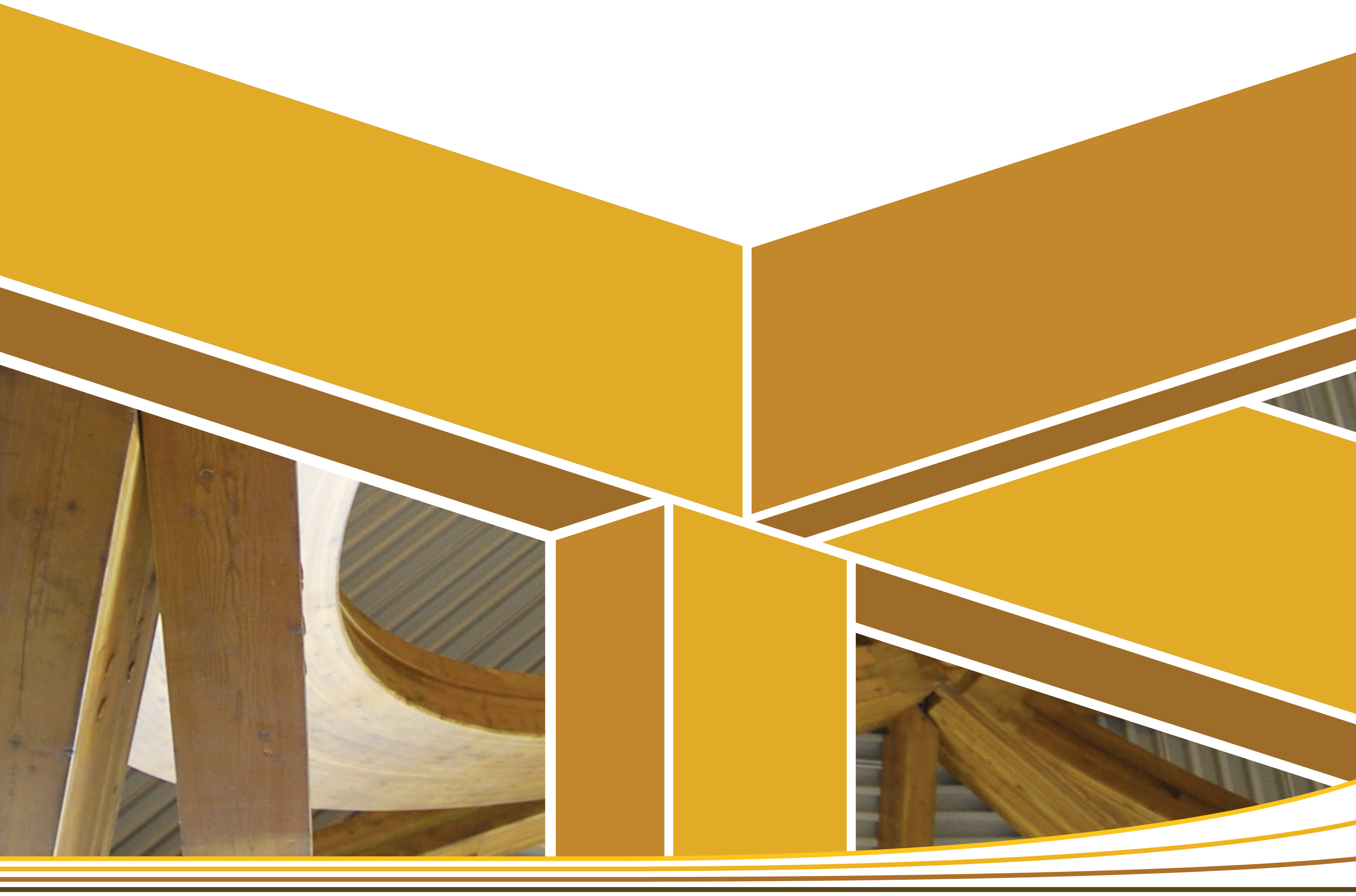
Ontario's Tall Wood Building Reference

A Technical Resource for Developing Alternative Solutions under Ontario's Building Code

October, 2017



Ontario

Ministry of Natural Resources and Forestry

Ministry of Municipal Affairs

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EXECUTIVE SUMMARY

The target audience for this technical resource includes building officials, fire service, architects, engineers, builders, code consultants and developers and other parties involved in the design and approvals of tall wood noted in Table 1 below. This technical resource is expected to help illustrate to applicants how tall wood buildings could be designed as alternative solutions in a way that achieves the level of performance required by Ontario's Building Code.

A tall wood building is defined as a building over six-storeys that uses wood for its structural system and is built using mass timber construction. Mass timber refers to large dimension solid lumber, glued-laminated lumber, cross-laminated lumber or other large dimension wood products referenced in this technical resource as opposed to conventional stick-frame construction typically used in low-rise and mid-rise buildings in Ontario. Mass timber offers the advantages of improved dimensional stability and better fire performance during construction and occupancy. Tall wood buildings are not new to Ontario – many such buildings are still in use in Ontario after nearly 100 years in service, however over time, changes to building codes and the introduction of steel and concrete for high-rise construction resulted in a decline in construction of tall wood buildings over the decades. But with new wood products and modern means of fire engineering, modern tall wood buildings are now being built in Canada. The new products and the way in which they are pre-fabricated and constructed offer tremendous opportunities to improve quality and speed of construction for buildings in Ontario.

Mass timber products have environmental advantages as well. Trees get their energy from the sun and absorb carbon from the atmosphere. As they grow, trees store carbon and by sustainably harvesting trees, the carbon is sequestered, which helps to reduce greenhouse gas. The carbon stored in wood is not released into the atmosphere when it is harvested. As new trees are planted to replace the harvested trees, the new trees will continue the cycle of carbon storage. Ontario and Canada have significant forest resources which, combined with sustainable forestry management practices, make tall wood buildings an attractive alternate to other materials which do not have these attributes.

This technical resource has two main sections: Fire Safety and Structural Design. These two major topics are normally of most concern during design and review of tall wood buildings and are at times inter-related. Thus, it is expected that design teams and building departments will work together at the early stages of design since structural decisions can affect fire performance and vice versa. The sections go into detail on aspects of compliance, methods of analysis, methods of design and the expected performance requirements for fire and structure. Other topics such as thermal performance, acoustic performance and constructability are covered in other references as noted throughout this technical resource.

MINISTER'S MESSAGE

Tall wood buildings are the way of the future. Advances in technology have made it possible for wood to once again become the material of choice for the construction of tall buildings. Wood is a renewable, sustainable resource and it helps mitigate climate change by storing carbon.

Back in 2014, Ontario amended the Ontario Building Code to allow new wood frame buildings to reach up to six storeys. Since then, we've seen tremendous interest and uptake in using wood and wood products in construction. This positive response -- along with increasing evidence about the environmental benefits of using wood in construction -- spurred us on to look beyond buildings that are up to six storeys high.

That's why I'm proud to introduce Ontario's Tall Wood Reference: A Technical Resource for Developing Alternative Solutions under the Ontario Building Code.

This document is a resource that will help architects, engineers and developers in coming up with alternative solutions for tall wood mass timber projects and help facilitate approval by a Chief Building Official. It provides information about fire safety and structural design among other useful topics that are of concern during the design and review process for tall wood buildings.

I want to thank the committee that helped to bring this document together: their work and perseverance has led to the development of a document that is practical and useful to the industry.

I'm proud to be working with our partners to increase the amount of Ontario wood sourced from sustainably managed forests that will be used in large scale building construction across the province. The use of Ontario wood will also help address climate change by storing carbon in buildings and by offsetting emissions associated with other construction materials. This is critical to our plan to mitigate the effects of climate change as outlined in Ontario's Climate Change Action Plan.

I encourage you to use this document to help you to visualize and build tall wood structures that are inspiring, innovative and environmentally friendly.

Kathryn McGarry

Hon. Kathryn McGarry

Minister of Natural Resources and Forestry

Hon. Kathryn McGarry,
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Minister McGarry,

On behalf of the multi-disciplinary committee that oversaw this project I am proud to present you with a copy of *Ontario's Tall Wood Building Reference: A Technical Resource for Developing Alternative Solutions Under Ontario's Building Code* for your consideration.

While Ontario has a number of mass timber buildings that exceed six storeys which were built prior to the introduction of the 1941 model National Building Code for Canada, the province has not seen any development of these structures since then. However, in recent years we have seen increasing interest in mass timber building systems for a variety of reasons, from the role that wood buildings can play in mitigating climate change, to the development of new innovative products that can offer design teams a range of new options.

This document is the product of the deliberations of a number of dedicated partners. It reflects our shared commitment to the safe use of mass timber building systems and our efforts to help Ontario meet its commitments under the Climate Change Action Plan. As a group, we see this document being a significant tool to help design teams, as well as municipal officials that are responsible for reviewing these innovative projects, to develop the alternative solutions under Ontario's Building Code.

This technical resource discusses a number of topics related to fire safety and structural performance that design teams need to consider when proposing a mass timber building as an alternative solution under Ontario's Building Code. It also provides a number of strategies and resources that they can draw on as they develop innovative project designs. This technical resource will also prove useful for municipal officials during the review of the strategies and resources adopted by design teams in the development of their projects.

It is our sincere hope that *Ontario's Tall Wood Building Reference* will be a step towards a future that will see the widespread use of mass timber building systems for buildings over six storeys, through which they are recognized as the best design solution.

In closing, I would like to thank all of our partners on the committee for volunteering their time and energy to help support us with completing this project. We came together from a wide array of backgrounds and disciplines to produce Ontario's Tall Wood Building Reference: A Technical Resource for Developing Alternative Solutions Under Ontario's Building Code and as such we feel that it has benefited from being the product of this process.

Respectfully yours,

Jason Koivisto
Chair of the Tall Wood Building Reference Committee

OUTLINE: WOOD BUILDING REQUIREMENTS

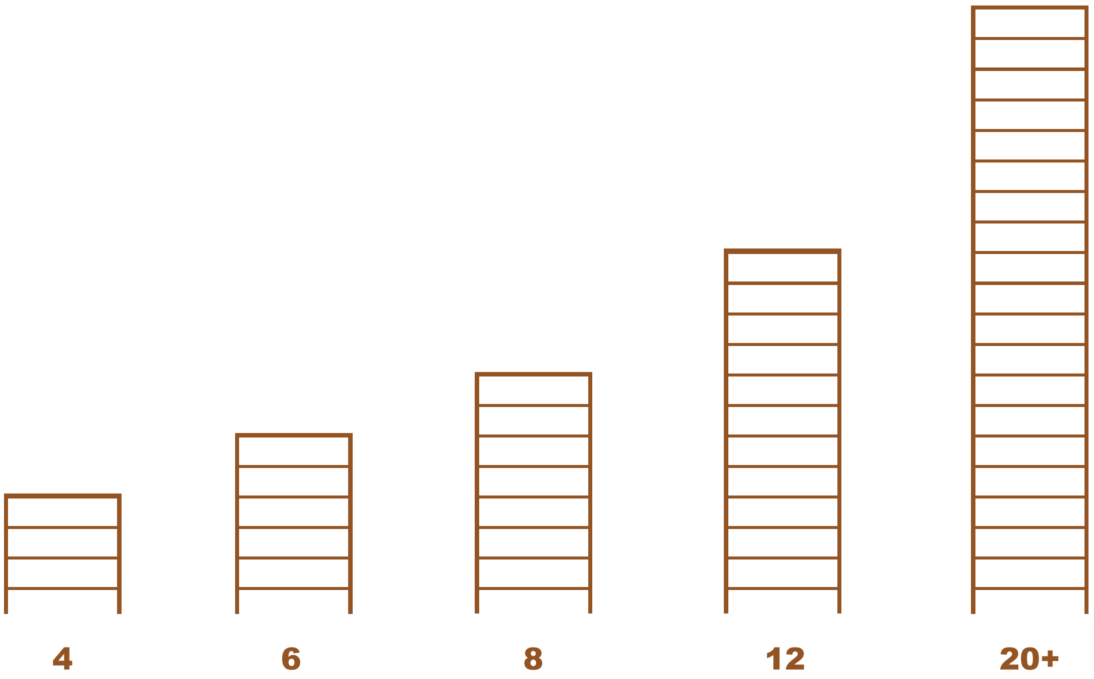

Figure 1. Illustration of building heights from 4 to 20+ storeys

Category	<= 3 Storeys	<= 3 Storeys*	<= 3 Storeys	<= 3 Storeys	<= 4 Storeys	<= 6 Storeys	7-12 Storeys	> 12 Storeys
OBC Designation	Acceptable Solution (Part 9 residential, some Part 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Alternative Solution	Alternative Solution
Maximum Building Area (area per floor)	1, 2, or 3 storeys: 600m^2	1 storey: 2700m^2 2 storey: 1350m^2 3 storey: 900m^2	1 storey: 3600m^2 2 storey: 1800m^2 3 storey: 1200m^2	1 storey: 5400m^2 2 storey: 2700m^2 3 storey: 1800m^2	1 storey: 7200m^2 2 storey: 3600m^2 3 storey: 2500m^2 4 storey: 1800m^2	1 storey: 9000m^2 2 storeys: 4500m^2 3 storeys: 3000m^2 4 storeys: 2250m^2 5 storeys: 1800m^2 6 storeys: 1500m^2		
Maximum Physical Height	-	-	-	-	-	18 m from ground floor to top floor		
Sprinklers	None	None	None	NFPA 13R	NFPA 13R	NFPA 13R for 1-4 storeys; NFPA 13 for 5 and 6 storeys		
Floor Assembly Construction	-	45-Minute Fire Rating	1-Hour Fire Rating	45-Minute Fire Rating	1-Hour Fire Rating	1-Hour Fire Rating		
Stairwell Construction	-	45-Minute Fire Rating	1-Hour Fire Rating	45-Minute Fire Rating	1-Hour Fire Rating	1.5 Hour Fire Rating for all exit enclosures (noncombustible construction)		
Elevator Shaft Construction	-	45-Minute Fire Rating	1-Hour Fire Rating	45-Minute Fire Rating	1-Hour Fire Rating	1-Hour Fire Rating		
Building Category	Low-Rise	Low-Rise	Low-Rise	Low-Rise	Low-Rise	Low-Rise & Mid-Rise	Mid-Rise	High-Rise

Table 1. Comparison of Ontario's Building Code (OBC) 2012 requirements for wood buildings.

* Maximum building area applicable if building is facing three streets; smaller areas permitted for facing one and two streets.

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CONTENTS

1. PREFACE

1.1. PURPOSE OF THIS TECHNICAL RESOURCE

This technical resource has been written to assist architects, engineers, builders, and developers in the development of Alternative Solutions for tall wood projects with mass timber and to help facilitate the approval by a Chief Building Official (CBO) under Ontario's Building Code (OBC) (O. Reg. 332/12, Div. A Section 1.2.). An Alternative Solution will be required until the building code includes acceptable solutions specific to tall wood buildings. Until then, submissions for building permit to building departments in Ontario will be required to provide additional documentation, additional engineering analysis, and testing (or results from relevant testing), for consideration by building officials on a project-by-project basis.

In Ontario, modern code development related to wood buildings has been a process that started over 25 years ago. OBC 1990 introduced requirements for 4-storey residential Group C occupancy including a requirement for sprinklers. In OBC 1997, Group D (business and personal services) were permitted to 4-storeys in wood, with sprinklers. And OBC 2012 was amended in January 2015 to allow 5- and 6-storey wood buildings with multiple-occupancies and many specific requirements beyond those for 4-storey wood buildings. Buildings that exceed the 2015 requirements for maximum number of storeys and height are not covered by the Acceptable Solutions in OBC 2012.

British Columbia and Quebec have approved designs and issued building permits for buildings that exceed the 6-storey limits using other mechanisms in their building codes.

This document is intended to provide information for design teams and building code plans reviewers in Ontario as they undertake the Alternative Solutions pathway to permit approval. The primary focus in this technical resource is on structural and fire safety requirements. This technical resource is intended to bring attention to key issues and highlight other recent documents, technical information and testing results that will be of use to these individuals. This technical resource is not intended as a prescribed solution to tall wood buildings or as a replacement for existing building codes and standards.

1.2. TARGET AUDIENCE

The target audience for this technical resource includes building officials, fire service, architects, engineers, builders, code consultants and developers and other parties involved in the design and approvals of tall wood buildings.

1.3. A NOTE ON FORMATTING

The standard definition of code references is used throughout this document, as follows:

A	Division
A-3	Part
A-3.5	Section
A-3.5.2.	Subsection
A-3.5.2.1.	Article
A-3.5.2.1.(2)	Sentence
A-3.5.2.1.(2)(a)	Clause
A-3.5.2.1.(2)(a)(i)	Subclause

2. INTRODUCTION

The term “Tall Wood Buildings” generally refers to any wood building greater than six storeys in building height, where the top floor is higher than 18 m above grade, and structural systems other than light-frame construction are used. Table 1 (in the Executive Summary) provides a comparison of wood building types where they are currently acceptable solutions in the building code as well as those that would require an alternative solution in the current building code. A confluence of events has created interest in tall wood buildings in Canada and around the world in just a few years. New wood products, referred to as ‘mass timber’, renewed interest in reducing the carbon footprint of buildings and increased densification of urban centres have all contributed to this trend for taller wood buildings.

In Canada, an 18-storey tall wood student residence will be ready for occupancy in 2017 on the campus of the University of British Columbia in Vancouver. And by the end of 2017, a 13-storey tall wood condominium will be completed in Quebec City. These two buildings are part of a demonstration project with the assistance of Natural Resources Canada, and leveraged by the provinces and industry, to aid in the development and approvals for this new type of construction in Canada. Each of these demonstration projects used Alternative Solutions for building department approvals, although the mechanism was different in each province.

The tall wood building in Vancouver was issued a site-specific regulation known as the UBC Tall Wood Building Regulation by the British Columbia Minister Responsible for Housing. The regulation exempts the project from some parts of the British Columbia Building Code such as limits on building size for combustible construction, ensuring occupant health and safety protection equal to or better than current code provisions for noncombustible construction of the same size.

The tall wood building in Quebec City was approved by the Régie du bâtiment du Québec (RBQ), as described in the publication titled, *Mass timber buildings of up to 12 storeys - Directives and Explanatory Guide*. The guidelines contained in that publication offer a specific alternative solution under the Quebec Building Act. This Act provides the RBQ authority to establish conditions allowing the use of wood as a material that differ from the Quebec Construction Code’s provisions for a building exceeding 6-storeys. The conditions presented in the form of guidelines in the RBQ’s publication were written specifically around the design of the Quebec City tall wood demonstration project with the assistance of experts from FPInnovations. Any project that deviates from this framework will require an Alternative Solution application to the RBQ.

Both building departments in BC and Quebec relied on work performed by FPInnovations, the National Research Council of Canada and other groups together with the FPInnovations 2014 publication Technical Guide for the Design and Construction of Tall Wood Buildings in Canada (FPI/TWBC).

The process in Ontario is distinct from the other provinces. It is expected that until the national and provincial building codes adopt tall wood buildings as one of the Acceptable Solutions in Division B, Alternative Solution submissions will be required to allow permitting of tall wood buildings in Ontario.

History of tall wood buildings in Canada

Historically, buildings constructed using large dimension solid timbers (as opposed to dimensional lumber such as 2x4s, 2x6s, etc.) were commonly built as recently as the early 20th century. This form of construction, normally referred to as ‘heavy timber’ can be found around the world. In Canada, many of these buildings were designed with heavy factory floors, up to 9 storeys. These buildings were often built with unreinforced brick-and-mortar exterior walls, with heavy timber posts and beams (see Figure 2.1). The buildings had storey heights of up to 6.9 m (22 feet) and were as tall as 30 m (100 feet) high with floor areas up to 29,000 m^2 (312,000 ft^2). See Figure 2.1 for examples of historical tall wood buildings in Toronto. Larger heavy timber buildings take on many forms. There are long-span examples of heavy timber structures still in use today, such as the Tillamook Blimp Hangar in Oregon, built 1942, which is 330 m (1080 feet) long, 58 m high (190 feet) and spans 90 m (300 feet) - this is equivalent to a 15-storey building.

312 Adelaide Street West, Toronto
Built 1895 - 8 storey - 71,000 ft^2

204-214 King Street East
Built 1901 - 7 storey – 134,430 ft^2

Figure 2.1. Typical brick and beam buildings in downtown Toronto. (Figure 1 from Koo, 2013).

Unfortunately, we do not see many modern examples of large, tall wood buildings. The adoption of building codes and concerns over fire performance led to a steady change in design and construction practice to other building materials and systems throughout Canada and the United States. Interestingly, many buildings from that early period remain in use today and are highly sought after real estate in major North American cities. The so-called ‘brick and beam’ buildings, with exposed timbers and clay brick have character that no other materials provide.

Today, modern infrastructure combined with modern fire suppression/protection systems and new technologies for acoustic and thermal performance of buildings, tall wood structures are an option again. And the market will likely demand these buildings if building owners are given the opportunity. Tall wood buildings will be good options for residential, commercial and institutional occupancies.

2.1. MASS TIMBER CONSTRUCTION – TYPES OF WOOD PRODUCTS

Conventional framing versus mass timber

Conventional light frame construction is used for 90% of homes in Canada and the United States. ‘Stick frame’ refers to light framing using 2x4, 2x6 and other small dimension lumber. In Ontario, Spruce-Pine-Fir (SPF) lumber is most commonly available with some Douglas fir (D.fir) from western Canada. Lumber is visually graded for strength and stiffness. Lumber is surface dry (i.e. moisture content between 12-19%), although kiln-dried material is available at additional cost. Light frame lumber is a commodity product and is the core of the wood construction industry. Light frame wood construction is almost always required to be used in a floor, roof or wall assembly (i.e. wood framing plus insulation and sheathing) that has been rated and approved as an assembly by OBC for fire, acoustic and thermal performance. Light frame construction in rated assemblies is not left exposed because small dimension lumber is susceptible to severe fire damage.

Platform frame wood construction uses conventional lumber and is effective up to six-storeys. Visually graded lumber will dry out while in service to approximately 8 to 14% moisture content. Up to three storeys, the effects of wood shrinkage are not significant. However, beyond three storeys, wood shrinkage and elastic shortening can result in problems such as damage to finishes, changes in balcony drainage slopes, damage to plumbing and structural issues for hold down hardware. These effects (shrinkage and elastic shortening) can be accommodated up to six-storeys, but become problematic as more floors are added. Also, with more floors, the added weight and loading from additional storeys results in reduced stud spacing which may limit the space for routing of electrical and mechanical services and the amount of insulation that can be placed in wall cavities.

To summarize, light frame construction is not intended for use in buildings over 6-storeys in height. The wood products that are recommended for taller wood buildings fall into a category called ‘mass timber.’

Structural design of conventional framing is specified in CSA O86 Engineering Design in Wood, as referenced by OBC Sentence B-4.3.1.1.(1).

Solid sawn - heavy timber

Large dimension lumber (i.e. cross-sections of at least 191 mm x 191 mm or 140 mm x 241 mm for members supporting floors plus a roof, and 140 mm x 191 mm for columns supporting roofs and 89 mm x 149 mm for beam supporting roofs) is recognized under OBC Division B Table 3.1.4.7 to have inherent fire resistance because, in contrast to light frame construction, heavy timber construction can char before losing its structural integrity under fire loads. There are existing office buildings in some of Canada’s major cities up to 8 and 9 storeys built in this fashion. Post-and-beam construction using heavy timber from local species were typically built with columns around 400 mm x 400 mm (16”x16”) on lower levels and beams around 400 mm x 600 mm (16”x24”) and larger. For example, an existing nearly-century-old 4-storey brick-and-beam office building in Liberty Village in Toronto is approximately 2,500 m2 (27,000 ft2) per floor with a 5.3 m x 6.0 m (17 feet x 20 feet) column grid. Typical posts are 380 mm x 380 mm (15” x 15”) and typical beams are 330 mm x 380 mm deep (13” x 15”) supporting 140 mm x 394 mm (5 ½” x 15 ½”) deep joists at 1068 mm (3’-6”) on-centre. All heavy timber columns, beams and floors were left exposed with no additional protection against fire. See Figure 2.2 and 2.3 for typical historic post and beam connections.

Figure 2.2. Typical historic post and beam connections (from Appendix C-2, Koo, 2013). Metal castings provide end-grain bearing to reduce the effects of wood shrinkage.

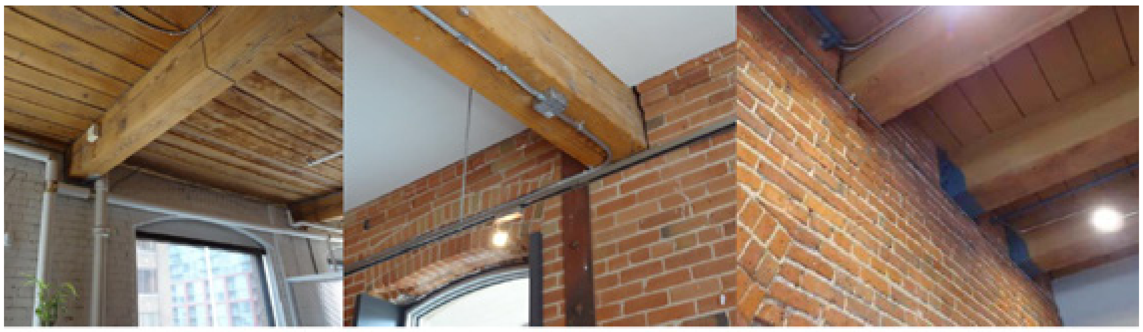


Figure 2.3. Typical brick and beam building connections (Koo, 2013). Beams are directly connected to the brick, with no indication of differential shrinkage accommodation.

To minimize the effects of shrinkage, designers over 100 years ago created steel castings that ensured end-grain bearing of columns thereby avoiding shrinkage perpendicular-to-grain in the beams. This clever technique also avoided elastic deformation due to compression perpendicular-to-grain in the beams. See Figure 2.4 below for an example.

Figure 2.4 Solid Sawn heavy timber construction (Photo: A. Franco)

Structural design of solid sawn timbers is specified in CSA O86 Engineering Design in Wood, as referenced by OBC Sentence B-4.3.1.1.(1).

Glued-laminated timber (glulam)

Solid sawn heavy timber is limited in availability for very large sizes and is not structurally efficient due to capacity reductions that result from natural defects such as knots and checks. Glulam is an engineered wood product made from 38 mm x 140 mm, 38 mm x 184 mm and 38 mm x 235 mm (approximately) and larger laminations that are kiln-dried and machine stress-rated rather than visually graded. The laminations are finger-jointed, glued and pressed into beams, columns and arches. All laminations are parallel, running in the long orientation of the beam or column. Building larger elements from smaller components reduces the effects of defects and shrinkage compare to solid sawn lumber. Higher grade lumber is typically used in the outer laminations to further increase capacity. Glulam beams and columns have tremendous structural capacity with long span beams over 2400 mm deep. Used in heavy timber applications, glulam beams and columns provide fire resistance similar to solid sawn heavy timber but with added structural capacity and improved shrinkage performance. Glulam can also be treated for outdoor use.

Glulam beams can be used on their side to create floor and roof planks, similar to nail-laminated timber (see below). Unlike cross-laminated timber (see below) glulam planks lack cross-oriented layers that provide dimensional stability and two-way action. The grade of material in this orientation can be similar in all laminations.

Structural design of glued-laminated timber is specified in CSA O86 Engineering Design in Wood as referenced by OBC Sentence B-4.3.1.1.(1), with referenced standards for quality control of production layups including CAN/CSA-O122 Structural glued-laminated timber, CSA O177 Qualification code for manufacturers of structural glued-laminated timber referenced by OBC Sentence 4.3.1.2.(1), CSA O112.9 Evaluation of adhesives for structural wood products (exterior exposure), and CSA O112.10 Evaluation of adhesives for structural wood products (limited moisture exposure). See Figure 2.5 below for a sample of glulam.

Figure 2.5 Glulam Member (Source: Figure 31L, section 4.1, FPI/TWBC)

Nail-laminated floors and roofs (now referred to as nail-laminated timber or NLT)

Many of the old post-and-beam heavy timber structures used all-wood floor assemblies. NLT floors are built from 38 mm x 140 mm or 38 mm x 184 mm or larger laminations of wood, placed on edge, spanning between beams. The laminations are nailed to each other to create a solid floor deck acting in unison and take advantage of load-sharing through shear transfer between laminations. In some cases, these floors have been paved with asphalt and used to support heavy machinery in post-and-beam buildings.

OBC recognizes this assembly as heavy timber construction provided the floor or roof laminations are at least 38 mm wide x 89 mm thick as specified in OBC Sentences B-3.1.4.7.(4)(a) and (b).

The conventional lumber that is used to build nail-laminated decks will shrink as it dries in service, however, the detailing of the post-and-beam structure (as noted above in Heavy Timber) limits the effects of such shrinkage to a single-storey.

Whereas in the past an asphaltic topping could be applied, in some cases modern applications of NLT have used concrete bonded to the NLT deck to create a composite that takes advantage of the best properties of wood and concrete to increase the span-to-depth ratio of the slab.

Plywood is commonly used on NLT decks to provide diaphragm action.

NLT can also be oriented vertically to form walls, as shown in Figure 2.6.

Figure 2.6 Nail-lam elevator core adjacent to masonry stair core. (Photo: M. Alexander)

NLT can often be a less expensive alternative to CLT but without the cross-laminations that provide dimensional stability and in-plane shear resistance. NLT can be more labour-intensive on site for installation but modern applications have used large panels of NLT that are prefabricated and installed on site. See Figure 2.7 for an example NLT floor.

Since NLT is commonly comprised of solid sawn members, it can be treated and used in outdoor conditions. Structural design of conventional nail-laminated timber is specified in CSA O86 Engineering Design in Wood, as referenced by OBC Sentence B-4.3.1.1.(1).

Figure 2.7 Nail-lam floor (Photo: M. Alexander)

Structural composite lumber (SCL)

Structural wood products manufactured from veneers or strands are referred to as structural composite lumber. These products are typically manufactured in large billets as panels or as very large individual members such as beam or columns. One of the benefits of these products is the way they improve capacity by removing natural defects in wood such as knots and checks. They are dimensionally stable, retaining their trueness, and can be cut to less than 1 mm accuracy. Until recently, the large elements at the time of manufacture have typically been cut into smaller pieces for sale as smaller header beams or even studs. In mass timber applications, the elements are not reduced in size, rather they are left as close to their maximum factory dimension to take advantage of their engineered properties and speed up construction.

SCL products are specified in CSA O86 *Engineering Design in Wood*, as referenced by OBC Sentence B-4.3.1.1.(1) and normally evaluated by the Canadian Construction Materials Centre (CCMC) in Canada in accordance with standards CSA O112.6 *Phenol and phenol-resorcinol resin adhesives for wood (high-temperature curing),* CSA O112.7 *Resorcinol and phenol-resorcinol resin adhesives for wood (room- and intermediate-temperature curing),* CSA O112.9 *Evaluation of adhesives for structural wood products (exterior exposure),* CSA O112.10 *Evaluation of adhesives for structural wood products (limited moisture exposure),* and ASTM D5456 *Standard Specification for Evaluation of Structural Composite Lumber Products.*

The most common SCL products are:

1. Laminated veneer lumber (LVL) – Developed in the late 1970's, this product is made from full sheet veneers that are glued to each other. Unlike plywood where each layer of veneer is laid perpendicular to its neighbouring veneers, LVL veneers are all oriented parallel to each other. The result is much stronger bending capacity for strength and deflection. LVL beams are typically manufactured in billets 44 mm (1 ¾") thick and approximately 1.2 m x 17.7 m (up to 24.4 m) and cut to standard depths of 241 mm (9 ½"), 302 mm (11 7/8"), 356 mm (14"), 406 mm (16") and 457 mm (18") to be used as headers and beams. The product is dimensionally stable because

the veneers are kiln-dried prior to pressing. When cut to these smaller dimensions, and only 44 mm thick, the smaller beams and headers are treated as light frame construction and must be in a rated floor or roof assembly. However, manufacturers can produce much thicker elements that can potentially provide better fire performance (check with manufacturer). Some manufacturers may be able to produce X-LVL, where some layers are orientated perpendicular to the main axis to provide additional dimensional stability.

