ARUP

Arup Guide

Fire Safe Design of Mass Timber Buildings.

Contents

Cover Image
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Tables

Figures

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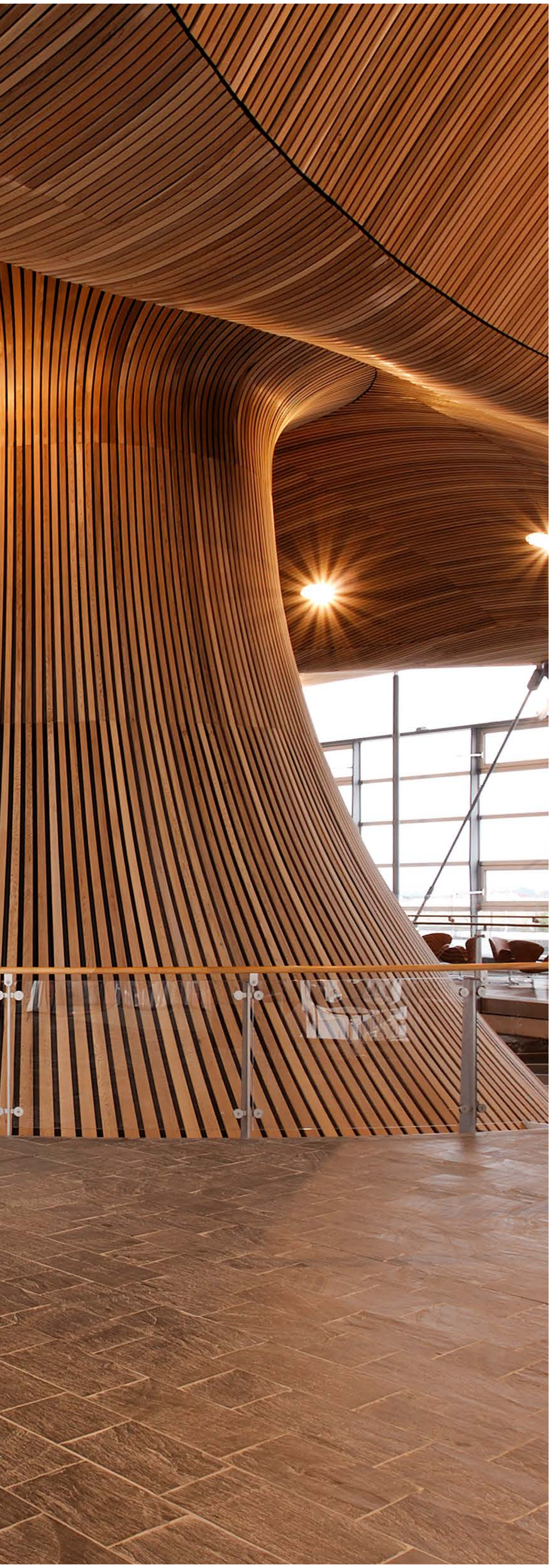

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Executive Summary

The demand to use mass timber in construction is increasing as society seeks to build with more sustainable materials. Building codes and design guidance for using mass timber vary substantially country to country as does the foundation on which the local codes have been developed.

Mass timber is a combustible construction material and may present a hazard for buildings. In a fire, exposed timber can contribute additional fuel to the fire, increasing the intensity and/or duration of the fire relative to a building of non-combustible construction and increasing the collapse risk.

To support the fire safe design of mass timber buildings, Arup has developed this Guide which proposes features to be incorporated into the design for residential, education and business occupancies (up to 50m tall for residential and business use and up to 25m tall for education use) which have a mass timber structure. From Arup's experience, these types of buildings currently have the greatest demand for using mass timber in their construction.

This document is primarily aimed at fire safety engineers, but also provides practical guidance for others involved in the design and construction of mass timber buildings, such as architects, clients, and contractors.

To develop this guidance, Arup has reviewed and analysed an extensive range of public documentation recording the fire dynamics in compartments of varying sizes and with differing degrees of exposed mass timber. Arup has previously co-funded compartment fire experiments and has undertaken a series of large scale compartment experiments that have informed this document. Arup has also gained valuable experience through the development and statutory approval of mass timber building solutions worldwide.

