Final Technical Report

Project Title

Timber High Rise Buildings and Fire Safety

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Summary

High rise buildings pose specific challenges for fire safety, notably in terms of egress strategy, firefighting operations, and increased consequences of failure. The use of mass timber for high rise structures requires special consideration because of the combustible nature of the material. As tall mass timber construction is a very recent trend, there is no return of experience from fire accidents in these buildings. However, case studies of fire tests on mass timber structures and fire accidents in other timber buildings, combined with theoretical and numerical analyses, reveal **specific risks/challenges:**

1. **Exposed timber fuels the fire.** When timber elements are not shielded from the fire by insulative protection/encapsulation, these elements contribute to the fuel load, altering the fire dynamics by increasing the duration and intensity of the fire. This is particularly significant for lining elements with large surface area (e.g. CLT floors and walls). From tests, the additional Heat Release Rate (HRR) has been evaluated approximately as up to 100 kW per square meter of exposed CLT, over a sustained duration. This increases the actual fire duration and intensity in comparison with the (same) design requirements applied to non-combustible structure.

→ Section 2.4.2: test data by Su et al. 2018, McGregor 2013
Section 3.4: evaluation method
Section 3.7.2: case study, effect on HRR
Section 4.3.2: case study, effect on fire curve (Figure 62)

2. **Tall mass timber buildings contain a lot of embedded fuel load.** The average weight of structural timber over gross floor area has been evaluated in 19 existing mass timber buildings as 152 kg/m². This translates into an average fixed fuel load of about 2600 MJ/m² embedded in the structure. For comparison, the average content fuel load in offices is 420 MJ/m² (Eurocode).

→ Section 3.1 and 3.2: evaluation for existing mass timber buildings

3. **The contribution of exposed timber to the fire intensity can be significant for firefighters.** Reviewed fire accidents in timber construction show that, once the fire spread, it can be very difficult to control. A numerical case study estimates that the contribution of all exposed surfaces of CLT panels in a compartment could result in an increase by up to about 300% of the required water supply to extinguish the fire, compared to a case of non-combustible linings.

→ Section 2: reviewed fire accidents, discussion p.51-52
Section 3.5: evaluation method
Section 3.7.3: case study, evaluation of water requirements

4. **The contribution of exposed timber to the fire intensity can be significant for neighboring buildings.** The heat radiated by the building in fire is increased by the contribution of exposed timber. This increased radiation results in an increased distance at which neighboring buildings may be ignited, as shown by a virtual solid flame radiative model.

> → Section 2: reviewed fire accidents, discussion p.52
> Section 3.6: evaluation method
> Section 3.7.4: case study, received heat flux through radiation

5. **The construction phase presents a higher fire risk.** Fire protection measures such as sprinklers and encapsulation may be absent in the construction phase, leaving large quantities of exposed timber at risk of an accidental fire. Numerous construction fire accidents with wood frame timber construction suggest this to be a potential issue for tall mass timber projects.

> → Section 2.2: reviewed fire accidents, discussion p.50

6. **The current design approach does not address stability until burnout.** The heat penetration and continued charring during the fire decay phase lead to further irreversible reduction of load-carrying capacity of the structure, even for protected timber elements. This can lead to failure during the decay phase, as shown by numerical analyses. Design based on a charring depth under prescribed duration of standard fire is inadequate to evaluate the actual (final) charring depth, especially when a fire may not be promptly extinguished. The current design approach based on sacrificial charring layer does not address structural stability until full burnout, which can be an issue in tall buildings as evacuation and firefighting are more difficult.

> → Section 2: reviewed fire accidents, discussion p.51
> Section 4.3.3: case study, structural failure during cooling

7. **Self-extinction and delamination are still not fully understood, thus not controlled.** These knowledge gaps limit the ability to design explicitly for burnout stability. For high rise buildings, less reliance should be put on inherent fire resistance through charring, while insulative protection should be designed to remain in place until full burnout.

> → Section 2.4: reviewed tests (e.g. Karuse, Hadden, Hevia, Janssens & Joyce)
> Section 2.5: discussion based on test observations (p.51)
> Section 3.3: discussion based on literature references

In conclusion:

1. **Mass timber structures can be designed to achieve the required level of fire safety** using a combination of measures that include (but not limited to) active protection (i.e. sprinklers) and sufficient amount of passive protection (e.g. encapsulation) to shield the timber elements from the fire until full burnout.

2. **However, current design methods based on a sacrificial charring depth under prescribed standard fire are inadequate for high rise construction**, being based on an extrapolation of the prescriptive approach developed for non-combustible materials that disregard (i) the increased fire intensity due to the contribution of exposed timber as fuel, and (ii) the continued pyrolysis and charring during the decay phases of the fire. The latter occur even for protected members depending on the actual thermal conditions and duration of the fire. Timber structures are more vulnerable when the fire is not promptly extinguished and the structure is not promptly cooled, which is more likely in high rise buildings. Design methods need to address explicitly the resistance to full burnout, as well as the consequences of increased fire intensity on stability, compartmentation, firefighters operation, and spread toward neighboring structures.

3. **The worst case fire scenario will be worst for a high rise building made of timber, compared to non-combustible material.** Building resilient cities require addressing low probability high consequence events. When using combustible materials for the structural systems of tall buildings, the consequences of a major failure in the fire resistance strategy, where the combustible elements become involved in the fire, are likely to be greater than for non-combustible construction. Particular attention should be put to the safety of occupants and firefighters throughout the stages of the fire, to the firefighting resources that would be needed to fight a fully engulfed building, and to the risk of conflagration involving neighboring structures. Engineering methods are needed to consider those risks, which cannot be addressed through prescriptive (standard) fire resistance design based on sacrificial charring depth. As knowledge gaps remain (e.g. self-extinction, fire dynamics, delamination) and no return of experience exists on fires in high rise timber buildings, caution should be exercised.

Table of Contents

1. Introduction

1.1 Objectives and scope

In recent years, the timber industry has developed engineered wood products aimed at enabling taller wood buildings. These products, such as cross-laminated timber (CLT) panels and glulam framing members, used in "mass timber" construction, are presented as a competitive solution for tall urban buildings. Completed projects include an 18-story student residence in Vancouver, a 7-story office tower in Minneapolis, the 18-story Mjøsa Tower near Oslo in Norway, and many more under consideration across the world. Currently, due to the combustibility of timber, its use as a building material is still limited by restrictions in building regulations in most countries [1,2]. However, different jurisdictions are considering relaxing these restrictions to allow the use of mass timber for higher and larger buildings.

The use of timber in mid-rise and high-rise buildings raises questions in terms of fire safety. Besides the fact that timber is combustible, research and understanding of fire performance of timber structures is limited and is mostly restricted to standard time-temperature exposure, which is insufficient to gauge the structure behavior under real fire conditions [2–4]. There is concern that timber elements in tall wood buildings can increase the fire load, affect the fire growth rate, and potentially compromise fire protection systems in buildings, all of which could result in more severe conditions for occupants and responding fire fighters and increase the threat of damage to adjacent properties [5]. There has been very limited research on questions such as the ability of fire brigades to contain and extinguish a severe fire in a tall wood building, the risks associated with fire spread within the building and toward nearby structures, and the risks associated with complete collapse of a burning tall wood structure in an urban environment. In this context, this document presents an investigation into the issue of fire safety of high rise timber buildings. The study includes literature review, case studies, and analytical and numerical modeling. The report is articulated into three main parts.

Section 2 of the report presents a review of case studies of fires in timber buildings. Both accidental fires in real buildings and experimental fire tests are reviewed. The emphasis is on the use of timber in multi-story construction. As the advent of tall mass timber buildings and the use of engineered mass timber products is recent, there is little return of experience from real fire events involving this type of construction. To understand the potential challenges and risks, it is thus necessary to conduct a broad review of case studies from accidents which also include traditional (light) wood frame construction and fires in historic (heavy timber) buildings, as well as from tests with the modern engineered wood products. In critically analyzing the case studies involving different types of timber construction, it is discussed which lessons and observations are applicable to mass timber and should inform fire safety considerations for modern tall timber buildings. From the review of accidents and tests, the objective is to provide insights into the expected fire behavior of tall mass timber buildings, notably in terms of fire dynamics, compartment integrity, structural failure, self-extinguishment, smoke control, and effects of sprinkler systems.

The reviewed case studies of accidental fires cover buildings that were in use at the time of the fire, buildings under construction, and historic buildings. When discussing accidents in buildings in use and in construction, a distinction is made between buildings made of light-frame timber construction (also referred to as wood frame construction) and buildings made of heavy timber construction. The sections include descriptions of selected accidents, including observations regarding the spread of the fire within the building and to neighboring structures, the intervention of the fire brigades, the duration of the fire, and the consequences in terms of the extent of damage. In addition, experimental tests on the fire behavior of mass timber elements and structures are reviewed. Tested specimens include full-scale buildings, compartments, assemblies (e.g. floor systems, wall panels), and connections. Selected specific issues investigated through the tests included: the contribution of the structural timber to the fuel loads, the impacts of delamination of CLT panels on the fire dynamics in a compartment, the performance of timber connections, and the fire confinement within a CLT compartment including the integrity of CLT-CLT panel joints.

Section 3 of the report focuses on the evaluation of the contribution of timber to the fire severity. As the reviewed case studies show, timber elements that are not protected from the fire by encapsulation contribute to the fuel load, altering the fire dynamics by increasing the duration and intensity of the fire. This contribution is analyzed in Section 3. Specifically, investigated questions include the heat release rate in a mass timber building subjected to fire, the water required to fight a fire in a mass timber building, and the additional heat flux emitted toward neighboring structures when the timber participate to the fire. A case study of a 10-story mass timber residential building is presented to illustrate the discussions.

Section 4 of the report presents numerical analyses into the thermal and mechanical behavior of timber structures in the fire situation. The objective is to gain a better understanding of the conditions under which a failure of compartmentation or stability may occur. Indeed, critical fire situations in high rise buildings occur when fire spreads beyond its compartment of origin, as fire spread endangers people evacuation and complicates fire brigade intervention. Numerical analyses are used to investigate heat transfer through a CLT panel throughout the different phases of a fire (including the cooling down phase). Then, the thermo-structural response of a 10-story mass timber frame is simulated. The case study includes a total of 36 configurations consisting of 18 fire scenarios applied to either protected or unprotected timber frame elements. The results highlight the role of thermal protection of the timber frame elements, the effect of the exposed timber lining elements on the fire intensity, and the possibility of structural failure during the cooling phase of the fire.

1.2 Terminology of timber construction

1.2.1 Wood frame construction

Light-frame timber construction is a system of construction using a repetitive combination of closely spaced members that are typically nail-assembled (Figure 1). Members include dimensional lumber, I-joists, trusses, structural composite lumber, and oriented strand board decking and sheathing. Advantages include the low cost and ease of assembly. Light-frame construction has been used frequently in low-rise residential and commercial buildings, notably in the United States, the United Kingdom, and Canada. According to the International Building Code (IBC) classification, there are two types of light-frame timber constructions, Type V-A and Type V-B. Type V-A is the protected wood frame, commonly used in the construction of newer apartment buildings; there is no exposed wood visible while Type V-B is the unprotected wood frame, commonly used in single-family homes and garages [6].

Figure 1. Type V wood frame construction.

1.2.2 Heavy timber construction

The term ‘heavy timber’ has been used for centuries, and commonly refers to a building made up of large wood beams and columns. Traditional heavy timber construction is also known as post and beam construction. Figure 2 shows a typical heavy timber structure’s components. For nearly two centuries, traditional heavy timber structures were predominantly utilized as industrial and commercial occupancies. The current fire-resistance requirements of IBC qualify all wooden members of traditional heavy timber construction (TYPE IV) must have a minimum nominal dimension not less than 8 inches (20 cm); the fire-resistance requirements are 2 hours for exterior walls and 1 hour for timber frame, floor, ceiling and roof assemblies. The requirements for fire sprinkler systems are classified according to the occupancy of the traditional heavy timber construction [7]. Many traditional heavy timber buildings were used as warehouses for storage. For those buildings, NFPA 13 [7] has a separate set of requirements accounting for the type of commodities they store and the way in which they are stored.

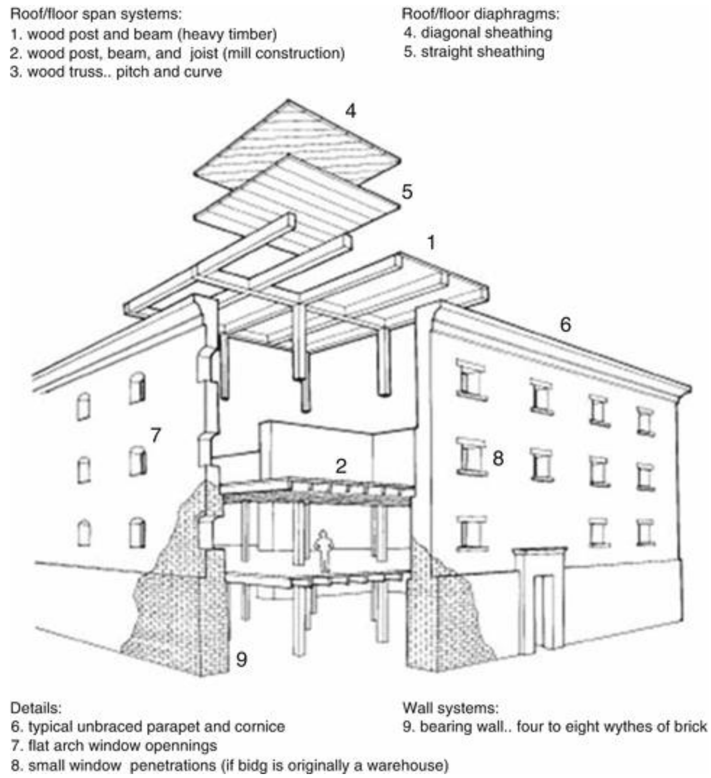


Figure 2. Artist's rendering of a typical heavy timber structure's components [8]

Recently, a renaissance in heavy timber construction is observed with the advent of 'mass timber' construction. According to the American Wood Council, mass timber "is a category of framing styles typically characterized by the use of large solid wood panels for wall, floor, and roof construction", as well as framing systems of large sizes. Mass timber products include, amongst others, Cross-Laminated Timber (CLT), Nail-Laminated Timber (NLT), Glued-Laminated Timber (glulam), and Dowel-laminated timber (DLT). Due to the emergence of the new mass timber technologies and engineered products, these new types of heavy timber buildings have been proposed or constructed in several countries around the world. Mass timber buildings differ from traditional heavy timber construction in several aspects [9]:

- most mass timber products used in new heavy timber buildings, such as glulam and cross-laminated timbers, are a series of smaller dimension wooden members held together with adhesives;
- new methods, such as post-tensioned construction and panelized construction, are used frequently in the construction of mass timber buildings;
- mass timber buildings are usually higher than traditional heavy timber buildings;
- new construction techniques allow for large span in mass timber buildings but also increase the susceptibility of these building to fire impingement;
- buildings usually do not have traditional heavy masonry bearing walls, instead favoring concrete or steel cores;

- the timber elements are highly finished with flammable materials and may possess sharp or protruding edges.

The largest mass timber building in the United States is the T3 building located in Minneapolis (Figure 3) [10]. The building is a seven-story, 220,000-square-foot (20,400 m²) structure. The T3 was constructed of NLT (nail laminated timber) panels combined with a spruce glulam post-and-beam frame, and a concrete topping slab. This building is classified as a "Type IV–Heavy Timber" system by the Minnesota State Building Code. As a sprinklered building, the building is not required to have specific (structural) fire rating. Though its exterior is clad in weathering steel, its interior is simply the timber framework, with the entire timber structure left exposed.

(a) T3 exterior

(b) T3 interior

(c) T3 structural connection detail

Figure 3. Mass timber Tower in Minneapolis [10]

2 Review of Fire Accidents and Fire Tests in Timber Buildings

2.1 Fires in Timber Buildings in Use

2.1.1 Wood frame construction

Case studies of fire accidents in light-frame timber buildings are provided hereafter. The reviewed examples include light-frame timber buildings between two and six stories, and composite concrete and timber-framed structure of eight stories (Marseilles) and fourteen stories (Camberwell [11]).

Worcester Park, London, UK, September 9, 2019

A fire occurred in Worcester Park in London, UK on September 9, 2019 ([12–15]). The wood-frame building was a four-story block of 20 flats. The construction system is light-frame construction with a cladding made of noncombustible material. There was no sprinkler system.

(a) The fire was ravaging the building (b) The building after the fire

Figure 4. An apartment fire in Worcester Park, London, UK, September 9, 2019 [16]

The fire started on a wood balcony. It spread into the cavities of the timber frames, quickly spreading through the whole building, as shown in Figure 4a. Firefighting operations were made very difficult by the fact that the fire was spreading through the cavities in the structure. About 125 firefighters were involved in the firefighting effort, with 20 fire engines, aerial platforms, and 20 pumps. The fire lasted for five hours. At the end, the building was completely destroyed, as shown in Figure 4b. The fire did not spread to the nearby structures.

One hundred and fifty residents were evacuated. Due to the absence of warning systems in some of the flats, many residents had not realized the occurrence of the fire before being warned by neighbors knocking on their doors. No injuries and casualties were reported. Fire causes are still being investigated. The incident has forced the UK government agency to rethink whether sprinklers systems should also be required in residential buildings with a height lower than 18 m [13,15]. Further, the incident shows the need for installing warning systems in individual flats, and not just in communal parts of a residential building.

Following the Worcester Park fire, investigators have looked at similar properties built by the same developer and found flaws in the fire protection measures [17]. Notably, fire surveyors found a large gap between the fire stopping and the cladding of the other buildings. This could render the fire barrier ineffective, as the gap can act as a chimney for the fire to spread (Figure 5).

Figure 5. Inspections of properties similar to the one catching fire at Worcester Park showed the presence of large gaps between the fire stopping and the cladding [17].

Crewe, UK, August 8, 2019

A fire occurred in Crewe, UK on August 8, 2019 ([12,18–22]). The building was a three-story wood-frame building, with facings of brick, block, render and timber. This building had once been reported by the Inside House magazine to have the largest timber content of any on-site housing project in Europe, using some 1,700 m³ of timber frame.

The fire is thought to be accidental and to have started in the roof space. It spread rapidly, involving the walls of the building that allowed the fire to extend into and led to the progressive collapse of those walls. Twelves fire engines and sixteen fire crews were involved in extinguishing the fire. The fire lasted for fourteen hours. The building sustained significant damage and partially collapsed. A number of road closures were in place and members of the public were asked to avoid the area. The fire did not spread to the nearby structures.

The building had to be destroyed after the event. One hundred and fifty residents of the complex had to seek alternative accommodation. No injuries and casualties were reported.

Camberwell, London, UK, July 3, 2009

A fire occurred in Camberwell in London, UK on July 3, 2009, known as the Lakanal House fire ([11,23–26]). The building was a 14-story concrete and timber-framed structure. It was built in 1959, was 42 m high and contained 98 flats.

The fire broke out in one of the flats on the ninth floor. It was caused by a faulty television. Within half an hour of the first 999 call, the fire had spread to several other floors, moving downwards as well as upward, through gaps in compartments and concealed spaces. Eighteen fire engines, 100 firefighters, and specialist fire rescue units were working on extinguishing this fire. Around 150 people were evacuated or rescued from the flats. The fire led to the deaths of six people and the injuries of at least twenty people.

The investigation of this fire incident has shown that some renovation work from the 1980s removed vital fire-stopping material between flats and communal corridors [24]. It also noted that asbestos window panels had been replaced with composite equivalents, which burned out in less than five minutes, accelerating the spread of the blaze. The absence of strips or seals on doors in the building and the lack of cavity barriers in the suspended ceiling has also accelerated the spread of fire within the building. Another noted deficiency was an inadequate fire protection to the timber stairs [26]. Those fire risks had not been noted until the fire due to the council's failure to inspect the building. It was believed that the confusion and chaos during the firefighting operation were also one of the reasons which lead to the death of six people in this fire incident.

Tustin, CA, USA, February 11, 2020

A severe fire ravaged an apartment complex in Tustin, CA, USA, on February 11, 2020 [27,28]. The complex was a 2-story wood frame construction. The fire was classified as a five-alarm fire based on the classification system used in North America.

The fire was caused by arson. It started in a unit on the first floor and quickly spread to the second floor and attic. The building was a center courtyard building. The fire progressed all the way around and engulfed the building, as shown in Figure 6a. The roof of the complex collapsed in about 24 minutes and left two residents injured. More than five hours after the 911 call, firefighters still worked to douse hot spots and determine if anyone was unaccounted for, as shown in Figure 6b. About 120 firefighters eventually put out the blaze, and 38 of the 40 apartments burned, authorities said. About 100 people were displaced.

(a) The fire was ravaging the building (b) Firefighters were checking for hot spots

Figure 6. An apartment fire in Tustin, CA, USA, February 11, 2020 [27,28]

Wisconsin, USA, 2018

A fire occurred in an apartment building in Wisconsin, USA, in 2018 [29]. The 16-unit apartment building was a two-story structure with a ground floor area of 7,500 square feet (697 square meters). It was a wood frame construction with a vinyl siding exterior. A wood roof deck was covered by asphalt shingles.

A discarded cigarette ignited a plastic box on an exterior porch. The fire ignited the vinyl siding and extended up from the siding into the attic rapidly. The fire chief attributed the fire spread to the absence of firewalls that caused extensive fire and smoke damage throughout the building. The building was equipped with interconnected smoke detectors in the hallways and battery-operated smoke alarms in apartment units. Because the smoke was located above the detection system, investigators reported that it did not activate. Over 70 firefighters from several departments were eventually involved in fighting the fire. All 20 residents were able to safely evacuate the building. The building was a total loss, valued at $624,000, as were the content, valued at $400,000.

New York, USA, November 2008

A fire occurred in a 114-unit motel in New York, USA, in November 2008 [30]. The building was a one- and two-story structure made of unprotected wood-frame construction. It was open and operating at the time of the fire.

The fire was ignited by an electrical malfunction in an attic. It started in a void above a wooden tongue-and-groove ceiling and spread to an attic above the pool, then burned unchecked above the fitness area into guest rooms on the second story and into the motel lobby. The motel had a complete-coverage smoke detection system that operated and alerted occupants and the fire department. It also had a complete-coverage wet-pipe sprinkler system, however, the sprinkler system was not covering the area of origin of the fire, and once the fully-developed fire reached it the system was overwhelmed. The ceiling and roof collapsed during the fire. The fire caused a $10 million loss.

Missouri, August 2012

A fire occurred in a four-story apartment building in Missouri, USA, in August 2012 [31]. The building, which had 68 condominium units, was made of unprotected wood-frame construction. The building was occupied at the time of the fire accident.

The fire originated on the second- or third-floor balcony and spread up the exterior, into the attic and fourth floor. No information was reported on the exact cause. The building had smoke detectors and manual pull stations in the building. The detection system operated as designed. There was a sprinkler system present that had complete coverage in the occupied area of the building, but its operation was reported as ineffective because there were no sprinkler heads neither in the attic, from where the fire spread into the building, nor on the balconies. Due to the lack of sprinklers in the attic area and on balconies, the fire was not controlled in its early stages. The fire department reported that two thunderstorms during suppression activities contributed to the spread and intensity of the fire, but no additional information was provided. This fire incident has caused a $14 million loss.

Marseille, France, February 9, 2012

A fire occurred in an eight-story building in Marseille, France, on February 9, 2012 [32]. The building was an eight-story wood-concrete hybrid building, including 337 apartments, a nursery school, a hotel, a restaurant, a gymnasium, a meeting room and a shop. The main structural frame of the building was constructed of concrete while walls, ceilings and floor joints are in wood.

An apartment (duplex) located at the first floor was first fully ablaze. The flames came out of the first floor. The spears stopped the spread of the fire along the facade effectively. However, the fire spread inside the building through the partition walls (light-frame timber wall, shown in Figure 7). Due to this fire spread though partition walls, the duplex located immediately above the initial fire location caught fire. Then more than three hours later, while the fire had seemed to be under control, the duplexes located in the upper compartments (3rd, 4th and 5th floors) suddenly caught fire; then three hotel rooms on the 7th and 8th floors also caught fire. In total, eight duplexes and three hotel rooms were destroyed by the fire, while about 30 apartments were affected by smoke. It took firefighters more than 28 hours to finally extinguish the fire. This fire has led to the evacuation of 1,600 people. No injuries and fatalities were reported in this incident.

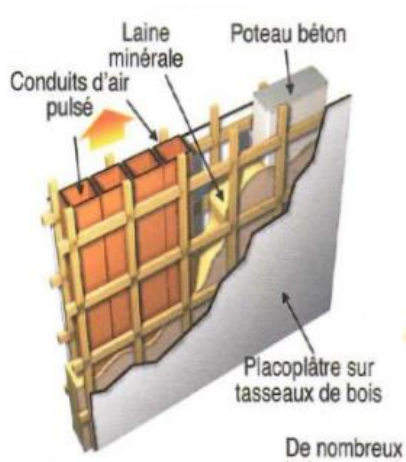


Figure 7. Fire spread through partition walls [32]

San Francisco, USA, July 2020

A major fire occurred in a commercial area in San Francisco, USA, on July 28, 2020 [33]. The fire ignited early in the morning and quickly spread to five neighboring buildings in a two-block area (Figure 8). The fire burned intensely and rapidly, requiring intervention from 160 firefighters via 60 vehicles. The firefighters managed to contain the blaze in a few hours. Six buildings were completely destroyed. Firefighters remained on site overnight to monitor for hot spots. A minor injury of one firefighter was reported.

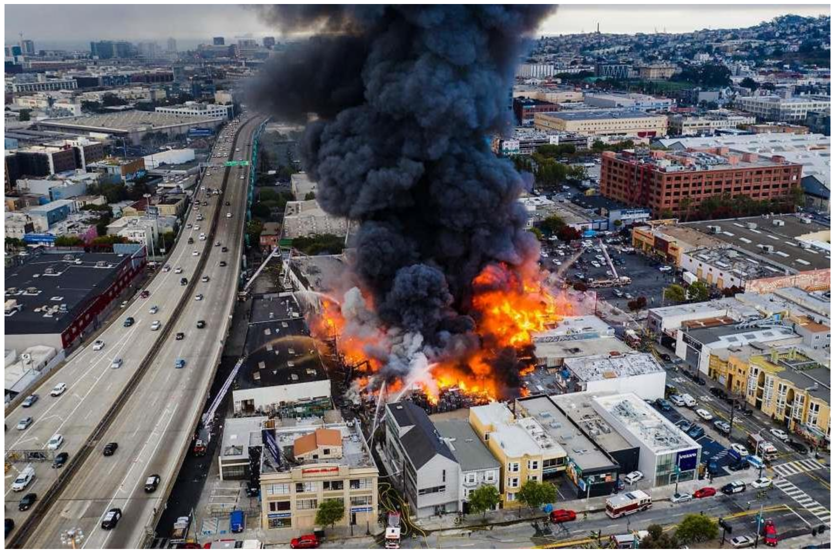


Figure 8. The large fire spread to multiple buildings (Photo Aaron Scales, SF Chronicle).

Other similar fire incidents

Other similar fire incidents in completed timber-frame buildings are summarized in Appendix A1.

2.1.2 Heavy timber construction

Hiroshima, Japan, October 2010

A fire occurred in Hiroshima, Japan in October 2010 [11,34], in a high-school gymnasium built in 1997. The building was a glue-laminated timber structure, i.e. a modern heavy timber construction. It was made of a reinforced concrete floor, heavy timber posts and heavy timber arches. The floor, the wall and the ceiling of the gymnasium were finished with wood-based materials (e.g. 5.5 mm thick plywood finish). This fire was the first blaze in Japan that has completely burned a large-scale glulam timber gymnasium. The fire burned the whole building of 979 m² floor area.

The fire began in the southeast corner of the gear supply storage on the east side of the second floor next to the stage of the gymnasium and spread to the combustible partition walls, the ceiling and arches. Flashover occurred very rapidly, in only 9 minutes after the activation of fire detectors. The occurrence of flashover was not thought to be likely in this structure given the low amount of content fuel load. The post-flashover fire lasted for about 20-30 minutes despite the efforts of the fire fighters on site. The entire timber gymnasium burned. Eventually the fire brigades managed to suppress the fire.

Almost all the combustible contents were lost. The only remaining elements were the heavy timber structural columns used to support the structure. Measured depths of char layer reached 18 mm for the post and 16 mm for the arch near the ignition location. This incident prompted a series of fire tests to assess why the fire spread so rapidly through the structure. Investigations suggested that the use of combustible walls (plywood finish) combined with the presence of urethane mattress were the cause of the very fast fire growth. As a result, the Hiroshima prefecture decided to replace the plywood finish of all similar gymnasium buildings with noncombustible board materials.

Chicago, USA, January 2013

A fire occurred in Chicago, USA in January 2013 [11,35]. The building was a traditional five-story heavy timber warehouse (Figure 9). The fire caused the collapse of the roof and of three external walls of the heavy timber warehouse, while the structure remained standing for the ten-hour duration of the fire. More than 200 fire fighters were displayed to extinguish the fire. The fire spread to at least one other building, but the fire fighters were quickly able to respond and suppress the spread of the fire [36].

Figure 9. Firefighters were battling a 5-11 blaze in a five -story heavy timber warehouse in Chicago, USA, January 2013 [35]

Pennsylvania, USA, June 2003

A fire occurred in Pennsylvania, USA, June 2003 [37]. The building was a three-story medical office building of heavy timber construction. This building was originally built as a shirt-making factory, but later renovated for offices. The fire was caused by a short circuit that ignited wood structural members in the attic; and the fire spread through a 4- to 6-foot (1.2- meter to 1.8-meter) void. There was a delay in the detection of the fire due to it starting in a void space. No automatic detection or suppression systems were present in the building. Loss to the building was $20,000,000 and loss to the contents was $3,000,000.

Indiana, USA, February 2007

A fire occurred in Indiana, USA, in February 2007 [37]. The building was a fiberglass manufacturing plant of heavy timber construction, 12 feet (3.7 meters) to 40 feet (12 meters) in height and covering 750,000 square feet (7,000 square meters).

This fire broke out in an office wall assembly when an overloaded relocated power strip lead to a malfunction of the wall outlet. The fire smoldered in the wall for a long time without being detected. The control of the fire was further delayed by employees who attempted to locate the fire for 15 minutes before notifying the fire department. The fire spread vertically inside the wall assembly to the attic area and spread horizontally throughout the attic. No automatic detection equipment was present in the building while a partial-coverage, dry-pipe sprinkler system was installed. The system operated, but its effectiveness was hindered by cold weather and a fire that was traveling horizontally above the heads. The fire-involved wall assembly had been layered over several times, with the original wall cover left in place, making the detection of heat in the walls very difficult by thermal imaging camera. There were also three roofs in place due to construction add-ons that left the original roofs in place, with many void spaces making it difficult to fight this fire. A firewall helped limit severe damage in the manufacturing area. One firefighter was injured in a flashover. The total dollar loss caused by this fire is $12,000,000.