2. Laminated strand lumber (LSL) – Unlike LVL, laminated strand lumber uses a different process to slice strands from logs to less than 1 mm thick. These strands are approximately 50 mm wide and approximately 300 mm long. The strands are coated in resin and pressed using a steam injection process to create billets up to 75 mm thick and 2.4 m x 19.5 m. LSL differs from oriented strand board (OSB) through careful control of the strand size and orientation. The billets are typically cut into smaller pieces similar to dimensional lumber to create header beams and studs. The strands are typically oriented with the majority of strands parallel to the length of the beam or stud. However, the off-axis strands in the layup increase the shear capacity of the elements. This differentiates LSL from LVL in its engineering properties. Like the veneers of LVL, the strands of LSL are kiln-dried prior to the addition of resin and pressing. The large billet size makes LSL a good option for mass timber construction.
3. Parallel strand lumber (PSL) – Developed in Canada in the 1980's and made available commercially in 1990, parallel strand lumber is made from the same veneers as LVL but the veneers are chopped into strands that are 3 mm x 12 mm x 1000 mm long. The strands are coated in resin and dropped into a long trough and pressed to create a 450 mm x 450 mm x 18 000 mm billet. The billet can be left intact or cut into smaller elements to create beams and posts similar to dimensional lumber. The veneers are kiln-dried which results in a dimensionally stable product. Used in its full size, PSL is a mass timber product and can be *block-glued* into larger components for use as beams, columns and as truss elements. PSL can be considered heavy timber and designed for fire rating. PSL is not recommended to be treated, and therefore should only be used in dry-service conditions.

Structural design of structural composite lumber is specified in CSA O86-14 *Engineering Design in Wood*, Clause 16.3 (formally Clause 14.3) which also references additional standards for testing and adhesives and notes that proprietary design values will be listed in the CCMC Registry of Product Evaluations. Relevant standards for adhesives and SCL include: CSA O112.6 *Phenol and phenol-resorcinol resin adhesives for wood (high-temperature curing),* CSA O112.7 *Resorcinol and phenol-resorcinol resin adhesives for wood (room- and intermediate-temperature curing),* CSA O112.9 *Evaluation of adhesives for structural wood products (exterior exposure),* CSA O112.10 *Evaluation of adhesives for structural wood products (limited moisture exposure),* and ASTM D5456 *Standard Specification for Evaluation of Structural Composite Lumber Products.*

Cross Laminated Timber (CLT)

Cross-laminated timber is a relatively new product that can be used in large panel format for walls, floor and roofs. Typical panel sizes are limited by shipping lengths to approximately 2800 mm x 12 000 mm. Whereas glulam is made from 38 mm thick material with all layers oriented parallel to the length of the member, CLT is laid up in a large panel in a series of glued and oriented layers where some layers are oriented perpendicular to others. The perpendicular layers improve dimensional stability and provide some two-way bending action of the panels when used in floor and roof applications.

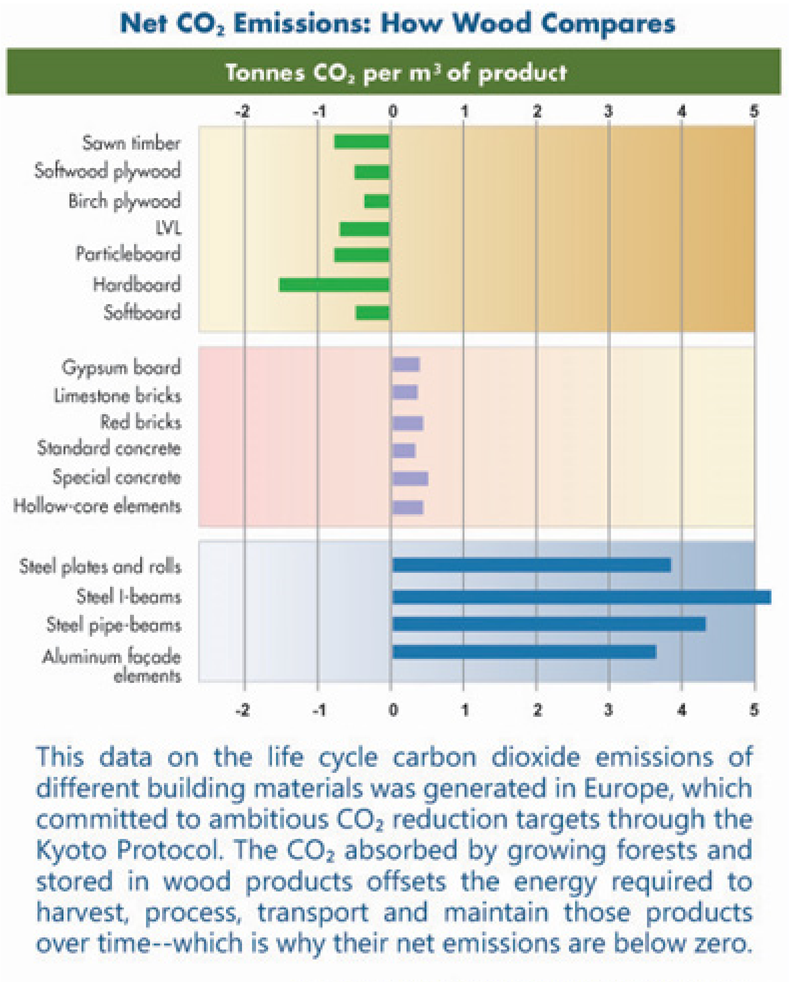
Figure 2.8 CLT floor panel detail with glulam columns above and below from UBC Brock Commons demonstration (Photo: D. Moses)

CLT is most commonly made up of an odd number of layers so that the top and bottom layers have the same orientation (see Figure 2.8). Some suppliers have CLT panel layups with some adjacent layers oriented parallel to each other in panels with five or more layers.

CLT is used as floor and roof assemblies in post-and-beam buildings and is used in tall wood buildings around the world for shear walls, loadbearing walls as well as floor and roof panels. CLT is used in beam applications for headers. In terms of fire performance, CLT can be left exposed to view or encapsulated in gypsum wall board (drywall). In recent years, many structural and fire tests have been performed to determine the properties of CLT under different types of loading and with different types of assemblies. For more detailed information about CLT manufacturing, design and test results on fire performance refer to the *CLT Handbook* by FPInnovations (Gagnon and Pirvu, 2011).

The production and design standards limit the use of CLT to dry-service conditions, largely due to the type of resin and the use of untreated wood.

Manufacturer qualification and manufacturer quality assurance testing is specified in ANSI/APA PRG-320 Standard for performance-rated cross-laminated timber and resins in accordance with CSA O112.10 Evaluation of adhesives for structural wood products (limited moisture exposure) (see PRG-320 for additional requirements). Structural design of CLT is specified in 2016 Supplement of CSA O86-14 Engineering Design in Wood and in the CLT Handbook by FPInnovations (Gagnon and Pirvu, 2011). CSA O86-14 currently limits the application of CLT to one-way out-of-plane bending applications and the use in lateral load resisting systems as “rigid bodies”. The CLT Handbook by FPInnovations is a guideline and not a design standard. Note that, OBC 2012 Sentence B-4.3.1.1.(1) references CSA O86-09, not CSA O86-14.



This data on the life cycle carbon dioxide emissions of different building materials was generated in Europe, which committed to ambitious CO_2 reduction targets through the Kyoto Protocol. The CO_2 absorbed by growing forests and stored in wood products offsets the energy required to harvest, process, transport and maintain those products over time--which is why their net emissions are below zero.

Figure 2.9. Net CO2 emissions for various construction materials. (Source: https://www.ontario.ca/page/benefits-using-ontario-wood and as noted in the figure).

2.2. ENVIRONMENTAL OPPORTUNITIES

Typically, the energy needed to operate buildings (for electricity use and mechanical systems) is the primary target for energy reduction through more efficient building envelopes, building orientation and by choosing more efficient methods of heating and cooling. For high performance buildings, progressive designers are looking at life-cycle analysis of buildings as an additional way to decrease the size of a building's environmental footprint. Specifically, this "cradle to grave" analysis includes the embodied energy of buildings (i.e. the energy used to harvest or extract materials, process them, transport them and construct them on site). This is where mass timber excels in lowering greenhouse gas emissions, as shown in Figure 2.9. Refer to section 3 of FPI/TWBC for more detailed information about wood sustainability.

Wood products used in building construction are able to reduce GHG emissions and mitigate the effects of climate change through the following mechanisms: forests are carbon sinks, substituting other construction products with wood avoids emissions, and wood in buildings sequesters (stores) carbon. The term carbon *sink* refers to the carbon pool which exists in Ontario and Canada's forests. By adhering to sustainable forest management strategies, combined with legal requirements for reforestation after harvest, our forests can be considered a stable carbon sink as they continue to absorb CO_2 from the atmosphere and store carbon within the trees and soil. As forests mature, their ability to store carbon slows down and eventually reaches a maximum concentration as shown in Figure 2.10 below. If trees are left to rot, or if a forest catches fire, carbon will be released in the atmosphere.


As a forest grows, trees absorb and store carbon. When a managed forest reaches maturity, it is harvested. The harvested wood can be used to make a variety of wood products for example, in construction materials to build a house. These wood products (i.e., the house) can store carbon for many years. After the managed forest is harvested, it is regenerated to grow more trees and ensure the sustainability of Ontario's natural resources. Sustainable forest management increases the amount of carbon stored over time by ensuring new trees grow after harvest (absorbing more carbon) and by harvesting the forest for wood products, storing more carbon for many years after.

Figure 2.10. Wood carbon lifecycle (From Figure 6 of Opportunities to enhance carbon storage, MNRF 2016).

By harvesting mature trees, the carbon remains stored within the wood fibre and is transferred from the forest to the built environment. Replanting younger trees allows the forest carbon pool to remain constant over time.

Product *substitution* refers to choosing wood over other more emissions-intensive products. While other common construction materials are net emitters of CO_2 (in terms of embodied energy due to extraction, manufacturing and transportation), the embodied GHG of wood is so low that it is an excellent alternative to the other materials for construction. Encouraging designers and builders to substitute building components using wood is a simple strategy for reducing the embodied emissions of buildings.

Sequestration is the third mechanism whereby wood products in buildings will continue to store carbon for long periods of time. Buildings made from wood sequester carbon, i.e. the wood stores carbon that may have otherwise been released into the atmosphere. This carbon can be used to offset the net carbon emissions from other sources or even other materials used in the construction of the same building and future operational energy costs.

The timber required to build tall wood buildings is a natural way to sequester large volumes of carbon. Based on the volume of wood used in a building, carbon calculators can be used to evaluate the amount of stored carbon contained within the wood products and the amount of GHG emissions avoided by using wood in place of more emissions-intensive materials. These calculators are becoming more precise as more data is collected on materials and energy sources. Some jurisdictions offer developers incentives, such as additional floor area, in exchange for offsetting carbon. In the future, it is possible that carbon benefits of wood building products and construction systems will be quantified financially through a carbon pricing scheme (or example, a carbon rebate).

The new technology that is used to create prefabricated mass timber buildings has added benefits to the environment and human health through accuracy, speed of construction, ease of construction and reduced site noise. The precision of fabrication of mass timber results in components that fit together tightly on site which helps create tighter building envelopes with better thermal performance. Faster construction times through prefabrication means less site disruptions to local neighbourhoods and considerably less site waste. The installation of mechanical and electrical services in mass timber buildings is straightforward as mass timber ceilings and walls are easy to attach to and offer many locations on which to attach, thereby simplifying installation using common tools. Finally, it has been observed that these sites are very quiet during construction compared to typical construction using other materials.

2.3. OPPORTUNITIES

There are many positive impacts that will result from constructing tall wood buildings in Ontario:

- Tall wood buildings offer an opportunity for construction in areas of poor soils as the super structure and foundations are lighter compared to other building materials.
- Tall wood buildings are often quieter to build on site than other materials, which means neighbours are less likely to complain and workers are not exposed to high levels of noise.
- Worker safety during construction may be improved because workers can work off large mass timber floor plates.
- Prefabricated components manufactured to tight tolerances reduce the duration of construction.
- Tight tolerances in the building structure and building envelope combined with energy modelling can result in better energy performance, reduced air penetration, better indoor air quality and improved human comfort

Compared to other materials, mass timber offers a competitive advantage on costs when speed of construction is considered. Opportunities for cost reduction are often associated with mass timber's lighter weight. There are savings in foundations (less weight equals smaller foundations), shorter construction time (less carrying costs), and lower shipping costs (less material to ship). As with any new technology, there are costs of entry to the market that will eventually reduce as more suppliers, building owners, designers and builders become familiar with the technology and improvements are made.

Mass timber buildings are a good fit for green building. As a construction material, wood is the only option that can offer net zero or net negative greenhouse gas emissions. This is because wood sequesters carbon, i.e. wood stores carbon dioxide and only releases carbon dioxide when it biodegrades or is burned. Wood is a sustainable resource when obtained from sustainably-managed and harvested forests as is the case in Ontario and Canada.

Carbon calculators for mass timber projects are available to illustrate the positive environmental attributes of building with wood compared to other materials. Athena Institute is one example of a free online tool that can be accessed at: https://calculatelca.com/software/overview/.

2.4. CHALLENGES

Public perception can be a set-back for design of any new construction methodology, often taking ten to twenty years until a new product or method becomes common practice. There are many who feel that wood buildings are not strong enough compared to concrete or steel and that a small fire will ignite the entire building very quickly– the science does not support these claims. Education is one solution to mitigate these negative perceptions. Examples of tall wood buildings around the world, including the new 18-storey Brock Commons building in Vancouver illustrate that these buildings can be built to perform to today's standards and structural and fire safety concerns can be addressed.

The introduction of six-storey wood frame buildings in Canada is a good example of education, research and acceptance of a new building typology. Whereas British Columbia allowed an increase to six-storeys in 2009, five years passed before Ontario accepted the increase in allowable building height from four storeys to six. The main obstacles for acceptance were concerns over fire, acoustics, building envelope and structural design – all the same issues now associated with tall wood buildings. The fast market uptake in British Columbia for six-storey wood construction has shown that there is a place in the building mix for this size of building and type of construction. Since the code change allowing six-storey wood buildings in Ontario in 2015, there has been similar uptake compared to BC.

The market will be slow to adopt new technologies if there is a perceived risk in the approvals process. If additional work is perceived to be involved and if there is a potential for delays in the approval process, many building owners and developers will tend to shy away from the perceived riskier alternative of trying something different rather than a 'business as usual' approach. If the approval process is simplified with design examples or if the code permitted tall wood construction, this would become a more attractive construction method for many.

Another potential challenge is worker training. In Ontario, the majority of trades familiar with wood construction are comfortable with Division B Part 9 residential construction. Unfortunately, tall wood construction (and even mid-rise construction) cannot be built like Part 9 buildings and workers will require expertise similar to commercial and high-rise construction. Training for typical component installation and commercial construction sites of tall wood construction is needed to move tall wood construction further. The potential time savings during construction using prefabricated mass timber components can be diminished if the trades are unfamiliar with appropriate construction techniques.

Heavy timber suppliers and installers, especially those with CLT expertise are much scarcer in Ontario than steel or concrete suppliers. Currently, Canadian CLT suppliers compete with many European suppliers on product variety, quality and competitive pricing including shipping costs. The supply chain will continue to evolve as more tall wood buildings are built.

A few common areas of concern include differential shrinkage, progressive collapse, acoustic performance, earthquake performance and fire performance. These are addressed in more detail in this technical resource. Some background is provided here.

Differential shrinkage

Accounting for differential shrinkage between wood and other materials is a new problem for most designers and installers – this requires designing details in advance. Connections between wood and other materials and for cladding and plumbing systems must be designed to accommodate differential shrinkage. Details related to relative shrinkage are provided in The *Tall Wood Buildings Guide* by FPInnovations, **FPI/TWBC**. For cladding or building envelope systems, OBC B-5.1.4.1.(5)(c) requires the design to accommodate the maximum relative deflection of the structure. OBC B-6.2.1.3 requires mechanical systems to be designed and installed for the maximum relative structural movement. OBC B-7.1.7.1 requires plumbing systems to be designed and installed for the maximum relative structural movement.

Progressive collapse

Designing for progressive collapse in tall wood buildings is new for designers. Progressive collapse is a potential failure mode of buildings that could occur if one bay of a structure fails and could possibly cause the failure of adjacent bays. See Section 4.4.7 below.

Acoustic performance

Acoustic performance and building envelope performance are of concern if not detailed correctly. The *Tall Wood Buildings Guide* by FPInnovations, **FPI/TWBC**, provides examples of acoustic assemblies and building envelope details for designers.

Earthquake performance

Earthquake resistance of tall wood buildings is an area of ongoing research. Some lateral systems are already recognized in OBC for earthquake resistance but may require more information for designers and building officials. Other lateral systems, such as CLT, are addressed in CSA O86 with information provided on R_d and R_o – currently OBC does not include these values for CLT. Some new lateral systems are still in development such as CLT shear wall buildings with centralized core structures where CLT shear walls perpendicular to the direction of loading become engaged. Section 4.3.6 below provides details on earthquake design provisions.

Fire performance

To date, tall wood buildings in Canada have followed an Alternative Solution path to address fire performance. Sections 3 below provides detail on fire performance for tall wood buildings in Ontario. The *Tall Wood Buildings Guide* by FPInnovations, **FPI/TWBC**, is an excellent reference with details on fire performance.

Once more tall wood buildings are designed and built in Ontario, design teams, building officials and builders will become more familiar with the requirements for design and construction which should lead to more streamlined understanding and approvals.

2.5. EXAMPLES OF TALL WOOD BUILDINGS

Examples of older tall wood buildings in Canada are noted in Section 2.1, above, as shown in Figure 2.1. Post-and-beam construction using heavy timber with column grids of approximately 5 m on-centre were built up to eight and nine storeys. Typical floor-to-floor heights are approximately 3 m to 4 m with heavy timber columns and beams left exposed with no additional protection against fire. Many of the existing buildings were used for industrial purposes such as factories with heavy equipment. Today they are typically used for retail or office space.

Modern tall wood buildings are a re-emerging building type in Canada and internationally. There are currently over 30 modern tall wood, mass timber buildings around the world. Of these, four are in Canada. In comparison, the USA has approximately 40 wood buildings that are 6 storeys or taller, and approximately 15 wood buildings at various stages of design and construction that are 8 storeys or taller.

Figure 2.11. Brock Commons, UBC, Vancouver. 18-storeys. (Photo: D. Moses)

Brock Commons, Vancouver

Brock Commons is a student residence on the campus of the University of British Columbia in Vancouver (see Figure 2.11). This building is 18-storeys tall. The main floor podium is concrete with two full height concrete cores for stairs, elevator and mechanical chases. The mass timber elements include cross-laminated timber floor slabs and glued-laminated timber and parallel strand lumber posts. The posts are on a roughly 3 m by 4 m grid. A new slab-on-post structural concept was developed to minimize the effects of shrinkage and to allow for adjustment during construction. A two-storey mock-up was built and tested for proof-of-concept and this allowed the design team to adjust their final design based on the results of the test. The structural design was based on higher earthquake forces than the current standard in anticipation of new requirements in the next edition of the building code. Using prefabricated timber, construction was completed at a very fast pace of almost two-floors per week on average, including the prefabricated exterior wall panel assembly.

Fire protection is provided by full encapsulation of the mass timber using three and four layers of gypsum wall board (GWB) rather than relying on charring of the timbers. Fire testing was conducted in laboratories of the different assemblies. The concrete shafts posed no concern for the building officials.

The alternative design was approved in British Columbia using a site specific regulation. Construction finished in mid-2017 and occupancy is expected for Fall 2017.

Figure 2.12. LCT One, Austria. 8-storeys. (Photo: D. Moses)

LCT One Tower, Austria

The Life Cycle Tower is an 8-storey office building (see Figure 2.12) with a concrete stair and elevator core and a hybrid timber-concrete prefabricated composite slab system with glued-laminated timber columns. The composite slabs span 9 m. The building was built in eight days, one day per storey including the exterior walls with windows. The building is also very energy efficient using new integrated mechanical and electrical systems and serves as a prototype for a 30-storey version using the same system.

Figure 2.13. Earth Sciences Building, UBC, Vancouver. (Photo: M.Alexander)

Figure 2.14. Origine, Quebec City. 13-storeys post-and-beam with CLT. (Photo: D. Moses)

Earth Science Building, Vancouver

This university building is a timber hybrid at UBC in British Columbia (see Figure 2.13). Most predominately known for its innovative "floating" stairs, the 5-storey building is comprised of CLT, LSL and glulam. The laboratories are located in the concrete portion of the building. The wood portion of the building houses lecture halls. The feature stairs in the atrium are wood-concrete composite slab using glulam. The building was completed in 2012 with the goal of presenting "science on display."

The floor system uses composite wood-concrete slabs for better vibration performance than wood-only floor panels. Between the wood and concrete is a 25 mm insulation foam board to enhance the acoustic performance. LSL was used for the composite floor slabs while CLT was used for the roof slabs and the canopy.

At the time of design and construction, 5-storey wood buildings were not permitted in British Columbia, so code compliance was met using a building code Alternative Solution.

Origine, Quebec City

This condominium building is 13-storeys (12 wood + 1 concrete) including underground parking. Construction began in 2016 and completion is expected by the fall of 2017. The structure is predominantly cross-laminated timber (see Figure 2.14), encapsulated in layers of gypsum wall board. The provincial building authority, the RBQ, created mass timber directives for buildings up to 12-storeys with prescriptive requirements that are met by this building. Future buildings that meet these requirements are not required to apply for alternative solutions, rather they can use pre-approved 'alternative solutions.".

Unique features of this building include the cross-laminated timber core for exit stairs and elevators and cross-laminated timber shear walls for party walls and corridor walls. The total design height is 40 m with approximately 800 m2 per floor. During the design and approval process, a full-scale demonstration fire was performed of a 3-storey cross-laminated timber shaft for a duration of 2 hours. The demonstration also served as a illustration and evidence for fire and building officials to witness the fire performance of the cross-laminated timber shaft. At the end of the 2-hour test, there was only a small amount of char on the exposed side and only slightly elevated temperature on the side of the stair core. All post and beam connections were concealed to enhance fire resistance. Details of the test are available: https://www.mffp.gouv.qc.ca/publications/forets/entreprises/rapport-resistance-feu-ang.pdf

Figure 2.15. Arbora, Montreal. 8-storeys, first of three buildings on this site. (Photo D. Moses)

Arbora, Montreal

This 8-storey apartment building is the first of three buildings on a single concrete underground parking garage (see Figure 2.15). This building is a combination of cross-laminated timber and glued-laminated timber, similar in concept to Origine in Quebec City. However, some areas of the Arbora buildings will have exposed timber and therefore required additional applications for alternative solutions beyond the prescriptive requirement of the RBQ 12-storey directive. The total building area of the three buildings is approximately 55,000 m2 making Arbora the largest residential CLT building to date.

2.6. OVERVIEW OF ALTERNATIVE SOLUTIONS PROVISIONS UNDER THE ONTARIO BUILDING CODE

2.6.1. BUILDING REGULATION IN ONTARIO

The regulation of building construction in Ontario is a provincial responsibility under the Canadian Constitution. The model National Building Code of Canada (NBCC) is developed under the direction of the Canadian Commission on Building and Fire Codes as one of five national model codes.

Some provinces adopt the model NBCC as published, while other provinces and territories make minor or, in some cases, major changes. Enforcement of the provincial codes is typically undertaken by municipalities and the respective Chief Building Official (CBO).

In Ontario, a majority of the model NBCC is adopted along with other Ontario-specific changes (i.e. mid-rise combustible construction), and is published as Ontario's Building Code (OBC). Ontario's Building Code is commonly released approximately 2 years after a new edition of the NBCC is published.

Similar to the NBCC, Ontario's Building Code is comprised of three divisions: Division A, "Compliance, Objectives and Functional Statements;" Division B, "Acceptable Solutions;" and Division C, "Administrative Provisions."

Other code requirements include compliance with Supplementary Standards SB-1 to SB-13 and other referenced documents specified in the Code along with other applicable law. The overall objectives and functional statements cited in Ontario's Building Code are listed in Part 2 and Part 3, respectively, of Division A, while the objectives and functional statements attributed to individual Division B requirements are listed in Supplementary Standard SA-1.

2.6.2. ACCEPTABLE AND ALTERNATIVE SOLUTIONS UNDER ONTARIO'S BUILDING CODE

Compliance with OBC can be demonstrated in one of two ways: complying with the acceptable solutions outlined in Division B (performance and prescriptive provisions outlined in OBC); or using an alternative solution that achieves at least the same level of performance as required by the acceptable solutions outlined in Division B of the Building Code in respect of the OBC objectives and functional statements attributed to the acceptable solution.

These two compliance options are outlined in OBC Article A-1.2.1.1., of Division A, which states:

Division A
1.2.1.1 Compliance with Division B
(1) Compliance with Division B shall be achieved,

(a) by complying with the applicable *acceptable solutions* in Division B, or

(b) by using *alternative solutions* that will achieve the level of performance required by the applicable *acceptable solutions* in respect of the *objectives* and *functional statements* attributed to the applicable *acceptable solutions* in MMAH Supplementary Standard SA-1, "Objectives and Functional Statements Attributed to the Acceptable Solutions".

(2) For the purposes of Clause (1)(b), the level of performance in respect of a *functional statement* refers to the performance of the *functional statement* as it relates to the *objective* with which it is associated in MMAH Supplementary Standard SA-1, "Objectives and Functional Statements Attributed to the Acceptable Solutions".

The Acceptable Solutions in Division B of OBC establish the performance level required with respect to the applicable objectives and functional statements. Based on this, if a designer wishes to submit an "Alternative Solution", the designer must first establish the level of performance required based on the Division B Acceptable Solution. This requirement to establish the required level of performance is the primary difference between an objective-based code and a performance-based code, which would explicitly provide the performance criteria.

The designer must determine the level of required performance, quantitatively, based on the expected performance of the Acceptable Solution.

In cases where there is a choice between several possible designs, where all satisfy Division B requirements, it is likely that the designs will not all provide equivalent levels of performance. As explained in the OBC Appendix Note that accompanies Article 1.2.1.1. of Division A, what is necessary is that the design provides the same or higher level of performance as that provided by the Acceptable Solution. It is not necessary to select the design that provides the highest level of performance just as it is not necessary to do this within the context of acceptable solutions.

In addition to the objectives and functional statements, which provide guidance as to the rationale for the Acceptable Solutions, the National Research Council (NRC) publishes intent statements for all the provisions in Division B of the model NBCC, which can be accessed from NRC's website.

For those provisions in OBC that are the same as in the NBCC, these intent statements may provide additional guidance to the user to help clarify the undesirable results each provision seeks to preclude.

2.6.3. DOCUMENTATION OF ALTERNATIVE SOLUTIONS UNDER ONTARIO'S BUILDING CODE

The OBC also includes provisions that address documentation required to demonstrate compliance with the OBC's alternative solution provisions.

It is important that alternative solutions proposal cover all of the documentation requirements identified below under Division C, subsection 2.1.1. "Documentation of Alternative Solutions".

Division C Part 2
2.1.1. Documentation of Alternative Solutions
2.1.1.1. Documentation
(1) The person proposing the use of an *alternative solution* shall provide documentation to the *chief building official* or *registered code agency that*,
(a) identifies applicable *objectives*, *functional statements* and *acceptable solutions*, and
(b) establishes on the basis of past performance, tests described in Article 2.1.1.2. or other evaluation that the proposed *alternative solution* will achieve the level of performance required under Article 1.2.1.1. of Division A.
(2) The documentation described in Sentence (1) shall include information about relevant assumptions, limiting or restricting factors, testing procedures, studies or *building* performance parameters, including any commissioning, operational and maintenance requirements.

2.1.1.2. Tests
(1) Where no published test method to establish the suitability of an *alternative solution* proposed under Article 2.1.1.1. exists, then the tests used for the purposes of that Article shall be designed to simulate or exceed anticipated service conditions or shall be designed to compare the performance of the material or system with a similar material or system that is known to be acceptable.
(2) The results of tests or evaluations based on test standards, other than as described in this Code, may be used for the purposes of Sentence (1), if the alternate test standards provide comparable results.

Further guidance is provided in Appendix A of OBC under A-1.2.1.1.(1)(b).

The model NBCC provides some additional guidance under Subsection 2.3.1, “Documentation of Alternative Solutions” of Division C, which may be deemed useful, while not explicitly required by OBC.

The NBCC subsection states that an Alternative Solution shall include a code analysis, which outlines the analytical methods and rationale used to determine that a proposed Alternative Solution will achieve at least the level of performance as required by Division B. The code analysis must also include special maintenance or operational requirements, including any commissioning requirements, that are necessary for the Alternative Solution to achieve compliance with the Code after the building is constructed.

In addition, the code analysis should include the following:

- Identification of the Acceptable Solutions (e.g. “noncombustible construction”), which are not explicitly satisfied, and the applicable objectives and functional statements related to the Acceptable Solutions.
- Any assumptions, limiting or restricting factors, testing procedures, engineering studies or building performance parameters that support the proposed Alternative Solution.
- Qualifications, experience and background of the person or persons taking responsibility for the design.
- Information in sufficient detail to convey the design intent and to support the validity and accuracy of the proposal.

Moreover, the NBCC requires that a single person coordinate the design for an alternative solution proposal. Alberta has adopted a requirement for a design coordinator in its own building code, specifically:

Alberta Building Code
Division C, Part 2, Administrative Provisions
2.3.1 Documentation of Alternative Solutions, 2.3.1.1

(6) Where the design of a building includes proposed alternative solutions that involve more than one person taking responsibility for different aspects of the design, the applicant for the permit shall identify a single person to co-ordinate the preparation of the design, Code analysis and documentation referred to in this Subsection.

The requirement for "letters of assurance" attesting to design coordination is already a well-established requirement in British Columbia where it applies to all Part 3 buildings and is thought to improve compliance, facilitate building innovation, and streamline building approvals. The letters of assurance process helps to reduce risk for municipal building departments.

It is good practice for a single design professional to take responsibility for coordinating the various aspects of the building design – structural, fire, mechanical and other building elements. For projects involving alternative solutions this is an especially good practice since designers and building officials are less familiar with the design and matters related to inter-relationships among building systems and components. Often the Architect will play the role of prime consultant and will be best suited to act as design coordinator. Engaging a prime consultant or design coordinator will help ensure that building systems work seamlessly together and will help to increase the likelihood that the design can be accepted by the municipal CBO.

In addition, given the specialized nature of many alternative solutions, and to reduce concerns and resistance from regulatory agencies, it is important that alternative solution proposals include expert peer review of key building components by other independent qualified engineers or architects. Peer review provides an additional third party check which can further provide assurance to the municipal building authority that the proposed alternative solution complies with the Building Code.

It is important for the owner or design team to include the third party peer reviewer early in the process to avoid problems later on.

While ensuring that adequate analysis and documentation is provided to support the alternative design, it is also important that the compliance and enforcement regime are robust and effective.

