA 503 (2014). All windows, like other openings within the building enclosure, should always be constructed with a second-line defence that anticipates water ingress (i.e., a window leak) over the life span of the window.

Replacement of insulating glass units of fenestration is typically required every 15–25 years. While this work can be done from the exterior, the cost of replacing one piece of glazing from the exterior can be very high; therefore, the use of fenestration in which the insulating glass unit can be accessed from the interior is generally preferable. This will also improve thermal performance because the window frames and glazing will line up with the insulation in the walls on the warm side of the assembly.

9.4.1.4 Dryer and Other Exhaust Vents

Vents require periodic cleaning due to the buildup of lint and other debris. The implications of not cleaning vents can be significant, not only in terms of equipment operation but also enclosure performance. The back pressure caused by plugged dryer vents can result in warm, moist air being forced into the exterior wall assembly. Design measures for mitigating the frequency and cost of vent cleaning include locating vent ducts in an exterior wall where they are readily accessible, such as on balconies or roof decks, and using common central exhaust shafts that terminate on the roof or other easy-access locations. The use of a secondary lint screen and clean-out location close to the equipment (within the laundry room, in the case of dryers) can also help reduce the need for more expensive access and cleaning on the exterior of the building. Exhaust locations should also allow exhaust air to mix very quickly with outdoor air; otherwise, the warm exhaust air can condense on cold building enclosure surfaces, and lead to staining and possibly premature deterioration.

[5] In tall residential buildings, openable windows should be equipped with stoppers to prevent a large enough opening that would be a risk to children.

9.4.2 Maintenance Planning

Building design and construction provides the baseline context for creating a maintenance plan that is unique to each building. When a building is completed, the construction team usually provides the owner or the condominium corporation (typically called “strata” in British Columbia for a multi-unit residential building) with a package of reference documents that typically includes drawings, specifications, warranty certificates, manufacturers' product literature, and equipment and supplies inventory, depending on the type of the building and the ownership. It is critically important to gather and maintain these documents. The package typically includes a maintenance manual that provides instructions, rules, and guidelines for future maintenance tasks. Based on this, the owner or the condominium corporation needs to prepare a detailed maintenance plan, with the assistance of qualified consultants, and needs to update the plan whenever necessary. Funding should be secured and set aside to accommodate maintenance and renewal needs.

The maintenance plan may include operational guidance associated with critical components, such as the cleaning of exhaust vents. In particular, the building's mechanical ventilation system deserves attention since it can have a significant effect on indoor air quality, occupant comfort, and durability of the building enclosure. Interior relative humidity may also require monitoring; the presence of high humidity may prompt a need to install a humidistat or timed controls on exhaust fans.

For residential buildings in British Columbia, all strata corporations of five units or more must complete a depreciation report, as required by the Strata Property Act, unless they have passed a three-quarters vote each year to be exempted from the requirements. A depreciation report provides an inventory of all assets and property that have to be maintained and renewed by the strata corporation. It must identify asset conditions, the remaining life of each major component, and the projected renewal date and costs, and must cover a 30-year renewal period. The depreciation report together with the annual maintenance plan can become valuable tools for budgeting, contingency reserve planning, and scheduling tasks associated with inspection, repair, and renewal.

9.4.3 Routine Inspection, Cleaning, Repair, and Renewal

Routine inspection and cleaning should be planned and scheduled as part of building maintenance, and small repairs should be conducted. This could include cleaning debris from roof drains, washing windows from the outside, and inspecting the roofing, wall cladding, balconies, exterior decks, and exterior sealants and coatings. Typically, exterior components (e.g., roof, cladding) should be inspected annually. Inspection of questionable areas may require the use of more active approaches than a visual inspection, such as infrared imaging and probing methods to detect wet areas. Differential movement of connected components, natural aging, or user abuse could cause rain to be redirected into the assembly through flashing, canopies, awnings, balconies, roof decks, and roofs after years of being in service; such problems must be fixed, once identified.

Post-Occupancy Damage

Encapsulation specified for encapsulated mass timber construction (EMTC) is based on a uniform standard fire exposure test. EMTC is a new concept (to protect the structure so that it does not contribute to the fire load). While physical damage to the encapsulation should be repaired, most localized damage should not affect the overall intended function of the EMTC. If fire does reach the mass timber due to some physical damage to the encapsulation, the mass timber will still have an inherent resistance, and the small area of exposed mass timber will likely not contribute to the fire load.