The Guide considers the different hazards that building users (for residential, education, and business occupancies) may experience, such as their familiarity with a building, and whether they are awake and alert or asleep. Additionally, the building height must be considered, as this can impact on firefighting operations and the time taken for occupants to evacuate.

Using the existing compartment fire dynamics data available to Arup, combined with Arup's experience in understanding the fire hazards for a building based upon the occupancy type and height, allows for a qualitative assessment of the resulting risk. Design features such as evacuation strategy, fire protection measures or encapsulation of timber, can be introduced to reduce the fire risk to occupants and firefighters.

The recommendations within the Guide are applicable to CLT Panel Construction, Mass Timber Frame Construction and Timber Hybrid Structures. Other mass timber floor systems such as nail laminated timber and dowel laminated timber floor systems are not directly addressed, though this Guide may be suitable for use with these composite timber systems, and this would be at the discretion of the fire safety engineer using the Guide. The Guide is not applicable to lightweight timber frame construction.

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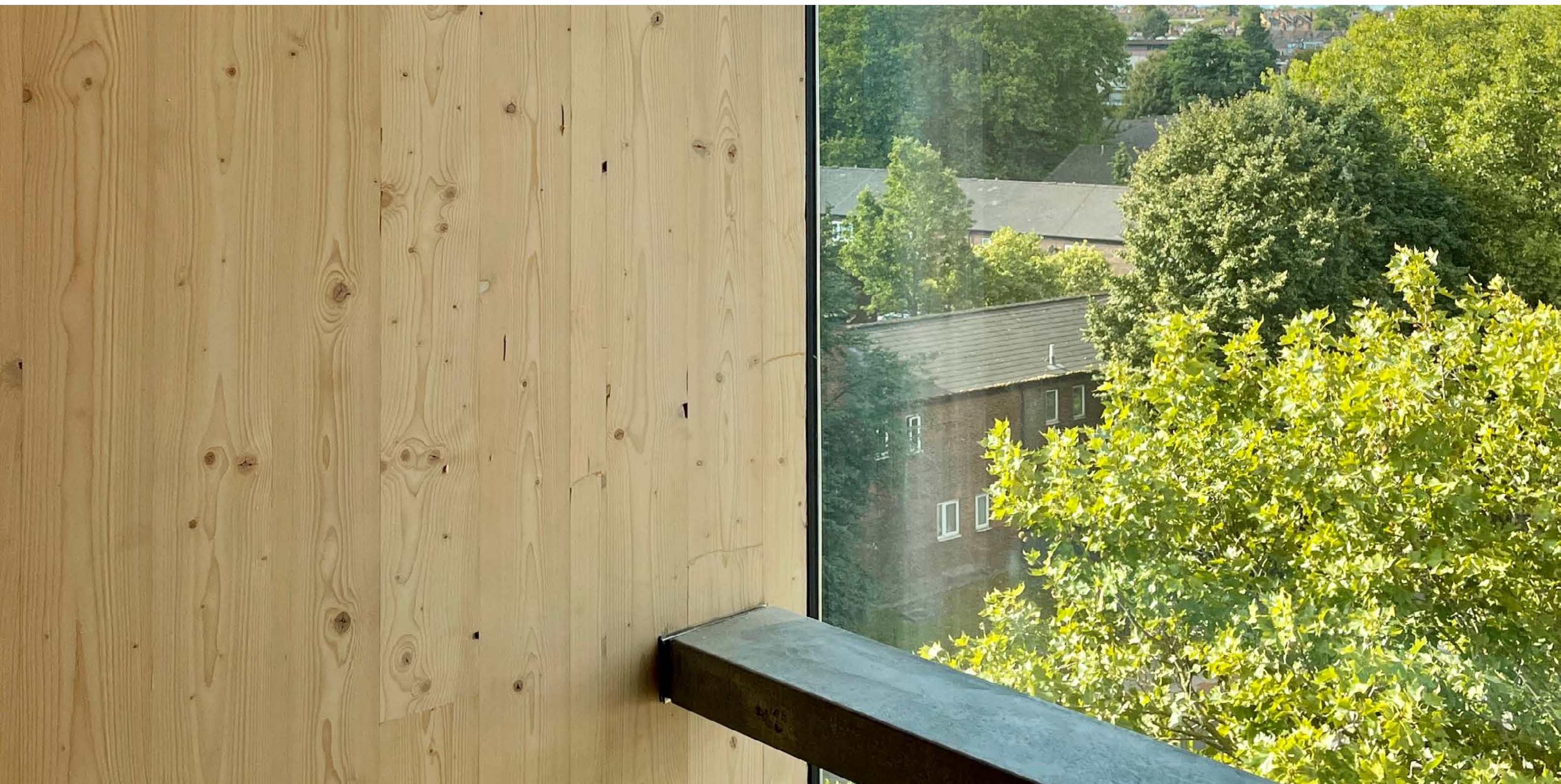

