Fire Safety Challenges of Tall Wood Buildings

Final Report

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FOREWORD

Recent architectural trends include the design and construction of increasingly tall buildings with structural components comprised of engineered wood referred to by names including; cross laminated timber (CLT), laminated veneer lumber (LVL), or glued laminated timber (Glulam). Construction is currently underway on a 10-story apartment building in Melbourne, Australia, with taller structures up to 30 stories under design in Norway, Austria and Vancouver. These buildings are cited for their advantages in sustainability resulting from the use of wood as a renewable construction material. Claims have been made that they are designed to be safer than buildings fabricated using structural steel due to the formation of an insulating char layer that forms on the perimeter of a laminated wood beam when exposed to a fire.

The Fire Protection Research Foundation initiated this project to gain an understanding of the performance of these buildings under credible fire scenarios to ensure the safety of the occupants to emissions and thermal hazards, as well as the property protection of the building and nearby structures. The goals of this first phase project was to gather information and data from relevant studies and analyze the knowledge gaps. In addition, a framework prioritization of research needs was produced.

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The content, opinions and conclusions contained in this report are solely those of the authors.

Keywords: high-rise buildings, timber, structural fire safety

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Fire Safety Challenges of Tall Wood Buildings

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References

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Executive Summary

Acknowledging the growing importance of designing sustainable buildings and addressing overpopulation concerns, the development of engineered wood products has introduced the possibility of constructing high-rise timber structures that can improve both these conditions.

However, as a combustible material, one of the biggest barriers to construction of tall timber buildings is the potential fire risk resulting from the combustible structure. In November 2012, the Fire Protection Research Foundation commissioned the Fire Safety Challenges of Tall Wood Buildings study to address this concern.

Phase I of this two-phase study seeks to collect the available knowledge of fire safety in timber structures and identify gaps in knowledge that would further the understanding of fire performance of tall timber buildings. Results of the study, including a summary of timber construction and fire dynamics, is presented herein.

1 Introduction

This study seeks to summarize the current knowledge of fire safety challenges in tall timber construction and identify gaps in knowledge needed to understand the potential for use in taller timber buildings.

1.1 Phase 1 of the Fire Safety Study

This report addresses Phase 1 of an expected multi-phase project. Phase 1 seeks to evaluate the current knowledge of tall timber construction, identify gaps in knowledge, and reflect on the gaps that, if fulfilled, will provide a better understanding of the potential fire safety performance of tall wood buildings.

Phase 1 is comprised of two tasks:

1.1.1 Task 1 – Literature Review

The *Task 1 – Literature Review* seeks to characterize the fire performance of timber as it relates to the design of tall buildings. The literature review collects and summarizes the resources available in literature that can be used to identify fire safety challenges in tall timber buildings. The section also provides case studies of tall wood buildings that provide examples of approved fire safety designs and strategies.

1.1.2 Task 2 – Gap Analysis

Results from the *Task 1 – Literature Review* are used to inform the *Task 2 – Gap Analysis.*

The *Task 2 – Gap Analysis* seeks to identify the design and material gaps in knowledge that need to be explored to better understand the performance of timber as applied to tall buildings. The gap analysis discusses specific areas of research necessary to better understand the fire safety challenges in tall timber buildings.

1.1.3 Phase 2 of the Fire Safety Study

Results from Phase 1 of the Fire Protection Research Foundation, Fire Safety Challenges of Tall Wood Buildings study are intended to inform Phase 2 of the project. Phase 2 will be addressed at a later time.

1.2 Background

In the past decade, the building design industry has been increasingly turning towards timber with an interest in taller timber buildings. This development has partially to do with the innovation of new engineered timber products and the potential economic benefits of prefabricated timber and timber composite systems. However, it is predominantly a shift towards green and sustainable architecture that has brought timber onto the agenda of many architects, building owners and governments (AWC, Green Building, 2013) (CWC, Sustainability, 2013).

Sustainability in the construction and operation of buildings is a key driver for owners, managers and designers. Timber can be considered an attractive material for green building construction, as it is often perceived as an environmentally friendly, sustainable resource (CWC, Climate Change, 2013). If sustainably sourced, timber is nearly carbon neutral compared to most industrial materials, and the wood itself is 100% renewable (AWC, US Wood Products - Good for Jobs, Rural Communitites and the Environment, 2010).

The growing desire to design sustainable buildings has started to raise the question, among others, as to how the use of timber construction can positively contribute to sustainable development:

- Timber is considered a renewable resource and the forests supplying timber can offer a natural carbon sink;
- The resource extraction and manufacturing phases of timber products demand relatively very low energy compared to more conventional structural materials used in commercial construction; and
- Innovative timber systems designed for prefabrication and disassembly allow for reuse of the material and a more resource-efficient product life cycle than typical demolition and down-cycling.

Timber has other positive attributes and qualities that include:

- Possibility of offsite prefabrication and minimized onsite work allowing for high-quality certified production, independence from weather and a rapid erecting progress;
- Provides for a lightweight building, resulting in savings in foundation works when compared to other construction materials;
- Ease of alteration on site; and
- Increase in architectural design options.

Timber has many uses in construction, which currently include:

- Structural and lining material for one- and two-story residential housing;
- Structural and lining material for low- and mid-rise assembly, commercial, educational, sports, sculptures, leisure and industrial buildings;
- External lining material for low- and mid-rise buildings; and

- Formwork for concrete.

Similar attributes can also be found in other conventional construction types, such as steel and reinforced concrete.

With the development of new engineered timber products and the growing awareness of the efficiencies provided by prefabricated timber composite systems, the construction industry has come to recognize that timber can also offer an economically favorable construction method.

Despite these attributes, timber as a construction material has been negatively viewed due to the perception of increased fire hazard. This has been reinforced by some model building codes through height and area limitations (APEC, 2005).

The use of timber as a construction material for urban mid-rise and high-rise developments has been traditionally restricted by building codes and regulations in many countries, reflecting concerns about the combustibility of the material (CWC, Building Code, 2013).

With a better understanding of new technologies, new design tools, recent research, experimental and full scale testing, and a more rigorous assessment of the true risks compared to other construction types, it is possible that the former concerns and current restrictions should be reconsidered.

While this study aims to characterize the fire performance of tall timber buildings, it focuses on addressing current fire safety challenges. Though the report presents internationally published literature, it is primarily written with a US regulatory context.

In some countries, the term “timber” is also referred to as “lumber” or “wood”. This report uses the term “timber”, which is typically used to define a sawn or engineered product used for construction.

Some countries also refer to heavy timber as “mass timber” or “massive timber” construction. This report uses the term “heavy timber” and distinguishes the type of heavy timber construction type being addressed.

1.3 Context: Visions of Tall Timber

Timber is becoming an increasingly desirable construction material as international architects and designers understand that timber has significant potential benefits in sustainability and construction. Traditional schemes for timber buildings as low-rise (two-stories or less) and mid-rise (three- to five-stories) are now being extended with schemes for new high-rise buildings, also referred to as tall timber buildings (six-stories or greater).

These include high-rise designs that attempt to maximize the use of timber as a renewable resource and feature exposed timber elements throughout the structure. Some proposed designs explore the potential to reach heights in excess of 30-stories (Green, The Case For Tall Wood Buildings, 2012).

While these buildings present ambitious designs for the future vision of tall timber structures, designers are currently limited by prescriptive code legislation. These codes restrict the potential for tall timber buildings based on the issues of structural and fire safety, as height and area limitations restrict use. As knowledge and understanding of fire and timber buildings develops, the potential for regulatory change becomes increasingly possible.

1.4 Principles of Fire Safety

This section presents a brief introduction to the fundamental principles of fire safety regulations in buildings. The references cited should be utilized for further reading.

Fire safety regulations provide a means to protect society in the event of a fire. The regulations typically include precautions in design, construction and maintenance, to prevent or reduce the likelihood of a fire that may result in death, injury or unacceptable property damage. The primary goals for fire safety are summarized in 2012 NFPA 5000 (NFPA, NFPA 5000 Building Construction and Safety Code, 2012):

- Safety from Fire Goal:
  - To provide an environment for the occupants inside or near a building that is reasonably safe from fire and similar emergencies.
  - To provide reasonable safety for fire fighters and emergency responders during search and rescue operations.
- Safety from Structural Failure Goal:
  - Provide a high confidence of a low probability of structural failure resulting in local or global collapse, or the creation of falling debris hazards that could threaten life.
  - Provide a high confidence that the structure will be capable of resisting regularly occurring loads and combinations of loads without significant damage or degradation.
- Safety during Building Use Goal:
  - Provide an environment for the occupants of the building that is reasonably safe during the normal use of the building.

Fire safety goals are also presented in 2012 International Building Code (IBC) guidance in Chapter 1 (ICC, 2012 International Building Code, 2012).

The overwhelming majority of buildings in the world are designed in accordance with prescriptive regulations. In such prescriptive regulatory environments, fire safety is recognized as being achieved by a structure that is designed to meet the prescriptive requirements of the code.

In some jurisdictions, codes and regulations allow a performance based approach to be adopted, whereby an engineered solution can be developed that provides an acceptable alternative to the prescriptive code requirements. Using an engineered approach, or performance based solution, is discussed in Section 1.4.5.

While the principles above list the fire safety goals for occupied buildings, a designer must also consider fire hazards and the building fire protection systems to develop a more fully integrated fire safety strategy to achieve the principles of fire safety.

1.4.1 Fire Hazards

Understanding potential fire hazards is critical to designing a building fire protection strategy. Fire hazards are often identified using a fire hazard assessment. This is intended to identify potential sources of ignition and conditions that may result from a fire.

Fire hazard assessments often include surveys or checklists. The SFPE Handbook of Fire Protection Engineering highlights the following items for identification as part of a fire hazard assessment (Meacham, 2002):

- Potential ignition sources;
- Potential fuel sources;
- Arrangement of fuel packages;
- Building and compartment configurations; and
- Presence of fire safety features.

Careful consideration of fire hazards helps to drive the selection of materials, products and their environments within the building.

1.4.2 Active Fire Protection: Detection, Alarm and Suppression

Once a building fire has started, the first line of defense is a building's active fire protection system. The Fire Protection Handbook defines active fire protection as (Janssens, Basics of Fire Containment, 2008):

> The fire protection devices that require manual, mechanical, or electrical power.

Active systems require an impulse, be it manual, mechanical or electrical for activation. Active fire protection systems include automatic detection, alarm and suppression systems. These systems are intended to provide early fire detection, alert building occupants to a potential fire event, control fire growth to a small size and potentially suppress the fire (Custer & Hall, 2008).

Active fire protection systems are designed based on identification of the fire hazards and consideration of the life safety objectives.

1.4.3 Passive Fire Protection: Fire Compartmentation and Structural Stability

Whereas active fire protection is the first line of defense in a building fire, passive fire protection is the final opportunity to control a fire. The Fire Protection Handbook defines passive fire protection as (Janssens, Basics of Fire Containment, 2008):

> Fire protection that does not require any external power, but relies instead on specific construction features and the use of materials, products, and building elements that meet well-defined fire performance requirements.

Passive fire protection systems are inherently designed into the building structure and architecture to confine fire and smoke to designated zones and protect life safety. This concept is referred to as compartmentation and is intended to limit the fire size and smoke spread through occupied areas (Custer & Hall, 2008).

Some forms of passive fire protection systems include the use of fire-resistance rated structural elements and limiting the use of materials within a building. Special consideration is given to structural integrity and occupant evacuation paths. This includes providing fire protection to structural elements and restricting flame spread and smoke production properties for materials along egress routes.

Designing passive fire protection systems relies on an understanding of both the fire hazards and the active fire protection systems to achieve the safety objectives.

1.4.4 Occupant Evacuation

Occupant evacuation depends upon early fire detection, alerting occupants to a building fire and consideration of the fire protection features to develop an effective occupant evacuation strategy (Custer & Hall, 2008). These features include:

- Fire detection and alarm systems to alert occupants of a fire event;
- Fire suppression systems to control or suppress fire growth to limit the spread of fire and smoke;
- Fire-rated assemblies to limit fire and smoke spread to the compartment of fire origin; and
- Fire- and smoke-rated elements to limit fire spread and smoke production along evacuation paths.

Consideration of the above information can be used to develop a performance approach to safe occupant evacuation. This involves calculating the following:

- The required amount of time for occupants to reach a place of safety starting at the time of ignition, also referred to as the required safe egress time (RSET); and
- The amount of time available until conditions are too dangerous for occupants, also called the available safe egress time (ASET).

Generally, life safety is considered to be achieved where the ASET is greater than the RSET (Nelson & Mowrer, 2002). Assumptions, calculations and factors of safety used to establish the ASET and RSET require approval from the building authority.

Occupant evacuation also relies on appropriate means of escape, such as stairs, exits, egress routes, exit signage, etc. The required means of escape are generally defined in the building codes.

In order to fully understand the occupant evacuation strategy, the fire hazards and active and passive fire protection systems must be carefully assessed to meet the safety objectives.

1.4.5 Using an Engineered Approach / Performance Based Design

Many building codes provide the option of proposing an alternative design method in lieu of following the prescriptive requirements. This strategy is also referred to as a performance based solution, performance based design, or in some cases, an alternative solution. The alternative design method is intended to provide a design solution that conforms to the intent of the code, providing the level of safety, reliability and durability intended by the prescriptive solution.

Performance based codes provide functional requirements that are intended to allow flexibility in structural material compared to traditional prescriptive codes (Ostman & Kallsner, National building regulations in relation to multi-storey wooden buildings in Europe, 2011).

2012 NFPA 5000 provides guidance for a performance based fire solution. The document suggests that an alternative method shall be approved where the building official agrees that a performance based design has met the required safety goals (See Section 1.4) (NFPA, NFPA 5000 Building Construction and Safety Code, 2012).

Guidance in 2012 NFPA 5000 also requires that the building design shall meet the following performance requirements:

- Safety from fire;
- Safety from structural failure;
- Serviceability performance;
- Immediate occupancy performance;
- Collapse and structural failure prevent performance;
- Safety during building use;
- Function;
- Cultural heritage;
- Mission continuity;
- Environment; and
- Uncontrolled moisture.

Details of the aforementioned objectives are available in 2012 NFPA 5000, Section 5.2 (NFPA, NFPA 5000 Building Construction and Safety Code, 2012).

Performance criteria in NFPA are similar to the minimum safety requirements in 2012 International Building Code (IBC) guidance (ICC, 2012 International Building Code, 2012). These are discussed in Chapter 1 of the 2012 IBC.

The designer must demonstrate that the alternative solution meets the previously listed goals and performance requirements to be considered as an alternative equivalent to the prescriptive requirement. Guidance for performance based design of timber buildings is also available in technical guidance for Europe (Ostman, Fire Safety in Timber Buildings - Technical Guideline for Europe, 2010).

In many countries, the prescriptive building codes are generally restrictive with respect to the maximum number of stories and building area allowed for timber buildings. Hence, a performance based approach is particularly relevant for the use of timber as the type of construction in taller or larger buildings.

The prescriptive limitation in height is primarily defined by the nature of the structural building material. Prescriptive height and area limits for non-combustible materials, such as steel and concrete, are practically unlimited. As a combustible material, prescriptive limits on timber buildings are generally capped at eight stories or less.

The table below presents a review of the prescriptive height limits for maximum number of stories in multi-story timber buildings with and without sprinkler protection, for a number of international codes at the time of this writing. As the understanding of, and familiarity with, timber structures improves, changes to the prescriptive height limits become increasingly feasible.

Table 1 – International code review for maximum number of stories in timber buildings

Country	**Applicable Building Code**	**Maximum # of Stories**	
		Sprinklered	**Non-Sprinklered**
Australia	2013 Building Code of Australia (BCA)	3	3
Austria	Austrian Building Codes	8 (*72 feet [22m])	4
Canada	2010 National Building Code of Canada (NBCC)	4	3
Germany	2012 Federal Building Code	8 (*59 feet [18m])	5
Sweden	2013 Planning and Building Act	8	2
United Kingdom	2010 Building Regulations	8	6
United States	2013 International Building Code (IBC)	5**	4**
	2012 National Fire Protection Association (NFPA) 5000	6**	5**

*Indicates a height limit in addition to a maximum story limit

**Number of Heavy Timber stories permitted

The maximum number of stories is presented for typical occupancies. There are exceptions for special occupancy types. For example, the National Building Code of Canada allows 4-story combustible construction for Group F, Division 3 light industrial occupancies. Similarly, the US Codes allow for the construction of a mezzanine level or fire-resistive non-combustible parking garage in lieu of an additional story.

Providing an alternate solution to the prescriptive code provides the mechanism for designers to exceed the maximum story limitations for combustible timber buildings. However, the justification for an equivalent level of safety as noncombustible construction is driven by a greater understanding of tall timber building performance.

1.5 Timber Building Fundamentals

The following section is intended to introduce a fundamental background for developing a working vocabulary and understanding of timber building design. Having a basic understanding of timber buildings is intended to give a greater context to the discussion provided in Phase 1 of this study.

Timber products, technologies, and methods of construction have evolved over time. The two most popular forms of timber framing can be categorized as:

- Light timber framing; and
- Heavy timber framing.

Light timber frame and heavy timber frame buildings, also referred to as light frame and heavy frame, or light timber and heavy timber buildings, have many fundamental differences, and are designed and constructed for different types of buildings depending on size, function, and height.

However, the primary difference between light and heavy timber construction is the section size of the timber members used in construction. This has a significant impact on the fire performance and method of fire protection.

Characteristics of light and heavy timber frames are discussed in a number of design guidance documents internationally (AFPA, 2001) (Buchanan, Structural Design for Fire Safety, 2001) (White R. , Analytical Methods for Determining Fire Resistance of Timber Members, 2002) (Ostman, Fire Safety in Timber Buildings - Technical Guideline for Europe, 2010).

A comparison summary is presented in the following table, with further explanation below:

Table 2 – Summary of light timber and heavy timber frame construction

Framing Type	Average Max Height	Typical Timber Elements	Typical Nominal Member Size	Typical Building Function	Protected vs. Unprotected
Light Timber Frame	Up to 5-6 Stories	Studs and joists	2” x 4” [50mm x 100mm] to 2” x 12” [50mm x 300mm] or similar	Residential	Gypsum board protection
Heavy Timber Frame	Up to 8+ Stories	Columns, posts and beams	Greater than 6” x 6” [150mm x 150mm	Residential / Commercial	*Unprotected beams and posts and / or gypsum board protection

*Application of gypsum board protection is dependent on approval authority requirements

To provide greater understanding of timber as a construction material, the fundamental differences between light and heavy timber frame construction, as well as their fire performance, are presented in the following sections. For further reading, please refer to the references cited.

1.5.1 Light Timber Frame Construction

Light timber frame construction, also referred to as light frame, or light timber construction, is characterized by timber walls and floors that are constructed from timber stud and joist members, respectively. Walls and floors are typically encapsulated within non-combustible gypsum plasterboard to offer sound insulation, surface finishes and protection from fire.

Wall and floor assemblies are often load-bearing and can also include linings and bracing elements, such as oriented strand board (OSB), plywood and gypsum board, for additional strength, or to improve lateral load resistance (wind, earthquake). Timber joists are used to carry loads for floors, and also distribute those floor loads to walls and other load-bearing elements.

The assembly of timber studs and joists, with wall and floor assemblies inter-connected, provides the structural stability and fire resistance for light timber frame buildings. This structural assembly is conceptually often referred to as platform or balloon frame construction and is primarily used for low- to mid-rise design with many partitions throughout the floor plate.

1.5.1.1 Products Used in Light Timber Framing

The primary structural elements for light timber framed buildings are timber beams, joists and trusses. These elements are typically nominally sized at 2” x 4” [50mm x 100mm] to 2” x 12” [50mm x 300mm] and other similar measurements (Buchanan, Structural Design for Fire Safety, 2001). Nominal dimensions for light timber represent the green, or rough, timber elements and are slightly larger than the actual finished dimensions due to shrinkage and planing.

Examples of timber stud members are shown below.

Figure 1 – Light timber frame stud members (TRADA, Treated Timber, 2012)

Figure 2 – Light timber frame stud members (Freeman, 2013)

The light timber framing elements, also referred to as studs in walls assemblies and joists in floor assemblies, are used to form the internal and external partitions for the structure (AFPA, 2001). Timber studs are quickly assembled to frame the structure, with mechanical services and insulation located within the light timber frame assembly.

The wall and floor assemblies are protected by rigid framing, such as oriented strand board or gypsum board, on any exposed surfaces. Timber studs and rigid panel framing form the wall assemblies. Floors are constructed using joists and rigid panel framing, clad to the underside with gypsum board.

Floor assemblies can also be constructed using "I-joists", or engineered timber sections consisting of timber flanges and a panelized web (TRADA, Timber I-joists: applications and design, 2012). Flanges typically consist of engineered timber composites and panelized webs of oriented strand board (OSB) or plywood. An example of timber I-joists are shown in the following image.

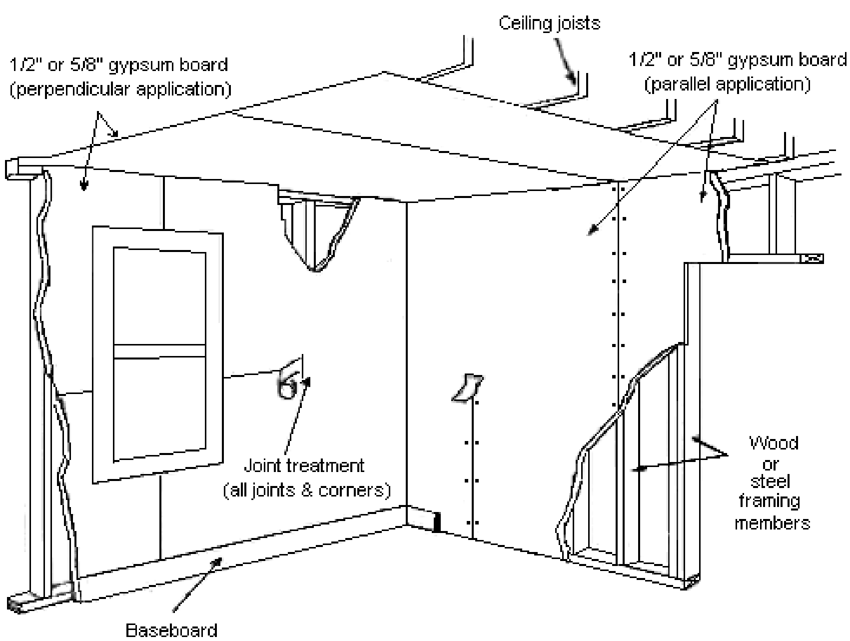
Figure 3 – Example of timber I-joists (TRADA, Timber I-joists: applications and design, 2012)

Examples of gypsum board protection are shown in the following images.

Figure 4 – Example of gypsum board (BritishGypsum, 2013)

Figure 5 – Gypsum board panels to be applied over timber framing (GypsumAssociation, 2013)

Figure 6 – Example of typical gypsum board framing for light timber frame construction (GypsumAssociation, 2013)



1.5.1.2 Construction Framing in Light Timber

Light timber frame is a popular construction type due to its simplicity and speed of assembly. It is often used for one- and two-story residential buildings, and occasionally used in buildings up to five- and six-stories, typically above a reinforced concrete ground floor.

Framing methods include "platform" and "balloon", or stick-framed construction. Platform-framing is characterized by framing where each floor is supported by the floor below, whereas balloon framing involves continuous vertical framing for exterior walls that brings loads directly to the ground (AFPA, 2001). Platform-framing is most generally used in home construction.

Framing elements and assemblies are typically connected by nails and screws at regular intervals. This combination of timber structure and ductile steel connections has been shown to perform well in seismic events (WoodWorks, Multi-Story Wood Construction, 2013).

The figures below indicate examples of light timber frame construction.

Figure 7 – Wall stud framing over concrete floor slab (platform-framing) (TRADA, Introduction to Timber Frame Construction, 2012)

Figure 8 – Typical platform-framing (AFPA, 2001)

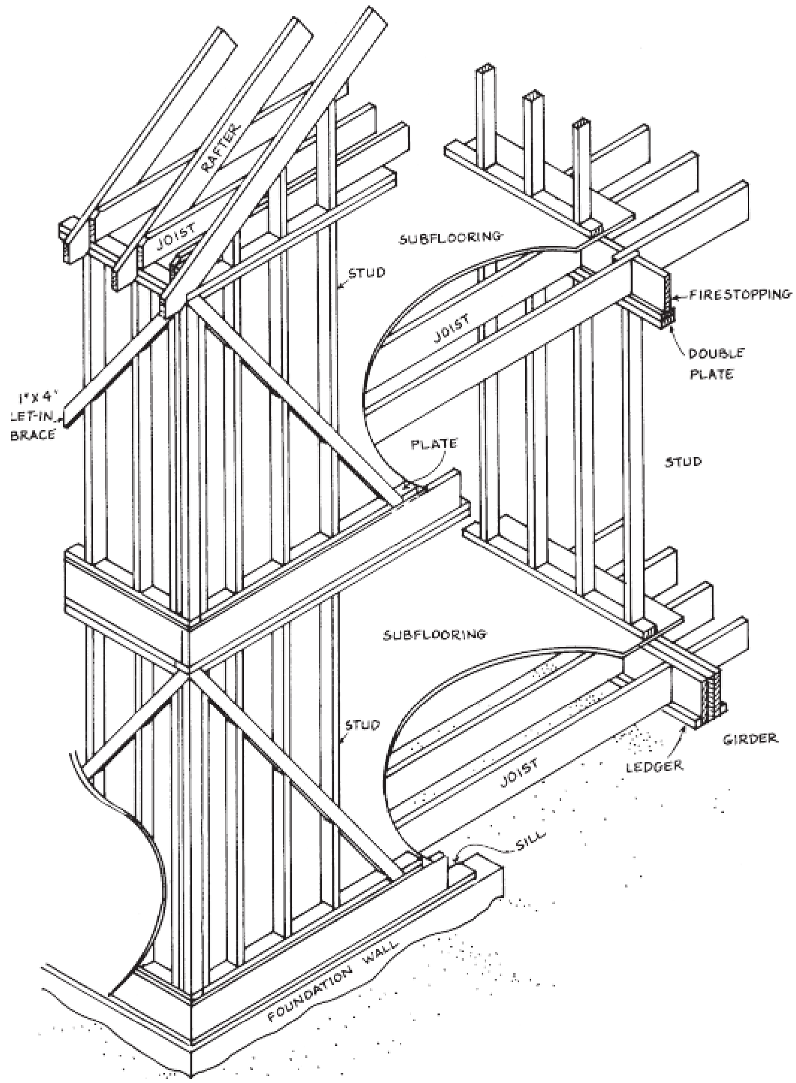


Figure 9 – Typical balloon-framing (AFPA, 2001)

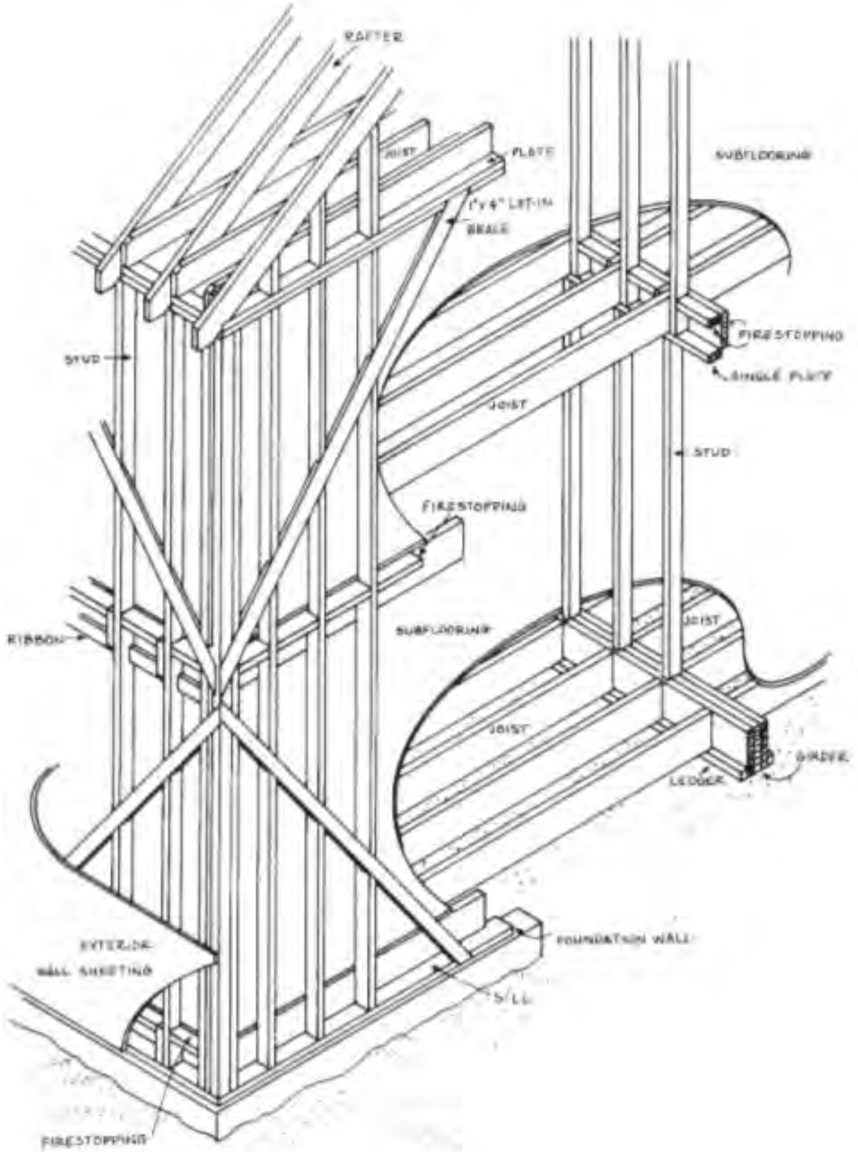
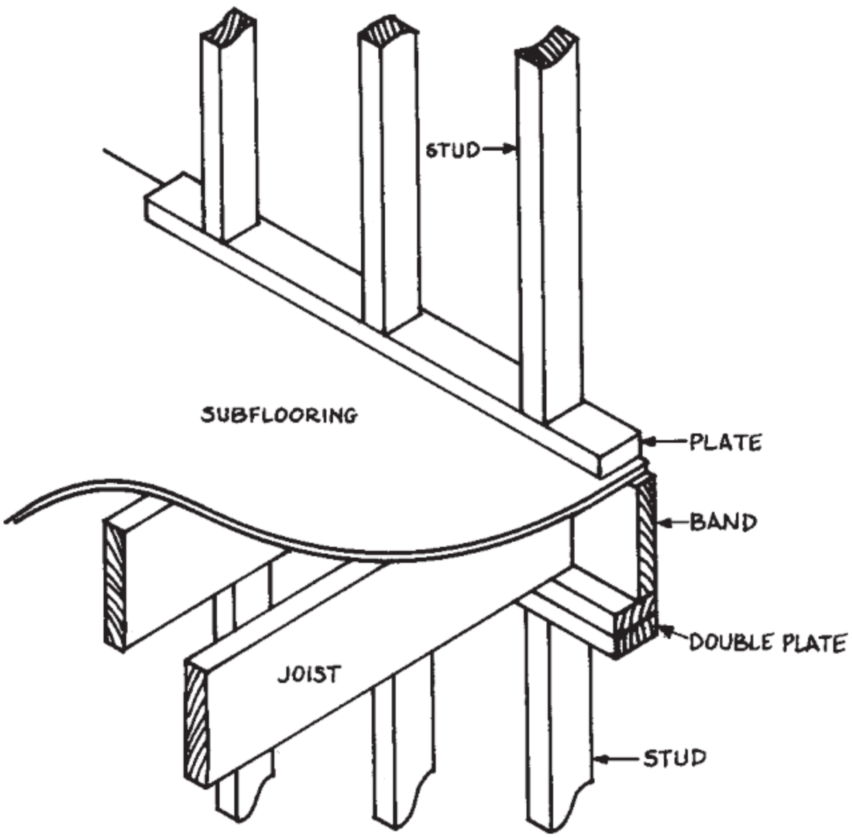


Figure 10 – Typical second floor framing showing floor joists, wall studs and plywood protection (AFPA, 2001)



1.5.1.3 Connections in Light Timber Framing

Connections in light timber frame buildings generally consist of a large number of small steel connectors that are connected to the timber framing using nails and/or screws. Panels and lining surfaces, including oriented strand board and gypsum board, are generally applied using nails and/or screws as well.