2.6.4. APPROVAL OF ALTERNATIVE SOLUTIONS BY THE MUNICIPAL BUILDING DEPARTMENT

Approval of an alternative solution depends on a strong and well-documented building application package along a strong design team that addresses all compliance issues.

Of course, the municipal building department still needs to satisfy itself that the alternative solution complies with the Building Code. (i.e. acheives level of performance in respect of objectives and functional statements). The Chief Building Official will still need to check for compliance with applicable law, the completeness and adequacy of the documentation provided and other requirements. An alternative solution is more likely to be approved where the proposal addresses all key objectives of the municipality which include:

- Compliance with key building code requirements,
- Coordination of design (clash analysis),
- Peer review of key building design elements (third party review),
- Field review (general review) of key building elements during construction

3. FIRE SAFETY DESIGN OF TALL MASS TIMBER BUILDINGS

3.1. INTRODUCTION

Tall mass timber buildings in North America are commonly classified as buildings that are greater than 6-storeys and built using mass timber. Mass timber products, as noted in Chapter 2 above, have a significant amount of inherent fire resistance due to their cross-sectional area and the relatively slow rate of charring when exposed to fire.

Heavy timber construction has long been recognized as having very good fire performance. This is reflected in OBC where provisions for heavy timber construction and solid wood wall and floor assemblies have remained in the code for many decades, as far back as the first National Building Code of Canada in 1941.

In OBC, heavy timber elements are not only permitted wherever combustible construction is permitted. There are several provisions that permit heavy timber elements to be used in buildings required to be of noncombustible construction where other wood structural elements are not permitted to be used.

The definition of “heavy timber construction” in OBC provides some insight into the attributes which are deemed to contribute to its fire performance. OBC states the following:

“Heavy timber construction means that type of combustible construction in which a degree of fire safety is attained by placing limitations on the sizes of wood structural members and on the thickness and composition of wood floors and roofs and by the avoidance of concealed spaces under floors and roofs.”

The attributes that make buildings of heavy timber construction perform better in fire are enhanced as we look towards using larger mass timber beams, columns and panels. The larger sizes used in tall mass timber buildings are a function of the increased loads as well as the requirement for 2-hour fire-resistance ratings (or greater, depending on the Alternative Solution) for the structure.

Note that a number of design standards and fire test standards are referenced throughout Section 3 which may be more recent versions of those adopted by the 2012 edition of OBC.

3.1.1. OVERVIEW OF CHAPTER

This fire chapter is written primarily for the Chief Building Official (CBO) who may receive an Alternative Solution proposal for a tall wood building as well as developers, engineers and architects who need to understand the various considerations that may be included in an Alternative Solution to apply for permission to construct a tall mass timber building.

This chapter titled Fire Safety Design of Tall Mass Timber Buildings is intended to provide an overview of how a tall wood building (greater than 6-storeys) can be designed from a fire perspective, and submitted as an Alternative Solution to the CBO of an Ontario municipality. As described below, until such time in the future that the Building Code provides a prescriptive set of provisions as an Acceptable Solution to design and construct tall wood buildings, every tall mass timber building project will require a fire safety engineer to put together a detailed Alternative Solution complete with an engineering analysis to demonstrate fire safety performance. The level of performance required is based on the current Acceptable Solutions in Division B of OBC as described in Section 3.2, below.

Some CBOs may have concerns that they do not have the in-house expertise to evaluate what could be a complex Alternative Solution to demonstrate the performance of a tall wood building. Therefore, Section 3.3 of this technical resource describes how a third-party review process can be used to support the decision-making process of the CBO which is a relatively common practice in fire safety engineering.

Since the Acceptable Solution in Division B of OBC sets the performance level(s) of how a tall mass timber building must perform, Section 3.4 of this technical resource describes where wood elements are currently permitted in noncombustible construction. Understanding these allowances provides some perspective to how a mass timber building can incorporate combustible elements safely.

A common concern among CBOs in Ontario has been the quality of the Alternative Solutions they have received on past projects. Therefore, the typical design process used in fire safety engineering internationally is described in Section 3.5 below. While Alterative Solutions for tall wood buildings will range from relatively simple analyses (for example, a building in which the mass timber structure is fully encapsulated with no exposed mass timber elements and expected to perform similarly to a noncombustible structure) to complex analyses, the methodology presented can be used to help frame and provide justification for the overall approach.

The different fire safety features of building design, including active and passive systems, are described in Sections 3.6 and 3.7 of this technical resource, respectively. Issues specific to mass timber construction are discussed as they relate to each feature.

Regardless of the complexity of the Alternative Solution being proposed, some comparison of the expected design fires between the Alternative Solution and the Acceptable Solution will likely be needed. The comparison may be qualitative or quantitative and may be relative to one another or may be absolute, such as predicting the actual heat release rate. Therefore, some understanding of how the mass timber structure, whether encapsulated or not, will contribute to the fire severity will be needed. Section 3.8 of this technical resource provides some understanding of how the mass timber structure may contribute to the fire growth, intensity and duration.

As Alternative Solutions for tall mass timber buildings become more complex, it is likely a risk analysis will be required to compare the level of performance between the Alterative Solution and the Acceptable Solution. Section 3.9 of this technical resource provides a brief overview of risk analysis methods which may be used to complete the comparison.

Based on the information presented in the chapter, Section 3.10 of this technical resource combines these ideas into some common strategies for preparing Alternative Solutions for tall mass timber buildings.

Lastly, similar to the recent changes to OBC permitting 5- and 6-storey combustible construction, there are concerns regarding the possibility of a fire occurring in a wood building under construction, particularly as these buildings get larger and taller. Section 3.11 of this technical resource discusses the major considerations for fire safety on construction sites of tall mass timber buildings while providing additional resources for those interested in delving into that topic in more detail.

3.1.2. MASS TIMBER CONSTRUCTION – FIRE PERFORMANCE

As interest in wood buildings has grown in recent years, particularly in larger buildings using timber members with large cross-sections, a new term to describe the type of construction has been needed. The traditional term of “heavy timber construction” is not sufficiently representative, given the current specific definition in the building code and related provisions. A new term has been sought that would not have a particular fire-resistance rating implied, but could describe a building type where one and two-hour fire-resistance ratings could be attained. The very large cross-section timber products used in this type of construction have become known as “mass timber” and described in chapter 2.

Recognizing that mass timber construction is able to provide increased levels of fire resistance, a new Annex was added to the Canadian national wood design standard, CSA O86, in 2014. Annex B of CSA O86, entitled “Fire resistance of large cross-section wood elements” is an informative annex that provides a calculation methodology to determine the structural standard fire-resistance rating for use in designing mass timber construction. A supplement to the standard was published in 2016 that added CLT to the standard, including Annex B to calculate its standard fire resistance.[1]

One of the attributes that afford mass timber its excellent fire performance is the large size of the beams, columns or solid timber panels. The author of “Structural Design for Fire Safety” (Buchanan, 2001), explains the behavior of timber structures in fire:

> *“When large timber members are exposed to a severe fire, the surface of the wood initially ignites and burns rapidly. The burned wood becomes a layer of char which insulates the solid wood below. The initial burning rate decreases to a slower steady rate which continues throughout the fire exposure. The charring rate will increase if the residual cross section becomes very small. The char layer does not usually burn because there is insufficient oxygen in the flames at the surface of the char layer for oxidation of the char to occur.”*

The formation of the char layer and the pyrolysis zone is shown in the illustration in Figure 3.1.

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[1] While the 2016 Supplement is not yet referenced in the 2012 edition of OBC, its use can be supported through the use of an Alternative Solution.

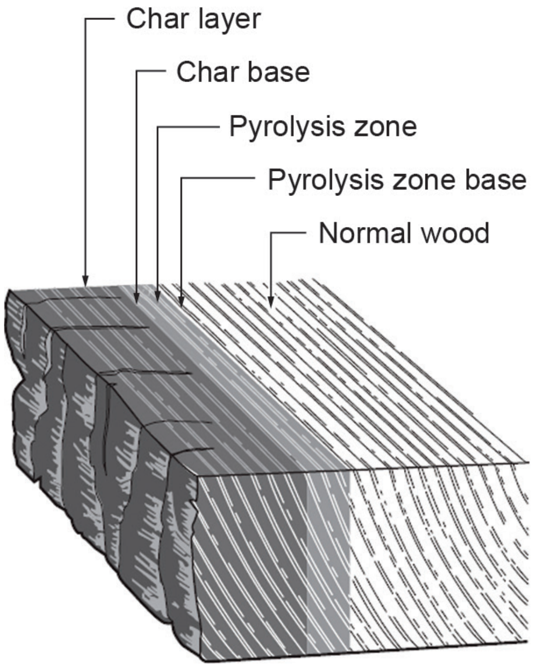

Figure 3.1. Formation of Char layer and pyrolysis zone in wood (one-dimensional) when exposed to high temperatures (CSA, 2011).

As indicated, as long as the residual cross-section remains of 'significant size', the charring will continue at a slow and predicable rate. Based on this, it is necessary to ensure the mass timber members are of sufficient size to prevent accelerated charring due to 2-dimensional heat transfer effects. Based on known char rates, heat penetration depth beyond the char front, and ensuring the material behaves as a semi-infinite solid so that the charring rate will not increase, Table 3.1 of minimum sizes for mass timber elements has been proposed for mass timber construction when left exposed (i.e. no encapsulation provided) (Craft, 2016).

Structural wood elements	Type of Dimension	Minimum Dimensions (mm)
Wall, floor and roof assemblies with 1- sided fire exposure	thickness/ depth	136
Beams, columns and arches with 2-sided or 3-sided fire exposure	cross-section	248 x 248
Beams, columns and arches with 4-sided fire exposure	cross-section	336 x 336

Table 3.1. Summary of minimum dimensions of structural wood elements proposed for mass timber construction if left exposed (Craft, 2016).

It should be noted that these minimum sizes are to provide assurance that timber elements will exhibit fire performance characteristics of mass timber rather than of lightweight, small-dimensioned wood elements (such as lumber), including reduced ignition propensity and reduced average rate of fuel contribution. The dimensions tabulated in Table 3.1 do not necessarily reflect a specific fire-resistance rating. In many cases, larger dimensions will be required to satisfy the desired standard fire-resistance rating. Additional information on calculating the fire resistance of mass timber is discussed in Sections 3.7.1 and 3.7.2 of this technical resource.

3.1.3. ENCAPSULATED MASS TIMBER

In addition to the relatively new term "mass timber", a related term "encapsulated mass timber" has been recently adopted to refer to mass timber construction where the mass timber elements are protected, to some degree, from fire exposure should a fire occur. As discussed through-out Chapter 3 of this technical resource, encapsulation can be provided by different materials such as gypsum board, mineral wool insulation, concrete or other materials demonstrated to stay in place and prevent charring of the mass timber elements for some duration when exposed to the standard fire resistance test exposure in CAN/ULC-S101. The amount of protection, in terms of time when exposed to the standard fire test exposure, that an encapsulation method provides will affect if and when the structure may contribute to a fire in a compartment. In many cases, the encapsulation material will also contribute to the fire-resistance rating of the mass timber structure. However, it is important to understand these two roles of the encapsulation material or system (reducing contribution to fire severity and contributing to fire resistance of the structure) are separate and need to be considered separately when looking at the fire performance of the building. Similar to the dimensions provided in Table 3.1 above, when the mass timber elements are encapsulated, the minimum dimensions can be reduced in size. Table 3.2 provides guidance for minimum sizes when the encapsulation is comprised of two layers of 12.7 mm Type X gypsum board.

Structural wood elements	Type of Dimension	Minimum Dimensions (mm)
Wall, floor and roof assemblies with 1- sided fire exposure	thickness/ depth	96
Beams, columns and arches with 2-sided or 3-sided fire exposure	cross-section	192 x 192
Beams, columns and arches with 4-sided fire exposure	cross-section	224 x 224

Table 3.2. Summary of minimum dimensions of structural wood elements proposed for mass timber construction if encapsulated with 2 layers of 12.7 mm Type X gypsum board (Craft, 2016).

In many cases, a proposed design for a building may include a partial encapsulation design strategy. An example of such a strategy could be a design in which a CLT ceiling is encapsulated with gypsum board while the beams and columns are left exposed. Any number of different combinations of encapsulated and exposed wood could be envisioned and the Alternative Solution will have to demonstrate the performance of such a building is acceptable.

3.1.4. COMPETENCY OF TEAM PREPARING ALTERNATIVE SOLUTION

It is important to understand that the preparation of an Alternative Solution for a tall mass timber building is a significant undertaking and requires a fire safety engineer to understand and apply fire safety engineering analysis and judgement. It is critical that the fire safety engineer works closely with the architect, structural engineer and other design professionals, from an early stage, since decisions made early on or in the later stages of design can have an impact on the fire safety and proposed Alternative Solution. For instance, modification of assemblies' details to address acoustics can have an impact on the fire resistance of the assembly, or changes to the structural design or layout can have an impact on the fire resistance of the structure and other fire protection design aspects.

3.2. COMPLIANCE WITH ONTARIO'S BUILDING CODE

Compliance with OBC can be demonstrated in one of two ways, as specified in Article A-1.2.1.1 of Division A, which states:

> *1) Compliance with Division B shall be achieved by,*
>
> > *a) complying with the applicable acceptable solutions in Division B, or*
> >
> > *b) using alternative solutions that achieve the levels of performance required of the applicable acceptable solutions in respect of the objectives and functional statements attributed to the applicable acceptable solutions in MMAH Supplementary Standard SA-1, "Objectives and Functional Statements Attributed to the Acceptable Solutions".*
>
> *2) For the purpose of Clause (1)(b), the level of performance in respect of a functional statement refers to the performance of the functional statement as it relates to the objective with which it is associated in MMAH Supplementary Standard SA-1, "Objectives and Functional Statements Attributed to the Acceptable Solutions".*

This means that the Acceptable Solutions in Division B of OBC establishes the performance level required with respect to the applicable objectives and functional statements. Based on this, if a designer wishes to submit an "Alternative Solution", the designer must first establish the level of performance required based on the Division B Acceptable Solution. This is the primary difference between an objective-based code and a performance-based code, which would explicitly establish the performance criteria. The designer must determine the level of required performance, quantitatively, based on the expected performance of the Acceptable Solution.

In cases where there is a choice between several possible designs, where all satisfy Division B requirements, it is likely that the designs will not all provide equivalent levels of performance. As explained in the OBC Appendix Note that accompanies Article 1.2.1.1. of Division A, generally the design that provides the lowest level of performance while satisfying the Acceptable Solution in Division B should be considered to establish the minimum acceptable level of performance to be used in evaluating Alternative Solutions for compliance with the Code.

In addition to the objectives and functional statements, which provide guidance as to the rationale for the Acceptable Solutions, the National Research Council (NRC) publishes intent statements for all the provisions in Division B of the model NBCC, which can be accessed from NRC's website[1]. For those provisions in OBC that are the same as in the NBCC, these intent statements may provide additional guidance to the user to help clarify the undesirable results each provision seeks to preclude.

Demonstration that an Alternative Solution Complies with OBC

Once the performance levels are established based on the performance of a design compliant with the Acceptable Solution as specified in Division B, the Alternative Solution can be evaluated to determine the provided performance level. OBC requires that the performance level of the Alternative Solution be equal to or greater than the performance level of the Acceptable Solution in respect of the OBC objective and functional statement attributed to the acceptable solution. This is the basis by which all Alternative Solutions, no matter how simple or elaborate, must be evaluated.

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[1] The 2010 National Building Code of Canada Intent Statements are available at the following url: http://codes-guides.nrc.ca/IA/10NBC/intentframe.html

Documentation of Alternative Solution

As stated above, it must be demonstrated that an Alternative Solution will achieve at least the minimum level of performance achieved by a design that complies with the applicable Acceptable Solution in the areas defined by the objectives and functional statements attributed to the Acceptable Solution. The documentation required to be submitted with an Alternative Solution is outlined in Section 2.1 of Division C of OBC with further guidance provided in Appendix A of OBC under A-1.2.1.1.(1)(b).

Additionally, Subsection 2.3.1, "Documentation of Alternative Solutions" of Division C of the model NBCC includes additional information which may be deemed useful, while not explicitly required by OBC. The subsection states that an Alternative Solution shall include a code analysis, which outlines the analytical methods and rationale used to determine that a proposed Alternative Solution will achieve at least the level of performance as required by Division B, as well as any special maintenance or operational requirements, including any commissioning requirements, that are necessary for the Alternative Solution to achieve compliance with the Code after the building is constructed. The code analysis should include the following:

- Identification of the Acceptable Solutions (e.g. "noncombustible construction"), which are not explicitly satisfied, and the applicable objectives and functional statements related to the Acceptable Solutions.
- Any assumptions, limiting or restricting factors, testing procedures, engineering studies or building performance parameters that support the proposed Alternative Solution.
- Qualifications, experience and background of the person or persons taking responsibility for the design.
- Information in sufficient detail to convey the design intent and to support the validity and accuracy of the proposal.

Approval of Alternative Solutions

Approval of Alternative Solutions is a decision of the Chief Building Official (CBO), which is often in the municipality in which the building is to be constructed. It is not uncommon that an Alternative Solution is sufficiently complex that it is beyond the level of in-house expertise of the CBO. In some cases, the CBO may want to request the Alternative Solution be reviewed by a third-party (person/organization) approved or chosen by the CBO.

Additional information and guidance on the peer-review process can be found in Section 3.3 of this technical resource.

Combustible Construction Alternative Solution

The first step in developing an Alternative Solution for a tall wood building starts with identifying the code provisions in Division B that will not be met by using mass timber construction as opposed to noncombustible construction. In the case of tall wood buildings, the actual code reference that requires noncombustible construction falls under the provisions in OBC Subsection 3.2.2., where the specific Article depends on the occupancy of the building. For example, the following Sentences from OBC would apply to a tall (greater than 6-storeys) residential or office buildings, respectively, of mass timber construction:

- Sentence 3.2.2.42.(2) prescribes noncombustible construction for a Group C (residential) building permitted to have unlimited area and unlimited height.
- Sentence 3.2.2.49.(2) prescribes noncombustible construction for a Group D (office) building permitted to have unlimited area and unlimited height.

The objectives and functional statements attributed to these Acceptable Solutions are as listed below in Table 3.3.

OBC Code References	Objective	Function	Link	Unacceptable Risks
Sentences 3.2.2.42.(2) and 3.2.2.49.(2)	OS1.2	F02: To limit the severity and effects of fire or explosions	so that	a person in or adjacent to the building is not exposed to an unacceptable risk of injury due to fire or explosion impacting areas beyond its point of origin.
	OP1.2			the building is not exposed to an unacceptable risk of damage due to fire or explosion impacting areas beyond its point of origin.

Table 3.3. Objectives and functional statements attributed to the requirement for noncombustible construction.

The National Research Council has published the following intent statement with respect to the noncombustible construction requirements in the corresponding two articles to those above in the model NBCC:

> 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 the 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.

Every tall wood building built following the Alternative Solution pathway to code compliance will likely be different. The Alternative Solution for some projects might only include the code reference above in Table 3.3, utilizing mass timber in place of the otherwise required noncombustible construction. Alternatively, some projects will have a mass timber structure and also have some of the structure exposed. In this case, the Alternative Solution would also have to address the use of exposed mass timber as interior finishes, which is limited to 25 mm thick wall linings in OBC for buildings required to be of noncombustible construction. Additional design and/or analysis within the Alternative Solution also may be required for exterior wall construction if the spatial separation requirements (Subsection 3.2.3. of OBC) mandate noncombustible construction, which are separate provisions from the height and area requirements in Subsection 3.2.2. of OBC, as well as any other deviations from the Division B provisions.

Other examples of OBC Division B acceptable solutions which are not met, and therefore requiring the Alternative Solution to address the corresponding objectives and functional statements might include but are not limited to:

- Article 3.1.5.1., “Fire-Retardant Treated Wood”
- Subsection 3.1.11., “Fire Blocks in Concealed Spaces”
- Subsection 3.1.13., “Interior Finish”
- Article 3.2.3.6., “Combustible Projections”
- Article 3.2.3.7., “Construction of Exposing Building Face”

However, it should be mentioned that a common strategy is to satisfy OBC Division B acceptable solutions as much as possible while achieving the overall objectives of the design such as utilizing a mass timber structure and possibly leaving exposed, to some extent, the mass timber structure.

3.3. THIRD-PARTY REVIEW PROCESS

When a CBO has the appropriate expertise and experience, the CBO may want to review and evaluate the proposed Alternative Solution themselves and ultimately approve or disapprove it. Factors a CBO may want to consider include the education, expertise and experience of the staff available to the CBO, and the complexity of engineering analysis used to demonstrate that the Alternative Solution provides the required level of performance.

In some cases, an Alternative Solution for a tall wood building using fire safety engineering principles may be beyond the level of in-house expertise of a CBO. In these cases, a third-party review can become an important resource used by CBOs to evaluate complex Alternative Solutions. A third-party review may be performed by a peer with a similar or greater degree of knowledge and experience as the proponent, or can be performed by a specialist to consider particular aspects of the proposed Alternative Solution in which they have an expertise. The third-party review may include any or all aspects of the design, including the fire protection engineering design brief, conceptual approaches, supporting analyses, calculations, and the application or the interpretation of code requirements.

When it has been determined that a third-party review will be required to evaluate an Alternative Solution, it is advantageous if the reviewer is selected and approved or hired by the CBO. The review should be independent of the project and independent of the firms involved in the project. The scope of the review must be clearly expressed to ensure all parties understand the extent of the review. The payment procedure for a reviewer should be determined early in the process and may be made by the proponent of the project or by the CBO, for example, by including the fees as part of the permit fee structure.

In general, it is advantageous to include the reviewer(s) early in the process so that an overall approach and methodology can be discussed. The third-party review is intended to be a constructive process to assist the CBO in evaluating and ultimately approving an Alternative Solution supported by a suitable fire safety engineering analysis. The third-party review should help facilitate the approval of an Alternative Solution by working with the proponents and the CBO.

The process of the third-party review should be documented throughout. Comments during the process, as well as the final report, should be explicit in the evaluation of the Alternative Solution and should be constructive in approach so that deficiencies in the Alternative Solution can be addressed in a timely manner.

If the reviewer has been retained and involved in the project from an early stage, it is unlikely that the rationale and justification for the Alternative Solution during the concluding stage of the review will not adequately address the objectives. The more likely outcome of a third-party review, where the reviewer(s) have been engaged early in the process, is that the documentation and analysis will adequately support the Alternative Solution. By having the reviewer engaged early on, the process should be much smoother and more streamlined since concerns with approach and/or methodologies can be identified at an early stage.

Further guidance on third-party review can be found in the following documentation:

1. Guidelines for Peer Review in the Fire Protection Design Process. Society of Fire Protection Engineers, Gaithersburg, MD. 2009.
2. International Fire Engineering Guidelines. Australian Government, State and Territories of Australia. 2005.

3.4. NONCOMBUSTIBLE CONSTRUCTION AND HIGH BUILDINGS

As previously described, an Alternative Solution that proposes the use of mass timber for the construction of a tall wood building must be compared to the Acceptable Solution, which in OBC current 2012 edition requires the use of "noncombustible construction". Therefore, it is important to have an understanding of where wood is currently permitted to be used in buildings required to be of "noncombustible construction," since the performance of the combinations of noncombustible and combustible materials and elements permitted by the code in "noncombustible construction" sets the level of performance for an Alternative Solution.

Note that it is also important to understand what material and design restrictions exist for buildings required to be of noncombustible construction, since most Alternative Solutions which utilize a mass timber structure will follow all other requirements for noncombustible construction with the exception of the structure itself.

The most significant areas where wood is permitted to be used in buildings required to be of noncombustible construction include the use of heavy timber elements, interior partition walls, interior finishes such as floor and wall coverings, and trim. To better understand what restrictions there are in noncombustible buildings, it helps to understand what exactly "noncombustible" and "noncombustible construction" means in the context of the code.

OBC provides the following definition of "noncombustible":

> Noncombustible is a material that *"meets the acceptance criteria of CAN/ULC-S114, "Test for Determination of Noncombustibility in Building Materials."*

The test method CAN/ULC-S114 (2005) consists of taking a small sample (38 mm x 38 mm x 50 mm) and placing it in a furnace at 750 °C for 15 minutes. The standard requires that three tests be conducted on three separate samples. A building material is considered to be noncombustible if:

- The average of the maximum temperature rise in the 3 tests does not exceed 36°C;
- No flaming is visible in the furnace during the last 14.5 minutes in any of the 3 tests; and
- The maximum mass loss of the specimen is less than 20% in each of the 3 tests.

Wood products, including typical fire-retardant-treated wood products, do not satisfy these requirements and hence are judged to be combustible. In fact, some gypsum board products are unable to pass this test which is an indication on how challenging the test is for materials to pass.
Note that an alternative test, CAN/ULC-S135 (2013) can be used to demonstrate low levels of heat release and materials which pass the requirements in Sentence 3.1.5.1.(2) of Division B of OBC may be used where noncombustible materials are required.

OBC provides defines “noncombustible construction” as follows:

> Noncombustible construction is *“that type of construction in which a degree of fire safety is attained by the use of noncombustible materials for structural members and other building assemblies.”*

It is important to note that the definition of noncombustible construction does not state that only noncombustible materials can be used; it just states that a certain degree of fire safety is achieved in this construction type by using noncombustible materials for certain elements of the building. In fact, as discussed in the next section, there are many combustible materials permitted to be used in buildings required to be of noncombustible construction.

3.4.1. WOOD USE IN NONCOMBUSTIBLE BUILDINGS

Wood can be one of the most prevalent combustible materials used in buildings required to be of noncombustible construction. It may be used as furring strips, or fascia and canopies, cant strips, roof curbs, fire blocking, roof sheathing and coverings, millwork, cabinets, counters, window sashes, doors, flooring, partition studs, joists and even as wall finishes. In tall buildings, restrictions on the flame-spread rating and smoke developed classification may limit wood use in areas such as exits, corridors and lobbies, however, fire-retardant treatments can be used to meet these requirements. Below is a summary of what types of wood products can be used in a building required to be noncombustible and where they may be used. The specific code references are provided for additional information.

Partitions
Both solid wood walls (not less than 38 mm thick) and wood-framed walls can be used extensively as nonloadbearing partitions in buildings required to be of noncombustible construction. However, an exception exists for care, treatment or detention occupancies in which the use of solid or wood-framed partition walls is not permitted. See OBC Division B, Article 3.1.5.13. for additional information.

Provided the noncombustible building is sprinklered throughout, which tall wood buildings will be, solid wood partitions and wood-framed partitions are permitted to be used with or without a fire-resistance rating. However, the solid wood partitions cannot be installed as enclosures for exits or vertical service spaces, and the partitions cannot be used as fire separations to enclose a mezzanine.

The allowances for the use of wood partition walls are based on the fact that the wood does not contribute to fire growth and may only contribute to fire after some time when the protective membrane falls away. Even at that point, the contribution of the wood is not significant compared to the rest of the combustibles, such as furnishings, in the compartment (Mehaffey, 1987).

Roofing Materials
Wood roofing materials are permitted to be used provided they meet the requirements of an A, B or C classification when tested in conformance with CAN/ULC-S107 (2010), “Fire Tests of Roof Coverings.” See OBC Division B, Article 3.1.5.3. for additional information.

Plywood or OSB is permitted to be installed as roof sheathing above a concrete deck on a building required to be of noncombustible construction. However the roof deck must be 50 mm or greater in thickness and the roof sheathing cannot be more than 1 m above the concrete deck. Additionally, parapets must be provided at the concrete deck perimeter and extend at least 150 mm above the sheathing to prevent the roof materials from igniting from flames projecting from a window.

In the construction of roofs, wood cant strips, roof curbs and nailing strips and similar components are permitted on a building required to be of noncombustible construction. Additionally, wood nailer facings to parapets, 600 mm high or less, are permitted on a building required to be of noncombustible construction, provided the facings and any roof membranes covering the facings are protected by sheet metal.

Furring and Blocking

Wood is particularly useful as a nailing base for different types of cladding and interior finishes. Wood furring attached directly to a noncombustible backing for the attachment of interior finishes is permitted provided the gap created between the interior finish and the noncombustible backing is 50 mm or less. Wood blocking is permitted to be used in wall assemblies of a noncombustible building for the attachment of fixtures such as handrails. See OBC Division B, Article 3.1.5.2. for additional information.

In addition, wood blocking may be used as fire blocks in buildings permitted to be of noncombustible construction. However, the fire block must pass a test in which it prevents the passage of flames for 15 minutes when subjected to the standard fire exposure specified in CAN/ULC-S101, “Fire Endurance Tests of Building Construction and Materials.”

Interior Finish

Wood products used as interior finishes can be used extensively in buildings required to be of noncombustible construction. The use of interior finishes is largely regulated based on restrictions of the flame-spread rating. In general, combustible interior wall finishes are permitted to be used in a building required to be of noncombustible construction, provided they are not more than 25 mm thick and have a flame-spread rating not more than 150 on any exposed surface, or any surface that would be exposed by cutting through the material. Some restrictions apply in certain areas such as in exit stairways, corridors not within suites, and certain lobbies. See OBC Division B, Article 3.1.5.10. for additional information.

Fire-retardant-treated wood (FRTW) can be used when the flame-spread rating is limited to 25 or less in a building required to be of noncombustible construction. The only limit placed on the use of FRTW is that the thickness is limited to 25 mm when used as an interior finish. Since the requirements for flame-spread rating of interior finishes in a building required to be of noncombustible construction apply to the exposed surface, or any surface that would be exposed by cutting through the material in any direction, fire retardant coatings cannot be used. Since FRTW is pressure impregnated, it is exempt from this requirement.

Flooring

Combustible subfloor and finished flooring, such as hardwood strip flooring is permitted in any noncombustible building, including high rise buildings. Additionally, wood supports for combustible flooring and subflooring such as wood joists, wood I-joists or wood trusses are permitted provided the supports are between 50 and 375 mm high and applied directly to a noncombustible floor slab. Of course, the concealed spaces created with this type of construction must contain fire blocks. See OBC Division B, Article 3.1.5.8. for additional information.

In addition to flooring, wood stairs can be installed within a dwelling unit in a building required to be of noncombustible construction. See OBC Division B, Article 3.1.5.9. for additional information.

Window Frames and Trim

Wood window sashes and frames are permitted in a building required to be of noncombustible construction provided each window is separated from adjacent windows by noncombustible construction and meets the limit (40%) on the aggregate area of openings on the outside face of a fire compartment. See OBC Division B, Article 3.1.5.4. for additional information.

Wood millwork, such as interior trim, doors and door frames, show windows and frames, aprons and backing, handrails, shelves, cabinets and counters, are also permitted in buildings required to be of noncombustible construction. Because these components contribute minimally to the fire hazard, it is not necessary to restrict their use. However, in some locations, such as an exit stairway or corridor, a limit is placed on the trim and millwork of 10 percent of the area of the wall or ceiling on which they occur. This restriction is related to the flame-spread rating of the interior finish and the fact that wood trim and millwork will have a flame-spread rating over 25 unless fire-retardant-treated wood is used. See OBC Division B, Article 3.1.5.7. for additional information.

3.4.2. ONTARIO'S BUILDING CODE TREATMENT OF HIGH BUILDINGS

OBC includes special provisions for what it classifies as High Buildings (under OBC Division B, Subsection 3.2.6.). The Subsection includes provisions to limit the risk to occupants and firefighters from exposure to smoke in addition to provisions related to elevators, venting, the fire alarm system and voice communication. A building is classified as a High Building if the floor level of the top storey is more than 36 m above grade for Groups A, D, E or F major occupancy or more than 18 m above grade for Group C occupancy. Therefore, a tall wood building of residential occupancy (C) will no doubt be classified as a High Building, while an office building may or may not be classified as a High Building depending on whether the top floor level is more than 36 m above grade as well as other factors such as occupant load and exit width (see OBC Division B, Clause 3.2.6.1.(1)*a*).