9.5 WOOD-RELATED MAINTENANCE AND REPAIR

All buildings require maintenance, repair, and renewal activities to be undertaken over their life spans. The use of wood for a structure does not necessarily increase maintenance needs or costs. Wood is usually considered to be vulnerable to water damage, but other materials, such as steel and gypsum, do not tolerate water either. Therefore, good design, construction, and maintenance must be used in all buildings to prevent water leaks. This section provides guidance on building design and material selection to reduce water damage in building operation, and related maintenance and repair of wood components. More information on exterior wood use, preservative treatment, and exterior finishing is provided in Chapter 7, by BC Housing (BC Housing, 2011a, 2011b, 2015), and on the durability website developed and maintained by FPInnovations and the Canadian Wood Council: www.durable-wood.com.

9.5.1 Exterior Wood

In general, structural timber members such as CLT and glulam columns and beams should not be used in exterior assemblies where they will be exposed to the elements (e.g., wind-driven rain, UV radiation), unless the material is naturally durable enough or properly treated to meet CSA O80 standards (CSA, 2015). Wood pressure-treated with preservatives must be used for all applications in ground contact. In general, the use of exterior mass timber should be limited to the ground level to facilitate access for inspection, refinishing, repair, and replacement. Higher elevations are also typically more exposed to exterior environmental conditions and associated hazards. When timber members such as glulam are used in exterior above-ground applications for appearance, they are most effectively protected from weather by design features such as generous overhangs and canopies, which improve durability and reduce maintenance needs (Figure 11). The wood should be inspected routinely, depending on whether it is untreated, preservative-treated, above-ground, in ground contact, or coated, and indications of decay should warrant further investigation and repair.

Figure 11. A canopy (left) and a roof overhang (right) used to protect exterior wood members.

Exterior timber is typically coated to reduce weathering and improve aesthetic appearance. However, exterior coatings have a limited service life and require a proactive maintenance plan to maintain their appearance and function. An opaque coating is typically better for protecting the base wood from weathering caused by sunlight and moisture, and tends to last up to several years in most Canadian climates. Conversely, a transparent or semi-transparent finish can better expose the wood grain and texture, but it tends to fail quickly and requires more frequent refinishing. The selection of coatings affects maintenance needs and costs, particularly for less accessible locations, and must be taken into consideration during development of the maintenance plan.

The use of combustible cladding for a tall wood building is governed primarily by fire safety regulations and must meet stringent requirements, typically based on large-scale fire testing (e.g., CSA/ULC-S134, 2013; Chapter 6). When the use of fire-retardant wood cladding is allowed, a fire resistance test must be conducted on specimens after accelerated weathering has occurred (ASTM D2898, 2017). Currently, there are only a few wood- or wood-fibre-based products on the market that meet fire safety requirements in Canada. In addition, the design of cladding systems, and selection of cladding material and finishing for a tall wood building must consider long-term durability performance and maintenance needs/costs. All claddings need to be periodically inspected, refinished, and repaired to maintain their appearance and function over their life spans.

9.5.2 Wood Forming Part of the Building Enclosure

The building enclosure of a tall wood building requires good design and workmanship to minimize maintenance and repairs over its life span (Chapter 7). In particular, when wood is used as structural members of building enclosure assemblies that have high wetting but low drying potential, more attention is required during design, construction, and building operation to ensure the wood's durability is maintained and to avoid premature repair/replacement needs. Such assemblies include sill plates and other members above a concrete slab/foundation, which are susceptible to moisture at grade. Similar to wood-frame construction, the building code requires that sill plates of a tall wood building be treated with preservatives if the vertical clearance to the finished ground level is less than 150 mm and a damp-proof membrane is not used (NRC, 2020). A good practice is to elevate the wood elements at least 200 mm above the finished ground and use a vapour-impermeable capillary break/waterproofing to separate the wood from the concrete.

Balconies and roof decks are other examples of higher-moisture-risk assemblies that are likely to be subjected to incidental water ingress over their life span and typically have poor drying capacity. The structure should be designed for easy repair and replacement in case localized damage occurs (see Section 7.6.1.5). The use of preservative-treated wood is recommended because of its increased durability and reduced repair needs over its life span, in addition to the expected protection provided by other building enclosure components (e.g., membrane). The creation of a cantilevered structure by directly extending the interior floor members, for example CLT floor panels, typically makes it difficult to repair or replace the members once decay occurs in the outside portion of the members due to water penetration. Moreover, the structure creates a thermal bridge across the insulated building enclosure and introduces discontinuities in the exterior wall assembly's moisture and air barrier. The design of a balcony or roof deck may be improved by separating the exterior balcony structure from the interior members. Like other building enclosure assemblies, all balconies and roof decks require periodic inspection by professionals. Their membranes should be repaired or replaced immediately when severe aging or breaching (typically at joints and interfaces that have to accommodate differential movement) is identified.