Michigan, April 2012

A fire occurred in Michigan, USA, April 2012 [11,38]. The building was a three-story furniture plant of heavy timber frame construction. The irregularly shaped structure ranged from 234 to 430 feet (71 to 131 meters) long and was approximately 80 feet (24 meters) wide.

Workers using a circular saw to cut through ductwork ignited lacquer that had built up in a spray room in the third floor. The fire quickly spread along the ceiling to combustible construction through the opening the salvage crew member had made in the ductwork. Although the sprinkler system in the area of origin was overwhelmed by the fire, it did help prevent the blaze from spreading any further. This fire damaged the building heavily and caused a partial collapse of the roof. The structure suffered a $3 million loss, while damage to its contents was estimated at $250,000. No injury was reported.

Portsmouth, UK, March 11, 2014

A fire occurred in Portsmouth, UK in March 11, 2014 [39]. The building was a heavy timber warehouse.

The fire started near the end of the two-block long building and the company’s sprinkler system was activated. Firefighters arrived on the scene and contained the fire to one end. The property owners told them that there was a flea market in that part of the building. There was smoke inside and some heat and minor damage to the building. No one was injured.

Other similar fire incidents

Other similar fire incidents in completed heavy-timber buildings are summarized in Appendix A1.

2.2 Fires in Timber Buildings under Construction

2.2.1 Wood frame construction

Washington, D.C., USA, February 8, 2020

A fire engulfed a five-story building under construction in Washington, D.C., USA, on February 8, 2020 [40], as shown in Figure 10. The event was classified as a four-alarm fire.

The fire began in a trash chute at the top floor of the five-story building. The building being under construction, it did not have any sprinkler system. This combined with extremely windy weather conditions made fighting the fire difficult. This fire spread to nearby buildings and finally destroyed five buildings and 14 townhouses under construction and damaged an additional 14 townhouses, four single-family homes, five apartment buildings, a commercial building, and 28 vehicles [40]. About 150 firefighters from different counties responded this blaze. It took firefighters eight hours to control the fire [41]. Residents in a nearby community were evacuated. Two firefighters and one resident were taken to hospitals with minor injuries.

Figure 10. Firefighters were battling a large fire in multi-story construction site in Fairfax Country, Washington, D.C., 2020 [41]

San Francisco, USA, March 11, 2014

A fire occurred in San Francisco, USA, on March 11, 2014 [32]. The complex in fire was a six-story wood frame building of 172 unit under construction, with scaffolding installed around its entire periphery, the sprinkler-type automatic water extinguisher system (EAE) being installed, and windows and doors on upper floors not installed [32]. The event was classified as a five-alarm fire indicating a major level of required response by fire departments.

The flames rose from the top floor at the southeast corner. The increasing severity of the fire quickly threatened the stability of the structures, forcing the emergency services to evacuate. The fire led to the windows of the adjoining buildings to burst. As the fire spread throughout the building, the last three floors collapse. The power of the blaze then forced the firefighters to focus their resources on protecting nearby buildings threatened by radiation. The flames exceeded 40 m. Flaming debris caused several fires to start by projections. Although the fire was considered to be under control, elements of the structure continue to collapse sporadically forcing the rescue team to retreat. The fire lasted for three hours. 150 firefighters were called for to fight this fire. No injuries or casualties were reported.

Waltham, Massachusetts, USA July 23, 2017

A massive fire occurred in Waltham, Massachusetts, USA, on July 23, 2017 [42]. The fire caused by arson destroyed a 260-unit luxury apartment complex under construction [42–44]. The complex had five buildings under construction. One of the buildings was near completion, meaning gas and electricity could have been turned on. Smoke detectors and sprinklers had been installed, but were not yet operational.

The blaze broke out around 4 a.m. and was heightened by winds that carried embers and smoke to neighboring cars and buildings. Two of the buildings were totally involved in the fire and the fire spread quickly to the other three. Some of nearby buildings were evacuated and 20 cars were damaged. All five collapsed finally. It caused an estimated $110 million in damage.

College Park, MD, USA, April 24th, 2017

A fire occurred in College Park, MD, USA, on April 24h, 2017 [45]. The apartment complex in fire was a seven-story doughnut-type construction.

It was said the fire begun at the back of the fifth and sixth floors and spread to the seventh floor and roof through empty space; however, three-hour firewalls between the back and the front of the building kept the inferno from spreading to the front of the building. The difficulty to access the back of the building where the fire spread made the control of the fire challenging. The fire has been the largest suppression effort and the highest fire loss estimate in the history of the Prince George's County Fire Department [45–48]. More than 200 firefighters and more than 50 pieces of equipment responded to the fire. It took firefighters almost six hours to make the fire under control. Fortunately, the fire did not spread to the nearby structures although some of them were evacuated. It caused an estimate $39 million in damage.

Hampshire, UK, September 2010

A fire occurred in Hampshire, UK, September 2010 [49]. The structure in fire was a four-story, 60-flats building of wood frame type under construction [49,50].

The fire was caused by arson. During the fire, there were fears the flats could collapse and two cranes on site were damaged. Burning wooden embers from the building and the prevailing wind conditions put a number of other nearby buildings at risk (i.e., about 50 surrounding homes and Brighton Hill Community College were affected by smoke and falling pieces of burning ash). More than 100 firefighters tackled the blaze, with 12 specialist support vehicles. About 40 people were forced to leave nearby homes.

Peckham, London, UK, November 26, 2009

A fire occurred in Peckham, London, UK, on November 26, 2009 [51–55]. The building in fire was a half-built four-story timber-frame block of 39 flats under construction.

The fire spread very rapidly to and damaged nearby buildings. More than 180 fire fighters with 30 fire engines were deployed to fight this fire, along with police officers and 20 ambulance crews on standby. The fire lasted for almost eight hours. Ten people, including two police officers, received hospital treatment for minor injuries; and about 310 people were forced to leave their homes.

Richmond, Canada, June 2010 and May 2011

In June 2010, a six-story light-frame timber building under construction in Richmond, Canada, caught fire and was complete destroyed [11]. Richmond Fire Department voiced concerns that they were not in possession of the necessary equipment to deal with a blaze in a wood structure of that size. On May 2011, another six-story timber-frame building under construction was in fire again in the same city, causing 38-60 million loss [56,57]. Fire safety features, such as sprinklers, gypsum board protection, fire doors and firewalls, had not yet been installed in both buildings. Fortunately, no injuries were reported in both incidents.

Sommerville, NJ, August 2020

A fire occurred in an apartment complex under construction in Sommerville, New Jersey, on August 21, 2020. The building was a four-story structure. The fire may have started in the attic area. Videos of the incident show the roof burning over a large area of the multi-story apartment complex.

Other similar fire incidents

Other similar fire incidents in wood frame buildings under construction are summarized in Appendix A.

2.2.2 Heavy timber construction

Pennsylvania USA, March 21, 2018

A fire occurred in Pennsylvania, USA, on March 21, 2018 [58,59]. The building was a large Type IV (heavy timber) construction mill building that was 140-year old. When the fire occurred, the building was under renovation to create an apartment complex, with inactive sprinkler system. The fire rapidly spread throughout the 53,000-square foot structure. Firefighters from five fire departments were called to extinguish the fire, with elevated aerial platform. The fire lasted for more than 24 hours. Two career firefighters, ages 50 and 29, died following a structure collapse; another two firefighters were seriously injured.

Figure 11. Firefighters on site during the 2018 fire in the mill building undergoing renovation.

Georgia, USA, 2001

A fire occurred in Georgia, USA, in 2001 [60]. The building in fire was an unoccupied university office building under renovation when a worker using a cutting torch to remove metal stairs unintentionally started a chain of events that led to a concealed fire in a wall space. The building is a three-story structure constructed of heavy timber with a brick veneer measuring 9,000 feet (836 meters) per floor. At the time of fire occurrence, all the fire detection and suppression systems had been disabled or removed during construction, and only temporary power remained in part of the building.

Investigators determined that the cutting torch had heated the metal bolts, which then conducted heat to wooden structural members inside the wall space. The resulting fire then smoldered for a while. The fire burned undetected, spreading to the third floor and attic. Oxygen supplied primarily through the roof vents, appears to have helped the flames spread from the concealed spaces to the attic. It took eight engines, two truck companies, two squads, and numerous support staff to extinguish the blaze. The building, which was valued at more than $1 million, was a total loss. Contents losses were not reported. No injury losses were reported.

Rhode Island USA, 2012

A massive fire occurred in a four-story building in Rhode Island, USA, in 2012 [38]. The building was constructed of heavy timber frame and brick walls, wooden floors, and a wooden roof. The building measured 300 feet (91 meters) by 50 feet (15 meters). At the time of fire occurring, the building was being converted into a wood pellet manufacturing plant. Its fire detection system was connected directly to the fire department. The fire sprinkler system had been turned off while the building was being renovated.

Investigators determined that workers using cutting torches on piping inadvertently heated the wooden structural framing to its ignition point and that the building caught fire 60 to 90 minutes after they completed work for the day. When firefighters arrived four minutes later, they could see no sign of fire on the outside of the building. While walking to the second floor, however, they smelled smoke and were informed that smoke was coming from several third-floor windows. When they got to the warehouse area on the second floor, they saw about 25 feet (8 meters) of fire near the ceiling. As smoke came pouring down the staircase, the firefighters made a fast exit and switched to exterior operations. The fire ultimately went to an eight-alarm according to the classification system in North America, and the last unit was not cleared until four days later. Two firefighters suffered dehydration and were transported from the scene by ambulance.

Allentown, PA, October 8, 2018

A fire occurred in Allentown, PA, USA, on October 8, 2018 [61,62], as shown in Figure 12. The mostly vacant four-story building in fire was constructed of heavy timber frame and brick walls. It was being converted into an apartment, with a lot of lumber insides the factory renovation that helped fuel the massive fire.

35 city firefighters and backup from the neighboring communities were called for to fight the blaze. Fire crews used aerial trucks to douse the building from above, aided by a drone that alerted them to hot spots. The building was further damaged by the water used to keep the fire under control, in addition to the impingement from the flame. It took 13 hours to get the blaze under control, but hot spots continued to flare up a day later. The building was completely damaged, and several floors collapsed. The fire incident has led the closure of several streets around the building. One firefighter burned his hands, and no other injuries or fatalities were reported.

Figure 12. Firefighters were battling a large fire in a four-story building under renovation in Allentown, PA, October 8, 2018 [63]

Kentucky, USA, July 2015

A fire occurred in Kentucky, USA, in July 2015 [64]. The building in fire was a four-story commercial property of heavy-timber construction that was under renovation. The building did not have automatic detection equipment. It had a full-coverage automatic suppression system, but the system had been shut down before the fire. This fire started in the basement when hot slag or sparks from an acetylene torch or grinder ignited old wood during welding or cutting operations earlier in the day. The loss was estimated at $11 million for the structure.

Nottingham, UK, September 13, 2014

A fire occurred in Nottingham, UK, on September 13, 2014 [65,66]. The £20m mass timber GlaxoSmithKline building was an unfinished University of Nottingham laboratory, completed at about 70%. The structure was built from glulam and CLT members.

The fire was caused by an electrical fault. The unfinished building had no fire doors or windows, allowing the blaze to spread with ferocity. Over sixty firefighters were dispatched to battle the fire. The building burnt completely. There were bits of debris in the air landing all over the road. Fortunately, the fire did not spread to the nearby buildings; no one was injured in this incident.

2.3 Fires in Historic Timber Buildings

Historic buildings are particularly vulnerable to fire because they were not designed or built to meet modern building codes. Some buildings may have been retrofitted up to code, but at times this is not possible due to architectural and/or historical considerations. Five common problems associated with meeting fire safety requirements in historic buildings are [67,68]: 1) Meeting dimensional requirements; 2) Achieving required fire resistance; 3) Meeting egress requirements; 4) Addressing problems with installed features; and 5) Avoiding aesthetic intrusions. Historic buildings are also inherently vulnerable to fire. Their interiors often feature generous open spaces and their structures frequently contain large quantities of timber that have dried over the years. Renovation works (e.g., hot work) increase fire risk of historical buildings. Some historic buildings are in remote and/or inaccessible locations where firefighter access and water supply may be issues. Even if a building is in a location with sufficient water supply, a fire may occur in an area of the building where it is difficult to access. Once a fire starts, it can be hard to extinguish. The process of fighting the flames can cause more damage than the blaze itself. Therefore, firefighting actions in a historic building may be also different from that in a normal building, in order to protect the building. Some major fire in historic buildings were started by natural causes, such as lightning. Usually, however, ignitions are caused by human activities.

2.3.1 Fires during renovation works

Notre-Dame de Paris, Paris, France, April 15, 2019

The Notre-Dame Cathedral in Paris experienced a fire on April 15, 2019 [69,70], as shown in Figure 13. The building had fire detection systems but had not installed any fire suppression systems. The Cathedral was under renovation at the time.

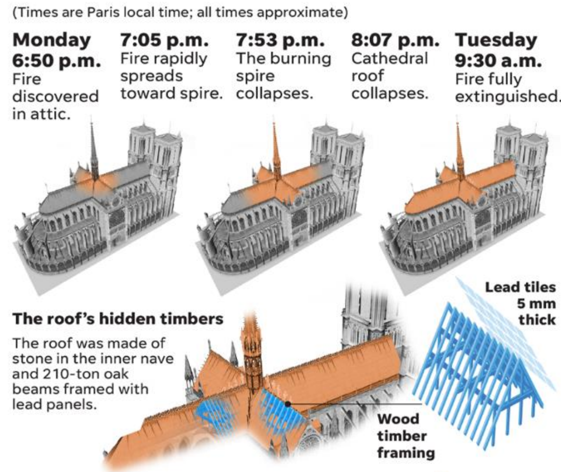
Figure 13. Fire at Notre Dame Cathedral in Paris, France, April 15, 2019 [71]

The fire broke out beneath the timber roof of Notre-Dame de Paris cathedral, shown in Figure 14a. However, the access to attic is a set of steep stairs, which makes the firefighting very difficult [72]. In the incident, the spire of the cathedral collapsed, creating a draft that slammed all the doors and sent a fireball through the attic. Shortly before the spire fell, the fire had spread to the wooden framework inside the north tower, which supported eight very large bells, as shown in Figure 14b. Had the bells fallen, it was thought that the damage done as they fell could have collapsed the towers, and with them the entire cathedral. Firefighters abandoned attempts to extinguish the roof and concentrated on saving the towers, fighting from within and between the towers.

More than 400 firefighters were engaged; another hundred worked to move precious objects to safety via a human chain also including police and municipal workers. The fire was primarily fought from inside the structure, which was more dangerous for personnel but reduced potential damage to the cathedral, applying water from outside risked deflecting flames and hot gases inwards. Deluge guns were used at lower-than-usual pressures to minimize damage to the cathedral and its contents. Water was supplied by pump-boat from the Seine. The spire of the building and most of its roof had been destroyed; and its upper walls were severely damaged. Fortunately, extensive damage to the interior was prevented by its stone vaulted ceiling, which largely contained the burning roof as it collapsed.

The cause of the fire is still under investigation as of September 2020. Suggested causes of the fire include an electrical fault (short circuit) or a cigarette left by workers.

(a) Wood Frame of the Notre Dame Cathedral [73]



(b) "How the Notre Dame Cathedral fire spread so fast" [74]

Figure 14. Notre-Dame de Paris Fire.

Tsinghua Hall, China, 2010

A fire happened in the Tsinghua Hall in 2010 [75,76]. The roof and floor of this hall were made of timber structures. The hall was under renovation when the fire occurred. The fire started at the northeast part of the hall. Due to strong wind at night, the fire spread to the east part of the hall very quickly; then shortly thereafter the fire spread to the west part of the hall. Fortunately, the fire did not spread to the nearby structures. 44 fire engines and 308 firefighters were working on extinguishing this fire. No injuries and casualties were reported.

Wangduephodrang Dzong Fire, Bhutan, June 24, 2012

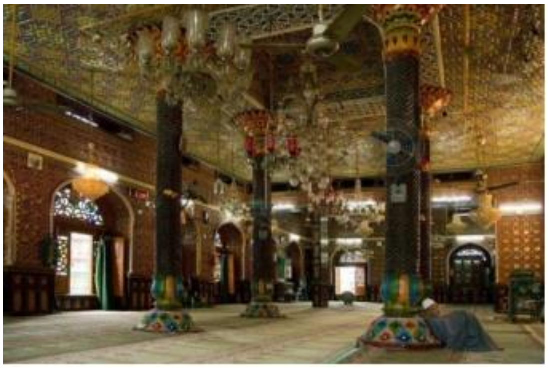
Wangduephodrang Dzong, a four-century-old architectural wonder in Bhutan, was completely destroyed by a major fire on June 24, 2012 [77–79]. 95% of the buildings were construct of timber. A short circuit in the wiring is believed to have caused the fire. There were no sprinklers nor other modern fire protection measures such as fire walls in the Dzong. The Dzong is inaccessible on three sides save for a narrow path in the front, which has hampered the efforts of firefighters.

2.3.2 Fires during normal operations

Peer Dastgeer Sahib Shrine fire, India, June 25, 2012

Peer Dastgeer Sahib shrine, a 250-year-old wooden landmark (heavy timber construction) in India, was completely destroyed by a major fire in June 25, 2012 [79,80]. There were no modern fire protection measures in the building.

When the fire was extinguished, the heavy timber structure of the building was still standing and even found to be of sufficient strength to allow its reuse in a restoration, as shown in Figure 15. The timber members remained sound through the long hot blaze owing to their large size. As the oversized beams char, the charring progresses slowly and the wood beneath the char layer maintained its integrity, which prevented the total consumption of the timber in the blaze. This fire has lead the government to conduct fire auditing of all shrines and upgrading of the fire checking mechanism installed in various Dargahs in India.



(a) Inside Peer Gastgir Sahib Shrine before the fire

(b) Same view after the fire

Figure 15. A fire destroyed the Peer Gastgir Sahib Shrine in India, June 25, 2012 [79]

Shuri Castle, Japan, October 31, 2019

Shuri Castle, a 500-year-old structure in Japan, suffered a fire on October 31, 2019 [81]. The blaze started near the main hall. The castle burst into flames; then the framework of the Seiden hall collapsed, with the fire spreading to an adjacent building; destroying seven wooden buildings occupying a total of 4,800 square meters [81–84]. More than 100 firefighters and more than 10 fire engines were engaged in this incident. It is believed that the large amount of wooden structures and the recently reapplied lacquer may have also had an effect on the severity of the fire.

The Castle was a World Heritage site and used to be the seat of a kingdom that spanned four centuries between the 1400s and the 1800s. The fire destroyed the building as well as many priceless artifacts. Fire prevention was mostly based on inspections, conducted twice a year, and fire drills once a year. No sprinklers had been installed inside the castle, but some sprinklers had been installed under the roof of the main building to prevent fire from entering from outside.

Figure 16. Shuri Castle Fire, Japan, 2019.

2.4 Fire Tests on Mass Timber Structures

2.4.1 Tests on buildings

This Section describes tests on 2- and 3-story mass timber buildings conducted between 2008 and 2018. The full building tests allowed observing the global performance of mass timber structures when subjected to uncontrolled fire exposure.

Hasburge et al., 2018

The main objective of the tests was to observe the performance of a two-story apartment type mass timber structure when subjected to fire. The fire test series included five tests [85,86]. The first three tests investigated varying levels of exposed cross-laminated timber. The surface area of the mass timber protected by gypsum wallboard ranged from 100% protected to no protection. The last two tests had glazing on the openings of walls and sprinkler systems; one test had automatic sprinkler activation while the other test had delayed sprinkler activation after 20 minutes. The two floors of the apartment structure each had a 9.1 m x 9.1 m x 2.7 m large compartment, in addition to corridors. For each experiment, the fuel load was identical.

In the first three experiments, the fire reached flashover, grew to fully developed, and subsequently underwent a cooling phase as the fuel load from combustible contents was consumed. The experiments were carried out for a duration of up to 4 h. Despite the differences in exposed CLT surfaces, flashover occurred at approximately the same time, with a similar fully developed fire phase.

In the fourth experiment, automatic fire sprinklers suppressed the fire automatically. In the fifth experiment, the activation of the automatic fire sprinklers was delayed by approximately 20 minutes to simulate responding fire service charging a failed sprinkler water system. In both tests, the windows did not break and there was no flashover. The sprinkler systems succeeded in suppressing the fire before flashover, while the window glazing limited the oxygen content in the compartment.

Karuse, 2017

The tested building was a two-story structure constructed of CLT [87]. The main objective of the test was to find the balance between the development of exposed mass timber surfaces and the ability to reach self-extinction when all content fuel load is consumed. The building had large exposed wood surfaces on the interior of the compartments, with no extinguishing system. Two of the inside walls and the ceiling were covered in double- and triple layers of fire rated gypsum respectively. The floor was also protected with stone wool and cement plates. The other two remaining CLT walls were exposed to the fire. Furniture was used as fuel load.

Figure 17 shows several stages of the fire test. The fire grew to fully developed and spread to the facade. After consuming the content fuel load, the fire continued through smoldering of the exposed CLT panels. Finally, delamination of CLT appeared and led to a second flashover (Figure 17g), meaning that there was no self-extinction. Hence, the test showed that using interior exposed wood surface (here, CLT panels) with no active extinguishment system can seriously compromise the fire response of the structure as the structural CLT can fuel the fire and thus prevent its extinction.

(a) before the ignition

(b) After breaking the first window, the fire starts to develop

(c) Flames are reaching the facade of the upper floor

(d) Fire has spread to the facades

(e) The flames are subsiding

(f) The CLT is smoldering

(g) The second layer of CLT is burning

Figure 17. Fire development in the 2017 Karuse test [87].

Frangi et al., 2008

A full-scale test on a 3-story building made of CLT panels was performed under natural fire conditions following shaking table tests, as shown Figure 18 [88]. The objective was to check the global performance and identify possible weaknesses of the timber structure. The building had an area of about 7 m x 7 m and a height of about 10 m. The building main structure consisted of 4 outer 85 mm thick CLT timber walls and an inner 85 mm thick CLT wall. The CLT panels were protected by one or two layers of non-combustible gypsum plasterboards. The total fire load density (calculated over the floor area) for the fire room was approximately 790 MJ/m^2, which includes the contribution from the wood floor. The fire room, with dimensions of 3.34 m x 3.34 m x 2.95 m, was located on the first floor and presented two window openings with dimensions of about 1.0 m by 1.0 m and a door with dimensions of 0.9 m by 2.1 m.

During the test, the fire remained contained in the compartment of origin. No significant elevation in temperature was measured and no smoke was observed in the room above the fire compartment. Hence, the test showed that compartmentation can be achieved for mass timber structures using appropriate protection of the CLT panels (in this case, gypsum plasterboards). Besides limiting the fire spread, protection from gypsum plasterboards also limited the fire damage of the CLT panels.

(a) After 32 minutes

(b) After 40 minutes

Figure 18. Fire development after fire ignition [88].

Osborne and Dagenais, 2015

A large-scale fire test was conducted to assess the fire performance of a CLT stairs/elevator shaft and validate the CLT design as an alternative to a shaft made of noncombustible construction for a thirteen-story residential mass timber building project [89]. The large-scale demonstration setup consisted of a nine-meter high stairs/elevator shaft and an adjacent apartment, representing a section of the proposed building. The interior of the apartment was finished with gypsum boards. No gypsum board was installed on the outside of the apartment except for a limited area around the window and door openings. The CLT stairs/elevator shaft was left entirely exposed.

The fire was started in the apartment. The fire load density of the room contents in the apartment was 790 MJ/m^2. The fire test was conducted without sprinklers to simulate a worst-case scenario where sprinklers would fail to operate or control the fire. The test showed that the severe, high-intensity fast-growing fire in the adjacent apartment did not propagate to the mass timber stairs/elevator shaft. Measurements in the shaft showed no significant change in conditions, indicating no impact from the adjacent fire on the CLT stairs/elevator shaft.

2.4.2 Tests on compartments

This Section describes fire tests in mass timber compartments. The reviewed mass timber compartment tests typically aimed to achieve one or several of the following objectives: a) evaluate the contribution of the timber construction materials to the fire development; b) study self-extinction of the timber structure; c) characterize the effect of gypsum boards on delaying or preventing the involvement of CLT in the fire under varied ventilation conditions; and d) assess the charring behavior of timber when used in a building structure.

Su et al., 2018

A study initiated by the Fire Protection Research Foundation on "Fire Safety Challenges of Tall Wood Buildings" included six large CLT compartment fire tests. The tests were conducted at the NIST National Fire Research Laboratory in Gaithersburg, MD, under a collaboration between the NIST and the Canadian NRC. The study addressed the need for evaluating the contribution of mass timber elements to compartment fires, specifically, considering "the concern that timber elements in tall wood buildings could increase the fire load, affect the fire growth rate, and potentially compromise fire protection systems in buildings, all of which could result in more severe conditions for occupants and responding fire fighters and increase the threat of damage to the property and adjacent properties". Therefore, the project aimed to quantify the contribution of CLT building elements to compartment fires, and to characterize the effect of gypsum boards protection of the CLT structural elements for delaying or preventing their involvement in the fire [90].

Six compartments of 9.1 m long x 4.6 m wide x 2.7 m high were tested. The compartments had an opening of 1.8 m wide x 2.0 m high in four tests and 3.6 m wide x 2.0 m high in two tests. The inside of the compartments was fully or partially lined using multiple layers of 15.9 mm thick Type X gypsum board. Real residential contents and furnishings were used to provide a fire load density of 550 MJ/m^2. Two baseline tests (Tests 1-1 and 1-2), with all CLT surfaces protected in the compartments but of different ventilation configurations, defined the contribution of the moveable fire load to the compartment fires and provided baseline data for quantifying the CLT contribution to the compartment fires in the other tests. The ventilation of the compartment in Test 1-1 is lower than that in Test 1-2. In addition to the baseline tests, two compartments (Tests 1-3 and 1-4) with an exposed wall were tested in both ventilation configurations; the ventilation configuration of the compartment in Test 1-3 is the same to that in Test 1-2 while the ventilation configuration of the compartment in Test 1-4 is the same to that in Test 1-1. Two compartments with an exposed ceiling (Test 1-5) and a combination of exposed ceiling and wall (Test 1-6), respectively, were tested in the relative lower ventilation configuration.

The test results indicated that CLT contribution to the compartment fire increased with the increasing surface area of the CLT panels that were exposed and involved in the fires. Gypsum board, where applied, was an effective means to delay or prevent the ignition and involvement of the timber structural elements in the fires. In contrast, exposed CLT surfaces contributed to the fires to variable extent and delamination of plies from exposed walls was observed.

Ventilation conditions had significant impacts on the fire development in the compartments, as well as on the CLT contribution to the fire. The fire duration of fully developed fire was longer in the tests with a smaller opening than that of the tests with a larger opening. As a result, the CLT became more involved in the fire over the duration of the tests with the smaller openings. In particular, in the test with the long CLT wall exposed and the smaller ventilation opening, more heat was trapped inside the compartment following the fully-developed phase and, after the initial decay, a large re-flash occurred on the exposed wall with delamination of the second ply of the CLT, which caused the second flashover and induced the full involvement of all originally protected CLT panels in the fire.

The presence of exposed CLT surfaces in four of the tests led to faster flashover by about 3 min to 5 min compared with the two baseline tests with all surfaces protected by gypsum. The peak compartment temperatures were similar in all six tests. However, the heat release rates and heat fluxes to the exterior façade were increased in the tests with exposed CLT compared with the baseline, indicating that the exposed CLT panels increased the fuel load in the test compartments, as shown in Figure 19. Besides, the exposed CLT surface(s) exhibited heat delamination, which led to one or more periods of fire regrowth after decay in three of the tests, and no decay of the fire prior to suppression in the fourth test, as shown in Figures 19 and Figure 20.

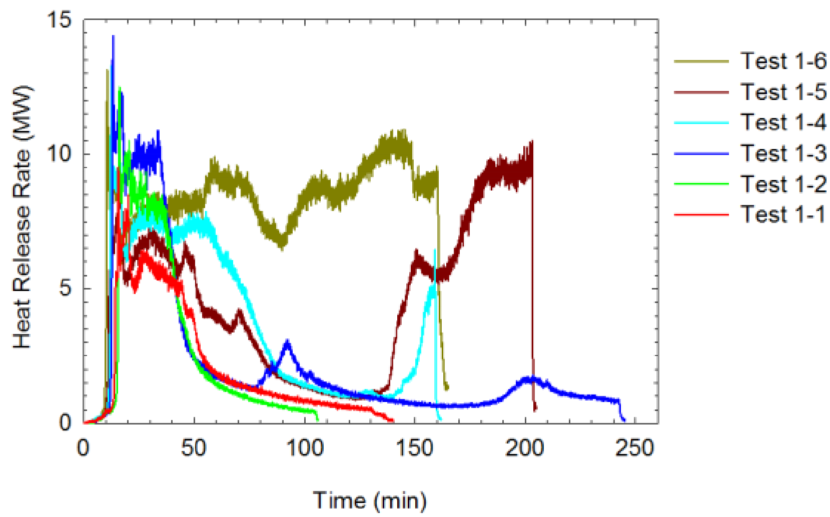


Figure 19. Heat release rates in CLT compartment tests [90]

(a) first item ignited in the corner

(b) outside view of ignition

(c) ceiling ignited above the dining area

(d) just before flashover

(e) flashover

(f) at 60 min

(g) at 120 min

(h) at 160 min

Figure 20. Photographs of the CLT compartment during Test 1-6 [90]

Emberley et al., 2017

The objective of this test was to demonstrate that self-extinction could be achieved for the proposed geometry, provided conditions to prevent debonding and the failure of the detailing could be ensured [91]. The base build compartment geometry of internal dimensions is 3.5 m × 3.5 m ×2.7 m. An opening was provided based on a typical door dimension. The front wall of the compartment was extended vertically by an additional 2.7 m (intended to represent one additional story). The entire front of the compartment was covered with two 13 mm Knauf Fire Shield boards. The CLT ceiling and one side of CLT wall are exposed to fire. In addition to the full-scale test, timber blocks (150 mm thickness) with a surface area of 120 mm × 120 mm were exposed to a range of external heat fluxes by a cone heater.

In the large-scale fire test, the fire started at the ceiling of the compartment and then exhibited rapid spread down to the bottom of the exposed CLT walls; and the compartment became fully involved with visible flaming CLT walls. Then the severity of flame begun to decrease. The self-extinction begun at the base of the exposed surface and then progressed to the ceiling, during the decay phase of the wood cribs. Fire protection remained in place.

This test has shown that self-extinction can occur in a partially exposed CLT compartment when conditions typically associated with debonding and delamination are avoided or minimized. For example, conditions favorable to prevent the debonding are a limited content fuel load and a large thickness of the outer lamella. Moreover, it is found that self-extinction occurred in the large-scale compartment within the range of the critical heat flux obtained from the small-scale tests.