One of the major concerns regarding smoke movement in high buildings is due to the "Stack Effect." The stack effect is caused by the buoyancy of warm air relative to cool, more dense air. This buoyancy of warm air indoors causes air flow up through a building when it is cooler outside, through continuous shafts such as stair shafts, elevator shafts or garbage chutes in much the same way hot gases rise in a chimney (see Figure 3.2). This difference in air temperature, causing the stack effect, is greatest during winter months when the difference in the air temperature between the heated air in the building and the outside temperature is greatest. The pressure difference is linear over the height of the building which means at mid-height the pressure difference between the interior and exterior is zero. The bottom of the building has lower pressure inside compared to outside and top half of the building has a higher pressure, with the highest at the top. The pressure difference is a function of the temperature difference and the height of the building. This pressure difference causes air leakage in any openings (in at the bottom and out at the top) since no building is perfectly air tight, which creates a movement of air up through any continuous shafts in the building.

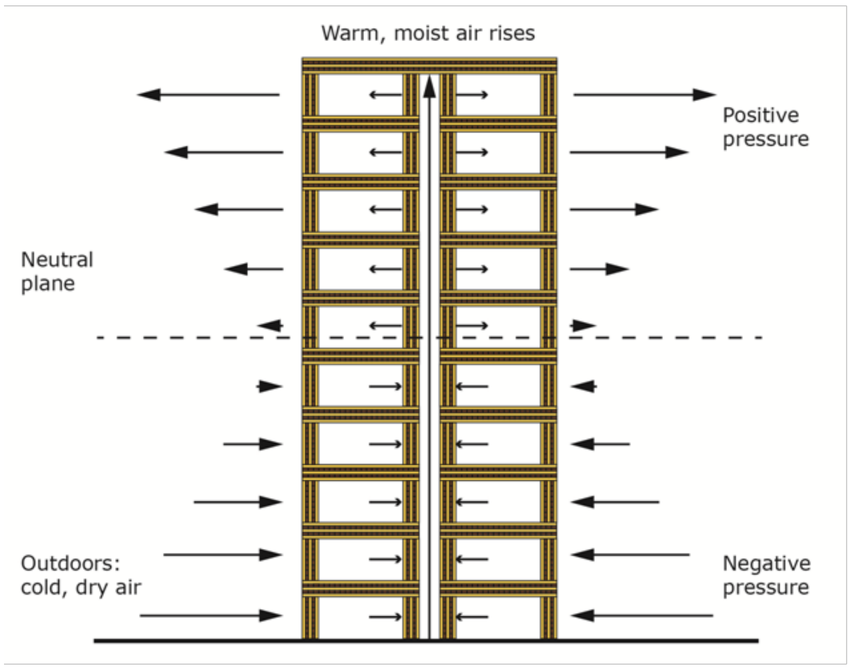

Figure 3.2. Illustration showing stack effect in high-rise building during winter months [From Figure 6 of Chapter 5 from FPInnovations *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada*].

The acceptable solutions in Division

B of OBC for High Buildings typically will be applied to tall wood buildings, when required, as they are applied to noncombustible construction. Some design details may need more careful attention than typically applied in noncombustible construction. For example, while mass timber exit stair shafts will most likely be protected by gypsum board on the inside in order to meet flame-spread rating requirements of 25, special consideration of the construction of solid wood shafts may be required to ensure smoke is not able to pass by or through the system. This is particularly important in the case of scissor stairs where the stair stringer panel acts as the fire separation. See Sub-section 3.7.2 of this technical resource, Designing for Compartmentation, for more discussion on this topic.

3.5. FIRE SAFETY ENGINEERING PROCESS

Alternative Solution submissions can take many forms, from simple trade-offs to complex fire safety engineering analyses. Alternative Solutions for tall wood buildings are likely to be on the more complex end of the spectrum. It is, therefore, recommended that fire safety engineers follow a standardized fire safety engineering process, such as that published in the international standard ISO 23932, “Fire Safety Engineering – General Principals” (ISO, 2009) or that published in the “International Fire Engineering Guidelines” (ABCB, 2005).

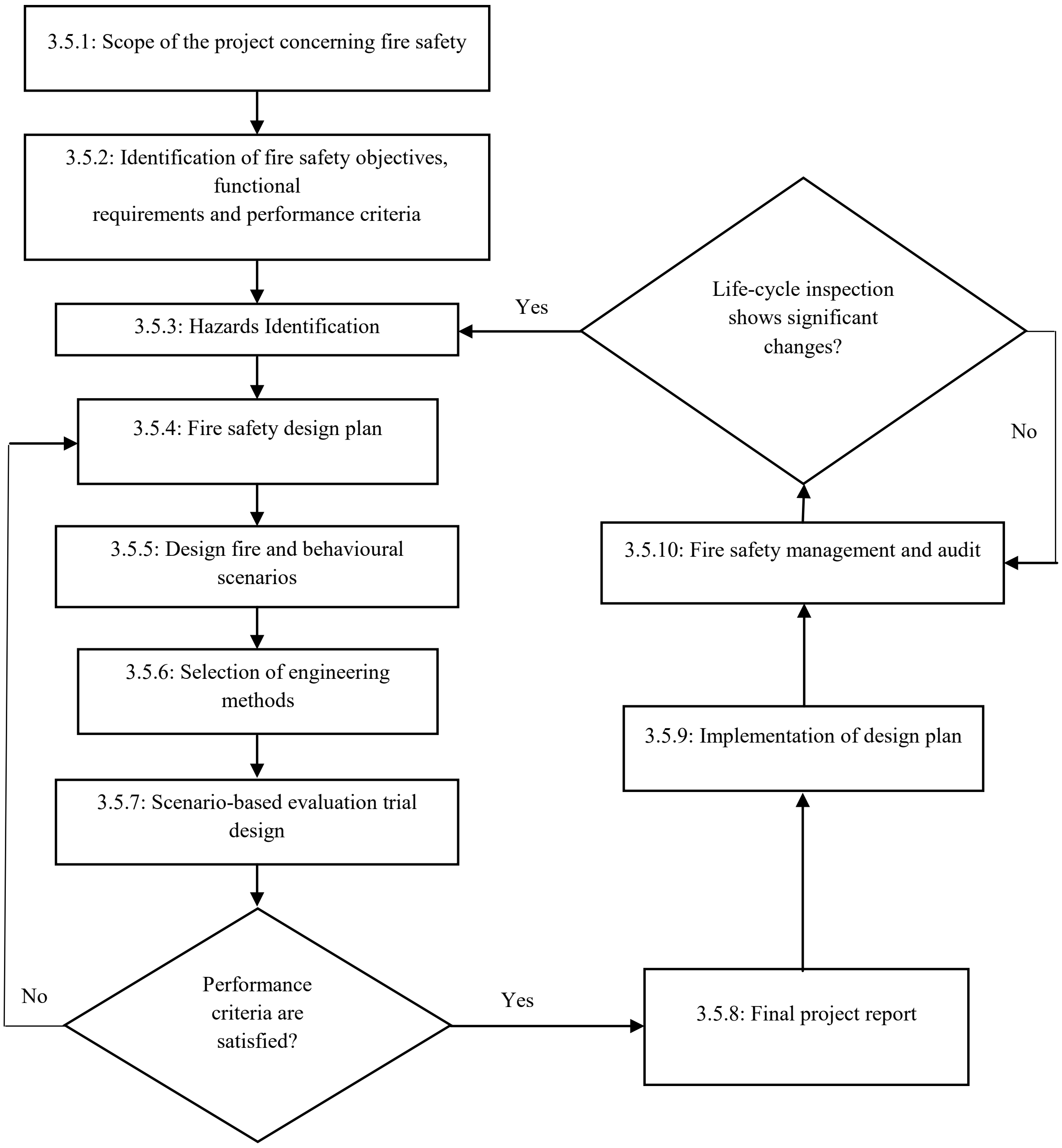

Figure 3.3. Flowchart illustrating the fire safety engineering process as presented in ISO 23932 (ISO, 2009).

The flowchart in Figure 3.3 illustrates the fire safety engineering process as presented in ISO 23932. Since the analysis compares two designs, the Alternative Solution compared to the Acceptable Solution, in many cases the overall analysis can be simplified based on similarities in the compared solutions. For instance, if the only difference between two building designs is that one (the Alternative Solution) envisions a combustible structure, which is protected with multiple layers of gypsum board, versus a noncombustible structure, there likely will be no difference in risk of ignition, early fire growth in the event of a fire or occupant response and evacuation times needed to exit the building, since the combustible structure would not be expected to become involved in a fire event until sometime well into the event, if at all. These similarities between designs can greatly simplify the process of determining if the Alternative Solution provides a performance level that is as good as, or better than, the Acceptable Solution.

Each step of the Fire Safety Engineering Process as described in ISO 23932 is described in the following sections.

3.5.1. SCOPE OF THE PROJECT CONCERNING FIRE SAFETY

The fire safety engineering process described in Figure 3.3 should begin at the earliest stage of a project. This way, the fire safety design can be integrated with all the other engineering disciplines since decisions made early on regarding structural, acoustic, and thermal envelope designs can have a significant impact on fire safety of the building. At this stage in the process, the general approach to fire safety and the Alternative Solution, that would allow the use of mass timber for a tall wood building, should be discussed with the design team. It is also strongly recommended that, at this early stage, the design team meets with the CBO and Fire Services to benefit from discussing the proposed Alternative Solution and identifying specific concerns the CBO and Fire Service may have. It would be at this meeting a decision should be made as to whether the CBO would like to have the Alternative Solution reviewed by a third-party as discussed in Section 3.3 of this technical resource.

3.5.2. IDENTIFICATION OF FIRE SAFETY OBJECTIVES, FUNCTIONAL REQUIREMENTS AND PERFORMANCE CRITERIA

The OBC explicitly identifies the objectives and functional statements related to the Acceptable Solution requiring the use of noncombustible construction. Therefore, it is relatively clear what objectives and functional statements must be addressed in developing an Alternative Solution.

However, through discussion with the CBO and building proponents/owners, additional objectives or performance criteria may be identified as needing to be addressed.

As previously described, the performance criteria for evaluating an Alternative Solution is the anticipated performance of the Acceptable Solution, which for a tall wood building would be a similar, code-compliant, building of noncombustible construction designed using Division B of the Code.

3.5.3. HAZARD IDENTIFICATION

Hazard identification for many projects can be based on statistics for the occupancies most likely to be present in a tall wood building, such as residential or business and personal services occupancies. In many cases, the hazards will be the same in the two buildings being compared (Alternative Solution and Acceptable Solution) while an example of additional hazards related to the Alternative Solution could include having additional combustible components on the exterior of a tall wood building that currently is not permitted in buildings required to be of noncombustible construction. In this case, the additional hazard would need to be investigated.

Information on hazards in high-rise buildings, and residential and business and personal services buildings can be found in the statistics collected by the National Fire Protection Association (Ahrens, 2016) (Campbell, 2013).

Depending on the proposed Alternative Solution, there may not be a significant difference in the hazards between the Alternative Solution building and the Acceptable Solution building of noncombustible construction, given the same occupancies (e.g. residential or office).

3.5.4. FIRE SAFETY DESIGN PLAN

The fire safety design plan is the overall fire safety design strategy and design elements that constitute the proposed Alternative Solution and that are to be compared to the Acceptable Solution. For example, the design plan may include mitigating features such as encapsulation of the mass timber construction to prevent its contribution to fire growth and intensity for some period of time, or increasing reliability of the sprinkler system to help off-set any additional risk associated with a combustible structure.

3.5.5. DESIGN FIRE AND BEHAVIOURAL SCENARIOS

Design fire scenarios and design fires must be developed. Design fire scenarios describe qualitatively the types of fires that need to be considered and would be based on the hazards identified in Section 3.5.3 of this technical resource. Design fire scenarios may or may not be different for the Alternative Solution and the Acceptable Solution. In cases where the primary hazards are deemed to be the same, the fire scenarios considered between the two will also be the same. For each design fire scenario, a design fire must be generated. Most commonly the design fire would be expressed in terms of heat release rates. While the design fire scenarios are typically the same for the Acceptable and Alternative Solutions, depending on the degree of protection of the combustible structure, or impact of mitigating features included in the Alternative Solution, the design fires may differ between the two solutions being compared. The comparison may be qualitative or quantitative and is discussed in more detail in Section 3.8 of this technical resource.

3.5.6. SELECTION OF ENGINEERING METHODS

The selection of engineering methods is dependent on many factors, including the overall complexity of the comparison. Simple trade-offs will not require the same degree of analysis as significant deviations from the Acceptable Solution, which may require complex solutions to address fire safety. The engineering methods used may range from simple deterministic fire models to predict fire resistance or comprehensive fire-risk assessment methods to evaluate overall risk to life and property.

3.5.7. SCENARIO-BASED EVALUATION TRIAL DESIGN

The fire safety design is evaluated for the various design fire scenarios identified in Section 3.5.5 of this technical resource. For example, a design fire scenario may consist of a case where a fire starts in an apartment and the automatic sprinkler system fails to control the fire. In this case, the outcome (or consequence) can be predicted using the engineering methods (fire models) described in Section 3.5.6 of this technical resource. The outcome can then be assigned a probability based on the probability that the sprinkler system fails to control the fire. Multiplying the probability of a scenario by the consequences of the scenario is the risk associated with that scenario. The risks associated with fire for the Alternative Solution can be compared with the risks associated with fire for the Acceptable Solution, based on the design fire scenarios. If it is found necessary, additional design features may be required to bring the risks associated with the proposed Alternative Solution in line with those of the Acceptable Solution.

As an alternative to comparing the risks associated with Alternative and Acceptable Solutions on a scenario by scenario basis, a full risk assessment can be undertaken whereby the combined risks of all design fire scenarios is analysed. This type of comprehensive analysis may be necessary for Alternative Solutions that significantly vary from the Acceptable Solutions.

3.5.8. FINAL PROJECT REPORT

Based on the work conducted under Sections 3.5.1 through 3.5.7 of this technical resource, and assuming the engineering evaluation demonstrates that the Alternative Solution performs as well as or better than the Acceptable Solution, the results need to be documented for review by the CBO and any third-party reviewers. It is at this point that the CBO must decide whether the Alternative Solution acheives the level of performance required by the applicable acceptable solutions in respect of the OBC objective and functional statement.

3.5.9. IMPLEMENTATION OF DESIGN PLAN

Once approved, the Alternative Solution must be implemented. In many cases, this requires the fire safety engineer to work with the other design professionals such as the structural engineer, the sprinkler designer, the fire alarm designer, and the architect to implement the design and ensure the Alterative Solution design attributes are implemented properly. Site visits during construction are also an important aspect of ensuring the Alternative Solution features are constructed as designed.

3.5.10. FIRE SAFETY MANAGEMENT AND AUDIT

Once the building is built, any special maintenance or inspection requirements should be documented in the building's fire safety plan.

3.6. TYPICAL FIRE PROTECTION DESIGN FEATURES: ACTIVE FIRE PROTECTION

The fire protection features used in building design can be divided into two categories; active fire protection and passive fire protection.

Active fire protection systems are those that activate when a fire is detected, either through sensing smoke or elevated temperatures or through manual activation. Examples of active fire protection include fire alarm systems, automatic sprinklers systems, or smoke management systems. See Section 3.7 of this technical resource for discussion of passive fire protection.

3.6.1. AUTOMATIC SPRINKLER SYSTEMS

Any building greater than 6-storeys in height is required by OBC to be sprinklered in accordance with NFPA 13, "Standard for the Installation of Sprinkler Systems" (NFPA, 2013). Automatic sprinkler systems are by far the most effective means to reduce risk to life and property from fire in buildings, as demonstrated by a study completed by Carleton University (Zhang *et al.,* 2015). Given the significant increase in fire safety provided by the sprinkler system, it is important to understand the level of reliability of these systems, and as a possible mitigating feature used in Alternative Solutions for tall mass timber buildings, look for ways in which their reliability can be increased.

A number of studies have been conducted over the years on sprinkler system reliability. One of the most recent reports published by NFPA looked at the period between 2007-2011 (Hall, 2013). In the study, it was found that sprinkler systems in all residential occupancies were effective 92 percent of the time. The number one cause for sprinkler system failures, accounting for approximately two-thirds, occurred because the system was shut off.

A comprehensive review of sprinkler system effectiveness studies conducted by New Zealand researchers found 15 studies that reported sprinkler system effectiveness between 70 and 99.5 percent (Frank *et al.*, 2013). It is obviously necessary to look at each study and what types of buildings, occupancies and time frame a study was conducted on before relying on a study's findings. The review also looked at the different reasons for the system failing along with frequency which is useful in order to design a system with greater reliability.

A Canadian study published by NRC in 1985 estimated sprinkler reliability to be in excess of 96 percent and provided recommendations on how the reliability can be further improved, such as using electrically supervised systems (Richardson, 1985).

There have been significant improvements to sprinkler systems over the years and therefore studies conducted on fires in buildings from the 1960's may not be fully representative of system performance for buildings constructed today. For instance, electrically supervised sprinkler systems mentioned above became a requirement in the 1986 edition of OBC and the 1995 edition of the model NBCC. Therefore, buildings built after OBC 1986 was adopted likely have a higher reliability but may have limited impact on fire loss statistics for some time, since the number of fires in newly constructed buildings likely will not make up a significant number of buildings that experience a fire and, as a result, are underrepresented statistically in the currently available fire loss statistics, overshadowed by fires in buildings constructed to earlier codes.

Another study of sprinkler systems in Australian high-rises estimated the reliability of the systems to have a failure probability between 3 and 14 percent (Moinuddin *et al.*, 2008). Acknowledging the number one cause of sprinkler system failures as reported above, systems being shut off, the paper recommends zone isolation valves be installed at each floor, which could reduce the failure probability between 13 and 62 percent.

Given the significant benefit of automatic sprinkler systems to the fire safety of any building, steps to increase the reliability and/or the effectiveness of the sprinkler system can be used as a means to partially or wholly off-set the additional risks associated with the use of combustible structural elements over that of noncombustible structural elements in tall buildings.

3.6.2. AUTOMATIC FIRE ALARM SYSTEMS

Fire alarm systems play a key role in the fire safety of high-rise buildings by notifying occupants of the need to evacuate in the event of a fire and notifying the fire department. As discussed above with respect to the design considerations of sprinkler systems, consideration as to the reliability and effectiveness of alarm systems and features that may be added to improved system performance may be considered as beneficial in reducing risk in the event of a fire.

In buildings having a top floor more than 36 m above grade, a voice communication system will be required and there may be similar opportunities for improvements. Similarly, there may be benefits to installing such a system in buildings less than 36 m as part of the mitigating features of the building.

3.7. TYPICAL FIRE PROTECTION DESIGN FEATURES: PASSIVE FIRE PROTECTION

The other form of fire protection features typically used in a building design is passive fire protection. Passive fire protection systems consist of features which are an integral part of the building providing compartmentation to prevent fire spread, and are always present to perform the intended function. This section includes discussion on passive fire protection including structural fire resistance, fire separations, firestopping in fire separations and treatment of concealed spaces.

Building regulations require that key building assemblies exhibit sufficient fire resistance to allow time for occupants to escape, fire-fighters to conduct search and rescue operations and fire suppression activities, and to minimize property losses. The intent is to compartmentalize the structure to limit the spread of fire and smoke, and to ensure structural adequacy to prevent or delay collapse.

In the early stages of a fire or when the sprinkler system activates and controls the fire, the fire resistance of the compartmentation is of little significance. However, the fire resistance becomes increasingly important if the fire is able to grow and approaches full-room involvement, also known as flashover. With respect to life safety, fire resistance is essential in tall buildings where a fire could grow large before all occupants are able to escape.

3.7.1. DESIGNING FOR STRUCTURAL FIRE RESISTANCE

Mass timber elements such as solid sawn timbers, glued-laminated timber (glulam), cross-laminated timber (CLT), and structural composite lumber (SCL) can provide excellent fire resistance. This is due to the inherent nature of thick timber members to char slowly when exposed to fire, allowing mass timber construction to maintain significant structural resistance for extended durations when exposed to fire.

In buildings of 7 storeys or more, Division B of OBC (Acceptable Solutions) requires floors to be fire separations with a fire-resistance rating of not less than 2 hours. Loadbearing walls, columns, and beams that support the floor assemblies must also have a fire-resistance rating of 2 hours. Therefore, an Alternative Solution for tall wood buildings will likely require the mass timber structure to have at least a 2-hour fire-resistance rating. The provision of fire resistance is just one aspect of the fire-safe design strategy for reducing the risk to the lives of occupants and fire-fighters, and for reducing the risk of property loss.

Subsection 3.1.7. of OBC specifies that, for an assembly or a structural member that is required to have a fire-resistance rating, it shall be determined according to the standard test method CAN/ULC-S101, “Fire Endurance Tests of Building Construction and Materials.” The standard test provides a relative measure of an assembly’s fire resistance. While the results of the test are reported as a fire-resistance rating of a specific number of minutes or hours (e.g. 45 minutes, 1 hour, 2 hours), this rating does not suggest the assembly will last the same amount of time in a real fire. In a real fire, the time to failure of the assembly may be greater or less than that in the standard test since the fire exposure will undoubtedly be different.

The test standard requires a wall or floor assembly, or a single structural element such as a column or beam, to be exposed to a severe fire in which the temperature of the fire gases increases over time following a specified temperature-time curve. With respect to combustible systems, the test standard also requires the member or assembly be loaded if it is to be used as a loadbearing element (not all noncombustible loadbearing systems are required to be tested under load). The fire-resistance test is designed to evaluate an assembly as a system, as opposed to individual components.

Criteria for testing and acceptance in this test method differ according to assembly type and/or structural member type. The assigned fire-resistance rating for an assembly or structural member is the length of time it can withstand the standard fire exposure, defined by a temperature-versus-time relationship, while still satisfying the following criteria:

- The floor assembly, load-bearing wall assembly, beam or column tested shall sustain the applied load for the duration of the test;
- The assembly shall prevent the passage of flame or gases hot enough to ignite cotton pads;
- The assembly shall prevent the average temperature measured on the unexposed surface of the wall or floor assembly to exceed 140°C above its initial temperature and prevent the temperature rise on the unexposed surface at any individual point greater than 180°C;
- For walls that must have a fire-resistance rating of one hour or more, the assembly shall prevent the passage of a hose stream through the assembly.

The first criterion is intended to limit the probability of structural collapse during evacuation of occupants or during firefighting operations. The second and third criteria are intended to limit fire spread from the compartment of fire origin to an adjacent compartment and are applied to wall and floor assemblies. The fourth criterion is intended to ensure a minimum resistance to the cooling and erosion effects of a hose stream that might be directed at the wall during firefighting. For the hose stream test, an assembly is first tested to determine its fire-resistance rating, then a duplicate assembly is then tested for half the fire-resistance rating time, to a maximum of one hour, before being subjected to a hose stream.

There are three main sources of information likely to be used by the fire safety engineer designing tall wood buildings for fire resistance. The first option is to base the design on a standard fire-resistance test which has been conducted on a replicate of the beam, column, wall or floor assembly that is required to be rated. The second option is to use the available methods in the MMAH Supplementary Standard SB-2 “Fire Performance Ratings”, which includes criteria for solid wood walls and floors up to 1.5 hours (SB-2, Section 2.4.) and the T.T. Lie equations for glulam beams in bending or columns in compression (SB-2, Section 2.11.). The third option, which is not cited in Part 3 of Division B,OBC but is standardized in the Canadian wood design standard, CSA O86 – Annex B (CSA, 2016), provides for the calculation of the fire-resistance ratings of several types of wood beams and columns, and CLT wall and floor assemblies. The three methods are discussed in more detail below.

Standard Fire-Resistance Testing

As previously stated, having a replicate of an assembly tested to the standard test method, CAN/ULC-S101, is one method to demonstrate that a particular assembly has a particular fire-resistance rating. The Canadian wood industry and CLT manufacturers have conducted a number of tests, (Osborne et al., 2012) (Craft and Van Zeeland, 2017) over the last decade. A photo of a CLT floor assembly fire-resistance test is shown in Figure 3.4. If a designer chooses to use one of the assemblies tested, such as a CLT floor assembly, the fire-resistance test report could be used to support the fire-resistance rating of the floor assembly. However, if changes to the assembly are required, such as to meet acoustic requirements, then it may be difficult to just use the fire test report. An engineering judgement would have to be made to determine if the deviations would negatively affect the fire-resistance rating of the assembly.

Figure 3.4. Photo taken at the end of a fire-resistance test on a 3-ply CLT floor assembly protected with gypsum board.

It is rare that fire-resistance testing can be completed for a specific project due to the high costs of conducting fire-resistance testing, particularly when one considers there may be many different components in a single project that would need to be tested (e.g. wall assemblies, floor assemblies, beams, columns, etc.). For this reason, unless a manufacturer would like to test a system which they can use in many projects, it likely is not economical to conduct fire-resistance testing on a project-by-project basis.

MMAH Supplementary Standard SB-2

As mentioned previously, there are two sections in Supplementary Standard SB-2 of OBC which provide a means to determine or assign a fire-resistance rating to solid wood walls and floors or to calculate the fire-resistance rating of glued laminated beams and columns.

Section 2.4. of Supplementary Standard SB-2 of OBC provides minimum thicknesses of heavy timber walls, floors and roofs for fire-resistance ratings ranging from 30 to 90 minutes. The fire-resistance ratings provided do not account for any loading scenario less than full-design load. This method tends to be very conservative when used for engineered wood products such as glue-laminated timber decking, cross-laminated timber panels or cross-laminated veneer lumber. This is because the newer engineered wood products are made into panels and, therefore, do not have nearly as many joints. These joints, between large panels, can be detailed to provide better fire resistance than that achieved by nailing dimensioned lumber (i.e. 2x4s or 2x6s) together, which is the basis for the solid wood assemblies in SB-2.

A 15 minute increase in the fire-resistance rating is also permitted by Section 2.4. of SB-2 when the described solid wood elements are covered by a layer of 12.7 mm thick gypsum board.

In any case, the fire-resistance ratings which can be achieved using this method are not sufficient to provide the 2-hour fire-resistance rating likely required for a tall mass timber building. The method could be used to develop the fire-resistance rating of a non-loadbearing fire separation, such as between suites where a 1-hour fire-resistance rating may be required.

Section 2.11. of Supplementary Standard SB-2 of OBC outlines a method for calculating the fire-resistance rating for glulam members based on research conducted in the 1970’s by T.T. Lie at the National Research Council of Canada (Lie, 1977). Lie derived a series of equations using an average charring rate of 0.6 mm/min, and a k factor of 0.33 that accounts for the ratio of design strength to ultimate strength (based on a safety factor of 3). He then applied a reduction to the remaining cross-section strength and stiffness of 20 percent.

The resulting equations allow for a straightforward calculation of fire resistance of glulam beams and columns as a function of member dimensions and load factor (stress ratio). However, the method is not able to account for design considerations such as eccentricity on columns, or composite action between beams and floors. The method described next in CSA O86 allows for a more complete and accurate design of the structure for fire resistance.

CSA O86-14 (2016) – Update 1, Annex B

In the 2014 edition of CSA O86 (CSA, 2014), a new informative Annex was added titled “Annex B – Fire resistance of large cross-section wood elements.” This annex was added to the wood design standard to bring it up-to-date with wood design standards used around the world, including the US (NDS, 2015), Europe (CEN, 2004), New Zealand, Australia, China and Japan. The design methodology incorporated in Annex B is the same as that used in the countries and continents listed above, namely the effective cross-section method. It is expected that this will typically be the methodology that will be used to complete the structural fire-resistance design of tall wood buildings in Ontario.

The effective cross-section method accounts for the reduction in cross-section of the timber element with fire exposure, while taking advantage of the fact that the strength and stiffness of the relatively cool interior section remain largely unchanged. An effective linear charring rate accompanied by a zero-strength layer, which accounts for the loss of strength of the heated wood beyond the char front, is used to calculate the effective cross-section. The material close to the char line will be exposed to increased temperatures and will experience a change in material properties, therefore, a portion of the heated zone is assigned zero strength while the member resistance of the remaining cross-section is determined using the average strength and stiffness. The illustration in Figure 3.5 shows how the cross-section is separated into the different zones. The point in time when the member resistance becomes equal to the applied load, in the case of a fire-resistance test, or the specified load in the case of design, the fire-resistance rating of the member has been reached.

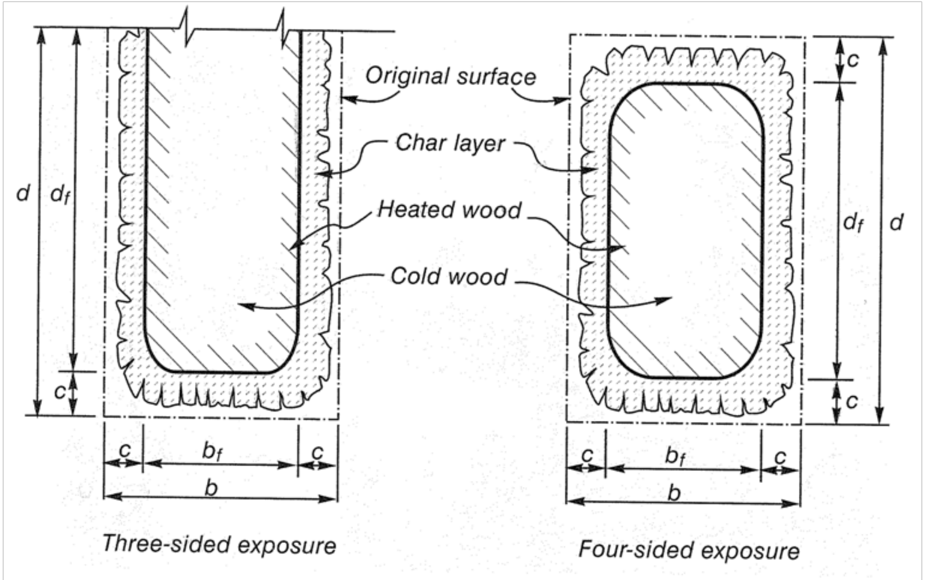

Figure 3.5. Illustration of wood beam or column exposed to fire with the char layer, heated wood layer and cool interior section indicated (Buchanan, 2001).

Calculating fire resistance of mass timber elements can be relatively simple because of the essentially constant rate of charring which occurs when the timber element is subjected to the standard fire exposure. This relatively constant rate of charring occurs even though the temperature in the test furnace is constantly increasing. This is due to the fact that the char layer slowly increases in thickness as the wood chars, insulating the remaining wood cross-section due to its low density and thermal conductivity. Charred wood is assumed to no longer provide any strength and stiffness, therefore, the remaining cross-section must be capable of carrying the load.

Since the design methodology contained in CSA O86, Annex B is not referenced in Part 3 of Division B of the 2012 OBC, an Alternative Solution may be required to seek acceptance of the method. With respect to using Annex B to calculate the fire resistance of CLT, the justification for the use of the method can be found in the paper by Craft and Van Zeeland which compares the calculated fire resistance following the standard to 12 full-scale fire-resistance tests conducted on CLT wall and floor assemblies (Craft and Van Zeeland, 2017).