9.5.3 Management of Interior Moisture

Wood used in most indoor spaces has much smaller moisture-related risks compared to exterior wood or wood used in building enclosures. The sources of interior moisture may include high indoor humidity and incidental water leaks. Indoor humidity is influenced primarily by indoor moisture sources (e.g., swimming pools, cooking, showering, and plants), exchange rates between indoor and outdoor air, and space heating conditions. Prolonged high humidity (e.g., above 80%) accelerates metal corrosion and mould growth, which may adversely affect the indoor environment and even structural durability (ASHRAE, 2016; Nielsen et al., 2004). Conversely, persistently dry air (e.g., RH below 20%) tends to cause occupant discomfort and exacerbate respiratory problems and allergies, and can cause excessive checking, cupping, and warping of wood members. Health Canada (2016) recommends maintaining an indoor RH between 35% and 50% to create healthy conditions. It may become necessary to control the indoor humidity as part of building operations. For damp indoor spaces, exhaust fans may need to be operated continuously to remove interior moisture. Dehumidification may also need to be integrated into the mechanical systems. For damp indoor spaces, the design of floors, ceilings, and walls may focus on the selection of more durable materials (e.g., water-resistant paint, drywall, treated wood) and the use of a continuous vapour control layer or even a water-resistant barrier to minimize moisture ingress into the structural members.

Post-Occupancy Moisture

Wetting that occurs over the typical duration of wood construction does not result in decay. Issues arise only when moisture is trapped and drying is impeded. A slow water leak or frequent accumulation of condensation also create conditions for decay. Good design for managing moisture and providing maintenance is important for maintaining a long service life.

Interior water leaks that result from factors such as plumbing leaks or activation of sprinklers typically affect floors and interior walls that are not designed for long-term exposure to moisture. There is little difference among CLT, other mass timber, light wood-frame, and even light steel-frame assemblies in terms of dealing with an interior water leak. Most floors have concrete topping covering the structural members (e.g., CLT, plywood, OSB), with finishing materials (e.g., flooring, carpet) on the top. Most interior walls are covered with drywall, except for exposed bare CLT, where permitted. When a leak occurs, bulk water should be removed (e.g., by vacuum) as quickly as possible to minimize wetting time. Remaining small amounts of moisture may be removed by heating and accelerating airflow, such as by blowing hot air toward the wet areas to accelerate drying. Non-structural components, such as drywall, batt insulation inside framed walls or floors, carpet, and wood or vinyl flooring, may need to be removed because they tend to trap moisture and reduce the drying capacity of the wood members. Prolonged wetting may allow decay to form in wood members, particularly in warm indoor environments. This could compromise the integrity of structural wood members, and result in the need to reinforce or replace them.

9.5.4 Design for Water Detection and Drying

For mass timber construction, the ability to quickly and conveniently detect both entrapped moisture during construction and water leaks in building service has become an important design consideration. This is due to mass timber's larger capacity to hold and conceal moisture but its reduced ability to dry compared with that of light-wood-frame construction. For example, a small leakage from a water pipe or a roof may not be noticeable until extensive damage has occurred. Some measures may be taken in design to make it easier to detect moisture and accelerate drying. For instance, embedding water pipes in mass timber members should be avoided if it allows water to accumulate before it becomes evident that a pipe leak has occurred. For a mass timber roof, an interior ventilation gap may be used to improve drying performance and leak detection. The Wood Innovation and Design Centre in Prince George, B.C. (Figure 12) provides an example of gaps incorporated between the plywood roof sheathing and CLT panels (Wang, 2018; Wang et al., 2016). Monitoring systems may also be installed at drainage paths built into an assembly to detect water leaks (Section 9.3.1).

Figure 12. Plywood furring used to create an air space between plywood roof sheathing above and CLT panels below, in the Wood Innovation and Design Centre, Prince George, B.C. (courtesy of Michael Green Architecture).

9.5.5 Condition Assessment

Condition assessment of structural timber members may become necessary when decay or prolonged wetting is identified in service. Questions such as “has decay started”, “how extensive is the decay”, and “how strong are the structural timber members” often arise during condition assessment of in-service timber members before decisions on remedial treatment, repair, and replacement can be made. Assessing decay and remaining structural capacity requires specific knowledge and skills. Visual assessment and measurement of MC can provide basic information. Changes in appearance, such as colour or even growth of mycelium, may not reveal the true condition of a timber member. A pick test can be used to determine whether the wood is still sound.[6] When decay is confirmed, its effect on the wood’s structural integrity needs to be further assessed depending on the severity and location of the decay. This type of assessment is always challenging and involves many uncertainties. In the case of treated wood, where surface decay is normally not present, non-destructive methods, such as hammer sounding, resistance drilling, stress wave testing (Figure 13), and ultrasound techniques, may be used by a professional to detect or locate decay inside a wood member. The U.S. Department of Agriculture’s Forest Products Laboratory has produced a *Wood and Timber Condition Assessment Manual* (USDA, 2014 [Ross et al., 2006 provide a short summary of condition assessment]) and offers a short course on in-service assessment in collaboration with a few universities in the United States. Credible information may also be found in Morris (1998) and TRADA (2014).