Hadden et al., 2017

The objective of this study was to evaluate the impact of combustible CLT linings on the compartment fire behavior [92]. Five large-scale compartment fires were undertaken under the 15 MW calorimeter in the Burn Hall at BRE Global, Watford, UK. The compartments had various configurations and number of exposed CLT internal surfaces. In the first two tests, the back wall and one side wall were exposed; in the third and fourth tests, the back wall and the ceiling were exposed; in the fifth test, the back wall, ceiling, and the sidewall were exposed.

Self-extinction of the compartment was observed only in one case, but was not observed when the experiment was repeated under identical conditions. Analyses suggested that self-extinction was highly dependent on whether the char layer delaminated. No self-extinction occurred in compartments with large areas of exposed timber linings. The measured peak compartment temperatures agreed relatively well with those predicted by existing correlations, which indicated that exposed timber surfaces had a minor influence on the compartment temperature. However, the total heat release rate was higher than predicted using existing methodologies developed for compartments with inert linings and fuel loads located on the floor. Therefore, more research is needed to quantify the effect of exposed mass timber surfaces and fuel position on the heat release rate.

Hevia, 2014

Three compartment fire tests were conducted at Carleton University Fire Research Laboratory. The objective was to determine the maximum percentage of unprotected CLT surface area that would yield similar results to that of a fully protected room [93]. The compartments had a single opening. A non-standard, parametric fire was used, and two layers of gypsum boards were used to cover the ceiling and the protected walls. In one test, only one wall was left exposed while in the other two tests, two walls were not protected (one test with unprotected walls facing each other, another test with unprotected walls adjacent to each other).

The heat release rate during the tests with two walls exposed was much greater than the heat release rate of the test with only one wall exposed. The maximum HRR of the test with unprotected walls facing each other was greater than the HRR of the test in which the unprotected walls were adjacent to each other. The charring rate decreased linearly in all three tests as the thickness of the char layer developed. Room temperatures during the early stages of the fire for all three tests were similar as only the room contents were involved in the fire. After flashover, the temperatures in the rooms with multiple unprotected walls decreased at a slower rate than the room with only one unprotected wall. The room in one test had an early integrity failure（CLT panel-to-panel joints through a half-lapped joint, leading to flaming outside of the room, which indicated the importance of using fire-rated caulking to seal CLT panel to panel connection, as shown in Figure 21). The test with one wall exposed did not delaminate and achieved self-extinction. The latter used CLT products from a different manufacturer than the two tests with two walls exposed. In the two tests with two exposed walls, early delamination of CLT plies occurred, leading to a second flashover.

Figure 21. Flaming through a half-lapped joint during the fire test [93]

McGregor, 2013

Five tests were conducted to assess the contribution of CLT panels to the development, duration and intensity of room fires [94]. The room dimensions were 3.5 m wide by 4.5 m long by 2.5 m high. Different fire conditions were considered based on two different fuels (propane and bedroom furniture) and two room lining configurations (protected and unprotected).

In the protected configurations, no noticeable contribution was observed from the CLT panels. However, in the unprotected configurations, the CLT panels contributed to the fire load and increased fire growth rates and energy release rates. When charring advanced to the interface between the CLT layers, the polyurethane-based adhesive failed, resulting in the delamination of CLT panels. Delaminated members contributed to the fire load and resulted in suddenly exposed uncharred timber which increased the intensity and duration of the fire. When delamination occurred, the fire continued to burn at high intensity well after the combustible contents in the room were consumed. These fires were extinguished manually as they could have resulted in structural failure of the test rooms.

Hakkarainen, 2002

Four fire tests were performed to study the gas temperature development and charring behavior of timber construction compartments [95]. The base build compartment had internal dimensions of 4.5 m × 3.5 m × 2.5 m with an opening of a typical door dimension. The front wall of the compartment was extended vertically by an additional 2.6 m. Tests 1 to 3 were heavy laminated timber structures with a solid frame while Test 4 had a wood stud frame with mineral wool insulations. The structure in Test 1 was unprotected while the timber structure in tests 2, 3 and 4 was protected by one or two layers of gypsum plasterboard.

The measured gas temperatures were lower than predicted by the parametric temperature-time curves of Eurocode 1 for all tested structures. Each protective layer of gypsum plasterboard delayed the onset of charring for 20 min. Reduced charring rates for long exposure times were observed. A larger part of the pyrolysis gases burnt outside the fire compartment in the case of bare or insufficiently protected timber surfaces compared to protected structures. Excessive flaming outside the fire compartment can lead to an increased risk of fire spread to other compartments and buildings.

2.4.3 Tests on assemblies

Most frequently studied mass timber assemblies include mass timber floors and walls. In addition, some tests have also focused on timber-concrete or timber-steel composite floor systems. The main objectives of these tests typically include: a) generate test data to validate design methods for mass timber assemblies; b) evaluate the reliability of CLT adhesives under fire; c) investigate the failure behavior of mass timber or composite assemblies.

Janssens and Joyce, 2017

The primary goal of these tests was to evaluate three CLT ceiling panels manufactured with different types of adhesives for the American Wood Council.

Tests were performed on three 8x16 ft (2.4 m by 4.9 m) CLT panels, each consisted of five 1 3/8 in. (3.5 cm) layers of softwood lumber, with average density of 31 pcf (497 kg/m^3) and average moisture content of 10.8% [96]. The panels were manufactured with different adhesives. The failure temperature of the polyurethane adhesive used in the fabrication of CLT #1 is in the range of 200 to 220^{o}C, which is consistent with the delamination that were observed at the fire glue-line around 60 min, and at the second glue-line around 180 min. The delamination in test CLT #1 resulted in re-ignition and significant combustion of wood on the ceiling, which caused a noticeable increase in the HGL temperatures and DFT heat fluxes, and a secondary flashover at the end of the test. During the first hour, temperatures and heat fluxes in the compartment for the tests of CLT #2 and CLT #3 were comparable to those recorded in the test of CLT #1. However, no delamination was observed during the cooling phase (>58 min) in the tests of CLT #2 and CLT #3. Consequently, temperatures and heat fluxes recorded in these tests were much lower than for CLT #1. The improved fire performance of CLT #2 and CLT #3 is attributed to the higher failure temperature for the adhesives used in the fabrication of these panels.

Osborne et al., 2012

One objective of this research is the creation of a design methodology for evaluating the fire-resistance of CLT assemblies. To establish such calculation methods, a total of eight full-scale CLT fire resistance tests, three wall tests and five floor tests, were tested under fire [97].

The fire curve is the Standard ULC S101 fire exposure. Each panel measured 763 mm wide. The floor panels were 4786 mm long and the wall panels were 3048 mm long. Each test was on a unique panel with a different number of plies and varying thickness; some of the assemblies were protected using CGC Sheetrock Fire Code Type X gypsum board while others were left unprotected (i.e. directly exposed to fire). The results show that the performance of CLT walls and floors were improved by gypsum board protection; and that the tested charring rate reasonably agrees with the theoretical values calculated according to EC5. The test results have been used to further validate and refine the CLT fire resistance calculation method currently published in the 2011 Edition of the Canadian CLT Handbook. However, the tests also showed that fire integrity is one of the predominant failure modes of CLT floor assemblies under load; flame-through was observed as shown in Figure 22. Such failure mode was not observed in CLT wall assemblies under load. The walls usually exhibit buckling failure due to increased second-order effects (i.e. P-Δ effects) due to charring of the fire-exposed surface.

Figure 22. CLT panel-to-panel fire integrity failure (flame-through) [97]

O'Neill, 2009

This study investigated the failure behavior of timber-concrete composite floors when exposed to fire [98]. Two full-size floor systems were tested under ISO 834 fire for over 60 minutes. Both specimens were 4 m long and 3 m wide, consisting of 65 mm concrete topping on plywood formwork, connected to double LVL floor joints. One specimen was made with LVL beam of height 300 mm and the other one with LVL beam of height 400 mm. Each specimen used two different connection systems to connect the timber beam to the concrete slab. The two specimens were tested over a 4 m span, subject to a nominal design live load of 2.5 kPa. The test results show that 1) the failure of the floors were governed by timber charring; 2) the thrust force induced in the concrete slab contributed to the fire resistance of the floor system; 3) the thickness of the concrete slab and concrete mix quality used had a large impact on the insulation performance of the floor unit; 4) the unanticipated separation of the double LVL members during the latter stages of burning induced a much faster rate of charring in the timber beams; and 5) the LVL beams with the steel plate connection system exhibited stiffer performance and lower deflections, compared with the notched connection beams.

2.4.4 Tests on connections

Connections or joints in timber structures exposed to fire generally have to fulfill the same requirements on fire resistance as the connected construction members. This Section reviews tests on timber connections, including bolted connections, epoxied rod connections, and CLT joints. The connections are used for column-beam connections, wall-floor connections, wall-wall connections, and panel-panel continuation joints. The performance of those connections or joints under fire is essential for maintaining the load-bearing capacity of a mass timber building and confining fire in its original compartment of ignition.

Bolted connections

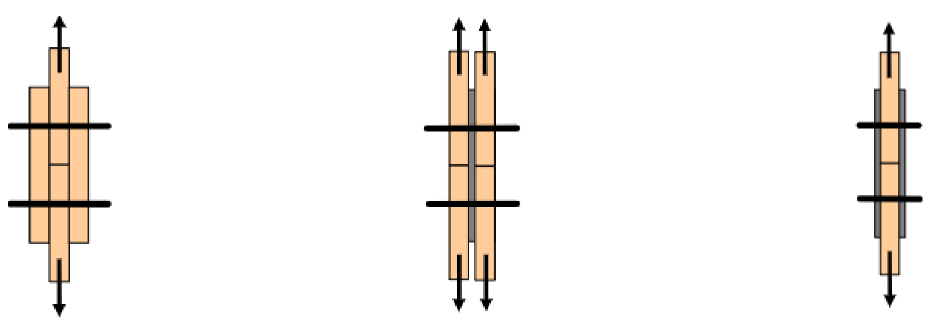
Bolted connections are used frequently in tall mass timber buildings. The fire behavior of bolted connections is complex due to the influence of several parameters such as the geometry of the connection, the fastener types, and the different thermal properties of steel, timber and charcoal.

Moss et al., 2009, Austruy, 2007 and Terence Chuang Biau, 2007

Experimental tests were conducted at the University of Canterbury to develop a prediction method for the time to failure of bolted connections under fire [99–101]. The tested connections were bolted tensile connections in laminated veneer lumber (LVL) made from radiate pine. The investigation was carried out on the axial tensile strength of three types of bolted connections that utilized either wood or steel splice plates, as shown in Figure 23, testing both single bolted joint and multiple bolted joints.

Some specimens were tested at ambient temperatures while similar specimens were tested in fire conditions with a constant applied load (fire tests). In addition, single-bolted connections were tested under constant elevated temperature conditions (constant temperature tests) to determine the embedment strength of the LVL. Connections with no steel plates, or with steel plates slotted between the timber members, performed better than those with exposed steel.

Results from the constant temperature tests indicated an almost constant rate of strength loss with increase in temperature. In most cases, approximately 50% of structural strength at ambient temperature was retained at temperatures up to 200°C. This was consistent for both the exposed and unexposed steel plate bolted connections. A simplified design approach was proposed, using an extension of the Johansen formulae, such that the embedment strength of the LVL depends on the temperature in the bolt.



(a) joint WWW (b) Joint WSW (c) joint SWS

Figure 23. Joint arrangement as tested in [99]

Erchinger et al., 2006

An intensive research program called “Fire safety and timber construction” was carried out in Switzerland to allow the use of combustible materials for the fire resistance class of 60 minutes. As part of this program, fire tests on multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels were performed at the ETH Zurich under ISO-fire exposure [102].

The connections were tested in tension parallel to the grain with different thickness, edge and end distances and diameter of the fasteners (6.3 and 12 mm). Temperatures were measured at different depths of the timber members. The test data were used to validate the finite element thermal simulation in order to analyze the interaction between steel fasteners, steel plates and timber members [103]. The temperatures obtained by the thermal simulation under ISO-fire exposure agree well with the test data. The validated FEM models show that, for timber members without steel elements, the charring depth is the same on each side. In contrast, if steel elements are present, the temperature distribution is changing and, due to the thermal conductivity of steel, the heat flux through the steel plates and the dowels led to higher temperatures of the timber inside.

Peng et al., 2012

A series of fire-resistance tests on bolted Wood-Steel-Wood (WSW) and Steel-Wood-Steel (SWS) connections have been conducted, including 16 WSW specimens and 6 SWS specimens, in accordance with CAN/CSA-S101 [104,105]. All specimens were subjected to a constant tensile load parallel to the grain during the tests. The effects of load level, wood thickness, fastener diameter, number of fasteners, edge distance, and protection on the fire resistance were studied.

The test results show that the fire-resistance ratings of all the tested WSW connections without protection were less than 45 minutes (a target rating for Canadian code compliance) and the fire-resistance ratings of all the tested SWS connections without protection were less than 25 minutes. Specimens with thicker wood side members were found to exhibit better fire resistances. The other potential solutions to increase the fire resistance is to increase the diameter of fasteners and number of fasteners. Protecting a connection by protection membranes, such as gypsum board and plywood, can significantly increase its fire resistance. However, the improvement of using intumescent paint to protect steel plates was limited due to the adhesion problem of intumescent paint at the steel plate edges. Test data were used to validate a three-dimensional numerical heat transfer and an analytical structural model based on Noren's approach [106].

Epoxied rod connections

Epoxy-grouted steel rods are becoming increasingly popular for connections in structural timber in glue-laminated timber (glulam) and laminated veneer lumber (LVL). They are easy to assemble and as the connection is typically hidden it has aesthetic appeal. These connections have been found to have high strength under service temperatures, but epoxy is known to soften at relatively low temperatures. Some research has been conducted to investigate the performance of epoxied rod connections at elevated temperature.

Harris, 2004

The primary objective of this research was to quantify and improve the fire resistance of epoxy-grouted steel rod connections in LVL timber [107]. The axial tensile strength of connections that utilized a threaded steel rod bonded into the timber using two epoxy resins and a composite adhesive were tested, as shown in Figure 24. Some specimens were tested at constant elevated temperatures while similar specimens were tested in simulated fire conditions under constant load.

The three adhesives tested gave different connection strengths at ambient temperatures and showed different strength losses at elevated temperatures. Overall it was found that epoxy-grouted steel rod connections in LVL could be designed with some fire resistance provided that there was sufficient timber surrounding the epoxy. It was found that although epoxy resins behave poorly at elevated temperatures, no suitable substitutes could be found to improve the fire resistance. In addition, tests were also conducted on specimens which had been heated in the oven and then cooled prior to testing. These tests demonstrated that, for an unloaded specimen, the adhesives regained their strength upon cooling. This means that for an epoxy-grouted steel rod connection where there has been a minor fire that it should regain its strength upon cooling, provided that there has been no slip of the adhesive.

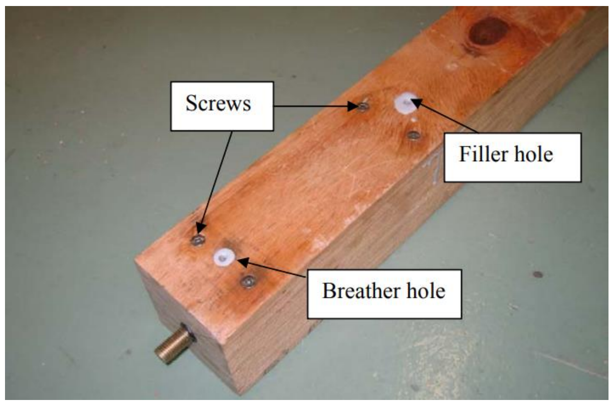


Figure 24. Test specimen cast using West System, showing screws, filler and breather holes [107].

Buchanan and Barber, 1996

The epoxied rod connections have been assumed to have good fire resistance due to timber possessing low thermal conductivity. Two sets of fire tests were conducted on epoxied rod connections, in order to investigates the fire performance of epoxied rod connections in glue laminated timber [108].

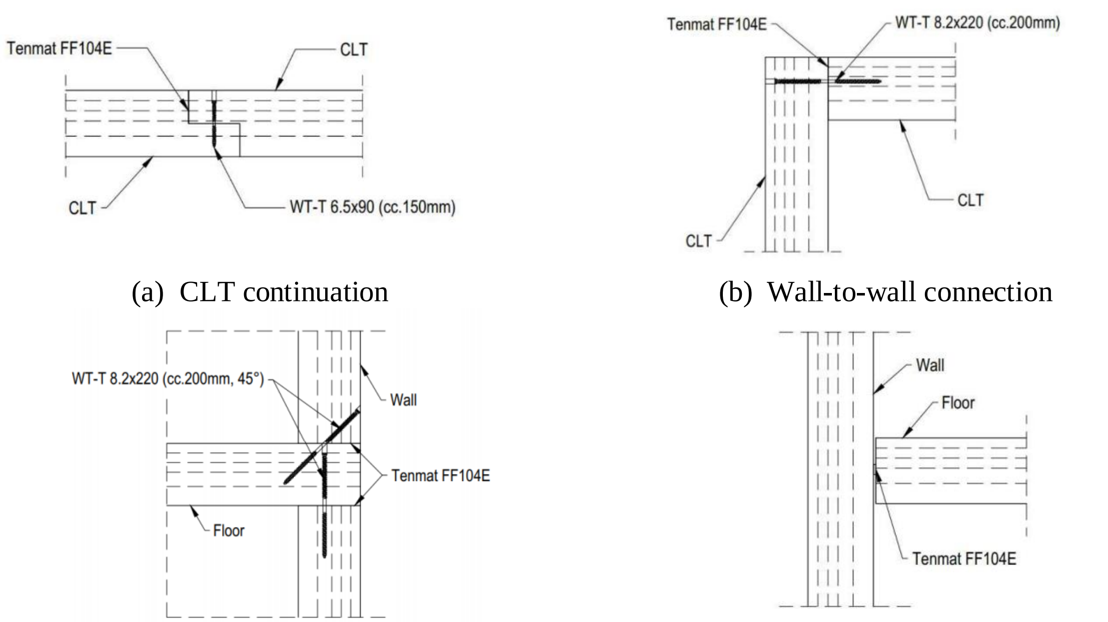
The first set of tests was to investigate the tension strength of the connection at elevated temperatures (40 °C to 90 °C) by using an oven to heat epoxied rod connection. The second set of tests were full-size tension members exposed to standard fire conditions in furnace. The epoxies used in the test reached a critical temperature at approximately 50 °C, with strength decreasing rapidly once this temperature was reached. Elevated temperature failure was by pull out due to shear failure within the epoxy or loss of bond. To investigate how full-size connections would react at elevated temperatures, computer modeling was used to analyze heat transfer through the charring wood and was validated by two series of tests.

CLT joints

The following section discussed tests on CLT joints, including CLT panel-panel joints, CLT floor-to-wall joints, and CTL wall-to-wall joints. The failure of those joints can degrade the load-bearing function of a building as well as impair the integrity of the fire compartment, leading to the spread of fire beyond the compartment of ignition.

Karuse, 2017

In Section 2.4.1, the fire tests of a two-story building constructed of CLT were described. Four main types of CLT joints were used in that building [87] and the joint designs performed well. Four main types of CLT joints were tested: a CLT + CLT continuation designed as an overlapping joint (Figure 25a); a wall-to-wall connection (Figure 25b); and two different wall-to-floor connections (Figure 25c and 25d). The joints were designed and built as airtight as possible and an intumescent tape was used inside the joints. The intumescent tape was to expand and seal the joint when having reached 200 °C. During the fire test, it was observed that the compartment was properly isolated from the surroundings with no smoke, heat or fire penetrating through the connections. Temperature inside and behind the joints remained very low.



(a) CLT continuation

(b) Wall-to-wall connection

(c) Wall-to-floor connection – Type 1

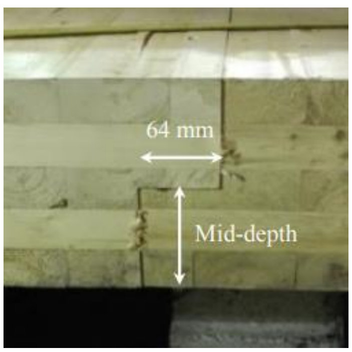
(d) Wall-to-floor connection – Type 2

Figure 25. Four main types of CLT joints used in the building [87]

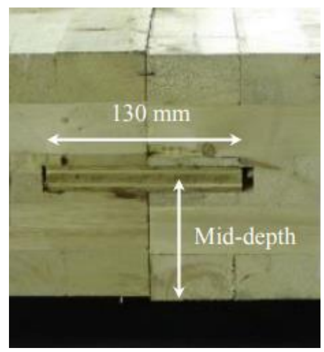
Dagenais, 2016

Ten intermediate-scale fire-resistance tests of CLT floor assemblies were conducted with four types of panel-to-panel joints and three CLT thicknesses [109]. The objective was to increase the knowledge of CLT exposed to fire and to facilitate its use in Canada and in the US by complementing current fire-resistance design methodologies of CLT assemblies with respect to the fire integrity criterion.

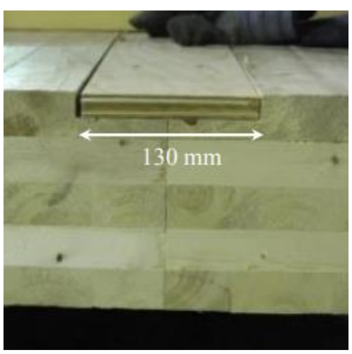
The details of the four types of CLT panel-to-panel joints before testing are shown in Figure 26. From the tests, surface splines were found to be the best CLT panel-to-panel joint detail, provided the panels are tightly fitted together and the spline is installed on the surface opposite to the source of fire. An internal spline was found to be the least efficient joint detail when compared to the other configurations due to potential gaps at the butt joint between the splines. It could be improved if tongue- and-groove or scarf joint is used between splines. Half-lapped joints provided better fire integrity performance when compared to the internal spline joints. In all fire tests, a 20% increase in the charring rate was observed, due to adhesive heat delamination, for the second and subsequent laminations exposed to the standard fire and should be considered in calculation models. Test data also showed that small diameter fasteners such as the used self-tapping screws were a negligible source of heat conduction within CLT panels and may be neglected in calculation models. The data generated from the intermediate-scale fire tests were used to validate a FE heat transfer model, a coupled thermal-structural model and a simplified design model. This study provided designers a way to verify both the load-bearing and separating functions of CLT assemblies in accordance with fire code provisions.



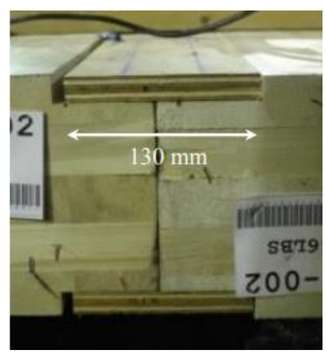
(a) Half-lapped joint



(b) Internal spline



(c) Single surface spline



(d) Double surface spline

Figure 26. CLT panel-to-panel joints before testing [109]

2.5 Discussion

2.5.1 Observations from case studies

Wood frame construction

A review of case studies of fires in wood frame buildings shows that the ignition can be due to accidental causes such as short circuits, overloaded relocatable power strip, lit cigarette, lightning [12,18,23,29–32], etc. The location of origin of the fire can vary, including inside the building, on balconies, or outside in the vicinity of the structure.

A disadvantage of light-frame timber buildings is that fire can spread rapidly. These buildings typically include enclosed spaces where fire can spread undetected. As a result, wood frame constructions need to include fire blocks in several locations within the structure (Figure 27) [110]. These fire blocks are required to prevent or slow the spread of fire (Figure 28) [111]. Absence or failure of such fire blocks has been observed to be a cause of fast spread of fire in a building. Combustible claddings and balcony may also accelerate the spread of fire through the building. Indeed, frequently observed paths of spreading are either along the claddings of a building, and/or through the cavities that exist in timber frames, under the ceilings, or in the roof system [12,23]. Given these vulnerabilities, case studies have shown that a fire in a wood-frame building may spread to the entire structure. In case of loss of compartmentation, the fire may grow out of control. In this case, the fire would result in the complete loss of the building, and the efforts of the firefighters focus on containing the fire in the building of origin and prevent spreading to neighboring structures.

Compared to other types of constructions, fires in wood-frame buildings pose specific challenges to fire brigades. When a fire spreads through the cavity of timber frames, it is difficult for firefighters to locate hot spots and extinguish the fire completely. It also happens that a fire that seems to have been extinguished continues burning as a smoldering fire in inaccessible or hidden locations within a wood frame structure, and later re-grow to a fully developed fire. Given the combustible nature of the structure and the brittle failure behavior of timber members, firefighters are wary of a sudden building collapse. Therefore, they typically fight the fire from outside the building once people have been able to evacuate and the fire has grown out of control. As a result, a frequent outcome in the reviewed accidents is that there is no (or few) casualties, but the structure is badly damaged or completely destroyed, resulting in significant economic loss.

In 1999, a full-scale fire test was conducted on a six-story light-frame timber building [112,113]. The test aimed to check the sufficiency of fire-safety provisions for wood frame buildings. However, the building re-ignited after the researchers thought the building had met the fire requirements, highlighting a common risk with timber buildings fires.

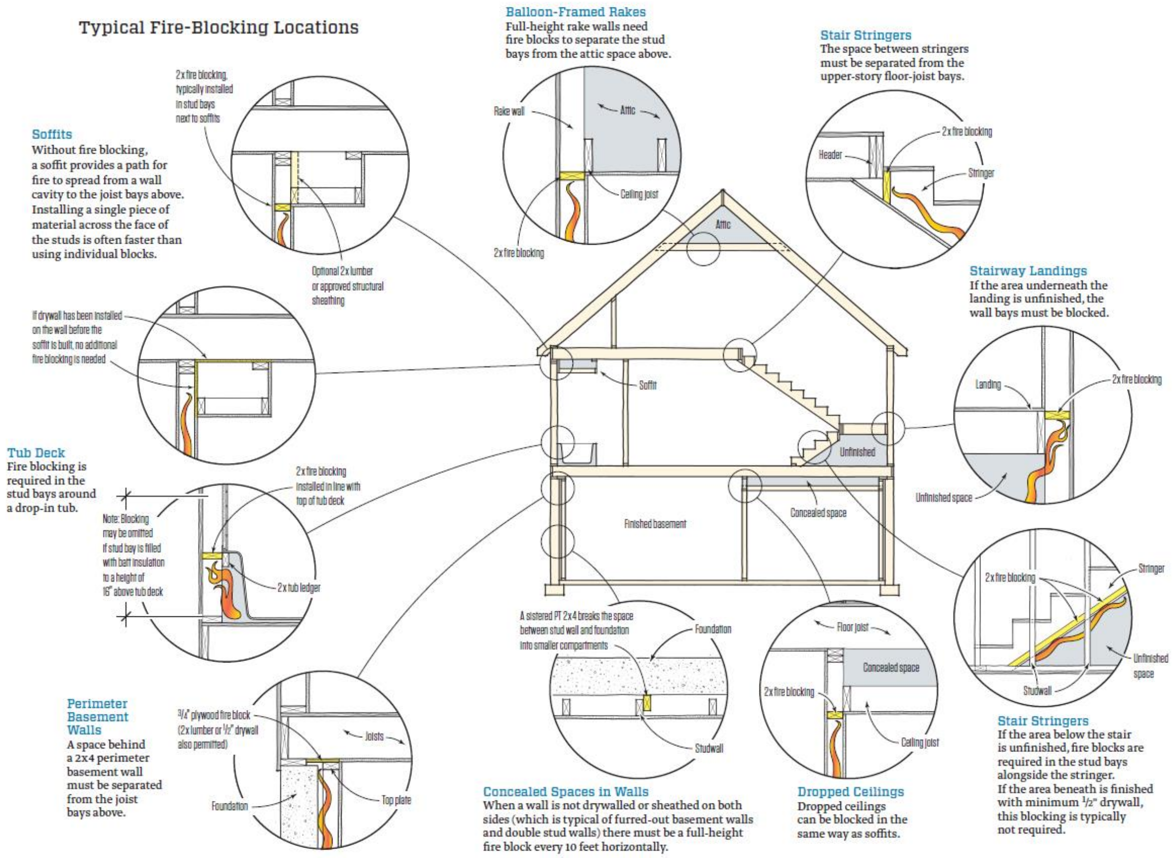


Figure 27. Typical fire-blocking locations in wood frame construction (from [110])

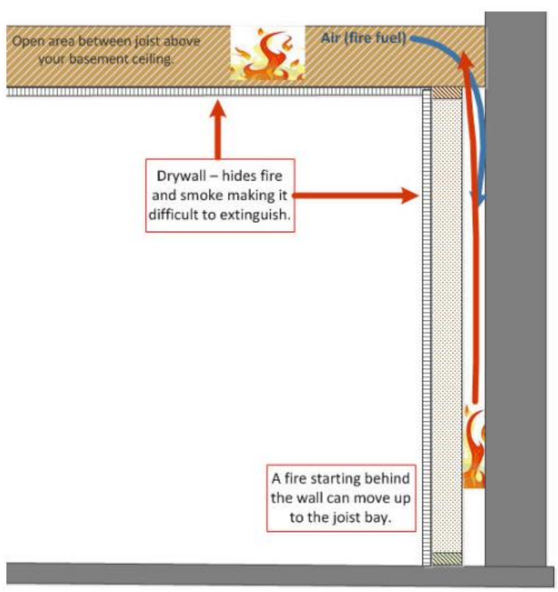


Figure 28. Fire spread path in cavities in the absence of fire blocks (from [111])

Several fire incidents have shown that the presence of automatic sprinklers is rather effective at controlling the growth of a fire and preventing its spread beyond the room of origin. The New York State Fire Prevention and Building Code Council requires that all fire areas in residential buildings be equipped with automatic sprinklers, except detached one- and two-family dwellings or multiple single-family dwellings (known as townhouses) [114]. It is important to note that the exception only applied if these buildings are not more than three stories high and means of egress are built separately for each dwelling. The UK government launched a consultation suggesting that building regulations be changed to make sprinklers compulsory in all new residential buildings of 18 m or taller, hence lowering the current threshold of 30 m height [115].

Heavy timber construction

Owing to the large size of the members, heavy timber construction typically benefits from increased fire resistance compared to wood frame construction. Traditional heavy timber construction is relatively hard to ignite, burns relatively slowly, and exhibits structural stability for a longer duration under fire. When reviewing fire accidents, it is observed that in several instances of heavy timber construction fires, the timber floors and/or roof had collapsed while the load-bearing heavy timber beams and columns remained standing after the fire. In addition, heavy timber constructions usually have less concealed spaces than wood frame construction [116], which reduces some of the risk of undetected ignition and spread.

In historic heavy timber structures, fire accidents can be amplified by factors such as modification of the occupancy (e.g. increase in fuel load) and/or layout (e.g. removal of fire barriers), abandonment and deterioration, years of flammable fluids soaking into timber floors, and the absence of sprinkler and alarm systems. A review of case studies reveal that such factors can and have led to severe fires resulting in both fatalities and the complete destruction of the structure. This is especially the case for old abandoned heavy timber structures that do not conform to the current fire code requirements. Besides the common ignition causes listed previously, accidents in abandoned buildings have also resulted from ignitions caused by squatters. In one instance in the reviewed accidents, the blaze in a five-story heavy timber warehouse led to the ignition of structures in the vicinity.