1. Introduction

1.1 Why a timber guide now?

The demand from clients and architects for mass timber buildings is rising globally. The increased use of mass timber in the built environment is seen as one means to contribute to the wider drive to reduce the embodied carbon in buildings. Arup has committed to the UN Sustainable Development Goals (SDGs), including a target of 80% carbon reduction in the construction sector, and to undertaking Whole Life Carbon Assessments of all of its buildings projects – both new and retrofit. Whole Life Carbon Assessments aim to track progress against the UN High Level Climate Champions 2030 Breakthrough Goals, requiring that by 2030 all new and refurbished buildings must be Net Zero in operation and achieve a 40% reduction in embodied carbon.

Many building and fire safety codes, standards and guides were not written for combustible structural materials such as timber. Mass timber may increase the fire risk to the safety of building occupants, firefighters, and neighbouring properties, if not addressed.

This Guide has been written to be used in any statutory jurisdiction; where local codes and regulations exceed the recommendations in this Guide they will take precedence.

1.2 What is the purpose of this guide?

Arup has written a methodology to enable the robust consideration of fire safety of loadbearing (structural) mass timber construction. Due to the slowly evolving large-scale timber fire experimental data and robust timber design guidance currently available to designers, this methodology is conservative and risk-based to enable transparent fire safe design of mass timber buildings. This Guide is written to address fire hazards posed by mass timber buildings such as the additional fuel load when the mass timber is exposed.

The purpose of this Guide is to provide designers with risk-based tools to assist in the design of adequate fire safety in buildings that use a mass timber structure. The approach is to provide a reasonable set of fire safety measures based on the required fire resistance periods for the building structure to achieve the desired fire safety goals. The framework considers both likelihood and consequence of a fire incident. Design solutions vary as a function of building height and building use which influence both the evacuation time and fire-fighting operations within the building. Relevant design parameters include consideration of the allowable extent of exposed timber, the number of escape stairs and additional fire safety measures that should be considered, such as automatic suppression, and controls on the fire performance of materials in the external wall.

The guidance provided herein addresses life safety and achieving building regulatory compliance for buildings where mass timber provides a loadbearing function and is required to have fire resistance under the applicable regulations or code. The requirement for the structure to withstand fire decay and burnout is assumed to also be addressed by applicable regulations or codes and required for high-rise, or high consequence, buildings only.

This Guide may recommend additional fire safety measures, over and above local code requirements, to enhance fire safety in mass timber buildings.

Non-life safety goals such as insurance requirements need to be reviewed and incorporated on a project-by-project basis as part of developing the fire safety strategy. It is recommended that insurance and warranty providers are contacted at an early stage in the design of a mass timber structure as they may impose requirements which exceed that set out in this guidance.

The design solutions proposed are intended to be used as guidance only. It is at the discretion of those using the guide to deviate from the guidance proposed but this should be based upon sound engineering justification within the context of the building project it is being applied to.

1.3 Who is the Guide for?

This Guide is written primarily for fire safety engineers who are designing and specifying fire safety in mass timber buildings. To apply this guidance, fire safety practitioners must have an adequate understanding of mass timber construction and fire safety goals. Design solutions need to be coordinated closely with relevant project stakeholders such as architects, structural engineers, and building services engineers, to demonstrate acceptable levels of fire safety.