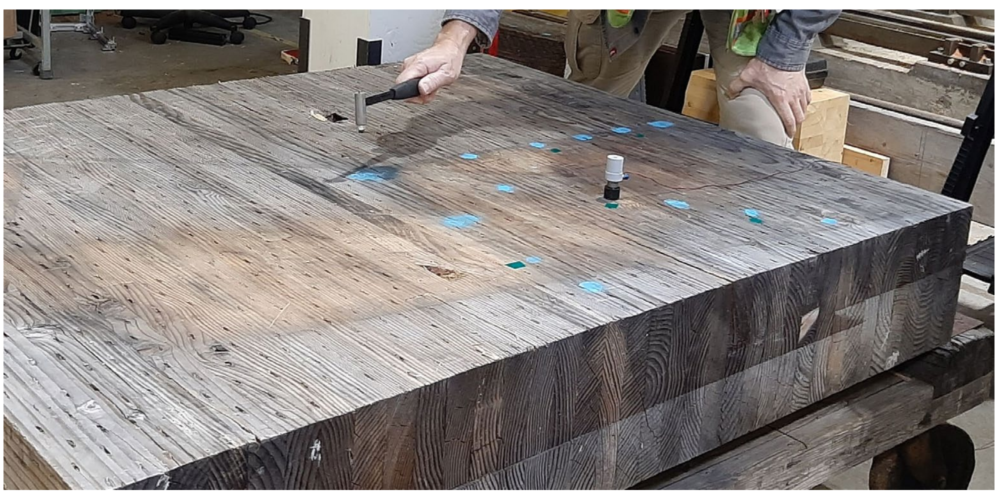

Figure 13. One-sided stress wave test using multiple accelerometers on a mass timber member.

[6] Information about the pick test is provided at Assessing and Restoration of Decay: https://cwc.ca/why-build-with-wood/durability/durability-by-treatment/assessing-decay/

9.5.6 Remediation, Repair, and Replacement

Once wetting occurs in service, actions should always be taken to identify the source of wetting, fix the leaks, and dry the wood as quickly as possible. The presence of sufficient moisture for long enough is a basic condition for decay to occur and progress. For wood members that are concealed (for example, in an assembly), the other components, such as drywall and insulation, usually need to be removed to accelerate drying. Remedial efforts may also involve mould cleaning if mould growth is identified. Related guidelines are available from Canada Mortgage and Housing Corporation (CMHC, 2019) and the Canadian Construction Association (CCA, 2004).

When decay is confirmed, practitioners often face the difficult choice of removing only the decayed portion or replacing the entire member. The former reduces the cost of remediation but increases potential liability; the latter may unnecessarily increase the cost of remediation and make it unaffordable for the owners. The bottom-line measure is to remove the source of wetting, dry the wood, and remove all the decayed wood, not only that which is obviously decayed but also 60 cm beyond any visible area of decay along the length of the member (Morris, 1998). If the area of damage is small and does not necessitate replacement of the timber member, localized repair or strengthening, such as filling holes with epoxy, adding new wood members (e.g., beams), adding fibre-reinforced polymer composite materials, and strengthening connections, may be used to restore structural capacity, depending on the load-bearing conditions (tension, compression, bending, etc.). When the timber member provides critically important structural integrity, a safe measure is to remove the entire member, even if it contains only a small amount of decay, because the decay likely will have compromised the strength and stiffness of the wood member, particularly its impact resistance. For critical locations, removal or localized strengthening of wood that appears to have been wet for a long time may be advisable if the full design strength of the member is required. However, for mass timber construction, any repair and replacement of a structural member (e.g., a CLT wall, floor, or roof) is challenging and incurs high costs. Therefore, it is critically important to design such structures not only for resiliency and long-term durability, but also for easier repair and replacement, if possible. For locations that have a high moisture risk, remedial treatment, typically using a boron-based product (e.g., soluble rods or spray/brush products), may be needed to improve the wood's decay resistance if the wood does not dry out quickly or water penetration reoccurs.

Post-Occupancy Fire

Encapsulation specified for encapsulated mass timber construction is based on a uniform standard fire exposure test. A real fire may be non-uniform and can be assessed by the degree of damage to the encapsulation or the depth of char if not encapsulation is not used. Beyond the visible damage (i.e., char), the duration of heating of the uncharred wood may need to be considered when designing a repair. Under an intense fire, the temperature gradient produced in the mass timber will depend on the type, if any, of the encapsulation.