Scope of CSA O86 Annex B

The method prescribed in Annex B is simply a means to predict the fire-resistance rating result of a mass timber element or assembly when tested in accordance with the standard CAN/ULC-S101. Since CSA O86 is a structural standard, the scope of Annex B is limited to determining the structural fire resistance. Therefore, if an engineer is designing a floor or wall assembly, the engineer must use other means to ensure the assembly meets the compartmentation aspect of fire resistance, such as the integrity and insulation failure criteria specified in the fire test standard as discussed in the next section. As the building code recognizes, large cross-section wood members have a degree of inherent fire resistance. In order to ensure that the members for which Annex B is being used to calculate the fire resistance possess these inherent fire resistance properties, minimum sizes are typically placed on the members.

Since testing to CAN/ULC-S101 is conducted under a load intended to represent the specified load on that member or assembly, the same approach is used in Annex B. The specified loads (i.e. D + L) are used in comparing to the structural resistance of the member after a set period of fire exposure in order to determine whether the structural resistance at that time is greater than the specified loads impacting the structural element or assembly.

A number of engineered wood products are included within the scope of Annex B, including solid-sawn timber, glued-laminated timber (glulam), structural composite lumber (SCL), and, most recently in the 2016 update, cross-laminated timber (CLT).

Charring Rates in CSA O86 Annex B

Charring rates for the different products to which Annex B applies when tested to CAN/ULC-S101 are found in Table 3.4. The one-dimensional charring rate, β_o, for standard fire exposure represents the rate expected for thermally thick slabs of wood; β_n is the notional (effective) charring rate which is an increased value to offset the loss of cross-section at corners, the opening of fissures and in the case of CLT, the fall-off of charred layers.

Product	βo mm/min	βn mm/min
Timber and plank decking	0.65	0.8
Glue-laminated timber	0.65	0.7
Structural Composite Lumber	0.65	0.7
Cross-laminated timber	0.65	0.8

Table 3.4. Design charring rates of timber products as specified in Annex B, CSA O86 (CSA, 2016).

It is not surprising that the char rates are all relatively constant between wood products since the underlining chemistry and heat transfer in the different wood products is similar. Additionally, the engineered wood products listed above all have requirements in their respective product standards for heat durability of the adhesives.

Gypsum Board Protection

The fire resistance of mass timber elements can be increased by protecting the timber with gypsum board. The contribution to the standard fire-resistance rating of the gypsum board protection can be accounted for by adding a fixed time to the calculated fire-resistance rating of the exposed timber member. The times included in Table 3.5 below are derived based on research conducted at the US Forest Products Lab by White (White, 2009) and based on the testing conducted on CLT by FPInnovations and the National Research Council (Osborne *et al*., 2012). Therefore, the fire resistance of any large cross-section timber beam, column, floor or wall can be increased by adding one or two layers of Type X fire-rated gypsum board.

Gypsum Board Protection	Additional Fire Resistance (min)
One layer of 12.7mm Type X gypsum board	15
One layer of 15.9mm Type X gypsum board	30
Two layers of 12.7mm Type X gypsum board (applies to CLT only)	60
Two layers of 15.9mm Type X gypsum board	60

Table 3.5. Additional fire resistance achieved with gypsum board protection as specified in Annex B, CSA O86 (CSA, 2016).

Connections

Connections are a critical component of any structure, whether or not the structure is exposed to a fire. Annex B takes the conservative approach that no steel components of connections, that require a fire-resistance rating (for those supporting gravity loads) be exposed, or be located within the depth of char. Since the char depth is commonly (and conservatively) assumed to occur at the 300°C isotherm, this ensures the steel temperature does not approach the commonly used temperature of 550°C that is approximately when the steel has lost half of its strength. It also ensures that the steel does not accelerate the charring around the steel components, which could happen if the steel is less protected. Some connection manufacturers have undertaken fire-resistance testing to demonstrate performance of particular proprietary connection types, in which case the design of the connections should follow the information of the tested system rather than needing to follow the conservative approach taken by the CSA O86 standard.

Additional information on the fire resistance of connections, along with methods for calculating the fire resistance when the connection includes exposed fasteners can be found in the Fire Safety in Timber Buildings technical guideline (SP Tratek, 2010).

3.7.2. DESIGNING FOR COMPARTMENTATION

A fire compartment can be compared to a box designed to contain a fire for a limited time within a building. A fire compartment is defined by OBC as “an enclosed space in a building that is separated from all other parts of the building by enclosing construction providing a fire separation that may be required to have a fire-resistance rating.” Rated fire separations such as building floors and interior walls are, therefore, basic elements of fire compartmentation. Fire separations are designed to resist the effects of fire for a given time based on the expected fire severity in a compartment. To achieve its purpose of containing the fire by its construction, a fire-rated fire separation generally must have both fire resistance and continuity. However, there are instances where an assembly may need to be built as a fire separation only to restrict the passage of smoke and fire but may not need a fire-resistance rating. In such cases the fire separation need only remain in place long enough to ensure that occupants can leave the area, or until a sprinkler system is activated that will control and likely suppress the fire.

As mentioned previously, mass timber, in addition to providing structural fire resistance, can perform very well with respect to compartmentation. For instance, the very first set of CLT intermediate-scale fire-resistance tests conducted in North America had a 3-ply CLT wall panel (nonloadbearing) providing over 2-hours of fire resistance (the photo in Figure 3.6 was taken during the fire-resistance test after 2 hours and 5 minutes of standard fire exposure) (Craft *et al.*, 2011). However, in most cases, CLT and other mass timber wall assemblies will be loadbearing and floor assemblies are always loadbearing. Therefore, if a CLT or other mass timber assembly has been designed for structural fire resistance (which usually requires even thicker members than nonloadbearing assemblies to meet the same fire resistance level), then the assembly will no doubt satisfy the insulation criteria of fire resistance. The only remaining concern for a CLT or other solid wood panel system, after it has been verified that it meets the structural fire resistance required, then is whether the joints between panels will satisfy the integrity criterion of fire resistance.

Figure 3.6. Photo during fire-resistance test on 3-ply CLT wall panel after 2-hours and 5-minutes of fire exposure with the unexposed surface still relatively cool.

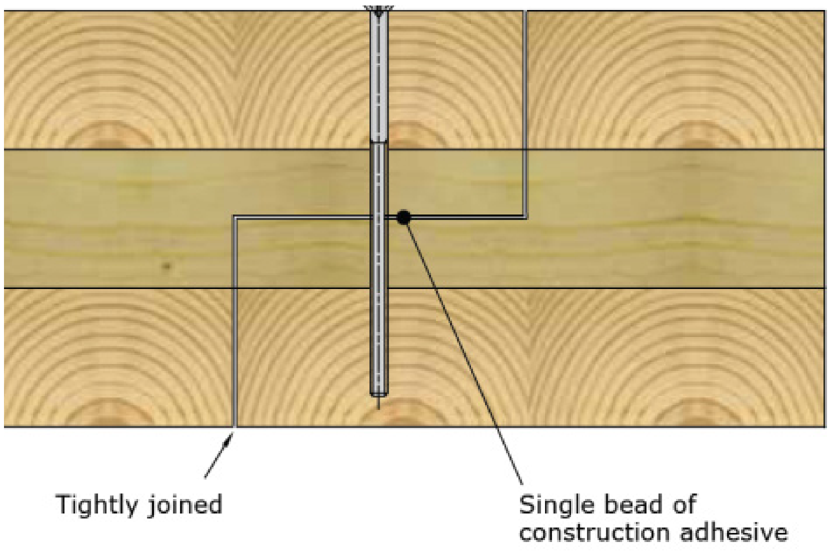

Figure 3.7. Illustration of half-lap joint detail between two CLT panels (FPInnovations, 2011)

After a large number of tests on CLT wall and floor assemblies (Osborne *et al.*, 2012)(Craft *et al.*, 2011)(Craft and Van Zeeland, 2017) and on a number of different CLT joint configurations, it is apparent that as long as the joint between panels or between assemblies is sealed from air movement and the seal is protect from the fire exposure (e.g. half-lap joint as shown in Figure 3.7), the joint will perform well when exposed to fire and will not allow integrity failure to occur.

Another way to ensure integrity failure does not occur on a wall assembly is to have fire-rated gypsum board installed on both sides of the wall assembly. Similarly, for floor assemblies, a concrete topping or other continuous topping which provides an air seal and is protected from the fire will ensure that integrity failure does not occur.

Sealing of joints between CLT or other solid wood panels, such as half-lap joints, or the use of splines, is often achieved with a caulking product such as construction adhesive or firestop caulking applied liberally enough to ensure any gap between mating surfaces within the joint is bridged. Additionally, tape products which provide an air seal have also been successfully tested and used.

Further guidance on the design of joints between solid wood panels and between solid wood assemblies can be found in the CLT Handbook (FPInnovations, 2011).

OBC requires that all fire separations be constructed as continuous elements. However, floors and interior walls of a building must incorporate openings to allow for the passage of people and building services. It is critical that these openings be protected so that the fire separation and the desired compartmentation are maintained. The most vulnerable points of fire separations are openings such as doorways and holes for the passage of building services. It is essential that these openings be protected with closures such as doors, shutters, fire dampers, wired glass or glass blocks and firestop systems (as required per OBC Division B, Sentence 3.1.8.1.(2). Such devices or assemblies typically are rated for fire exposure in accordance with specific test standards, depending on the type of closure.

Lastly, in some special cases, extra care needs to be taken in detailing solid wood wall and floor assemblies, such as CLT assemblies, and their joints to ensure smoke is not able to travel through the assembly. For example, as briefly discussed in Section 3.4.2 above on OBC “high buildings” requirements, in the case of scissor stairs where the two exit stairs are separated by the stairs themselves, it is important to ensure that the two stairs are fully sealed to prevent smoke from one exit stair from entering the other. For example, when two CLT panels meet, the outside ply will have cracks open between individual strips of lumber as the wood dries and shrinks. These gaps that open between the individual strips in the outer lamination of the panel can provide a path for smoke movement from one space to another since any other wall or floor assembly which meets the laminations at any angle other than parallel will result in small gaps which can allow air movement though the joint. The following joint shown in Figure 3.8 is an example where air/smoke leakage could occur at the intersection of the two panels. These same possible leakage paths are also an issue for building envelope engineers.

3.7.3. FIRESTOPPING

Fire stops and fire blocks are similarly named but have different roles in preventing fire spread within a building. In both cases, the objective is to prevent or reduce the likelihood of fire spread. Fire stops are discussed in this section while fire blocks are discussed in the following section.

Fire stops help aim to maintain the continuity of fire compartmentation around fire separations or around items that wholly or partially penetrate fire separations.
OBC provides the following definition of fire stop:

> Fire stop is *“a system consisting of a material, component and means of support used to fill gaps between fire separations or between fire separations and other assemblies, or used around items that wholly or partially penetrate a fire separation”.*

Article 3.1.9.1. of Division B of OBC specifies that, except as otherwise required, penetrations of fire separations or a membrane forming part of an assembly required to have a fire-resistance rating shall be sealed by a fire stop that when tested to CAN/ULC-S115, “Standard Method of Tests of Firestop Systems” has an F rating not less than the fire-protection rating required for closures in the fire separation. The test method CAN/ULC-S115 tests the fire stop system by exposing the system installed in a representative assembly (e.g. CLT wall sheathed with Type X gypsum board) and subjected to the standard temperature-time exposure, which is the same as that used in the CAN/ULC-S101 fire-resistance standard. Below are the two types of ratings based on testing to CAN/ULC-S115 which are cited in the 2012 OBC.

- **F** rating is based on flame occurrence on the unexposed surface.
- **FT** rating is based upon a temperature rise criterion and flame occurrence on the unexposed surface.

There are a number of firestop systems that may be required in a building. Below is a list of the most common examples:

- Through-penetration of fire separation: a through-penetration exists when a penetrating item, such as a pipe, passes entirely through the fire separation. In this case, listed fire stop systems will specify not just the fire stop material(s) or product(s) and the configuration, but also the construction of the fire separation and the penetrating item.
- Membrane-penetration of fire separation: a membrane-penetration exists when a penetrating item, such as a pipe or electrical box, passes through only one membrane of a fire separation that is made up of multiple materials. A common example is a light-frame wood wall assembly in which the services are run in the cavity of the wall and exit where needed (e.g. wall switch). Similar to through-penetrations, listed fire stop systems will specify the fire stop material(s) or product(s) and the configurations, as well as the construction of the fire separation and the penetrating item.
- Construction joint: a construction joint exists between two adjacent fire separations or components of fire separations and are typically linear. These locations may include joints between a ceiling and wall, roof and wall, wall and floor, two walls, two floors or two ceilings.
- Building perimeter joint: the building perimeter joint is the space between a fire-rated floor assembly and a fire-rated or non-fire-rated curtain wall. Fire stop systems for building perimeter joints are also commonly called “perimeter fire barrier systems.” Test method CAN/ULC-S115 can be used between a fire-rated exterior wall and a fire-rated floor assembly.

Fire Stop Systems

Currently, only one generic fire stop solution is available to a designer in the 2012 OBC which permits penetrations of a fire separation or of a membrane forming part of an assembly required to have a fire-resistance rating to be “tightly fitted” as specified in Clause 3.1.9.1.(1)(b) of Division B of OBC. The corresponding appendix note suggest “cast in place” as one means to satisfy the requirement such as a service penetration through a concrete slab or wall. Therefore, if a concrete topping is to be applied over a mass timber floor system, it is possible that if the topping is poured after the particular penetrations are installed, they could be considered to be cast in place and not require further treatment.

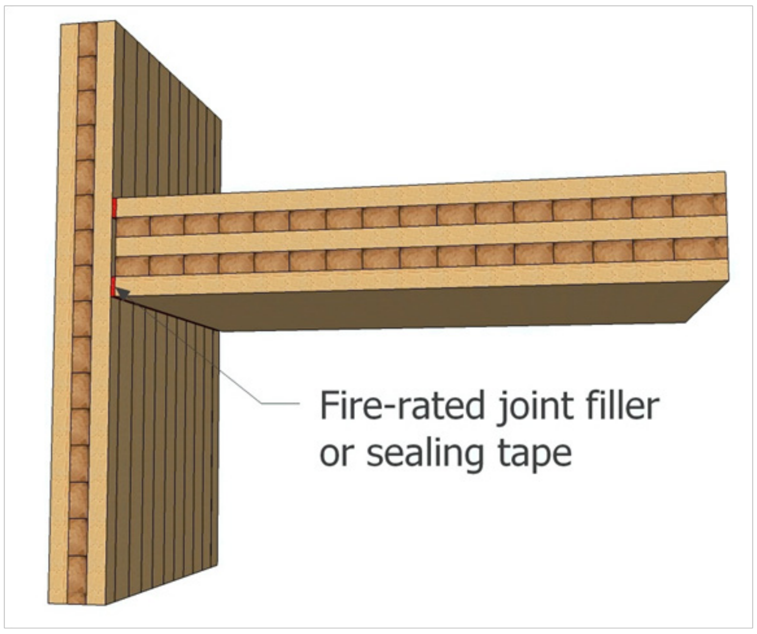

Figure 3.8. Illustration of joint between CLT panels where air leakage can result due to shrinkage of individual strips of lumber in the outer lamination of wall panel [From Figure 19 of Chapter 5 from FPInnovations Technical *Guide for the Design and Construction of Tall Wood Buildings in Canada*].

A multitude of fire stop system tests have been conducted on behalf of fire stop manufacturers at accredited fire test laboratories. In many cases, the results are available through listing services provided by third-party certification organizations, such as:

- Underwriters’ Laboratories of Canada
- Intertek Testing Services
- QAI Laboratories
- Underwriters’ Laboratories Incorporated

However, there are few, if any, listed firestop systems for installation in solid wood walls and floors at this time. Testing conducted for the Wood Innovation Design Centre mass timber building built in Prince George, BC found that metallic pipe penetrations could be suitability firestopped using traditional methods provided the metallic pipe was centered in the hole as opposed to resting against one edge, which is the common method of installation in concrete slabs. Some pictures of those tests are shown in Figures 3.9 and 3.10.

The firestop solution used in the wall and floor tests depicted in Figures 3.9 and 3.10 consisted of centering the metallic pipe in the center of the bored hole, stuffing the annular space with mineral wool insulation and filling the annular space with 25 mm of firestop caulking on both sides of the assembly (for both walls and floors). The results demonstrated that the firestop solution installed in 3-ply CLT panels in either the vertical or horizontal orientation resulted in a 90-minute F-rating which is sufficient for installation in a 2-hour fire-resistance rated assembly (with some exceptions noted in OBC). Installation in thicker wall and floor assemblies (e.g. 5 or 7-ply CLT) would increase the performance of the firestop system tested.

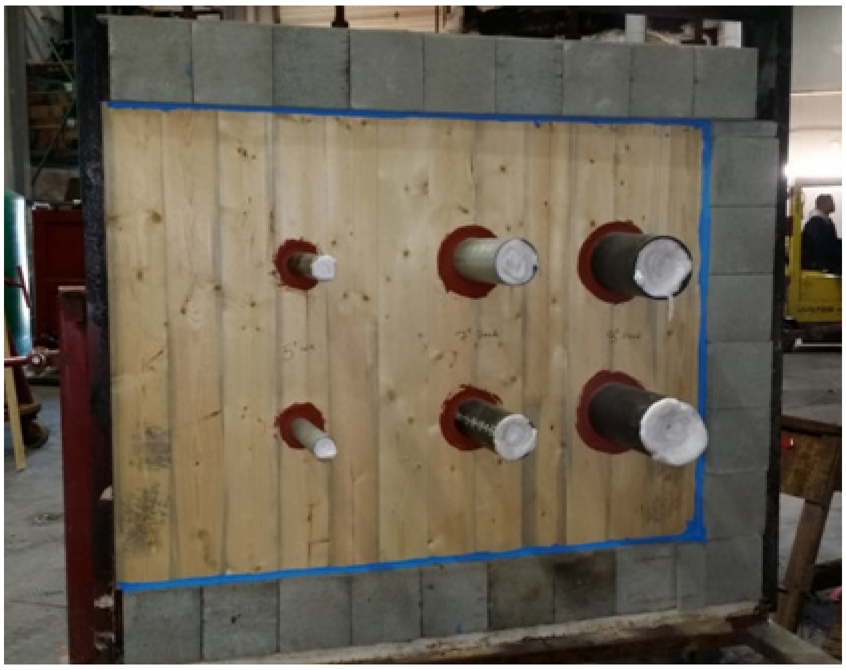

Figure 3.9. Firestop test assembly (exposed side) prior to test consisting of CLT wall assembly with 6 metal pipes of different materials and sizes penetrating the assembly

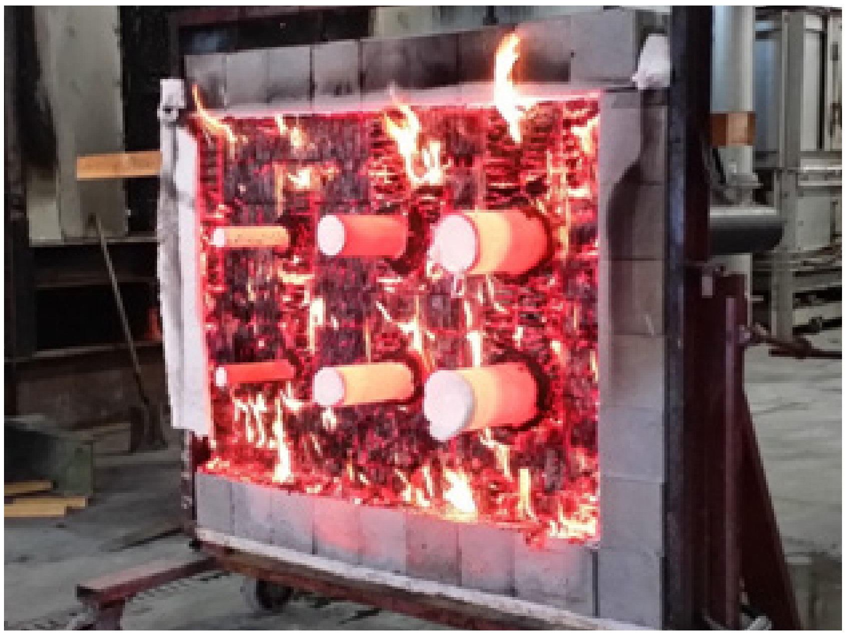

Figure 3.10. Firestop test assembly (exposed side) after 90-minutes of fire test exposure.

As more mass timber buildings of all sizes are designed and constructed, manufacturers of firestop systems will likely develop, test and list more firestopping solutions for solid wood assembly applications. And, since it is impossible to test designs for all possible firestopping scenarios, firestop manufacturers often work with designers and engineers to develop specific solutions appropriate to particular situations in specific building projects.

3.7.4. CONCEALED SPACES AND FIRE BLOCKS

Fire blocks are used to restrict the size of concealed spaces and to separate one concealed space from to another.

OBC provides the following definition of Fire Block:

> Fire block is *"a material, component or system that restricts the spread of fire within a concealed space or from a concealed space to an adjacent space".*

Virtually all buildings will have concealed spaces, which are non-occupied spaces/voids created by building construction that may or not be accessible. Examples of concealed spaces may include attics, spaces between double walls or above suspended ceilings, or vertical chases used to run services. The fire safety concern related to concealed spaces, and particularly combustible concealed spaces, relate the ability of a fire to start in or spread via a concealed space away from detection or sprinkler protection. Also, vertical concealed spaces can see rapid flame spread due to a chimney effect occurring. Therefore, steps to ensure the concealed spaces are sprinklered or have limited combustible components in them help minimize the chances a fire will start or spread in them.

Generally, it is advisable at the early stages of designing tall wood buildings to avoid or minimize design details which will introduce concealed spaces. This is because with a combustible structure, many of the voids will be consider to be combustible concealed spaces (i.e. concealed spaces with one or more combustible surfaces). Since tall wood buildings are sprinklered to NFPA 13, combustible concealed spaces are required by that standard to be sprinklered, lined, or filled, as described below.

NFPA 13

NFPA 13 (NFPA, 2013) requires combustible concealed spaces to be sprinklered, with some exceptions. However, due to economical or access reasons, it is advantageous to address the concealed spaces with other means than sprinklering. NFPA provides a number of exceptions where combustible concealed spaces do not require sprinklers by using alternative methods to deal with the hazard.

One option provided in NFPA 13 to address an unavoidable concealed space such as between a CLT floor slab and a dropped ceiling below is to protect the combustible CLT surface with a product with a flame-spread rating of 25 or less when tested to ASTM E84 (2010) (for an extended 20-minute test). A common example would be to line the combustible surfaces in the concealed space with gypsum board or a noncombustible insulation board. This type of solution can have the added benefit that the gypsum board or insulation board will likely also contribute to the fire-resistance of the floor assembly. Alternatively, another option which may be considered is to use a spray-applied fire resistive material or an intumescent coating which would similarly reduce the flame spread rating of the interior surfaces of the concealed space to 25 or less.

Another option provided to avoid having to sprinkler a combustible concealed space is to fill the space with a noncombustible insulation. In such cases, an air gap of 50 mm or less is permitted at the top of the space.

If the space formed by a ceiling attached to a solid wood floor assembly is less than 150 mm, the space is not required to be sprinklered. However, fire blocking is required to separate the spaces into allowable volumes.

A number of other more specific exceptions are included in NFPA 13-2013 under Section 8.15.1 Concealed Spaces in lieu of sprinklering combustible concealed spaces.

OBC requires fire blocks at regular intervals in all concealed spaces. Even in situations where it is not explicitly required, fire blocking is a good practice in both combustible and noncombustible construction. Below is a summary of the locations where fire blocks are required in buildings which fall under Part 3 of Division B of OBC:

- Fire blocks in concealed spaces in walls are required at every floor level and at every ceiling level where the ceiling forms part of an assembly required to have a fire-resistance rating. Also, fire blocks are required in a wall assembly so that the maximum horizontal dimension of a concealed space is not more than 20 m and the maximum vertical dimension is not more than 3 m. Fire blocks are not required in walls when the void is filled with insulation or the exposed construction materials and any insulation within the concealed space are noncombustible. Additional exceptions can be found in OBC, Division B, under Article 3.1.11.2.
- In a building required to be of noncombustible construction, wood can be used in a number of locations, as outlined in Section 3.4.1 of this technical resource. When a concealed space is created by wood elements supporting a ceiling with the exposed concealed space surface(s) having a flame-spread rating greater than 25, the created concealed space must be fitted with fire blocks between wood nailing elements so that the concealed spaces are not more than 2 m^2. Similarly, when concealed spaces are created by wood members supporting a floating floor in a building required to be of noncombustible construction, the spaces must be fire blocked so that the areas are not more than 10 m^2 in area.
- Fire blocks are required between concealed vertical and horizontal spaces such as that created by coved ceilings, drop ceilings and soffits when the flame-spread rating of the exposed construction materials in the concealed space is greater than 25.

Fire Block Materials

Fire block materials restrict the passage of flames, hot gases and smoke. The following materials can be used as fire blocks in Part 3 of Division B of OBC in buildings required to be of noncombustible construction:

- gypsum board no less than 12.7 mm thick and sheet steel no less than 0.38 mm thick, provided all joints have continuous support;
- wood nailing elements attached directly to or set into a continuous noncombustible backing for the attachment of interior finishes, provided the concealed space created by the wood elements is no more than 50 mm thick; and,
- in some specific situations (e.g. in a combustible roof system or in a raised platform permitted as described in Section 3.4.1. of this technical resource on wood use in noncombustible buildings), solid lumber not less than 38 mm thick; phenolic bonded plywood, waferboard, or strandboard not less than 12.5 mm thick with joints supported; or two thicknesses of lumber, each not less than 19 mm thick with joints staggered, where the width or height of the concealed space requires more than one piece of lumber not less than 38 mm thick to block off the space.

Where the generic fire block materials listed above are used, any penetrations must be sealed using a fire stop.

Alternatively, other materials may be used if it can be demonstrated that they can remain in place and prevent the passage of flames for no less than 15 minutes when subjected to the standard fire exposure in CAN/ULC-S101, “Fire Endurance Tests of Building Construction and Materials.”

3.7.5. EXTERIOR CLADDING

The exterior cladding is regulated in OBC in order to control the risk of exterior fire spread, whether the fire starts on the exterior of the building or the interior and vents to the exterior. With respect to tall buildings, OBC Acceptable Solutions in Division B require any building over 6 storeys be constructed with noncombustible cladding. This is in contrast to the model NBCC (Div. B, Sentence 3.1.5.1.(2)), which recognizes the test method CAN/ULC-S134 (2013) as a suitable means to qualify an exterior wall assembly for use on tall buildings that are sprinklered. It should also be recognized that the recognition in the NBCC of the test method also provides a means to include combustible components in exterior non-loadbearing wall assemblies.

Therefore, it is expected that any tall wood buildings constructed in Ontario will have noncombustible cladding and noncombustible exterior wall components, otherwise the Alternative Solution will also be required to demonstrate equivalence of the exterior wall to a noncombustible exterior wall which could rely on CAN/ULC-S134 testing or other fire-resistance type exposure testing.

In cases where there are combustible concealed spaces within an exterior wall assembly (for example, a rain gap in rainscreen assemblies), fire blocking may be considered to reduce the likelihood of fire spread within the concealed space.

3.8. FIRE SCENARIOS/DESIGN FIRES

An important goal in fire safety design is to limit the risk that fire can spread from the fire compartment (e.g. a suite) of fire origin to other fire compartments, and to limit the risk that loadbearing assemblies are compromised when exposed to fire. Under the Acceptable Solutions of the Code, fire-resistance ratings are prescribed to accomplish these ends. In performance-based design, compartment boundaries and structural elements must be tailored to perform satisfactorily. To do so, it is important to identify and quantify severe but probable fires that can develop in a compartment and challenge its boundaries and any exposed structural elements. Such fires are referred to as “design fires.” Guidance on developing design fire scenarios and design fires can be found in ISO 16733-1:2015 (ISO, 2015) as well as the SFPE Handbook of Fire Protection Engineering (SFPE, 2008). Establishing design fire scenarios and design fires is a necessary first step in the process of establishing the relative performance of the Alternative and Acceptable Solutions.

It is acknowledged that if a fire remains small or is suppressed by sprinklers or trained staff, the fire will not mount a significant attack on the compartment boundaries (e.g. the walls and floor/ceilings in a suite) or on structural elements. It is only if the fire experiences flashover – that is, the fire progresses from a small, localised fire to involve all combustibles in the compartment – that the compartment’s boundaries and structural elements are challenged. It is therefore the post-flashover fire that typically is of most concern; however, guidance is provided in this document on how to generate a design fire for the entire fire duration; that is, from ignition to flashover to the decay of the fire.

Design fires are commonly expressed in either temperature as a function of time or heat release rate as a function of time. A typical design fire is described by a number of phases and transition points as listed below:

- Early fire growth (pre-flashover fire),
- Time to flashover,
- Fully-developed (post-flashover) fire,
- Duration of the post-flashover fire, and
- Decay phase.

The approach to developing design fires presented herein follows closely that recommended by ISO/TS 16733, “Fire Safety Engineering – Selection of Design Fire Scenarios and Design Fires” (ISO, 2015).

3.8.1. ROOM FIRE DYNAMICS

A fire that starts in a room, suite or compartment may fizzle out on its own (self-extinguish), or may be suppressed by occupants, trained staff or automatic sprinklers. However, if the fire continues to grow, a layer of hot gases (smoke) forms under the ceiling. If the fire grows sufficiently that the temperature in the upper layer reaches levels close to 600°C, heat radiated by the hot layer to all other objects in the room becomes so intense that all exposed combustibles in the room quickly reach their ignition temperatures, causing the room to be entirely engulfed in flame. This transition from localized burning in a room to full-room involvement is referred to as flashover.

Note that since suite boundaries may or may not be required to have a fire-resistance rating based upon the occupancy of the building, the discussion in the following sections will refer to compartments to indicate a fire compartment or suite in a building which is separated from other fire compartments by fire-resistance rated wall and floor/ceilings assemblies.

The rate of fire growth during the pre-flashover phase of a fire impacts on how much time occupants in the fire compartment or suite have available to escape. However, during the pre-flashover stage, a fire does not pose a significant threat of spread through walls or floors/ceilings into neighbouring compartments or suites, or cause structural failure of loadbearing walls or floors/ceilings. On the other hand, fires that proceed to flashover and hence engulf entire rooms within a compartment or engulf the entire compartment are potentially of sufficient intensity to pose a threat of fire spread to neighbouring compartments or cause structural failure.

Figure 3.10 provides a schematic of a typical design fire for a room fire when expressed in terms of the rate of heat release as a function of time. The upper curve represents what happens in the absence of sprinklers: the rate of heat release grows steadily through the pre-flashover phase, levels off following flashover until much of the fuel load has been consumed, and then decreases steadily during the decay phase. The Figure also shows how the rate of heat release is affected when sprinklers activate, which, if that does occur, always does so during the pre-flashover phase since the activation temperature of the sprinkler is well below temperatures associated with flashover.