Historic heavy timber structures commonly present characteristics that pose specific challenges for firefighting [117]. These may include narrow stairs and stairways, limited openings due to small area of windows and doors (as shown in Figure 2), pitched roof covered with slates that can become missiles in the fire situation hence threatening firefighters, insufficient compartmentation, large quantity of utility lines that can hamper rescue attempts when these lines start to fall to the floor, presence of hazardous residue, or large wall thickness precluding any breaching operation.

Recently, mass timber buildings, which are different from the traditional heavy timber buildings, are being increasingly adopted. The behavior of mass timber buildings under fire may not resemble that of the traditional heavy timber buildings. For instance, CLT, made from gluing together layers of solid-sawn lumber, has been used frequently for both floor and wall systems in mass timber buildings. A fire compartment constructed with CLT panels may experience a second flashover when unburned wood is exposed to hot gases if the gypsum wallboard falls, if there is char fall-off from the CLT, or if there is delamination of a layers from the CLT due to the failure of adhesive, which has been observed in fire tests on CLT compartments [86].

In the U.S., the 2021 version of the IBC will allow for mass timber structure up to 18 stories [118]. The existing timber construction classification (Type IV) will remain unchanged, but the 2021 IBC will introduce three new timber construction types (Type IV-A, Type IV-B and Type IV-C), each with an increased level of fire resistance and decreased amount of exposed wood. Within the three new timber construction types, Type IV-A construction provides the greatest level of fire resistance and does not allow any exposed timber.

Specific risks associated with construction and renovation

Construction and renovation phases are associated with specific fire risks in timber buildings. As a result, fire accidents are relatively frequent during these phases and their severity can be significant, as evidenced by the review of case studies.

Ignitions can be caused by hot work (e.g. welding, cutting), cooking equipment [119], or cigarette butts left on the construction site. Some of the reviewed accidents were also started by arson.

Fire protection measures are not yet installed during the initial stages of the construction, or may be deactivated during renovation works. The absence of sprinkler systems or smoke detection systems in multi-story timber buildings under construction means that a fire starting in such structure has a higher risk of growing out of control and spreading to the entire structure. In addition, compartments may not have been closed yet, which facilitates the spread. Internal rescue means may also not be operational in the construction phase, which complicates the intervention of the fire fighters by preventing them to fight the fire from the inside of the building. These factors not only increase the risk of losing the building entirely to the fire but also that of having the fire spread to nearby buildings. Windy conditions increase the likelihood of fire spreading to adjacent structures and growing out of control.

These specific risks are well-known and mitigation measures have been proposed. For example, the NFPA 241 [120] outlines measures to reduce the fire hazards for buildings under construction, renovation or demolition. Measures should address the risk of fire ignition, the fact that compartments should be closed as soon as possible to limit the spread of fire, and the fact that the amount of exposed timber surfaces during construction is often higher than that after construction, amongst other issues. Yet despite this type of guidance, construction sites remain at risk for timber buildings fire, and large construction fires of timber structures occur regularly (see Section 2.2).

2.5.2 Fire safety considerations for tall mass timber buildings

Based on the review of case studies, the following considerations are drawn regarding fire safety of tall mass timber buildings. This discussion pertains to a hypothetical tall (> 20 m) mass timber building in a dense urban area, built from modern engineered wood products, as is under consideration in many countries at this time.

Challenges associated with the construction phase

The construction phase poses important challenges for the fire safety of timber buildings, which also apply to modern mass timber construction. Mostly, the issue comes from the fact that while the structure being erected is combustible it is not yet protected against fire in the construction phase. Indeed, the protection of the timber structure typically requires a combination of active fire protection measures (e.g. alarm, sprinklers) and passive fire protection measures (e.g. gypsum boards, compartmentation), which are not (or only partially) effective during the construction phase. Without these measures, the bare timber structure represents an enormous amount of fuel load which, if ignited, lacks any mechanism to prevent the fire to grow and spread.

Past construction fires in wood frame construction have shown that even with tremendous firefighting resources, these fires could not always be controlled. In the 2020 Washington DC fire, despite the efforts of 150 firefighters during 8 hours, the fire spread to nearby buildings and destroyed multiple structures and vehicles. In the 2009 Peckham fire involving a four-story timber-frame block of 39 flats, more than 180 fire fighters and 30 fire engines were deployed to fight the fire for eight hours, along with 20 ambulance crews on standby. Despite these efforts, the fire spread rapidly, lasted for eight hours and damaged nearby buildings, resulting in about 310 people being forced to leave their homes.

Similar situations of construction/renovation fires growing out of control have been observed with mass timber buildings, as discussed in Section 2.2 and in Section 2.3.1 for historic buildings (e.g. Notre Dame Fire). These case studies indicate that, despite the differences between light-frame structures and mass timber structures, the latter are also at risk of experiencing large, uncontrollable fires when fire protection measures are not put in place. Further, this observation is confirmed by the analysis of experimental tests on modern mass timber construction in Section 2.4. Both for mass timber buildings (e.g. Karuse test) and mass timber compartment (e.g. Su test), it has been shown experimentally that interior exposed wood surfaces (such as CLT panels) with no active extinguishment system can fuel the fire and thus prevent its extinction.

As a result, the fire risk during the construction phase will be a major challenge to be addressed when considering tall mass timber building projects. The construction phase will generate a situation where a very large amount of combustible material is erected and left exposed, surrounded by work activities that are factors of ignition sources, while evidence suggests that should a fire occur in these structures it would be unlikely to self-extinguish nor to be controllable by fire brigades. The prospect is particularly daunting in a high-density urban setting.

Challenges associated with the integrity of the compartmentation

The integrity of the compartmentation is critical to ensuring the fire safety of tall buildings. With mass timber construction, a number of challenges have been identified.

Failure of compartmentation can result from an integrity failure of the structure. For example, reviewed tests have shown fire integrity failure of CLT panels. Section 2.4.3 (Osborne et al., 2012) has shown flame-through of CLT floor assemblies under load, while Section 2.4.2 (Hevia 2014, Figure 21) showed that in one of the tested compartment the room had an early flame-through of the CLT panel-to-panel joints through a half-lapped joint.

Failure of compartmentation can also result from a loss of stability of the structure. Combustible load-bearing member can fail during a fire, which accelerates the spread. This has been observed in heritage timber structure fires (e.g. Notre Dame Fire). Meanwhile, tests on modern mass timber structures and assemblies (Section 2.4) have highlighted specific issues with delamination of CLT panels and with joints. When debonding occurs in a CLT panel, the fire is revived due to the sudden availability of uncharred wood, which can result in an increase of heat release rate akin to a second flashover (Figure 19). It is important to note that designing a timber member for a given (code-mandated) fire resistance does not ensure that the member would not fail in a real fire situation.

Fire spread can also occur from outside of the building through windows, if the façade contains combustible material. This was observed experimentally in Section 2.4.1 (Karuse, 2017), as well as in some accidents in Section 2.1.1. Research has shown that timber lined compartments can experience increased external flaming due to additional fuel loading [121].

Challenges associated with the extinction (either self-extinction or by fire brigades)

Once a fire grows and spreads in a timber building, it may become very hard to extinguish given the large amount of combustible material and the large heat release rate of the fire.

With combustible material, the resistance until burnout is of concern. Even if the timber components have been individually designed to satisfy a standard (code-mandated) fire resistance, this does not guarantee that they will eventually survive a real fire until this fire dies out [122]. In contemplating burnout resistance [123,124], there is a fundamental difference between non-combustible and combustible construction material. For the former, once the content fire load has been consumed, the fire dies out due to lack of fuel. Yet for the latter, the fire might be continuously fed by the structure itself, eventually burning the structure to the ground. Tests have shown (Section 2.4) that delamination of CLT panels is a major issue in this regard. But even with solid timber frames, the continued burning of the structure might be a major issue, see e.g. Notre Dame Fire. Self-extinction of a timber structure seems to be a complex function of the materials, structure, and conditions (e.g. ventilation, content fuel load, orientation) [125] [126] which, at this time, cannot be claimed to be controlled with sufficient reliability by the designers.

While self-extinction is far from guaranteed in a real building fire, the ability of fire brigades to extinguish a fire that has spread in a tall mass timber building is also questionable. The reviewed case studies have shown that mid-height timber building fires required huge fire brigade resources to be fought, and often the building itself could not be saved. In the case studies, it was common to have between 100 and 200 fire fighters on the site, while this number raised to 400 for the Notre Dame fire, as shown in Figure 29. The number of fire fighters involved in the reviewed timber building fires is larger than that for fire accidents in buildings of similar sizes made of noncombustible materials [127,128]. Despite such resources, the blaze from a fully engulfed multi-story timber structure generally exceeded the capabilities of fire-fighting operations and the building was a complete loss. For a tall mass timber building, it is thus unclear at this time how the challenge of mitigating the worst-case scenario of a fire engulfing the whole building would be addressed.

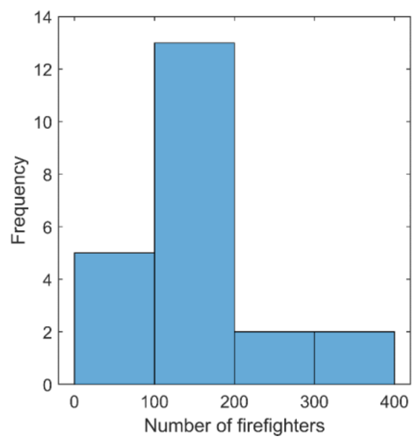


Figure 29. Histogram of the number of fire fighters involved in the reviewed fire accidents of wood frame and historic heavy timber buildings.

Challenges associated with the risk of conflagration

For a fire that engulfs a large timber structure, the heat flux radiated toward the nearby structures can be increased by the contribution of the burning structure. Debris can also fly out and ignite structures and vehicles in the vicinity. One reviewed case study has shown that propagation to nearby structures can occur with heavy timber construction (i.e. the five-story warehouse in Chicago, Section 2.1.2), while another has shown that it can occur with wood frame buildings (i.e. the five-story building under construction in Washington DC, Section 2.2.1). In these two cases, fires started in nearby structures despite the actions of more than 150 firefighters. While no such accident has occurred to date with modern mass timber buildings, this risk should be assessed.

The reviewed tests have shown that external flaming can develop (Section 2.4.1) and that the heat release rate for a CLT structure can be large and exhibit a second peak once the structure itself gets ignited (Section 2.4.2). These effects could contribute to increasing the risk of spread to other structures. Another possible factor that might influence the risk of conflagration with tall timber building fire lies in the possibility of structural collapse. While any building has a (small) probability to collapse due to fire, the consequences of a fire-induced structural collapse of a tall timber building could be aggravated by the fact that the collapse would spread around a large amount of burning combustible material.

3 Contribution of Timber to Fire Severity and Spread

3.1 Evaluation of the quantity of timber in mass timber buildings

Table 1 lists existing mass timber buildings in different countries. The volume of timber used in these buildings is given and compared with the gross floor area. The volume of timber was obtained by reviewing documentation about the projects, such as press releases and technical publications. The gross floor area is defined as the sum of the building footprint of each story. Table 1 provides the ratio of the timber volume over the gross floor area ($V_{f,tmb}$), where the gross floor area is that of the stories built in timber (i.e. for buildings with a concrete podium, the surface area of the concrete story is not counted). The ratio $V_{f,tmb}$ ranges between 0.14 m^3/m^2 and 0.64 m^3/m^2. Forté, a tall mass timber building in Melbourne made of a nine-story CLT structure over a one-story concrete podium (Figure 30) has the highest ratio at 0.64 m^3/m^2. The distribution of $V_{f,tmb}$ has a mean of 0.31 m^3/m^2 and coefficient of variation of 0.45 (Figure 31).

Figure 30. Forté, a ten-story CLT building completed in 2012 [129].

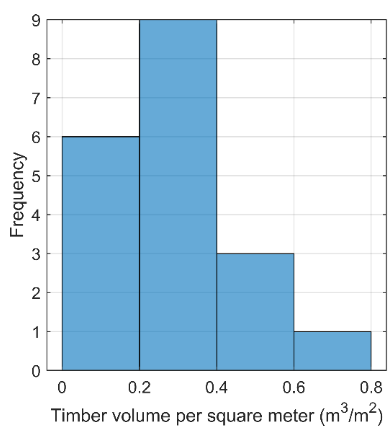


Figure 31. Distribution of the timber volume per square meter ($V_{f,tmb}$) in existing mass timber buildings.

Table 1. List of existing mid-rise and high-rise mass timber buildings with their timber quantity.

Building	Year	Location	# stories	Gross floor area (m^2)	Volume of timber (m^3)	Timber volume/area (m^3/m^2)	Ref
Brook common	2017	Canada	18 [(1)]	15,200	2,233	0.16	[130]
T3	2016	USA	7 [(1)]	20,439	3,600	0.21	[131][132]
Stadthaus	2009	UK	9[(1)]	2,890	901	0.35	[133][134]
Carbon12	2018	USA	8	3,902	544	0.14	[135] [136]
Mjøstårnet	2019	Norway	18	11,300	2,035	0.18	[137][138][139]
Origine	2017	Canada	13 [(1)]	13,124	3,111	0.26	[140][141][142]
Banyan Wharf (The Cube)	2015	UK	10	6,750	1,313	0.19	[143][144][145]
Treet	2015	Norway	15[(1)]	7,140	935	0.14	[146]
Strandparken	2014	Sweden	8	15,924	4,777	0.30	[147] [148]
Trafalgar Place	2015	UK	10	1,800	820	0.46	[149][150]
Via Cenni	2013	Italy	9	17,000	6,100	0.36	[149][151]
Lintuviita	2013	Finland	6[(1)]	3,100	1,300	0.50	[149]
Bridport House	2012	UK	8	4,154	1,576	0.38	[152][153]
Forté	2013	Australia	10[(1)]	1,728	1,000	0.64	[154]
Wood Innovation & Design Centre	2014	Canada	8	4,820	1,700	0.35	[155][156]
25 King	2018	Australia	10[(1)]	14,965	6,239	0.46	[157][158][159]
Dalston Lane	2016	UK	10[(1)]	15,960	4,500	0.31	[160][161][162]
Holz8	2011	Germany	8	1,740	570	0.33	[163]
HoHo	2019	Austria	24	25,000	4,620	0.18	[164][165]

[(1)] First story is a concrete podium.

3.2 Evaluation of fixed fuel load from timber in mass timber buildings

The fuel load corresponding to the volume of timber used in existing mid- and high-rise timber buildings, listed in Table 1, is evaluated by considering the density and heat of combustion (i.e. calorific value) of the timber products. For CLT, the most commonly used species is spruce with a density from 480 kg/m^3 to 500 kg/m^3 [166]. Combining a timber density of 490 kg/m³ with the mean timber volume per square meter of 0.31 m^3/m^2 yields a mean timber weight per square meter of **152 kg/m²**.

The fuel load can be estimated using Eq. 1 from Eurocode [167], with M_i the amount of combustible material in kg; $H_{c,net,i}$ the net calorific value; and Ψ_i the optional factor for assessing protected fire loads. The fuel load density is given by $q_{fi} = Q_{fi}/A_f$, where A_f is the floor area of the fire compartment.

$$Q_{fi} = \sum M_i \cdot H_{c,net,i} \cdot \Psi_i = \sum Q_{fi,i} \qquad \text{Eq. 1}$$

The net calorific value of wood is taken as 17.5 MJ/kg [168]. The mean value of the fixed fuel load (i.e. resulting from the timber as a construction material) in the reviewed mass timber buildings is then evaluated as:

$$\mathrm{q_{tmb}} = 152\ kg/m^2 \times 17.5\ MJ/kg \times 1 = \mathbf{2660\ MJ/m^2} \qquad \text{Eq. 2}$$

This estimation is the highest bound, obtained with $\Psi_i = 1$ and no application of combustion factor. It should not be taken as an exact estimate of the energy that would fuel a real fire in a completely engulfed mass timber building, but rather as an order of magnitude of the maximum available energy embedded in the structure.

Table 2. Comparison of content fuel load and timber structure fuel load.

Occupancy type	**Average content fuel load (MJ/m²)**	**Ratio of fixed fuel load (timber construction) to content fuel load**
Dwelling	780	3.4
Hospital	230	11.6
Hotel	310	8.6
Library	1500	1.8
Office	420	6.4
Classroom of a school	285	9.4
Shopping center	600	4.4
Theatre	300	8.9
Transport (public space)	100	26.7

The fixed fuel load from the timber structure can be compared to typical content fuel load to provide context. Table 2 lists average content fuel loads for different occupancies according to Eurocode [167]. The last column of the table gives the ratio between the mean fixed fuel load in the reviewed mass timber buildings (2660 MJ/m²) to the average content fuel load. In providing these ratios, a few simplifying assumptions are made. The ratios consider the entire quantity of timber as fixed fuel load, i.e. no distinction is made between exposed timber that may burn and contribute to the fire, and unexposed or encapsulated timber (i.e. $\Psi_i = 1$). The reference area for the fixed fuel load is the gross floor area whether that of the content fuel load is the usable area (A_f). Finally, most buildings listed in Table 1 are dwellings or offices. The quantity of timber used in the structure for these buildings may differ from that used for, say, a theatre or airport building. Notwithstanding these assumptions, the ratios provide useful order of magnitudes to give a sense of the amount of fuel (energy) embedded in the construction of mass timber buildings.

3.3 Basics of burning behavior of wood

The burning behavior of wood involves four important phenomena, ***pyrolysis, ignition, flaming combustion, and flame extinction*** [168]. Pyrolysis is the process by which materials decompose upon heating, and produce inert and combustible gases, liquid tars, a solid carbonaceous char, and inorganic ash [169]. The volatile products of pyrolysis may then undergo a rapid, exothermic combustion reaction with oxygen. Ignition, as the onset of combustion, can either be piloted, in which a pilot source (e.g., a spark or flame) energizes the gaseous species, or unpiloted, where the volatiles must achieve the necessary energy for ignition in the absence of a pilot source. Ignition can lead to either flaming combustion (oxidation in the gas phase of volatiles) or smoldering combustion (solid-phase char oxidation). The combustion reaction generates heat that may cause the charring layer to propagate further into the timber and perpetuate the production of volatiles. Under certain conditions, a self-sustaining reaction is created. However, a fire will extinguish if its heat losses exceed its heat release.

There are several critical parameters and concepts related to the four phenomena of wood burning, including but not limited to 1) charring rate, 2) criteria for ignition, 3) criteria for automatic extinction, and 4) heat of combustion of wood. Those parameters are discussed hereafter.

Charring rate: Charring is just one part of the pyrolysis process; however, pyrolysis is typically simplified into "charring" for structural application. The charring rate is influenced by material properties (e.g., density of wood, moisture content, permeability, species), system properties (e.g., sample orientation, sample size, grain direction, encapsulation, delamination), thermal exposure (i.e., incident heat flux), and oxygen concentration. The char layer has a lower thermal conductivity than wood and thus delays the onset of pyrolysis of the underlying virgin wood. Therefore, the charring rate in a fire-exposed timber member is initially high when no protective layer exists, and then decreases to a lower quasi-constant value once a char layer has formed. Equations have been proposed to predict the charring rate and charring depth of wood [167][170][171][172].

Criteria for ignition**:** For ignition to occur, a flammable mixture must exist somewhere in the gas phase, which must then be elevated to a temperature at which a combustion reaction can occur. Criteria for ignition are typically defined by either the ''critical heat flux'', the lowest heat flux for which ignition will occur, or the ''critical surface temperature'', the lowest surface temperature for which ignition will occur. Critical heat fluxes for piloted and unpiloted ignition are around 10 to 13 kW/m^2 and 25 to 33 kW/m^2 respectively [168]. Critical surface temperatures range from 204°C to 395°C but these values are also heavily dependent on the external heat flux [168]. Ignition in actual setting will notably depend on sample setup and orientation, density, moisture content, thickness, ambient temperature, and heat transfer mode.

Criteria for automatic extinction: For a compartment constructed of engineering timber products, any exposed timber will add to the fuel load and burn as described above; therefore, it is vital to understand the conditions under which it will continue to burn, and the conditions in which it will extinguish. Extinction is governed by the oxidation kinetics and is difficult to accurately predict. Generally, a flame will extinguish if its heat losses exceed its heat release. For this to occur, the mass flux of flammable gases must drop below a critical value. However, the extinction conditions are less well defined and understood. The existing research gives a range of the critical mass loss rate for extinction, from 2.5 g/m^2 s to 5 g/m^2s [168] [173] [174][175].

Heat of combustion of wood: The gross heat of combustion is the amount of heat produced by the complete combustion of a unit quantity of fuel, which can be measured in a bomb calorimeter. The gross heat of combustion is around 20 MJ/kg for oven-dry wood [176] for complete combustion of the wood and char. Different from gross heat of combustion, the net heat of combustion is obtained by subtracting the latent heat of vaporization of the water vapor formed by the combustion from the gross heat of combustion. The net heat of combustion of oven-dry wood of different species varies within a very narrow interval, from 18.5 to 19 MJ/kg [177], about half to two-thirds of which is released through flaming, the rest through smoldering. The net heat of combustion of moist wood will be lower than the net heat of combustion of oven-dry wood. In a real fire, a part of the wood is not pyrolyzed leaving some soot and not all the volatile produced by pyrolysis is converted in heat. Therefore, the actual heat of combustion observed in real fires is the effective heat of combustion, which is lower than the net heat of combustion.

In addition to those discussed above, with engineered mass timber products, other important considerations may influence the fire dynamics. For example, CLT members can undergo ***delamination***. Delamination is a phenomenon through which the outer lamella (or part thereof) detaches from the second lamella, thus exposing unburned timber directly to the fire. Since delamination exposes unburned timber directly to fire, it causes an increase in the charring rate until a protective char layer is built up again. Whilst the effects of delamination are understood, its causes remain difficult to predict and the failure modes and conditions of different adhesives used in the manufacture of engineered timber products are still under investigation.

In a tall mass timber building, the first consideration is whether timber will be exposed to heat from the fire. This is the case when exposed timber is used, or if the thermal protection on the timber members is insufficient, or if this thermal protection fails (e.g. due to the occurrence of a primary hazard event such as an earthquake). When timber is exposed to the fire, the pyrolysis process starts as described above, and as a result the fire will be prolonged due to additional fuel brought by this structure timber. The fire safety design then needs to adopt either of the two strategies, for dealing with cases where a structurally significant fire develops (i.e. cases where sprinklers and other active prevention measures have failed to suppress the fire):

(i) Accept structural failure: the design is made to ensure a certain amount of time integrity in a fire to allow for evacuation; the fire safety strategy should not include any kind of stay in place policy, or internal firefighting.

(ii) Design for burnout: the design is made to survive the fire until full burnout; however this requires demonstrating that self-extinction occurs prior to loss of structural stability or loss of compartmentation, and demonstrating that the structure maintains stability during the decay phase of the fire. These two verifications are currently hindered by the lack of experimental data and design methods for the behavior of timber structures under natural fires.

3.4 Evaluation of timber contribution to heat release rate

3.4.1 Data from mass timber compartment fire tests

Experimental studies have been conducted in the past decade on the fire dynamics in CLT compartments, as discussed in Section 2.4. The tests by Hevia (2014) [93], McGregor (2013) [94], and Su et al. (2018) [5] are further reviewed here to study the contribution of timber to the heat release during a fire.

Figure 32 shows the Heat Release Rate (HRR) measured in the five tests by Hevia and McGregor [93][94]. The tests were performed on an identical room, with varying degrees of protection for the timber members. The room was 3.5 m wide by 4.5 m long by 2.5 m high with a single opening of 1.07 m by 2 m. The content fuel load from the furniture was 533 MJ/m^2. The degree of exposed (i.e. unprotected) surface of the timber members varied from 0% exposed (McGregor #2 and 4) to 100% exposed (McGregor #5) with intermediate values of 21% (Hevia #3), 37% (Hevia #1) and 42% (Hevia #2). The HRR was measured by the oxygen consumption calorimetry method, including the heat released both inside and outside the compartment. Figure 32 shows that as the exposed surface of CLT increased, the HRR increased. The test with 42% of the surface exposed yielded significantly more heat than the tests with higher degree of protection. The test with 100% exposed timber surface yielded the highest HRR peak and overall heat released. Delamination occurred in all tests with 37% or more exposed surface, due to failure of the polyurethane-based adhesive when charring progressed to the interface layers, leading to re-ignition of the fire compartments (occurrence of second HRR peak in Hevia #1 and #2 and in McGregor #5). In contrast, tests Hevia #3 and McGregor #2 and #4 achieved self-extinction.

Figure 33 shows the HRR measured in the six tests by Su et al. [5]. Six compartments of 9.1 m long by 4.6 m wide by 2.7 m high were tested. The inside of the compartments was fully or partially lined using multiple layers of 15.9 mm thick Type X gypsum board. Real residential contents and furnishings were used to provide a fuel load density of 550 MJ/m^2. Two baseline tests (Tests 1-1 and 1-2), with all CLT surfaces protected in the compartments (i.e. 0% exposed) but of different ventilation configurations, defined the contribution of the moveable fuel load to the compartment fires and provided baseline data for quantifying the CLT contribution to the compartment fires in the other tests. Test 1-1 had an opening of 1.8 m wide by 2.0 m high while Test 1-2 has an opening of 3.6 m wide by 2.0 m high. The ventilation configuration of Test 1-3 is the same as that of Test 1-2 while the ventilation configuration of Tests 1-4, 1-5 and 1-6 is the same as that of Test 1-1.

However, Test 1-3 has an exposed wall (W1, 9.1 m x 2.7 m); Test 1-4 has an exposed ceiling (9.1 m x 4.6 m) ; Test 1-5 has an exposed wall (W1, 9.1 m x 2.7 m); Test 1-6 has a combination of exposed ceiling (9.1 m x 4.6 m) and wall (W1, 9.1 m x 2.7 m). In the tests, the exposed CLT surfaces exhibited heat delamination, which led to one or more periods of fire regrowth after decay in three of the tests, and no decay of the fire prior to suppression in the fourth test. The ventilation conditions had significant impacts on the fire development in the compartments, as well as on the CLT contribution to the fire.

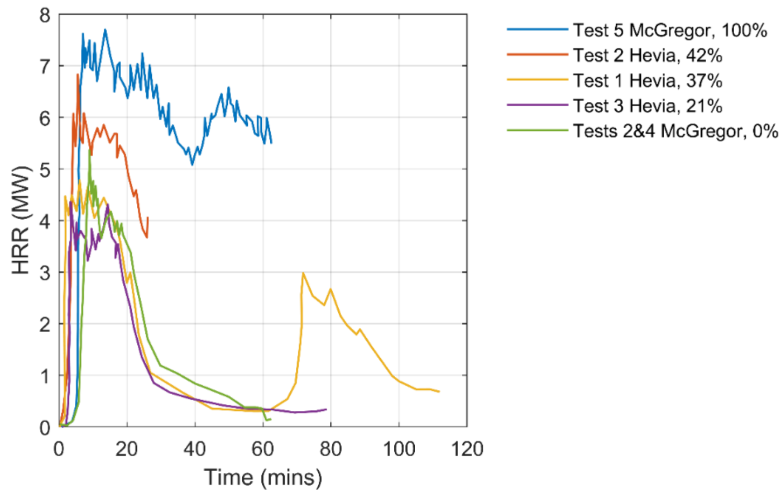


Figure 32. HRR in the fire compartment tests by McGregor [93] and Hevia *et al* [94]. The percentage indicates the relative surface of timber exposed.

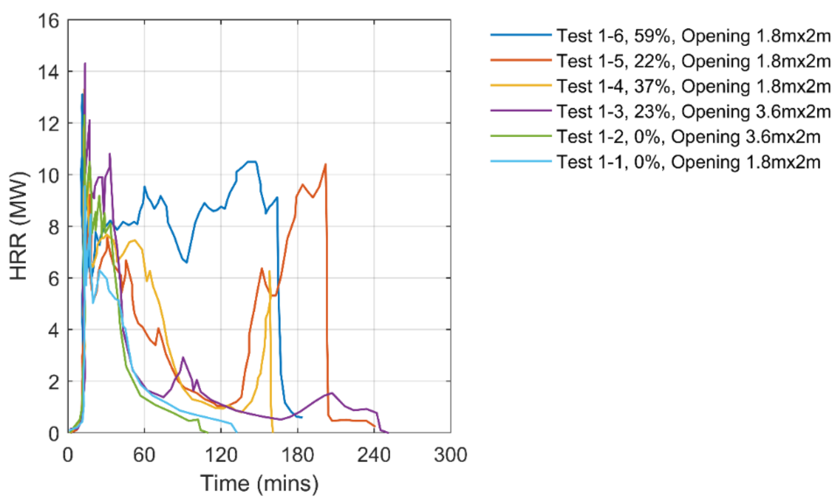


Figure 33. HRR in the fire compartment tested by Su et al. (2018) [5]. The percentage indicates the relative surface of timber exposed.

The total heat release in the tests of Figure 32 and 33 have been calculated over a reference duration and plotted in Figure 34. For Figure 32, the total heat release is evaluated over the first 26 minutes. For Figure 33, it is evaluated over the first 110 minutes. These totals are normalized by the total heat release in the case of the reference test with 0% of the timber surface exposed (i.e. timber fully protected). The heat release from Hevia's Tests 1, 2 and 3 and McGregor's Test 5 are normalized by the average of McGregor's Tests 2 and 4. The heat release from Su's Tests 1-4, 1-5 and 1-6 are normalized by that of the Test 1-1; while the heat release from Su's Test 1-3 is normalized by that of Test 1-2. Figure 34 shows that as the area of the exposed timber surface increases, the total heat release increases with almost linear trend. However, the slope varies between the different test sets, indicating a dependence on factors such as the dimensions and ventilation conditions of the fire compartment, and the movable fuel load.

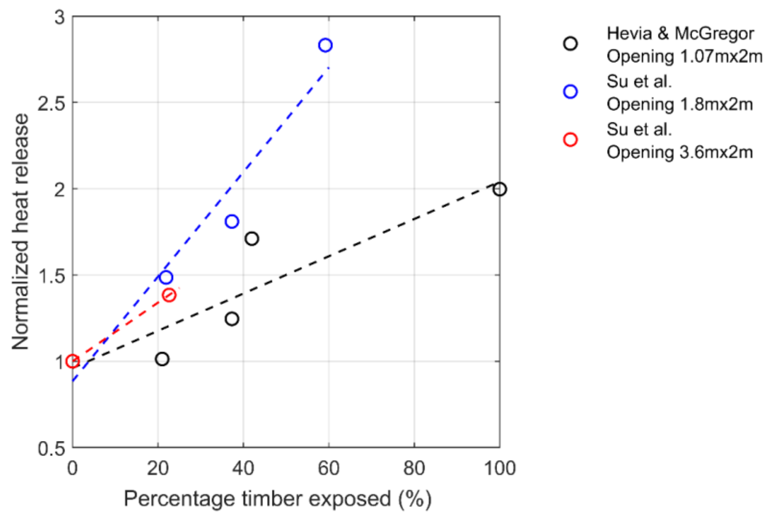


Figure 34. Effect of exposed timber surface on the total heat release (over a reference duration) during fire tests on mass timber compartments.