Further information on field inspection, structural assessment, and repair of timber structures is available (AITC, 2005a, 2005b, 2007; Russell, 2019; TRADA, 2014; Yeomans, 2003). Most studies were conducted for historical timber structures or timber bridges. Post-fire structural assessment and repair and replacement may be similar to that of decayed wood but is not dealt with in this section. Limited information can be found in Henjum (2019).

9.6 CONCLUSION

Building maintenance and renewal should be based on a proactive maintenance plan. Routine inspection, repair, and replacement should be carried out to achieve satisfactory performance and prolong service life. Unexpected costly repairs and replacement can result not only from poor design and workmanship but also negligent or improper building maintenance. Condition assessment, repair, and replacement of timber structures should be conducted by knowledgeable and experienced professionals when prolonged wetting or decay is identified to ensure structural integrity is maintained.

9.7 REFERENCES

American Architectural Manufacturers Association (AAMA) 503. (2014). *Voluntary specification for field testing of newly installed storefronts, curtain walls and sloped glazing systems*. Schaumburg, IL: Author.

American Institute of Timber Construction (AITC). (2005a). *AITC Technical Note 13: In-service inspection, maintenance and repair of glued laminated timbers subject to decay conditions*. Portland, OR: Author.

American Institute of Timber Construction (AITC). (2005b). *AITC Technical Note 14: Use of epoxies in repair of structural glued laminated timber*. Portland, OR: Author.

American Institute of Timber Construction (AITC). (2007). *AITC Technical Note 26: Design values for structural glued laminated timber in existing structures*. Portland, OR: Author.

American National Standards Institute and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ANSI/ASHRAE). (2019). *ANSI/ASHRAE Standard 62.1*: *Ventilation for acceptable indoor air quality*. Washington, DC: Author; Atlanta, GA: Author. https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2

American National Standards Institute and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ANSI/ASHRAE). (2019). *ANSI/ASHRAE Standard 62.2*:*Ventilation and acceptable indoor air quality in residential buildings*. Washington, DC: Author; Atlanta, GA: Author. https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2

American National Standards Institute and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ANSI/ASHRAE). (2020). *ANSI/ASHRAE Standard 55*:*Thermal environmental conditions for human occupancy*. Washington, DC: Author; Atlanta, GA: Author. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

American National Standards Institute, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., and Illuminating Engineering Society (ANSI/ASHRAE/IES). (2019). *ANSI/ASHRAE Standard 90.1*: *Energy standard for buildings except low-rise residential buildings*. (I-P ed.). Washington, DC: Author; Atlanta, GA: Author; New York, NY: Author. https://www.ashrae.org/technical-resources/bookstore/standard-90-1

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE). (2016). *Standard 160*: *Criteria for moisture-control design analysis in buildings.* Atlanta, GA: Author. https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/160_2009_e_201601209.pdf

ASTM International (ASTM). (2019). *ASTM C177*: *Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus*. West Conshohocken, PA: Author. https://www.astm.org/Standards/C177.htm

ASTM International (ASTM). (2013). *ASTM C1046*: *Standard practices for in-situ measurement of heat flux and temperature on building envelope components*. West Conshohocken, PA: Author. https://www.astm.org/Standards/C1046.htm

ASTM International (ASTM). (2015). *ASTM C1060: Standard practice for thermographic inspection of insulation installations in envelope cavities of frame buildings*. West Conshohocken, PA: Author. https://www.astm.org/Standards/C1060.htm

ASTM International (ASTM). (2015). *ASTM C1153*: *Standard practice for location of wet insulation in roofing systems using infrared imaging*. West Conshohocken, PA: Author. https://www.astm.org/Standards/C1153.htm.

ASTM International (ASTM). (2013). *ASTM C1155*: *Standard practices for determining thermal resistance of building envelope components from in-situ data*. West Conshohocken, PA: Author. https://www.astm.org/Standards/C1155.htm

ASTM International (ASTM). (2014). *ASTM C1199*: *Standard test method for measuring the steady-state thermal transmittance of fenestration systems using hot box methods*. West Conshohocken, PA: Author. https://www.astm.org/Standards/C1199.htm

ASTM International (ASTM). (2019). *ASTM C1363*: *Standard test method for thermal performance of building materials and envelope assemblies by means of a hot box apparatus*. West Conshohocken, PA: Author. https://www.astm.org/Standards/C1363.htm

ASTM International (ASTM). (2017). *ASTM D2898*: *Standard practice for accelerated weathering of fire-retardant-treated wood for fire testing*. West Conshohocken, PA: Author. https://www.astm.org/Standards/D2898.htm.