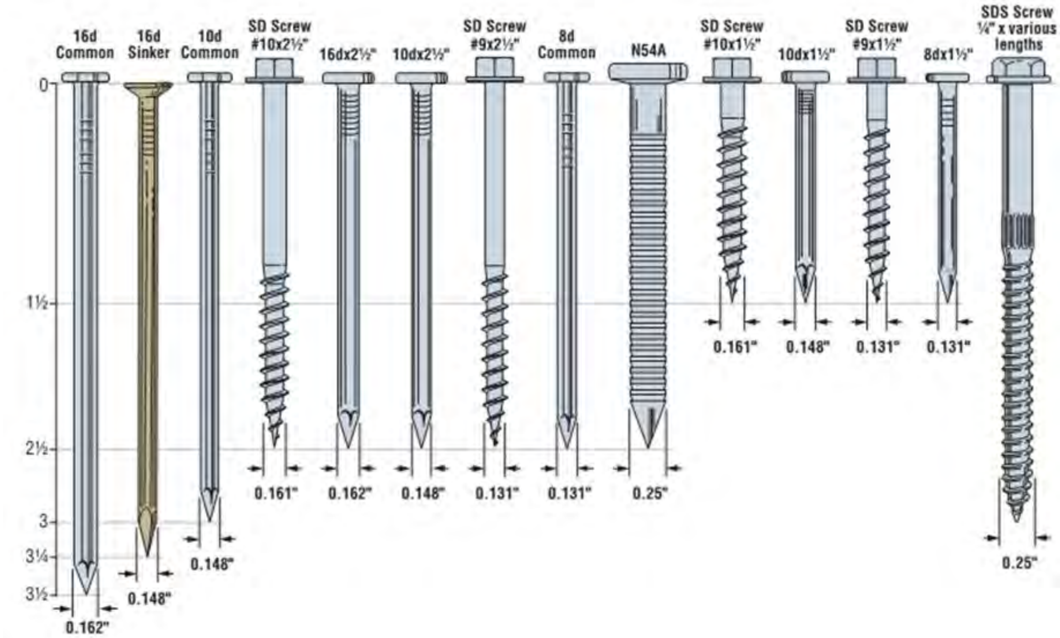
The primary light timber frame connector elements are discussed below.

Nails and Screws

Nails and screws are typically used to fix steel connectors and panels and boards to timber elements. They can consist of a single nail or screw, but often are composed of multiple nails or screws that are located at regular spacings.

Examples of typical nails and screws are shown below.

Figure 11 – Example of typical nails and screws (SimpsonStrongTie, 2013)



Nails and screws are traditionally applied by hand, but can also be applied by mechanical nail and screw guns. An example of mechanical application is shown in the image below.

Figure 12 – Screw-fixture to wall panel (Karacebeyli & Douglas, 2013)

Panels and boards are attached to timber elements using nails and screws. The following images show examples of gypsum board framing to timber elements.

Figure 13 – Section showing nailed connection between gypsum and timber (GypsumAssociation, 2013)

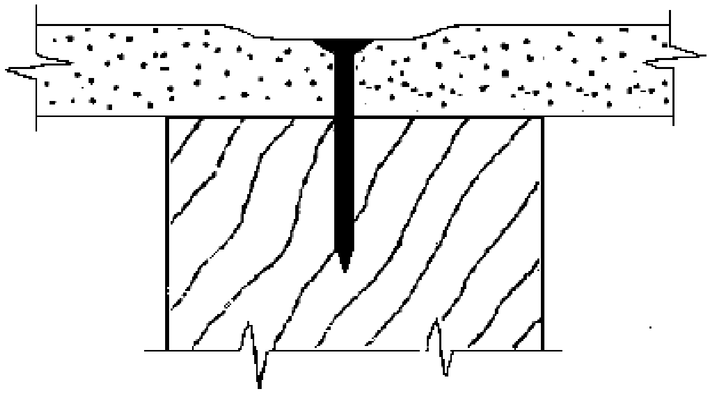
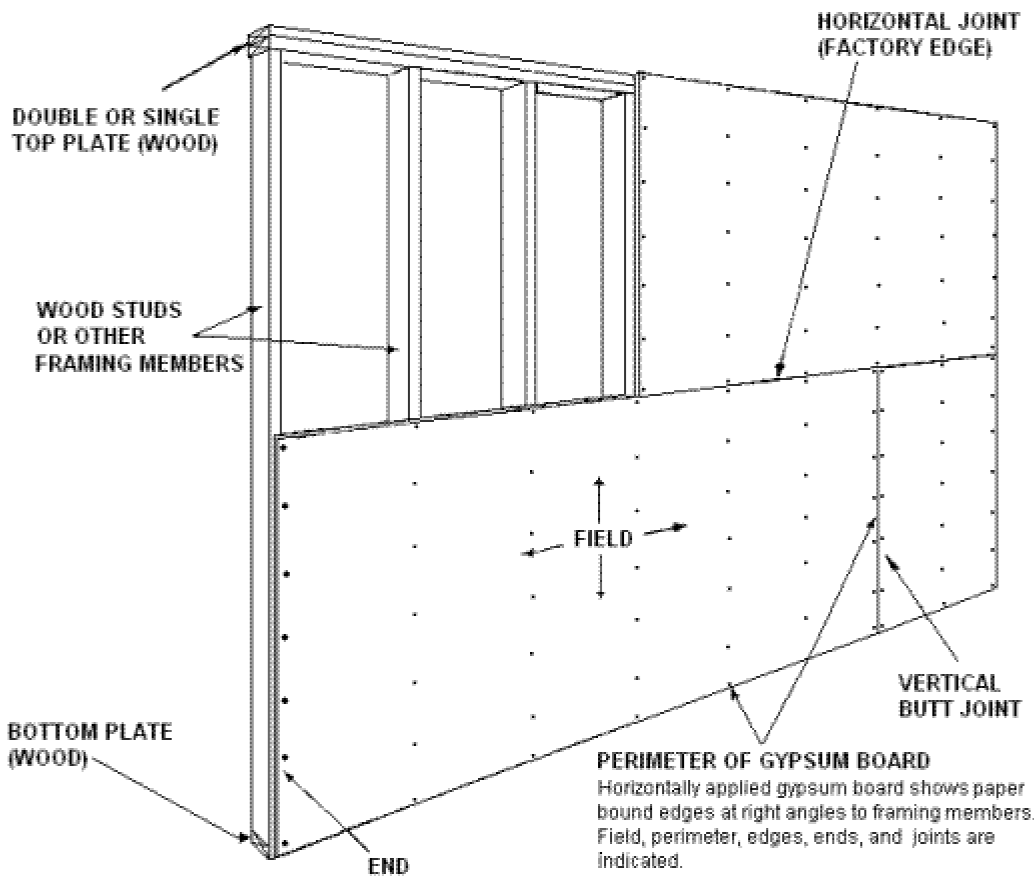


Figure 14 – Example of gypsum board framing to timber wall studs (GypsumAssociation, 2013)



Hangers

Steel connectors are commonly used to attach timber framing elements in light timber frame buildings. These are typically fixed to timber members using nails or screws.

Common applications for steel connectors include joist hangers for floor and roof framing. This involves nailing hangers onto primary timber structural elements, such as beams, and connecting smaller elements, such as joists, as part of the secondary framing.

Examples of joist hangers and joist framing are shown below.

Figure 15 – Example of a typical joist hanger (SimpsonStrongTie, 2013)

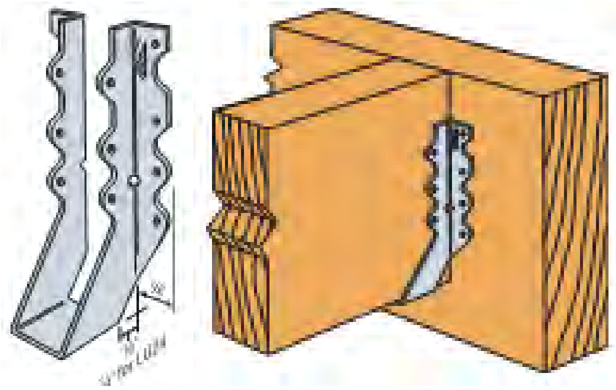


Figure 16 – Typical joist hanger framing (HomeBuildingAnswers, 2008)

Plates

Steel plates can be used to connect stud members to assemble timber frames, also called trusses. Trusses are groups of studs that form triangular frames that are specially designed to act like beams to resist structural loads. These are often used as roof framing in light timber frame buildings. Plates generally utilize “teeth” that grip the timber surface, but can also be fixed using nails or screws.

Examples of plate connections and truss frames are shown below.

Figure 17 – Example of a tie plate (right) (SimpsonStrongTie, 2013)

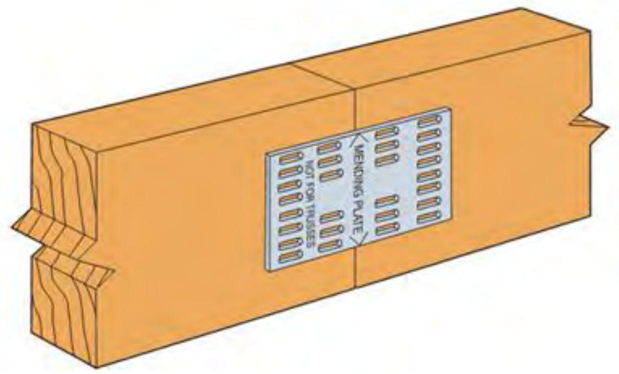


Figure 18 – Example of truss plate frames (Drang, 2010)

1.5.2 Heavy Timber Frame Construction

Heavy timber frame construction, also called heavy frame, or heavy timber construction, is characterized by beams and columns with timber section sizes greater than 6" x 6" [150mm x 150mm]. While this can include solid sawn lumber sections greater than 6" [150mm] square, this report focuses on the use of engineered timber products. Engineered timber products offer greater strength and design flexibility and have become increasingly popular as building elements in tall timber construction.

1.5.2.1 Engineered Timber Products Used in Heavy Timber Framing

Generally, engineered timber / wood consists of derivative timber products that are manufactured to increase the strength and stiffness of the engineered timber element. This is often achieved by using thin veneers or timber studs and applying adhesives to form composite materials with greater structural strength than the individual elements.

Engineered products can be prefabricated offsite to any size, shape, dimension and strength specification based on the type of product. This enables greater precision, speed of construction and design flexibility compared to conventional timber framing methods.

A summary of the primary engineered timber products and building elements used in heavy timber construction are provided below.

Glue Laminated (Glulam) Wood

Glue laminated wood (Glulam) is an engineered composite product that consists of smaller pieces of stress graded wood (nominally 2"x 4", 50mm x 100mm) that are adhered, or laminated, together. This produces a product that is stronger than solid timber (WoodSolutions, Glulam, 2013).

Glulam sections can be manufactured curved or straight, and are commonly available in lengths up to 65 feet [20m] and sizes of up to 6" x 24" [150mm x 600mm] though additional sizes can also be produced. Glulam elements are most commonly used as posts and beams.

Examples of glulam members are shown below.

Figure 19 – Glulam beam (APA, Glulam Product Guide, 2008)

Figure 20 – Examples of glulam members (R&R, 2007)

Laminated Veneer Lumber (LVL)

Laminated veneer lumber (LVL) is the most widely used engineered structural composite lumber (SCL) product (APA, Structural Composite Lumber (SCL): A Practical Alternative, 2013). SCL, and specifically LVL, consists of multiple layers of thin wood veneers (approximately 1/8" [3mm] thick) that are laminated parallel to each other under heat and pressure. Additional examples of SCL include laminated strand lumber and parallel strand lumber.

Slicing the timber into thin veneers and laminating them back together reduces the effect of imperfections in the wood, due to knots or curved sections (Gerard, 2010). The resulting LVL product demonstrates improved structural performance compared to solid timber members.

LVL is manufactured in long straight sheets, and is usually available in sheets of 48: [1200mm] width, up to 60 feet [20m] long, with thickness from 2" to 4" [50mm to 100mm]. These sheets can be cut down to the desired size and are typically used as post, beam and joist elements (WoodSolutions, Laminated Veneer Lumber (LVL), 2013).

Examples of LVL members and applications are shown below.

Figure 21 – LVL lamination process (WoodSolutions, Laminated Veneer Lumber (LVL), 2013)

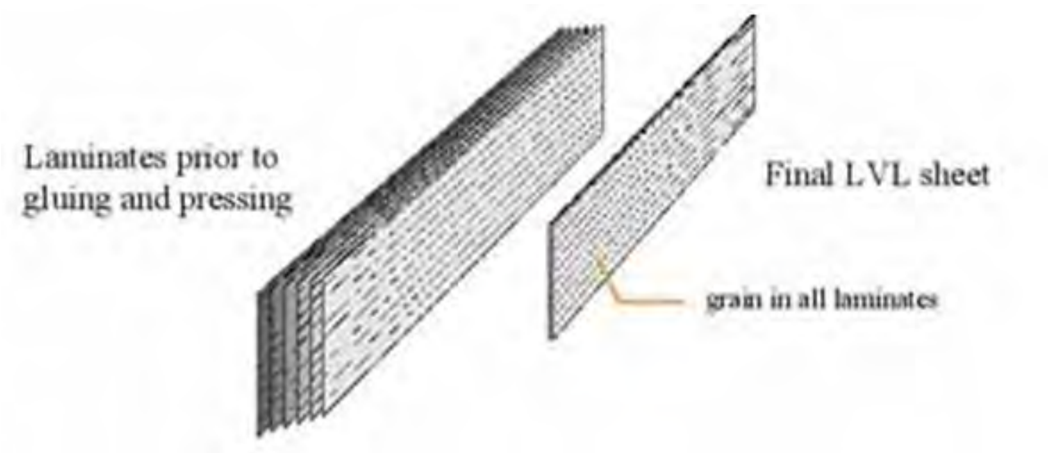


Figure 22 – LVL elements (Green, The Case For Tall Wood Buildings, 2012)

Figure 23 – Close up of an LVL section (Spellman, The Fire Performance of Post-Tensioned Timber Beams, 2012)

Cross Laminated Timber (CLT)

Cross-Laminated Timber (CLT) is an engineered composite product that consists of multiple layers of boards that are adhered perpendicularly to each other to achieve strength in multiple directions (Karacebeyli & Douglas, 2013). In some countries it is referred to as "solid timber", "solid timber panels" or "mass timber", though it is referred to as "CLT" and "panelized construction" in this report.

CLT can be manufactured curved or straight, and is generally available in panel sizes up to 60 feet [18m] long and up to 10 feet [3.0m] tall. Panel thickness ranges from 3 layers to up to 9 layers, with an average panel thickness of 3" [75mm] to 20" [500mm] (FPInnovations, Cross Laminated Timber (CLT), 2013).

One of the primary benefits of CLT panels is the use of offsite prefabrication. Holes and notches in CLT panels can be pre-cut before arrival to site. This minimizes work onsite, reduces construction time and costs and increases the accuracy of structural components (Sutton, Black, & Walker, 2011) (FPInnovations, Cross Laminated Timber (CLT), 2013).

CLT panels are most commonly used for load-bearing walls and floors. Walls typically consist of 3-5 layer panels, whereas floors consist of 5 or more layers for greater stability.

Examples of CLT members and applications are shown below.

Figure 24 – Diagrammatic cross-section of a 5-layer CLT panel (Karacebeyli & Douglas, 2013)

Figure 25 – Example of a 5-layer CLT panel showing layer orientation (FPInnovations, Cross Laminated Timber (CLT), 2013)

Figure 26 – 5-layer CLT panels with pre-cut notches (FPInnovations, Solid Advantages, 2012)

Figure 27 – CLT wall and floor elements (FPInnovations, Solid Advantages, 2012)

1.5.2.2 Construction Framing in Heavy Timber

The use of engineered timber products has enabled the design of larger, taller timber structures, with a great variety of applications. These are typically achieved using the following construction framing methods:

- Post and beam construction; and
- Panelized construction.

Other new heavy timber technologies include:

- Post-tensioned heavy timber construction; where metal cables ("tendons or strands") are used to assist with deflection control in longer span beams and improve lateral movement in walls or columns; and
- Timber composite; where timber and concrete are used for floor systems to gain the best of both materials for improved floor performance in fire and acoustics.

These are presented in greater detail below.

Post and Beam Construction

Post and beam construction is typically composed of large, engineered timber or timber composite sections. Structural elements are typically constructed of glulam or LVL, as these engineered products provide greater structural strength compared to solid timber sections.

The use of large engineered timber sections allows for greater spans, open areas and heights compared to light timber and other forms of heavy timber construction. Given the potential for an open plan layout, post and beam construction is typically used for commercial and office spaces.

Feasibility studies using post and beam construction indicate it may be possible to design these structures to heights exceeding 40-stories using engineered and timber composite elements (SOM, 2013).

Examples of post and beam construction are indicated below.

Figure 28 – Glulam beams and column (WoodSolutions, Glulam, 2013)

Figure 29 – Glulam beams (APA, Engineered Wood Construction Guide: Glulam, 2011)

Figure 30 – Glulam beams (WoodSolutions, Glulam, 2013)

Figure 31 – LVL roof beams (WoodSolutions, Laminated Veneer Lumber (LVL), 2013)

Figure 32 – Post and beam construction (Lignum, 2010)

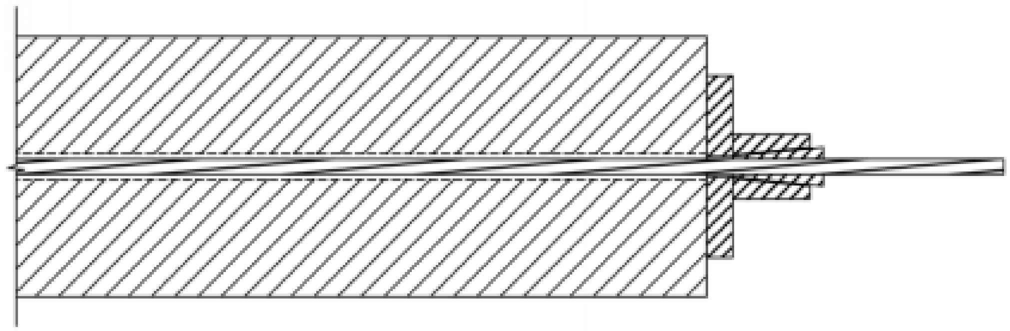
New technology in post and beam construction includes the use of post-tensioned cables for additional strength and stability. This technology is commonly known as post-tensioned timber construction and is discussed below.

Post-Tensioned Timber Construction

Post-tensioned timber construction is similar to post and beam construction: the structure is characterized by large timber post and beam sections. However, structural elements in post-tensioned timber construction are designed with steel post-tensioning cables embedded within the sections. This is designed to increase the strength and stiffness of the timber elements, thereby increasing the structural potential for larger spans and taller heights (Spellman, Carradine, Abu, Moss, & Buchanan, 2012). The use of timber and steel makes post-tensioned timber elements composite assemblies.

Post-tensioned timber construction is similar to post-tensioned concrete construction, except that the concrete element is replaced by large timber sections, usually constructed in glulam or LVL (Buchanan, Deam, Fragiacomo, Pampanin, & Palermo, 2008). The timber is post-tensioned with unbonded high strength steel tendons with fixed anchors at either end (Gerard, 2010). An example of a post-tensioned timber beam is shown in the figure below.

Figure 33 – Cross section through a post-tensioned timber beam (Spellman, The Fire Performance of Post-Tensioned Timber Beams, 2012)



Additional benefits of post-tensioned timber buildings are that all elements can be prefabricated offsite to minimize onsite work and reduce total construction time and cost. The structure has also been shown to perform well in seismic testing (STIC, 2009).

A two-story post-tensioned timber building used for experimental analysis is shown below.

Figure 34 – Two-story post-tensioned LVL structure (Gerard, 2010)

Panelized Construction

Panelized construction generally relies on CLT panels as the primary building structure. Given their structural strength in multiple directions, this allows them to be oriented vertically as load-bearing walls, or horizontally, as load-bearing floors. The use of CLT panels for walls and floors is typically applied in mid-rise residential buildings, generally up to nine stories (Karacebeyli & Douglas, 2013).

The load-bearing CLT panels are used to create numerous internal and external partitions within the structure (Klingbeil, 2012). This results in partitioning that is practical for walls within residential buildings.

Panelized construction greater than five stories often utilizes a central core to provide greater strength and stability (LendLease, Forte Building Australia's First Timber HighRise, 2013). While studies have shown this can be accomplished using CLT as the main structural element, many panelized buildings incorporate a concrete core. Feasibility studies have shown the use of a concrete core for the elevator shafts and stairwells, with CLT panelized elements, may be used for buildings greater than 25-stories (Waugh, Wells, & Lindegar, 2010).

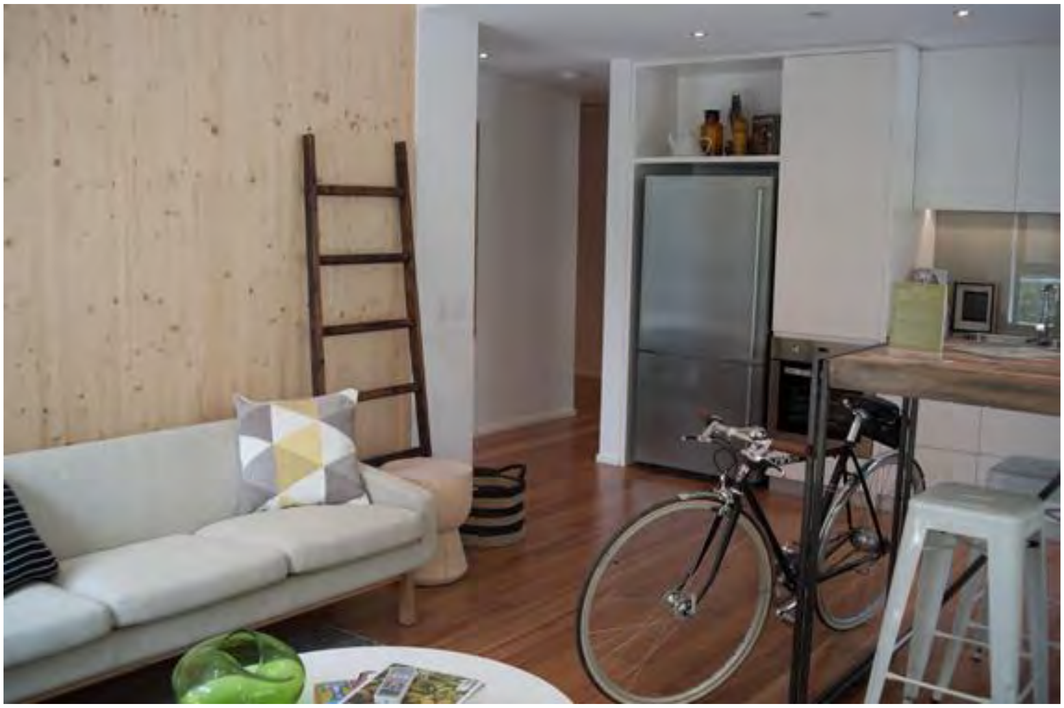
Examples of panelized construction buildings are shown below.

Figure 35 – Panelized wall and floor construction (Sutton, Black, & Walker, 2011)

Figure 36 – Lifting prefabricated CLT panels for assembly (Crespell & Gagnon, 2010)

Figure 37 – Plan view of CLT wall and floor elements (Sutton, Black, & Walker, 2011)

Figure 38 – Exposed CLT wall in Forté Building (FPInnovations, Cross Laminated Timber (CLT), 2013)



The use of panelized construction has also been used in structures other than buildings, such as bell towers, wind turbines and observation towers. Examples are shown in Section 2.6.3.

1.5.2.3 Connections in Heavy Timber Framing

Compared to connections in light timber, connections in heavy timber frame buildings generally consist of a relatively small number of larger steel connectors that are fixed to the framing using nails, screws and bolts. Nails and screws are generally restricted to panelized construction, with bolts primarily used in post and beam construction.