The Guide also provides practical guidance and theoretical knowledge for others involved in the design and construction of mass timber buildings, such as architects, clients, and contractors, as well as building control bodies, fire and rescue services and insurers.

1.4 Outcomes of using the Guide

By using this Guide the following outcomes can be achieved:

- Understand the fire hazards associated with selecting mass timber as part, or all, of the structure.
- Understand the design features to mitigate those fire hazards.
- Develop a building solution (combination of design features) to address the fire hazards of the mass timber structure.
- Understand the limitations of the recommendations within this Guide.

1.5 Scope and limitations

The risk-based methodology and derived outcomes within this guide are limited to the following applications:

- Buildings that are predominantly used as businesses, residential or for education purposes only, or combinations of those occupancies up to 50m in height for business and residential use and 25m for educational use.
- Mass timber elements, typically consisting of cross laminated timber (CLT), glulam and laminated veneer lumber (LVL).
- Mass timber construction and associated composite and hybrid construction typologies as described below:
  - CLT Panel Construction.
  - Mass Timber Frame Construction.
  - Timber Hybrid Structures (steel or concrete frame with timber or partly timber floors).

Other mass timber floor systems such as nail laminated timber and dowel laminated timber floor systems are not directly addressed, though this Guide may be suitable for use with these composite timber systems and this would be at the discretion of the fire safety engineer using the Guide.

The Guide is not applicable to lightweight timber frame construction.

Recommendations are formulated for the evacuation strategy, means of egress, fire suppression, compartmentation and firefighting measures, as well as the type and extent of the mass timber structure.

This Guide does not address:

- Super high-rise buildings (>50m in height), complex mass timber buildings (e.g. those with inter-linked floors with atria and open stairs, or where uses are mixed).
- Extension and refurbishment projects where mass timber is used (for example where new mass timber floors are added on top of an existing structure).

These will need the fire safety engineer to develop a full performance-based approach to fire safety.

Other assumptions and caveats of the Guide

- This Guide does not address the fire hazard presented by mass timber structures during the construction phase, when fire safety measures are not yet complete. This must be assessed carefully during the design stage so that the risk of fire during construction is adequately mitigated.
- Glulam mass timber elements typically use glues that maintain bond line integrity in fire. The guide is based on the assumption that this is the case.
- The use of timber as part of the façade or as exterior cladding is only supported in defined arrangements where the consequences of fire spread via the façade is low, i.e. low-rise buildings that do not require subdivision with compartment walls or floors. Where mass timber is used in the external wall where a building is divided by compartment floors or walls, a performance based design or project specific façade fire testing would be required considering any exposed timber within the building (refer to Section 6.5.2).
- This Guide does not provide detailed design guidance for vertical fire spread via openings (i.e. windows) given limited available research data. However, it does consider this risk holistically as part of the risk-based methodology.
- This Guide is based on the information available at the time of writing and is therefore limited by current research. As a result, the design guidance is necessarily conservative. This Guide will be updated, as appropriate, as advances in mass timber fire safety research are made.

1.6 Deviating from the Guide

The Guide does not preclude the adoption of solutions that use combinations of design features different to those suggested in this Guide, subject to established performance-based design procedures being followed.

The fire safety engineer should consider the technical data when forming their engineering justification, and follow available standards for the development of performance based fire safety design approaches.

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2. Glossary

The following terminology and definitions are used within this Guide. Additional definitions for terminology used in the design of timber structures can be found in the version of EN 1995-1-2 current at the time of publication of this guide (Eurocode 5 or EC5) (CEN, 2014).