ASTM International (ASTM). (2020). *ASTM E336*: *Standard test method for measurement of airborne sound attenuation between rooms in buildings*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E336.htm

ASTM International (ASTM). (2016). *ASTM E413*: *Classification for rating sound insulation*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E413.htm

ASTM International (ASTM). (2017). *ASTM E741*: *Standard test method for determining air change in a single zone by means of a tracer gas dilution*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E741.htm

ASTM International (ASTM). (2019). *ASTM* E779: *Standard test method for determining air leakage rate by fan pressurization*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E779.htm

ASTM International (ASTM). (2018). *ASTM E783-02*: *Standard test method for field measurement of air leakage through installed exterior windows and doors*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E783.htm

ASTM International (ASTM). (2021). *ASTM E1007*: *Standard test method for field measurement of tapping machine impact sound transmission through floor-ceiling assemblies and associated support structures*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E1007.htm

ASTM International (ASTM). (2015). *ASTM E1105*: *Standard test method for field determination of water penetration of installed exterior windows, skylights, doors, and curtain walls, by uniform or cyclic static air pressure difference*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E1105.htm

ASTM International (ASTM). (2017). *ASTM E1186*: *Standard practices for air leakage site detection in building envelopes and air barrier systems*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E1186.htm

ASTM International (ASTM). (2020). *ASTM E2235-04*: *Standard test method for determination of decay rates for use in sound insulation test methods*. West Conshohocken, PA: Author. https://www.astm.org/Standards/E2235.htm

BC Housing. (2011a). *Cladding*. (Maintenance Matters No. 8). Burnaby, BC: Author. https://www.bchousing.org/research-centre/library/consumer-maintenance-renewals/maintenance-matters-08-cladding

BC Housing. (2011b). *Exposed wood structures*. (Maintenance Matters No. 9). Burnaby, BC: Author. https://www.bchousing.org/research-centre/library/consumer-maintenance-renewals/maintenance-matters-09-exposed-wood-structures

BC Housing. (2013). *Building envelope maintenance and renewals planning*. (Maintenance Matters No. 7). Burnaby, BC: Author. https://www.bchousing.org/research-centre/library/consumer-maintenance-renewals/maintenance-matters-07-building-envelope-maintenance-and-renewals-planning

BC Housing. (2015). *Guide to managing renewals projects in multi-unit residential buildings.* Burnaby, BC: Author. https://www.bchousing.org/research-centre/library/consumer-maintenance-renewals/guide-to-managing-renewals-projects.

BC Housing. (2017). *Illustrated guide: Achieving airtight buildings.* Burnaby, BC: Author. https://www.bchousing.org/research-centre/library/residential-design-construction/achieving-airtight-buildings

Boardman, C. R., Glass, S. V., & Carll, C. G. (2011). Moisture meter calibration for untreated and ACQ-treated southern yellow pine lumber and plywood. *Journal of Testing and Evaluation, 40*(1),1-10.

Boardman, C. R., Glass, S. V., & Lebow, P. K. (2017). Simple and accurate temperature correction for moisture pin calibrations in oriented strand board. *Building and Environment, 112*, 250-260.

Breyer, D., Fridley, K., Cobeen, K., & Pollock, J. D. (2006). *Design of wood structures* (6th ed.). New York, NY: McGraw-Hill Professional.

Canada Mortgage and Housing Corporation (CMHC). (2018). Air leakage control manual for existing multi-unit residential buildings. Ottawa, ON: Author.

Canada Mortgage and Housing Corporation (CMHC). (2019). *Mould in housing*. Ottawa, ON: Author. https://www.cmhc-schl.gc.ca/en/professionals/industry-innovation-and-leadership/industry-expertise/indigenous-housing/develop-manage-indigenous-housing/maintenance-solutions/mould-in-housing

Canadian Construction Association (CCA). (2004). *Mould guidelines for the Canadian construction industry*. (Standard Construction Document CCA 82-2004). Ottawa, ON: Author.

Canadian Standards Association (CSA). (2015). *CSA O80-15*: *Wood preservation*. Rexdale, ON: Author.

Canadian Standards Association (CSA). (2019). *CSA S478-19*: *Durability in buildings.* Rexdale, ON: Author.

Canadian Standards Association and Underwriters Laboratories of Canada (CSA/ULC). (2013). *CSA/ULC-S134*: *Standard method of fire test of exterior wall assemblies.* Rexdale, ON: Author.

Canadian Wood Council (CWC). (2005). *Introduction to wood design.* Ottawa, ON: Author.

City of Vancouver. (2018). *Energy efficiency requirements.* Vancouver, BC: Author. https://vancouver.ca/home-property-development/energy-efficiency-requirements-and-resources-for-homes.aspx

European Committee for Standardization (CEN). (2007). *Standard EN-15251: Indoor environment al input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. Brussels: Author.