3.4.2 Empirical evaluation

Test data in Section 3.4.1 showed that exposed timber in fire compartments increases the heat release. Herein, the HRR contributed by square meter of exposed CLT is quantified from the test data. The HRR attributable to the CLT for the tests discussed above are plotted in Figure 35 and Figure 36. This CLT contribution is obtained by taking the difference between the total HRR of the considered test and that of the corresponding baseline test in which the timber was fully protected (0% exposed). As the area of exposed timber surface increases, the contribution of CLT to the total HRR increases. This contribution can reach 5 MW in the first set of tests and 10 MW in the second. The occurrence of negative values in Figure 35 can be due to the adopted method to evaluate CLT contribution by difference of two tests rather than by direct measure, with the uncertainties and approximations that this entails. It is also noted that volatiles contributed by CLT may be transported away and not combusted [94].

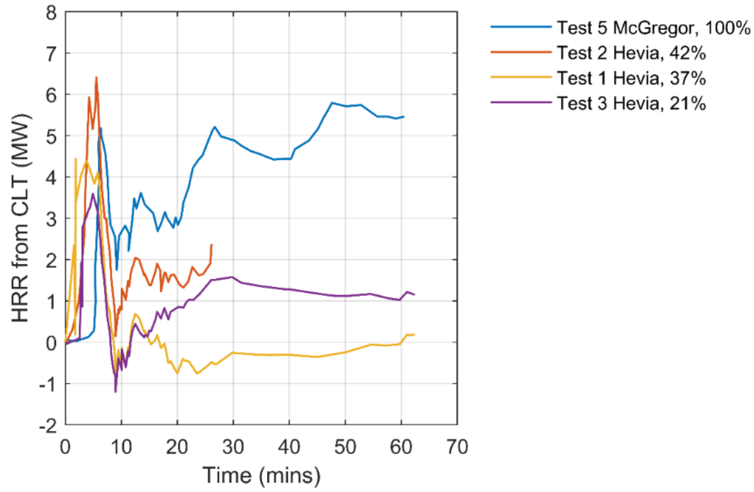


Figure 35. Heat release rate contributed by CLT panels in the fire compartment tested by Hevia (2014) [93] and McGregor [94]. The percentage indicates the relative surface of timber exposed.

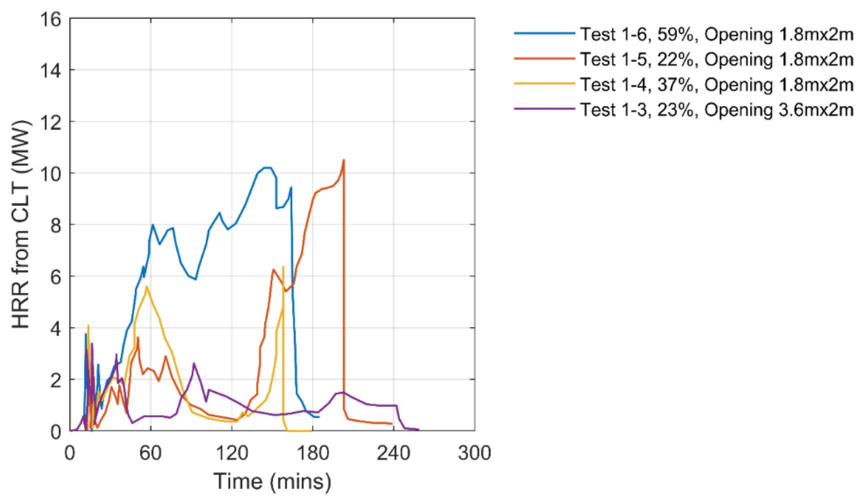


Figure 36. Heat release rate contributed by CLT panels in the fire compartment tested by Su et al. (2018) [5]. The percentage indicates the relative surface of timber exposed.

In their paper, Su *et al.* [5] analyzed the contribution to peak HRR as a function of the surface of CLT involved in the fire, as plotted in Figure 37 [5]. The figure includes two data entries for Tests 1-5 and 1-6, corresponding to peak HRRs at two times at which different numbers of CLT panels were involved in the fire (i.e. Wall 1 only; all walls and ceiling). The CLT contribution to the peak HRR increases with the surface area of burning CLT panels. This contribution is also influenced by the ventilation condition, as shown by the two curves fitting data points in Figure 37.

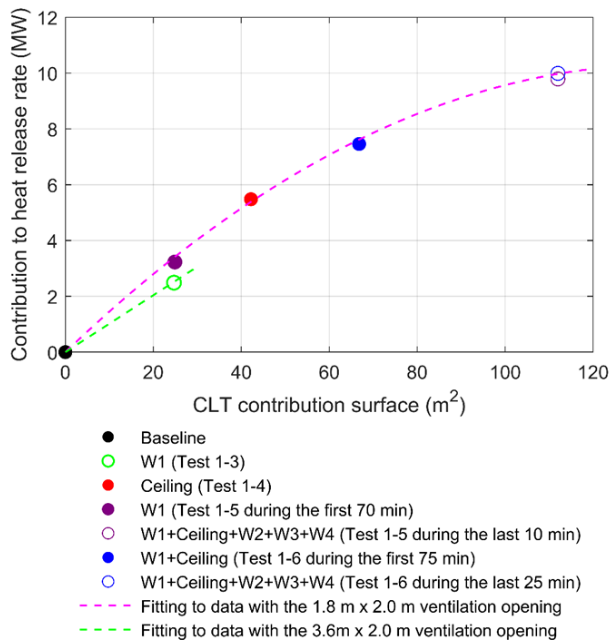


Figure 37. Contribution of CLT to peak HRR value in the tests by Su et al (2018); figure from [5]. Data points are given for peaks obtained when different surfaces of CLT are involved in fire.

The HRR contributed by timber per square meter of exposed CLT, noted $\dot{q}_{tmb,CLT}$, is obtained by dividing the HRR contributed by the CLT (i.e. Figures 35-36) by the surface area of the exposed timber (A_{tmb}). It is plotted in Figure 38. This HRR attributable to the exposed timber mostly ranges between 0 and 100 kW/m^2 per square meter of exposed CLT panel. Extreme values of 300 kW/m^2 and -100 kW/m^2 are observed temporarily. Based on the plot, a conservative estimate of the (sustained) HRR per square meter of exposed CLT is given by Eq. 3:

$$\dot{\mathbf{q}}_{\mathbf{tmb,CLT}} = \mathbf{Q_{CLT}}/\mathbf{A_{tmb}} = \mathbf{100}\ \boldsymbol{kW/m^2} \qquad \text{Eq. 3}$$

It is noted that, in the calculation of $\dot{q}_{tmb,CLT}$, the initial value of the exposed timber surface is used, which may lead to large values at the later stage of some tests when additional timber surfaces get involved due to failure of fire protection, which significantly increases the HRR (such as the Test 1-5 by Su in which, during the last 10 minutes, all walls and ceiling surfaces were burning).

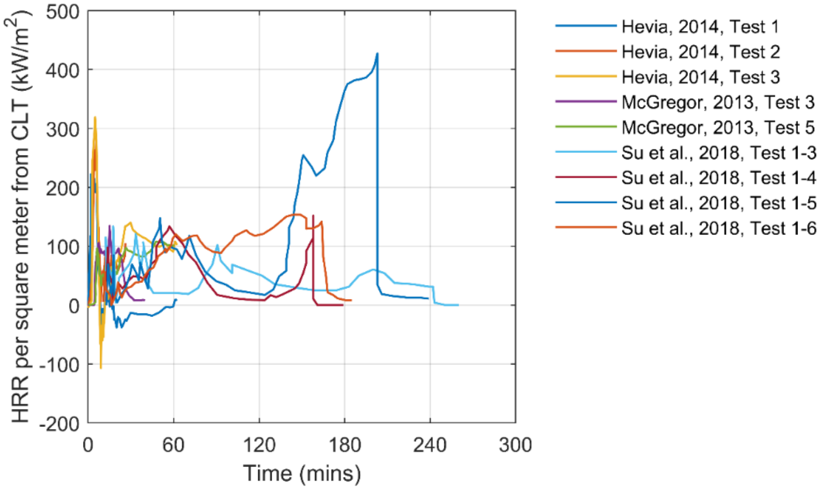


Figure 38. Timber contribution to HRR per exposed surface of CLT panels, from tests [93][94][5].

3.4.3 *Analytical evaluation*

The HRR contributed by square meter of exposed CLT can also be evaluated analytically. It is noted that the fire dynamics of timber compartments is a very complex issue that is still the focus of much research efforts. In this section, simplifying assumptions are adopted to allow a reasonable analytical evaluation of the heat output from burning CLT in mass timber buildings; while the empirical data of Section 3.4.2 (with $\dot{q}_{\mathrm{tmb,CLT}} = 100\ kW/m^2$) can serve as a benchmark.

In fuel-controlled conditions, the EN 1991-1-2 [178] evaluates the maximum HRR associated to the movable content fuel in different occupancies as $A_f \cdot RHR_f$, where A_f is the floor area of a fire compartment and RHR_f is the maximum heat release rate density of movable content fuel loads (given in Table E.5. of the EN 1991-1-2 [167]). However for ventilation-controlled conditions, the combustion is limited by the availability of oxygen, and the maximum HRR inside the compartment ($\mathrm{Q_{vent}}$) is estimated by Eq. 4:

$$\mathrm{Q_{vent}} = \mathrm{H_{c,eff}} \cdot \dot{\mathrm{m}} \qquad \text{Eq. 4}$$

where $\mathrm{H_{c,eff}}$ is the effective heat of combustion of fuel (MJ/kg) and $\dot{\mathrm{m}}$ is the burning rate (kg/s). The effective heat of combustion is given by: $\mathrm{H_{c,eff}} = m \cdot \mathrm{H}_{c,net}$, where $\mathrm{H}_{c,net}$ is the net calorific value (17.5 MJ/kg for wood) and *m* is the combustion factor (0.8). An empirical relationship for the ventilation controlled burning rate is given by [179]:

$$\dot{\mathrm{m}} = \mathrm{k_p} \cdot \mathrm{A_v} \cdot \sqrt{\mathrm{h}} \qquad \text{Eq. 5}$$

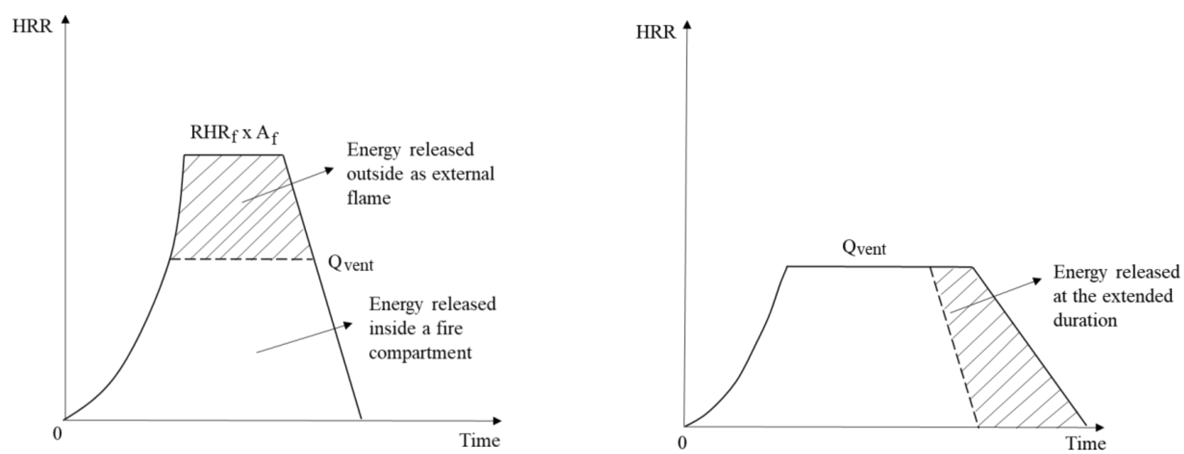
where $\mathrm{A_v}$ is the total area of wall openings (m^2); h is the weighted average height of openings (m); and $\mathrm{k_p}$ is the combustion factor (pyrolysis coefficient) which can be estimated by Eq. 6 and Eq. 7:

$$k_p = \frac{1}{148 \cdot F_{o2} + 3.8} \qquad \text{Eq. 6}$$

$$\mathrm{F_{o2}} = \mathrm{A_v} \cdot \sqrt{\mathrm{h}} / \mathrm{A_{T2}} \qquad \text{Eq. 7}$$

where A_{T2} is the total internal surface not including openings. The relationships of Eq. 6-7 is equivalent to EN1991-1-2 (E.6) when the factor $\mathrm{k_p}$ is approximated as 0.10.

In ventilation-controlled conditions, the products of pyrolysis cannot be entirely consumed in the compartment at the time they are released due to lack of oxygen. Two models are typically adopted to account for the energy contained in these unburned pyrolysis products: an external flaming combustion model and an extended fire-duration model. The external flaming model assumes that there is external burning, meaning that the total pyrolysis rate of a compartment fire remains unchanged but the extra pyrolyzed fuel burns outside (Figure 39a). The extended fire duration model supposes that the total mass of fuel is burnt inside the compartment under the ventilation-controlled maximum heat release rate $\mathrm{Q_{vent}}$, meaning that the curve of the HRR is extended to correspond to the available energy given by the fire load (Figure 39b).



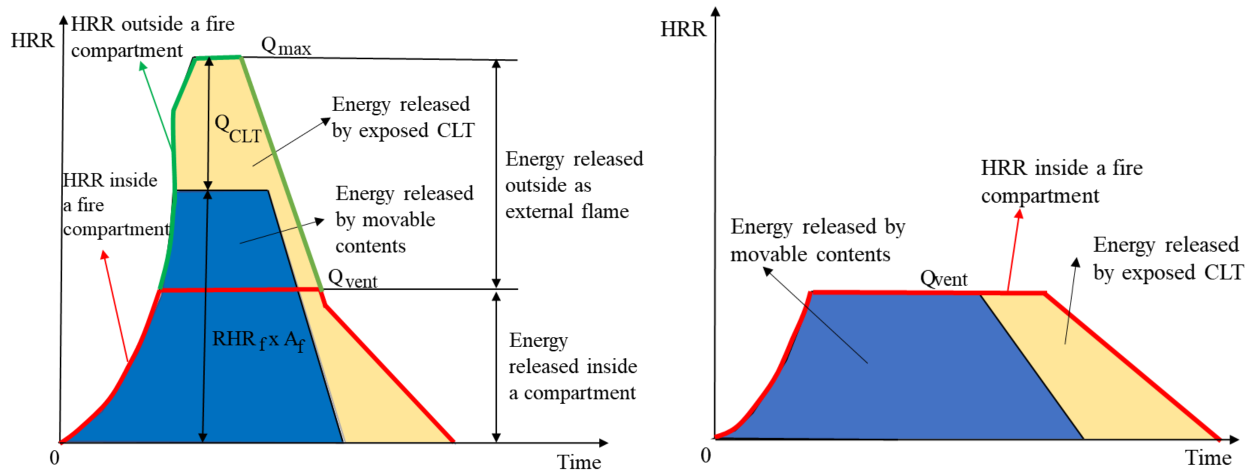
(a) External flaming combustion model (b) Extended fire duration combustion model

Figure 39. Combustion models for ventilation-controlled compartment fires [180].

Exposed timber surfaces in building compartments contribute to the heat output in case of fire. In theory, the maximum possible HRR is equal to the sum of that of the content fuel plus that of the exposed timber as given by Eq. 8:

$$\mathrm{Q_{max}} = \mathrm{A}_f \cdot RHR_f + \mathrm{Q_{CLT}} \qquad \text{Eq. 8}$$

This is shown by the envelope HRR curve in Figure 40a (assuming that timber charring begins when the fire comes to flashover). For a ventilation-controlled fire, due to the limited amount of oxygen, the maximum HRR inside the compartment is limited by Eq. 4. To account for the excess HRR, the two models presented in Figure 39 can be extended. Figure 40 presents the HRR in ventilation-controlled compartments with exposed timber. The red curves represent the HRR inside the compartment. In the external flaming model (Figure 40a), the maximum HRR Q_{max} is reached but part of it is released outside the compartment. The blue area is the energy contributed by the movable content fuel, equal to $q_{f,mc} \cdot A_f$. The yellow area is the energy contributed by the CLT, equal to $q_{tmb,CLT} \cdot A_{tmb}$. Here, $q_{f,mc}$ is the effective fire load density contributed by movable contents, relative to the floor area (A_f), while $q_{tmb,CLT}$ is the effective fire load density contributed by the exposed timber surface, relative to the area of the exposed timber surface (A_{tmb}).



(a) External flaming combustion model (b) Extended fire duration combustion model

Figure 40. Combustion models for ventilation-controlled fires in CLT compartments.

In Eq. 3, the value of 0.1 MW/m^2 was suggested as a reasonable upper bound of HRR per square meter of exposed CLT involved in fire, based on test data. Herein, the HRR and fuel load contributed by the exposed timber surface are evaluated analytically from wood charring models. Assuming self-extinction, the charring depth is evaluated as a function of time according to the model in Eurocode 5 part 1-2, Annex A for parametric fire exposure:

$$d_{char} = \beta_{par} \cdot t \qquad t \le t_o \qquad \text{Eq. 9}$$

$$d_{char} = \beta_{par} \cdot \left(1.5t - \frac{t^2}{4t_o} - \frac{t_o}{4}\right) \qquad t_o < t \le 3t_o \qquad \text{Eq. 10}$$

$$d_{char} = 2 \cdot \beta_{par} \cdot t_o \qquad t \ge 3t_o \qquad \text{Eq. 11}$$

β_{par} is the initial charring rate, calculated according to Eq. 12,

$$\beta_{par} = 1.5 \cdot \beta_o \cdot \frac{0.2\sqrt{\Gamma} - 0.04}{0.16\sqrt{\Gamma} + 0.08} \qquad \text{Eq. 12}$$

where β_o is the one-dimensional charring rate corresponding to standard fire resistance tests following ISO 835. The one-dimensional charring rate corresponding to softwood is 0.65 mm/min according to most design standards [181]. Γ is the heat rate/time factor, the calculation of which refers to the parametric fire model in the Eurocodes [167].

The time period with a constant charring rate, t_o, is calculated in minutes as $t_o = 0.009 \cdot q_t/O$, where O is the opening factor, the calculation of which refers to the parametric fire model in the

Eurocode [167]. q_t is the effective fire load density relative to the total surface area of the enclosure A_{T1} (including openings) (note: it is different from q_f).

The final thickness of the char layer, given by Eq. 11, is reached when the time reaches $3t_o$; it is noted $d_{char,3to}$. The final total fuel load density contributed by CLT, relative to the exposed timber surface, is estimated by Eq. 13:

$$q_{tmb,CLT} = \int_0^{d_{char,3to}} a_1 \cdot d\, d_{char} \qquad \text{Eq. 13}$$

where a1 is the heat release per square meter per mm of charring depth. Here, a_1 is assumed to be 2.7 MJ/m^{2}mm at the beginning and then linearly increase to 5.39 MJ/m^{2}mm until the charring depth is 10 mm [182].

The HRR per square meter contributed by the exposed timber, $\dot{q}_{tmb,CLT,t}$, is then obtained by time derivation of Eq. 13, where $d_{char,3to}$ is replaced by the charring depth of CLT at any time, $d_{char,t}$:

$$\dot{q}_{tmb,CLT,t} = \frac{d\, q_{timb,CLT,t}}{dt} \qquad \text{Eq. 14}$$

The maximum HRR corresponding to the exposed timber, Q_{CLT}, is then evaluated as:

$$\dot{q}_{tmb.CLT,max} = \max(\dot{q}_{tmb,CLT,t}) \qquad \text{Eq. 15}$$

$$Q_{CLT} = A_{tmb} \cdot \dot{q}_{tmb,CLT,max} \qquad \text{Eq. 16}$$

The evaluation of the charring depth does not include the effect of the fuel load contributed by the exposed timber surface on t_o. It is possible to calculate d_{char} by iteration to include the fuel load corresponding to the exposed timber surface [181].

For the calculation of fuel load contributed by CLT panels, Eq. 13 is only applicable where the fire achieves self-extinction. If a fire does not self-extinguish and instead burns continuously (e.g. due to delamination of CLT panels), the fuel load corresponding to the exposed timber is calculated by considering the full thickness for the exposed timber surfaces, instead of a charring depth smaller than the section thickness.

3.5 Evaluation of fire flow and water supply required to put out a fire

3.5.1 Water requirement in firefighting

In firefighting, enough water should be supplied to absorb the heat generated from a fire at a rate that can control and finally extinguish a fire effectively, which governs the requirements for fire flow (in L/s) and total water supply (in L). For firefighters at a fire scene, the evaluation of the required quantity of water to effectively control the fire is a primary consideration. It impacts the determination of needed resources and implementation of tactical operations. This evaluation relies on a balance between the heat-absorbing capacity of water and the heat generated by the fire.

On the fire ground, the application of water from a fire main into a fire entails losses (in heat-absorbing capacity) because: 1) the area of the footprint of a hose jet fired through a window may often cover only a part of the burning area of a large fire inside the building but providing extra water will not solve this problem; 2) water may also be used to cool down smoke gases and hot surfaces to enable a firefighter to approach closer to the actual fire; 3) parts of the fire may have to be extinguished first to enable the firemen to reposition to carry out extinction of other parts of the fire; and 4) water may also be used to wet down exposed combustible surfaces not yet involved in the fire, such as neighboring buildings. Meanwhile, building fires do not retain 100% of the heat energy in the room where the fire is occurring; a significant proportion of the energy released from the fuel may escape out the openings in the form of hot gas, hot unburned fuel, hot excess air, hot synthesized moisture, hot natural moisture, and radiation. The more energy that flows out via the openings, the less remaining energy there will be to affect the structure and the less will be the water required inside the building. The heat production efficiency coefficient for building fires, noted $\mathrm{k_F}$, typically ranges from 0.50 down to 0.10 [183]. This means that the heat retained in a building is usually lower than 50% of $\mathrm{Q_{max}}$ [183], where Q_{max} is the max heat release of the fire.

3.5.2 *Evaluation from energy balance*

Most existing methods for calculating fire flow and total water supply are empirical, based on firefighting practice or test data. These empirical methods are functions of a building geometry (including volume, floor area, height, or non-divided developed surface area of a building), construction type, occupancy type, surrounding environment (distance from nearby buildings, hazard exposure, etc.), and fire safety measures (e.g., whether a building is sprinklered), see [184][185][186][187][188][189]. Yet, these empirical methods do not allow evaluating the specific influence of the contribution of exposed timber on the water requirements.

A physics-based method is proposed in New Zealand SFPE Method TP 2004/1 [183], as given by Eq. 17. This equation yields the required fire flow, F in L/s, to fight the fire. The equation numerator is the effective heat from a fire that is retained in the compartment, where Q_{max} is the maximum heat release rate of the fire (MW), and $\mathrm{k_F}$ is a heating efficiency factor which can conservatively be estimated as 0.5 [183]. The equation denominator is the effective heat-absorbing capacity of water per unit volume. Q_w is the absorptive capacity of water at 100°C, including the energy to heat water from ambient temperature to the boiling temperature of 100°C and the energy to convert water to steam. Water has a specific heat capacity in liquid form of 4.18 kJ/kgK and a heat of vaporization of 2.26 MJ/kg, resulting in Q_w equal to 2.6 MJ/L. The factor $\mathrm{k_w}$ is the heat-absorbing efficiency of water, which is conservatively estimated as 0.5 [183].

$$\mathrm{F} = \frac{\mathrm{k_F} \cdot \mathrm{Q_{max}}}{\mathrm{k_w} \cdot \mathrm{Q_w}} \qquad \text{Eq. 17}$$

The New Zealand SFPE Method TP 2004/1 does not specify how to calculate $\mathrm{Q_{max}}$.

Adopting the external flaming model (Figure 40a), the maximum HRR, Q_{max}, can be calculated using Eq. 8. This value of Q_{max} for the fire flow estimation is conservative, as it includes the heat released both inside and outside the compartment. While heat released outside should not be included when assessing the temperatures in the fire compartment, this heat may be relevant to the firefighting efforts and affect the amount of water needed to fight the fire. Indeed, fire accidents in tall buildings have shown the importance of actively controlling the spread of external flame along the façade (and this is expected to be even more important if the façade is made of combustible material). Meanwhile, if the fire is fought from outside, the heat from the external flames will need to be taken into account in the energy balance against water. Finally, the accurate assessment of the HRR inside a timber compartment depends on the complex interaction of many variables such as the ventilation conditions and geometry of the room, which will vary from case to case, hence it is reasonable to adopt an upper bound estimation. In conclusion, it is chosen to conservatively adopt Q_{max} from Eq. 8 in the evaluation of the fire flow from Eq. 17. This yields Eq. 18 for the evaluation of the fire flow in fire compartments constructed from mass timber:

$$F = \frac{k_F\ (Q_{mc} + Q_{CLT})}{k_W \cdot Q_w} \quad \text{Eq. 18}$$

where Q_{mc} is the maximum HRR associated to the movable content fuel in different occupancies, equal to $A_f \cdot RHR_f$ (referring to Table E.5 in the EN 1991-1-2 [167]); and Q_{CLT} is the maximum HRR associated to the exposed timber, estimated by Eq. 16.

Adopting a similar reasoning, a method is provided in the New Zealand SFPE Method TP 2005/2 [190] for the total water supply. The total water supply (in L) can be approximated by expressing the balance between the total (effective) heating potential of the fuel load in a compartment and the (effective) heat-absorbing capacity of the water for unit volume. This yields:

$$S = \frac{k_F \cdot E}{k_W \cdot Q_w}\ SM \quad \text{Eq. 19}$$

where E is the total (effective) fuel load (MJ) (with a combustion factor of 0.8), and SM is a safety coefficient recommended as 1.3 [190]. The total water supply is thus estimated by Eq. 20, where the energy E accounts for the contribution of the effective exposed CLT surfaces (yellow area in Figure 40) plus the effective movable fuel load in a compartment (blue area in Figure 40):

$$S = \frac{k_F \cdot \left(q_{f,mc} \cdot A_f + q_{tmb,CLT} \cdot A_{tmb}\right)}{k_W \cdot Q_w}\ SM \quad \text{Eq. 20}$$

where $q_{f,mc}$ is the effective movable (content) fuel load per square meter of floor area, equal to the moveable fuel load per square meter of floor area multiplied by the combustion factor (m), 0.8, as recommended by Eurocode [167]; and $q_{tmb,CLT}$ is the effective fuel load per square meter of exposed timber surface, contributed by the exposed timber surface, estimated by Eq. 13.

3.6 Evaluation of heat flux received by neighboring buildings

3.6.1 Mechanisms of fire spread between structures

When a fire spreads to nearby buildings, it may result in significant additional loss, as seen in several real accidents including the fire in Washington D.C., on February 8, 2020 [40], the fire in Waltham, Massachusetts, on July 23, 2017, the fire in Hampshire, UK, September 2010 [49], and the fire that damaged the 500-year old Shuri Castile on October 31, 2019, in Japan [81].

A fire can spread to nearby buildings through four main paths, i.e., flying brands, projected flame, convective heat transfer, and radiation. Ignition of combustible materials may occur due to flying brands emitted from a building on fire, which can travel far distances. Usually, flying brands do not represent a significant hazard by itself concerning the ignition of buildings, but they may act as an igniting source together with radiation. Projected flames from an opening may impinge onto an adjoining building, leading to ignition. The convective heat transfer of hot stream of several hundreds of degrees Celsius may also result in the ignition of an adjoining building, but this phenomenon generally only happens to buildings that are close to the fire source. Radiation is the most common mechanism of fire spread between buildings.

Radiation can generally ignite neighboring buildings at greater distances than by direct flame contact and convection. A review of external fire spread to neighboring buildings is given in [191]. A value of 12.5 or 12.6 kW/m^2 is used in most building codes and calculation methods as the maximum tolerable level of radiation at the exposed façade [192][193][194] while the Swedish Building Regulation [195] uses a value of 15 kW/m^2. There is no simple model to evaluate the radiation from a building in fire to a neighboring building. When a compartment is in fire, radiation to other buildings will occur through both the windows and the eventual external flames, so that the fire dynamics inside and outside the compartment will impact the amount of radiation received by the façade of a nearby building. The latter also depends on the emissivity of the façade and the configuration factor.

3.6.2 Evaluation from virtual solid flame radiative model (LOCAFI)

This section presents a simplified method to investigate the fire spread through radiation based on a localized fire model, in the case where a building is engulfed by the fire. The method relies on the simplifying assumption that the building in fire can be treated as an external localized fire. The adopted localized fire model is based on the work made in the research project RFSR-CT-2012-00023 LOCAFI – "Temperature assessment of a vertical steel member subjected to localized fire". Radiative heat exchanges toward the neighboring building are calculated by representing the building in fire as a virtual solid flame that radiates in all the directions. Further details about the LOCAFI fire model are given in [196], including comparison against experimental data with fire diameter up to 50 m and estimated power of 3040 MW [197].

A conical shape is adopted for the virtual solid flame. The flame length L_f (in m) is calculated in accordance with Annex C of Eurocode 1991-1-2:

$$L_f = -1.02D + 0.0148Q^{2/5} \qquad \text{Eq. 21}$$

where D is the diameter of the fire (in m); Q is the heat release rate of the fire (in W). The temperature in the plume along the symmetrical vertical flame axis is given by:

$$T(z) = 20 + 0.25Q_c^{2/3}(z - z_o)^{-5/3} \leq 900 \qquad \text{Eq. 22}$$

where Q_c is the convective part of the rate of heat release taken as 0.8 Q by default; z is the height along the flame axis (in m); z_o is the virtual origin of the axis (in m) given by:

$$z_o = -1.02D + 0.00524Q^{2/5} \qquad \text{Eq. 23}$$

For calculating the radiation emitted from the conical solid flame, the cone is divided into cylinders as shown in Figure 41. The total radiation arriving at a target point is the summation of the radiation arriving at the target point from each small cylinder; where the radiation from each cylinder includes two parts, from the vertical side and from the top face of the ring.