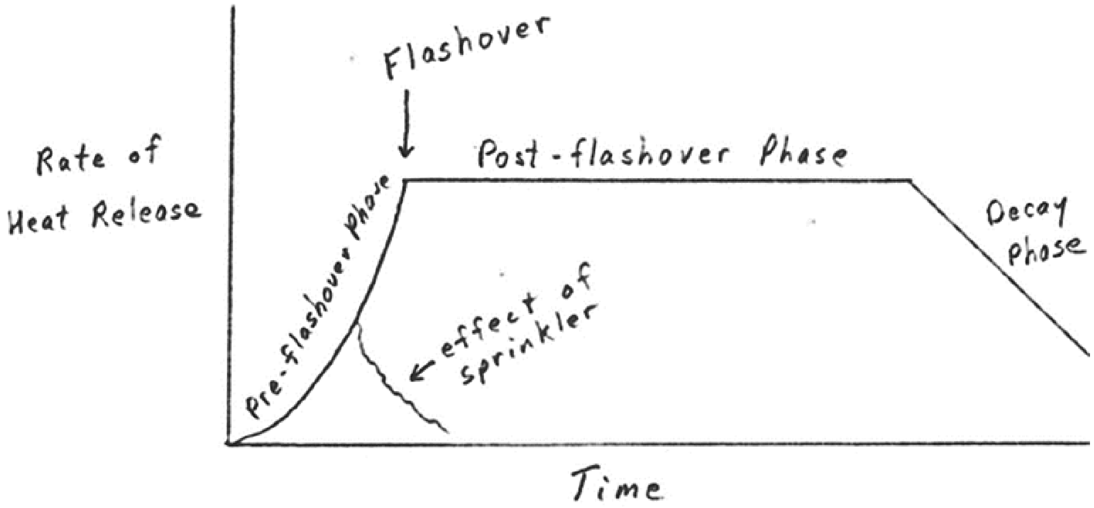

Figure 3.10. Simplified schematic of a design fire for a typical room

3.8.2. COMPARTMENT FIRES IN MASS TIMBER BUILDINGS

In the event of a fire in a tall mass timber building, the first line of defense will typically be an automatic detection and alarm system which is intended to provide early warning to occupants of the threat of fire. As such systems in tall buildings are designed to operate very early in a fire, commonly by detecting smoke, it is highly unlikely that the structure of the building, whether it is of noncombustible materials or mass timber, will have any appreciable effect on early detection or warning. Consequently, an automatic detection and alarm system that meets the specifications for the Acceptable Solution for tall buildings (noncombustible construction), can generally be considered to be equally appropriate for the Alternative Solution (mass timber construction).

The next line of defense in a tall building is the automatic sprinkler system, which is known to exhibit a high level of performance for code-compliant residential and office buildings of noncombustible construction, that is, for the Acceptable Solution. As sprinkler systems are designed to suppress or control fires well before flashover occurs, it can be assumed that a code-compliant sprinkler system in a tall wood building constructed with mass timber (that is an Alternative Solution) would operate just as early and would suppress or control the fire just as quickly as in a similar building of noncombustible construction thereby preventing any contribution of the mass timber to the fire.

Although rare, the fire scenario of most concern would be one in which the sprinkler system does not operate or is unable to prevent flashover; that is, unable to prevent the fire from progressing from a small, localized fire to one involving all exposed combustibles in the room. Following flashover, the compartment's boundaries and structural elements would be challenged. This then would likely be the principal design fire scenario to be evaluated.

Pre-flashover Phase and Time to Flashover

The pre-flashover phase represents the time from the start of a fire until it grows to a point when the entire room becomes fully involved in the fire, at which point flashover is said to have occurred. Typically, this period of fire growth is assumed to be "fuel-surface-controlled," as opposed to "ventilation-controlled", largely because a fire that is fuel-surface-controlled is the more challenging scenario (e.g. this could assume a window is open from the start of the fire or breaks early on).[2] This period of fire growth, without limiting ventilation, is often modeled using a "t-squared" fire (SFPE, 2008). A recent multi-year research project on residential design fires conducted by NRC (Bwalya *et al.*, 2008) reaffirmed the suitability of the ultra-fast t-squared fire to predict the heat release rate of the fire in a residential occupancy during the pre-flashover phase. These tests were conducted in gypsum board lined rooms and during this stage of the fire development, had no contribution from the structure.

Similar to buildings required to be of noncombustible construction, where the amount of usage of the permitted interior finishes of combustible materials may affect the rate of growth and spread of a fire in the pre-flashover stage, the influence of any mass timber during the pre-flashover stage will depend on the quantity of mass timber elements and their degree of encapsulation.

A fire compartment in a mass timber building in which the mass timber elements are fully encapsulated (i.e. there is no exposed wood) even with a single layer of gypsum board will ensure that the structure does not contribute to the pre-flashover fire growth phase. Therefore, the same behaviour during the pre-

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[2] A "fuel-surface-controlled" fire is one in which there is enough oxygen supply entering the room to burn all volatile gases driven off the combustible fuel surfaces so that it is the surface area of exposed combustibles that governs the amount of heat released by the fire. A "ventilation-controlled" fire is one where there is not enough oxygen supply entering the room to burn all volatile gases that are being driven off the combustible fuel surfaces as a result of constricted ventilation conditions. In this case, the amount of heat released in the room by the fire is governed by the supply of oxygen into the room.

flashover stage can be expected between a fully encapsulated mass timber building and a building of noncombustible construction protected with gypsum board.

However, it should be pointed out that if a comparison between the design fires for an Alternative Solution is being made to an Acceptable Solution, OBC Division B does permit many of the walls and some ceilings of a high-rise building to be lined with up to 25 mm of a combustible (e.g. wood) interior finish, as discussed earlier under Interior Finishes in Section 3.4.1 of this technical resource. As well, exposed solid wood partition walls of a minimum of 38 mm thick are also permitted by Division B of OBC to be used in many places in high buildings required to be of noncombustible construction. Therefore, a comparison between what is proposed in the Alternative Solution can be, and will likely be, compared to a compartment lined with wood interior finishes and/or wood partition walls.

To better understand the contribution of wood room linings to fire growth, a number of room corner tests were conducted by researchers in New Zealand (Peel *et al.*, 2016) who found that lining only the ceiling did not lead to flashover in the otherwise standard ISO 9705 (ISO, 2003) room corner test. However, if the walls (but not the ceiling) were lined with wood flashover did occur after the burner had increased to 300 kW. This is an interesting result since high-rise buildings restrict the use of combustible ceiling linings to those with a flame-spread rating less than 25 in the majority of situations while many of the walls are permitted to have a flame-spread rating of 150 which allows for the use of non-fire-retardant-treated wood wall linings up to 25 mm thick.

Additionally, a number of different configurations were tested that could be used to compare the code accepted lining of walls to various other configurations of exposed mass timber in order to rationalize the impact that exposed wood might have on the pre-flashover fire growth.

To have a better understanding of the impact on fire growth in a CLT room, a series of CLT room burn tests were conducted at Carleton University (pictures shown in Figures 3.11 and 3.12).

Figure 3.11. Furnished (bedroom furniture) CLT room constructed for compartment fire test conducted at Carleton University.

Figure 3.12. During fire test on CLT room with bedroom furniture at Carleton University.

Tests conducted with fully-furnished bedrooms and the CLT fully encapsulated led to flashover in 7 – 9 minutes while a fully exposed room (CLT walls and ceiling) reached flashover at 5 minutes (McGregor, 2013). Therefore, an extreme case of fully exposed mass timber walls and ceiling in a small compartment can have an impact on the pre-flashover fire, while lesser degrees of exposed CLT will have less impact.

It is expected that in many cases, it will be possible to demonstrate that the extent of exposed mass timber in a fire compartment will not significantly reduce the time to flashover when compared to the Acceptable Solution.

Of course, it is important to reiterate that in the discussion of a fire growing to a point at which flashover occurs, it has been assumed that the sprinkler system has failed to control the fire.

Fully Developed Post-flashover Fire

A post-flashover fire can be either ventilation controlled (that is, controlled by the size of windows and hence the rate at which air can enter the compartment) or can be controlled by the surface area of exposed fuel (combustibles). In modern buildings where the fuel loads are relatively high, it is typical to assume the fire in this phase will be ventilation-controlled and this is typically the more challenging scenario.

The severity of a fire is often described by the intensity (expressed in terms of heat release rate or temperatures) and duration of the post-flashover phase. It is during this phase of the fire that the exposure to the structure may challenge the fire resistance of the structure.

Again, the influence of mass timber construction during the post-flashover stage will depend on the degree of encapsulation. Full encapsulation (all mass timber surfaces protected) will prevent the structure from becoming involved in the fire during the pre-flashover phase as well as well into the post-flashover phase of the fire. The time at which the encapsulated mass timber begins to contribute to fire severity depends on the thermal protection provided by the encapsulation materials. For instance, fire tests conducted at Carleton University found that the mass timber did not contribute to the fire at all when the CLT was encapsulated with two layers of 12.7 mm type X gypsum board (Medina, 2014). Obviously, the amount of encapsulation required to ensure the mass timber does not contribute to the fire for the full duration of the fire (until burnout) will depend on the initial fuel load of the contents and the ventilation (which is proportional to the area of all unprotected openings). For comparison purposes, it should be noted that two layers of 12.7 mm Type X gypsum board prevented the mass timber from beginning to char until 1-hour into a standard fire-resistance test (Osborne *et al.*, 2012).

Alternatively, some exposed mass timber or encapsulated mass timber with less encapsulation protection will likely allow the mass timber to contribute to the fire severity. In most fires, that are ventilation-controlled, the contribution to fire severity of the mass timber does not significantly change the conditions inside the fire compartment since the temperature is a function of the rate at which oxygen (air) can enter the fire compartment. The contribution of the mass timber can affect the burning that takes place outside of the room, either in the plume exiting a window or fire which spreads into a corridor. The degree to which the mass timber contributes will be a function of how much is exposed or becomes exposed as the encapsulation material allows the heat to penetrate to the wood.

However, the greatest impact the mass timber structure may have will likely occur when the room contents are consumed and the fire would normally enter the decay phase. The time at which this occurs is typically modeled based on the fuel load in the fire compartment. However, if mass timber is exposed, or becomes exposed during the fire, there is a possibility that the fire may continue to burn after the contents have been consumed as a ventilation-controlled fire. Whether the fire is able to enter the decay phase or it keeps burning vigorously will depend on how much exposed mass timber there is at this point as well as its configuration. To better understand this, Carleton University conducted a series of room burn tests in CLT rooms (Medina, 2014). Tests were conducted with bedroom furniture to simulate a residential occupancy. A total of 5 tests were conducted on CLT rooms with varying levels of exposure of the mass timber. The tests ranged from fully encapsulated by 2 layers of 12.7 mm Type X gypsum board, to fully exposed mass timber. The conclusions drawn from the tests were that as long as two walls were exposed, either adjacent to one another or across from one another, the walls would allow the fire to radiate between the two exposed surfaces allowing the fire to continue to burn. However, when only a single wall in the fire compartment was left unprotected, the fire entered the decay phase and the fire decreased in size as expected when the room contents were consumed.

Therefore, based on this, it is clear the mass timber structure can contribute to the fire severity during the post-flashover fire by contributing to the burning outside of the fire compartment, and to the duration of the post-flashover fire phase if there is sufficient exposed mass timber to allow the structure itself to sustain a ventilation-controlled fire. Whether additional burning outside of the fire compartment is considered to be a hazard will depend on the buildings construction and possibly the exterior cladding and window arrangement.

Decay Phase

As discussed under the post-flashover phase, whether the fire in a compartment enters the decay phase will depend on the extent of exposed mass timber when the room contents have been consumed. In the case of no exposed mass timber, or limited exposed mass timber, the NRC research on design fires suggest the fire enters a decay phase during which the heat release rate can be assumed to drop linearly from the post-flashover value to zero over a period of time equal to three times the sum of the time to flashover and the duration of the post-flashover fire (Bwalya *et al*., 2014).

In the case where there is sufficient exposed mass timber when the room contents have been consumed, the fire can continue to burn at a significant and steady intensity. This is only significant in a scenario in which the sprinklers have failed to control the fire and the fire service has not been able to access and fight the fire. The probability associated with such a scenario can be estimated as described in Section 3.9 of this technical resource.

3.8.3. RESEARCH ON COMPARTMENT FIRES IN MASS TIMBER BUILDINGS

In describing the impact of mass timber on the different stages of a compartment fire above, some fire tests have been referenced. However, a comprehensive review of 45 compartment fire tests has recently been completed by SP of Sweden (Brandon and Ostman, 2015)

The fire experiments typically involved a fully-furnished room (such as a bedroom) or a fully-furnished residential suite, with the principal structural elements and fire separations constructed of mass timber encapsulated by fire-rated gypsum board and, most significantly, without sprinklers installed. These tests have demonstrated that 2 layers of 12.7 mm Type X gypsum board provide adequate encapsulation; that is, the encapsulated mass timber would be very unlikely to contribute fuel to the compartment fire. In fact, in most tests the mass timber beneath the gypsum board did not even show signs of charring.

Furthermore, one test conducted in a fully-furnished bedroom constructed with mass timber (CLT) with one wall left unprotected (not encapsulated), the fire behaved much like a fire in a similar room but with all the mass timber encapsulated and actually “self-extinguished” after the room contents were consumed (Medina, 2014).

3.9. RISK ANALYSIS METHODS

Risk analysis is a scientific process that can be used to determine what may happen (unwanted event), how significant are the consequences if the unwanted event occurs, and what is the likelihood that this event will occur. Fire risk analysis focuses on fire events. The end result of fire risk analysis is the fire risk, which is defined as the product of consequences due to fires in a building multiplied by the probability of fires occurring. There are number of methods used to estimate the risks from fires in a building depending on the level of complexity and data available. They can be classified into three groups: qualitative; semi-quantitative and quantitative.

3.9.1. QUALITATIVE METHODS

Qualitative methods do not attempt to perform any calculations to assess risk. They are used to identify the most hazardous events and they are used as screening methods for identifying events that should be used in a quantitative risk analysis. They use techniques such as “what-if analysis”, checklists, event trees and risk matrices. They use terms to characterize identified events, such as high (or low) probability of occurring, and high (or low) consequence.

3.9.2. SEMI-QUANTITATIVE METHODS

Semi-quantitative methods used tools and models to either quantify the consequence of unwanted events or their frequency, but not both. Using these methods, unwanted events may be ranked in terms of frequencies or consequences or based on a defined scoring system. For example, deterministic models may be used to determine the severity and impact of a fire on the occupants of a building or to estimate building damages, without considering the frequency of such a fire occurring.

3.9.3. QUANTITATIVE METHODS

Quantitative methods use computational tools to determine the consequences of unwanted events and their frequency, resulting in an overall fire risk. A number of computer models exist that perform a quantitative risk analysis: FiRECAM (Yung *et al*., 1997) and FIERAsystem (Benichou *et al*., 2005) are models developed by the National Research Council of Canada, and CUrisk (Hadjisophocleous and Fu, 2005) is a risk analysis model developed at Carleton University to calculate the fire risk in mid- and high-rise buildings.

3.9.4. FIRE RISK ANALYSIS PROCESS

The SFPE Engineering Guide: Fire Risk Assessment (SFPE, 2008) provides a recommended process to follow for fire risk analysis and guidance on the selection of appropriate tools and data. The SFPE recommended process is shown in Figure 3.13. The main tasks of risk analysis are the following: identifying the hazards and fire scenarios, determine the frequency of each scenario, and determine the consequence of each scenario. Scenario frequencies can be obtained using tools such as fault trees or event trees, and statistical data on fire frequencies and the reliability of fire protection systems. An example of an event tree is presented in the next section. The consequences of each scenario can be determined in terms of number of injuries and fatalities and property damages. Impact of fires on building occupants can be estimated using computer models to model the fire and the response and evacuation of occupants. A commonly used method to assess the risk to life is to determine the available safe egress time (ASET) using fire modelling tools and the required safe egress time (RSET) using tools to predict the time required for occupants to evacuate the building. The difference between ASET and RSET is the safety margin, which is a performance parameter that can be used to compare different designs. Fire costs include damages to the building and its contents, as well as losses due to loss of use of the building. Damages can be determined using the fire intensity and spread predictions of computer models and the associated costs of the contents and repairs to the building.

In evaluating an Alternative Solution, a comparative analysis is commonly used, in which fire risk analysis is used to calculate the risk of a building that satisfies the prescriptive requirements of OBC, as well as the risk of the proposed Alternative Solution. The proposed design would be acceptable if its risk is lower than the risk of the acceptable design.

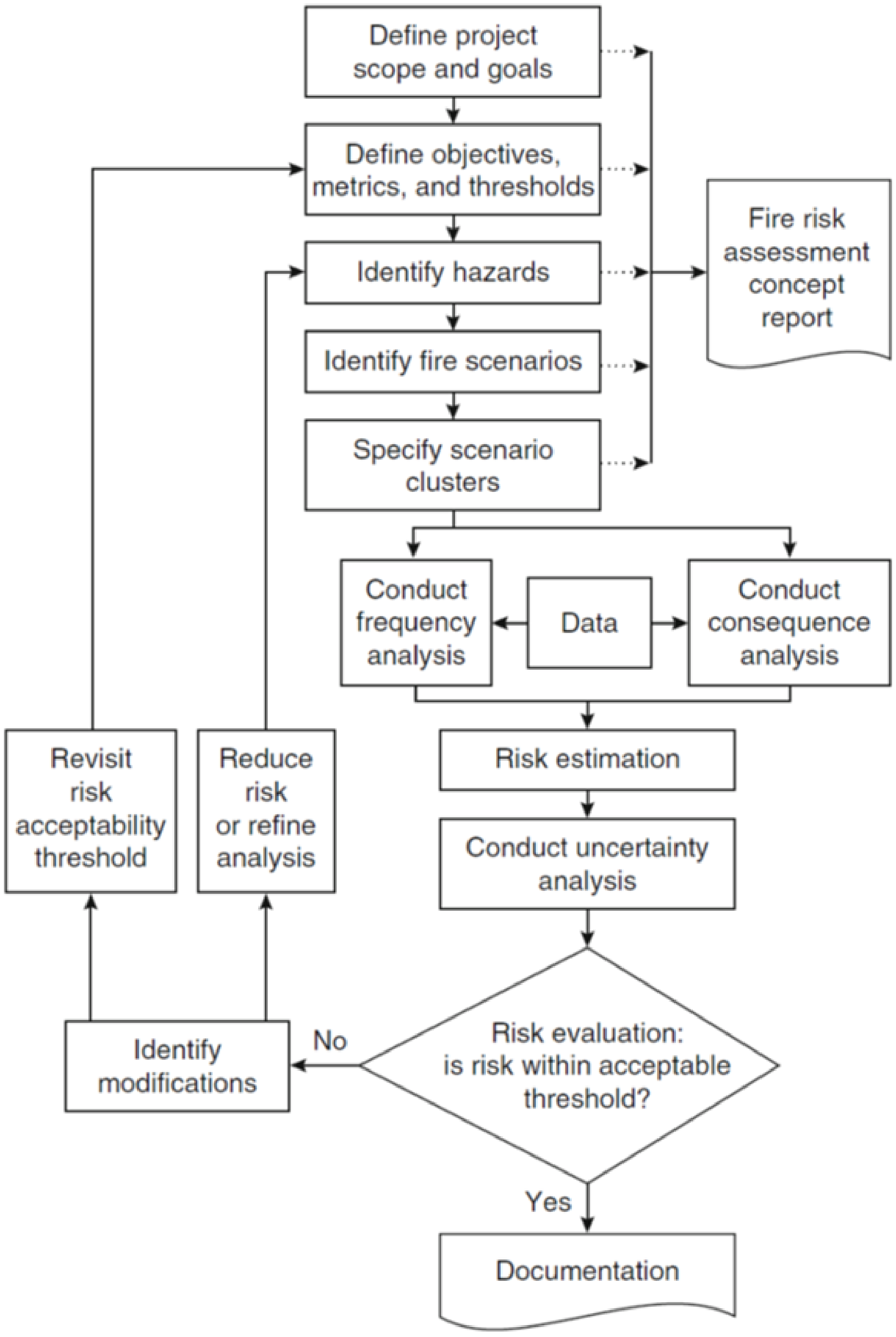

Figure 3.13. SFPE recommended process for fire risk analysis SFPE, 2008)

3.9.5. EXAMPLE OF EVENT TREE ANALYSIS

One of the most commonly used methods for fire risk assessment that assists in structuring fire loss scenarios are event trees. Event trees start with the initiating event and then, by considering the impact of other events that can influence the fire and its consequences, result in different fire scenarios. Each of these resulting scenarios can be considered to determine its outcome. The advantage of event trees is that they can be incorporate both the consequence of unwanted events as well as their frequency.

A simple example of an event tree is shown in Figure 3.15. The initiating event in this example is a fire that starts in the kitchen of a unit in a multi-storey building. The building is equipped with smoke detectors, an alarm system, and a sprinkler system. The events considered are whether the occupants will respond to the various warning signals on time and be able to extinguish the fire, whether the automatic sprinklers will extinguish the fire and whether the fire department will extinguish the fire before it spreads to other units. The probabilities used for each of the events in this example are: occupants will extinguish the fire: 0.6; sprinklers will extinguish the fire: 0.95; and fire department will extinguish the fire before spreading to other units: 0.7. Probabilities for the occurrence of various events can be determined from a variety of sources, including fire statistics data and analysis.

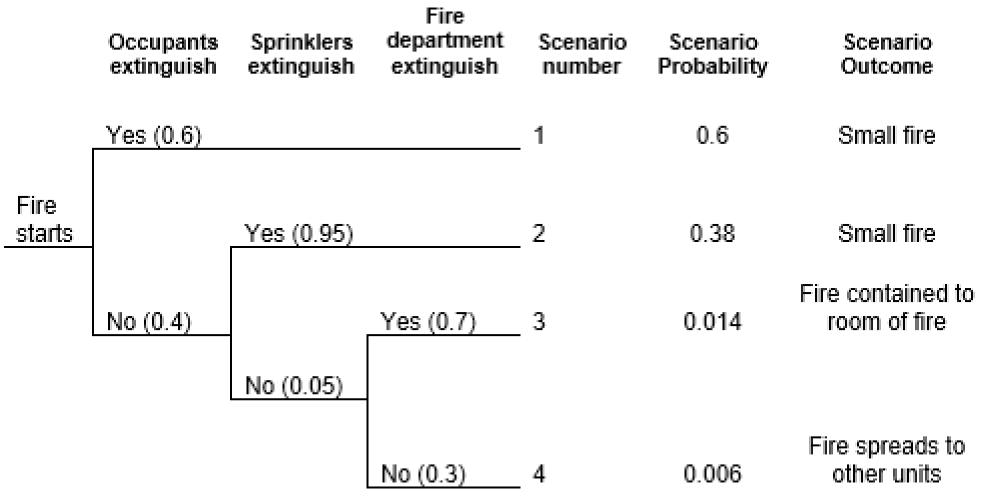

Figure 3.14. Example of simplified event tree of various fire scenarios.

The event tree in this example has 4 events including the initiating event, and results in four scenarios. The probability of each of the scenarios is the product of the probabilities along the scenario branches. The outcome or consequence of each scenario can be expressed in qualitative terms as shown in the figure or it can be estimated using computational tools in terms of impact on occupants and property damages. In the case of quantitative outcomes, the overall risk can be computed by summing the product of consequence times probability of each scenario.

$$Risk = \sum_{i}^{all\ scenarios} Probability\ i\ x\ consequence\ i$$

The probability of fire starting in the kitchen could also be obtained from statistical data and could be included in the event tree.

In applying risk analysis using event trees to tall wood buildings, it is most likely the event trees will be compared between the Alternative Solution and the Acceptable Solution. In this case, the probability of having a fire which threatens the boundaries of a fire compartment may be used as the comparisons, with the assessment that if the fire is not more likely to challenge the fire resistance of the boundaries of the compartment, it is no more likely to spread beyond the compartment of fire origin. This could be one criteria used to evaluate the Alternative Solution.

3.10. COMMON TALL WOOD BUILDING FIRE SAFETY STRATEGIES

The primary strategy which is often the starting point for developing a Fire Safety Design Plan strategy for the use of a mass timber structure where noncombustible construction is required, is to follow all other requirements for a noncombustible building, that is the requirements under Subsection 3.1.5 of Division B of OBC are applied to the building design, with the exception of the mass timber structure. As mentioned in Section 3.4.1 of this technical resource, combustible components are permitted in a number of ways in buildings required to be of noncombustible construction; however, there also are a number of specific restrictions on the use of those combustible components, including restrictions on combustible insulation, combustible pipe, and combustible wires, cables and raceways.

3.10.1. ENCAPSULATION

Encapsulation, which is a term often used when describing the protection of mass timber in buildings that would otherwise be required to be of noncombustible construction, is a means of preventing the mass timber structure from contributing to the fire for some period of time. While encapsulation of the mass timber will likely contribute to the fire resistance of the structure, which can be beneficial, that is not the primary intent of encapsulation since fire resistance can be achieved by mass timber without encapsulation.

One starting point for formulation a Fire Safety Design Plan to use mass timber structural elements is to provide sufficient encapsulation to prevent the mass timber from contributing to the fire. This premise would allow the fire to completely burn out (all the contents in the fire compartment consumed) without the structure contributing to the fire, thus allowing the structure to have no impact on the expected fires in the building. This is the approach which was taken in the design of Brock Commons recently built on the UBC campus in Vancouver, BC. This is an example where full encapsulation can provide a relatively straight forward path to demonstrate equivalence between a combustible and a noncombustible structure. Note that full encapsulation can provide a number of benefits beyond preventing the structure from contributing to fire severity. Full encapsulation can provide the fire resistance of the structure, or a significant portion of the fire resistance, as well as significantly reduce sound transmission paths by using products such as resilient channels to mount gypsum board or using concrete toppings to increase the mass of floor assemblies.

However, many designers interested to building a tall wood building are motivated to show some of the mass timber structure for aesthetic purposes. One key question is how much wood can be exposed without significantly affecting fire severity (i.e. intensity and duration). As described previously under the section on design fires, exposed mass timber can contribute to the different stages of a compartment fire to varying degrees depending on the amount of exposed wood. While full encapsulation with sufficient thickness can be demonstrated to prevent the contribution of the structure to the fire, lesser amounts of protection can be demonstrated to have varying degrees of impact on the design fire. With other mitigating features, some of which are discussed next, it can be possible to demonstrate the limited amount of exposed wood does not create additional risk to occupants, the fire service or property.

In order to quantify the level of encapsulation provided by a material such as gypsum board or insulation, the National Research Council reviewed many years of fire test data to determine the level of encapsulation provided by different combinations of gypsum board. These encapsulation times are reported in the report by Lougheed *et al*., (2014). Another source of encapsulation times based on fire-resistance tests has been prepared by FPInnovations and includes gypsum board and mineral wool board insulation (Osborne, 2015).

3.10.2. SPRINKLER RELIABILITY

As previously discussed under 3.6.1 of this technical resource, automatic sprinkler systems are by far the most effective means to reduce risk to life and property from fire in buildings. Therefore, anything that can be done to increase the reliability of the sprinkler system, both in terms of the probability it will activate and deliver water to the fire as well as the effectiveness of the sprinkler system to control the fire once activated, can be of significant benefit.

The use of fire statistics can be used to identify common causes for sprinklers failing to control the fire. Designs can then take steps to minimize the probability that these failures will occur in the tall wood building being designed. Below are just a few examples of improvements that can be made to the sprinkler system design to improve reliability.

Since closed valves are often cited as the main cause for failure of a sprinkler system to control a fire, installing isolation valves at each floor as recommended by (Moinuddin *et al.*, 2008) allows for only a partial shut-down of the system during maintained or retrofits as discussed above in Section 3.6.1 of this technical resource, reducing the probability that a fire event occurs in a part of the building in which the sprinkler system is shut off.

Incorporating redundancy into the design of the sprinkler system can help avoid sprinkler failure such as having more than one water supply, back-up fire pumps, or additional risers. Of course, these types of considerations will always be project-specific, based on available water supplies and building design and construction.

Steps may be taken to increase the effectiveness of the sprinkler system by improving the robustness of the design beyond the standard minimum. Design considerations that might increase effectiveness may include reducing spacing of sprinkler heads and/or allowing for a greater number of heads activating than the minimum called for in the standard in determining water flow rates required. These possible considerations also may be specific to the ceiling profile(s) in the building design (e.g. based on exposed beams).

One concern in areas with significant seismic risk is that the earthquake may damage the municipality's water infrastructure resulting in a loss of water supply in the event of a post-earthquake fire. To address this concern, onsite water supply may be provided in order to ensure water is available in the event of a fire. It should be noted, however, that performance in a post-earthquake fire scenario is typically not addressed by the Division B requirements of the building code for buildings required to be of noncombustible construction, and therefore would likely be considered an additional objective that could be included in the list of objectives to be met by an alternative solution for a tall wood building when discussions occur between the CBO and the design team, as discussed in Section 3.5.2 of this technical resource.

3.10.3. EXIT STAIR PRESSURIZATION

Exit stairs play a critical role in allowing the evacuation of any multi-storey building in the event a fire occurs, being the sole means of egress, and provides access to the fire floor for the fire service. It is important that the exit stair shaft remains smoke free in the event of a fire, and additional features may be considered beyond those required by OBC to ensure the stair shaft remains smoke free in the event of a fire. The introduction of exit stair pressurization may be considered as an additional mitigating feature. Additional guidance on smoke control methods may be found in NFPA 92 (NFPA, 2015) and the Handbook of Smoke Control Engineering (Klote *et al.*, 2012).

3.10.4. BUILDING AREA

When considering the risk of a fire starting in a building, the size of the building, either in terms of area or number of units/suites will have an impact on the probability. For instance, if the risk is being compared between two buildings in which one has half the area (and half the units) of the other, the risk of a fire starting in the first place will be half in the one that is half the area, all else being equal. Therefore, the size of the building may be a consideration in any risk analysis that is performed.

3.11. FIRE SAFETY DURING CONSTRUCTION

In a completed building using combustible materials, there are many components which contribute to the overall fire safety of the building. These may include the automatic sprinkler system, the alarm system, fire separations, limits on the surface flammability of room linings, etc. However, in a building under construction using combustible materials, there is a period of time in which none or few of these systems, measures or attributes are installed or in service. During this time, the building is especially vulnerable to fire. In the past, construction site fires were considered to be of little risk to life, but sometimes resulted in large property losses due to the lack of containment of the fire and the abundance of combustible materials. However, as we look to building larger and taller buildings using combustible structural elements, particularly in denser urban areas, the risk to life increases, as does the potential for even larger property losses. For these reasons, special care is needed during the construction of tall wood buildings in order to minimize the risks associated with construction site fires.

General construction site safety has made large strides over the last few decades with respect to regulation and procedures. The time has come to include fire safety as part of this overall culture of safety on construction sites.

3.11.1. CAUSES OF CONSTRUCTION SITE FIRES

In order to work towards reducing the likelihood of a construction site fire occurring, it is important to understand the hazards which occur on construction sites that are most likely to lead to fires. As with all fires, it can be difficult sometimes to determine cause; however, by looking at a number of studies on fire loss statistics, some generalizations can be made.

In reviewing statistics, it is often helpful to look to the US since the data sets available are much larger and allow for a more detailed look at causes of construction site fires. The US Fire Administration (USFA, 2001) published a study in 2001 titled “Construction Site Fires.” The study found that the two main causes of construction site fires were classified as incendiary/suspicious (at 41%) and open flame (at 30%). Incendiary fires are those set intentionally, where arson is the criminal act, while open flame includes hot work activities such as using roofing torches, welding, soldering, or cutting activities, all of which create significant heat and sparks. Additional causes found in the study include smoking (5%) and heating (4%). Similarly, a study published by the NFPA Fire Analysis and Research Division (NFPA, 2001) found that 40% of fires were found to be started by incendiary or suspicious activities, 21% caused by open flame, ember and torches and 10% caused by heating equipment.