Finch, G., Burnett, E. & Knowles, W. (2010). Energy consumption in mid and high rise residential buildings in British Columbia. In *Proceedings of the BEST2 Conference*. Portland, OR, April 12-14, 2010.

Finch, G., Wang, J. Y., & Ricketts, D. (2013). *Guide for designing energy-efficient building enclosures for wood-frame multi-unit residential buildings in marine to cold climate zones in North America.* Vancouver, BC: FPInnovations.

Garrahan, P. (1988). Moisture meter correction factors. In *Proceedings of the Workshop on the In-Grade Testing of Structural Lumber*. Madison, WI, April 25-26, 1988.

Gilles, D. & McClure, G. (2008). Development of a period database for building in Montreal using ambient vibrations. In *Proceedings of the 14th World Conference on Earthquake Engineering.* Beijing, China, October 12-17, 2008.

Government of British Columbia. (2019). *BC energy step code: Building beyond the standard.* Victoria, BC: Author. http://www.energystepcode.ca/

Hanam, B., Finch, G., & Hepting, C. (2013). *Meter calibrated energy simulation of high rise residential buildings: Lessons learned*. https://www.rdh.com/wp-content/uploads/2017/07/CCBST-2011-Energy_Simulation_of_High_Rise_Residential_Buildings.pdf

Health Canada. (2016). *Fact sheet: Relative humidity indoors.* Ottawa, ON: Author.

Henjum, J. (2019). *Post-fire restoration of cross-laminated timber (CLT).* Presented at the International Mass Timber Conference. Portland, OR, March 19-21, 2019.

Hu, L. J. (2000). *Serviceability design criteria for commercial and multi-family floors.* Sainte-Foy, QC: Forintek Canada Corp.

Hu, L. J. (2012). *Guide for wind-vibration design of wood frame-buildings.* Quebec City, QC: FPInnovations.

Hu, L. J. (2014). *Vibration performance of wood floors and staircases, and sound insulation performance of wood/ceiling and wall assemblies: Protocols for field evaluation.* Quebec City, QC: FPInnovations.

International Organization for Standardization (ISO). (2016). *ISO 18324: 2016 Timber structures – Test method – Floor vibration performance.* Geneva: Author.

International Organization for Standardization (ISO). (2017). *ISO/TR:21136: 2017 Timber structures – Vibration performance criteria for timber floors.* Geneva: Author.

James, W. L. (1988). *Electric moisture meters for wood.* (General Technical Report FPL-GTR-6). Madison, WI: U.S. Department of Agriculture.

Kennedy, S. & Wang, J. Y. (2019). *The heights: A passive house journey.* Presentation for BC Building Envelope Council. Vancouver, BC, May 16 2019.

Kim, J., Kong, M., Hong, T., Jeong, K., and Lee, M. (2018). Physiological response of building occupants based on their activity and the indoor environmental quality condition changes. *Building and Environment, 145*, 96-103.

Maref, W., Lacasse, M., and Booth, D. (2009). Experimental assessment of hygrothermal properties of wood-frame wall assemblies—Moisture content calibration curve for OSB using moisture pins. *Journal of ASTM International, 7*(1),1-12.

Morris, P. I. (1998). *Understanding biodeterioration of wood in structures.* Vancouver, BC: Forintek Canada Corp.

Morrison Hershfield. (2011). *Thermal performance of building envelope details for mid- and high-rise buildings*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Morrison Hershfield. (2016). *Building envelope thermal bridging guide: Analysis, applications & insights* (version 1.1). BC Hydro, BC Housing, Canadian Wood Council, Fortis BC, FPInnovations, and Morrison Hershfield. https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/power-smart/builders-developers/building-envelope-thermal-bridging-guide-1.1.pdf?utm_medium=website&utm_source=archdaily.com

Munoz, W., Mohammad, M., & Gagnon, S. (2012). In-situ monitoring of a 6-storey hybrid wood-concrete office building in Quebec, Canada. In *Proceedings of the World Conference on Timber Engineering.* Auckland, New Zealand.

Mustapha, G., Khondoker, K., & Higgins, J. (2017). Vertical movement and moisture performance monitoring of pre-fabricated cross laminated timber – featured case study: UBC tall wood house. In *Proceedings of 15th Canadian Conference on Building Science and Technology.* Vancouver, BC.

National Research Council (NRC). (2017). *National energy code of Canada for buildings (NECB).* Ottawa, ON: Author.

National Research Council (NRC). (2020a). Building vibration. In: *User's guide – NBC 2020, Structural commentaries* (Part 4 of Division B). Ottawa, ON: Author.

National Research Council (NRC). (2020b). *National building code of Canada.* Ottawa, ON: Author.