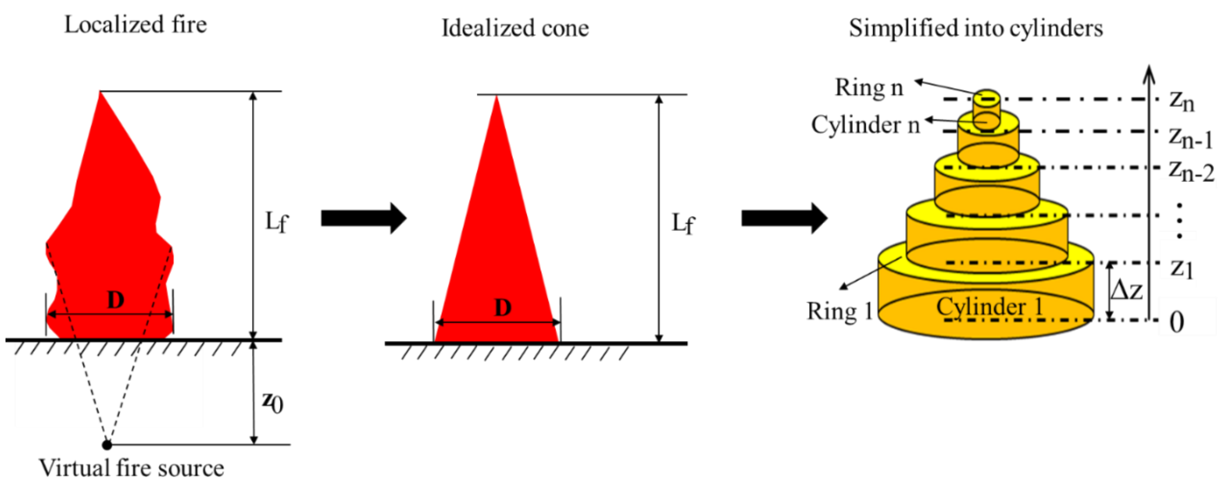


Figure 41. Idealized and simplified virtual solid flame.

The radiation arriving at a target point in a vertical surface opposite the cone is estimated by Eq. 24:

$$R = \sum_{i=1}^{n} F_{1\to2,si}\sigma\left[T\big((i-1)*\Delta z + \Delta z/2\big) + 273.15\right]^4 + \sum_{i=0}^{n} F_{1\to2,ci}\sigma\left[T\big((i-1)*\Delta z + \Delta z\big) + 273.15\right]^4 \qquad \text{Eq. 24}$$

where $T\big((i-1)*\Delta z + \Delta z/2\big)$ is the temperature at middle height of the small cylinder i, which is used at the average temperature of that cylinder; and $T\big((i-1)*\Delta z + \Delta z\big)$ is the temperature of the small ring i. $F_{1\to2,si}$ is the configuration factor between the side of the cylinder i and the target point in a surface parallel to the cylinder side [198]; $F_{1\to2,ri}$ is the configuration factor between the top ring and a target point in a surface perpendicular to the top ring [199][200]; σ is the Stefan-Boltzmann constant, 56.7x10^{-12} kW/m^{2}K^4.

To illustrate the method described above, the incident radiation arriving at a vertical surface opposite the tested rooms by McGregor [94] is investigated, as shown in Figure 42. The target point at the receiving surface is at an elevation of 1.25 m from the ground. In the calculation, the measured HRR curves from the compartment fire tests (Figure 32) are used as input into the localized fire model tested fire compartments. Two of the tests were studied, with 0% timber surface exposed and 100% timber surface exposed. D is the equivalent diameter of the floor plan, which is equal to $2\sqrt{4.5 \times 3.5/\pi}$=4.48 m.

The calculated peak incident radiation arriving at the target point is shown in Figure 43. The incident radiation arriving at the target point is larger for the test with 100% of the exposed timber surface exposed, compared to the test with 0% exposed. The critical distance beyond which the peak incident radiation is less than the threshold (12.5 kW/m^2) is 2.3 m for the fire compartment with 0% timber surface exposed and 3.3 m for the one with 100% timber surface exposed.

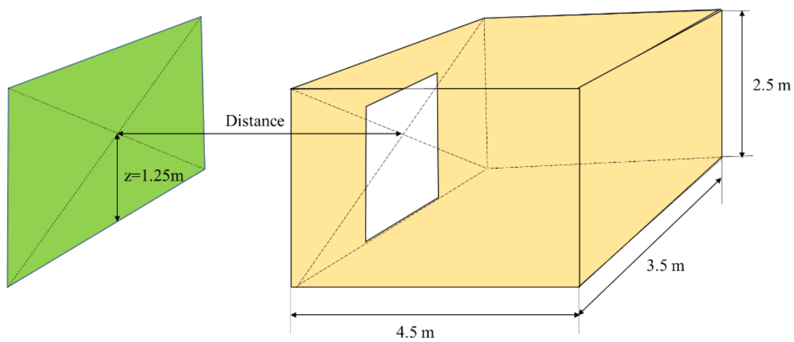


Figure 42. Vertical receiving surface opposite the tested fire compartment (Note: Distance used for the calculation is from the target surface and the idealized cone fire at the ground level).

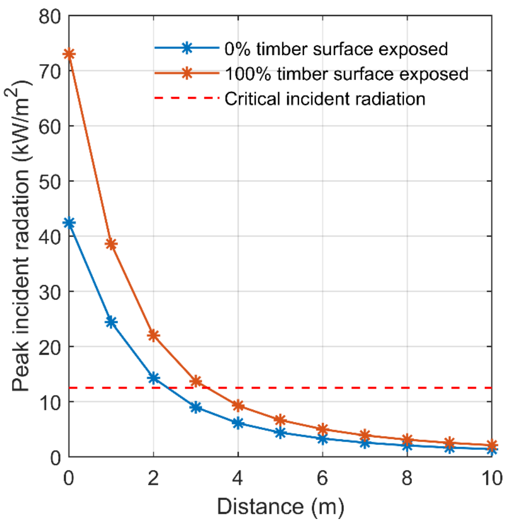


Figure 43. Maximum incident radiation arriving at the target point, evaluated using the measured HRR from the fire tests by McGregor [94].

3.7 Case study

3.7.1 Description of the mass timber building

A 10-story mass timber residential building is considered as a case study. The floor plan of the building is shown in Figure 44. The story height is 4 m. The ratio of opening area to the total surface of each compartment (opening ratio A_V/A_{T1}) is 0.03, with opening height of 1.5 m. The enclosure thermal insulation parameter b is 300 J/m^{2}s$^{1/2}$K. The movable fuel load density is 780MJ/m^2 (average value for residual buildings according to Eurocode), and the effective movable fire density ($q_{f,m}$) is 0.8 x 780 = 624 MJ/m^2. The density of timber (ρ) is 490 kg/m^3 and its net heat of combustion ($H_{c,net}$) is 17.5 MJ/kg. The effect of sprinkler system is neglected, as the focus is on the structural fire behavior as a necessary layer of the fire safety strategy. Therefore, while sprinklers may be present in the building, the case study focuses on the worst case situation where the sprinklers have been ineffective (e.g. due to a failure, a primary hazard event, etc.).

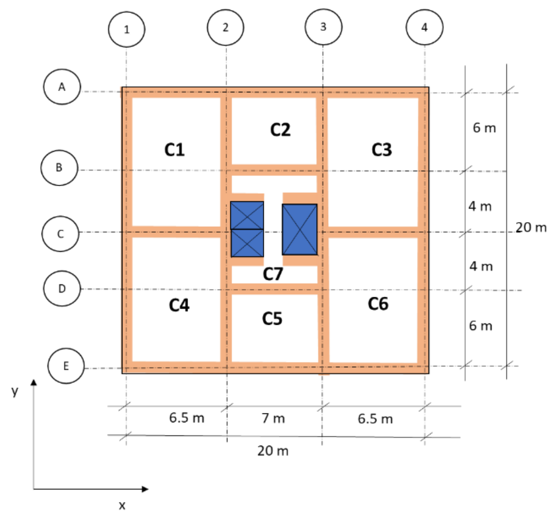
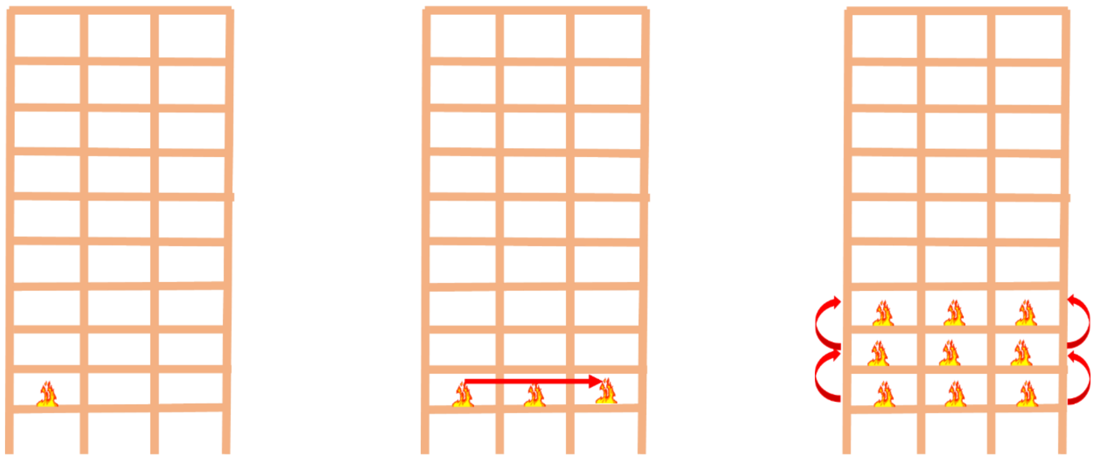


Figure 44. Floor plan of the prototype building.

Three cases are discussed, as shown in Figure 45: 1) the compartment C1 is in fire, 2) a full floor is in fire except the interior compartment C7, and 3) three full floors are in fire except C7. The transition from Case 1 to Case 2 represents the failure of fire compartmentation in the horizontal plane, for example due to the failure of the joint connecting CLT wall panels or the burning through of CLT wall panels. The transition from Case 2 to Case 3 represents the failure of fire compartmentation along the height of the building, which could be due to fire spreading through windows to the upper stories, burning through of CLT floor panels, or the failure of the joints connecting CLT floor panels, etc. The calculations are based on the simplifying assumption that the fire dynamics in each room develops independently. For each case, five different percentages of exposed timber are considered, 0% (fully protected), 25%, 50%, 75% and 100% (fully exposed). Furthermore, two situations are considered: either the exposed timber achieves self-extinction, or it burns until it is fully consumed. This results in a total of 30 configurations.



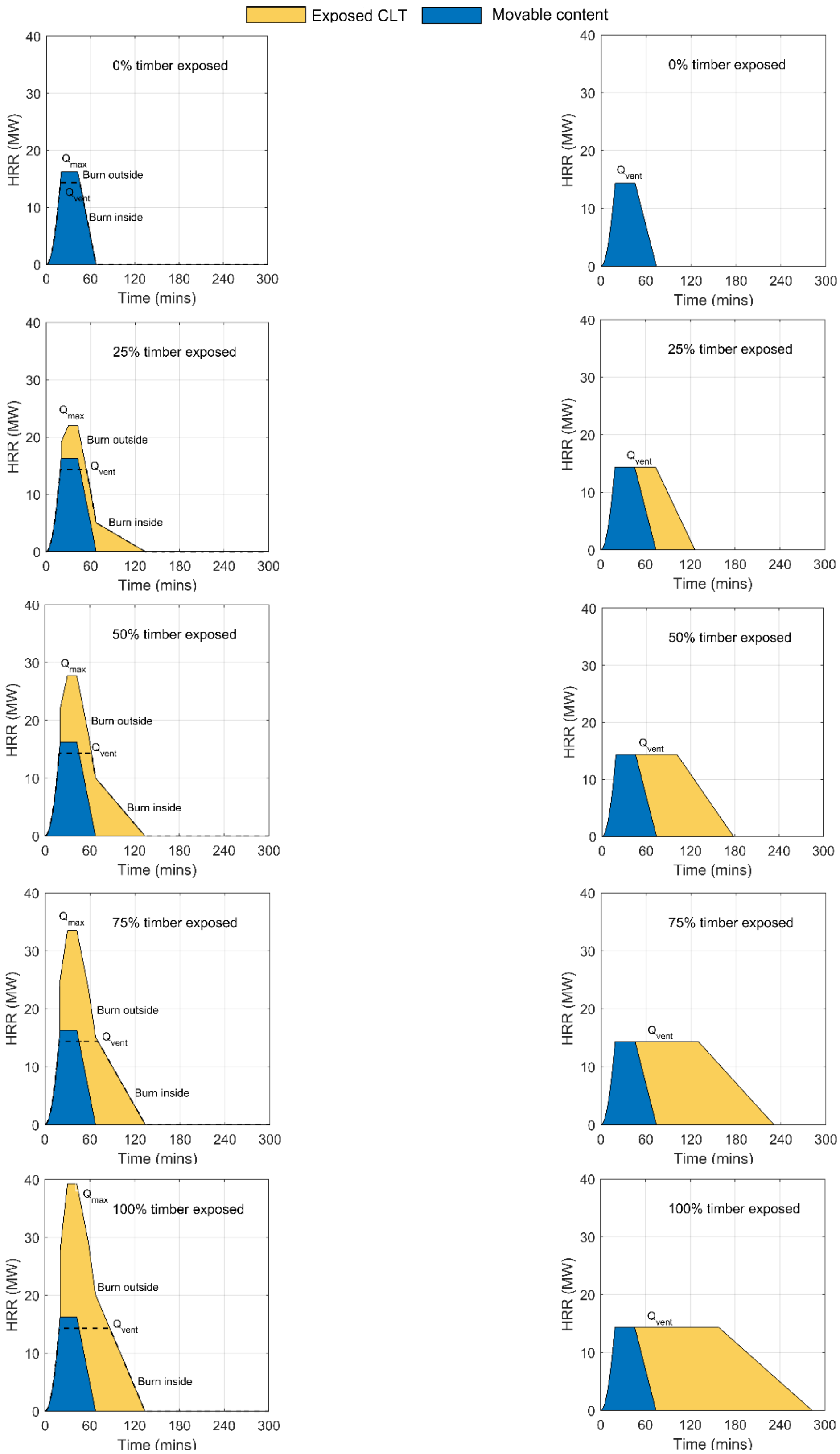
(a) Case 1 (b) Case 2 (c) Case 3

Figure 45. Three fire scenarios.

3.7.2 Heat release rate

The HRR is evaluated for the 30 different cases using the method of Section 3.4.3. As a sample of result, Figure 46 shows the HRR for a fire in the compartment C1. Results are plotted for both the external flaming combustion model and the extended fire duration combustion model. In Figure 46, the self-extinction model is assumed, meaning that the final charring depth of timber (d_{char}) is calculated according to Eq. 11 and then the fuel load per square meter of exposed timber surface ($q_{tmb,CLT}$) is calculated according to Eq. 13. The total fuel load contributed by the exposed timber is represented by the yellow area.

Table A2-1 in Appendix details the calculation for a fire at the second story in the compartment C1 (which is identical to C3, C4, and C6) and in the compartment C2 (identical to C5), with 50% of CLT exposed. The calculated $\dot{q}_{tmb,CLT}$ is equal to 0.091 MW/m^2, which reasonably agrees with the empirical estimation of 0.1 MW/m^2 obtained from test data in Section 4.2 (Eq. 3). This HRR per square meter of exposed CLT is the same for the two compartments. The final charring depth corresponding to the self-extinction scenario is equal to 76.5 mm for the compartment C1 and 68.8 mm for the compartment C2. As a result, the effective fuel load contributed by the exposed CLT is 398.7 MJ/m^2 of exposed surface (779.4 MJ/m^2 relative to the floor area) for the compartment C1 and 357.6 MJ/m^2 (776.4 MJ/m^2 relative to the floor area) for the compartment C2. However if the fire continuously burns until all exposed timber is consumed, the effective fuel load contributed by the exposed CLT is 543.9 MJ/m^2 (1063.3 MJ/m^2 relative to the floor area) for the compartment C1 and 489.8 MJ/m^2 (1063.3 MJ/m^2 relative to the floor area) for the compartment C2.

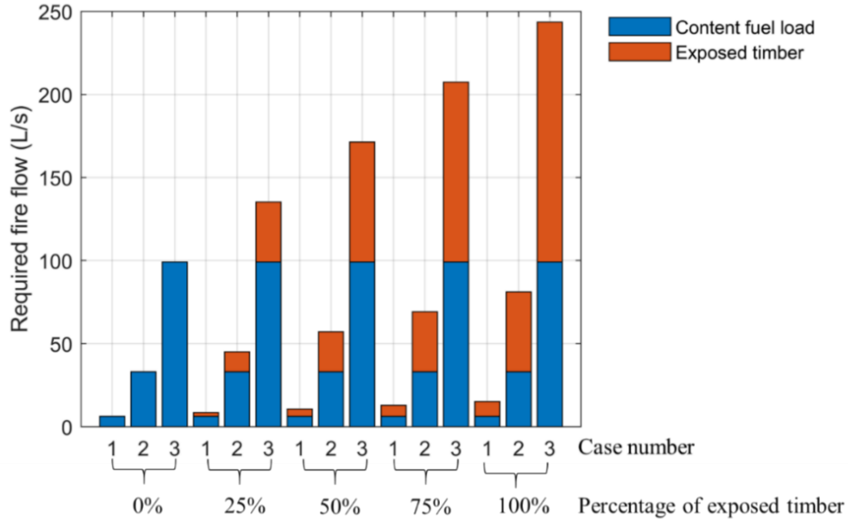


(a) External flaming (b) Extended fire duration

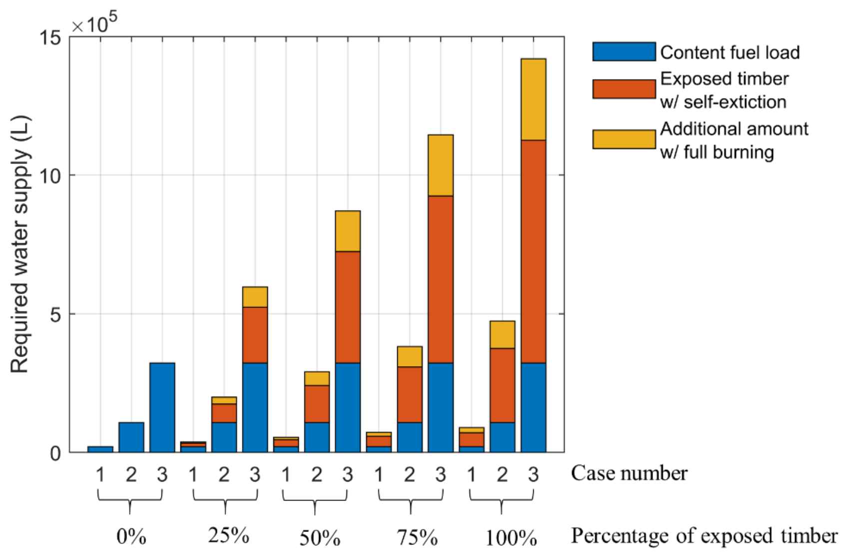
Figure 46. HRR for a fire in compartment C1, assuming self-extinction model.

3.7.3 *Fire flow and water supply*

The required fire flow and water supply to extinguish the fire are evaluated for the different cases using the method of Section 3.5.2, i.e. Eq. 18 and Eq. 20. Table A2-2 in Appendix details the calculations for the compartments C1 and C2. Table A2-3 summarizes the required fire flow and water supply for all scenarios. The results are plotted in Figure 47. Blue bars represent the contribution of the content fuel load, red bars represent the contribution of the exposed timber with the assumption of self-extinction (thus a final charring depth smaller than the full cross-section thickness), and the yellow bars represent the additional water supply required if the exposed timber burns until being completely consumed (i.e. no self-extinction).



(a) Fire flow

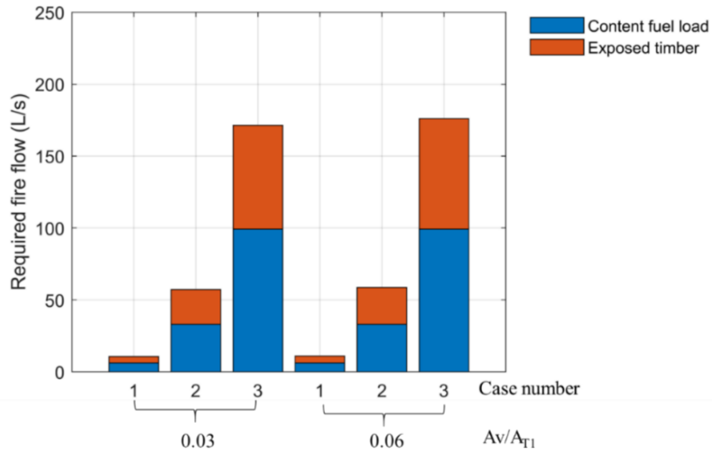


(b) Water supply

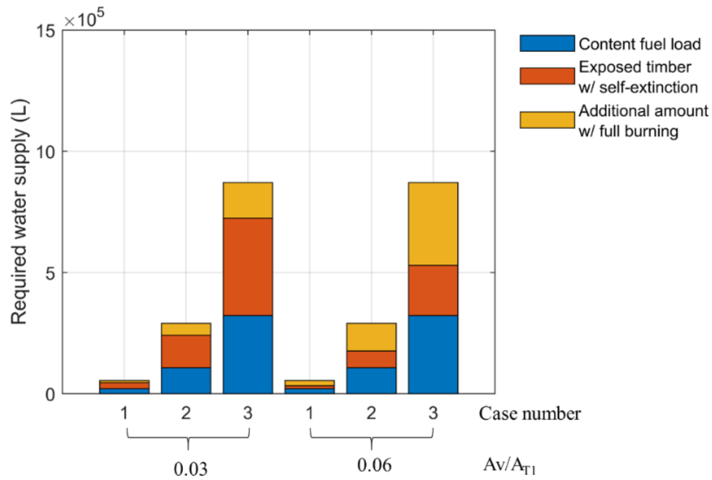
Figure 47. Required fire flow and total water supply for the different scenarios.

Figure 47 shows that, from Case 1 to Case 3, the required fire flow and water supply increase, because the fire has spread to more compartments. For a given case, both the required fire flow and water supply increase with the percentage of exposed timber. This is because the maximum HRR (Q_{CLT} in Eq. 18) and the total fuel load ($q_{tmb,CLT} \cdot A_{tmb}$ in Eq. 20) contributed by the exposed timber increase with the increase of exposed timber surface (A_{tmb}). As the exposed timber surface increases from 0 to 100%, the required fire flow increases by 146% to balance the additional heat contributed by the burning timber (Figure 47a). The fire flow is not influenced by the assumption of self-extinction versus full burning, because this assumption does not influence the maximum HRR contributed by timber. However, this assumption influences the total fuel load contributed by timber, and thus the water supply. As the exposed timber surface increases from 0 to 100%, the required water supply increases by 250% if the fire self-extinguishes, and by 340% if the fire continuously burns until all the exposed timber is consumed (Figure 47b).

The influence of the opening ratio is investigated next. The scenarios listed in Table A2-3 and plotted in Figure 47 all had an opening ratio of $Av/A_{T1} = 0.03$. In Table A2-4 and Figure 48, the required fire flow and water supply are evaluated for an opening ratio Av/A_{T1} of 0.06. The additional HRR attributable to CLT increases from 0.091 MW/m^2 to 0.099 MW/m^2, indicating the influence of ventilation on the HRR. This leads to a slight increase in the required fire flow. However, the total water supply decreases for the scenario when self-extinction can be achieved, because the increase of opening ratio leads to a decrease in charring depth (e.g., the final charring depth decreases from 76.5 mm to 42.0 mm for the compartment C1), thus a decrease in the total fuel load contributed by the exposed timber surface. Under the assumption of full burning of the exposed timber, the total water supply does not depend on the ventilation conditions.



(a) Fire flow



(b) Water supply

Figure 48. Required fire flow and total water supply as a function of the opening ratio.

3.7.4 Heat flux received by neighboring structures

The heat flux received by neighboring structures is investigated in this section to consider the possibility of fire spread by radiation. The method of Section 3.6.2 is applied, for the case where the entire prototype building is engulfed in fire and adopting the assumption that it can be treated as a virtual solid flame. The evaluation is made for three cases of exposed timber surface, namely 100%, 50% and 0% of the timber exposed. Where 0% of the timber is exposed, only the content fuel load contributes to the HRR. The external flaming combustion model is adopted. The total HRR for the building, plotted in Figure 49, is obtained by summing the contribution of each fire compartments. These total HRR curves are used in the method of Section 3.6.2. The diameter D of the fire is taken as the equivalent diameter of the floor plan, equal to $2\sqrt{20 \times 20/\pi} = 22.57\ m$. The exposed surface is a vertical façade opposite the prototype building.

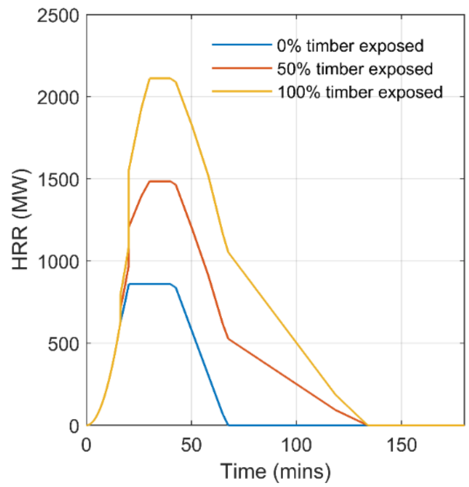
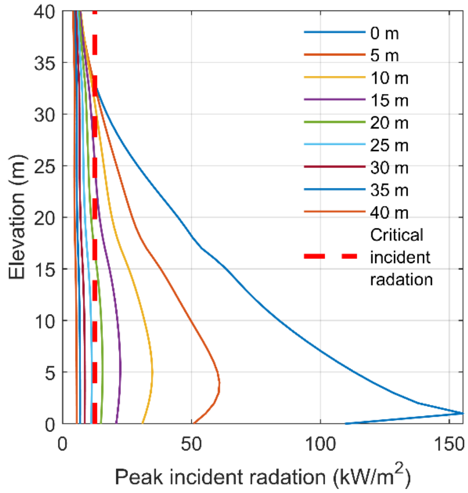
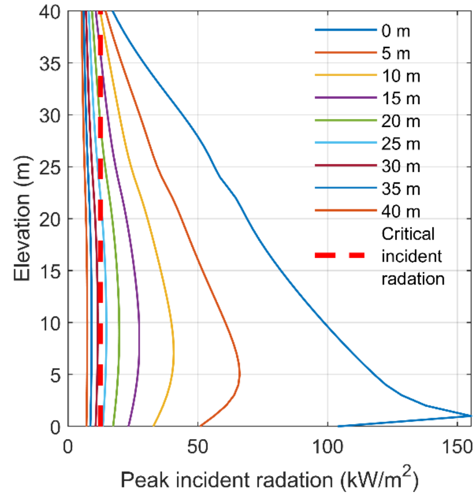


Figure 49. HRR curves for the ten-story building engulfed in fire.

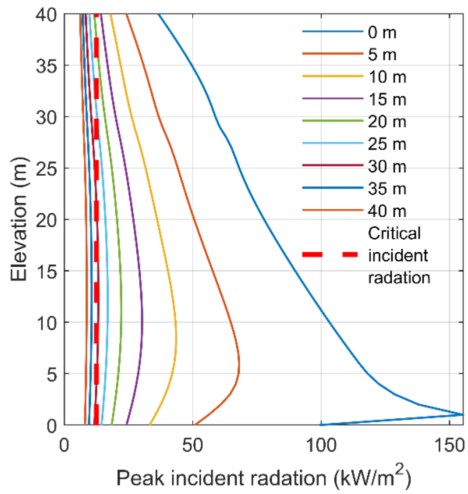
Figure 50 plots the maximum incident radiations arriving on a vertical surface (façade) parallel to the façade of the fire-engulfed building. The vertical axis gives the elevation of the target point where the incident radiation is evaluated. Incident radiations are given for horizontal distances between the two façades ranging from 0 m to 40 m. Figures 50a, 50b and 50c show results for exposed timber surfaces of 0%, 50% and 100%, respectively. The critical incident radiation of 12.5 kW/m^2 is indicated by a vertical line. As can be seen, spread by radiation to the neighboring building is expected to occur if the distance between buildings is 20 m or less, in the situation where all the timber is protected and does not get involved in the fire (i.e. 0% exposed). However, this distance increases to 25 m with 50% of timber surfaces exposed, and to 30 m with 100% of the timber exposed. Figure 51 shows the variation of the peak incident radiation as a function of the horizontal distance between facades, at an elevation of 5 m. The critical distance beyond which the peak incident radiation is less than the critical value (12.5 kW/m^2) is 23 m for the building with 0% timber surface exposed, 28 m for the building with 50% timber surface exposed, and 30.3 m for the building with 100% timber surface exposed. This suggests that the minimum prescribed distance between tall mass timber buildings and neighboring buildings should increase with an increasing proportion of the mass timber at potential of getting involved in a fire.



(a) 0% timber surface exposed



(b) 50% timber surface exposed



(c) 100% timber surface exposed

Figure 50. Peak incident radiation on neighboring façade, function of elevation and horizontal distance.

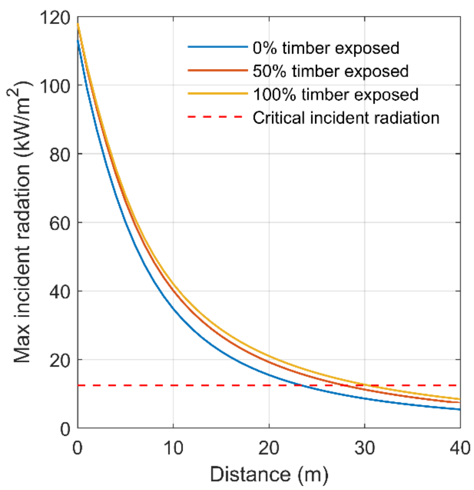


Figure 51. Peak incident radiation on neighboring façade at 5 m elevation, function of horizontal distance.

3.8 Discussion

This section focused on the contribution of (exposed) mass timber from the structure to the heat release rate, the water required to fight the fire, and the heat flux received by neighboring structures. It presented a method to evaluate these contributions and application to a case study. The analyses were based on the premise that an uncontrolled fire starts and grows in a mass timber building, where prevention and active fire protection measures (e.g. sprinklers) have failed.

First, from a review of existing tall mass timber buildings, it was found that the average weight of structural timber per square meter in such buildings is about 152 kg/m², which translates into an average fixed fuel load of 2660 MJ/m² embedded in the structural components. From a review of compartment fire tests data, it was found that exposed timber burns, which increases the heat release rate and total energy measured in compartments with exposed timber surface compared with the same compartments where all timber is protected. The HRR contributed by the exposed CLT over a sustained duration in the reviewed tests can be roughly evaluated as 100 kW/m² (per square meter of exposed CLT).

The required fire flow and water supply to fight a fire can be estimated from an energy balance method as proposed in a New Zealand SFPE Technical Publication. The method requires evaluating the HRR and total energy from the fire. Capturing the fire dynamics in a timber compartment is very complex and a topic still under research. Here, an assessment is made using simplifying assumptions consistent with the Eurocode; notably the external flaming and extended duration concepts are adopted to evaluate the boundaries of the HRR and total energy. For a 10-story building case study, results show that the required fire flow may increase by up to 146% to balance the additional heat contributed by the burning timber, while the required water supply may increase by up to 250% (assuming the timber self-extinguishes) or 340% (assuming full combustion of the members). These numbers are maximum values obtained when the timber is left exposed over its entire surface; lower values are obtained if thermal protection is used and the integrity of the protection is maintained over the duration of the fire.