A Canadian study, conducted by CFT Engineering Inc. for Forestry Innovation Investment Ltd. (CFT, 2012), reviewed the fire reporting system maintained by Emergency Management BC’s Office of the Fire Commissioner, which included 275 construction site fires that occurred in British Columbia during the 5-year period between 2005 and 2009. During this period, it was found that 63% of fires were reported as incendiary and 22% were reported with reasons that could not be determined. Furthermore, the study demonstrated that the greatest portion of incendiary fires occurs between 5:00 pm and 4:00 am when workers are likely not present on site.

Lastly, the Office of the Fire Commissioner, Public Safety Division of Alberta Municipal Affairs looked at construction site fires in Alberta between 2000 and 2009. They found, on average, that there are 31 construction site fires per year, which represents 1 percent of all structural fires and 2.2 percent of losses in direct property damage. They found that 35% of fires were classified as incendiary and 60% of fires started between 8 pm and 8 am. The highest concentration of fires (34%) occurred between midnight and 4 am. Approximately 22% of fires were caused by heating equipment and hot work.

Based on the four studies above, it is clear that the majority of construction site fires are a result of arson, hot work activity and heating equipment. In all cases, steps can be taken to significantly reduce the likelihood of a fire starting by taking a serious look at the design of the building, ensuring the site is secure, and treating possible ignition sources on the construction site with caution.

3.11.2. ONTARIO REGULATION

In Ontario, construction site fire safety (along with general construction site safety) falls under the Occupational Health and Safety Act, R.S.O. 1990, c. O.1, Ontario Regulation 213/91 entitled "Construction Projects." However, with the recent changes to OBC allowing combustible construction up to 6 storeys, the Ontario Ministry of Municipal Affairs together with the Ministry of Labour and the Office of the Fire Marshal and Emergency Management, have worked with a number of stakeholders to develop a best practice guideline titled "Fire Safety During Construction for Five and Six Storey Wood Buildings in Ontario" (MMAH, 2016). The guideline provides an extensive overview of best practices and recommendations to address the risks of a fire occurring on a construction site for wood buildings, many of which are equally useful for tall buildings using mass timber elements. It is strongly recommended that design teams make use of this best practices guide as they develop fire safety plans for mass timber buildings in excess of six storeys.

3.11.3. CONSTRUCTION SITE FIRE SAFETY PLAN

The Construction Site Fire Safety Plan (CSFSP) is a plan that should be prepared by the general contractor/developer who has the responsibility of fire safety on the construction site. Since, in many cases, the individuals preparing the CSFSP will not have sufficient experience or knowledge to assess all hazards onsite, it is recommended the fire safety engineer for the project work with them to help identify hazards and possible solutions to address those hazards.

A CSFSP is required by the 2015 National Fire Code of Canada [NFC 5.6.1.3] and mandated by most provincial fire codes outside of Ontario. However, while it is not a requirement in the regulations, it is highly recommended that a CSFSP be completed. It is likely that the municipality, including the fire service, will want to see the plan prior to work commencing onsite, and certainly before combustible materials begin to arrive. Similarly, the insurance provider likely will also want to review the plan as a condition of insurance, as they will have a number of their own requirements (warranties) that will likely need to be met.

The CSFSP is a detailed document that identifies key people and their responsibilities in the event of a fire. The plan should also identify the fire hazards onsite in terms of potential for ignition (e.g. arson or hot work) and means for reducing or controlling them (e.g. security measures; hot work permit system), as well as possible hazards and how they should be mitigated or addressed in the event of a fire (e.g. evacuation of workers or adjacent buildings).

The development of the CSFSP should begin during the earliest meetings of the design team so that ideas can be discussed to limit sources of ignition onsite during construction (e.g. welding or roofing options), as well as other methods to reduce risk such as an accelerated building schedule (e.g. panelized construction may reduce the time that the building remains more vulnerable and allow for the installation of some degree of protection prior to arriving onsite).

As a starting point, it is recommended that the “Fire Safety During Construction for Five and Six Storey Wood Buildings in Ontario” guideline be followed in the development of the CSFSP.

3.11.4. FIRE SAFETY COORDINATOR

The Fire Safety Coordinator for the project should be one of the primary people involved in writing the CSFSP and will be the point person to liaise with the local fire service during construction.

In many cases, the Fire Safety Coordinator will be responsible for health and safety on the construction site, with fire being one component of that responsibility. It is important that the Fire Safety Coordinator is familiar with the regulations governing health and safety on construction sites, such as Ontario Regulation 213/91. They should also be familiar with the provincial guidelines, having used them to initially help develop the fire safety plan.

The Fire Safety Coordinator typically will have the authority to implement the CSFSP and must ensure that all workers on site adhere to the procedures described in the plan. The Fire Safety Coordinator will be responsible for ensuring that all fire safety features of the plan, such as location of fire extinguishers and access routes for the fire service, are maintained.

3.11.5. CONSIDERATIONS FOR MASS TIMBER BUILDINGS

As mentioned above, while the “Fire Safety During Construction for Five and Six Storey Wood Buildings in Ontario” guideline was written for mid-rise combustible construction, most of the best practices outlined in the guide are equally applicable to mass timber buildings. However, there are a few differences between light-frame combustible construction and mass timber buildings that should be considered when developing or evaluating a CSFSP.

Prevention

Due to the vulnerability of combustible buildings to fire during the construction process, it is important to, as much as possible, prevent a fire from starting in the first place. This will include steps to ensure that the site is secure during working hours and outside of working hours, minimizing the need for hot work on site, and, when hot work is required, that a hot work permit process is in place.

Site security is critical once the combustible structure starts to be built. However, some simple steps can help make access difficult. While site fencing and site security may be the primary method to keep the construction site secure early in the construction process, making the first storey secure once it is closed in may be more effective. The installation of a temporary set of steel doors, for example, while installing or otherwise blocking window openings can make the building difficult to enter once the first couple of storeys are up.

Reduction of Growth Potential

Unfortunately, while steps are taken to minimize the chance of a fire starting on a construction site, the risk of a construction site fire can never be zero, whether the project is of combustible or noncombustible construction. Therefore, additional steps are prudent to attempt to minimize growth and spread of a fire, should one occur.

If a fire occurs in a tall wood building under construction, the rate of growth and spread will depend on the combustible items available to contribute to the fire, as well as their arrangement. One avenue to control the combustible components available is to have protective materials such as gypsum board installed as soon as possible. While panelized construction has the benefit of reducing the time that a building is under construction, thereby reducing the risk of a fire, this construction method also allows for the possibility of having components show up on site with some level of protection (e.g. CLT floor panels arrive on-site with gypsum board or noncombustible insulation fastened to the ceiling surface). Similarly, the addition of a concrete topping to the floors is sometimes used to help address sound transmission; the early installation of the topping could further reduce the combustible surfaces that could contribute to fire growth.

Large mass timber buildings under construction tend to be relatively tidy due to the use of premanufactured components, resulting in little waste on-site. This is an advantage, in that it is much more difficult for the mass timber structure to be the first item ignited compared to waste material such as sawdust and cut-offs of lumber. In this light, it is important to keep the construction site and building tidy during construction to minimize the material which could allow a fire to start and grow.

In the event of a fire during working hours, it is important to be able to have workers safely evacuate the building. This becomes more challenging in a tall wood building since the time to exit the building could be substantial. Therefore, it is recommended that two exit stairs be accessible for the evacuation of workers in case one is compromised due to the proximity of the fire to the exit stairs. The exit stairs should be protected from the rest of the building with some degree of fire resistance (e.g. minimum 1-hour rating) and have self-closing doors (e.g. these could be temporary doors with some fire resistance) that will prevent fire or smoke spread into the exit stair. Not only is this important for the evacuation of workers, but it can be important for the response of firefighters to access the fire.

Fire fighters can expect significant differences in fighting a construction site fire of a mass timber building compared to a light-frame combustible building. The primary differences between a mass timber building and a light-frame building during construction are the inherent fire resistance of mass timber construction and the size and arrangement of the combustible structure. These two factors will have an effect on the intensity and duration of the fire.

When a fire starts in a light-frame combustible building during construction (prior to the installation of gypsum board, for example) and if the fire is not successfully controlled when small, it will quickly grow due to the relatively small-dimensioned lumber arranged in a way that allows the fire to grow rapidly. While the smaller dimensions of the combustible structure allow the fire to grow quickly, it also is consumed quicker than larger dimension members, which can result in the structure collapsing not long after the fire fully involves the structure. Therefore, the fires can be relatively short and intense.

Conversely, tall mass timber buildings under construction that experience a fire during construction could remain standing for an extended period, allowing time for the fire fighters to bring the fire under control. If the fire is not brought under control, it could increase the duration of the exposure to adjacent buildings. Overall, depending on the size of the buildings, a fire in a mass timber building during construction could result in a fire of lesser intensity, but of longer duration.

One significant risk in many tall wood building projects is the potential for fire exposure to adjacent buildings in the event of a fire during construction before the fire safety features of the building are complete. By taking steps to address construction site fire safety as described in *Fire Safety During Construction of Five and Six Storey Wood Buildings in Ontario*, the risk of a fire occurring will be significantly decreased. In certain cases, however, additional steps may be required to minimize the likelihood of a construction site fire starting and growing to a size that would threaten adjacent buildings (e.g. a care facility). In such cases where there are vulnerable occupancies in adjacent buildings, solutions to address the risk should be developed in cooperation with a qualified fire safety engineer.

In the planning of the construction sequencing, anything that can be done to bring fire safety features that are part of the finished building into service as soon as possible during construction will be a benefit. For example, once the building is weather tight, the installation of gypsum board on surfaces that will ultimately be covered, will help reduce the risk of a fire. Similarly, any fire separations that can be completed early in the construction schedule in order to help compartmentalize the building also will be beneficial should a fire occur.

Occupancy of Tall Wood Building – Occupancy Permit

The Building Code sets out occupancy permit requirements for certain types of buildings. For example, in the case of buildings described in Division C, Article 1.3.3.1., the fire safety systems (fire separation, exits, sprinklers, standpipe, fire alarm system, lighting, means of egress, fire access route, etc.) are required to be in-place and operational in the portion of the building the occupancy permit would apply to.

However, given the potentially increased risk of fire during construction, there are additional considerations for tall wood buildings. In order to mitigate this risk and achieve the level of performance of a noncombustible building during construction, it is recommended that the building permit applicant agree, as part of the alternative solution, to not apply for an occupancy permit until all fire and life safety systems of the building are complete and operational. Relevant objectives and functional statements to consider include those related to Safety - Fire Safety; Fire, Structural, Water and Sewage Protection of Buildings – Fire Protection of the Building; Fire, Structural, Water and Sewage Protection of Buildings – Protection of Adjacent Buildings from Fire. Provisions set out in Division C, Article 1.3.3.5.(3) could be used as a starting point when considering which fire and life safety requirements should be satisfied before the building is occupied. The CBO should be consulted at an early stage in the project design process to evaluate what additional fire safety measures should be considered.

4. STRUCTURAL DESIGN

To be in conformance with OBC, the structural design may require an Alternative Solution due to code limitations or lack of specific requirements in the current edition of the building code. For example, exceedance of height limits on wood buildings, new materials, unlisted types of structural systems and behaviour (such as ductility under earthquake loading), and others. While new research and standards are being developed, it is reasonable to expect detailed explanation of the proposed structural system to show conformance to the building code and standards. A mechanism exists in the building code to allow this, as described in Section 4.1 below. Specific OBC provisions related to structure are noted in Section 4.2. Other areas of design that should also be addressed are listed in Section 4.4. Additional information that should be provided on structural drawings or in a project outline specification are listed below in Section 4.5.

Per OBC Article 1.1.2.2, Division A, buildings greater than three storeys in height or with an area greater than 600 m^2 must be designed to OBC Part 4, Division B.

Additional technical details on structural design for tall wood buildings are available in FPInnovations *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada,* **FPI/TWBC** published in 2014. That document, and other research reports from experts at FPInnovations, are regularly relied upon by building officials for technical support on tall wood buildings.

4.1. PRINCIPLE OF CODE COMPLIANCE

To be structurally compliant, the design must demonstrate compliance with OBC and all applicable CSA material standards. Tall wood structures are not outlined in CSA O86 specifically but are permitted to be designed based on CSA O86-14 Article 4.3.2 ***New or special systems of design and construction*** which states:

> “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.”

New provisions that have been added to CSA O86-14 Update No.1 specific to CLT design is already adopted in NBC 2015 and are expected to be adopted in the upcoming Provincial building codes in Canada.

OBC Sentence B-4.1.1.3.(1) *Design Requirements* states:

> “Buildings and their structural members and connections…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.”

On this basis, designers are provided the basis for loading and resistance per OBC and the materials standards.

The design shall meet the requirements for ultimate limit states and serviceability limit states in accordance with OBC.

4.2. COMPLIANCE WITH ONTARIO’S BUILDING CODE

Ontario’s Building Code is an objective-based code. The objective-based format is intended to assist Building Code users to understand the “why” behind Code requirements, as well as the “what”.

Compliance is achieved by using either an “Acceptable Solution” or an “Alternative Solution”. Acceptable Solutions are set in Division B of the Code, and can either be prescriptive or performance in nature. A prescriptive-based Acceptable Solution is putting a certain number of nails a certain distance apart. A performance-based Acceptable Solution is performance: it directs the Code user to make sure that their method of attaching the roof to the house is able to withstand the same wind, snow, rain loads that the prescriptive method does.

Using an “Alternative Solution”, the designer needs to show that the objective (as illustrated by the functional statement) will be met through whatever means the designer is able support/prove while acheiving the same level of performance or better as the qacceptable solution. Objective-based codes are more flexible and more responsive to innovation, as they provide Code users with more information to evaluate alternative solutions to the requirements of the Code.

OBC presents two paths to achieve code approvals; Acceptable Solutions or Alternative Solutions. Refer to OBC A-1.2.1.1.(1).

4.2.1. ACCEPTABLE SOLUTIONS (DIVISION B)

OBC Division B contains Acceptable Solutions and by following the requirements of Division B, a design is deemed an Acceptable Solution. From Appendix Note A-1.2.1.1.(1)(a):

> “If a building design (e.g. material, component, assembly or system) can be shown to meet all provisions of the applicable Acceptable Solutions in Division B (e.g. it complies with the applicable provisions of a references standard), it is deemed to have satisfied the objectives and functional statements linked to those provisions and thus to have complied with that part of the Code. In fact, if it can be determined that a design meets all the applicable Acceptable Solutions in Division B, there is no need to consult the objectives and functional statements in Division A to determine its compliance.”

Following Division B is generally a straight-forward application and approval process.

4.2.2. ALTERNATIVE SOLUTIONS

When a design does not satisfy the requirements for Acceptable Solutions in Division B, an Alternative Solution is required. This a more involved process for approval. From OBC Appendix Note A-1.2.1.1.(b) an Alternative Solution must meet at least the same level of performance as an Acceptable Solution with respect to the objectives and functional statements in Ministry of Municipal Affairs (MMA) Supplementary Standard SA-1. OBC Appendix A, A-1.2.1.1(1)(b) notes that since the objectives and functional statements are qualitative, demonstrating compliance with them in isolation is not always possible.

Objective Statement Categories
OBC Part 2 Division A has the following categories of objectives:

- (OS) Safety (fire, structural, in use, and unwanted entry)
- (OH) Health (indoor conditions, sanitation, noise protection, vibration and deflection limitation, hazardous substances contamination, privacy, and view of the outdoors)
- (OA) Accessibility (barrier-free path of travel and facilities)
- (OP) Protection of the building (fire protection, structural sufficiency, protection of adjacent buildings, and water and sewage protection)
- (OR) Resource conservation (water and energy, and infrastructure capacity)
- (OE) Environmental integrity (air quality, water and soil quality)
- (OC) Conservation of buildings

Functional Statement Categories

Part 3 Division A of OBC lists the functional statements in the following categories:

- Fire or explosions
- Emergency response
- Structural sufficiency
- Life safety
- Contaminants and hazardous materials
- Air quality
- Protection from moisture
- Potable water
- Minimize damage
- Privacy and outdoor views
- Sewage control
- Pool safety
- Resource conservation
- Reuse and material alternation and repair of existing buildings
- Low greenhouse gas emissions.

The design of tall wood structures (over 6-storeys or over the 20 m height limitation) requires an Alternative Solution to be compliant with OBC.

Below is a simplified list of steps to assess an Alternative Solution.

a. Identification of the applicable Division B provisions
b. Identification of the applicable objectives and functional statements
c. An evaluation of the level of performance of the applicable Division B provisions
d. An evaluation of the level of performance of the proposed Alternative Solution
e. Identification of any assumptions, limiting or restricting factors, in respect of the objectives and fucntional statements
f. Identification of testing procedures, engineering studies, or building performance parameters.This could be any of the following:
    i. Test results
    ii. Calculations
    iii. Computer modelling
    iv. Fire scenarios
    v. Design fire documentations
    vi. Evidence of successful performance

All information in the Code Analysis must be detailed sufficiently to convey the design intent and to support the validity, accuracy, relevance and precision of the Code Analysis.

4.2.3. THIRD PARTY REVIEW OF ALTERNATIVE SOLUTIONS

A third party review is not always required but recommended for jurisdictions that do not have expertise in tall wood building design. The review is conducted by an expert in the field (i.e. a qualified timber engineer for the structural review). If a third party review is required, each municipality may have their own specific requirements as to the construction and procedure of the third party review process. However, in general, this can be initiated by either the applicant or the CBO, and should be performed early in the design process. Additionally, the third party reviewer should be encouraged to provide aid in finding appropriate solutions not just noting the errors and omissions. The structural design of tall wood structures will require non-traditional modelling and a full independent third party review for design and construction. The use of hybrid structures with concrete or steel lateral systems with wood gravity systems will significantly simplify the lateral design (and therefore approval process) (FPInnovations, 2014).

4.2.4. OBJECTIVES AND FUNCTIONAL STATEMENTS

The specific statements that relate to tall wood building Alternative Solutions are as follows. The Objectives presented in Part 2 Division A of OBC related to the structural design of tall wood buildings are:

- OS2 – Structural safety
    - OS2.1 – Loadbearing capacity
    - OS2.2 – Foundation capacity
    - OS2.3 – Damage/deterioration of structural members
    - OS2.4 – Vibration and deflection
    - OS2.5 – Structure stability
    - OS2.6 – Excavation
- OH4 – Vibration and deflection limitation
- OP2 – Structural sufficiency of the building
    - OP2.1 – Loadbearing capacity
    - OP2.2 – Foundation capacity
    - OP2.3 – Damage/deterioration of structural members
    - OP2.4 – Vibration and deflection
    - OP2.5 – Structure stability
    - OP2.6 – Foundation movement
- OP4 – Protection of adjacent buildings from structural damage
    - OP4.1 – Foundation settlement
    - OP4.2 – Building collapse
    - OP4.3 - Impact
    - OP4.4 - Excavation

The Functional Statements presented in Part 3 Division A of OBC related to the structural design of tall wood buildings are:

- 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
- F23 – To maintain equipment in place during structural movement
- F80 – To resist deterioration resulting from expected service conditions
- F82 – To minimize the risk of inadequate performance due to improper maintenance or lack of maintenance

The **FPI/TWBC** also points out items that should be considered that are not necessarily noted in the objectives or functional statements of OBC.

- Combustibility
- Protection of combustible concealed spaces
- Fire stopping
- Mechanical and sprinkler flexible joints
- Behaviour of mass timber panel shear-walls and their connections
- Size effect of mass timber panel construction
- Low pressure adhesives in mass timber panel assemblies
- Connection behaviour in mass timber panels
- Prefabrication and erection considerations
- Weather protection

For statements related to fire, see Chapter 3 above.

4.2.5. REQUIRED LEVEL OF PERFORMANCE

As noted above at the start of Section 4.2, OBC is an objective based code. An Alternative Solution for a tall wood building in Ontario would require providing the same level of performance as an Acceptable Solution, achieved by meeting the objectives and functional statements set out in Division A of OBC. Since OBC does not specify an exact performance level, a performance based design should refer to other standards or codes such as the ASCE 7-10. ASCE 7-10 for performance based design requires that the engineer must show from analysis, testing or from a combination of the two, that the structure can provide reliability equal to or greater than using the strength (i.e. objective) design approach. However, OBC Division B Part 4 is primarily written as a performance based code (with the exception of OBC Division B Table 4.1.8.6 Structural Irregularities, that is prescriptive based). This does not imply that an Acceptable Solution is not required for structural design of tall wood buildings since there are many systems that are not entirely covered in OBC or CSA O86 (for example CLT applications are limited in CSA O86).

4.3. ULTIMATE LIMIT STATES AND SERVICEABILITY LIMIT STATES

OBC B-4.1.1.3 states that a building shall be designed with sufficient capacity to resist all loads and that the building and structural members be designed for serviceability. The following code sections of OBC are highlighted here because they may need to be addressed in an application for Alternative Solution. Reference to the **FPI/TWBC** is recommended.

4.3.1. GENERAL REQUIREMENTS

OBC Sentence B-4.1.1.4.(1) states:

> "…buildings and their structural members shall be designed in conformance with the procedures and practices provided in this Part."

OBC Sentence B-4.1.1.4.(2) further states:

> "…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."

In other words, the design must show conformance with the procedures in OBC or, for systems not otherwise covered by OBC, prove otherwise from testing or other studies. An Alternative Solution submission may be required in cases where the system falls outside of the Acceptable Solutions of OBC Part 4, Division B.

OBC Sentence B-4.1.1.3.(1) addresses preventing progressive collapse when it mentions "structural integrity". In addition, as stated in CSA O86-14 *Engineering Design in Wood*, Article 4.3.3, the design shall prevent widespread collapse in the event of load failure:

> "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."

As will be shown below, to achieve such structural integrity, the design for gravity and lateral loads (wind and earthquake) and possible progressive collapse will depend on the ability of the structural and connections to absorb energy and to redistribute loads.

4.3.2. SPECIFIED LOADS AND LIMIT STATES DESIGN

The following list of sections is highlighted here as a reminder of design elements that should be reviewed in tall wood buildings. Items are listed in the sequence they appear in OBC 2012 Part 4, Division B. It is recommended that the design review be used to confirm that the items have been addressed where applicable. They may not specifically require an Alternative Solution submission.

Serviceability and shrinkage
OBC Subsection B-4.1.2 lists the categories of loads to be considered. While all load categories are relevant, tall wood building designs must address **T**, for shrinkage and moisture changes, as noted in OBC Sentence B-4.1.2.1.(1). **T** is a load case that is for effects due to contraction, expansion or deflection caused by temperature changes, shrinkage, moisture changes, creep, and/or ground settlement. If the structural system is designed in a way to avoid load effects due to differential shrinkage, then there are no load effects due to imposed deformation and the designer should indicate as such. Otherwise, note the limit states design requirements for load factors on imposed deformations listed in Sentence 4.1.3.2.(4).

Stability of the structure as a whole as well as lateral, torsional and local stability are requirements under OBC Sentence B-4.1.3.2.(11).

Sway effects and potential P-delta effects shall be accounted for in the design per OBC Sentence B-4.1.3.2.(12).

Serviceability limit states are to be checked in accordance with OBC Sentence B-4.1.3.4.(1) and the relevant material standards (including CSA O86). OBC Clause B-4.1.3.5.(1)(d) states that shrinkage is to be accounted for in deflection calculations.

Lateral building drift limits due to wind and gravity loads are listed in OBC Sentences B-4.1.3.5.(2) and (3). Lateral drift requirements due to earthquake loads are noted in OBC Sentence B-4.1.3.5.(5). If mass timber is used as the gravity load resisting system, it shall be designed for the lateral load demand imposed on it and to accommodate the lateral drift due to seismic loads.

Floor vibrations are limited to having "no significant adverse effects on the intended occupancy of the building" as noted in OBC Sentence B-4.1.3.6.(1).

CSA O86-14 Article 5.1.3 and Section 5.4 provides Serviceability Limit States design requirements for wood.

Load effects

Dead loads listed in OBC Subsection B-4.1.4 shall include partition loads in Sentences (1) to (5). Designers should verify that the minimum code allowance of 1 kPa is sufficient for the proposed use and occupancy of the building.

Live loads listed in OBC Subsection B-4.1.5 may be multiplied by the live load reduction factor per OBC Article B-4.1.5.8 for members supporting large areas meeting the requirements of OBC. However, this live load reduction factor is not intended to two-way slab structures.

Live loads on guards listed in OBC Article B-4.1.5.14 shall be reviewed for members and for connection forces to the wood substructure. See Section 4.4.5 below. Note also walls around shafts, are acting as guards as required in OBC Article B-4.1.5.16.

Forces on firewalls are noted in OBC Article B-4.1.5.17.

Rainwater ponding on flat roofs is determined in accordance with Article B-4.1.6.4.

CSA O86-14 Article 5.1.2 provides Ultimate Limit States design requirements for wood.

Again, as noted above, these items may not require an Alternative Solution, but should be noted in the review process to determine if they are required and, if so, to ensure they are addressed in the design.

4.3.3. GRAVITY DESIGN

Design for gravity resistance is to be in accordance with the materials standards and shall account for P-delta effects. NBCC 2010 Commentary J *Design for Seismic Effects* Sentence 97.(c) notes:

> “The effects of the interaction of gravity loads with the displaced configuration of the structure will increase lateral displacements and moments throughout the structure; these additional moments reduce the capacity of the structure to resist lateral loads.”

Moreover, P-delta effects must be considered in ductile structures as displacements enter the inelastic range (see Lateral Design below).

4.3.4. LATERAL DESIGN - INTRODUCTION

The procedure for lateral and gravity design in tall wood buildings is shown in Figure 4.1. The pathway depends on the type of lateral load resisting system (i.e. wood-based or steel- or concrete-based). The fundamental difference between pathways is the availability of R_d and R_o values for earthquake design of wood-based lateral systems or other lateral systems with wood-based gravity systems and relevant CSA material standards.

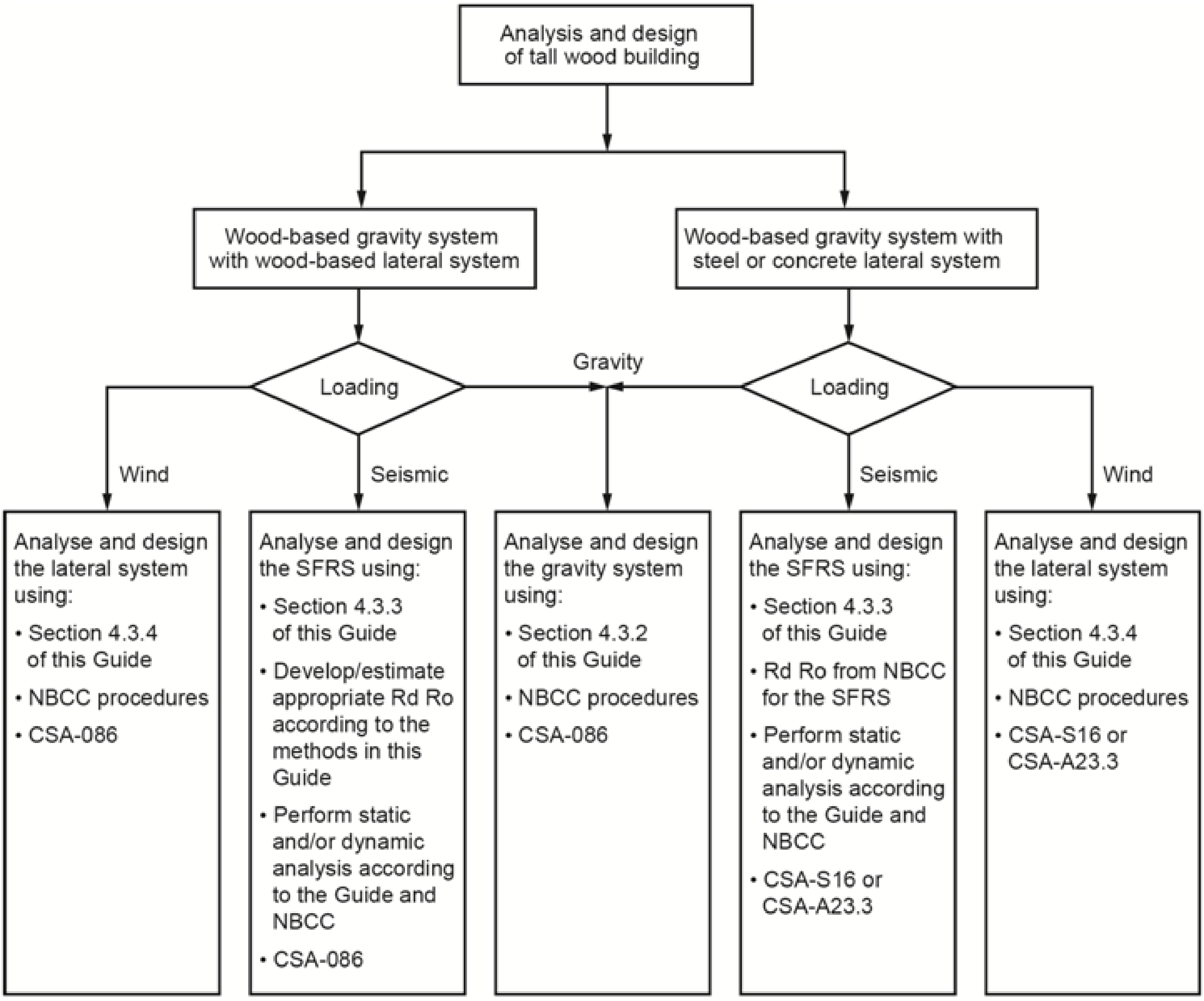

Figure 4.1. Tall wood design flow chart – section references in the figure are section in the FPI/TWBC (Source: Figure 1, section 4.3, FPI/TWBC) Note: figure references "of this Guide" are for the FPI/TWBC.

As noted in the previous section, P-delta effects must be considered for interaction between gravity and lateral loads. More detail can be found in NBCC Commentary J *Design for Seismic Effects* Sentence 97.(c).

4.3.5. LATERAL DESIGN - WIND

OBC Subsection B-4.1.7 states the requirements for wind loading. The tall wood building must be designed to account for wind loads and effects in accordance with OBC Subsection B-4.1.7.

OBC Article B-4.1.7.2 notes that dynamic effects must be considered if the building height is greater than four times the minimum effective width, or greater than 60 m tall, and for buildings that are sensitive to wind-induced vibrations, specifically, if the lowest natural frequency is less than 1 Hz (but greater than 0.25 Hz). In this case, experimental methods or using dynamic analyses are required (such as dynamic procedure or wind tunnel procedure) to determine wind effects. This should be reviewed, particularly for lighter buildings as well. Wind tunnel procedure is required in all cases for buildings with lowest natural frequency less than 0.25 Hz or when the building height is more than six times its minimum effective width. NBCC Commentary I – *Wind Load and Effects*, provides detail on the procedure for wind analysis. The building shall be designed to resist the most critical of wind load effects and earthquake load effects.