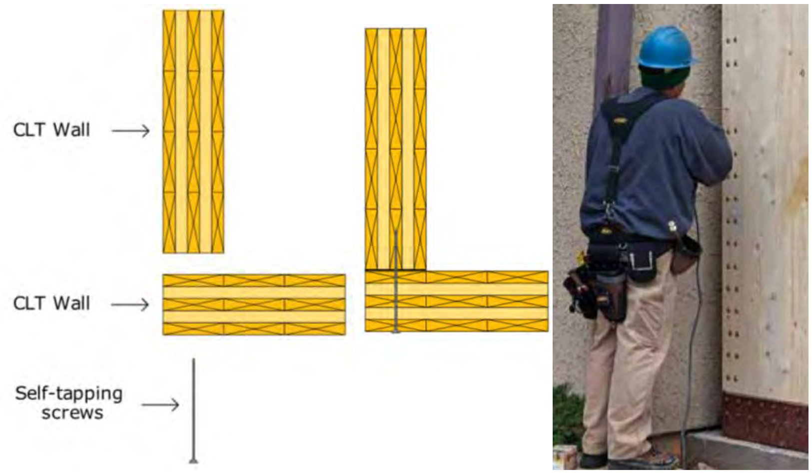
Some of the primary heavy timber frame connector elements are discussed below.

Nails and Screws

Nails and screws are typically reserved for use in panelized construction, as there is a considerably greater connection area between panels compared to post and beam elements. Examples of types of nails and screws are provided in Section 1.5.1.3.

The image below shows an application of screws in panelized construction.

Figure 39 – Example of CLT connection using screws (left and right) (Karacebeyli & Douglas, 2013)



Bolts

Bolts function in a similar manner as nails and screws, but are considerably thicker and stronger. Bolt diameters typically range from 1/2" [12mm] to 1" [25mm] (AFPA, 2001). Single bolts or bolt groups are often used to fix steel connectors to heavy timber elements. Examples of common bolts are shown below.

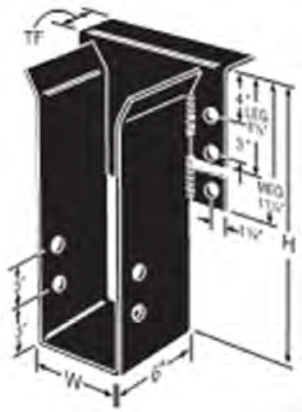
Figure 40 – Examples of common bolts (top left, top right and below) (PortlandBolt, 2012)

Hangers

Hangers for heavy timber construction are similar in function to hangers in light timber construction. The primary differences are that hangers in heavy timber construction are typically considerably larger, as they are intended for connecting larger timber sections, and are fixed to the timber elements using bolts instead of nails or screws.

An example of a heavy timber hanger is displayed below.

Figure 41 – Example of an exposed heavy timber hanger (SimpsonStrongTie, 2013)



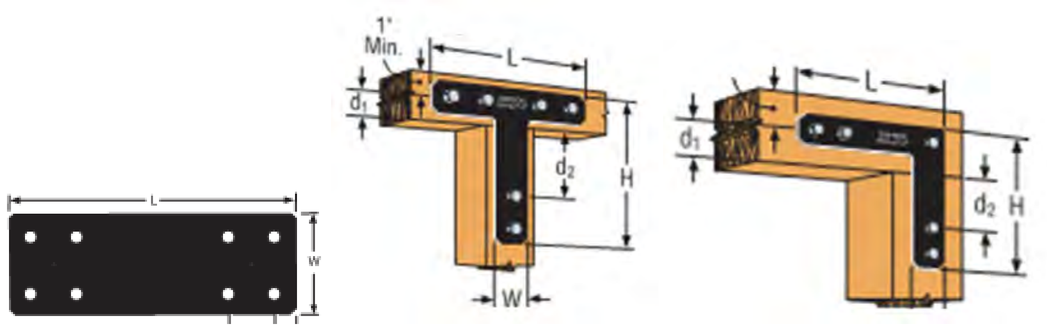
Plates

Similar to light timber frame construction, steel plates are also used to connect heavy timber framed elements. However, steel plates in heavy timber are generally thicker than plates in light timber, and are also fixed to the heavy timber elements by bolts, instead of nails, screws or teeth.

Given the larger section size of heavy timber members, plates can either be fixed externally or internally. Grooves cut in heavy timber sections can allow for embedded plates to be inserted and fixed in place using bolts or dowels. Embedding steel elements within the timber section provides additional protection from heating in a fire event, but also requires a greater amount of workmanship, as grooves are pre-cut into the timber elements.

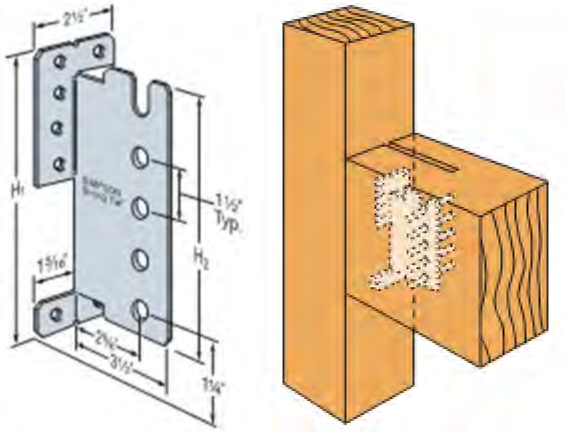
Examples of exposed plate connections are shown below.

Figure 42 – Example of exposed plates connecting column and beam elements (SimpsonStrongTie, 2013)



Examples of embedded steel plate connections in heavy timber are shown in the image below.

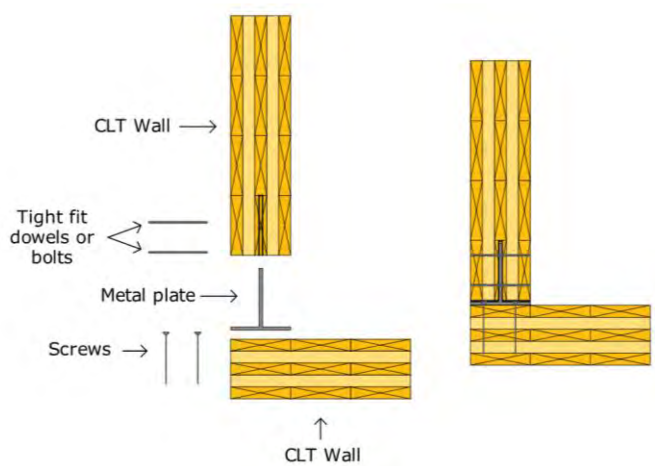
Figure 43 – Example of an embedded heavy timber plate connecting a column and joist (SimpsonStrongTie, 2013)



Plates can also be embedded in panelized construction. While these plates are thicker than plates in light timber frames, they often still utilize screws to fix the connector in place (Gagnon & Pirvu, 2011).

The image below shows a groove used to connect wall elements in panelized construction.

Figure 44 – Example of an embedded plate connection in LVL (Karacebeyli & Douglas, 2013)



Additional examples of plate connectors in heavy timber are shown in Section 0.

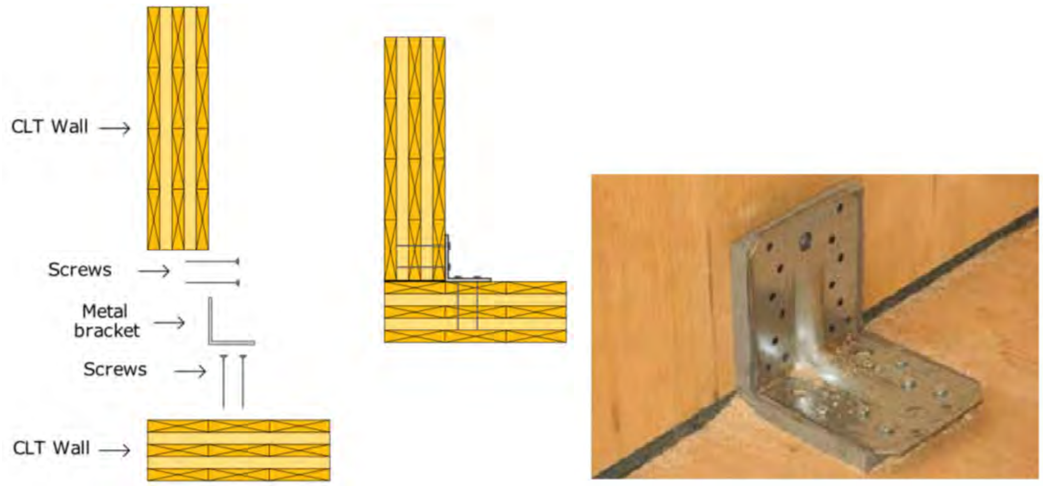
Brackets

Steel bracket connectors are typical in panelized construction. These connectors generally connect wall panels to wall panels, and wall panels to floor panels. Brackets are typically fixed to the CLT panels using screws, as opposed to nails or bolts (Gagnon & Pirvu, 2011).

Bracket connections can also be replaced by plate connections, as shown above.

An example of steel brackets in panelized construction is shown below.

Figure 45 – Example of a steel bracket connection in LVL (left and right) (Karacebeyli & Douglas, 2013)



Post-Tensioned Steel to Timber

Connections in post-tensioned timber framed buildings are very similar to that for post and beam construction. The main difference is the inclusion of post-tensioned steel tendons embedded in the heavy timber elements.

The connection consists of a steel tendon within the heavy timber section, connected by thick steel anchor plates at either end of the timber element. The tendon is then post-tensioned to increase the strength of the timber element.

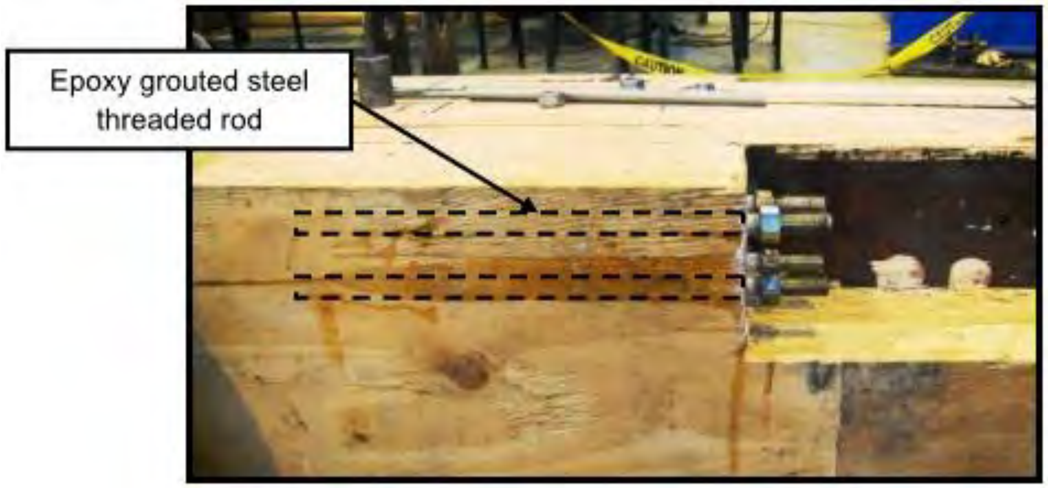
Additional details of the post-tensioned steel to timber connection are presented in Section 1.6.4.2.

Epoxy Grouted Steel Rods

Research has investigated the use of epoxy grouted steel rods in heavy timber sections, typically composed of glulam or LVL. Oversized holes are drilled into the heavy timber section, filled with epoxy grout, and a steel rod is inserted into the connection. This can be used to connect other timber elements or steel elements to the timber section (Harris, 2004).

An example of an epoxy grouted steel rod connection is shown below.

Figure 46 – Epoxy grouted steel rod connection in heavy timber (Gerard, 2010)



1.5.2.4 Heavy Timber Composites

Heavy timber composites consist of a combination of building materials that are intended to optimize building performance. For heavy timber buildings, this often includes the use of timber-concrete composite floor systems.

Timber-concrete composite is a construction assembly used for structural floor framing that is typically composed of large glulam or LVL beams supporting a concrete slab above. Plywood is laid over heavy timber sections to act as formwork for the concrete topping slab and steel connections achieve composite behavior between the timber and concrete elements (Lukaszewska, Johnsson, & Fragiacomo, 2008).

Timber-concrete composite assemblies are typically used in post and beam construction, though the design concept can be applied to panelized construction as well.

This composite solution satisfies the acoustic, structural and fire performance requirements for floor slab design (O'Neill, Abu, Carradine, Spearpoint, & Buchanan, 2012). The concrete topping slab provides acoustic and fire separation between adjacent compartments and is supported by the timber structural elements below.

Examples of timber-concrete composite floor assemblies are shown below.

Figure 47 – Detail of a timber-concrete composite floor (O'Neill, The Fire Performance of Timber-Concrete Composite Floors, 2009)

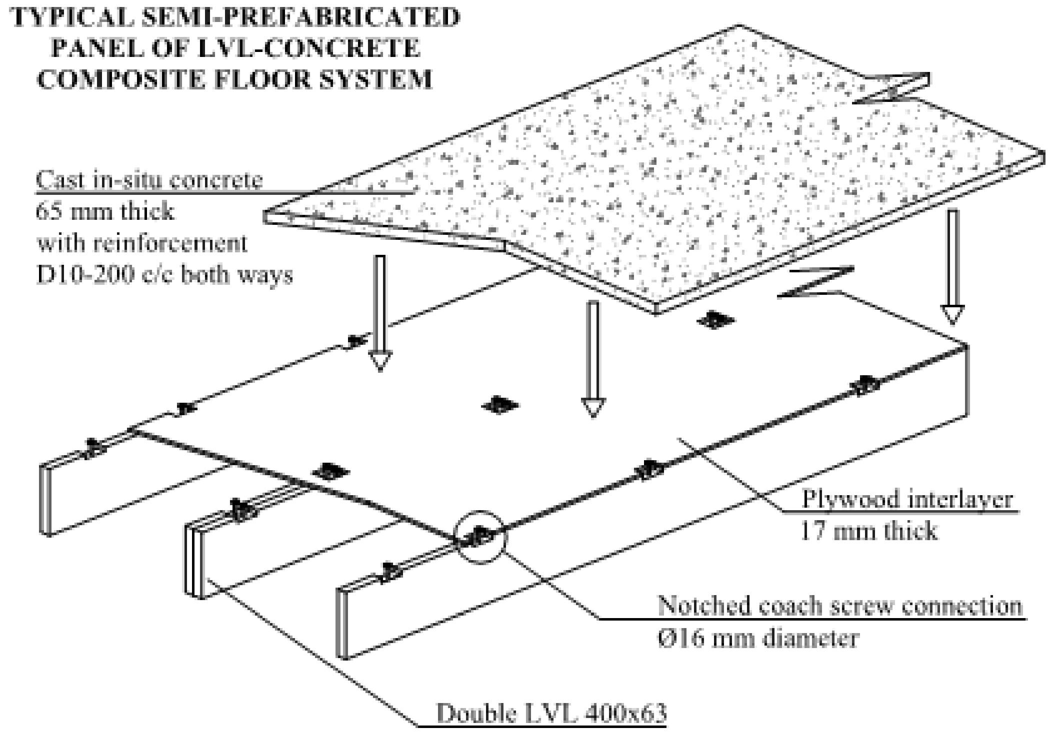


Figure 48 – Rendering of timber-concrete composite floors in a multi-story post and beam building application (Rhomberg, Life Cycle Tower, 2012)

1.6 Timber Fire Fundamentals

This section presents an overview of the fundamentals of timber in fire. This includes fire performance of exposed timber sections, as well as a discussion of fire resistance in both light and heavy timber frame buildings. For further detail, please refer to the cited references.

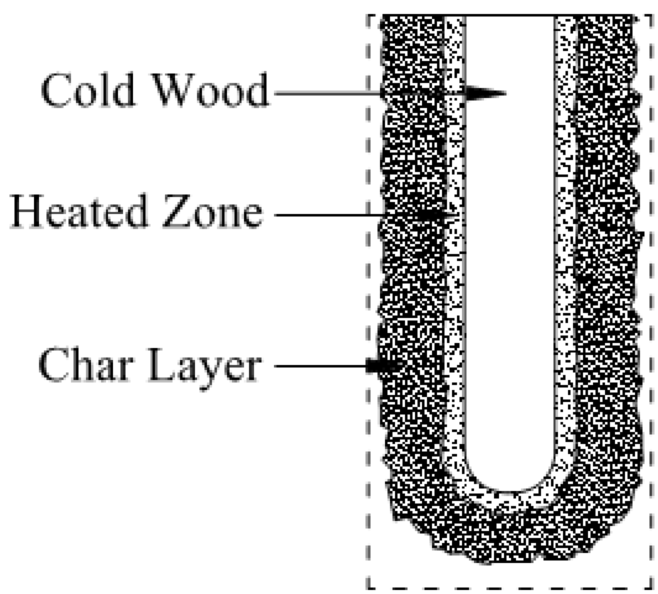
1.6.1 Fire Performance of Exposed Timber

Research and testing have shown that the fire performance of exposed timber is generally well understood, and importantly, predictable (AWC, Calculating the Fire Resistance of Exposed Wood Members, 2003).

When timber is exposed to fire, the outer layer burns and turns to char. This occurs at a temperature of approximately 572°F [300°C] (Forintek, Wood-Frame Construction, Fire Resistance and Sound Transmission, 2002). This creates a protective charring layer that acts as insulation and delays the onset of heating for the unheated, or cold, layer below (White R. , Fire Resistance of Exposed Wood Members, 2004). This process of charring allows timber elements to achieve a level of inherent fire resistance (White R. , Analytical Methods for Determining Fire Resistance of Timber Members, 2002).

The char layer, heated zone and cold timber are shown in the following figure.

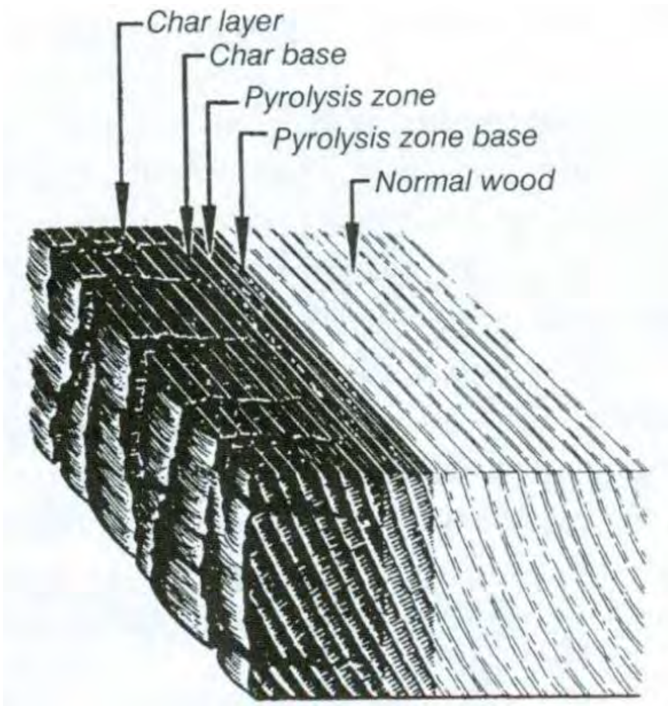
Figure 49 – Charring of a timber / wood member with exposure on three sides (AITC, 2012)



The section of timber in the heated zone beyond the char layer is known as the pyrolysis zone, and corresponds to temperatures between approximately 392°F [200°C] and 572°F [300°C] (AWC, Calculating the Fire Resistance of Exposed Wood Members, 2003). Within this zone, timber is assumed to undergo thermal decomposition and pyrolysis.

The char layer, pyrolysis zone and cold/unheated timber are shown graphically in the figure below.

Figure 50 – Charring of an exposed timber member (Schaffer, 1967)

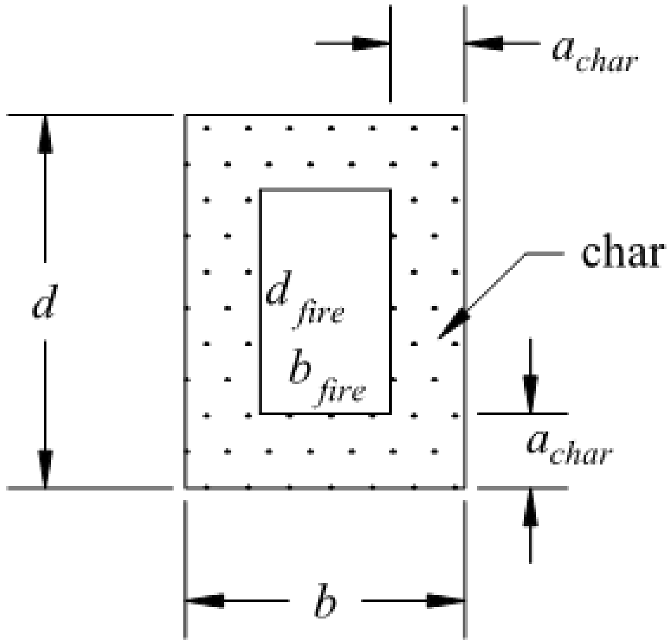


The char layer grows with sustained exposure to fire, creating even more insulation, slowing down the burning rate and reducing the unheated cross section of the member (AITC, 2012). This behavior continues until the end of heating, or the section has completely combusted.

Testing of this charring process has shown that timber demonstrates a constant, predictable charring rate (Buchanan, Structural Design for Fire Safety, 2001). The charring rate, section size and the required fire duration can be used to calculate the fire resistance time for a timber element (White R. , Analytical Methods for Determining Fire Resistance of Timber Members, 2002). This allows for a structural fire assessment to determine if the post-fire section size is able to maintain stability at the end of fire exposure (Bregulla & Enjily, 2004).

A post-fire, reduced or residual, section size for a timber element with four-sided exposure is shown in the figure below. The char layer depth can be estimated by multiplying the charring rate by the fire exposure time to determine the reduced section properties (Frangi, Fontana, & Knoblock, Fire Design Concepts for Tall Timber Buildings, 2008).

Figure 51 – Reduced dimensions of four-sided fire exposure (AITC, 2012)



The fire resistance calculation is particularly applicable to heavy timber frame members compared to light timber frame members. The larger section size results in significantly greater inherent fire resistance. This fire resistance can be incorporated as part of the building structural fire strategy.

This is further discussed in Section 1.6.4.

1.6.2 Expected Fire Performance of Light and Heavy Timber Frame Buildings

Fire performance of timber buildings differs based on construction type. The primary difference is the means by which the fire resistance is provided. This also dictates fire performance characteristics.

A comparison of fire performance for light timber and heavy timber construction is shown below. Additional details are provided in the following sections.

1.6.3 Light Timber Frame Construction

Given the section size of nominally sized 2” x 4” [50mm x 100mm] to 2” x 12” [50mm x 300mm] stud framing members, the inherent fire resistance of the studs alone is effectively negligible, as the members are small. Hence, unprotected, or exposed, light timber frames provide little structural fire resistance. Fire resistance is achieved by providing protection to the light timber assembly to delay the onset of heating and combustion.

Fire resistance in modern-day light timber frames typically relies on at least one layer of rigid, non-combustible gypsum board (AFPA, 2001). The gypsum board panels are nailed or screw-fixed in place. The gypsum board may be a standard type of gypsum, or a gypsum board with additional additives to improve fire resistance.

This strategy of surrounding the exposed combustible timber framing with non-combustible gypsum board is also referred to as encapsulation, and is shown in the figures below.

Figure 52 – Gypsum board protection encapsulating timber stud framing (Forintek, Fire Safety - A Wood-Frame Building Perfromance Fact Sheet, 2002)

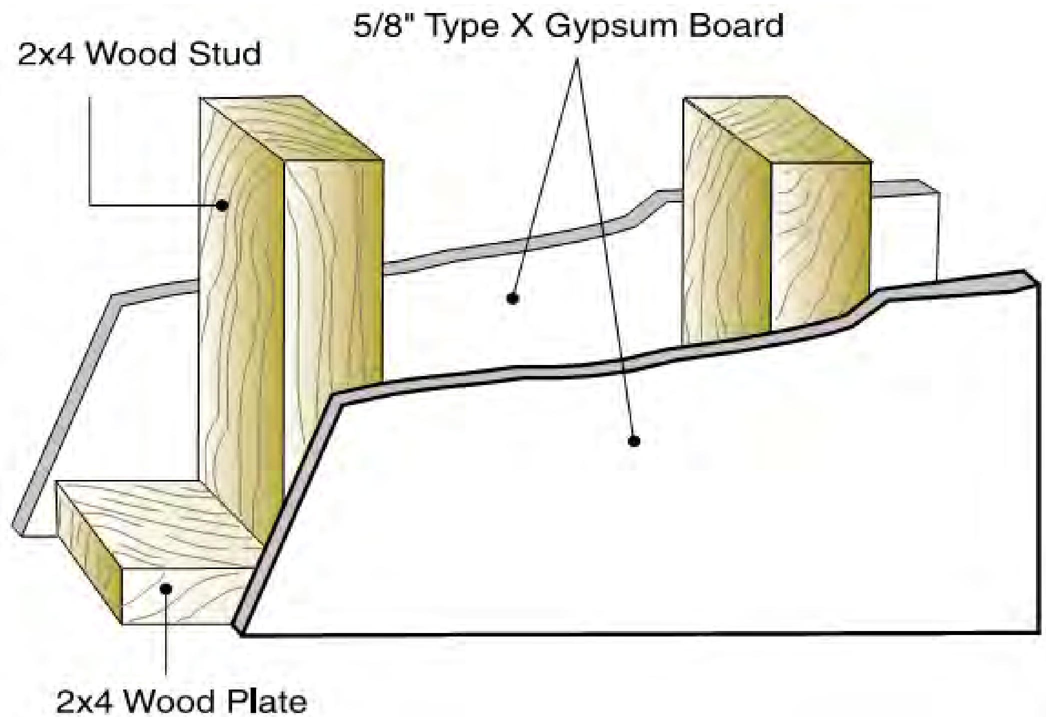
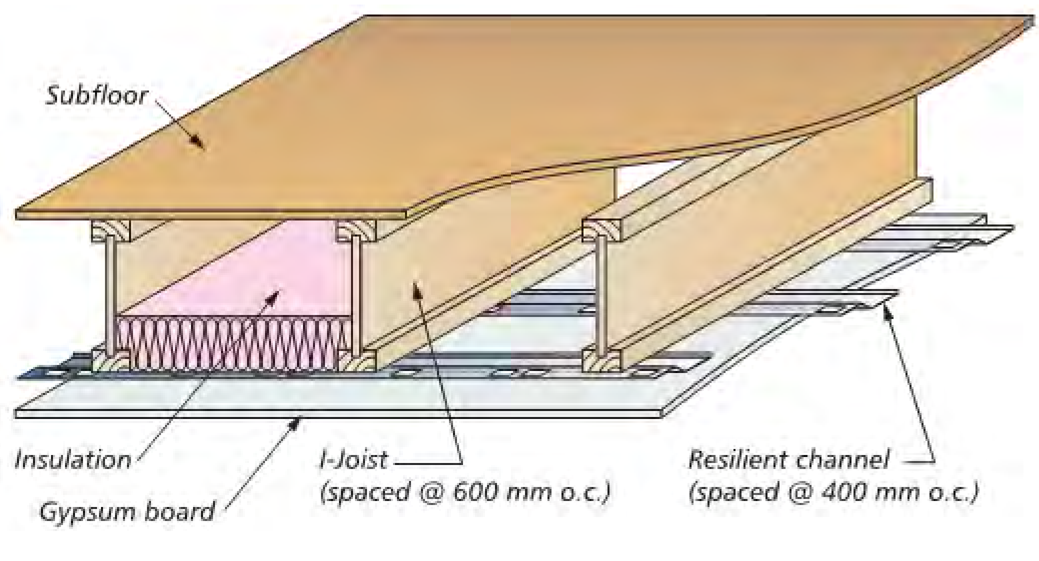


Figure 53 – Example of a typical floor assembly showing timber I-joists and gypsum board (Forintek, Wood-Frame Construction, Fire Resistance and Sound Transmission, 2002)



1.6.3.1 Connections

Connections in light timber frame buildings, and timber frame buildings in general, utilize steel connectors for stability. Research and testing have shown that exposed steel significantly loses structural strength with increase in temperature (Milke, 2002).