Table 1: Glossary of selected terms

Term	Definition / explanation (for the purposes of this guidance document)
Building Height	The following height thresholds are adopted within this Guide. – Low rise: $H \leq 12m$ – Medium-rise: $12m < H \leq 25m$ – High-rise: $25m < H \leq 35m$ – Very high-rise: $35m < H \leq 50m$ – Super high-rise: Above 50m (not covered in this Guide) Definitions for how building height is measured differ between codes. The local code definition should be used.
Burnout	Fire burnout criteria must be agreed between the design engineer and the approval authorities. The criteria for burnout can be based on a minimum heat release rate (<0.5 MW), minimum compartment temperature (<100°C) or temperature being reached within a timber member (<150°C) for example.
Char	Rigid carbon-rich layer formed on the surface of timber undergoing pyrolysis. Char has no loadbearing strength or stiffness. However, it is highly insulating and, therefore, reduces the heat which is conducted into the remaining uncharred timber.
Char debonding	Refer to definition of “Bond Line Integrity in Fire” below.
Char-line	Borderline between the char layer and the residual cross-section, assumed to be equal with the position of the 300°C isotherm.
Bond Line Integrity in Fire	Bond Line Integrity in Fire defines the ability of a mass timber element with a constant rate of temperature increase to char through the bond line between lamella without the char layer separating from the element, or excessive char debonding. Failure of the bond line is also referred to as char fall-off, char debonding, failure of glue line integrity, or delamination and is the behaviour observed in some types of cross laminated timber (CLT) panels where the adhesive between mass timber lamina loses strength when heated. CLT manufactured with certain adhesives have been shown to be prone to this behaviour. Eurocode 5 defines bond line integrity in fire as the ability of the bond line for face bonds to provide stickability between layers in a fire situation.

Term	Definition / explanation (for the purposes of this guidance document)
Compartment	An enclosed space, which may be subdivided, separated from adjoining spaces by fire resisting construction.
Design features	The safety measures (e.g. automatic suppression, etc. that can be adopted to meet the fire safety goals.
Design fire	A specified fire development assumed for design purposes.
Encapsulation (protected timber)	Non-combustible board protection to mass timber that may prevent ignition, charring and other damage for a specified period of time. The aim of encapsulation is to decouple the fire dynamics of combustible mass timber construction from the compartment fire dynamics and is an important control tool in the design of a mass timber building. The specification for application needs to include thickness of non-combustible material, the type and spacings of mechanical fixings and joint protection that has been proven to achieve the acceptance criteria (refer to EN 14135 "Coverings. Determination of fire protection ability"; which is used to inform fire protection ability classifications under EN 13501-2 using the designation 'K_2' or CAN/ULC-S146:2019 "Standard method of test for the evaluation of encapsulation materials and assemblies of materials for the protection of structural timber elements").
Exposed surface	All mass timber surfaces which are not encapsulated as described above.
Exterior / external wall	The wall assembly consisting of the exterior cladding, insulation, water restive barrier and supporting structure.
Flashover	The stage of fire that transitions to a state of total surface involvement in a fire of combustible materials within an enclosure.
Fully developed fire	The state of total involvement of combustible materials in a fire (from BS EN 13943) (also called a post-flashover fire).
Local Codes	Local fire safety codes and regulations in the jurisdiction that the project is located.
Mass timber	Method of designing and constructing multi-storey timber buildings, also referred to as massive timber, heavy timber, solid timber, engineered timber, or Massivholz (German). The term used in this document is mass timber and assumes the timber is load bearing and part of the building structure.
Movable fuel	Combustible content within a room that is expected to be modified during refurbishments, comprising furniture and fittings and surface linings.
MF and MUF adhesives	Melamine Formaldehyde (MF) and Melamine Urea Formaldehyde (MUF) resin adhesives are thermosetting adhesives. Traditionally used for glulam and also used for some CLT.