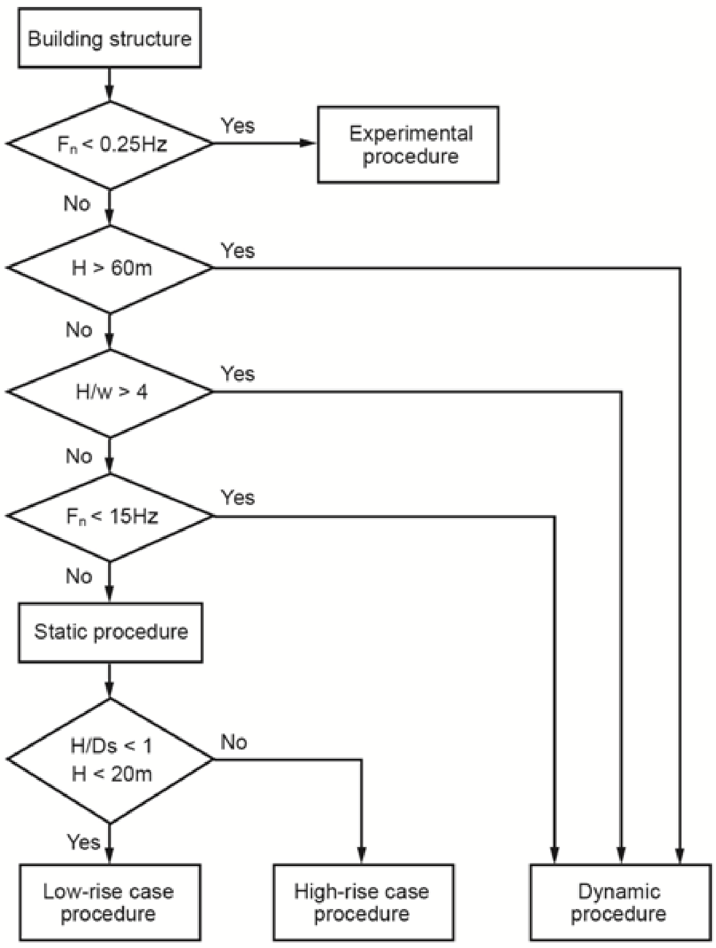

Figure 4.2. Methods for wind analysis (Source: Figure 1, section 4.3, FPI/TWBC)

4.3.6. LATERAL DESIGN - EARTHQUAKE

OBC has specific performance objectives for earthquake design performance. As noted in NBCC Commentary J *Design for Seismic Effects,* paragraph 3(1)(2)(3), these objectives are:

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.
3. To ensure that post-disaster buildings can continue to be occupied and functional following strong ground shaking, though minimal damage can be expected in such buildings.

A tall wood building must be designed to account for seismic loads and effects in accordance with OBC Subsection B-4.1.8. As noted in NBCC 2010 Commentary J, Paragraph 5:

> “It is generally considered both unnecessary and uneconomical to design and construct buildings that will not be damaged during the [event]. The primary objective of seismic design is to provide an acceptable level of safety for building occupants and the general public as the building responds to strong ground motion; in other words, to minimize loss of life.”

The Seismic Force Resisting System (SFRS) of a building is responsible for resisting lateral load effects due to earthquakes. The SFRS can be wood, concrete or steel and is intended to dissipate earthquake energy as well as resisting the lateral forces resulting from an earthquake.

NBCC 2010 Commentary J, Paragraph 6 notes that:

> “SFRS that do not have a significant inelastic energy dissipation capacity, i.e. those with limited ductility, are subject to higher loads and have less stringent detailing requirements…The capacity of various kinds of SFRS to resist the anticipated seismic loads is achieved by applying the design and detailing provisions contained in the NBC [2010] and in the referenced material standards”

Much like other material SFRS systems (see below), tall wood buildings must be designed using capacity design principles. For wood buildings, connections at specified locations are not only designed to the design earthquake loads, but also absorb seismic input energy, but still maintain the overall structural integrity. The goal is to prevent a brittle (unsafe, sudden) mode of failure in the event of an earthquake.

OBC Sentence B-4.1.3.2.(10) states the required load combinations for earthquake shall include the horizontal earth pressure due to earthquake loads.

There are currently five common SFRS for tall wood buildings which are not explicitly referenced in OBC. This is likely to change with time as new types of SFRS are proposed and tested. A few types are:

1. Platform shear wall structures with all mass timber floors and shear walls;
2. Balloon shear wall structures with mass timber floors and shear walls;
3. Tube-in-tube structures with hybrid systems using concrete or steel cores with mass timber floors and post-and-beam (gravity system);
4. Outrigger structures with braced cores and tension or compression members at the perimeter; and
5. Vertically post-tensioned shear wall elements or moment frames with controlled rocking and self-centering capability.

OBC Subsection B-4.1.8 *Earthquake Loads and Effects* states detailed requirements for capacity-based design. The design of the SFRS depends on many variables such as location and soil type.

Non-SFRS structural members

Elements of the Seismic Force Resisting System (SFRS) are distinguished from structural members that are not designed to resist lateral forces that result from earthquakes. OBC Sentence B-4.1.8.3.(5) requires that all framing elements that are not part of the SFRS are to:

> "…behave elastically or to have sufficient non-linear capacity to support their gravity loads while undergoing earthquake-induced deformations."

In addition, stiff elements, such as concrete, that are not part of the SFRS shall be separated from the building to prevent interaction during an earthquake, otherwise they are to be made part of the SFRS (OBC Sentence B-4.1.8.4.(6). The stiffness of these non-SFRS elements may, however, influence the behaviour of the building during an earthquake and should be considered per OBC Sentence B-4.1.8.4.(7) for effect on building period; excluded for possible improvements to irregular structures or torsional behaviour, but included if the stiffness could have an adverse effect on the SFRS. Wood structures may be influenced by these non-structural components since they are relatively stiff and may affect the period of the building (**FPI/TWBC** Section 4.3.3.1).

Structural modelling for earthquakes

Most wood frame buildings are low-rise, up to four -storeys are not usually designed with modelling. Mid-rise wood frame buildings of five or six-storeys do require modelling and dynamic analysis. Seismic design of mid-rise buildings with concrete podiums is not well understood yet by many designers. The behaviour of a tall wood building with its own SFRS will be quite different. OBC Sentence B-4.1.8.3.(8) states that the model:

> "…shall be representative of the magnitude and spatial distribution of the mass of the building and of the stiffness of all elements of the SFRS…"

Interaction between wood and concrete or other materials in the SFRS shall be modelled where applicable to determine the effects on building period, torsional behaviour and deformations. The mass and stiffness of these non-SFRS components can have an effect on building period and may need to be considered. (This is similar to considering the stiffness of gypsum board on wood-sheathed shear walls in light-framed construction). However, these effects should be minimal in tall wood buildings (specifically in post and beam construction), whereas OBC Sentence B-4.1.8.3.(8) is intended for infill brick or masonry walls that can inherently provide more stiffness to the building, attracting more load. This includes elements in structures with a concrete or steel podium.

Structural irregularities

OBC Article B-4.1.8.6 defines the types of features that are designated as irregulates for earthquake design. For more information see below under Methods of Analysis.

Methods of analysis

OBC Article B-4.1.8.7 requires that a dynamic analysis be performed unless any of the following apply, in which case the Equivalent Static Force Procedure may be used:

1. When $I_E F_a S_a(0.2)$ is less than 0.35;
2. For regular structures that are less than 60 m in height and have a fundamental lateral period, T_a, less than 2 s in each of two orthogonal directions; or
3. For structures with structural irregularity, of Type 1, 2, 3, 4, 5, 6 or 8 as defined in Table 4.1.8.6., that are less than 20 m in height and have a fundamental lateral period, T_a, less than 0.5 s in each of two orthogonal directions.

Tall wood buildings can be analyzed with the Equivalent Static force procedure if they meet these requirements and do not have "significant coupling of the lateral and torsional modes" (**FPI/TWBC** 2014 Section 4.3.3.2.1). Dynamic analysis procedures are described in detail OBC Part 4 Division B, the NBCC 2010 Commentary J and the **FPI/TWBC** Section 4.3.3.2.2.

Other SFRS

OBC Article B-4.1.8.9 provides the ductility-related force modification factor, R_d, and the related overstrength factor, R_o, for many types of SFRS along with height limitations for each system for concrete, wood, steel, masonry and light gauge steel. If the SFRS is not wood in a tall wood building, the design shall use the requirements for the non-wood SFRS. For hybrid structures with a combination of materials and/or types of SFRS, such as concrete shear walls or steel braces mixed with mass timber frames, OBC Sentence B-4.1.8.9.(3) states:

> "For combinations of different types of SFRS acting in the same direction in the same storey, $R_d R_O$ shall be taken as the lowest value of $R_d R_0$ corresponding to these systems."

While it may be simpler to use a non-wood SFRS, the design must account for the transfer of lateral loads from connections between the wood gravity system and the non-wood SFRS while accounting for differential movement between the two materials due to shrinkage.

For systems not listed in OBC Table 4.1.8.9, OBC Sentence B-4.1.8.9.(5) allows that with testing, research and analysis, other types of SFRS can qualify for values of R_d and R_o corresponding to the equivalent type in the table. Unless otherwise provided by the applicable referenced design standards for elements, R_d=1.0 and R_o=1.3 shall be used.

Table 4.1.8.9 lists only five types of SFRS for wood structures, to be designed and detailed in accordance with CSA O86. This includes two types of sheathed shear walls, two types of braced frames or moment frames with different ductility, and 'other' wood systems not listed. The table does not currently include cross-laminated timber shear walls although they are discussed in the CLT Handbook by FPInnovations (Gagnon and Pirvu, 2011) and in CSA O86-14 Update No.1 for design and detailing based on research, analytical modelling and testing from 2006 to 2013 in Canada and around the world. Limits on wall length (aspect ratio) for CLT shear walls and design of connections for elastic and ductile behaviour are provided in CSA O86. CLT shear walls meeting the limits on aspect ratios are permitted using R_d=2.0 and R_o=1.5. CLT shear walls that do not meet the requirements are permitted to use a combined $R_d R_o$=1.3 per CSA O86 and OBC Sentence B-4.1.8.15.(7).

For new systems, where the R-factors are not established, there are no specific procedures in Canada to aid in the development of ductility factors for new systems. Procedures are available from other countries and are outlined in the **FPI/TWBC** Section 4.3. Accredited research and testing facilities, such as FPInnovations, are able to determine these values as was the case for establishing the design values for CLT as noted above.

OBC Article B-4.1.8.10 lists additional restrictions on SFRS including limited use of Weak Storey designs (Type 6 Irregularity per OBC Sentence B-4.1.8.10.(1), and limiting the use of Type 4 (In-plane discontinuity in vertical lateral force resisting systems) and Type 5 (Out-of-plane offsets) per OBC Sentence B-4.1.8.10.(3).

OBC Sentence B-4.1.8.10.(4) prohibits wood-framed structures over 4 storeys to have Type 4 and 5 irregularities. Arguably, Type 4 and 5 irregularities could be permissible following an Alternative Solution, however, it is good engineering practice to avoid these two types of irregularities as it provides simplified lateral force transfers without the need for large transfer beams.

The determination of fundamental lateral building period can be determined with the Equivalent Static Force Procedure when the method is valid (as noted above) in accordance with OBC Sentence B-4.1.8.11.(3). The period calculation is listed in this sentence for different types of SFRS (e.g. moment frames, brace frames, or shear walls).

OBC Sentence B-4.1.8.11.(5) states:

> "The higher mode factor, M_v, and its associated base overturning moment reduction factor, J, shall conform to Table 4.1.8.11."

Note (5) of OBC Table 4.1.8.11 states that hybrid systems may require a Dynamic Analysis in accordance with OBC Article B-4.1.8.12.

Where Linear Dynamic Analysis is performed, OBC Clause B-4.1.8.12.(1)(a) states that either the Modal Response Spectrum Method or the Numerical Integration Linear Time History Method shall be used. Details on the modelling approach including the application of accidental torsional moments and scaling are listed in OBC Article B-4.1.8.12.

Lateral deflections and sway resulting from lateral earthquake loading are to be calculated in accordance to OBC Article B-4.1.8.13 and must be within the limits stated in OBC Sentence B-4.1.8.13.(3).

Diaphragms and associated chord members and struts are to remain elastic in accordance with OBC Sentence B-4.1.8.15.(1). However, wood diaphragms may be allowed to yield if designed for higher force levels with wood shear walls or other SFRS. In cases where wood diaphragms are designed to yield, collectors, chords and connections from the diaphragm to the SFRS shall be designed to the capacity of the diaphragm in accordance with OBC Sentence B-4.1.8.15.(3) and CSA standards for those elements. CSA O86-14 Subsection 11.8.6 requires that load transfer elements shall be designed for seismic loads that at 20% higher than the design seismic load on the diaphragm.

Foundations are to be designed to resist the lateral load capacity of the SFRS except when allowed to rock per OBC Sentence B-4.1.8.16.(1).

The building shall be designed to resist the most critical of wind load effects and earthquake load effects.

Connections, described below in Section 4.4.3, are critical parts of the SFRS to ensure behaviour that matches the assumed system ductility.

4.4. OTHER STRUCTURAL TOPICS

4.4.1. ANALYSIS AND TESTING

The analysis of a tall wood building is not the same as a conventional low-rise light framed building.

Lateral analysis
Common practice for the design of light framed wood construction is to use an envelope case of flexible and rigid diaphragm assumptions. Whether or not a diaphragm is flexible or rigid is based on the diaphragm stiffness compared to the SFRS, typically, mass timber floors, in contrast, are assumed to act as rigid diaphragms, which almost always requires the aid of structural software to determine the lateral load distribution to the SFRS.

Lateral analysis of a tall wood building can be done using either a static or dynamic analysis method. Dynamic analysis is more analytically involved, but is generally used to reduce the total base shear calculated from static analysis or when a static analysis procedures are not acceptable. Static analysis may not be appropriate in regions with high earthquake hazard, for torsionally susceptible buildings, or for buildings whose height exceeds the limits described in OBC Article B-4.1.8.7. See Section 4.3.4 above for more detail.

Testing
Tests are required for new material types or systems that are not covered in OBC or material design standards and when information about a product is not available (for example, fire rated assemblies, acoustic assembly performances, or custom connections). For more detail see section 4.2 of the **FPI/TWBC**.

Third-party reviews
Third party reviews may be required for submitting an Alternative Solution and should be prepared during the design phase to streamline the review process. Third party reviews are not always mandatory, but highly recommended since not all CBO’s will have the in-house expertise in the design of a tall wood building.

4.4.2. WOOD STAIR AND ELEVATOR SHAFTS

Wood stair and elevator construction is not commonly used in Ontario. In 5- and 6-storey wood construction, OBC requires that the stairs shafts are of noncombustible construction such as concrete, masonry or a rated assembly using steel. Elevator shafts, can be constructed of combustible construction. From a construction perspective, it makes sense to construct the elevator shafts with the same system as the stair shafts (especially if they are structurally connected). Additionally, many elevator suppliers require elevator cores to be steel, concrete or masonry construction due to very tight measurement tolerances with their elevators (the designer should confirm with the elevator supplier if shrinkage caused by wood can be tolerated in their design).

Construction of mass timber tall wood buildings most commonly use CLT for stair and elevator shafts, however, nail-laminated wood can also be used as is common on 5- and 6-storey wood buildings in other provinces and states.

Other design considerations as discussed above in Section 4.3 include accounting for shrinkage, elastic shortening and detailing for drag struts into shafts.

4.4.3. CONNECTIONS

Connections shall be designed per CSA O86 and may rely on CSA O86-14 Article 4.3.2 ***New or special systems of design and construction*** for fastener systems that are not found in Chapter 12 of CSA O86. If reports are available for certain proprietary connection systems, the Canadian Construction Materials Centre (CCMC) Registry of Product Evaluations should be consulted.

The project engineer may authorize an innovative fastener system, with or without third-party evaluation, if there is evidence that due diligence has been carried out through testing and research in accordance with CSA O86-14 Article 4.3.2. However, if confirmation by a third-party evaluation body is required, the CCMC evaluation report (or other third party organization evaluation reports) must be provided. The procedure for calculating the design values of innovative fasteners and assemblies, according to test data is detailed in FPInnovations *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada,* Article 4.2.3.6 and must be compatible with CSA O86-14.

The following are typical connections or details that can be found in tall wood buildings.

Connections using end-grain bearing – avoiding shrinkage
End-grain bearing connections have two benefits: the first is minimized shrinkage and the second is higher compressive resistance compared to perpendicular-to-grain bearing. Wood loaded parallel-to-grain is much stronger than wood loaded perpendicular-to-grain and is much less susceptible to shrinkage. The elastic shortening parallel-to-grain is not zero, and should be calculated, but also is much less than elastic shortening perpendicular to grain.

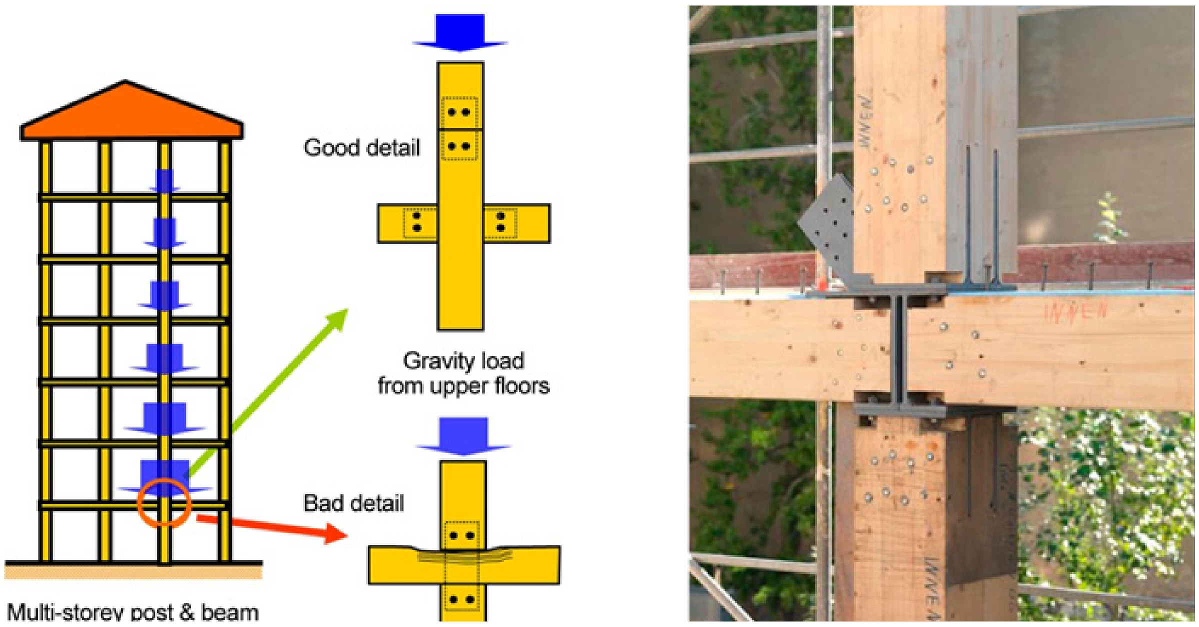

Figure 4.3. Example of an end grain bearing connection [From Figure 2 Section 4.2 of FPI/TWBC].

As a result, it is best to stack wood columns and bear through steel hardware, rather than sandwiching a wood beam between columns. Avoid direct wood-to-wood end-grain bearing since the end grain of each column can start to cut into each other.

This approach can be used in post-and-beam construction and floor slab and wall construction. See Figure 4.3. for an example of end-grain bearing. Variations to this are also possible with composite wood-concrete slabs to ensure diaphragm rigidity and continuity of load path for gravity and lateral loads.

Connections for hold-downs and prestressed rod systems

Tall wood buildings that rely on wood for lateral resistance to wind and earthquake, may require hold-downs and prestressed rod systems that can compensate for wood shrinkage over time. Such systems are readily available on the market and have been used successfully in wood mid-rise buildings (see Figure 4.4). Since shrinkage accumulates per floor, this problem is more prominent in tall wood buildings than in low-rise buildings but will depend on details such as end-grain bearing to minimize the effects of shrinkage.

Figure 4.4. Example of a hold-down rod system with shrinkage compensator (Photo: M. Alexander)

Connections for lateral loads

The behaviour of tall wood buildings subjected to wind and/or earthquake loads is typically controlled by the ability of connections to absorb energy, remain ductile and remain intact in case of overloading. Connections that need to be designed as energy dissipative are up to the designer. Generally, in wood SFRS these connections are the well panel to wall panel connectors, or hold downs at the base of the wall. See Section 4.2.3.3 of the **FPI/TWBC** and CSA O86-14 Update 1 for more detail.

Load duration, service condition (dry or wet) and mode of failure (brittle or ductile) are important variables in wood connection design. In high seismic risk regions, brittle connection failure modes must be avoided. See Section 4.2.3.1 of the **FPI/TWBC** for more detail.

Figure 4.5. Example drag strut at Origine, Quebec city (Photo: D. Moses)

As noted in the RBQ *Mass timber buildings of up to 12 storeys* guide:

> “The energy produced by wind or seismic activity is dissipated by several mechanisms, such as internal friction, friction between structural elements and plastic deformation. During extreme seismic events, a large part of this energy dissipation is obtained by non-linear deformation of the mechanical connections resulting from the elasticity of the metal connectors and support of the wood elements. When wood is used in long, tall and light structures, the dynamic response to the wind load and man-made vibrations can be significant, and joints can contribute significantly in terms of damping and rigidity, to the structure’s behaviour as a whole. For more details, see Section 4.2 of **FPI/TWBC**.”

Diaphragm connections

Where a diaphragm connects to the SFRS, the most common connector is a steel angle with fasteners penetrating into the diaphragm and into the SFRS (see Figure 4.5). This connection will transfer the shear force from the diaphragm (floor or roof) at that level and may also be used to transfer gravity forces (if applicable). In the case of a centralized core, or openings, the shear force needs to be transferred via tension straps, chords or drag struts. In the simplest form, these connections can be made with steel plate straps with fasteners to transfer the load.

CLT Panel to Panel Connection

There are three types of panel to panel connections in CLT buildings: wall-to-wall, floor-to-floor, and wall-to-floor. All of these connections need to be designed to transfer lateral loads, gravity loads (if applicable), and maintain the proper ductility requirements based on its Rd Ro values. The deformation of the connections needs to be considered when analysing interstorey drifts (similar to wood shear walls and nail slippage). See Figure 4.6 below for a sample wall to wall panel connection.

Figure 4.6. Example wall to wall panel connection (Photo: D. Moses).

Connections for wood to non-wood elements

Connections at interfaces with other materials such as concrete, masonry or steel, may require slotted connections to accommodate shrinkage of wood. Attention to detailing is required to ensure that gravity and/or lateral loads are still transferred. For example, providing a vertical slotted connection to permit the wood to shrinkage when connected to another material. See Figure 4.7 and FPI/TWBC for more details.

Figure 4.7. UBC Brock Commons demonstration connection of a CLT panel to concrete shear wall with tension strap and vertically slotted connection (Photo: D. Moses)

Figure 4.8. Concealed connection by Nordic, Quebec (Photo: D. Moses)

Fire rating of connections

In systems with exposed structures, steel connectors must be protected to achieve the appropriate fire rating. If structural members are encapsulated, then the connections need to be encapsulated also. In exposed conditions, connections should be concealed within the wood member (see Figure 4.8 for example concealed connection). If there is an expected cross sectional loss due to fire, the connection must be designed with spacing and end distance requirements of the cross-section loss. Gypsum board can also be used to provide protection. Requirements are provided in CSA O86-14 Annex B.9. Also refer to Sub-section 3.7.1 above for more detail.

4.4.4. ROOF ANCHORS

Roof anchors are designed in accordance with CAN/CSA-Z91 "Health and Safety Code for Suspended Equipment Operations" to provide resistance for life-safety for window washing equipment or other uses for access to the building façade such as maintenance and repair work. The design forces are significant for wood buildings and may require additional testing by the supplier of the roof anchor system to ensure the capacity is adequate for the applied loads. Serviceability is limited by potential damage to finishes. A design review of load path for uplift forces that result from roof anchor overturning is required to ensure that uplift forces are resisted by engaging the self-weight of the building structure over sufficient height to resist these forces (the designer shall use appropriate force reduction factors for the self-weight resistance in accordance with OBC Sentence B-4.1.3.2.(5).

4.4.5. GUARDS

Live loads on guards listed in OBC Article B-4.1.5.14 shall be reviewed for members and for connection forces to the wood substructure. OBC SB-7 Guards for Housing and Small Buildings lists pre-approved details for guards on low-rise buildings under 600 m^2 and should not be relied upon for guard design in tall wood buildings. Guard assemblies for tall wood buildings are to be designed to the requirements of OBC Article B-4.1.5.14 and may require testing to confirm performance in accordance with the strength requirements for guards in OBC. Serviceability of guards may be controlled by wind loading requirements on the guards.

4.4.6. DURABILITY

In regions susceptible to termites, OBC Sentence B-4.3.1.3.(1) referring to OBC Articles B-9.3.2.9., B-9.12.1.1. and B-9.15.5.1 provides requirements to avoid contact and damage. OBC Sentence B-5.1.4.2.(3) states:

> *"Design and construction of assemblies separating dissimilar environments and assemblies exposed to the exterior shall be in accordance with good practice, such as described in CSA S478, "Guideline on Durability in Buildings"."*

4.4.7. PROGRESSIVE COLLAPSE

As noted above in section 2.4 designing for progressive collapse in tall wood buildings is new for designers. As stated in CSA O86 Article 4.3.3, the design shall prevent widespread collapse in the event of local failure:

> “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.”

NBCC 2010 Structural Commentary B *Structural Integrity* Sentence 6 (Safety Measures) has a similar statement requiring the design to prevent widespread collapse (i.e. progressive collapse). OBC B-4.1.1.3.(1) hints are design to prevent progressive collapse when it mentions “structural integrity”.

Progressive collapse is a potential failure mode of buildings that could occur if one bay of a structure fails and could possibly cause the failure of adjacent bays. This mode of failure is normally associated with explosions from gas appliances, impact from vehicular collisions or blast loading. Other causes of collapse are from impact loads, such as snow or ice falling off a roof onto balconies or lower roofs or floors and should be addressed as well. Eliminating the use of gas appliances is a simple solution to avoid the additional detailing associated with progressive collapse, but this is not always an option due to user needs. Note that in Ontario the Technical Standards and Safety Authority (TSSA) has issued an article *Guidelines for the Distribution of Natural Gas in Multi-Family Buildings* which provides information progressive collapse for the design of concrete and masonry buildings. This article notes that for other structural systems should be designed for a very high blast pressure is required.

In concrete buildings, the addition of *integrity steel* reinforcement over columns or peripheral ties in precast buildings are used to minimize this possible mode of failure. FPInnovations *Technical guide for the design and construction of tall wood buildings in Canada* has examples of design concepts to help designers mitigate the possibility of progressive collapse including:

- Arranging longitudinal interior walls to provide additional support in wall bearing structures
- Providing an integrated system of ties along the principal elements designed as secondary elements that can sustain large deformations
- Using walls that are perpendicular to the load bearing walls for stability
- Reinforcing one-way slabs to sustain loads in the perpendicular direction as an alternate load path
- Designing one-way slabs to span an increased span if one line of support fails (larger deflections are acceptable)
- Designing load bearing walls to withstand additional loads due to an increased tributary width
- Providing redundancy in design (e.g. an upper floor supporting a lower floor) (allowing an upper floor to support a lower floor provides a secondary load path)
- Using ductile connections to accommodate large deformations

4.4.8. HYDROSTATIC UPLIFT

Because tall wood buildings are lighter than concrete buildings, foundation size must be designed to resist overturning (either by weight or rock anchors). Hydrostatic uplift must be considered in the design of foundation in accordance with OBC Article B-4.2.4.8.

4.4.9. SPRINKLER AND MECHANICAL EQUIPMENT

The design of sprinkler systems and attachments shall allow for shrinkage of the building and deflection/

sagging that may occur during and after earthquake events to ensure that the sprinklers remain operational and limit damage from fire that may occur after an earthquake (see Section 4.3.2.2.8 of FFPI/TWBC). OBC B-6.2.1.3 also requires that mechanical systems shall be designed and installed for the maximum relative structural movement.

4.5. INFORMATION TO SHOW ON STRUCTURAL DRAWINGS/SPECIFICATIONS

Designers should provide additional information on drawings beyond the minimum requirements of NBC Article B-4.1.1.4 which refers to Subsection 2.2.4 of Division C for structure (Article C-2.2.4.3) and foundations (Article C-2.2.4.6). These NBC requirements include sealing drawings, locating and providing sizes of structural elements, noting applied loads and foundation bearing capacities. This information can be provided on the structural drawings, or in an outline specification, at the discretion of the building department.

The recommended additional information is meant to aid the review process and should include the following:

1. Structural material properties;
2. Loading;
3. Shrinkage; and
4. Connection details.

Structural Material Properties

As a minimum, the drawing notes should specify the following:

1. Wood species and grade for all types of wood products specified, member deflection criteria, material treatment, reinforcement requirements and yield strength of steel fasteners, anchor bolts and other hardware.
2. Member dimensions and associated connections including connection type, connection spacing, and fastener diameter, length and spacing. Note limits on allowable notches, size and location in beams, columns, walls, and floors.

Loading

Loading information should be listed for gravity, lateral and other load effects. Dead loads, live loads, snow loads, soil loads, wind and earthquake loads are required.

Dead loads, live loads and soil loads should be illustrated on plan particularly if they vary between levels and areas and should include uniform and concentrated loading conditions. Partition loads are to be noted per OBC Sentence B-4.1.4.1.(3) and NBC Clause C-2.2.4.3.(1)(d).

Snow drifts due to parapets, varying roof heights, adjacent buildings, and balconies should be illustrated on plan. Impact of snow drifting to adjacent buildings should be reviewed. Impact of snow or ice falling from sloped roofs on lower portions of the structure, people, equipment, etc, must also be considered.
Lateral loads should be listed with detailed breakdowns of the base shear calculations for each of wind and earthquake loads.

Wind loading should be broken down to reflect: location, $q_{1/50}$, building dimensions, terrain type, analysis method, importance category, C_e, C_p, C_g, design pressure, diaphragm forces, shear flow around openings, drag strut forces, calculated storey displacements, inter-storey drift allowable compared to calculated, total base shear, and overturning moment in each of the principal horizontal design directions per OBC Subsection B-4.1.7. Parameters from dynamic analysis and/or experimental wind studies should be listed or provided in a separate report. Elevations should be provided of the lateral system to illustrate force distribution in the principal horizontal directions.

Earthquake loading should be broken down to reflect: location, S_a and PGA values, importance category, number of stories, building height, period for each direction for earthquake loads and deformations, site class, F_a, F_v, earthquake hazard, risk category, structural irregularities (whether they present and not present), method of analysis, SFRS type, R_d, R_o, total earthquake weight as defined in OBC Sentence B-4.1.8.2.(1), M_v, J, diaphragm forces, shear flow around openings, drag strut forces, total base shear, overturning moment, and inter-story drift (allowable compared to calculated). Torsional effects should be listed for each floor with calculated storey displacements in accordance with Sentences B-4.1.8.11.(8), (9) and (10). Elevations should be provided of the SFRS to illustrate force distribution in the directions of loading noted in OBC Article B-4.1.8.8.

Shrinkage

A list of calculated shrinkage and differential shrinkage of materials over the building height should be provided. The expected building shrinkage should also include assumptions in the shrinkage factor used, materials considered, and the assumed moisture content change. An estimate of expected shrinkage is required for non-loadbearing wall construction, plumbing, cladding attachment, and separated balcony alignment.

Connection details

Connection details for shear and gravity transfer should be provided at the following interfaces: floor-wall, floor panel-floor panel, wall panel-wall panel, beam-column, beam-wall, super structure to foundation, super structure to podium, and all wood to non-wood structural elements. Details and location of anchorage systems, including additional reinforcement and any shrinkage compensators, if required.

Construction notes

Limits on construction tolerances should be listed. Limits on notching elements on site (or restrictions on site modification) shall be noted.

5. ADDITIONAL RESOURCES

http://www.cwc.ca
http://www.fpinnovations.ca
http://www.naturallywood.com/resources
http://www.rethinkwood.com/tall-wood-mass-timber
http://www.ontario.ca/page/building-with-wood
http://www.timbereducation.org
http://bookshop.trada.co.uk

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