Burning buildings can ignite neighboring buildings, most notably through radiation. A simple assessment is presented assuming the worst case scenario where the mass timber building is completely engulfed in a fire, and evaluating radiative heat exchanges toward the neighboring building from a virtual solid flame. For the 10-story case study, the critical distance for ignition of a neighboring building is 23 m if all the timber is protected and does not get involved in the fire, but this distance increases to 30 m if 100% of the timber is exposed. This result shows that minimum prescribed distances between tall buildings should account for the potential of combustible materials to contribute to the fire intensity.

4 Thermo-Structural Response of Tall Timber Buildings

4.1 Possible causes of compartmentation failure

The critical fire situations in high-rise buildings occur when fire spreads beyond its compartment of origin. Fire spread endangers people evacuation and complicates fire brigade intervention. Understanding the conditions under which fire can spread within tall timber buildings is essential to examine the fire risk for building occupants, fire brigades, and surrounding areas.

4.1.1 Failure of compartment integrity

Compartmentation may be lost due to an integrity failure of (at least) one of the boundaries of the enclosure. The integrity is the ability of a separating element of building construction, when exposed to fire on one side, to prevent the passage through it of flames and hot gases and to prevent the occurrence of flames on the unexposed side. Integrity failure results in possibly a fire that spreads beyond the compartment of origin within the rest of the building. Several possible causes can lead to the failure of compartment integrity.

Fire may spread to nearby areas through deficiencies of wall-to-wall connections or wall-to-floor connections. These connections are possible paths to lack of integrity of the compartmentation. Yet tests by Karuse (2017) [87] have shown that well-designed wall-to-wall and wall-to-floor connections can succeed in isolating a fire compartment from the surroundings with no smoke, heat or fire penetrating through the connections; the temperature inside and behind the joints remained very low in those tests.

Fire may also spread to the nearby areas through panel-panel joints. This has been observed in the tests by Osborne et al. [97] described in Section 2.4.3 and the tests by Hevia [93] in Section 2.4.2. In the former, flame-through at the panel joints was observed for the tested cross-laminated timber (CLT) floor assemblies under load, and was noted as one of the predominant failure modes of CLT floor assemblies under mechanical loads and fire. In the latter, CLT wall panels were jointed through a half-lapped joint. During the tests, the flame spread to outside of the fire compartment.

Another path for the flame to spread to other regions is through the compartment openings. This was observed in the tests by Karuse [87] in Section 2.4.1. When a fire is ventilation-controlled, there is insufficient supply of oxygen to allow all of the fuel (products of pyrolysis) to burn within the compartment. As a consequence, unburnt fuel can escape from the compartment (e.g. through the window openings) and burn in an external fire plume. In the case of compartments with timber linings, there is a larger exposed area of fuel than for noncombustible linings – but no additional oxygen. It is logical, therefore, to expect more burning to occur externally. It is possible to prevent the spread of external flames along the façade through fire stopping measures such as spears, as highlighted in the fire incident in Marseille described in Section 2.1.1 [32].

Finally, the failure of integrity can also be due to the integrity failure of CLT panels themselves. Integrity failure of CLT panels can be caused either by the delamination of CLT panels or by the sustained burning of CLT panels. Delamination has been observed for timber members directly exposed to the fire and having inadequate adhesives (i.e. not fire resistant). On the other hand, sustained burning occurs if the timber members are directly exposed to fire and meanwhile no self-extinction occurs. The problem of self-extinction is complex and can be related to high mass-loss rate of timber. As a result, a CLT panel may burn continuously until burn-through, resulting in the integrity failure of CLT panels themselves, even in the absence of delamination. The prerequisite for both delimitation of CLT panels and sustained burning of CLT panels is that the timber surface is directly exposed to fire. CLT compartments can be fully protected, partially protected or not protected at all. For the protected CLT panels, the ignition of CLT panels usually occurs after the delamination of the fire protection layers (e.g. gypsum board). The failure of fire protection layers can be due to the connection failure of the fire protection layers, the insufficient thickness of the fire protection layers or other poor-design practices for fire protection layers.

4.1.2 Failure of thermal insulation

Compartmentation may be lost due to an insufficient thermal insulation from the boundaries of the enclosure. The insulation is the ability of a separating element of building construction, when exposed to fire on one side, to restrict the temperature rise of the unexposed face below specific limits. The limits are generally taken as 140 K average temperature rise over the whole of the non-exposed surface, and 180 K maximum temperature rise at any point of that surface.

Generally speaking, timber panels with sufficient thickness provide a very good thermal insulation capacity. However, one possible cause of insulation failure is if the thickness of the CLT panels is insufficient with respect to the severity of the fire. In Section 4.2, a finite element model is used to evaluate the insulation capacity of CLT panels of different thicknesses. In design practice, the typical range of the CLT panel thickness is between 80 mm and 200 mm, which provides insulation at the unexposed face for a relatively long-duration fire exposure. However, if the heating leads to the delamination of CLT panels, the residual thickness of CLT panels may be insufficient in maintaining the relatively low temperature at the unexposed side. Therefore, delamination of CLT panels is also a possible cause of insulation failure. Another possible cause is the sustained burning of the CLT panels, which finally leads to the insufficient residual thermal insulation of CLT panels even without the delamination of the CLT panels. It is thus noted that delamination and sustained burning (i.e. absence of extinction) can lead to both integrity and insulation failure.

4.1.3 Failure of load-bearing capacity

Compartmentation may be lost due to structural failure (loss of stability) of a member that has a load-bearing function necessary for the compartmentation. For example, a floor collapse creates a breach of compartmentation.

The insufficient capacity of a timber member may be due to sustained burning, delamination (for CLT panels), or poor design. Fire exposure results in a reduction of the effective section of the member (through the process of pyrolysis and charring) as well as a reduction in the mechanical properties of the remainder of the section (due to temperature elevation in the uncharred part of the section). These two reduction effects may decrease the strength of a structural member to a level unable to resist the imposed mechanical loads. Besides the strength reduction, one need also to consider the possible instability phenomena amplified by the increase in slenderness for the charred member. The reduction in capacity would indeed become too severe if the effect of fire exposure is too severe, as is the case if the panel loses layers at once (delamination), if the char front in the member continues its progression indefinitely (sustained burning), or if the design did not have sufficient reserve in capacity for the given fire exposure in the first place (poor design).

On the other hand, an excessive demand on the member can result from either excessive mechanical loads or excessive heating. The excessive thermal demand may lie in the fact that the design fire load may be lower than the actual fire load in the compartment. Specifically in the case of timber construction, however, this excessive thermal demand may also be due to additional fire loads from the combustible construction materials themselves which contribute to feeding the fire. This contribution of the structural timber to the fuel load could lead to a fire much more severe than considered in design, eventually resulting in structural failure and therefore breach of compartmentation and fire spread to the whole building.

4.2 Case study: Heat transfer through a CLT panel

In this section, the thermal insulation of CLT panels is studied numerically using the nonlinear finite element software program SAFIR [201]. First, the ability of the numerical analysis to capture heat transfer in wood sections is validated against test data. Then the thermal insulation of CLT panels of different thickness is analyzed.

4.2.1 Validation of the numerical method

A series of spruce timber specimens were tested [202] under ISO 834 standard fire [203] for 90 minutes on one side, with all other sides of the specimens sections protected by gypsum plasterboard or rock fiber. Temperatures were measured at a depth of 6, 18, 20 and 42 mm from the surface exposed to fire. The specimens had a moisture content of about 12% with a dry density of 420~430 kg/m^3.

A 2D finite element model was built using conductive solid elements in SAFIR [201] to replicate the test results, using the material model WOODEC5. For the side exposed to fire, the emissivity and convection coefficient were assumed to be 0.8 and 25W/m^{2}K, respectively, as recommended by EN 1995-1-2 [204]. The other sides of the model were assumed to be adiabatic.

Figure 52 shows the SAFIR model and the temperature distribution in the cross section of the timber specimen at 3600 seconds. Figure 53 shows the comparison of the numerical and experimental results. The dash black lines are the average measured temperatures at each depth. The numerical results agree with the experimental results. This validates the heat transfer model and effective thermal properties of wood for an exposure to the standard ISO fire.

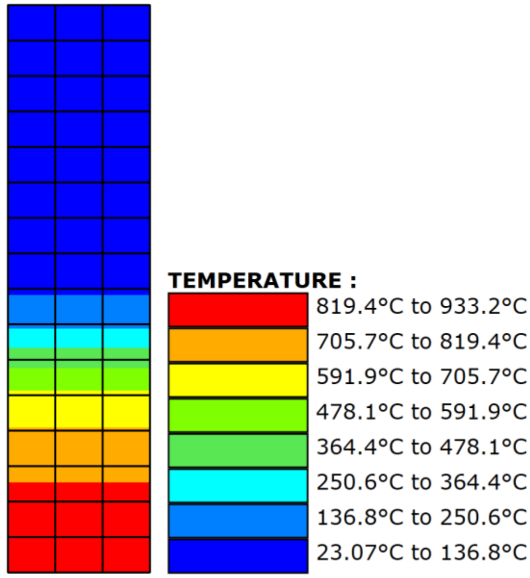


Figure 52. Temperature distributions within the cross-section of solid timber after 60 minutes of fire exposure.

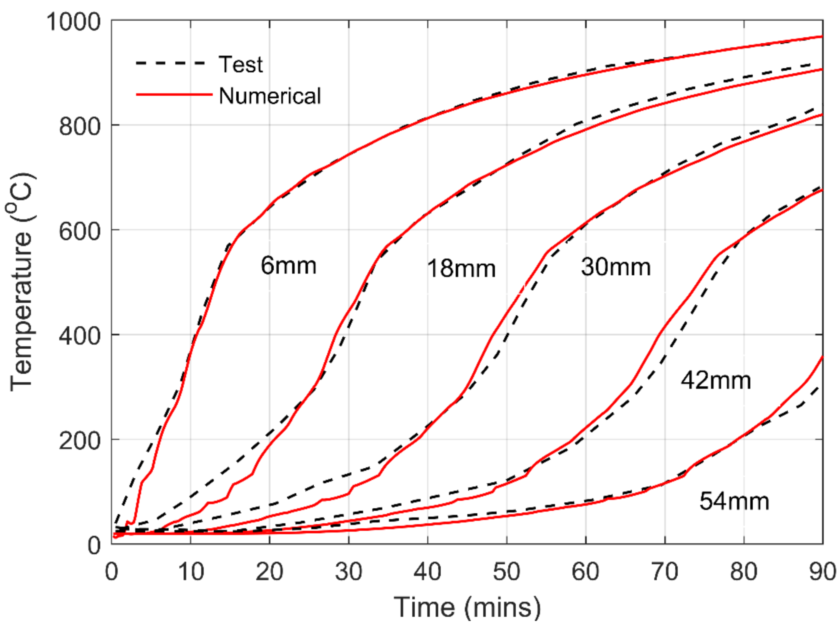


Figure 53. Experimental [16] and numerical temperature evolution at various depth across the cross section of a spruce timber specimen subjected to ISO fire.

Another fire test was conducted on a CLT panel specimen as reported in [205]. The CLT panel was 150 mm thick, 600 mm wide and 5600 mm long. The specimen was built using five bonded layers of 42, 19, 28, 19, and 42 mm, as shown in Figure 54. Polyurethane (PU) adhesive was used to manufacture the tested panels. The specimen had a moisture content of about 12% with a density of 450 kg/m^3. The bottom side of the specimen was exposed to heat in the furnace, exposed to the standard ISO 834 standard fire. No delamination of CLT panels occurred in the tests.

Figure 54. Cross-section of XLAM panels.

A 2D finite element thermal analysis was conducted in SAFIR. In the model, the CLT cross section consists of five layers, with each layer oriented perpendicular to adjacent layers. In the definition of material models, the direction of each layer is oriented as that in Figure 54. No delamination behavior of the charred layer was considered in the numerical modelling. The adhesive layer between the CLT layers is relatively small (less than 0.2 mm) and it was neglected in the model.

Figure 55 shows the 2D SAFIR model and the temperature profile across the cross-section of the CLT panel specimen at 3600 seconds. Figure 56 compares the experimental and numerical temperature history curves recorded at depth 21 and 52 mm from the bottom surface that was exposed to fire. The experimental and numerical temperature history curves at 21 mm depth agree very well. The curves recorded at 52 mm depth show a good agreement from the beginning till after 60 minutes fire exposure. At 60 minutes, the numerical temperature starts to increase faster while the experimental temperature maintains approximately the same rate of increase for an additional 20-25 min, at which point the experimental temperature increases suddenly and exceeds the numerical temperature. This change of rate in the test happens at around 85 min when the temperature crosses the charring temperature.

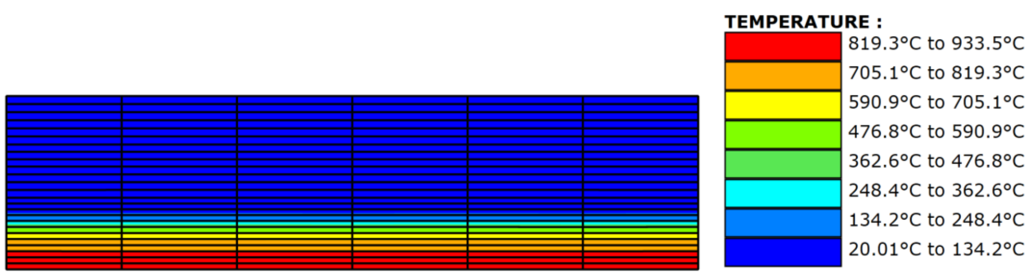


Figure 55. Temperature distributions within the cross-section of the CLT panel specimen after 60 minutes of fire exposure.

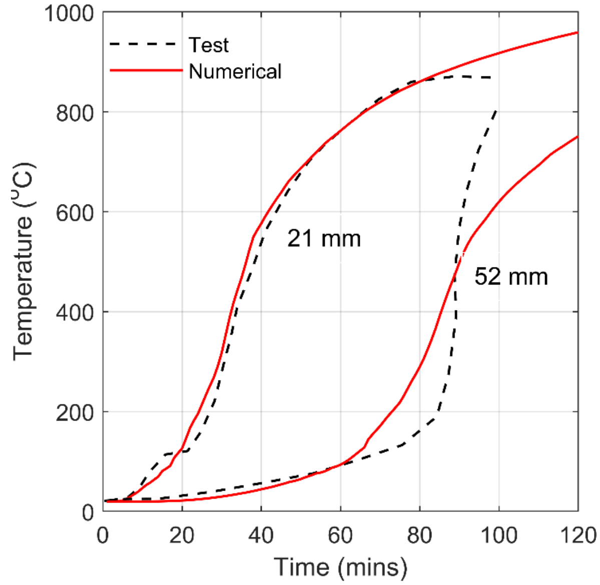


Figure 56. Comparison between predicted and measured temperatures for CLT panel in fire.

4.2.2 Thermal insulation of CLT panels of different thicknesses

A parametric numerical analysis is then conducted to evaluate the temperature rise on the unexposed face for CLT panels of different thickness. The typical thickness of CLT panels ranges from 75 mm to 200 mm, with a layer thickness between 20 mm and 45 mm. The number of layers usually is an odd numbers (e.g. 3, 5, 7 and 9) and should be not less than 3. Three-layer, five-layer, seven-layer, and nine-layer CLT panels were analyzed, with layer thickness of 25 mm. The length of the CLT panel section is 600 mm. The moisture content of the CLT sample was assumed as 12%, and the corresponding initial density was 490 kg/m^3.

The bottom side of the CLT panels is exposed to ISO 834 fire followed by a cooling phase, as shown in Figure 57. Three different heating durations are considered, 1 hour, 2 hours and 3 hours. The cooling rate during the cooling phase is 5 °C/min. The emissivity and the convection factor are assumed to be 0.8 and 35 W/m^{2}K for the bottom surface. The top surface is exposed to ambient temperature 20°C, with an emissivity of 0.8 and a convective coefficient of 4 W/m^{2}K. The two side surfaces are considered as adiabatic. In the thermal analysis, it is assumed that fire-resistance adhesive was used and thus no delamination occurred. The adopted gas temperature-time curve is also a simplification and does not account for the possible sustained contribution of the CLT panel itself (self-extinction is assumed). The objective is to provide a simple assessment of the insulation property of the panel based on a conductivity model (Fourier equation with effective properties).

Figure 58 shows the temperature distribution in the CTL panel sections after 60 minutes of fire exposure. The heat penetration depth is similar regardless of the panel thickness, with a penetration depth of isotherm 300°C of about 43 mm (charring rate 0.72 mm/min). Figure 59 shows the maximum temperature reached on the unexposed side. As shown in Figure 59, panels of 125 mm thickness and above fulfil the thermal insulation criteria for the 3 hour temperature-time curve including decay phase. Only for the thin panel (75 mm) is the temperature rise on the unexposed face excessive for the 2 and 3 h fire scenarios. This simple analysis suggests that, as long as delamination can be avoided and self-extinction guaranteed, based on pure conduction across the section, CLT panels of 125 mm thickness and above provide sufficient thermal insulation for a compartment boundary when exposed to the fires plotted in Figure 57.

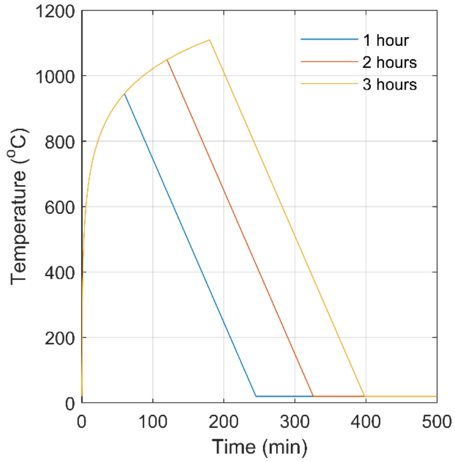


Figure 57. Fire curves.

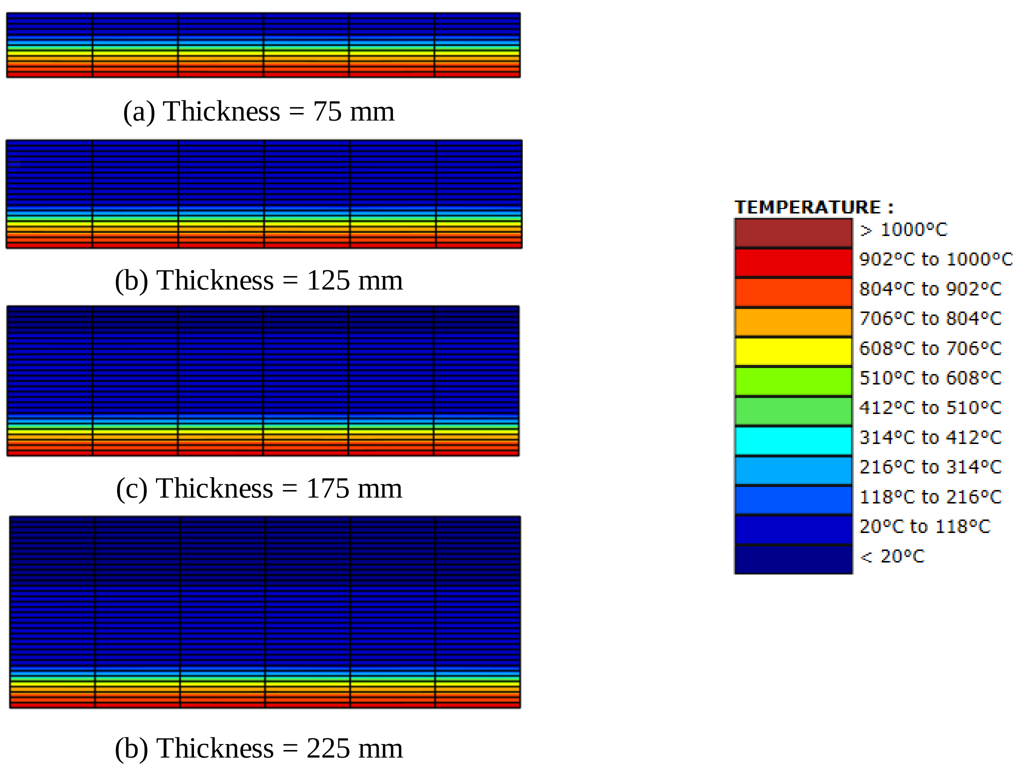


Figure 58. Temperature distributions within the cross-section of the CLT panel specimen after 60 minutes of fire exposure.

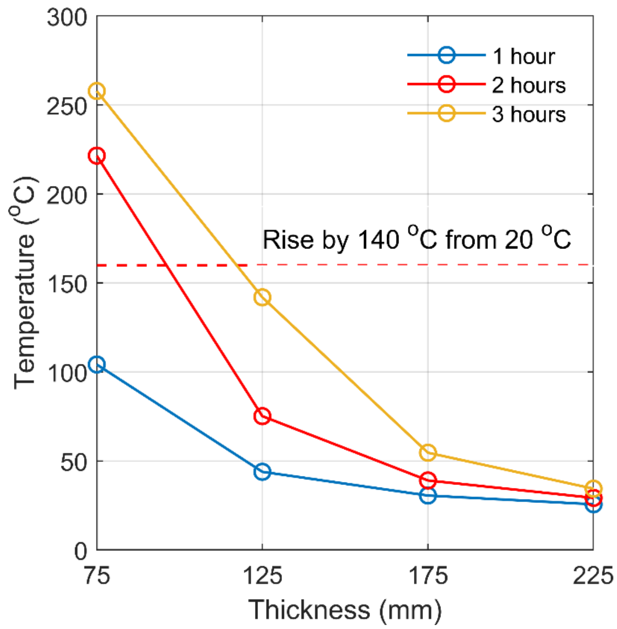


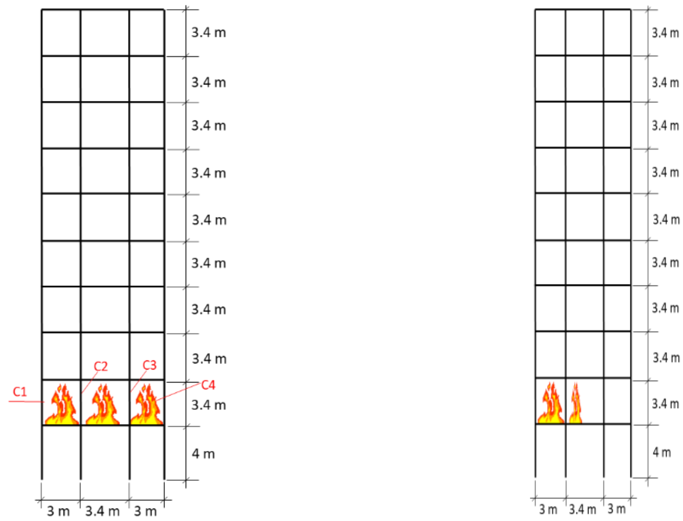
Figure 59. Temperature at the unexposed side of a CLT panel as a function of the panel thickness and fire duration.

4.3 Case study: Timber frame subjected to fire

In this section, the thermo-mechanical response of a structural frame part of a multi-story mass timber building is analyzed using the nonlinear finite element software SAFIR [201]. Analysis of the thermo-mechanical response is important to assess the possibility of structural collapse under fire. Collapse of high-rise building structures pose a risk for brigades and first responders inside and in the vicinity of the building, as well as a potential risk for surrounding structures and fire spread to the surrounding area (considering the amount of combustible material that is spread).

4.3.1 Description of the prototype building

The studied structure is a ten-story mass timber frame, as shown in Figure 60. This frame is adapted from the prototype 10-story mass timber building presented in the NHERI TallWood Project [206]. The story height is 4 m for the first story and 3.4 m for the other stories. The frame consists of 3 bays with end spans of 3 m and a central span of 3.4 m. The beams and columns are glulam members, with sizes given in Table 3. The floor system consists of glulam timber beams, CLT deck, and concrete topping slabs, as shown in Figure 63. The dead load is 3.35 kN/m^2 while the live load is 3.11 kN/m^2 [206]. The tributary floor width in calculating the gravity load of this frame is 3.5 m. The 2D frame is part of a compartment of 9.4 m length by 7 m width by 3.4 m height. Based on the layout of the compartments, a total surface area of 100 m^2 of CLT panels is present in each compartment; this includes three CLT shear walls and the CTL ceiling.



(a) Fire over the entire 2nd story (b) Fire over half of the 2nd story

Figure 60. Prototype 10-story mass timber frame and studied fire scenarios.

Table 3. Column and beam sizes.

Member	Size, mm x mm (in. x in.)
Column (Floor 1-2)	311x381 (12.25x15)
Column (Floor 3-6)	311x343 (12.25x13.5)
Column (Floor 7-10)	311x305 (12.25x12)
Beam	311x343 (12.25x13.5)

The layup combination of the glulam members is 24F-1.8E. The allowable strengths of 24F-1.8E can be obtained from the ASD reference values in [207], and are listed in Table 4. The average and characteristic strengths are then derived from the allowable strengths, as shown in Table 4 [207][208] [209]. The average strength is estimated by multiplying the ASD reference values by a factor of 2.85 for bending and tension strengths and 2.58 for compression strength [208][209]. The Young modulus provided by the ASD reference values is the average apparent Young modulus, which is multiplied by 0.95 [210] to yield the average true Young modulus listed in Table 4. The characteristic values are obtained by multiplying the average values by an adjustment factor of (1-1.645 σ), with σ the standard deviation, considering a coefficient of variation 0.16 for strength and 0.1 for Young's modulus [208][207]. Finally, the material properties used in the numerical analysis consider the modification from load duration, moisture content, member size, and also adopt partial safety factors specific for fire situation, according to Eurocode 5 [204]. The material properties used in the analysis are listed in the last column of Table 4.

Table 4. Material properties.

	Allowable strength (MPa)	Average strength(MPa)	Characteristic strength (MPa)	SAFIR material properties (MPa)
Bending strength	16.5	47.2	34.7	38.9
Tension strength	7.6	21.6	15.9	18.3
Compression strength	11.0	28.5	21.0	24.1
Young modulus in bending	---	13064	10915	12552
Young modulus for axial load	---	11612	9702	11157
Poisson ratio	0.3			

Under the load combination for structural design at ambient temperature (1.5 dead load plus 1.35 live load), the total gravity load applied on the timber frame (demand) is equal to 59% of the capacity at ambient temperature. The capacity is calculated using SAFIR, by increasing the gravity loads proportionally at each story until failure of the structure. Failure occurs in the columns at the first story. Under the load combination for fire design (1.0 dead load plus 0.5 live load) [211], the total gravity load applied on the frame is equal to 18% of the initial capacity. The material properties used for analyzing the capacity are different for the two design situations; for fire design, the initial capacity (at 20°C) is evaluated with the material properties applicable for fire design.

The response of the frame was analyzed under the fire scenarios listed in Table 5. The scenarios consider the following variations: (i) the fire area is either the full area of the second story or half of this area (Figure 60); (ii) the design (content) fuel load density is either that for dwelling occupancy (948 MJ/m^2) or that for office occupancy (511 MJ/m^2); (iii) the beam and column glulam members are either protected by two layers of ½'' gypsum boards or are directly exposed; and (iv) the CLT panel lining of the compartment is either fully protected (0%), partially exposed (50%), or fully exposed (100%). Where CLT panels are exposed, their contribution to the development of the fire was considered. However, the contribution to fire of the glulam columns and beams was neglected in all cases. In total, 18 scenarios were studied (note: the combination of half story fire area and office occupancy was not considered).

Table 5. Fire scenarios considered in the analyses.

	Full story exposed to fire w/ q_f=948 MJ/m^2	Full story exposed to fire w/ q_f=511 MJ/m^2	Half story exposed to fire w/ q_f=948 MJ/m^2
Glulam members insulated	0%	0%	0%
	50%	50%	50%
	100%	100%	100%
Glulam member exposed	0%	0%	0%
	50%	50%	50%
	100%	100%	100%

4.3.2 Description of the numerical model

Fire model

The story height is 3.4 m. The ratio of opening area to the total surface of each compartment (opening ratio Av/AT1) is 0.045, with opening height of 1.5 m. Thus, the corresponding opening factor is 0.055 [167]. The weighted thermal property of the enclosure, b, is 762 J/m2 $s^{1/2}$K. The combustion efficiency is 0.8. The density of CLT (ρ) is 490 kg/m^3 and its net heat of combustion ($H_{c,net}$) is 17.5 MJ/kg. The effect of the sprinkler system. Self-extinction of the CLT panels is assumed.

The heat release rate (HRR) in the compartment depends on the contribution of the exposed CLT. This HRR is evaluated for the different cases using the method of Section 3.4.3. As a sample of results, Figure 61 shows the HRR curves for the scenarios where the whole second story is exposed to a fire with content fuel load equal to 948 MJ/m^2, for different degrees of exposure of the CLT panels. Results are plotted for both the external flaming model and the extended fire duration model. It can be seen that the fire is ventilation controlled, already when the CLT panels are protected and therefore do not add to the fuel. In Figure 61, the self-extinction model is assumed, meaning that the final charring depth of timber (d_{char}) is calculated according to Eq. 11 and the fuel load per square meter of exposed timber surface ($q_{tmb,CLT}$) is calculated according to Eq. 13. The total fuel load contributed by the exposed timber is represented by the yellow area. In the scenarios where only half the second story is exposed to fire, the maximum surface of exposed CLT panels is 50 m^2, i.e. half of that for the scenarios where the entire second story is exposed to fire.

The fire development in a compartment is calculated with the zone-model numerical tool Ozone [180], using the input heat release data discussed above. Table 6 lists the properties of the lining materials, used to determine the thermal properties of the boundaries of enclosure. The compartment has four partition walls with thermal properties similar to wood and two composite CLT-concrete floors. The maximum fire floor area is 66 m^2 for the scenarios where the whole second story is exposed fire and 33 m^2 where half the second story is exposed to fire.

Table 6. Summary of the enclosure thermal properties used in the zone model.