Term	Definition / explanation (for the purposes of this guidance document)
Opening factor	Factor representing the amount of ventilation depending on the area of openings in the compartment walls, on the height of these openings and on the total area of the enclosure surfaces. Calculated as $A_T/A_W H^{1/2}$, where: – A_T = Internal surface area of walls and ceiling excluding ventilation openings – A_W = Ventilation area – H = Height of ventilation opening
Parametric or natural fire	A design fire scenario determined on the basis of fire models and the specific physical parameters defining the conditions in the fire compartment.
PUR adhesives	Polyurethane (PUR) adhesives are thermoplastic adhesives. Used commonly in CLT due to their production efficiencies and lack of formaldehyde.
Pyrolysis	Combustion behaviour involving thermal decomposition, production of flammable gases and irreversible change in chemical composition (see Appendix A.2.1.1). Pyrolysis of timber produces a rigid layer of char at the exposed surface.
Smouldering	Flameless combustion involving the oxidation of the timber char layer, producing heat. Can occur during and after flaming, providing additional heat to the charring process (see Appendix A.2.1.1, A.2.3.4, and A.4.3.5).
Standard fire	A fire curve adopted for classification or verification of fire resistance, however not reflecting natural fire behaviour as it never decays.

3. Fire Safe Design of Mass Timber Buildings

The fire safety of mass timber construction is a complex technical field and this Guide aims to provide direction, given that many prescriptive fire safety standards were written without considering mass timber.

To develop design solutions, one must understand the fire safety goals being designed for and the impact that mass timber has on the fire hazards present.

3.1 Fire safety goals

Arup's approach to mass timber buildings is based upon the following four fire safety goals:

- Supporting safe evacuation and firefighting access.
- Limiting fire growth within the fire compartment (slowing or preventing rapid fire growth).
- Delivering a suitable period of structural fire resistance (based on the height and use of the building).
- Limiting fire spread beyond the fire compartment (both to other areas of the building or to adjacent buildings).

These fire safety goals can be achieved by various combinations of fire safety systems and building components (design features). The extent of measures required to achieve the goals will be driven by the risk profile of the building.

3.2 Structural fire resistance

The fires that all buildings need to withstand must consider the relevant fire safety goals which will be based upon the height of the building, the use of the building and the number of occupants. For low and medium-rise buildings, structure survival through all credible design fire scenarios may not be a fire safety goal. For most medium-rise buildings, this will need to be agreed between the approval authorities and the project team, so that an informed determination of fire protection and fire safety can be made. High rise buildings are expected to achieve structural survivability in all reasonable fire scenarios.

For this Guide, the fire safety goals related to the structural fire resistance are:

- For low-rise buildings ($H \leq 12m$): Minimal structural fire resistance, given the speed of evacuation and ability for external firefighting, reflective of typical building code fire safety goals. Expectation that the structure would not survive a fully developed fire.
- For medium-rise buildings ($12m < H \leq 25m$): Structural fire resistance that will allow for whole building evacuation and time for reasonable external firefighting response. The structure may not survive a fully developed fire.
- For high-rise buildings ($25m < H \leq 35m$): Structural fire resistance to prevent building collapse for foreseeable and credible worst-case fire scenarios, through fire decay, to enable safe evacuation and internal firefighting.

– For very high-rise buildings (35m < H ≤ 50m): Structural fire resistance to prevent building collapse for foreseeable and credible worst-case fire scenarios, through fire decay, to enable safe evacuation and internal firefighting.

Prescriptive fire resistance requirements have been developed for non-combustible buildings and are prescribed in codes and regulations (Buchanan and Abu, 2017). The use of an exposed timber load bearing structure might alter the expected fuel load (depending on the amount of exposed timber) within the space and the subsequent compartment fire dynamics, should a fire occur. The appropriate fire resistance period for a building therefore needs to be determined based on the derivation of potential fire scenarios and their effect on the structure. The possibility of a fully developed fire (assuming the sprinklers - if present - are not operational and there is delayed firefighting intervention) should be considered.

3.3 Exposed mass timber structure as a fire hazard

Exposed timber within buildings is not a new issue to be addressed for fire safety. Many building codes permit timber as an interior finish and in many cases, permit timber structures to be constructed of exposed loadbearing timber for low and medium-rise buildings.

For exposed individual timber members, their load-bearing capacity is based on the insulating benefits of charring, a process of inherent protection based on the section size and the material properties of timber, as a function of the temperature of the material. Mass timber members can be designed to carry applied forces when exposed to fire, given the rate of charring and insulation is predictable, when exposed to a standard fire.