Accordingly, connection performance in fire relies on protecting steel elements from heating. This is generally achieved by limiting the exposed area and designing connections behind gypsum board, timber and other surface lining materials. However, steel connections in light timber buildings often have high redundancy such that the failure of localized connections can often be sustained.

Providing appropriate fire protection at penetrations and joints is also necessary to prevent heat exposure to elements within the gypsum and timber fire resistive assembly. This can be achieved by appropriate use of fire stopping, fire sealants and cavity barriers.

1.6.4 Heavy Timber Frame Construction

Fire performance and means of providing fire resistance for heavy timber construction is significantly different than light timber construction. Given the larger section sizes and the predictable charring rate of timber, the heavy timber sections are considered to have an inherent fire resistance. The larger the section size, the greater the inherent fire resistance (Frangi & Fontana, Fire Safety of Multistorey Timber Buildings, 2010).

This section summarizes the fire performance of the previously discussed heavy timber framing types. This includes a discussion of the inherent fire resistance of the structural elements and other fire performance issues related to the construction method.

1.6.4.1 Post and Beam Structures

Fire performance of post and beam structures is reliant on the section size of structural glulam and LVL elements. The greater the member section size, the greater the inherent fire resistance, and thus the structural fire performance. Timber structural elements can be encapsulated with non-combustible gypsum board for additional protection and to increase the fire resistance rating.

Glulam members typical of post and beam construction are shown below. They demonstrate the charring behavior that is used to design for structural fire resistance (Buchanan, Timber Design Guide, 2011).

Figure 54 – Charring in heavy timber sections (Bregulla & Enjily, 2004)

Fire performance of heavy timber sections is demonstrated in the image below, showing floor framing after a fire. The panel above the floor framing has burnt away, but the heavy timber members have survived the fire.

Figure 55 – Floor framing after a fire event (Babrauskas, 2004)

Post and beam structures are often designed with concrete floor slabs above glulam or LVL framing. This not only provides a fire rated separation between compartments, but also satisfies acoustic and structural vibration requirements (Rhomberg, Life Cycle Tower, 2012). An example of a concrete floor slab over timber framing is shown in the following image.

Figure 56 – Concrete floor slab over heavy timber beams (Wurm, Gockel, & Unger, 2012)

While the heavy timber elements are shown to perform well in fire, it is important to consider the entire post and beam assembly for structural fire resistance. Protection of steel connectors, including bolts, seats and plates, is critical to maintaining stability, as heating of exposed steel connectors in timber could potentially result in instabilities (Buchanan, Structural Design for Fire Safety, 2001).

1.6.4.2 Post-Tensioned Heavy Timber Structures

The fire performance of post-tensioned heavy timber structures is very similar to that of post and beam structures. The structure is composed of large glulam or LVL sections that are shown to have inherent fire resistance.

One of the primary differences is the embedded steel post-tensioning within the timber elements. This has several design implications for the fire performance of heavy timber structures, including how to prevent heat from entering the cavity, and how to protect the steel post-tensioning elements (Gerard, 2010).

Glulam and LVL elements in post-tensioned heavy timber structures are designed with cavities in the middle of the member to protect the post-tensioning steel tendons. It is important to protect the openings at either end of the element, as heat entering the cavity can result in elevated temperatures, combustion, and loss of strength from potential interior and exterior exposures (Spellman, The Fire Performance of Post-Tensioned Timber Beams, 2012).

This behavior is shown in the figure below, where charring can be seen externally due to fire exposure and internally due to exposure to high temperatures.

Figure 57 – Post-tensioned beam charring for four-sided exposure (Spellman, The Fire Performance of Post-Tensioned Timber Beams, 2012)

Additionally, it is important to protect the post-tensioned steel elements from heat exposure at the anchorage plate at the end of the element. An example of gypsum board encapsulation of the anchorage plate at the end of a post-tensioned beam is shown in the figures below.

Figure 58 – Longitudinal section showing gypsum board protection for post-tensioning anchorage (Spellman, The Fire Performance of Post-Tensioned Timber Beams, 2012)

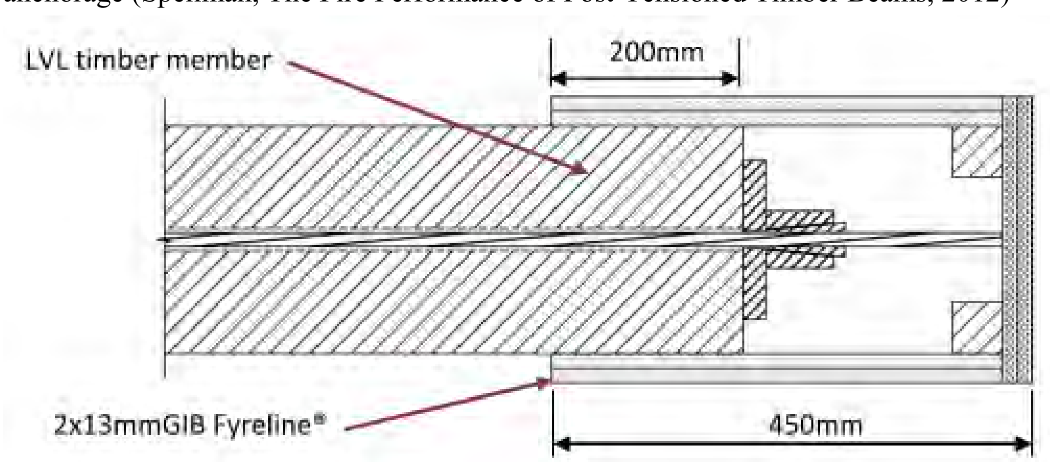
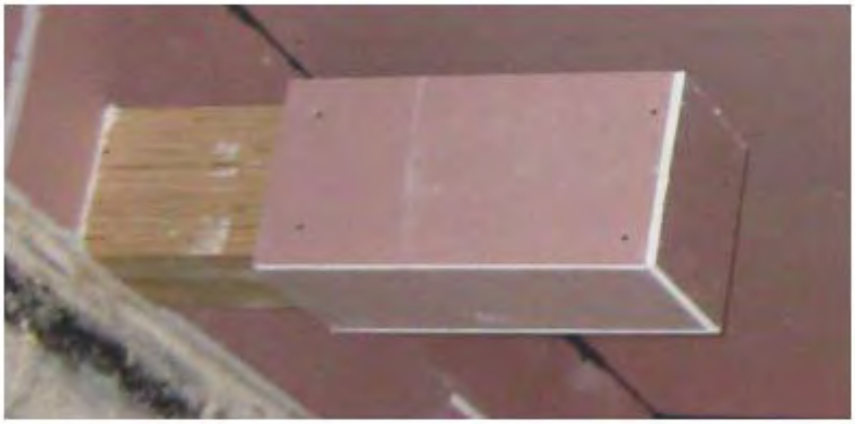


Figure 59 – Gypsum board protection for post-tensioning anchorage (Spellman, The Fire Performance of Post-Tensioned Timber Beams, 2012)



Similar to post and beam construction, post-tensioned timber structures are also designed with a concrete slab above glulam or LVL timber framing members. This is intended to meet the requirements for fire separations, acoustics and structural floor vibrations.

1.6.4.3 Panelized Structures

Fire performance for panelized structures is similar to that of CLT panels. This is expected, as panelized structures are effectively made up of a number of individual CLT panels that are quickly and easily assembled on site to define internal and external partitions.

Examples of charring on CLT panels are shown in the figures below.

Figure 60 – CLT member showing charring depth on a floor member (Craft, Fire Performance of CLT Assemblies, 2009)

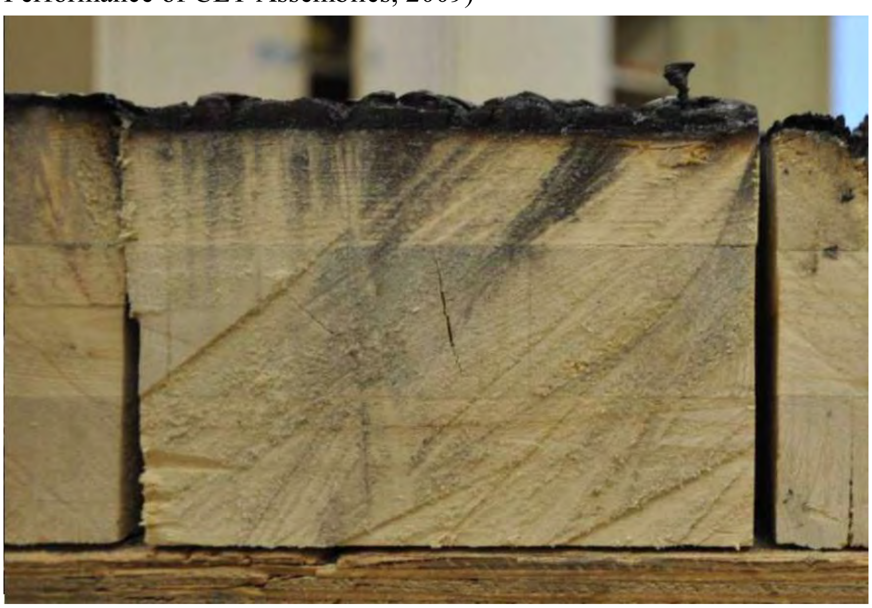
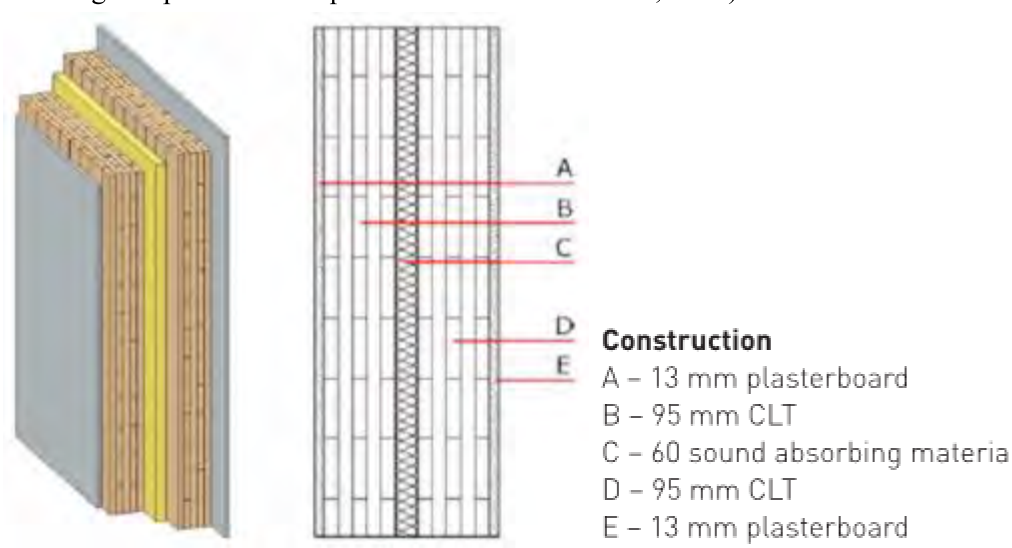


Figure 61 – CLT member showing charring depth on a wall member (Osborne, Dagenais, & Benichou, 2012)

Despite the inherent fire resistance of heavy timber CLT panels, CLT elements are often required to be encapsulated by non-combustible gypsum board protection. This is intended to protect exposed CLT panels from heating and combustion and increase the fire resistance rating of the structural assembly. An example of gypsum board protection for a CLT wall is shown in the figure below.

Figure 62 – Example of applied fire protection for a CLT wall panel (WoodSolutions, Alternative Solution Fire Compliance: Cross-laminated Timber (CLT), 2013) (Dataholz, Building components - compartment wall - tmwxxo03a, 2013)



Many panelized structures are constructed with a concrete floor slab for fire separation, acoustic and structural floor vibration requirements. However, feasibility studies and recent case studies have shown that CLT floor panels can be designed to meet the requirements that are often achieved through concrete (Birch, 2011).

Whereas providing fire protection for steel connections is critical in post and beam and post-tensioned timber constructions, the high redundancy of steel plates, nails and screws that are used in CLT construction provides adequate fire performance for connections in panel assemblies (Osborne, Dagenais, & Benichou, 2012).

1.6.4.4 Connections

Connections in heavy timber structures generally consist of large steel connectors with embedded bolts. Similar to connections in light timber, it is important to provide sufficient protection to exposed, or unprotected, connector elements to maintain stability.

Connection protection can be achieved through multiple means, including gypsum board encapsulation, embedding steel connectors in timber elements and even application of fire-protecting, or intumescent, paint.

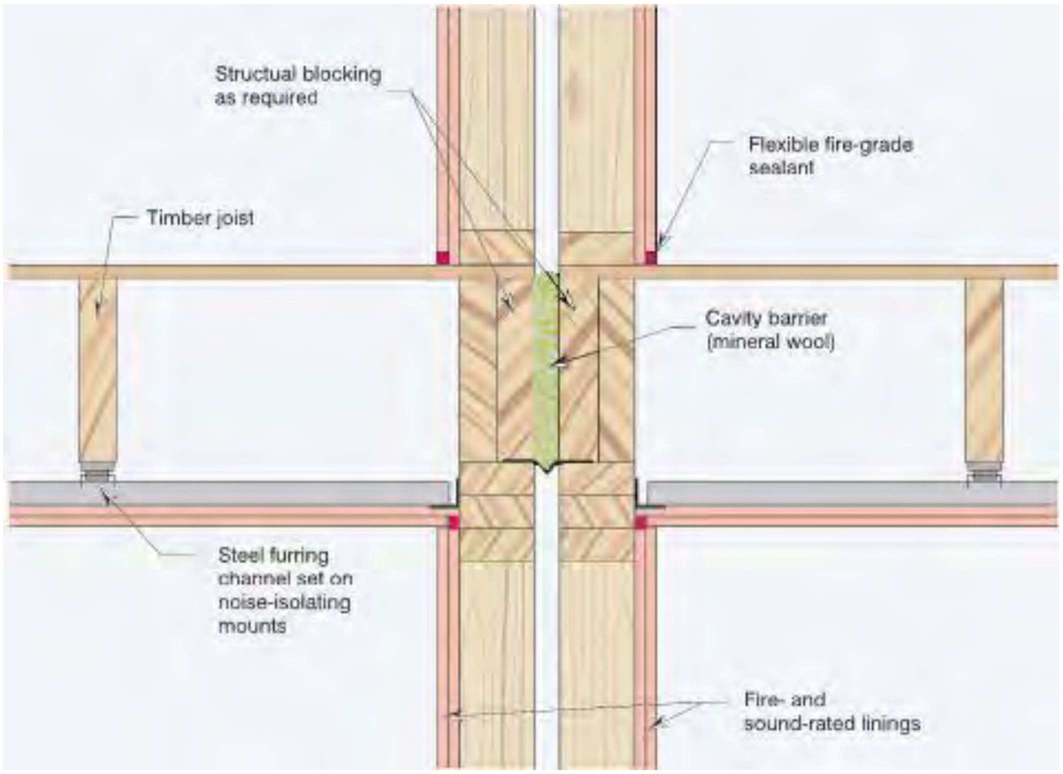
As previously discussed, opening protection for penetrations and joints is also necessary for preventing elevated temperatures from reaching connections in protected spaces.

1.6.5 Concealed Spaces

A primary difference in light and heavy timber construction is the design of concealed spaces. Light timber frame assemblies are designed with concealed spaces in wall, floor and ceiling voids to allow the passage of building utilities (TimberFrameFires, Background, 2011). This presents a fire hazard, as a small fire in a concealed space has the potential to grow and spread throughout the structure and cause considerable damage (Babrauskas, 2004).

Fire separation in concealed spaces for light timber frame buildings is achieved by providing cavity barriers. The cavity barrier is indicated in the section view of floor and wall framing below.

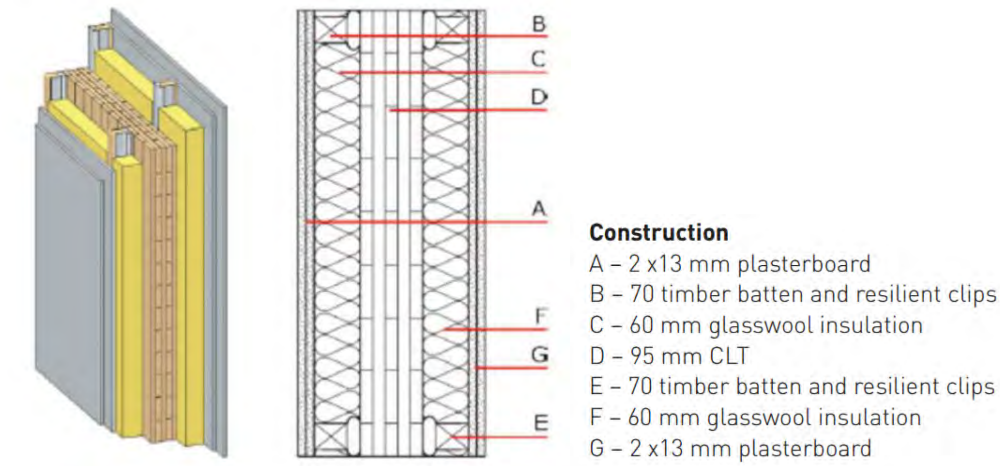
Figure 63 – Section view showing cavity barrier fire separation (WoodSolutions, Timber-Framed Construction for Multi-Residential Buildings, 2012)



While heavy timber structures are also designed to accommodate building utilities, the number of concealed spaces is significantly fewer than light timber construction. The primary building structure utilizes large timber elements, relative to light timber, with minimal concealed spaces. This is also true for panelized construction.

An example of a compartment wall in panelized construction is shown below. The image indicates the solid nature of panelized construction.

Figure 64 – Example of a compartment wall in panelized construction (WoodSolutions, Alternative Solution Fire Compliance: Cross-laminated Timber (CLT), 2013) (Dataholz, Building components - compartment wall - twmxxo04a, 2013)



1.6.6 Fire Risk During Construction

A significant advantage of heavy timber frames compared to light timber frames is the lower risk of full burnout due to fire during construction. Heavy timber members do not rely on additional protection measures and are inherently designed to resist fire. Once exposed to fire, the charring layer provides protection for the solid, unheated timber below.

An additional benefit is the ease of repair following a fire. The charred members can be quickly visually assessed and then evaluated for residual capacity (Ross, 2005). Where deemed appropriate, the damaged timber can be cut away and replaced, or strengthened with solid timber or composite materials to provide the required structural capacity (Babrauskas, 2004) (King, 2007).

Unprotected light timber frame structures, on the other hand, can present significant fire risks, not just to the building site, but also adjacent buildings. This is especially true during the construction phase, prior to the completion of the fire resistive assembly with the installation of gypsum board protection. This makes light timber buildings under construction particularly vulnerable to arson (TimberFrameFires, Background, 2011).

A lack of fire protection has the potential to result in complete burnout of a timber site, as shown in the figure below. This can result in large fires that can potentially threaten adjacent buildings due to severe heat exposure.

See Section 2.4.2 for summaries of fire incidents in buildings under construction.

Figure 65 – Complete burnout of a light timber building under construction in Salford, UK (ManchesterEveningNews, 2013)

2 Task 1 – Literature Review

2.1 Overview

The *Task 1 – Literature Review* summarizes the current knowledge and understanding of fire safety in timber buildings, with a focus on tall timber buildings. This is intended to assess the resources available in literature that can be used to categorize fire safety challenges in tall timber buildings.

The literature review consists of reports, articles, studies and other relevant information. Contributions are collected from international resources, with significant research provided by universities and organizations in Australia, Canada, New Zealand, Sweden, Switzerland, the United States and the United Kingdom.

This summary is organized into the following general themes:

- Testing data on timber structural components in fire;
- Ongoing research studies;
- Relevant fire incidents;
- Existing design guidance; and
- Global case studies of high-rise timber framed buildings.

2.2 Testing Data On Timber Structural Components in Fire

This section presents available fire testing data on the primary timber structural components. This includes light and heavy timber assemblies and associated connections.

Fire tests are organized into two main categories: standardized testing and experimental testing. Each category is separated for light timber, heavy timber and connections.

2.2.1 Standardized Testing

Standardized testing consists of fire tests performed using internationally recognized standard fire time-temperature curves. This includes ASTM E 119 in the United States, CAN/ULC S101 in Canada, and ISO 834 in the UK and Australia, among others.

While results from standard fire tests can be used to advance the body of research, they are the primary means for indexing and comparing fire performance by using a similar thermal heating regime.

2.2.1.1 Light Timber Frame Assemblies

The primary difference in fire performance of various light timber assemblies is the thickness and number of layers of gypsum board that are provided for fire protection. Generally, a greater thickness, or number of layers, will provide a higher fire resistance rating for the assembly. See Section 1.5 for additional information.

Summaries of fire performance of light timber frame are provided in various documents. Benichou and Sultan present a literature review of fire performance for light timber assemblies (Benichou & Sultan, 2000). The review includes research by the National Research Council of Canada (NRC) to develop and evaluate fire resistance models for light timber frame assemblies.

TRADA discusses light timber assembly reaction to fire, as well as the fire classifications and associated test standards for fire resistance (TRADA, Wood-Based Panel Products and Timber in Fire, 2009). The document summarizes fire performance for products including plywood, gypsum board and particle board. A discussion of behavior, performance, smoke control and production is also provided.

Fire tests with fire retardant and resistive coatings applied to plywood indicate that topical applications can also increase the fire resistance rating. The application of a multi-layer fire retardant coating increased fire resistance by up to 15 minutes. The use of a multi-layer fire resistive coating increased fire resistance by almost 45 minutes (White R. , Use of Coatings to Improve Fire Resistance of Wood, 1984).

Sultan and Lougheed focus on the fire performance of gypsum wall board assemblies, identifying how differences in gypsum board ratings provide the necessary fire resistance (Sultan & Lougheed, 1997). Guidance is presented for the various factors that influence the fire resistance, such as types and number of gypsum board panels.

Test results for light timber frame floor joist assemblies are also presented in Janssens & Douglas, Benichou & Sultan and Hopkin (Janssens & Douglas, Wood and Wood Products, 2010) (Benichou & Sultan, 2000) (Hopkin, 2011). Similar to wall assemblies, the type and rating of gypsum board provides the necessary fire resistance to the assembly. The greater the thickness or number of layers of gypsum board protection, the better the fire performance (Elewini, Sultan, & Hadjisophocleous, 2007).

A method for predicting the fire endurance of timber floor and ceiling assemblies using either metal-place-connected trusses or timber joists was developed by Cramer and White (Cramer & White, 1996). The model was based on a series of floor and ceiling assembly tests, and predicts the structural performance of the timber assembly based on the mechanical properties at high temperatures to provide conservative fire endurance times.

The importance of timber floor stability in fire, particularly for fire fighter operations, is highlighted in several documents (APA, Wood I-Joist Floors, Firefighters and Fire, 2012) (Dunn, 2010). Understanding the structural stability for timber elements in fire is an important consideration when assessing fire conditions and deciding if a structure is safe for fire fighter operations.

Given the understanding of fire performance of light timber frames, Konig and Walleij present a design model to calculate the fire resistance for timber frame assemblies with exposure to the ISO 834 standard fire (Konig & Walleij, Timber Frame Assemblies Exposed to Standard and Parametric Fires: Part 2: A Design Model for Standard Fire Exposure, 2000). The model utilizes charring and mechanical analysis based on previous fire testing to generate a thermo-mechanical model (Konig, A design model for load-carrying timber frame members in walls and floors exposed to fire, 2000).

Specific guidance is also available on failure times, or fall-off times, of gypsum board assemblies (Just, Schmid, & Konig, Failure Times of Gypsum Boards, 2010). Just evaluates testing data from more than 340 full-scale test results to develop a set of rules that can be used to calculate the gypsum board failure times.

A database and summary of full-scale gypsum board fire tests, as well as guidance on failure times of different gypsum board assemblies is provided. A discussion of the gypsum board design method per EN 1995-1-2 is also presented (Just, Schmid, & Ostman, Fire Protection Abilities Provided by Gypsum Plasterboards, 2012).

2.2.1.2 Heavy Timber Frame Assemblies

Whereas fire testing of light timber frame assemblies focuses on gypsum board protection for floor and wall assemblies, fire testing for heavy timber assemblies has been performed on a wider spectrum of products. This focuses around engineered timber products, post-tensioned timber framing and CLT assemblies.

Multiple references provide a summary of fire test data for engineered timber products exposed to fire. Hopkin provides a comprehensive literature review of fire testing in heavy timber assemblies (Hopkin, 2011). The American Wood Council (AWC) presents design calculation methods of fire resistance of heavy timber sections compared to experimental test results (AWC, Calculating the Fire Resistance of Exposed Wood Members, 2003). Generally, results compare favorably with design equations.

Fire behavior of engineered timber is similar to that of wood sections. However, the larger section size provides a greater area, allowing the charring behavior to provide inherent fire resistance.

This behavior for laminated veneer lumber (LVL) products is discussed in several papers. Tsai performed a series of fire tests to determine the charring rate for different sections of LVL (Tsai, 2010). Results indicated charring rates for LVL compared favorably to rates for solid wood. Harris and Lane performed fire testing with LVL sections to establish charring rates and fire performance (Harris, 2004) (Lane W. , Ignition, Charring and Structural Performance of Laminated Veneer Lumber (LVL), 2001). Testing was also performed for structural composite lumber (SCL), which consists of laminated veneer lumber (LVL), parallel strand lumber (PSL) and laminated strange lumber (LSL) (White R. , Fire Resistance of Structural Composite Lumber Products, 2006).

Fire test results for glulam sections are presented in Barber and Buchanan. Tension testing with steel rods epoxied into glulam sections indicated strength loss with increasing temperature (Barber, 1994). Tests to establish the charring rates for glulam sections were also performed (Buchanan & Moss, Design of Epoxied Steel Rods in Glulam Timber, 1999). Results for charring rates in glulam compared favorably to solid wood sections.

Primary findings from the above documents demonstrate that fire performance and charring rates of glulam, LVL and SCL are similar to that of large, solid wood sections. The engineered materials char at a constant rate when exposed to the standard fire and form the insulating char layer that protects the unheated timber below. Once the charring rate and section size are determined, the fire resistance time for exposed timber members can then be calculated (AITC, 2012).

The fire resistance time for wood elements can be increased by providing gypsum board protection at exposed surfaces. Fire testing with LVL beams has shown that 30 minutes fire resistance can be added for a single layer of 16mm gypsum board. Application of a double layer of gypsum board indicated at least a 60 minute increase in fire resistance time (White R. , Fire Resistance of Wood Members with Directly Applied Protection, 2009).

With the recent trend of CLT construction, there has been considerable research in fire testing of CLT panel assemblies. CLT is shown to char at a constant rate with exposure to the standard fire. The charring rate can be used to calculate the fire resistance of the section based on the depth of the panel.

Fire testing of CLT floor beams in bending was performed to develop an advanced thermo-mechanical model that can be used to predict CLT performance in fire (Schmid, Konig, & Kohler, 2010). The model uses the effective cross-section method with zero-strength layers for structural fire design and accounts for different temperature gradients in the CLT members.

Full-scale testing and fire performance is summarized in separate testing performed by Frangi and Fragiacomo. A summary of fire testing and numerical analysis results is presented by Frangi (Frangi, Fontana, Knoblock, & Bochicchio, Fire Behaviour of Cross-Laminated Solid Timber Panels, 2008). Results indicate that the fire performance of CLT panels depends on the behavior of single layers, accounting for delamination or fall-off.

Fire testing of unprotected and protected CLT panels was performed to establish the fire performance of panels subjected to out-of-plane loading. Results were compared to finite-element models used for sequential thermal and structural analysis to evaluate the model accuracy. Results indicate failure times of 99 minutes and 110 minutes for unprotected and protected CLT panels, respectively, and good agreement with the finite-element models (Fragiacomo M. , Menis, Clemente, Bochicchio, & Ceccotti, 2012).

A summary of fire testing on 5-layer CLT floor panels is summarized by Fragiacomo (Fragiacomo M. , Menis, Clemente, Bochicchio, & Tessadri, 2012). Testing results indicated that numerical predictions for CLT panel performance proved to be accurate for predicting fire resistance.