	Thickness (mm)	Density (kg/m3)	Conductivity (W/mK)	Specific heat (J/kgK)	Real emissivity at hot surface	Real emissivity at cold surface
Wall	314	490	0.12	1530	0.8	0.8
Ceiling	175	490	0.12	1530	0.8	0.8
	57	2300	1.6	1000	0.7	0.7
Floor	57	2300	1.6	1000	0.7	0.7
	175	490	0.12	1530	0.8	0.8

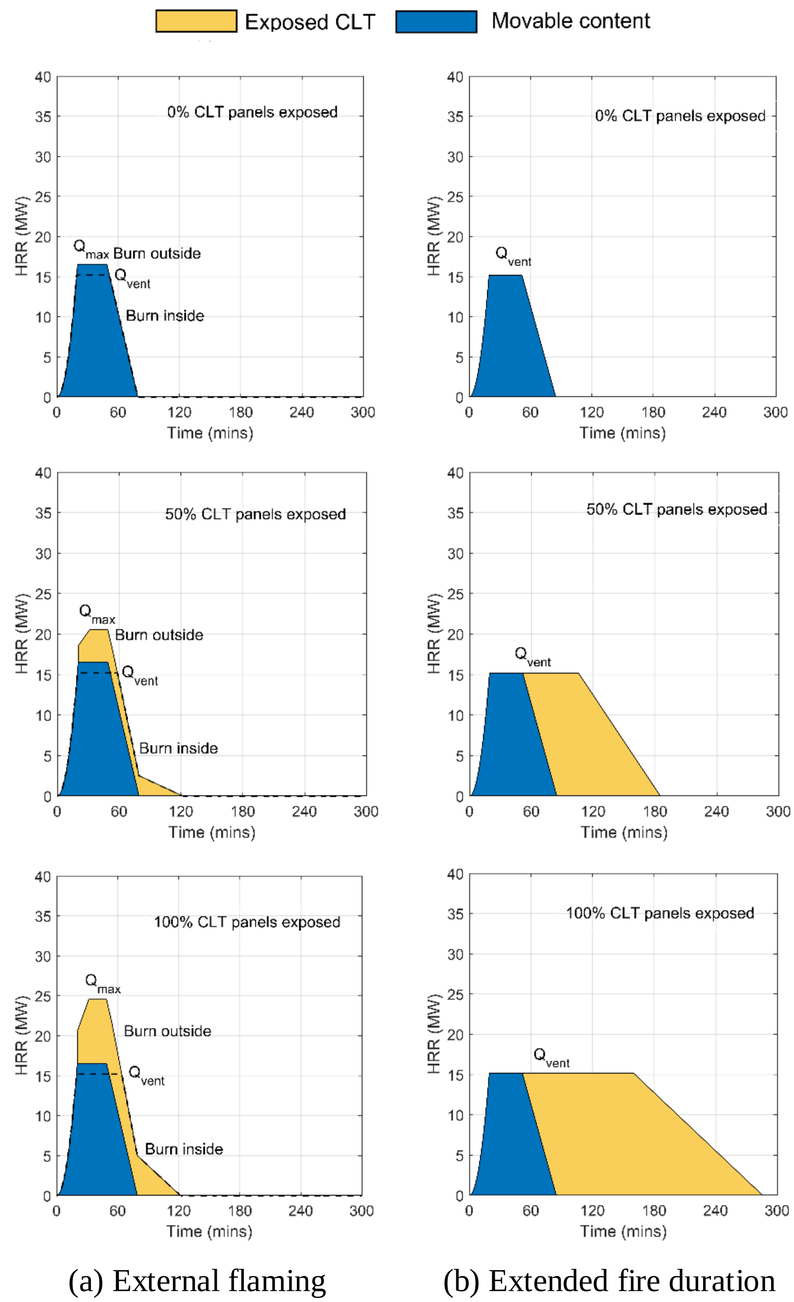
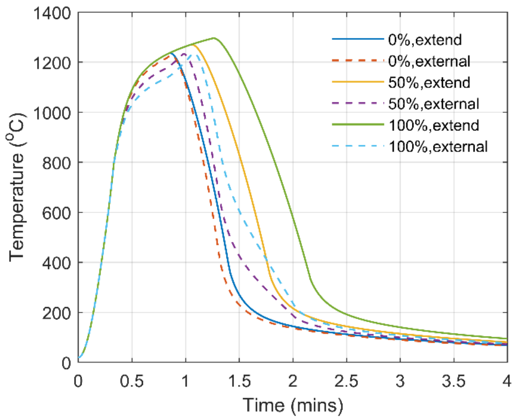
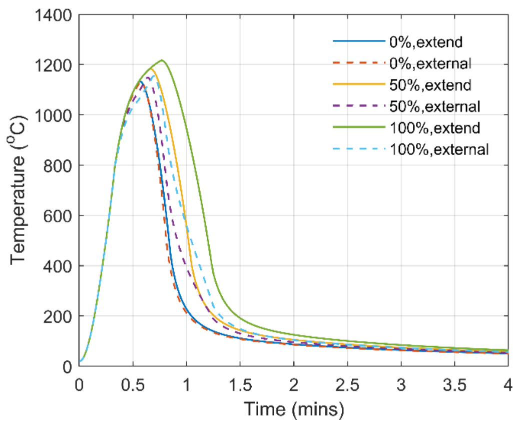


Figure 61. HRR curves for the scenarios where the entire second story is exposed to a fire with content fuel load equal to 948 MJ/m^2.

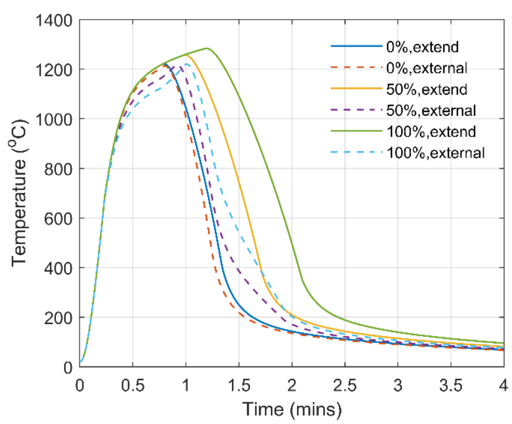
The temperature development of hot gas for different scenarios are shown in Figure 62. For the scenario with all the CLT panels protected, the temperature curve based on the extended fire duration combustion model is very close to that based on the external flaming combustion model. As the percentage of timber surface increases, the heating phase of the temperature curves based on the extended fire duration model becomes longer than that from the external flaming model; and the maximum compartment temperature based on the extended fire duration model is also greater than that based on the external flaming combustion model. The durations of the heating phase of those curves are summarized in Table 7, ranging from 0.57 hours to 1.27 hours.



(a) Fire developing over the entire second story, with 948 MJ/m^2 content fuel load.



(b) Fire developing over the entire second story, with 511 MJ/m^2 content fuel load.



(c) Fire developing over half of the second story, with 948 MJ/m^{2}content fuel load.

Figure 62. Compartment fire curves.

Table 7. Summary of the duration of heating phases (hr).

% of CLT exposed	q_f=948 MJ/m^2, full story		q_f=511 MJ/m^2, full story		q_f=948 MJ/m^2, half story	
	Extended	External	Extended	External	Extended	External
0%	0.85	0.87	0.57	0.57	0.80	0.80
50%	1.07	0.98	0.67	0.63	1.00	0.92
100%	1.27	1.08	0.77	0.70	1.20	1.00

Thermal model

The thermal analysis is conducted next using the finite element software SAFIR. The time-temperature curves of Figure 62 are applied as boundary conditions to the surfaces of the section in contact with the fire compartment (Figure 63). The emissivity is taken as 0.8 for wood and gypsum and 0.7 for concrete. The convection coefficient is taken as 35 W/m²K for hot surfaces and 4 W/m²K for cold surfaces. The material model used for wood is WOODEC5. For glulam timber members protected by gypsum boards (two layers of ½'' boards, modeled as a 25.4 mm thick layer of gypsum), the gypsum boards are modeled with user-defined material models, using the temperature-dependent properties given in [212]. The glulam beams are topped by a CLT decking and concrete slab (Figure 63), which are modeled in the thermal analysis but neglected in the structural analysis.

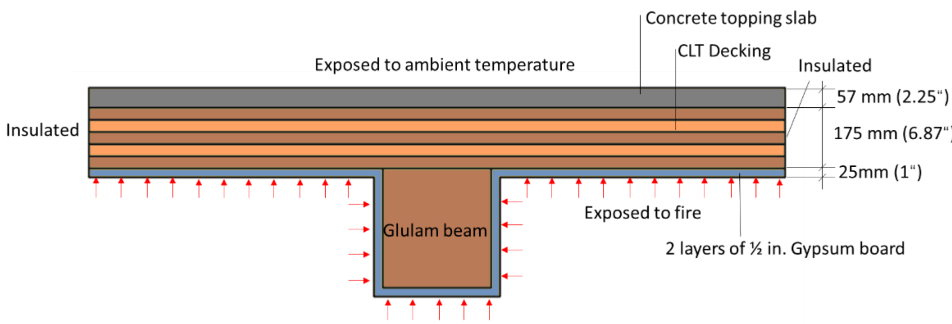


Figure 63. Modeling of glulam beam in thermal analysis.

Structural model

The structural analysis of the 10-story mass timber frame under different fire scenarios was conducted next. The temperature history from the thermal analysis is used in the structural analysis. The gravity load applied to the frame is 1.0 dead load plus 0.5 live load; this loading is applied as a distributed load on the beams. In the structural analysis of the frame under fire, the effect of the initial sway imperfection of the frame is included through application of equivalent horizontal forces [213]. The material model used for the glulam is WOODEC5 while the material model used for gypsum boards is INSULATION without any strength and stiffness. The contribution of the composite CLT-concrete floor to the bending resistance of the beams is conservatively neglected in the structural analysis due to the insufficient research about how to calculate the effective flange width and how to consider the composite effect between concrete topping slab and CLT decks [214][215].

4.3.3 Results of the numerical analyses

A total of 36 analyses were performed, corresponding to the 18 fire scenarios described in Table 5 with, for each one, use of the external flaming and extended duration HRR assumptions (Figure 62). The failure time for each analysis is given in Table 8. The simulations were run until full burnout and dissipation of the elevated temperatures in the sections. 'NA' means that the frame does not fail.

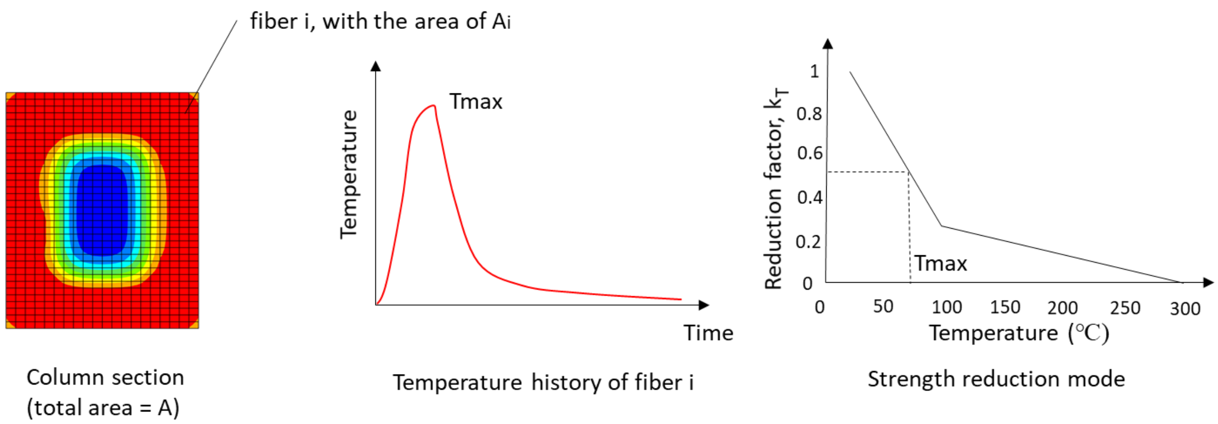
When the frame glulam members are protected by gypsum boards, the frame structure is able to survive until full burnout the different fire scenarios, except the most severe one for which a failure occurs. This most severe scenario is where the full second story develops a fire fueled by both content fuel load of 948 MJ/m^2 and 100% exposed CLT panels, and an extended combustion model is assumed meaning that the released energy remains entirely in the compartment. In this case, the simulation predicts a failure after 7h40 which is after the temperature in the compartment has cooled down. In protected members, the temperature can continue increasing in the core of the section long after the gas temperature has decreased, due to delayed conduction through the insulation and member materials, which explains that failure is still possible at that stage. These results for protected glulam members indicate that, generally, adequate thermal protection (here, with gypsum boards) to timber framing can provide effective fire performance. The only simulated case where failure occurs is based on very conservative assumptions regarding the severity of the fire, with a contribution of all the CLT panels and with an extended fire duration model, which suggests a low probability of occurrence. Other important assumptions of the simulations include self-extinction and no delamination of the CLT panels, and no sprinklers.

A very different behavior is observed when the frame glulam members are exposed to fire (i.e. unprotected). In 15 out of 18 studied scenarios, the frame fails during the fire event. The comparison of Table 7 and Table 8 shows that failure occurs in the cooling phase, generally between 1h and 2h after the beginning of the fire but possibly as late as 4h afterwards. The failure time decreases with an increase of the content fuel load or of the percentage of exposed CLT. This emphasizes the importance of limiting the fuel load from the exposed timber surface by protection layers such as gypsum boards. The 3 scenarios where the frame survives until burnout are cases where a content fuel load of 511 MJ/m^2 is considered with no to little contribution of the exposed CLT. These results for unprotected glulam members show that timber structures are vulnerable to fire-induced failure in the late stage of a fire event (i.e. during or after the cooling phase). An approach based on a charring depth for a standard fire resistance time is not adequate for addressing this vulnerability. Besides, the results show that exposed timber surfaces, such as CLT panels, increase the duration and severity of fires, thereby increasing the probability to have a fire-induced failure in timber structures.

Table 8. Failure time (in hours).

	% of CLT exposed	q_f=948 MJ/m^2, full story exposed to fire		q_f=511 MJ/m^2, full story exposed to fire		q_f=948 MJ/m^2, half story exposed to fire	
		Extended	External	Extended	External	Extended	External
Glulam members insulated	0%	NA	NA	NA	NA	NA	NA
	50%	NA	NA	NA	NA	NA	NA
	100%	7.40	NA	NA	NA	NA	NA
Glulam members not insulated	0%	1.38	1.42	NA	NA	1.51	1.62
	50%	1.25	1.41	2.49	NA	1.42	1.51
	100%	1.24	1.44	1.43	4.27	1.36	1.54

Figure 64 illustrates the heat penetration in the cross section of a glulam member after a certain duration of fire exposure. The temperature-time evolution is different in all fibers of the section. For fibers closer to the core, the peak temperature T_{max} is reached later than for fibers near the perimeter. As a result, the load bearing capacity continues to decrease long after the gas temperature has peaked. The strength reduction factor with temperature shows that strength decreases as soon as the temperature increases from ambient (according to Eurocode). Therefore, even fibers at the core which experience moderate temperature increase have their strength reduced, while fibers near the perimeter experience a large, irreversible loss of strength. Delayed structural failure during or after the cooling phase of a fire arise as a result of these phenomena. This has been noted by other researchers based on experimental results, where it was noted that: "During experiments in which the timber surfaces achieved auto-extinction after consumption of the compartment fuel load, the thermal penetration depth continued to increase for more than one hour (..) thereby increasing the potential for structural collapse during the decay phase of the fire." [216].



Residual axial strength ratio = $\frac{\sum_{i=1}^{N} k_{i,Tmax} \cdot A_i}{A}$

Figure 64. Calculation of residual strength ratio of a column section.

4.4 Discussion

This section started by reviewing possible causes for loss of compartmentation in tall timber buildings. The use of combustible structural and lining materials raises specific issues that may act as underlying cause for fire spread. Factors potentially contributing to failure of the compartmentation include delamination of CLT panels; sustained burning of mass timber members (i.e. no self-extinction) which leads to either structural failure, integrity failure, and/or insulation failure; increased external flaming which leads to façade spread; flame-through at joints or connections; and increase in fuel load which leads to a fire severity exceeding that of the design fire.

Then, the section presented numerical analyses into the thermal and mechanical behavior of timber structures in the fire situation. The analyses provided insights into the conditions under which a failure of compartmentation or stability may occur. The simulations were conducted with SAFIR under physically-based fire exposures ("natural fires") including the cooling down phase to capture the behavior until full burnout, which is crucial for tall buildings. It is noted that, for several of the specific issues highlighted above, prediction through numerical modeling is currently beyond reach due to lack of knowledge and experimental data. Therefore, simplifying assumptions need to be made.

To investigate the thermal insulation criteria, numerical analyses of the heat transfer through a CLT panel were conducted throughout the different phases of a fire. First, the model was validated against experimental tests on spruce timber specimens and on a CLT panel specimen subjected to ISO fire. Comparison of the numerical and experimental data showed that the model can capture the thermal response of the timber specimens under ISO fire. Unfortunately, there is a lack of data regarding the response under physically-based fires. A parametric numerical analysis was then conducted to evaluate the temperature rise on the unexposed face of CLT panels with thickness ranging from 75 mm to 225 mm. The panels were subjected to ISO fire on one face for 1h, 2h or 3h, followed by a cooling phase at a rate of 5 °C/min. The results showed that panels of 125 mm and beyond were able to fulfil the thermal insulation criteria even under the most severe fire (ISO heating for 3h followed by cooling). This analysis assumes that there is no delamination or integrity problem, that the panel undergoes self-extinction, and that effective thermal properties established under ISO fire can be extrapolated to the cooling phase. Under these assumptions, the analysis shows that CLT panels can exhibit a good thermal performance and provide sufficient insulation as compartment boundary.

To investigate stability, thermal-structural analyses of a 10-story mass timber frame were conducted. The frame was made of glulam beams and columns and the compartment was lined with CLT panels for the walls and floors. The case study included a total of 36 configurations, consisting of 18 fire scenarios applied to either protected or unprotected glulam frames. The fire and thermal models showed that exposed CLT surfaces increase the severity of the fire action. Even if the fire is ventilation controlled, the cooling phase lasts longer and has higher temperatures when the CLT is exposed, which leads to deeper charring front and higher temperatures inside the glulam frame members. The structural analysis highlighted the key role of thermal protection of the glulam frame members. When the latter were protected with 25.4 mm thick gypsum boards, the structure survived until full burnout in 17 out of 18 fire scenarios. However, when the frame members were unprotected, structural failure occurred in 15 out of 18 scenarios, including in cases where the CLT lining elements were not contributing to the fire. Structural failure occurred in the cooling phase, generally between 1h and 2h after the beginning of the fire but possibly as late as 4h afterwards, due to continued heat transfer toward the core of the section. An approach based on a charring depth for a standard fire resistance time is not adequate to address this vulnerability to fire-induced failure in the late stage of a fire event. Overall, the results suggests that timber frame members protected with sufficient insulation can achieve resistance to full burnout, under the assumption of self-extinction and absence of delamination of the timber linings, but the design of the insulation should account for the heating and cooling phases of the fire.

5 Conclusion

This report presented a study of the issue of fire safety in timber high rise buildings. It investigated the implications of the use of mass timber for the structural system of high rise buildings in terms of severity of the fire, safety of the fire brigades, and possibility of fire spread. The report was structured in three parts which presented, respectively: (i) a review of case studies of fires in timber buildings and fire tests on timber structures, (ii) an evaluation of the contribution of timber to the fire severity in terms of heat release rate, required water flow for fire brigade operations, and heat flux toward neighboring structures, and (iii) numerical analyses by the finite element method to assess the thermal and structural behavior of timber structures in the fire situation.

The study highlighted specific challenges with the use of mass timber for high rise buildings. The contribution of exposed timber to the fire dynamics, the risk of delamination, the issue of self-extinction, and the behavior until full burnout need to be better understood and quantified. Case studies showed that the contribution of exposed timber to the fire increases the water requirements for firefighters and increases the radiated heat flux to neighboring buildings. As the amount of timber embedded in the building structure largely exceeds the expected amount of content fuel load, it is important to prevent the involvement of this embedded fuel in a fire. Passive protection (encapsulation) plays a crucial role to minimize the possibility of involvement. The construction phase poses specific risks as the layers of protection (including encapsulation but also sprinklers, alarms, etc.) may not yet be present or effective.

For tall buildings in which egress and firefighting are more complex, design for burnout is the safest strategy. For mass timber, designing for burnout requires demonstrating that self-extinction occurs prior to loss of structural stability or loss of compartmentation, and demonstrating that the structure maintains stability during the decay phase of the fire. These two verifications are currently hindered by the lack of experimental data and design methods for the behavior of timber structures under natural fires. Protecting the timber elements with adequate thermal insulation, to avoid their involvement in the fire dynamics throughout the different stages of the fire, appears as a reasonable approach to achieve burnout resistance as long as the abovementioned knowledge gaps remain. Experimental and numerical case studies suggest that protected timber structures can achieve the required level of fire performance. However, a design method based on a sacrificial charring depth under prescribed standard fire is inadequate to demonstrate burnout resistance.

For any building, the risk to have a fire ignite, grow and spread to the whole structure is non-zero. Even when active fire protection measures such as sprinklers are implemented, there remains a probability that these measures fail and the consequences must be assessed, especially for large structures. As of now, tall timber buildings are very rare, but there are many projects under consideration especially in dense urban settings. Should a large number of these projects be built, probabilities dictate that fire accidents will occur in a few of these buildings. This study suggests that the fire risk associated with these tall timber projects will pose challenges that have not yet been adequately addressed, notably in terms of the fire risk during the construction phase, the integrity of the compartmentation until full burnout, the extinction of a fire which would engulf the entire building, and possibly the risk of spread to nearby structures.

Beyond the consequences of fire accidents, the large-scale use of combustible construction materials in dense urban settings also poses a demand on the mitigation resources. It is referred here to the required resources for fire brigades, and the incurred risk for these firefighters. Case studies showed that even mid-size timber buildings could generate fires that require more than a hundred firefighters to prevent spread to nearby structures, while the building under fire often had to be considered as a complete loss. When considering tall mass timber projects of tens of stories, cities will need to be prepared with adequate fire brigade resources in the vicinity of these structures to have a chance at mitigating a fire and preventing its spread to neighboring structures should a major accident occur.

Appendix

A1. Additional Cases of Fire Incidents

Tables A1-1, A1-2 and A1-3 list additional cases of fire incidents.

Table A1-1. Other fire incidents in wood frame buildings in use.

Location	Date	Description of the building	Fire safety measures	How did it spread in the building?	Did the building collapse?	Spread to nearby structures?	Firefighting operations
South Dakota, USA [217]	2017	Three-story 17-unit apartment building of wood frame construction	Smoke alarms, heat detectors, a wet-pipe automatic sprinkler system	Start and spread in the attic	No	No	N.F.
Maine, USA [30]	2007	Four-story 10-unit apartment building of unprotected wood frame construction	A full coverage smoke detection system and a full coverage wet-pipe sprinkler system but no coverage in the attic area	A grill on a third-story balcony ignited wood construction members. The fire spread to the soffit and went undetected into and throughout the attic area; then spread down to the living areas.	N.F.	No	N.F.
Virginia, USA [30]	2003	Four-story 100-unit apartment house of protected wood frame construction	A complete coverage combination heat and smoke detection equipment and wet-pipe sprinkler system, but not cover balconies	The fire started on a third-story balcony, spread up the exterior and entered the attic through roof soffits; then spread horizontally and down to the apartments on the fourth and third floors.	N.F.	No	N.F.
Croydon, UK [218]	2007	A block of five-story apartment buildings of wood frame structure	N.F.	The fire spread through concealed wall spaces to adjacent levels and into the roof space of the flats.	The top floor collapsed plus two floors below.	N.F.	N.F.

Wolverhampton, UK [219]	2012-08-12	A three-story residential building of wood frame construction	N.F.	N.F.	No, but the building was structurally unsound after the fire.	N.F.	40 firefighters; 11 hours
Barking, UK [220–222]	2019-06-09	A six-story block of flats, with timber cladding and timber balconies	Both fire alarm and sprinkler system did not work	Fire spread through wooden balconies	No, but twenty flats were destroyed by the flames and a further 10 were damaged by heat and smoke.	N.F.	About 100 firefighters, 15 fire engines

*N.F. = information not found

Table A1-2. Other fire incidents in heavy-timber buildings in use.

Location	Date	Description of the building	Fire safety measures	How did it spread in the building?	Spread to nearby structures?	Firefighting operations	Collapse of load-bearing timber component?
Worcester, MA, USA [223,224]	1993	Six-story cold storage warehouse with upper floors of heavy timber construction	No sprinkler and fire detection systems	Fire at the 2nd floor and spread via combustible interior finishes	N.F.	Six firefighters died in this incident	Four upper floors collapse to the second floor
New Jersey, USA[29]	2018	Multi-story warehouse of heavy timber construction with saw-toothed roof system	Wet-pipe sprinkler system	N.F.	N.F.	N.F.	N.F.
North Carolina, USA [225]	2016	Two-story residential building of heavy timber construction; wood and rock walls, cedar shingles.	Electric smoke alarms with battery backup, but had no sprinkler system	A large fire was burning above the grill and extending into the residence	N.F.	N.F.	$1.25 million in damage to the house and $175,000 in damage to contents
Seattle, Washington, USA [226,227]	1995	A commercial building construct of heavy timber members; L-shape, with two two-story sections along the north-south axis and a single-story wing extending to the west.	Brick fire walls with opening and breaches	The fire started in the basement of the center section; the floor above the basement collapsed; then the fire spread to the north wing.	No	More than 100 fire fighters; five-alarm according to US classification	Floor collapse due to the failure of a wood frame pony wall that supports the ends of the floor joints.
Iowa, USA[29]	2018	A four-story dormitory was constructed with a heavy timber frame covered by a brick exterior, with wood floor and roof framing, as well as a wood roof deck.	Wet-pipe sprinkler system and hard-wired smoke detectors connected to a central station alarm, but the fire originated in an area above the equipment.	A lightning strike to the roof of the four-story structure	No	N.F.	$500,000 in damage to the building; $300,000 in damage to contents
St. Louis [228]	2013	A three-story brick building of heavy timber construction	N.F.	N.F.	N.F.	Eighty firefighters; four-alarm fire	The warehouse was destroyed

*N.F. = information not found

Table A1-3. Other fire accidents in timber-frame construction sites.

Locations	Date	Description of the building	Fire safety measures	How did it spread in the building?	Building collapse?	Spread to nearby structures?	Firefighting operations
Salford, UK [11,229,230]	2010-08	A complex of wood frame construction	N.F.	N.F.	No, but major damage to 30 apartments	No	Last for 8 hours; more than 50 firefighters, with two aerial jets
Colindale, UK [231–233]	2006-07-12	Six-story and five-story blocks of wood frame construction	No	N.F.	Yes	Yes, damage the halls of nearby residence building	Last for 5 hours; 100 fire fighters
Camberwell, UK [234]	2010-01-06	Five-story building of wood frame construction	N.F.	N.F.	N.F.	No	Last for four hours; 75 firefighters, 15 fire engines and 4 aerial appliances
Dorchester, MA, USA [235,236]	2017-07-26	Six-story building of wood frame construction	Sprinklers installed but not active	Fire got into the void space; start at ceiling and then spread to the roof	N.F.	N.F.	More than 125 firefighters
Wilsonville, USA [237]	2019-03-31	Three-story apartment complex of wood frame construction	N.F.	N.F.	Major damage to at least 20 occupied condominiums	Yes	Last for three hours
Renton, Washington, USA [238]	2009-06-30	Five-story timber frame complex (60% completed)	N.F.	N.F.	Totally damaged	Yes	More than 100 firefighters
Kingston, ON, Canada [239–242]	2013-12-17	Four-story student-housing block of wood frame construction	N.F.	N.F.	Yes	Yes, spread to a nearby housing project and a hotel.	Last for almost 6 hours; dozens of firefighters; a helicopter team

*N.F. = information not found

A2. Calculations for the contribution of exposed timber to the fire severity

Table A2-1. Calculation of additional HRR per square meter from exposed timber surface (opening ratio: 0.03; exposed timber surface (1): 50%).

Parameter		Value for C1	Value for C2	Unit
ρ		490.00	490.00	kg/m^3
ρ_{dry}		462.26	462.26	kg/m^3
A_f		65.00	42.00	m^2
A_{T1}		262.00	188.00	m^2
Av/A_{T1}		0.03	0.03	[-]
A_v		7.86	5.64	m^2
A_{tmb}		127.07	91.18	m^2
h		1.50	1.5	m
b		300.00	300 .00	$J/m^2s^{1/2}K$
O		0.037	0.037	$m^{1/2}$
m(2)		0.8	0.8	[-]
$q_{f,mc}$		624.00	624.00	MJ/m^2
$q_{t,mc}$		154.81	139.41	MJ/m^2
Γ		12.62	12.62	[-]
β_o		0.65	0.65	mm/min
β_{par}		1.01	1.01	mm/min
$H_{c,net}$		17.50	17.50	MJ/kg
$H_{c,eff}$		14.00	14.00	MJ/kg
t_o		37.92	34.15	min
$\dot{q}_{tmb,CLT,max}$		0.091	0.091	MW/m^2
Q_{CLT}		11.51	8.26	MW
Self-extinction	d_{char}	76.46	68.85	mm
	$q_{tmb,CLT}$ ($q_{f,CLT}$)	398.67 (779.38)	357.65 (776.45)	MJ/m^2
Full burning	$V_{f,tmb}$	0.31	0.31	m^3/m^2
	$q_{tmb,CLT}$ ($q_{f,CLT}$)	543.91 (1063.30)	489.79 (1063.30)	MJ/m^2

(1) This percentage is the exposed timber surface relative to the total surface of a fire compartment excluding its opening area, which is different from the percentage exposed in Section 4. In Section 4, the percentage exposed is the exposed timber surface relative to the total surface of a fire compartment excluding its floor area and opening area.

Table A2-2. Fire flow and water supply by room (opening ratio: 0.03; exposed timber surface: 50%).

Parameter	C1	C2	Unit
A_f	65.00	42.00	m^2
RHR_f	0.25	0.25	MW/m^2
Q_{mc}	16.25	10.5	MW
Q_{CLT}	11.51	8.26	MW
F_{mc}	6.25	4.04	L/s
F_{CLT}	4.43	3.18	L/s
S_{mc}	20280,00	13,104.00	L
$S_{CLT,selfext}$	25329.70	16305.36	L
$S_{CLT,burn}$	34,557.25	22,329.30	L

Table A2-3. Summary of required fire flow and water supply.

Percentage of exposed CLT (%)	Case number	F (L/min)	Percentage of F due to exposed CLT (%)	Self-extinction		Full burning	
				S (L)	Percentage due to exposed CLT (%)	S (L)	Percentage due to exposed CLT (%)
0	Case 1	6	0	20,280	0	20,280	0
	Case 2	33	0	107,328	0	107,328	0
	Case 3	99	0	321,984	0	321,984	0
25	Case 1	8	26	32,945	38	37,559	46
	Case 2	45	27	174,293	38	198,772	46
	Case 3	135	27	522,878	38	596,315	46
50	Case 1	11	41	45,610	56	54,837	63
	Case 2	57	42	241,258	55	290,216	63
	Case 3	171	42	723,773	55	870,647	63
75	Case 1	13	52	58,275	65	72,116	72
	Case 2	69	52	308,222	65	381,659	72
	Case 3	207	52	924,667	65	1,144,978	72
100	Case 1	15	59	70,939	71	89,394	77
	Case 2	81	59	375,187	71	473,103	77
	Case 3	244	59	1,125,561	71	1,419,310	77

Table A2-4. Required fire flow and water supply for Cases 1, 2, and 3
(opening ratio: 0.06; exposed timber surface: 50%).

`	F (L/s)	Percentage of F due to exposed CLT (%)	Self-extinction		Full burning	
Case number			S (L)	Percentage of S due to exposed CLT (%)	S (L)	Percentage of S due to exposed CLT (%)
Case 1	11	43	33,377	39	54,837	63
Case 2	59	44	176,522	39	290,216	63
Case 3	176	44	529,565	39	870,647	63

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