The methods of determining loadbearing capacity have been historically based on standard fire tests for individual building elements. Building construction is progressing towards more mass timber being used on larger and taller buildings including for use types with sleeping risks (e.g. hotel and residential). The fire safety goals for these types of buildings are different to low-rise structures where mass timber has been more commonly used in the past. It is therefore important that the implications of a fully developed fire within compartments with exposed mass timber structure are properly understood and controlled so that the fire safety goals can be achieved. To assess structural capacity of load-bearing members the depth of char and the associated ‘zero strength layer’ needs to be evaluated, using either variable char rates when designing using natural fires where the rate is based on the heat flux received from the compartment fire, or fixed char rates which are applicable for standard fires. Fixed char rates are not appropriate for use in natural fire assessments.

Exposed mass timber provides fuel and if available in sufficiently large quantities, can impact the room fire dynamics (fire growth rate, fire heat release rate (HRR), fire duration and temperature).

Once the fire has reached full development and all the fixtures and furnishings have been consumed, there are three possible outcomes for the HRR within the compartment (refer Figure 1):

1. Decay of the fire due to the limited area of exposed timber and/or effective protective timber encapsulation and ventilation.
2. Re-growth, where fire growth and decay are followed by re-growth due to CLT bond line integrity failure, or failure of protective timber encapsulation (with possible further decay and re-growth).
3. Continued flaming (or a very long decay period with sustained smouldering in structural elements) due to the area of exposed timber and the ventilation available, with an expectation of structural failure due to the prolonged exposure.

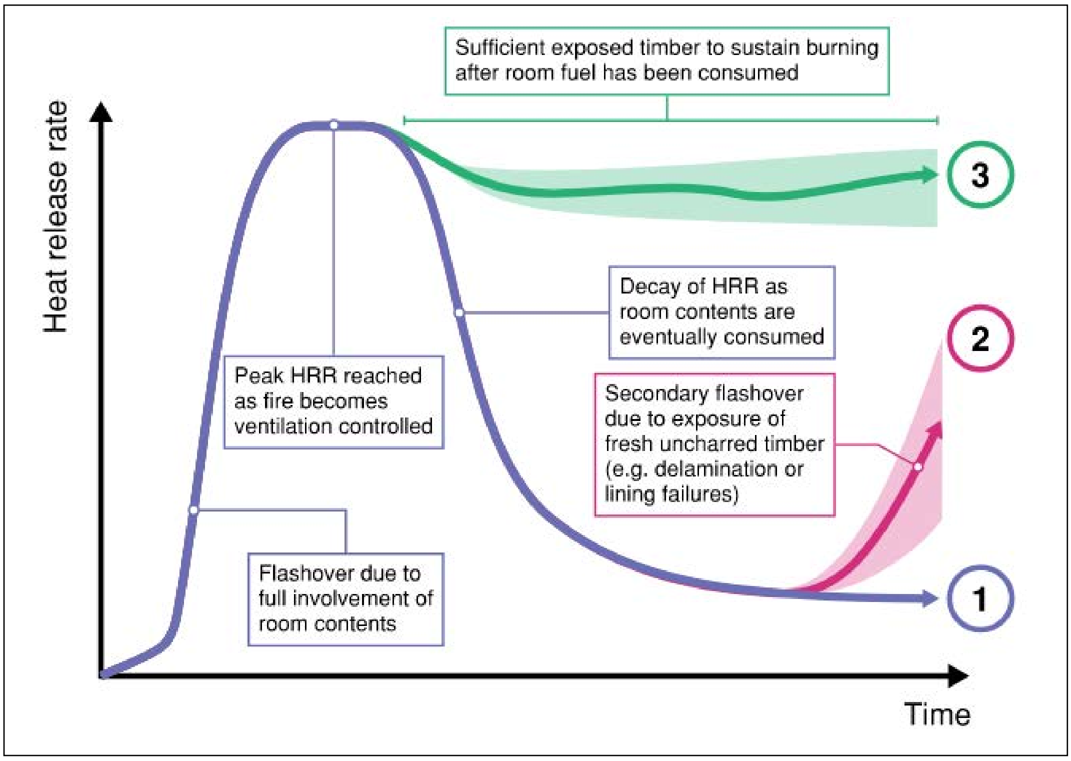

Figure 1: General trendlines of heat release rate (HRR) vs time plots from experimental data of ventilation controlled fires within exposed mass timber compartments