Testing on unloaded CLT members was performed by FPInnovations in Canada using exposed CLT and CLT protected by gypsum board panels (Craft, Desjardins, & Mehaffey, Investigation of the Behaviour of CLT Panels Exposed to Fire, 2011). Results confirmed existing charring rate values for CLT panels, and demonstrated that gypsum board protection delays the onset of charring and combustion for the protected CLT panels below.

A series of eight medium-scale fire tests using standardized and non-standardized fires was performed to evaluate the performance of CLT floors. Testing assessed charring rate, temperature profile, deflection, gypsum protection and overall fire resistance (Hadjisophocleous & Benichou, Fire Resistance Tests on Cross-Laminated Timber Floor Panels: An Experimental and Numerical Analysis, 2011). Results were used to develop a numerical model that is intended to assess fire resistance of CLT floors for any possible design fire or structural load.

Additional testing on CLT walls and panels was performed to demonstrate the performance of loaded CLT assemblies (Osborne, Dagenais, & Benichou, 2012). Testing also considered the effect of gypsum board protection for CLT panels, as scenarios included protected and unprotected CLT. Results indicate that the greater the depth of the section (3, 5 or 7 layers), the greater the fire resistance.

Additionally, gypsum board protection was shown to also increase the fire resistance time. Discussion on performance of gypsum board protection and charring rates is also provided (NRCC, 2013).

Full-scale fire testing for post-tensioned timber frame assemblies has primarily been performed in New Zealand, with summaries provided by Spellman (Spellman, The Fire Performance of Post-Tensioned Timber Beams, 2012) (Spellman, Carradine, Abu, Moss, & Buchanan, 2012). These assemblies consist of large timber sections with embedded steel tendons that provide increased structural strength. While the timber sections provide inherent fire resistance due to their depth, it is important that sufficient protection be provided to post-tensioned connection elements to maintain stability in fire.

As the understanding of fire performance of engineered timber products increases, innovative solutions seek to combine timber with conventional materials to optimize structural design. Timber-concrete composite floor systems offer the benefits of heavy timber performance, while having a concrete topping that provides non-combustible fire separation and acoustic performance (O'Neill, Timber-Concrete Composite Floors in Fire, 2010).

Fire testing has evaluated different designs for timber-concrete systems (O'Neill, The Fire Performance of Timber-Concrete Composite Floors, 2009) (O'Neill, Carradine, Moss, Fragiacomo, & Buchanan, 2010), and existing systems have been shown to behave well in full-scale fire tests (O'Neill, Abu, Carradine, Spearpoint, & Buchanan, 2012).

2.2.1.3 Connections

While there are many different types of timber connections, these can largely be classified into groups: primarily timber and steel connections. Fire performance of timber connections is similar to that of timber itself, with the potential for increased charring due to gaps in the connection. As such, fire testing data is focused on steel connections, which generally consist of screws, bolts, nails, fasteners and plate connections.

Several references provide overviews of fire testing data and performance of steel connections in timber (Austruy, Fragiacomo, Moss, & Buchanan, 2007) (Lau, 2006) (Gerard, 2010). Embedded connections such as screws, nails and bolts tend to demonstrate better fire performance than fasteners and plate connections. This is due to the amount of steel area that is exposed to high temperatures, as steel strength rapidly decreases with increase in temperature (Milke, 2002).

The greater the steel area exposed to high temperatures, the worse the connection performance in fire. Accordingly, fasteners and plates tend to fail more quickly than nails, plates and bolts, which are generally embedded, and thus protected, by the structural timber elements (Noren, 1996) (NRC, 2003).

Given the strength loss at elevated temperature in steel, protecting steel connections in timber is critically important to maintaining stability in fire conditions. This can be achieved using gypsum board or other passive fire protection means, including embedding connections in timber sections, or providing proprietary products (Ostman, Fire Safety in Timber Buildings - Technical Guideline for Europe, 2010) (Frangi, Fire Resistance Assessment of Timber Structures, 2012).

Standardized tests were performed to evaluate the fire performance of unprotected and protected, or exposed and unexposed, steel plates and develop a finite element model to predict the fire resistance of steel plate connections (Erchinger, Frangi, & Mischler, 2006). Exposed steel plates were placed on the exterior of a timber section and connected with dowels through the timber member. Unexposed steel plates, also called slotted plates, were embedded in the timber section and then connected by dowels through the section.

Results demonstrated that the slotted plates display significantly better fire resistance than exposed plate connections. Embedding the steel plate provided a layer of timber protection that reduced the exposed area of steel to high temperatures. Testing results were then used to develop the finite-element model, which showed good agreement with fire testing.

Testing performed by Peng evaluated the performance of bolted connections in timber when subjected to the standard time-temperature fire curve. Tests involved both exposed and unexposed bolted steel plate connections, and considered the effects of a single layer of either gypsum board or plywood protection (Peng, Hadjisophocleous, Mehaffey, & Mohammad, Fire Performance of Timber Connections, Part 1: Fire Resistance Tests on Bolted Wood-Steel-Wood and Steel-Wood-Steel Connectinos, 2012).

Exposed bolted steel plate connections performed the worst, due to the rapid heating with exposure to high temperatures. Providing a single layer of gypsum board was shown to nearly double the fire resistance time, with nearly a 50% increase for plywood protection. Additionally, fire resistance was shown to improve with increase in wood section width and decrease in the applied structural loading.

Results from testing were used as part of a second phase of research designed to develop a model for calculating the fire resistance of bolted connections (Peng, Hadjisophocleous, Mehaffey, & Mohammad, Fire Performance of Timber Connections, Part 2: Thermal and Structural Modelling, 2012). A strength-reduction model was developed to calculate the load-bearing capacity of bolted connections for given temperature profiles. Comparisons with experimental tests showed good agreement for predicting the fire resistance of bolted timber connections.

Additional fire testing of bolted connections was performed by Chuo, Austruy and Moss (Chuo, Buchanan, & Moss, 2007) (Austruy, Fragiacomo, Moss, & Buchanan, 2007) (Moss, Buchanan, Fragiacomo, Lau, & Chuo, 2009). Results of the standardized fire testing supported the results of previous tests in bolted connections. Reducing the exposed area of steel connections results in greater fire resistance times for the bolted connections.

Innovative connection design has also been tested utilizing hybrid connections between steel and epoxy to create epoxy-grouted steel rod connections in heavy timber. Fire testing performed at the University of Canterbury indicates that increases in steel rod temperature results in loss of connection strength (Barber, 1994) (Buchanan & Moss, Design of Epoxied Steel Rods in Glulam Timber, 1999) (Harris, 2004) (Gerard, 2010). Furnace testing using standardized fire curves provides failures times for the different timber connections to demonstrate how modifications to the timber connection affect the fire performance.

Planned testing at Carleton University will evaluate the fire performance of timber connections with exposure to the standard fire. This data will be used to develop and validate a 3-D heat transfer model to predict temperature distribution through hybrid timber connections (Hadjisophocleous, Wasan, & Ali, Fire Performance of Timber Connections, 2012). The model is intended to evaluate timber connection performance to resist experimental time-temperature curves.

2.2.2 Experimental Testing

Experimental testing consists of fire tests performed using non-standardized fire time-temperature curves. This includes natural fire tests, full-scale fire tests, furnace tests, or any other tests that use a non-standardized fire time-temperature curve.

While experimental testing does not always follow recognized fire time-temperature curves, tests are often performed for research purposes to better understand the fire performance of timber structural components.

2.2.2.1 Light Timber Frame Assemblies

Fire testing of light timber frame assemblies is primarily focused on using standardized testing to obtain the appropriate ratings and approvals. As such, fire testing data is more concentrated on standardized testing than experimental testing.

However, in 1996 a research project called Timber Frame 2000 (Grantham & Enjily, 2003) was conducted to explore the fire performance of light timber frame buildings and demonstrate compliance with the functional fire safety requirements in the United Kingdom.

A series of fire compartment burnout tests involving wood cribs in a six-story light timber building was performed at the Building Research Establishment facility in Cardington, UK. One of the key objectives was to evaluate compartmentation in medium-rise timber buildings, including the ability to prevent fire spread beyond the compartment of origin (Almand, 2012).

Results of the fire testing demonstrated that timber building performance in fire was able to meet the functional safety standards of the building regulations. This led to legislation that increased the prescriptive height allowance for timber buildings, allowing for taller timber structures.

In 2005, a total of six full-scale fire tests were performed to examine the fire performance of light timber frame buildings. Fire scenarios evaluated the effect of fast response sprinklers on a light timber assembly with no gypsum board protection (Frangi & Fontana, Fire Performance of Timber Structures under Natural Fire Conditions, 2005). The experiments included a typical room fuel load for a residential occupancy, with thermocouples located in the fire compartment and adjacent rooms to measure tenability conditions.

Results of the study indicated that fast response sprinklers were very effective in controlling and suppressing the fire. Flame spread was controlled to the area of ignition, with no additional spread to combustible materials. The study suggests sprinkler protection is able to satisfy the life safety objectives for any type of construction, including timber buildings with or without gypsum board encapsulation.

In a second set of tests, sprinklers were deactivated to evaluate the fire performance of light timber frame buildings with no automatic sprinkler protection. While the rate of fire growth was greater for the tests with no additional protection, the maximum temperatures were similar for both tests. Further, results from one of the complete burnout tests indicated no flame spread or increase in temperature beyond the room of fire origin.

2.2.2.2 Heavy Timber Frame Assemblies

In the past decade, valuable research has been obtained from experimental fire testing of heavy timber assemblies. This is often the result of full-scale testing simulating real fire conditions with a fuel load representative of actual building contents.

Testing is generally focused on demonstrating the effects of different fire protection systems in heavy timber assemblies, such as sprinklers and gypsum board protection. Results can also be used to investigate the potential for exposed heavy timber elements.

In October 2000, a large gymnasium fire in a glulam structure prompted a series of tests by Waseda University in Tokyo, Japan. The tests involved exposing glulam partition walls to a constant heat exposure from a propane burner to better understand the fire performance of glulam partition walls (Nam, Hasemi, Kagiya, & Harada, 2002).

A first exposure test resulted in charring of the wall, with no significant combustion occurring on the member. The second exposure, approximately 2.5 times more severe, resulted in full panel burnout, consistent with expected conditions within the gymnasium. Charring rates were recorded for both tests and were shown to be consistent with literature values and estimates for the case study fire.

A full-scale fire test of a 3-story CLT building was performed in 2008 to evaluate the fire performance of a CLT building with gypsum board protection and no sprinklers (Frangi, Bochicchio, Ceccotti, & Lauriola, 2008). The test simulated a standard residential fuel load and evaluated temperatures in adjacent fire compartments, both to the side and above the fire room. The fire room consisted of 3.4” [85mm] CLT wall panels protected by two layers of 0.5” [12mm] gypsum board. The floor and roof included 5.6” [142mm] CLT panels with one layer of 0.5” [12mm] gypsum board. The fire was allowed to burn a full 60 minutes, at which point it was manually exterminated.

Intense burning consistent with flashover occurred about 6-7 minutes into the fire growth (Frangi & Fontana, Fire Performance of Timber Structures under Natural Fire Conditions, 2005). This behavior was consistent with results in additional tests performed by Hakkarainen (Hakkarainen, Post-Flashover Fires in Light and Heavy Timber Construction Compartments, 2002). Findings indicate that flame spread and elevated temperatures were restricted to the room of fire origin. The study also suggested that protecting the timber structure with non-combustible gypsum board resulted in minimal damage to the CLT structure.

2.2.2.3 Connections

Testing of timber connections is primarily restricted to the standard fire curve to allow comparisons in fire resistance to identical fire exposures. However, several studies have utilized experimental time-temperature curves to better understand connection performance.

Experimental testing of connections is generally characterized by allowing a timber connection to heat in an oven to a constant temperature. Heating regimes for testing range from ambient temperature 70°F [20°C], to elevated temperatures of less than 570°F [300°C]. Heating at increments up to 570°F [300°C] are intended to better understand connection performance with increase in temperature prior to charring.

Testing performed by Chuo evaluated the strength of bolted connections in LVL with increase in temperature. Connection types included single-bolt configurations involving exposed steel plates connecting wood bolts, and steel plates protected by wood elements (Chuo, Buchanan, & Moss, 2007). The tests compared connection strength at ambient temperature with strength in fire tests with exposure to temperatures ranging from 70°F [20°C] to 480°F [250°C].

Results of experimental oven testing indicate a fairly constant rate of strength loss with increase in temperature. In most cases, approximately 50% of structural strength at ambient temperature is retained at temperatures up to 390°F [200°C]. This was consistent for both the exposed and unexposed steel plate bolted connections.

Additional testing of bolted connections in LVL was performed by Austruy (Austruy, Fragiacomo, Moss, & Buchanan, 2007). The experimental setup was identical to Chuo, with exposed and unexposed steel plate connections and an oven heating testing regime from ambient up to 480°F [250°C]. However, connections were tested with multiple bolts in bolt groups as opposed to single bolts.

Similar to previous results, as the temperature of bolted group connection assemblies increased, there was a marked decrease in strength. Results indicate a decrease of approximately 40% up to 210°F [100°C], with constant strength until 390°F [200°C]. Connection strength was shown to rapidly decrease beyond 390°F [200°C].

Results from experimental testing of bolted connections in LVL were used by Moss to develop a prediction method for the time to failure of bolted connections when exposed to fire (Moss, Buchanan, Fragiocomo, & Austruy, 2010). This prediction method was evaluated against further experimentation of single-bolt connections involving exposed and unexposed steel plates.

Results indicate that exposed steel connections demonstrated the most rapid strength loss with increase in temperature. Test results at elevated temperature were then used to develop a simplified design approach that predicts connection strength based on bolt temperature.

Testing was also performed using multiple oven heating regimes for epoxied connections in LVL (Harris, 2004) (Gerard, 2010). Assemblies involving steel rods grouted in LVL sections using epoxy were tested for ultimate strength at ambient temperature.

Epoxy grouted steel-timber connection assemblies were also placed in an oven and heated to a range of temperatures from 120°F [50°C] to 570°F [300°C] overnight. Heated specimens were tested at elevated temperatures to evaluate connection strength at high temperatures. Results from the oven and cooled testing indicate strength loss at elevated temperatures, with about 50% strength retained beyond 210°F [100°C] (Gerard, 2010).

A second series of tests involved heating the connection assemblies and allowing them to cool to ambient temperature prior to testing. This was intended to better understand post-fire performance of epoxied connections. Generally, results indicate that ambient strength is maintained when the connection is allowed to cool to ambient temperature. In some cases, the strength after cooling actually increased compared to ambient conditions.

2.2.3 Other Experimental Test Considerations

Generally, fire testing of structural components is performed using the standard or an experimental fire curve. However, given the unique nature of combustible construction materials representative of timber assemblies, research has been performed to evaluate the potential for modifications to experimental fire temperature-temperature curves. These studies are discussed in the following section.

2.2.3.1 Contribution of CLT to Room Fires

A series of five fire tests was performed to establish the contribution of CLT panels to fire growth and intensity. The tests were conducted in rooms consisting of protected and unprotected 3-ply CLT panels (McGregor, Hadjisophocleous, &

Benichou, 2012). Where protection was provided for CLT panels, there was no noticeable contribution from CLT to the fire behavior. However, for unprotected CLT, char layer fall-off was shown to contribute to the fire load, resulting in increased fire growth and heat release rates at later stages in the fire duration. It should be noted that the gas burner in the tests over-heated, potentially causing increased burning for the exposed CLT members.

While it is difficult to determine if char layer fall-off occurred naturally or due to delamination related to the type of adhesive, test results indicated that when charring advanced to the interface between CLT layers, delamination was shown to occur (Osborne, Dagenais, & Benichou, 2012). When delamination occurred, the fire in the compartment was shown to continue to burn at high intensity even after all the combustible contents had been consumed.

Results from the study suggest special consideration of design fires and time-temperature curves for unprotected CLT configurations to better understand the effect on compartment fire dynamics.

2.2.3.2 Guidelines for Design Fires

Researchers in Canada are currently evaluating design fire scenarios that may be more representative of actual conditions in residential and non-residential mid-rise buildings. This is intended to provide fire time-temperature curves that are more realistic to expected fire behavior.

Fire loads and design fires are evaluated based on a survey of fire loads, fuel packages and fire statistics (Ocran, Zalok, & Hadjisophocleous, 2012). This data is also being used to develop a fire spread sub-model, with possible expansion to Fire Dynamics Simulator (FDS) with future testing and validation.

2.2.3.3 Traveling Fires

Recent research has considered the potential impact of traveling fires in building compartments. While traditional methods assume uniform burning and temperature in a fire compartment, a traveling fire scenario considers that burning is limited to a specific area at a given time, with elevated temperatures remote from the fire (Stern-Gottfried, 2011).

The concept of traveling fires has been shown to be more realistic for large, open plan floor plates. Smaller fires travel across a floor plate for long periods of time with relatively low compartment temperatures, whereas larger fires have hotter compartment temperatures, but for shorter durations. This behavior can have a considerable impact on the structural response at high temperatures.

Special consideration is given to the fuel load within the fire compartment. This is often characterized based on occupancy type and any additional fire hazards. The potential for contribution of combustible linings should be considered.

The use of traveling fire scenarios has been shown to have considerable impact on the structural response with exposure to high temperatures. As a result, it is recommended for modern, open plan buildings, and is intended for structural analysis and design for fire safety and structural fire design, alike.

2.3 Ongoing Research Studies

This section discusses research studies that are currently in progress. While a primary component of research involves fire testing of structural components, this section is limited to highlighting a sample of the ongoing work being performed internationally. Fire testing results from ongoing and completed studies are presented in Section 2.2.

This section highlights several ongoing research studies being performed at universities, by timber initiatives (interest groups) and tall timber research consortiums/networks. As research and development of timber technology progresses, it is very likely this body of knowledge will continue to grow.

2.3.1 University Research

As momentum for heavy timber construction continues to build, universities across the world are actively supporting the timber industry to provide valuable research and testing data. While there are numerous universities performing valuable research, this section highlights some of the universities and associated research being performed.

Research at the University of Canterbury has focused on the development and testing of heavy timber structural elements and systems (UC, 2013). This includes glulam and LVL beams, columns, walls and associated connections. Research and development has resulted in the design of timber-concrete composite floors and post-tensioned heavy timber buildings.

A broad spectrum of timber research has been performed at ETH Zurich in Switzerland. This includes research and fire testing of light and heavy timber assemblies and their associated structural elements and connections (ETH, 2013). One of the primary areas of research at ETH is the performance of heavy timber structures, particularly in CLT construction. Both standard and experimental fire testing has provided significant insight into fire performance of CLT structures.

Carleton University in Ontario, Canada has engaged in a significant body of research in both light timber and heavy timber buildings (CU, Fire Safety Engineering, 2013). Carleton is uniquely positioned with two other research bodies, FPInnovations and the National Research Council (NRC), to further investigate the fire performance of timber buildings (CU, Fire Safety Engineering, 2013). Recent research is focused on fire performance of CLT buildings, as part of an initiative to promote tall timber construction.

Other universities that are active with furthering the design and understanding of timber structures include the University of Auckland in New Zealand, Delft University of Technology in the Netherlands, the ROSE School in Italy, MPA Stuttgart in Germany, the University of Edinburgh in Scotland and Worcester Polytechnic Institute in the United States, to name a few.

2.3.2 International Timber Initiatives

Many organizations in the timber frame industry have partnered to form timber initiative groups. These groups are intended to provide education, resources and technical support to promote the use of timber construction. Initiative groups often hold seminars, webinars and provide education and technical information in all aspects of timber design. This includes sustainability information, structural design and fire design, among others.

In North America, the primary timber initiative groups are WoodWorks, reThinkWood and MassTimber (WoodWorks, Wood Works, 2013) (reThinkWood, 2013) (MassTimber, Mass Timber, 2013). These initiative groups are supported by the American and Canadian Wood Councils, among others, and focus on promoting non-residential and multi-family wood buildings.

In the United Kingdom, WoodFirst, formerly known as Wood For Good, is an initiative group supported by many members of the UK timber industry. The primary goal is to call for “Wood First” legislation for planning, whereby, where feasible, wood has to be considered as a primary construction material for all publically funded new build and refurbishment projects (WoodFirst, 2013).

An Australian initiative group called Wood Solutions is intended to provide independent, non-proprietary information about timber and wood products to promote timber design and construction (WoodSolutions, Wood Solutions, 2013). The initiative group is supported by industry representatives and technical associations, and provides many resources, including publications, professional seminars and other technical guidance.

2.3.3 Tall Timber Research Studies

While this study focuses on summarizing the current body of research in fire safety of tall timber buildings, other research projects around the world are making progress and contributing to the understanding of fire safety challenges in timber buildings. Two ongoing research studies are presented below.

2.3.3.1 Structural Timber Innovation Company (STIC)

The Structural Timber Innovation Company (STIC) is a research consortium that is aimed at developing new technologies to enable structural timber to compete more effectively with traditional building materials (STIC, 2009). The group is composed of commercial and industrial partners, and is supported by research at multiple universities and organizations across Australia and New Zealand.

Research at STIC is focused on investigating the performance of prefabricated glulam and LVL structural building systems. This includes the development of technologies such as post-tensioned heavy timber buildings and timber-concrete composite floor systems.

2.3.3.2 NEWBuildS (Network for Engineered Wood-based Building Systems)

The Network for Engineered Wood-based Building Systems, referred to as NEWBuildS, is a multi-disciplinary research effort that is intended to advance scientific knowledge and construction technology to enable mid- and high-rise timber construction (NEWBuildS, Welcome to NEWBuildS!, 2012). The group is supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada, and is composed of researchers from organizations including FPInnovations, the Institute for Research in Construction of the National Research Council, the Canadian Wood Council, and academics from universities across Canada.

The research program is organized into four themes, including:

- Theme 1: Cross laminated timber (CLT) – material characterization and structural performance;
- Theme 2: Hybrid building systems – structural performance;
- Theme 3: Building systems – fire performance, acoustic and vibration serviceability; and
- Theme 4: Building systems – durability, sustainability and enhanced products.

Research is composed of studies, modeling analysis and experimentation to advance the understanding of timber construction.

Theme 3, which includes fire performance research, investigates the fire safety challenges posed by tall timber buildings (NEWBuildS, Theme 3: Building Systems - Fire Performance, Acoustic and Vibration Serviceability, 2012). Fire research and testing includes the following:

- Fire risk analysis;
- Rationalization of life safety code requirements;
- Fire behavior of cross laminated timber panels; and
- Fire performance of timber connections.

A primary output of the research is the release of a Technical Guideline for the Design and Construction of Canadian Tall Wood Buildings. This document is intended to incorporate results from the NEWBuildS study to address the many challenges, including fire safety, posed by tall timber buildings through research, testing and demonstration projects (Karacabeyli & Lum, 2013).

2.4 Review of Fire Incidents in Timber Structures

It is generally perceived that timber frame buildings are more susceptible to fire, and therefore present a greater fire safety risk compared to steel and concrete buildings. The historical record has shown a number of incidents where entire cities, primarily built in timber, have been destroyed due to fire.

In modern times, large, sensational timber frame fires tend to receive media amplification, as they make for better photo and video representations, and therefore result in a greater audience.

This section presents recent fire incidents involving timber structures. Incidents are organized based on the time in which they occurred during the building lifetime.

2.4.1 Historical Fire Incidents

The Great Fire of London, England, in 1666 was one of the most devastating fires in history. The fire started in a bakery and burned for four days, destroying nearly 80% of the buildings in London. While the great majority of structures were timber framed and pitch buildings, standards of construction in the 1600's were very different from modern-day buildings (Bell, 1971).

In 1904, the Norwegian city of Ålesund experienced a large fire which was allegedly caused by a cow kicking over a torch near the timber framed Ålesund Preserving Company's factory. Gale winds traveling over the village caused the fire to spread to the entire city, which mainly consisted of timber-framed houses (Alesund & Sunnmore, 2013).

In 1906, a magnitude 7.9 earthquake rocked the city of San Francisco. While the earthquake damaged the city's main water supply used for firefighting, the resulting fire caused significant damage to the many timber-framed buildings throughout the city. Many small fires throughout the city quickly grew to engulf entire neighborhoods. The fire resulted in over 80% of the city being destroyed due to fire (Buffalo, 2008).

The incidents summarized above include some of the better known and more sensational historical fire events. Standards of construction, fire protection systems, fire fighter response and advances in building technology and design makes a repeat of such events very unlikely, even for extreme events.

The following sections indicate more recent fire incidents in modern timber structures. Fire incidents are separated based on if the building was under construction or completed at the time of the fire. Notably, the fires are typically limited to a single site, are not designed with automatic sprinklers, and are generally suppressed by fire fighter operations.

2.4.2 Fire in Buildings Under Construction

2.4.2.1 Colindale, London, UK, 2006

In July 2006, there was a fire in a six-story light timber frame residential complex under construction in Colindale, London, UK. Over 100 fire fighters responded to fight the blaze for over five hours. During that time, the neighboring buildings were evacuated due to the size of the fire and the concern of fire spread. Fire spread to the adjacent light timber building also under construction, with severe damage to an adjacent University hall.

The fire was seen from several miles away, as the flames reached hundreds of feet into the air. Given the building was under construction with no fire separations, it was observed that the entire building was engulfed in fire 10 minutes after fire fighters arrived to the scene. The structure fully collapsed another 10 minutes later (GreaterLondonAuthority, Fire Safety in London - Fire Risks in London's Tall and Timber Framed Buildings, 2010).

A London Fire Brigade findings report suggests the fire could have started due to a lit cigarette in an unoccupied area of the construction site (Ovolo, 2007).

2.4.2.2 Peckham, London, UK, 2009

In November 2009, a fire broke out at a five-story, light timber frame construction site in Peckham, London, UK. In response, 30 fire engines and 150 fire fighters were deployed. Upon arrival, the entire site was ablaze. The size of the fire caused damage to adjacent properties (GreaterLondonAuthority, Fire Safety in London - Fire Risks in London's Tall and Timber Framed Buildings, 2010).

2.4.2.3 Richmond, British Columbia, Canada, 2010

In June 2010, a six-story building constructed in light timber construction in Richmond, Canada, caught fire and was completely destroyed. This sparked fire safety concerns, as this was the first six-plus story timber building to be approved in Canada (Alter, Wood Construction Under Fire After the First 6 Storey Wood Building in Canada Burns Down, 2011).

The Canadian Wood Council quickly pointed out that the building was still under construction. Fire safety features, such as sprinklers and gypsum board protection, had not yet been installed at the time of the fire. The Canadian Wood Council statement indicates the severity of the fire would not have been possible had the fire safety systems been installed and functional (Giroux, 2011).

2.4.2.4 Hampshire, UK, 2010

In Hampshire, UK, a light timber four-story frame residential timber construction site caught fire in September 2010. 16 fire engines and more than 100 fire fighters were deployed. When fire fighters arrived to fight the blaze, the complex was in danger of collapse and spreading to surrounding buildings (Morby, 2010).

2.4.2.5 Salford, Ordsall, UK, 2011

In Salford, Ordsall, UK, a fire completely destroyed a light timber frame building under construction in August 2011. 50 fire fighters tried to control the fire for an entire night. The fire and rescue services managed to prevent fire spread to adjacent buildings, though the fire resulted in complete burnout of the complex (ManchesterEveningNews, 2013).

2.4.2.6 Rhode Island, USA, 2012

A large, heavy timber framed mill building that was being converted into a wood pellet manufacturing plant was destroyed by a fire in Rhode Island, USA in 2012. Workers using cutting torches on pipes were alleged to have heated the wooden structural framing, causing ignition approximately 60 to 90 minutes after completing work for the day.

While the fire detection system was linked to the fire department, the automatic fire suppression system had been turned off during the renovation (Tremblay, Firewatch, 2012).

2.4.3 Fire in Completed Buildings

2.4.3.1 Hiroshima, Japan, 2000

In October 2000, a fire completely destroyed a glulam timber gymnasium in Hiroshima, Japan. The entire building was on fire nine minutes after fire detector activation, and continued burning for approximately 20-30 minutes following detection. This prompted a series of fire tests to assess why the fire spread so rapidly through the structure (Nam, Hasemi, Kagiya, & Harada, 2002). Almost all the combustible contents were lost. The only remaining elements were the heavy timber structural columns used to support the structure.