Natural Resources Canada (NRCan). (2007). *Survey of household energy use 2007: Detailed statistical report*. Ottawa, ON: Author. https://oee.nrcan.gc.ca/publications/statistics/sheu07/pdf/sheu07.pdf

NHBC Foundation. (2012). *Understanding overheating – where to start: An introduction for house builders and designers.* NHBC Foundation, Housing Research in Partnership with BRE Trust, United Kingdom.

Nielsen, K. F., Holm, G., Uttrup, L. P., & Nielsen, P. A. (2004). Mould growth on building materials under low water activities: Influence of humidity and temperature on fungal growth and secondary metabolism. *International Biodeterioration & Biodegradation, 54,*325-336.

Onysko, D., Schumacher, C., & Garrahan, P. (2010). Filed measurement of moisture in building materials and assessments: Pitfalls and error assessment. In *Proceedings of the BEST2 Conference.* Portland, OR, April 12-14, 2010.

Passive House Institute. (2018). *Passive House requirements.* https://passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm

Pfaff, F. & Garrahan, P. (1984). *Moisture content correction tables for resistance-type moisture meter (revised temperature corrections).* (Report SP511E). Ottawa, ON: Forintek Canada Corp.

RDH Building Science Inc. (RDH) (2017). *Energy consumption in low-rise multi-family residential buildings.* BC Housing.

RDH Building Science Inc. (RDH). (2018). *Low-energy monitoring research report: North Park Passive House, Victoria, BC.* BC Housing.

Ross, R. J., Brashaw, B. K., & Wang, X. P. (2006). Structural condition assessment of in-service wood. *Forest Products Journal, 56*(6), 4-8.

Russell, R. (2019). *Structural timber repairs.* https://www.buildingconservation.com/articles/structural-timber-repairs/structural-timber-repairs.htm

Standards Council of Canada (SCC). (2019). *CAN/CGSB-149.10-2019: Determination of the airtightness of building envelopes by the fan depressurization method*. Ottawa, ON: Author.

TRADA Technology Ltd. (TRADA). (2014). *Condition surveys and strength grading of timber in buildings.* Technical information. Bucks, UK: Author.

United States Department of Agriculture (USDA). (2010a). Biodeterioration of wood. Chap. 14 in: *Wood handbook—Wood as an engineering material.* (General Technical Report FPL-GTR-113). Madison, WI: Author.

United States Department of Agriculture (USDA). (2010b). Drying and control of moisture content. Chap. 13 in: *Wood handbook—Wood as an engineering material.* (General Technical Report FPL-GTR-113). Madison, WI: Author.

United States Department of Agriculture (USDA) (2010c). Moisture relations and physical properties of wood. Chap. 4 in: *Wood handbook—Wood as an engineering material.* (General Technical Report FPL-GTR-113). Madison, WI: Author.

United States Department of Agriculture (USDA). (2014). *Wood and timber condition assessment manual* (second edition). (General Technical Report FPL-GTR-234). Madison, WI: Author.

Wang, J. Y. (2018). *Field measurement of vertical movement and roof moisture performance of the Wood Innovation and Design Centre Building.* Vancouver, BC: FPInnovations.

Wang, J. Y. (2019a). *High energy performance six-storey wood-frame building: Field monitoring.* Natural Resources Canada, Canadian Forest Service.

Wang, J. Y. (2019b). *Performance of a six-storey wood-frame building in Vancouver built for high energy performance based on field monitoring.* Vancouver, BC: FPInnovations.

Wang, J. Y., Clark, J., Symons, P., & Morris, P. I. (2010). Time to initiation of decay in plywood, OSB and solid wood under critical moisture conditions. In A. Baskaran (Ed.), *Proceedings of the International Conference on Building Envelope Systems and Technologies (ICBEST 2010)*. (Vol. 2, 159-166). Ottawa, ON: National Research Council of Canada, Institute for Research in Construction.

Wang, J. Y., Karsh, E., Finch, G., & Chen, M. (2016). Field measurement of vertical movement and roof moisture performance of the Wood Innovation and Design Centre. In *Proceedings of the World Conference on Timber Engineering.* Vienna, Austria, August 22-25, 2016.

Wang, J. Y., & King, L. (2015). Impact of moisture and load on vertical movement in a simulated platform-frame wood structure. *Journal of Testing and Evaluation*, 43(4), 792-802.

Wang, J. Y. & Ni, C. (2012). Review and survey of differential movement in wood frame construction. In *Proceedings of the World Conference on Timber Engineering.* Auckland, New Zealand, July 16-19, 2012.

Wang, J. Y., Ni, C. & Mustapha, G. (2013). Monitoring of vertical movement in a 4-story wood frame building in coastal British Columbia. *Journal of Testing and Evaluation, 41*(3), 611-618.

Yeomans, D. (2003). *The repair of historic timber structures.* London, UK: ICE Publishing.

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