2.4.3.2 Alaska, USA, 2007

A fire was intentionally set in a crawl space in an older light timber frame hotel in Alaska, USA in 2007. While smoke alarms were installed throughout hallways and guest rooms, many did not activate. In some cases batteries had been removed or devices were missing. Automatic sprinklers were effective at preventing fire spread to rooms, but fire spread throughout the unsprinklered concealed spaces resulted in complete burnout of the structure (Tremblay, Firewatch, 2007)

2.4.3.3 Croydon, London, 2007

A block of five-story light timber frame apartments built in the 1970's were completely destroyed on Christmas Day 2007 by a fire in Croydon, London, UK. The fire was believed to be caused by a child playing with matches, and spread through concealed wall spaces to adjacent levels. This incident raised questions about the safety of timber-framed buildings (Stothart, 2009).

2.4.3.4 Massachusetts, USA, 2008

In 2008 a cutlery manufacturing plant constructed of heavy timber and a brick exterior in Massachusetts, USA was spared a major loss when automatic sprinklers were able to control fire spread and allow firefighters to suppress the fire. The fire started when a lit cigarette was disposed in a trash can in a vacant restroom and was allowed to smolder until combustion occurred (Tremblay, Firewatch, 2009).

2.4.3.5 Camberwell, London, UK, 2009

In July 2009, the 14-story concrete and timber-framed Lakanal House in Camberwell, London, UK caught fire. The fire started on the 9th floor and spread through the structure, resulting in six casualties on the 11th floor. The fire and rescue services deployed 100 fire fighters and specialist fire rescue units to fight the blaze. It is believed that fire spread through gaps in compartments and concealed spaces could have led to fire spread throughout the structure (BBCNews, Safety Questions After Flat Fire, 2009).

2.4.3.6 Michigan, USA, 2012

In 2012, a heavy timber frame furniture plant in Michigan, USA caught fire. Workers using a circular saw to cut through ductwork ignited lacquer that had built up in a spray room. Openings in the ductwork cut by the workers allowed fire spread from the spray room through the structure.

Despite many fire doors having been removed from the structure, automatic sprinklers and fire fighter intervention were able to limit the damage and salvage most of the building (Tremblay, Firewatch, 2012).

2.4.3.7 Wolverhampton, UK, 2012

In Wolverhampton, UK, an accidental fire set ablaze a three-story light timber frame building in August 2012. According to West Midlands Fire Service, 40 fire fighters were at the scene and worked all night to put out the fire. Further investigation revealed the timber framed building was structurally unsound (BBCNews, BBC News, 2012).

2.4.3.8 Chicago, USA, 2013

A fire broke out in an abandoned heavy timber warehouse in Chicago, USA in January 2013. While the roof and three external walls collapsed, fire was contained to the warehouse and the structure remained standing for the duration of the 10 hour fire before the nearly 170 fire fighters deployed could extinguish the blaze (Dudek & Shelton, 2013). The cause of the fire was purported to be due to homeless that were known to occupy the building during the winter.

2.4.4 Other Fire Incidents

In August 1993, a fire burnt part of the Kapell Bridge, the oldest timber bridge in Europe. The original bridge was dated to 1333 and located in Lucerne, Switzerland. The fire occurred late at night and burned for nearly an hour and a half, destroying approximately two-thirds of the bridge. The bridge was quickly reconstructed in eight months, reproducing the timber structure and decorative artwork (Boswell, 2013).

In June 2011, a fire destroyed an eight-car train and a 50 year old wooden avalanche cover in Hallingskeid, Norway. The fire was first detected close to the avalanche cover tunnel, which was designed to protect the track from snow during the winter. The fire caused the oncoming train to lose its electric power supply, which brought the train to a halt within the avalanche tunnel. All 257 passengers were brought to safety. The closest fire and rescue service was located 37 miles [60 km] away which meant that the fire fighter operations started 2 hours after detection. By that time, the fire had spread to the train, which was completely destroyed (Sandelson, 2011).

A timber railway bridge crossing over the Colorado River between San Saba and Lorneta in Texas, US, burned down and collapsed in May 2013. Fire fighters attempted to extinguish the fire for over 15 hours before they decided to discontinue operations. The bridge was a vital link for freight transport and is estimated to cost around $10m to rebuild (BBCNews, Burning Texas Railway Bridge Collapses, 2013).

2.4.5 Conclusion

The fire incidents presented above indicate that fire in timber buildings under construction tend to result in a greater potential for complete burnout. This is particularly true for light timber frame buildings, as the largest fires occurred prior to the installation of gypsum board fire protection or automatic sprinkler protection. This allowed fire to rapidly spread through the entire structure, typically resulting in complete burnout and threatening adjacent structures.

Fire incidents in heavy timber buildings tend to result in smaller fires, as large timber sections have an inherent fire resistance. Additionally, charring in the heavy timber member will delay the onset of combustion, providing greater time for fire fighter intervention.

While complete burnout has been shown to occur in completed buildings, the finished fire separations generally restrict fire spread to the room of origin. This also provides a greater amount of time for fire service intervention.

For timber buildings, particularly those in light timber frame, effective fire stopping relies on quality workmanship to reduce any gaps in construction that could allow fire spread between compartments (Derlinaldis & Tampone, 2007). When this is done effectively, fire is generally limited to the room of origin and controlled by fire fighter intervention (AFPA, 2001).

2.5 Review of Existing Design Guidance

Many organizations from different regions across the globe have developed design guides. These are typically focused on prescriptive design guidance in one of two themes: multi-story timber construction or fire safety in timber buildings.

Design guides on multi-story timber construction generally focus on structural design challenges specific to low- and mid-rise timber buildings. While most multi-story timber design guides present issues such as fire safety, acoustics and other considerations, these are discussed in less detail.

Design guides on fire safety in timber buildings focus on the unique fire hazards, dynamics and behavior associated with construction in combustible buildings. This is generally limited to low- and mid-rise timber buildings, with detailed information on fire protection systems, including structural fire performance, and more limited discussion on issues such as detailing, acoustics and architectural design and flexibility.

Generally, there is minimal overlap between the two sets of guidance documents. This section presents an overview of the design guidance available for both of these two themes. Discussion is limited to design guidance for heavy timber buildings, as this is the most relevant to the study. A section on alternative design guidance is also presented.

It is important to note that ongoing research is beginning to fill the void between multi-story timber construction and fire safety in timber buildings, particularly in the area of fire safety in tall timber buildings. Further information about ongoing research is discussed in Section 2.3.

2.5.1 Multi-Story Timber Construction

A number of existing design guides are available that focus on multi-story timber construction. These typically highlight the advantages of tall timber construction and focus on structural information, including design and detailing. Issues such as fire safety, acoustics and floor vibration, are often presented as a basic introduction.

Prescriptive design guidance on multi-story timber buildings is available in many countries. This includes Eurocode 5: Design of timber structures Part 1-1 (BSI, Eurocode 5: Design of Timber Structures, 2004) in the UK, and the National Design Specification (NDS) for Wood Construction (AWC, National Design Specification for Wood Construction, 2012) in the United States. These documents provide design guidance for stability, focusing on structural design and detailing, but also discuss fire safety.

One of the primary guidance documents was published in 2003 by the BRE (Grantham & Enjily, 2003). While this document touches on fire safety aspects of timber buildings, the focus is on existing testing and designing for structural safety. This includes a summary and discussion of the TF 2000 project, as well as introducing fire safety and structural performance issues.

Summaries of multi-story timber design guidance are provided in multiple documents (Crespell & Gagnon, 2010) (WoodSolutions, Building With Timber - Nine Storeys and Beyond, 2013) (WoodWorks, Wood Buildings Aim High, 2012) (Wells, 2011). These provide brief overviews of the many aspects that need to be considered for multi-story timber design, including technical design for structural and fire safety.

North America has produced several guidance documents specifically for multi-story design of CLT Buildings. Considerable research and testing performed by FPInnovations has led to the development of CLT Handbooks that can be used for prescriptive building design in the United States and Canada (Karacebeyli & Douglas, 2013) (Gagnon & Pirvu, 2011). These documents discuss a wide spectrum of multi-story timber design elements ranging from manufacturing and structural design, to fire and environmental performance.

2.5.2 Fire Safety in Timber Buildings

Prescriptive design guidance for fire safety in timber buildings is internationally available in a number of documents. Eurocode 5: Design of timber structures Part 1-2 in the UK (Konig, Structural fire design according to Eurocode 5 - design rules and their background, 2005) (BSI, Eurocode 5: Design of Timber Structures, 2004) and the SFPE Handbook and American Wood Council in the US (White R. , Analytical Methods for Determining Fire Resistance of Timber Members, 2002) (AWC, Calculating the Fire Resistance of Exposed Wood Members, 2003) provide design guidance for fire safety in timber structures. These documents focus on structural fire safety, but emphasize the significance of other aspects of fire safety including design fires, fire dynamics and fire separations.

Design guidance from New Zealand provides a thorough summary of structural design for fire safety in all types of buildings, including a discussion of fire safety in timber structures (Buchanan, Structural Design for Fire Safety, 2001).

Information specific to timber frame buildings is available in additional guidance from Buchanan (Buchanan, Timber Design Guide, 2011). Fire performance of timber buildings, connections and behavior is presented, in addition to fundamentals of fire dynamics.

Summaries of fire safety in timber buildings are also published by multiple timber initiative groups across the world (WoodWorks, Designing for Fire Protection, 2011) (Maxim, Plecas, Garis, & Clare, 2013) (Dunn, 2010) (White N. , 2012). These provide descriptions of many of the fire safety risks unique to timber design, as well as design solutions. The initiative websites provide an abundance of background and technical information to further understand the performance of timber buildings. See Section 2.3.2 for additional details on timber initiatives.

In addition to fire safety summaries, design equations for calculating fire performance and resistance of timber buildings are provided in multiple documents (CWC, Fire Safety Design in Buildings, 1996) (Frangi & Fontana, Fire Safety of Multistorey Timber Buildings, 2010) (AWC, Calculating the Fire Resistance of Exposed Wood Members, 2003). These allow a designer to quantify the performance of the structure in addition to identifying and appropriately mitigating potential hazards.

One of the most recent technical guidelines that focuses on fire safety in timber buildings was released in 2010 as a technical guideline for Europe (Ostman, Fire Safety in Timber Buildings - Technical Guideline for Europe, 2010). The guideline is based on a large body of empirical testing performed by SP Tratek and a number of universities and organizations across Europe. An overview of timber structures, including structural and fire safety considerations for connections, service penetrations and structural elements are provided. The guide also includes a discussion of fire protection strategies and performance based design intended to enable design and approval of timber structures for fire safety.

As previously discussed, timber construction is most vulnerable to fire during construction. Several documents have been published that provide guidance for fire safety of timber structures during construction (UKTFA, 2012) (Garis & Clare, 2013) (TRADA, Fire Safety on Timber Frame Construction Sites, 2012) (WoodWorks!, Fire Safety and Security, 2010). Generally, guidance recommends providing appropriate separation distances between the construction site and adjacent buildings. The use of 24-hour fire and security watches, in addition to heat and smoke alarms, and even temporary sprinklers, is also suggested.

2.5.3 Engineered Approaches / Performance Based Solutions

As understanding of timber and fire safety progresses, the potential for engineered approaches and performance based design solutions increases as well. Engineered approaches allow the designer to propose a design strategy that is intended to meet the level of safety intended by the prescriptive code. Refer to Section 1.4.5 for additional information.

Numerous studies on the fire safety risks and hazards of tall timber construction identify the key challenges to design, for which engineered approaches may provide solutions (Frangi, Fontana, & Knoblock, Fire Design Concepts for Tall Timber Buildings, 2008) (Frangi & Fontana, Fire Safety of Multistorey Timber Buildings, 2010) (Osborne, Dagenais, & Benichou, 2012). This is evidenced by recent design guides and technical studies that discuss performance based solutions that can be used to demonstrate safety in tall timber buildings.

A user-friendly matrix is available online that demonstrates where engineered solutions may be necessary for approval (WoodWorks!, The Wood Use Matrix, 2013). This matrix allows a user to check characteristics of a building design against the prescriptive code to determine where an engineered solution may be necessary, or a performance based solution could be used.

The technical guideline for Europe describes the basic principles for fire risk assessment principles and performance based design. This includes fire safety engineering design, analytical approaches and calculation, design fires and statistics (Ostman, Fire Safety in Timber Buildings - Technical Guideline for Europe, 2010). While the design guide document is focused on timber design, the guidance on performance based solutions can be applied to all building types. This allows a designer to propose an engineered solution using fire risk assessment principles to comply with the prescriptive regulations.

In Canada, a technical and practice bulletin combines both prescriptive and engineered solutions to meet an equivalent level of safety required by the building code (APEG, 2011). This document focuses on solutions for structural and fire safety strategies for Canadian mid-rise residential buildings.

Australian guidance includes a series of technical documents intended to provide performance based design solutions for tall timber buildings (WoodSolutions, Alternative Solution Fire Compliance: Cross-laminated Timber (CLT), 2013) (WoodSolutions, Alternative Solution Fire Compliance: Facades, 2013) (WoodSolutions, Alternative Solution Fire Compliance: Internal Linings, 2013) (WoodSolutions, Alternative Solution Fire Compliance: Timber Structures, 2013). While these documents focus on fire safety information for CLT structures, they also discuss design strategies for building components including facades and internal linings.

Guidance in Canada provides a technical guide for the design and construction of tall timber buildings (Karacabeyli & Lum, 2013). This design guide is unique in that it is intended to follow performance based design philosophies utilizing alternative solutions to meet the life safety objectives of the prescriptive code. The technical guide discusses recommendations for redundancy and resiliency and emphasizes a multi-disciplinary approach with reference to technical information.

2.6 Global Case Studies Of High-Rise / Tall (Six-Stories And Above) Timber Framed Buildings

Timber is one of the oldest and most common construction materials for buildings. Historically, timber has been used not only for houses, but also for churches, pagodas and even offices, among other uses. Given the human experience with large, city-wide fires, building codes globally have enacted legislation to limit the height and area of timber buildings.

In the past decade however, a number of countries have relaxed the prescriptive height limits for timber buildings and allowed the possibility of performance based design solutions. This has encouraged the design, construction and approval of a number of high-rise or tall timber buildings.

This section provides examples of historic timber buildings, as well as a summary of modern high-rise timber buildings (six-stories or greater) that have either been constructed, or are currently in the design and/or construction phase. A summary of feasibility studies incorporating tall timber design is also presented.

Case study summaries of modern buildings are limited to heavy timber construction, as, to date, heavy timber framing members have been chosen as the most suitable system for use in high-rise timber building design.

Case studies are organized based on primary construction methods and are organized as follows:

- Post and Beam Construction: Post and beam construction typically utilizes large glulam and LVL beams and posts and a central core for structural stability. This construction type is typically used for open plan commercial design.
- Panelized Construction: Panelized construction is generally characterized by CLT panel assemblies, and typically used for residential occupancy types.
- Other Construction Types: Any other design, such as towers and sculptures, are presented as other construction types.

Additional discussion and information on the construction methods are presented in Section 1.6.

2.6.1 Historic Structures

2.6.1.1 Yingxian Pagoda, Shanxi, China, 1056

The Yingxian Pagoda, also called the Sakyamuni Pagoda of Fogong Temple, is a 9-story, 221 foot tall [67m] tall pagoda located in the Shanxi province of Northern China. Constructed in 1056 by the Liao Dynasty, the structure is cited as the oldest and tallest multi-story timber building in the world (UNESCO, Wooden Structures of Liao Dynasty - Wooden Pagoda of Yingxian County, Main Hall of Fengguo Monastery of Yixian County, 2013).

The pagoda was designed with an octagonal floor plan approximately 100 feet [30m] in diameter that decreases in area going up the building. The structure is built on a 13 foot [4m] stone platform foundation and consists entirely of wood construction, including an exterior and interior circular arrangement of timber columns to support the five visible stories, as well as the four blindstories within the pagoda (Lam, He, & Yao, 2008).

Figure 66 – Yingxian Pagoda, Shanxi, China (eTeacherGroup, 2013)

As one of the oldest surviving timber structures in the world, the Yingxian Pagoda has survived over 900 years of seismic activity in addition to the fire risk inherent to timber structures.

This includes more than seven strong seismic events, with minimal damage. According to the UNESCO site, the Yingxian Pagoda can be described as "a miracle in the history of Chinese architecture" (UNESCO, Wooden Structures of Liao Dynasty - Wooden Pagoda of Yingxian County, Main Hall of Fengguo Monastery of Yixian County, 2013)**.**

2.6.1.2 Urnes Stakirke, Sogn og Fjordane, Norway, 1132

The Urnes Stakirke is a medieval church located in Sogn og Fjordane, Norway that is estimated to have been constructed around 1130. The church is entirely constructed out of timber and includes large columns and arches to support the structure.

Of the 1,000 churches to be built during this period, the Urnes Stakirke is one of 28 that still remains (UNESCO, Urnes Stave Church, 1979).

Figure 67 – Urnes Stakirke, Sogn og Fjordane, Norway (UNESCO, Urnes Stave Church, 1979)

2.6.1.3 Leckie Building, Vancouver, Canada, 1908

The Leckie Building is a six-story structure built in 1908 in Vancouver, Canada. The construction method is described as “brick and beam”, consisting of an unreinforced masonry (brick) façade and heavy timber post and beam internal superstructure (Koo, 2013).

The use of brick and beam construction created a large, open floor plan that was used for office and industrial functions for the Leckie Company, makers of footwear for soldiers during both World Wars (TaliaJevan, 2013).

The building went through seismic renovations in the early 1990’s and is currently in use as office and gallery spaces.

Figure 68 – Leckie Building, Vancouver, Canada (ParksCanada, 2013)

2.6.1.4 Perry House, Brisbane, Australia, 1913

Figure 69 – Perry House, Brisbane, Australia (Culwulla, 2009)

The Perry House, originally a 7-story timber building that was expanded to 8-stories in 1923, is one of the oldest and tallest timber structures in Brisbane, Australia, at a full height of approximately 122 feet [37m] (AusPostalHistory, 2013).

The structure was originally occupied by the Perry Bros for business activities and storage of goods. After renovation in 1996 and refurbishment in 2008, the Perry House is currently in use as a 73-room boutique hotel called the Royal Albert (Amparose, 2013).

2.6.2 Post and Beam Construction

2.6.2.1 Limnologen, Vaxjo, Sweden, 2009

Limnologen is an 8-story building composed of 1 level of concrete construction and 7 levels of glulam construction. Upon completion, it was the largest timber residential building in Sweden (SwedishCleantech, 2010).

The building is part of a project called Valle Broar, which aims to support timber-building technology and create a modern timber city in Vaxjo, Sweden (MIDROC, 2011).

The structure is composed of glulam members and prefabricated solid wood frame construction for walls and floor members to take advantage of the environmental benefits of timber (Serrano, 2009). The structure is designed with instruments to measure deformation and track the vertical displacement of the structure over time. The total vertical displacement was approximately 20mm more than a year and a half after construction.

Figure 70 – Limnologen, Vaxjo, Sweden (MIDROC, 2011)

2.6.2.2 Life Cycle Tower One, Dornbirn, Austria, 2012

Life Cycle Tower One, also referred to as Life Cycle Tower (LCT), is the first structure to be built as part of the CREE, sustainable timber-hybrid high-rise design, promoted by architect Hermann Kaufmann and Austrian builder, Rhomberg (Rhomberg, Life Cycle Tower, 2012).

LCT One was completed in 2012 in Dornbirn, Austria as an 8-story commercial office building. The building is the result of a feasibility research project with engineering consultants, Arup, for a 20-story timber-hybrid high-rise building.

Figure 71 – Life Cycle Tower One, Dornbirn, Austria (Rhomberg, CREE: The Natural Change in Urban Architecture, 2012)

The Life Cycle Tower structural design is based on post and beam construction with large internal and perimeter glulam columns. These are combined with a concrete core for stability and hybrid timber-concrete floor slabs for fire separation and acoustic performance (Wurm, Gockel, & Unger, 2012).

The primary difference compared with panelized construction is the large, open plan floor plate that is more practical for commercial layouts.

A second Life Cycle Tower was completed in Vandans, Austria in June 2013, with plans to expand the CREE design to multiple sites across the world, including Oakland, California, and Vancouver, Canada (Rhomberg, CREE: The Natural Change in Urban Architecture, 2012).

2.6.2.3 Bullitt Center, Seattle, Washington, USA, 2013

The Bullitt Center is a 6-story office building designed by Miller Hull and the Bullitt Foundation, located in Seattle, Washington. Completed in 2013, the building is one of the most ambitious sustainable projects to date (BullittFoundation, 2011). The project goal is to improve long-term environmental performance and promote renewable and sustainable technologies. This objective made timber the natural choice for the structure.

The glulam post and beam construction and timber-concrete floor slabs maximize the use of timber as the primary structural material. This carbon-neutral performance is accompanied by solar panels for energy, rain capture for water and geothermal wells for heat (Newcomb, 2012).

The Bullitt Center is one of the first timber buildings that aims to meet the goals of the Living Building Challenge. This requires that a building be self-sufficient for energy and water for at least 12 continuous months, and meet green material standards and quality (Nelson B. , 2013) (BullittFoundation, 2011). The use of timber structural material contributes to the sustainable benefits of the project, and is likely to be used for other buildings attempting Living Building Challenge certification.

Figure 72 – Bullitt Center, Seattle, Washington, USA (BullittFoundation, 2011)

2.6.2.4 Wood Innovation Design Centre, Prince George, Canada, 2014

Scheduled to be completed in late 2014, the Wood Innovation Design Centre is a 6-story commercial building located in Prince George, Canada. The building is designed by Michael Green Architects, and maximizes timber structural elements through the use of glulam post and beam construction with hybrid wood-concrete floor slabs and a timber core (Green, WIDC, 2013).

The concept design of the structure was part of a Canadian government endowment of $2.25 million CAD as part of a Tall Wood Building Construction commission (Newsroom, 2013).

When it is completed, the building will be the tallest timber building in North America at a height of approximately 90 feet (DesignBoom, First Look: North America's Tallest Wooden Building, 2013).

Figure 73 – Wood Innovation Design Centre, Prince George, Canada (Green, WIDC, 2013)

2.6.3 Panelized Construction

2.6.3.1 Stadthaus, London, United Kingdom, 2009

One of the first examples of tall panelized construction is Stadthaus, completed in London in 2009 by Waugh Thistleton Architects. Stadthaus, also known as Murray Grove, is a 9-story residential apartment complex that consists of a reinforced concrete ground level and 8-stories completely constructed of CLT panels (Lowenstein, Timber Towers, 2012).

Figure 74 – Stadthaus, London, UK (TRADA, Stadthaus, 24 Murray Grove, London, 2012)

The prefabricated CLT panels allowed a team of four carpenters to construct the super-structure in less than four weeks (Waugh, Wells, & Lindegar, 2010).

While the CLT panel thickness was shown to be adequate for 60 minutes fire resistance rating, the building was provided with gypsum board protection to gain approval (TRADA, Stadthaus, 24 Murray Grove, London, 2012).

Construction of the Stadthaus project generated substantial interest in CLT construction for prefabricated residential buildings, not only in the UK, but also around the world (Lowenstein, Towering Timber, 2008) (Fountain, 2012).

2.6.3.2 Bridport House, London, UK, 2011

The Bridport House, completed in 2011 in London, UK, was the first fully CLT building to be constructed in the UK (WillmottDixon, 2011). The 8-story residential structure was designed by Karakusevic Carson, and is fully composed of prefabricated CLT construction with a concrete topping slab for acoustic performance.

Figure 75 – Bridport, London, UK (TimberInConstruction, 2010)

CLT construction was chosen over steel and concrete due to weight concerns as a storm relief sewer is located under the site. The use of CLT allowed the building to be lightweight, and prefabricated panelized construction resulted in a construction time of 10 weeks, less than half the estimated time for a concrete structure (Birch, 2011).

Additionally, the CLT panels were edge-glued to provide increased acoustic and fire performance to make the connection locations more air- and water-tight (Powney, 2011).

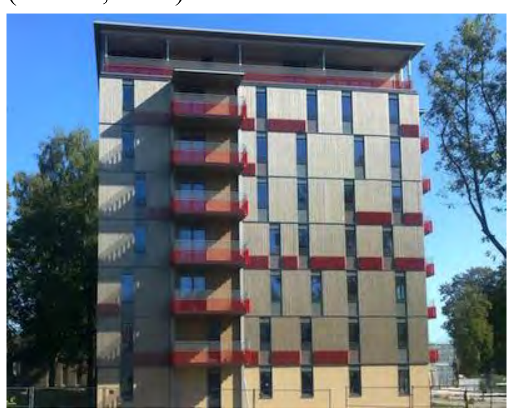
The Bridport House is the first phase of a regeneration project in London's Borough of Hackney, with plans for up to 900 new residential homes. The construction of two CLT residential buildings in North London, Stadthaus and Bridport, are among the first examples of CLT residential building construction in the UK (TimberInConstruction, 2010).

2.6.3.3 H8, Bad Aibling, Germany, 2011

The H8 structure in Bad Aibling, Germany, is one of the first applications of CLT construction for residential occupancies in Bavaria. Designed by Schankula Architekten and completed in 2011, the 8-story building is composed of CLT floors and walls, with a concrete core provided at the request of the building department (Klingbeil, 2012).

The CLT elements are composed of prefabricated panels with gypsum board protection to provide additional fire protection. This allowed a construction assembly time of approximately 16 working days, or one story every two days (Goethe, 2012).

Figure 76 – H8, Bad Aibling, Germany (Goethe, 2012)

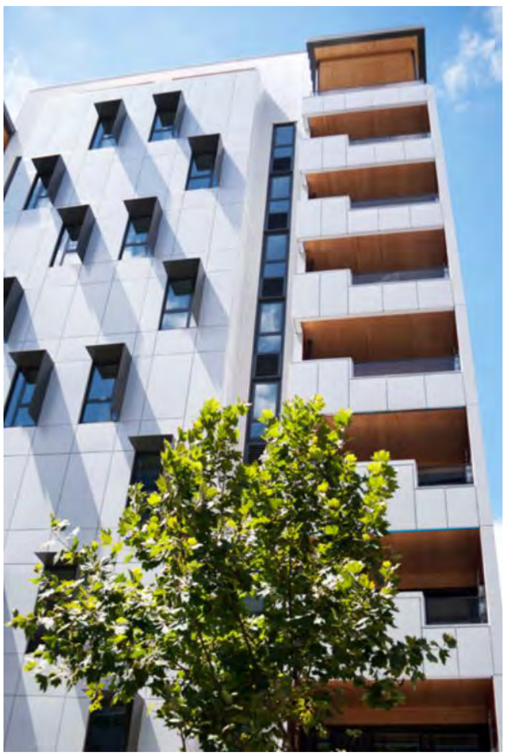


2.6.3.4 Forté Building, Melbourne, Australia, 2012

The Forté Building, constructed in Melbourne, Australia in 2012, is not only Australia's first tall CLT building, but, at the time of this writing, is the tallest residential timber building in the world (LendLease, Explore the world's tallest timber apartments, 2012).

Constructed by Lend Lease, the Forté Building is a 10-story residential apartment building constructed of prefabricated CLT panels and a concrete floor slab above CLT panels for fire separation and acoustic performance.

Figure 77 – Forté Building, Melbourne, Australia (LendLease, Forte Building Australia's First Timber HighRise, 2013)



Following completion, it was found that the use of prefabricated CLT panels resulted in significantly faster, safer and higher precision construction than traditional construction materials (Fedele, 2013).

Similar to Stadthaus, the building was designed with adequate inherent fire resistance due to the depth of the CLT panels. However, gypsum protection was provided for many wall and ceiling elements to provide additional protection to structural panels (LendLease, Forte Building Australia's First Timber HighRise, 2013).

Protection was provided despite considerable fire testing demonstrating CLT performance in fire conditions.

2.6.3.5 Via Cenni, Milan, Italy, 2013

The first CLT structure in a high seismic zone is scheduled to be completed in late 2013 in Milan, Italy. The Via Cenni is a 4-building social housing project that consists of 9-stories of prefabricated CLT construction (Bernasconi, 2012). The primary structure consists of 7-layer CLT panels at the base, with 5-layer CLT panels at the upper levels.

Connection details are considered to be essential structural components to the design due to the high seismic concerns in the region. The use of large nailed web plates and self-tapping screws enable a continuous load transfer between structural elements.

The required fire resistance for the structure is provided by gypsum protection elements encapsulating the CLT panels. However, the depth of the CLT panels are also able to provide the sufficient fire resistance time to meet the building requirements.

As observed in previous case study projects, gypsum board protective covering is required despite sufficient inherent fire resistance for CLT structural panels.

Figure 78 – Via Cenni, Milan, Italy (Bernasconi, 2012)

2.6.4 Other Construction

A unique application of panelized timber assemblies is the design and construction of tall towers using prefabricated panels. Examples of timber towers and sculptures are presented below.

2.6.4.1 Bell Tower, Gastonia, North Carolina, USA, 2011

Figure 79 – Bell Tower, Gastonia, North Carolina, USA (Thatcher, 2011)

Recognized as the first structure in the US to be built in CLT, the 78 foot tall [24m] bell tower at the Myers Memorial United Methodist Church in Gastonia, North Carolina was completed in 2011 (Thatcher, 2011).

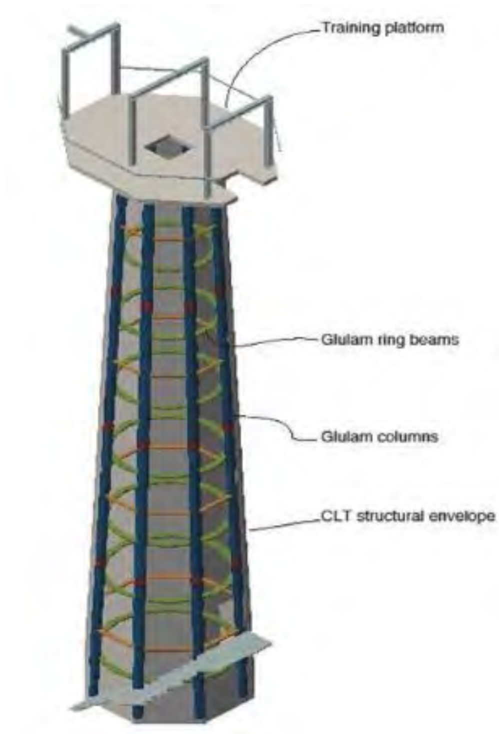
The structure is composed of prefabricated CLT panels, which allowed an assembly and construction time of three days to complete. CLT was chosen as a lightweight material that is able to provide the strength and stiffness to resist strong winds typical in the region (WorldConstructionNetwork, 2010).

2.6.4.2 Training Tower, Dawson Creek, Canada, 2011

In 2011, a training tower was constructed of heavy timber at Northern Lights College in Dawson Creek, Canada. The nearly 100 foot tall [30m] tower consists of glulam columns and ring beams with a CLT structural envelope (CTS, 2011).

The tower is designed to replicate the conditions technicians will face to maintain wind turbines at tall heights (NorthernDevelopment, 2013).

Figure 80 – Training Tower, Dawson Creek, Canada (NorthernDevelopment, 2013)



2.6.4.3 Metropol Parasol, Seville, Spain, 2011

The Metropol Parasol, a tall timber sculpture located in Seville, Spain and completed in 2011, is currently the tallest timber sculpture in the world. The 4-story structure is designed by Jurgen Mayer Architects, has a maximum height of approximately 94 feet [29m] and covers an area of approximately 54,000 square feet [5,000 square meters] (Argyriades, 2011).

Figure 81 – Metropol Parasol, Seville, Spain (Arup, 2012)

The structure is composed of micro-laminated timber sections protected by a waterproof polyurethane coating. Structural elements are connected by over 3000 connection nodes at the intersection of timber elements (Arup, 2012).

2.6.4.4 TimberTower, Hannover, Germany, 2012

Figure 82 – TimberTower, Hannover, Germany (TimberTower, TimberTower - A Timber Made Revolution, 2012)

Completed in Hannover, Germany in 2012, TimberTower is a wind turbine constructed of glulam prefabricated panels that were assembled onsite (Quick, 2012).

TimberTower is approximately 328 feet high [100m] and contains a ladder and lift system around a hollow octagonal base (TimberTower, TimberTower - A Timber Made Revolution, 2012).

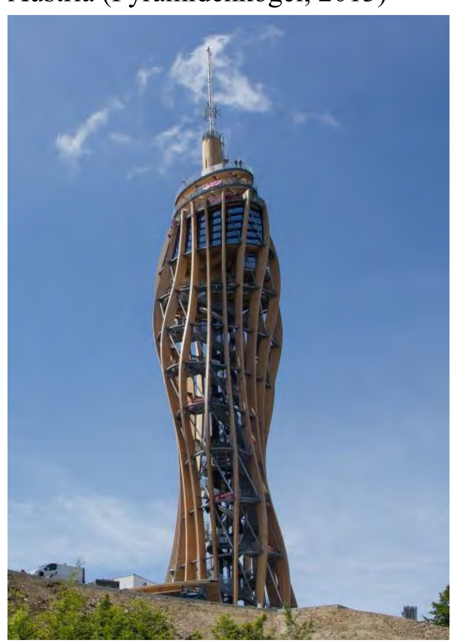
The tower is designed to meet insurability, certification and fire protection regulations, with claims the design can achieve a height of 626 feet [200m] in the future (TimberTower, The TimberTower: Structure and Operation, 2012).

2.6.4.5 Pyramidenkogel, Carinthia, Austria, 2013

Opened in June 2013 in Carinthia, Austria, the Pyramidenkogel, translated to Pyramid Tower, is the tallest timber observation tower in the world. The structure is designed by Architects Klaura, Kaden + Partners, and is composed of 16 curved glulam columns that spiral to form a lattice basket structure around a set of internal stairs and an elevator (Rubner, 2013).

The columns support 10 levels of structure, with the highest observation deck at 230 feet [71m]. The structure also features the longest slide in the world, descending from a height of nearly 170 feet [52m] (Pyramidenkogel, 2013).

Figure 83 – Pyramidenkogel, Carinthia, Austria (Pyramidenkogel, 2013)



2.6.5 Case Study Feasibility Designs

Whereas previous case studies have focused on buildings that are currently in design or have finished construction, this section presents recently published feasibility designs, or architectural studies, of tall timber buildings. These projects push the prescriptive and performance limits of the code. While they might not have been analyzed by qualified fire safety engineers, they present future concepts for tall timber design.

In Australia, CLT construction is proposed as a sustainable means of developing multi-story residential buildings (Hough, Kell, & Koopman, 2012). Hough presents a development proposal for 75 residential units in 3-blocks of 6, 7 and 8 stories of above-ground construction. The paper includes a discussion of the feasibility of structural components and the use of a fire engineering alternative solution to the Building Code of Australia.

Figure 84 – Rendering of a high-rise CLT structure (Waugh, Wells, & Lindegar, 2010)

A paper by Waugh (Waugh, Wells, & Lindegar, 2010) discusses design and construction experiences with Stadthaus, and considers the potential of future timber high-rise design. The paper proposes the possibility of a 25-story timber residential building design, achieved by replacing a CLT core with a concrete core for greater strength, stability and fire separation.

This height limit is eclipsed by a proposal for a 34-story timber high-rise in Stockholm, Sweden by timber architects Berg | CF Moller Architects (ArchDaily, 2013).

Figure 85 – Timber skyscraper proposed by Berg | CF Moller Architects (ArchDaily, 2013)

Chapman presents the structural feasibility of a potential 30-story CLT building designed to Eurocode 1 (Chapman, Reynolds, & Harris, 2012). While this case study is limited to structural design, it demonstrates CLT's structural capabilities.

A comprehensive feasibility study for a 41-story timber building is presented by Timmer (Timmer, 2011). Structural stability and fire safety challenges are identified, with engineering design solutions proposed to meet stability and safety requirements.

A Canadian firm called CEI Architecture based in Vancouver, Canada proposes a design for a 40-story "Office Building of the Future". The design includes sustainability features such as maximizing the use of timber, black and grey water irrigation and optimized mechanical and electrical systems to generate building energy (CEIArchitecture, 2011).

The proposed structural system seeks to maximize composite structural behavior through the use of a reinforced concrete core and perimeter external columns and large engineered wood trusses that cantilever from the reinforced concrete structural elements. The design proposes the use of timber-concrete composite floor panels, similar to those used for Life Cycle Tower One (Alter, 40 storey office tower is a hybrid of concrete and wood, 2013).

Figure 86 – Rendering of a 40-story office building proposed by CEI Architecture (Alter, 40 storey office tower is a hybrid of concrete and wood, 2013)

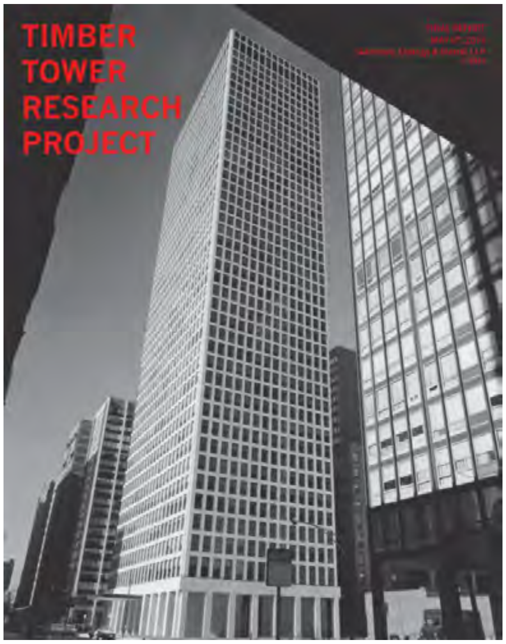
One of the most well-known conceptual design case studies is presented in a feasibility project for a 30-story timber building by Michael Green, an architect based in Vancouver (Green, The Case For Tall Wood Buildings, 2012). The report presents a new CLT construction system that is intended to be competitive with concrete and steel high-rise construction, while offering the sustainability benefits of timber buildings.

Figure 87 – Rendering of a high-rise timber building by Michael Green Architecture (Green, The Case For Tall Wood Buildings, 2012)

The structural system is based on a CLT core with steel beams supporting a timber floor slab. While the report highlights the need for fire engineering analysis, the report also presents fire performance solutions including charring and encapsulation approaches, in addition to fire alarm, detection and automatic sprinkler protection systems. To date, the Case for Tall Wood represents the most ambitious and comprehensive design for tall timber construction.

Feasibility design for a 42-story timber high rise is presented in a paper by Skidmore, Owings and Merrill (SOM, 2013). The primary goal is to demonstrate the technical and architectural feasibility using performance based design solutions for a tall CLT building.

Figure 88 – Timber Tower Research Project (SOM, 2013)



The report focuses on demonstrating the feasibility of designing a structural assembly in timber that is capable of supporting loads for the 42-story structure.

The SOM project proposes a new system called Concrete Jointed Timber Frame. It consists of solid timber products connected with steel reinforcement through concrete joints located at the perimeter and wall/floor intersections. The system is approximately 70% timber and 30% concrete by volume when the substructure and foundations are considered.

While the focus is on structural design, issues such as architecture, building services and sustainability are highlighted. The need for fire safety engineering, including research, analytical modeling and fire testing, is also mentioned as important remaining challenges to tall timber design.

3 Task 2 – Gap Analysis

3.1 Overview

Phase 1 of the study is comprised of two tasks;

- *Task 1 – Literature Review* and
- *Task 2 – Gap Analysis*.

Task 1 seeks to evaluate the current knowledge of tall timber construction, identify gaps in knowledge, and reflect on the gaps that, if fulfilled, will provide a better understanding of the potential fire safety performance of tall wood buildings.

The *Task 2 – Gap Analysis* is intended to identify gaps in current knowledge that are required to be better understood to advance the performance of tall timber buildings.

The gap analysis focuses on aspects related to building performance and consequences of credible fire scenarios in timber structures.

Readers should note that many "gaps" in knowledge are often only perceived gaps. Timber as a building material, whether used as light timber framing or heavy timber construction, is very well-studied and understood with regard to fire, given its use as a multi-story building material for well over 500 years.

As would be expected with any new technology, the many new and innovative timber design methods now being developed, including CLT, composite timber structures and post-tensioning of timber, introduce gaps in knowledge related to fire safety.

3.1.1 Task 1 – Literature Review

The *Task 1 – Literature Review* collected and summarized the resources available in literature that can be used to identify fire safety challenges in tall timber structures. Sections include:

- Testing data on timber structural components in fire;
- Ongoing research studies;
- Relevant fire incidents;
- Existing design guidance; and
- Global case studies of high-rise timber framed buildings.

The literature review presents resources, references and organizations that can be consulted to better characterize the fire performance of tall timber structures and consequences in credible fire scenarios. This includes discussions on research studies, fire incidents, design guidance and case studies of tall timber structures.

The background knowledge provided in these sections is intended to inform the gap analysis.

3.1.2 Task 2 – Gap Analysis

Based on the results from the *Task 1 – Literature Review*, the *Task 2 – Gap Analysis* consists of the following sections:

- Structural and non-structural component sub-system fire tests;
- Compartment fire dynamics;
- Environment;
- Economics; and
- Society.

3.2 Structural and Non-structural Component and Sub-system Fire Tests

Currently engineers and fire researchers have a substantial body of knowledge of how load-bearing timber elements perform in fire. Structural performance is predictable and well-understood due to the wealth and history of testing.

However, there are still some areas where further research is needed in tall wood buildings to improve knowledge of timber element performance in fire.

This section presents specific gaps in current knowledge that are intended to further the understanding of the structural fire performance of timber buildings, and, in particular, the safety from structural failure principle.

Structural and non-structural component and sub-system fire tests are discussed for different building elements and systems to better characterize fire performance.

Many of the issues are best addressed with real fire tests. However, there is an important opportunity to carry out predictive computer modeling, so that modeling tools can be validated or adjusted, then better calibrated based on experimental outcomes.

3.2.1 Effects of Structural Loading on Fire Performance

The effect of structural loading on the fire performance of structural elements is well studied for many building types (Buchanan, Structural Design for Fire Safety, 2001). In general, the greater the structural demand compared to the capacity, also known as the load ratio, or utilization, the worse the expected fire performance for the element. This is true for all building materials, whether it be concrete, steel, timber or a composite material.

The load ratio has the potential to affect structural behavior including:

- Deflection;
- Delamination;
- Load redistribution;
- Connections;
- Eccentricities; and
- Failure modes.

The effect of structural loading on fire performance is documented in Eurocode 3: Design of steel structures (BSI, Eurocode 3: Design of Steel Structures, 2005), where the temperature at which a steel element can be heated before failure (the critical or limiting temperature) is assumed to decrease with an increase in utilization. The greater the structural loading, the lesser the temperature for which stability can be assumed to be maintained. This is a fundamental aspect of structural design to resist fire.

As a further illustrative example, fire testing with varying utilizations in steel members is shown to have an effect on structural fire performance (Milke, 2002). The load ratio at elevated temperatures can potentially impact factors such as deflection and bowing, and could affect load redistribution through framing elements (the difference between single element design and frame action). Importantly, extensive fire testing has indicated that the effect of loading on fire performance in steel buildings is predictable and reproducible.

For multi-story timber buildings, particularly frame buildings (post and beam construction), several tests have considered multiple load ratios to evaluate the fire performance of specific timber elements (O'Neill, The Fire Performance of Timber-Concrete Composite Floors, 2009) (Fragiacomo M. , Menis, Clemente, Bochicchio, & Tessadri, 2012) (Osborne, Dagenais, & Benichou, 2012). Generally the greater the load ratio, the worse the fire performance.

Additional analysis and testing will improve the understanding of the effect of loading on fire performance, and also the impact of load-sharing (frame action) on timber elements.

This is important as the current testing is based on single elements with fixed load ratios. In a real fire situation, a building will involve heating of multiple timber elements. The load-bearing elements are expected to “load-share”, or “redistribute” in a method that is not easily predicted in simple fire testing.

Understanding this frame action is expected to result in fire performance that exceeds current design estimates, as is the case for steel frame buildings. Greater understanding of the effect of loading on the fire performance of timber frame buildings will enable designers to more accurately predict and design to prevent structural failure during fire. Fire testing of timber building elements when loaded within a frame can be used to demonstrate predictable and reproducible fire performance.

This issue of load-sharing during a fire event may also be relevant for panel type buildings, such as those using CLT, where floor and wall loadings may result in load redistribution and sharing as a fire continues through to burnout.

3.2.2 System-Level Testing

While previous testing has considered exposure to standard and experimental fires, testing is generally limited to single-element tests. This involves fire testing of a connection or element in isolation from the rest of the structure (Lane B. , 2008).

Single-element fire tests are generally simple tests used to better understand fire performance a single structural element, assembly or connection type. They are useful for a general understanding of that element in isolation. However, they are limited in that they do not capture the fire performance of a structural system assembly, or frame action, as would occur in completed buildings.

System-level fire testing of frames and assemblies has the potential to achieve greater understanding of the fire performance of structural systems exposed to high temperatures. This captures structural response such as (Pakala & Kodur, 2013):

- Structural continuity;
- Structural restraint;
- Load redistribution;
- Interaction between structural framing elements;
- Connection ductility; and
- Failure modes.

For example, fire tests with exposed steel framing subjected to natural fires at Cardington in the UK is one such example of system-level testing (Usmani, Drysdale, Rotter, Sanad, Gillie, & Lamont, 2000). This program of fire testing improved the understanding of full-structure response of exposed steel systems in natural fire conditions, including the consequences to the structure during and following a fire scenario.

A comparable system-level fire test for a multi-story timber structure would have the potential to lead to a significant step-change in the understanding and acceptance of multi-story timber frame buildings.

In the same way that the Cardington tests resulted in a step-change in the acceptance of exposed structural steel, a multi-story building test may assist with the acceptance of large timber buildings. This large-scale testing to evaluate timber structural performance is proposed potential research for the National Fire Research Laboratory (NFRL) in the US (Almand, 2012).

3.2.3 Use of Composite Assemblies

Composite assemblies in timber buildings have been used in many forms in the past, including steel plates to assist with timber beams, tension rods in timber trusses and post-fire rehabilitation efforts to strengthen or reinforce timber members.

Many modern designers view the application of composite assemblies as useful to satisfy the structural demands of tall timber structures. Combining the benefits of multiple construction types, primarily steel, concrete and timber, maximizes material properties and allows a designer greater flexibility for design (Green, The Case For Tall Wood Buildings, 2012).

One of the areas of significant further development is the use of timber-concrete composite floor systems. Composite timber and concrete floors offer potential for timber buildings as an economic and efficient flooring system. They can provide the structural soundness, acoustics and fire resistance, using the benefits of concrete, combined with a lightweight timber sub-structure. This has led to the use of timber-concrete systems in multiple buildings, including Life Cycle Tower (Wurm, Gockel, & Unger, 2012) and the Bullitt Center (Newcomb, 2012).

Fire testing of timber-concrete composite floors is limited, but fire testing performed by O'Neill has improved the understanding of fire-performance of timber-concrete composite systems (O'Neill, Timber-Concrete Composite Floors in Fire, 2010).

Current feasibility designs for tall timber buildings seek to maximize the use of composite assemblies to enable the construction of taller timber buildings due to the efficiencies offered.

A 42-story feasibility design by SOM proposes the use of a proprietary composite system called a Concrete Jointed Timber Frame system (SOM, 2013). The load resisting system uses solid timber CLT structural elements, connected by steel rebar reinforcement through concrete joints. The combination of steel, concrete and timber is approximately 80% timber and 20% concrete for a floor, by volume.

Designs for tall timber buildings by Canadian architect Michael Green consider the use of interior steel beams over CLT floor panels (Green, The Case For Tall Wood Buildings, 2012). The floor system utilizes the timber-concrete composite system that has been used in several tall timber buildings.

The use of composite assemblies in timber buildings can be utilized to enable the design of taller timber buildings. However, it is important to have an appropriate understanding not only of the structural performance of these innovative systems, but also the fire performance of the hybrid assemblies.

As new and innovative composite technologies are developed, fire testing of the hybrid load-resisting systems and assemblies, including those proposed by SOM and Green, will be needed. Accordingly, greater understanding is necessary to better understand structural response of these new systems in fire conditions.

Providing the most efficient use of the respective composite materials may require new fire tests to further the understanding of these composite assemblies. This may include the use of small-scale and large-scale fire testing.

Other innovative composite construction methods, such as combining steel and timber to gain additional tensile and compressive strength through a combined building element, will also require fire testing to understand the fire resistive properties.

3.2.4 Connections Between Timber Components and Composite Assemblies

Current understanding of the fire performance of connections in timber buildings has benefitted from a number of fire tests. Section 2.2 of the literature review presents summaries of structural fire testing performed for timber connections. Connections involved in fire testing range from nails and bolts, to plates and steel rods and epoxy adhesive. Fire testing also includes results from standard fire testing of composite elements with timber-concrete composite floors.

Results from fire testing of steel connections suggest the importance of providing protection for exposed steel elements. Fire protection strategies generally involve providing a protective layer of gypsum board over exposed structure and connection elements. However, this is neither an aesthetic, efficient or cost-effective solution for construction.

Steel elements for connections can also be embedded within the structure. While this may be beneficial for fire safety, it is not efficient for construction and is also costly. Embedding steel plate connections can also have a potential impact on the structural component size. Elements may need to be over-sized to provide the appropriate thickness and protection from heating. Workmanship and protection of such connections is important for demonstrating predictable and reliable fire performance in timber connection applications.

Thus, there is more work to be carried out in the understanding of fire protection of connections, given that connections that are most efficient for the structure and constructability may perform poorly in fire. Additionally, those connections that may perform well in fire may be expensive or structurally inefficient.

New timber technologies such as CLT have developed relatively effective and fire-safe connections. These often utilize long screws embedded in the solid panels. This offers good fire performance, as the screw head is a relatively small exposed area for heating in fire and the large screw length is protected within the solid timber.

Given the recent development of tall timber structures, a designer must consider the types of connections that will be used and their overall effectiveness and cost. With the new emerging timber technologies, such as CLT box beams, post-tensioned timber and timber-concrete composite floors, efficient and fire-safe connections need to be developed to allow the systems to be easily constructed, structurally-efficient and cost-effective.

Additionally, the ability to understand and predict fire performance of connections in structural systems and composite assemblies is critical to demonstrating structural safety in fire.

3.2.5 Experimental Fire Testing

As previously discussed, time-temperature curves in fire testing can be characterized as exposure to the standard fire or experimental fire curves (see Section 2.2.2). The standard fire curve consists of rapid fire growth and continuous heating for the duration of the test (Buchanan, Structural Design for Fire Safety, 2001). An experimental fire curve is considered to be any other non-standardized time-temperature curve.

Experimental fire curves generally consist of uniform heating or natural fire regimes that are discontinued at a specific point. These tests are valuable for furthering the understanding of structural performance at elevated temperatures. However, they do not include the final phase of fire development, referred to as the decay phase.

In the decay phase, compartment temperatures cool as the fire intensity decreases. Generally the most structurally severe fire conditions are assumed to occur during peak heating. However, testing of exposed steel structures has shown that structural behavior in the cooling phase can result in structural failure (Usmani, Drysdale, Rotter, Sanad, Gillie, & Lamont, 2000).

While the focus of fire testing is on the fire performance of timber elements and connections with exposure to elevated temperatures, consideration of the decay phase and cooling of structural assemblies would help to better understand structural performance.

3.2.6 CLT Delamination / Char Fall-Off

Previous CLT fire testing has resulted in delamination and char fall-off when exposed to fire conditions. This can occur where unprotected CLT panels are exposed to the fire (not all CLT is exposed and in some buildings the CLT is covered with gypsum plasterboard for fire protection or acoustic reasons).

Partial delamination of the exposed layer is shown to occur when the charring layer advances to the interface between layers in CLT panels (Osborne, Dagenais, & Benichou, 2012). Char fall-off can occur when charred timber, or fire protective panels, falls-off and exposes the cold structural wood below to high temperatures.

This occurs in CLT due to the formation of the timber product, whereby layers are impacted uniformly by fire. This behavior is unique to fire testing of CLT panels and is not apparent in other engineered timber products, as these members generally consist of much thinner layers, or veneers.

CLT element charring and separation from the assembly can result in increased charring rate and fire intensity (Frangi, Fontana, Knoblock, & Bochicchio, Fire Behaviour of Cross-Laminated Solid Timber Panels, 2008). This has the potential to increase the fire temperature and burning rate within the compartment, and could impact the structural fire resistance at later stages in the fire duration. While this is part of the CLT burning process, this behavior will be better understood as more tests are carried out.

Additional fire testing would seek to characterize the fire performance of CLT elements, to not only predict the conditions for if, or when, delamination or fall-off may occur, but also understand the impact on the fire compartment and structural assembly when this does occur. The aim is to better account for the delamination and better predict how this impacts the CLT fire resistance rating.

3.2.7 Penetrations for Services

Penetrations in building elements are generally provided for mechanical, plumbing, air-conditioning and electrical services throughout a structure. Openings in elements are typically provided for pipes, cables, ducts and other services for business operations and building occupants. These penetrations require fire stopping where these services pass through a fire rated assembly.

Appropriate fire-stopping at penetrations is necessary to contain fires and prevent smoke and fire spread to adjacent areas. Fire testing of penetrations is used to test the following conditions (Kampmeyer, 2008):

- Through-penetration firestop systems – used to seal openings through rated walls and floors;
- Perimeter fire containment systems – used to seal openings between floors and curtain walls; and
- Joint systems – used to seal openings where two elements of construction intersect as joints.

Typically, fire-stopping at penetrations and openings pass through non-combustible construction. The seal at the penetration where the structure and fire-stopping meet is non-combustible and assumed to not be affected by exposure to high temperatures. In combustible elements, such as timber, potential charring at the seal between the structure and fire-stopping could compromise the firestopping effectiveness. This behavior may impact the fire-stopping fire performance.

The sealing of penetrations is achieved through the installation of proprietary products such as dampers, collars, mastics, foams, pillows and similar products. The companies that produce these products test them to a relevant standard, which varies from country to country.

The issue of penetration seals that can be used in timber construction is an area requiring substantial work as it requires:

- Test standards to be altered to allow for the tests to be carried out with combustible bases or substrates, where the test standard only permits testing to be carried out with non-combustible substrates, such as concrete or gypsum plasterboard; and
- Requires manufacturers to test a range of products that can then be used in floors and walls for timber buildings.

Fire-stopping for penetrations and openings in combustible structures would have to achieve the performance requirements to be approved for use in timber structures. This requires that the entire fire-stopping assembly, including the product and combustible material it penetrates, achieves the appropriate performance when exposed to the fire testing protocols.

The importance of maintaining the integrity of fire-proofing materials is emphasized in recommendations for fire resistance of timber buildings (Lennon, Bullock, & Enjily, 2000). Additionally, while maintaining compartmentation and having confidence in the fire-stopping solution is important to demonstrating fire safety, fire testing of the entire fire-stopping assembly would be necessary to meet the required performance.

An additional area for further study is evaluating the fire rating of penetrations through fire-rated boards that are used to clad timber panel construction. There is a risk of loss of overall fire rating when building occupants relocate fittings like power outlets and lights, which may penetrate rated board cladding. These rated elements would require proper reinstatement of that rating after relocation. This is a maintenance issue of some concern to fire authorities. Systems and procedures for better dealing with maintain fire ratings represent a worthwhile area of further study.

3.2.8 Timber Façades

As the use of timber increases, architects and designers have been seeking additional applications for timber as an alternative building material. One potential use is the application of timber to building façades.

As a combustible material, there are several hazards associated with combustible façade design (WoodSolutions, Alternative Solution Fire Compliance: Facades, 2013):

- Façade ignition and fire propagation;
- Fire spread through openings in external walls; and
- External fire spread between buildings and parts of buildings.

Ignition of combustible material could potentially lead to internal and external fire spread. Fire testing of façades is limited to a number of cases, and additional testing is necessary to determine the potential impact on both the safety from fire and structural failure principles (Hakkarainen & Oksanen, Fire safety assessment of wooden facades, 2002).

One potential mitigation strategy is the application of fire retardant on a combustible timber façade. However, research with fire retardant applications that improve fire resistance and flame spread rating have proven inconclusive (Ostman & Tsantaridis, Innovative eco-efficient high fire performance wood products for demanding applications, 2006). Additionally, there are durability concerns with topical applications due to exposure to weather, damage, or general wear and tear. Additional research is necessary to clarify if this has a potential effect on fire performance of combustible façade assemblies.

Given that timber façade design is a relatively recent innovation, establishing the fire performance of the structural façade assembly is necessary to demonstrate fire safety. This includes not only evaluating the façade itself, but also the framing and connections that are necessary to maintain stability and compartmentation in fire conditions.

Research and fire testing used to characterize the fire performance of timber facades enables designers to propose design solutions and manage the associated fire hazards.

3.2.9 Concealed Spaces

Concealed spaces within a building have the potential to result in fire spread throughout a structure. Fire incidents in timber frame buildings have highlighted the need for appropriate fire blocking within concealed spaces (see Section 1.6.5 and Section 2.4).

One benefit of heavy timber construction is the frequency of concealed spaces compared to light timber construction. Solid CLT panels and open plan post and beam framing has significantly fewer concealed spaces compared to light timber framing. Nonetheless, it is important to understand the consequences of a potential fire within a concealed space in a heavy timber structure.

There are few fire tests to understand how fire will spread through concealed spaces in heavy timber buildings. Further testing could be used to evaluate the potential for fire spread through compartments. Consequences have the potential to range from self-extinguishment to complete burnout of the entire structure.

A greater understanding is necessary to determine if a fire in a concealed space is a credible scenario, and potentially determine the appropriate fire protection solution to manage the risk to the structure and the building occupants.

3.2.10 Protection of Egress Routes / Fire-Fighter Access Routes

Further research is needed to consider the conditions under which combustible construction for circulation elements such as stairwells, elevator shafts and vertical cores is acceptable. These vertical elements are not only the primary means of escape for building occupants, but also provide access routes for fire-fighter operations.

Australia and New Zealand have examples of timber cores in multi-story heavy timber buildings, including the world’s tallest timber apartment building (LendLease, Forte Building Australia's First Timber HighRise, 2013). In Germany, Austria, Switzerland concrete cores are more common above a certain height.

There is an important difference in speed of construction for a timber core versus a core of a different construction material. Protection of vertical egress elements requires additional research, as the potential for a timber core could represent a reduction in overall construction time.

3.3 Compartment Fire Dynamics

This section presents gaps in analysis that are focused on better understanding the consequences in tall wood structures due to credible fire scenarios. While there has been considerable testing of fire dynamics in conventional timber buildings, the recent development of post and beam and panelized structures has created the need for greater understanding of fire dynamics in these new types of structures.

Testing and research of compartment fire dynamics and consequences of fire and smoke in new and innovative timber buildings is intended to gain a better understanding of multiple fire safety principles, particularly in unprotected timber buildings. This includes the safety from fire principle for occupants, fire fighters and emergency responders, and safety from structural failure. The ability to reproduce testing results and predict fire behavior and compartment conditions is critical to gaining confidence in fire safety designs.

3.3.1 Contribution of Exposed Timber to Room Fires

One of the primary challenges for the design of timber structures for fire safety is wood's combustible nature. In wood buildings, the timber structure can be assumed to contribute to the fuel load. While the literature review discusses several tests with exposed (unprotected) timber (Frangi, Bochicchio, Ceccotti, & Lauriola, 2008) (Osborne, Dagenais, & Benichou, 2012) (McGregor, Hadjisophocleous, & Benichou, 2012), it is important to better understand what contribution exposed timber will have to room fire behavior – both qualitatively and quantitatively. This includes considering not only *if* timber makes a contribution, but evaluating *by how much*.

Exposed timber has the potential to impact compartment fire dynamics throughout the fire duration. Further analysis is necessary to understand the effect of exposed timber elements on the early fire hazard when occupants are expected to evacuate a structure.

Previous testing has shown that structural timber elements can make a contribution to the room fire behavior and effect the structural fire resistance at later stages of the fire duration (Frangi, Bochicchio, Ceccotti, & Lauriola, 2008), though this could be relatively insignificant. While Section 3.2.6 discusses the structural implications of exposed timber, this section is focused on compartment fire dynamics.

Although charring has been shown to not have a significant effect on compartment fire dynamics, char fall-off has. This can occur where exposed CLT is used for walls and the underside of floors. This is particularly important in unprotected timber buildings where there could be a greater potential for char fall off.

When exposed CLT timber elements char and separate from the structure, they have the potential to contribute to the amount of burning material and increase the fire temperature within the compartment. Given that char is burned wood material, it is not considered to increase the fuel load, though it may impact the compartment conditions. This behavior is unique to CLT structures, and is not apparent in other heavy timber construction types.

While the impact of timber fall-off is assumed to occur late in the fire duration, it could have a potential impact structural fire resistance rating due to impact on compartment conditions. Further testing is necessary to characterize and quantify this impact.

This could include long duration burn-out tests to gain a better understanding. A change in fire compartment conditions could potentially impact the structural response for timber buildings exposed to high temperatures for long durations, and needs to be accounted for within the design.

Improving the understanding of timber's contribution to the fuel load content and compartment fire dynamics through additional research and testing is important to achieving a better understanding of required compartment fire resistance ratings.

3.3.2 Complete Burnout – Self-Extinguishment

As previously discussed, fire testing has shown that timber has the potential to contribute to the combustible fuel load in a fire compartment, though the extent may be minor for post and beam type construction, it can be relatively significant for exposed CLT panels in panelized construction. This is largely dependent on the amount of protection provided for timber structural elements.

Important aspects when considering the combustibility of the structure is to be able to:

- Establish if and when extinguishment may occur;
- Characterize the structural and fire compartment impact; and
- Be able to accurately predict the performance.

One method of evaluating the level of contribution is to allow a fire compartment to continue to burn without intervention. Results could be used to better understand the consequences of complete burnout of timber buildings, including evaluating the potential for acceptable self-extinguishment. This is assumed to occur when all the combustible contents have been consumed and the timber elements are able to maintain their load-carrying strength or provide acceptable compartmentation.

Previous testing on timber compartments has generally been performed for a finite fire testing period. Where testing is performed with exposure to the standard fire, the fire duration is usually measured in increments of 30 minutes to determine the fire resistance rating. In experimental test setups, such as natural fire tests, testing is often stopped at a pre-determined time.

One example of fire testing that was discontinued is natural fire testing in a light timber frame building. Fire extinguishment was pre-arranged with the fire department, as the test was intended to evaluate the potential for fire spread for a fire duration of 60 minutes only (Frangi, Bochicchio, Ceccotti, & Lauriola, 2008).

Fire testing in Canada simulated room contents in an unprotected CLT building assembly to evaluate the consequences of fire in exposed CLT buildings. Results indicated that fire in unprotected rooms continued to burn at high intensity even after the combustible contents were consumed. The fire was extinguished to prevent potential structural damage to the test room (McGregor, Hadjisophocleous, & Benichou, 2012).

Additional fire testing is required to establish the extent of the contribution, the potential for self-extinguishment, and better understand potential credible fire scenarios in timber buildings. A greater understanding of the performance of timber structures in a complete burnout scenario could affect the fire resistance ratings required for a building.

This could result in providing a greater level of fire protection for timber assemblies, or allowing timber to be exposed if the results are quantified.

3.4 Environment

One of the most publicized benefits of timber construction is the impact on the environment. Research suggests that timber construction appears to have many environmentally-friendly benefits, such as carbon sequestration during growth, a less energy intensive manufacturing process compared to steel and concrete, renewability, and potentially long-term carbon storage (see Section 1.2).

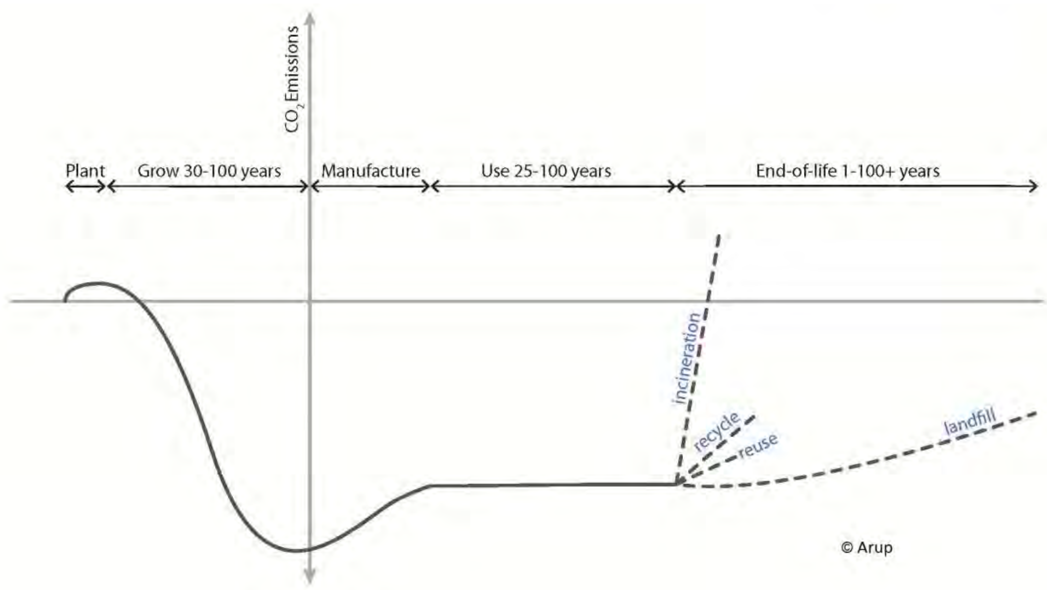
This section presents a brief introduction to some of the relevant topics related to the potential environmental impacts of timber buildings, and highlights a number of gaps in analysis that warrant further research.

Additional research and greater understanding of environmental issues can help to more clearly define the impact on the environment for timber construction relative to other building materials. Some of the primary environmental gaps in knowledge are presented below.

3.4.1 Carbon

Carbon emissions are often the focus of sustainability claims. The figure below is an abstraction of the carbon emissions over the life of wood products.

Figure 89 – Qualitative depiction of CO_2 emissions of typical wood product over full life-cycle (Charlson, 2011)



At the beginning there is a relatively small amount of carbon emitted, assuming some human activity in fostering tree growth. During growth the greatest amount of carbon is absorbed, shown by the dip in the graph. In harvesting and manufacture, some carbon is emitted again, but not nearly as much as has been absorbed if the tree was allowed to grow throughout the time it could absorb carbon at its highest rate.

In the use phase, wood products are not expected to emit much carbon. In fact, this is the period in which wood products could potentially store carbon for decades. Lastly, the fate of the product at its end of life can vary with significant differences in the rate of carbon emitted back to the atmosphere (Charlson, 2011).

From this qualitative information, practitioners can see how their choices can affect the environment and, in particular, global warming potential.

The most relevant points for use of wood products include:

- The carbon absorbed by trees will eventually be released back to the environment by burning or decay. Thus, those who claim wood is net negative in its carbon emissions are cutting short the period of accounting;
- To maximize the benefits of carbon absorption, trees should not be harvested until they have reached, or at least neared, their maximum sequestration capacity. Wood products should be sourced from forests where management practices uphold this principle;
- Pushing the release of CO_2 further into the future does mitigate the near-term effects of global warming. Thus, wood products that offer long-term carbon storage could contribute to delaying climate change. How to ensure the long term storage is more complicated and should be considered before making such claims; and
- In terms of CO_2, the best end-of-life scenario is reuse. Systems that can use salvaged wood and employ design for deconstruction and reuse will likely have the least embodied carbon impacts.

Considering the above, carbon implications of using more timber in construction are much more complex than they may first appear. One should not accept simplistic claims, but should rather carefully consider where their actions can generate and insure the greatest benefit.

3.4.2 Life Cycle Assessment

Life cycle assessment offers one way to quantify environmental impacts over a building's lifetime on more metrics than carbon, offering a more holistic evaluation. A life cycle assessment (LCA) typically considers metrics such as energy and resource consumption, and emissions to land, air and water that can affect global warming, smog formation, ozone depletion, and other types of ecological damage (Curran, 2006).

An LCA can consider the life cycle impact of a timber building relative to the impact from a building constructed of more non-combustible materials like steel and concrete. Limited research on comparative life cycle assessments indicates there may be benefits in terms of embodied energy and emissions in timber compared to alternative materials (Fernandez, 2008) (John, Nebel, Perez, & Buchanan, 2008).

However, research comparing these systems with different assumptions can arrive at slightly opposing conclusions (Oschendorf, 2012) Thus, if one desires to use the results of such studies towards decision-making, it is important to note the assumptions of such comparative studies and compare them to the situation at hand.

To make an equitable comparison using LCA, the two options should be functionally equivalent, as is required in the principles of life-cycle assessment (ISO 14040, 2006) (ISO 14044, 2006). That is, the assembly of materials should meet the same performance requirements, including their service life.

Consistency in service life does not necessarily mean the service life must be equivalent, but rather that the study period should be held consistent, so that if one system requires replacement or maintenance before the other, the extra materials and energy are accounted for in that option.

These LCA fundamentals are essential to consider when it comes to timber systems because of the very different ways in which they can meet fire safety performance requirements.

Whereas a concrete system may have required more energy to manufacture, the timber system must take into account the measures to meet the same fire safety performance, such as oversizing for the char layer, or addition of gypsum board to connections or the general assembly. Similarly, comparisons to a steel system should include the spray or intumescent fire-proofing.

Furthermore, the multiple metrics of LCA often reveal trade-offs, where certain materials and processes in a timber assembly may show benefits in some environmental impact categories, but worse impacts in others. Some studies have found that these trade-offs often result from the adhesives used in engineered wood products (Yang, 2013).

It is also essential to understand the limitations of LCA. For timber in particular, three things should be kept in mind:

1) The data for conducting LCA on wood products is currently averaged over large regions that include forests of various management practices. Thus, the differences between levels and types of forest stewardship will not be apparent in LCA results (Athena SMI, 2000);
2) The metrics of conventional LCA methodologies do not include habitat loss, biodiversity, land use, and water resources. Thus, some ecological impacts that are very relevant to responsible sourcing of wood products are missing from current LCA studies (Curran, 2006); and
3) LCA is built upon an inventory of the inputs from the environment and outputs to the environment, and is most robust from raw material extraction to the factory gate. It does not account for the in-use and end-of-life phases very well because of the uncertainty and variety of these conditions. Thus, many LCA studies do not attempt to quantify these life-cycle phases (Simonen, 2014).

Conventional LCA studies tend to not account for the probability of reduced service life due to increased fire risk of unprotected, combustible systems;

especially when making comparisons of timber construction to non-combustible systems in residential applications (Suzuki & Oka, 1998) (Hsu, 2010) (Ramesh, 2010). Two papers presenting exceptions are summarized in the following section about environmental impact of fire protection.

3.4.3 Environmental Impact of Fire Protection

Results of previous research studies suggest that the installation of fire protection systems, specifically automatic sprinkler protection, can have a significant effect on the environmental impact of a building fire (Gritzo, Doerr, Bill, Ali, Nong, & Krasner, 2009) (Wieczorek, Ditch, & Bill, 2010).

This behavior was witnessed in a 2010 FM Global study that engaged in a series of tests to evaluate the environmental impact due to a fire in a non-sprinklered and sprinklered residential unit. Results indicate that sprinklers were not only effective in controlling the fire, but there were many environmental benefits, including (Wieczorek, Ditch, & Bill, 2010):

- A reduction in greenhouse gas emissions by 97.8%;
- A reduction in water usage between 50% and 91%;
- A significant improvement in water runoff quality as measured by pH value; and
- A reduction in fire-damaged contents.

While results of the fire testing indicate there are potential environmental benefits to providing automatic sprinkler protection, it would useful to be able to financially quantify the benefits to demonstrate the additional value gained through the installation of fire protection systems.

Additionally, the environmental impact analysis could consider the influence of fire risk factors, such as the statistical frequency of a fire, building lifetime, expected fuel density and other such factors (Gritzo, Doerr, Bill, Ali, Nong, & Krasner, 2009). These could have an effect on not only on the environmental impact of a fire, but also the economic costs associated with such an event.

Further research and testing to better understand the environmental and economic impact of fire protection, using life-cycle assessment and other tools for evaluation, will help a designer to determine an appropriate level of fire protection for different material types used in construction.

3.5 Economics

While this study focuses on characterizing challenges and identifying gaps in understanding of fire safety in timber buildings, there are also additional challenges associated with tall timber construction.

One such challenge is the gap in understanding of the economic and financial considerations related to the design, construction and use of tall timber structures.

This section addresses the economic gaps in analysis that are highlighted as necessary to better understand the implications of timber buildings.

3.5.1 Fire Costs (Relative to Conventional Construction)

Given the large number of non-combustible tall buildings, the fire cost estimates in high-rises is fairly well known (Manfredonia, Majewski, & Perryman, 2010). While the case study section presents examples of tall timber construction, additional research is necessary to better understand the economic fire costs of combustible tall buildings.

Research could consider cost implications of fire protection systems in timber structures compared to traditional materials (John, Irving, McDonnell, & Buchanan, 2012). A consideration of the post-fire rehabilitation effort in timber relative to conventional construction could identify differences in cost related to structural and non-structural repairs and potential business continuity implications.

A greater understanding of these potential fire costs is intended to allow for a cost comparison between combustible and non-combustible tall structures.

3.5.1.1 Fire Protection

For most tall buildings within the United States, timber or otherwise, fire proofing, automatic fire suppression systems, and automatic fire alarm systems are typically required by the building and fire codes. The cost of some of these systems for conventional buildings in non-combustible construction can be estimated with relative confidence. However, estimating fire protection costs for tall timber buildings may be challenging due to the limited number of examples and the uncertainty associated with the fire protection design.

As a new and developing building system, the financial costs associated with fire protection for tall timber structures are not well established. While these costs can be estimated, greater experience with design and construction of fire protection systems in timber buildings will improve the fire cost analysis.

Additional research is necessary to fully understand the implications of costs of fire protection systems in timber buildings, relative to conventional building types. Cost factors could include connections, penetrations, system interfacing, construction time and general unfamiliarity with combustible building construction.

One potentially significant cost that may differ between combustible and non-combustible construction is applied fire protection. A performance based design for applied fire protection in timber buildings can be pursued to evaluate the necessary level of applied fire protection for a timber structure.

Fire protection strategies could range from full protection and encapsulation of building elements, to the possibility of exposed timber elements that do not require applied fire protection. A fire protection solution with no or limited applied fire protection represents a potential cost-savings compared to conventional fire protection solutions.

3.5.1.2 Post-Fire Rehabilitation

The fire costs related to the post-fire rehabilitation of an existing building warrants consideration. Post-fire rehabilitation can be very costly. Costs often include rehabilitation of both structural and non-structural elements, as well as potential disruptions to business continuity.

Structural elements exposed to high temperatures may require inspection before occupation is allowed. Replacement or strengthening of structural elements or systems may be necessary. Non-structural elements may suffer smoke and fire damage, at significant cost to repair or replace.

The time and extent of repair may also have an impact on business continuity. The more extensive the rehabilitation, the greater the likely impact on business operations and continuity. Time to repair may have a significant financial impact as well.

While the post-fire issues are similar for all building types, additional research in timber buildings is necessary to characterize the financial implications and costs of post-fire rehabilitation in tall timber structures.

Post-fire issues unique to timber buildings could potentially include the following:

- Post-fire assessment and inspection by timber specialist in structural fire engineering;
- Repair and strengthening using additional timber elements; and
- Repair and strengthening using hybrid steel and/or concrete elements.

3.5.2 Post-Earthquake Fire Performance

A post-earthquake fire scenario has the potential to cause significant damage to buildings and even entire cities. This is especially true for timber buildings, which are shown to perform well in earthquakes due to their overall ductile behavior.

However, damage to timber structural elements, in particular fire separations, can make a post-earthquake building vulnerable to fire.

Research and testing of earthquake-damaged timber elements can help to predict structural and fire performance. This information serves to better understand the fire safety consequences in earthquake-damaged timber buildings, and is additionally important for fire fighters to assess stability for emergency operations.

Greater understanding could lead to optimized design for post-earthquake fire performance. This would aim to not only provide greater safety for building occupants, but also protect against collapse, satisfying property protection and external fire spread objectives. This is particularly important in high seismic zones, where there is a greater likelihood of a large seismic event.

Additionally, an economic analysis of the damage in a post-earthquake fire scenario has the potential to inform the structural and fire protection design strategies. A lower financial tolerance could result in a more conservative fire protection solution for a structure.

3.6 Society

While this study is focused on characterizing the fire safety challenges and gaps in knowledge for tall timber buildings, there is arguably a challenge regarding the *perception* of fire safety in tall timber buildings. This primarily includes perceptions from society as expressed through the building codes. These perceptions can be affected by a number of concerns, some emotional, from unfamiliarity to dread of catastrophe.

These sentiments about living, working and occupying tall buildings that are combustible by nature could affect the acceptance of this type of building. There is very little written on the subject of public perceptions and the building regulatory process, with even less available solely on the subject of timber or high-rise construction.

Publications such as Timber Frame Fires seek to promote the debate about fire safety in timber buildings. This is encouraged by tracking major fire incidents and highlighting the causes and outcomes to keep the public well-informed about the risks associated with occupying timber buildings (TimberFrameFires, Background, 2011).

An article by Gregory Havel, a retired deputy chief and training officer in Wisconsin, cautions about the potential risks of CLT construction to fire fighter safety (Havel, 2013). Havel suggests that not enough is known about CLT to provide fire fighters with the necessary information about structural behavior in fire to appropriately address fire safety in CLT buildings.

Commentaries such as Timber Frame Fires and Gregory Havel emphasize the need for better understanding of the fire safety challenges in combustible buildings to make informed decisions and appropriately manage society's real or perceived risk of fire safety in tall timber buildings. Issues such as these can be directly addressed through research, testing and greater understanding and education about fire performance of timber structures and the fire safety solutions.

3.6.1 Risk Communication

This study is intended to fill a gap in understanding by not only characterizing the current understanding of fire safety challenges in timber buildings, but also identifying where additional research, testing and understanding is recommended.

An additional gap is the need for effective risk communication of these fire safety challenges to the general public. This involves using research, testing and studies such as this to educate about the fire safety challenges in timber buildings. Communicating results of fire performance in tall timber structures can potentially dispel preconceptions about safety in timber structures.

Initiative groups such as those presented in Section 2.3.2 are intended to provide technical information about tall timber buildings for architects, developers, engineers, code officials and other relevant building stakeholders. These groups are key players for informing the public.

Broader-based dissemination is also needed through a range of public media. How best to achieve this dissemination, and how to frame the message, are some of the questions that are highlighted in this study.

Effective risk communication is intended to allow society to make informed decisions about the fire safety challenges and fire protection strategies for tall timber buildings.

3.6.2 Codes

Society's perception of fire safety in timber buildings is also reflected in the building and fire codes. Building and fire codes are sets of standards that reflect the minimum safety regulations for building design (Wolski, Accommodation perceptions of risk in performance-based building fire safety code development, 2000) (ICC, Building Codes: How They Help You, 2013).

Generally, codes are more restrictive when the perceived level of risk to safety is higher. This is intended to provider a greater level of confidence in the design by enforcing more conservative prescriptive code requirements.

Building codes can also differ from region to region. A country that is familiar with the use of timber construction may have fewer restrictions in the building codes compared to other countries. The comparison of building code regulations for tall timber construction is a gap in and of itself.

As presented in Section 3.6.1, a better understanding of the fire safety challenges and design solutions for building authorities and code officials promotes informed debate that has the potential to affect the regulations in building and fire codes.

One example of risk communication at this level that resulted in a change to the building code occurred in 2012. A proposal for CLT to be included for use as walls and floors in Type IV construction in the International Building Code (IBC) was submitted to the International Code Council (ICC) on behalf of the American Wood Council (AWC, 2012 IBC Challenges, 2013).

The proposal was supported by full-scale fire testing data performed by FPInnovations that demonstrated the fire performance of CLT panel assemblies (Osborne, Dagenais, & Benichou, 2012). Test results presented along with the proposal for code modification were ultimately approved as submitted.

Effective risk communication with building and code officials is intended to improve the understanding of fire safety in timber buildings and promote safe timber design. Communication can involve the sharing of research and testing to demonstrate the fire performance of elements in timber buildings, and structural systems as a whole. This discussion has the potential to dispel preconceptions of fire safety in timber and modify the model building codes with respect to prescriptive design.

3.6.3 Fire Risk Assessment

A fire risk assessment is often used as an evaluation of risk that considers factors such as assumptions, uncertainties, hazards, probability, mitigation strategies, and consequences, to name a few. A brief discussion of these factors related to fire safety is presented in Section 1.4.

While fire risk assessments are typically uncommon for buildings in the US, their application to timber structures may serve to better inform building stakeholders about the relevant risks, hazards and opportunities. This may also aid with a building's insurability, as risk assessments can be considered by insurance companies.

The current gap regarding fire risk assessment in timber structures is appropriately synthesizing fire safety risks with fire protection systems. This also requires an understanding of fire performance in timber buildings to develop an effective fire protection strategy that results in an acceptable level of risk.

Many of the feasibility studies presented herein identify the challenges associated with high-rise timber structures. However, there is also a knowledge gap for how to prioritize these issues, how to determine an appropriate level of fire protection necessary and how to achieve the level of safety intended by the model building codes.

Greater research, testing, understanding and discussion of the factors related to fire risk assessments are intended to fill these gaps in knowledge.

3.7 Prioritization

The *Task 2 – Gap Analysis* presents a number of issues for which greater research and understanding is necessary to better assess structural fire performance and credible fire scenarios.

While all these issues are considered necessary to achieve a greater level of understanding, the following gaps are selected as having the greatest priority. These gaps are based on the need to establish a greater understanding about the potential challenges to life safety in tall timber buildings.

- Contribution of Exposed Timber to Room Fires (Section 3.3.1) – This gap is critical to not only better understand the implications of exposed timber on compartment fire dynamics, but also dispel potential myths and preconceptions regarding fire safety in timber buildings;
- Connections Between Timber Components and Timber Composite Assemblies (Section 3.2.4) – Further understanding of connection performance is necessary to demonstrate safety for a whole structural assembly in fire. This includes understanding what types of connections designers can expect, but also how these new connections perform in fire conditions; and
- Penetrations for Services (Section 3.2.7) – Understanding penetration behavior through structural elements is critical to achieving compartmentation and enabling the installation of building services for fire safety.

Note that these gaps represent the author’s opinions based on previous research and discussions with a number of leading timber experts.

4 Summary and Recommendations

Phase 1 of this study seeks to evaluate the current knowledge of tall timber construction, identify gaps in knowledge, and reflect on the gaps that, if fulfilled, will provide a better understanding of the potential fire safety performance of tall wood buildings. Phase 1 is comprised of two tasks, the *Task 1 – Literature Review* and the *Task 2 – Gap Analysis.*

The *Task 1 – Literature Review* characterizes the fire performance of timber as it relates to the design of tall buildings. The review collects and summarizes resources in literature to identify fire safety challenges in tall timber structures. The literature review focuses on the following items:

- Testing data on timber structural components in fire;
- Ongoing research studies;
- Relevant fire incidents;
- Existing design guidance; and
- Global case studies of high-rise timber framed buildings.

The resources in the sections above are used to identify gaps in knowledge for discussion in the *Task 2 – Gap Analysis*.

The *Task 2 – Gap Analysis* seeks to identify the design and material gaps in knowledge that need to be explored to better understand the performance of timber as applied to tall buildings. The gap analysis discusses specific areas of research necessary to better understand the fire safety challenges in tall timber buildings. These include discussions of the following primary issues:

- Structural component and sub-system fire tests;
- Compartment fire dynamics;
- Environment
- Economics; and
- Society.

Based on the resources presented in the *Task 1 – Literature Review* and *Task 2 – Gap Analysis*, recommendations for future research and testing include the following:

- Fire testing of new and innovative timber and hybrid solutions;
- Full-scale / large-scale fire testing of mock up tall timber frames;
- Natural fire testing in full-scale / large-scale tall timber frames;
- Economic analysis to quantify construction, operation and costs of tall timber buildings; and
- Emphasis on effective risk communication and education.

This study presents broad recommendations that are intended to cover the many gaps in analysis presented in Section 3, as well as uncover potential gaps in analysis that have yet to be encountered. One specific example of effective risk communication could be the proposal of code changes at ICC, though there are many opportunities for specific research in the future.

Ultimately, research, fire testing and greater experience with combustible construction will increase the understanding of fire safety in tall timber buildings. It is the effective communication of this understanding that is critical to demonstrate fire safety in timber buildings and support change in the regulatory environment.

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