Compartment fire experiments have shown that fire decay may be delayed or not occur if there are significant areas of exposed mass timber, or the non-combustible protection of the mass timber fails and additional timber becomes exposed during the fire, or if bond line integrity failure occurs in the CLT. Once the combustible fuel of the furniture, fixtures, and contents are consumed by the fire, understanding if the radiative heat from the decaying fire will keep the timber pyrolysing or lead to fire decay is vital. Where the fire safety goals require the structure to remain stable for a range of credible design fires, this needs to include the full fire decay and also address possible smouldering.

The determination of HRR and duration of the fire is critical as the char rate and char depth as well as mechanical properties of timber, are proportional to the received heat flux and period of heating, including the smouldering of the timber.

These important topics for determining project specific engineered solutions for char depth (char rates) in fully developed fires and determination of structural response of an exposed mass timber structure in decaying and smouldering fires, are purposely not addressed in this Guide. This is because the fire safety design features proposed for different building types in this Guide are based on minimum fire resistance periods expected in Section 6.4.1 and defer to the methods presented in Eurocode 5 for demonstrating the fire resistance period of elements of structure; it does not rely on undertaking performance based engineered solutions.

Smouldering fires in structural timber are a recently studied hazard (Appendix A.4.3.5, and Mitchell et al., 2023), and require further research to provide guidance to mitigate their occurrence during and after the decay phase.

Designing out voids with exposed timber, avoiding gaps at junctions with structural timber, and detection and suppression by firefighting intervention are currently considered to be the best methods of controlling the structural hazard of smouldering in mass timber.

The additional fuel in compartments from exposed mass timber structure can result in more substantial external flaming, both in relation to flame height and lateral projection of flames (Glew, et al., 2023). That in turn presents a hazard that needs to be considered when assessing external fire spread over the external wall of the building, and from one building to another. Existing design solutions to control external fire spread comprise a combination of control measures, for example through controlling combustibility and arrangement of materials used, and adding fire protective features like cavity barriers that make up the external wall, or demonstrating adequate performance via fire testing.

Our research compared the observed external flaming from our large scale fire experiments with exposed timber, with the fire severity of medium and large-scale façade fire tests, and analysis methods evaluating fire spread risk to adjacent buildings. It found that not all current fire tests and calculation methods can adequately represent the fire severity observed in experiments, and proposed alternatives to use instead.

3.4 Summary of findings from Arup large scale compartment experiments

As part of Arup's commitment to safety and sustainability, working with CERIB (France) and the fire science group at Imperial College London (Hazelab), a series of full-scale fire experiments in a large, purpose-built compartment of 352m^2 were undertaken in 2021. The experiments investigated the impact of large areas of exposed mass timber on the fire dynamics that occur in an open-plan compartment, and to understand how exposed timber structures withstand fire decay and smouldering. Key findings from the series of experiments are:

1. Fire spread across large areas of exposed timber is relatively fast, compared with limited-combustibility ceilings; flame spread rates were observed to be three to eight times greater within exposed timber linings compared to similar sized compartments with non-combustible linings.
2. External flaming is significantly influenced by the exposed timber and hence:
   a. Fire spread occurring via external openings for two floors above the fire floor needs to be considered and addressed, and;
   b. Fire spread to neighbouring properties also needs to take into account the external flaming.
3. Where the exposed mass timber structure is required to provide stability through to compartment burnout:
   a. Transient heating in timber needs to be addressed given the peak temperature in a timber member can occur well after the fire has reached its peak.
   b. Exposed timber columns are vulnerable in the decay phase as char that initially protected the column during the fire now acts as an insulator slowing heat dissipation from the column and impacting material properties for longer (e.g. reducing compressive strength).
   c. The lower portion of exposed columns are vulnerable in the decay phase of a fire, due to the smouldering that occurs in the combusted fuel at the floor.
   d. Smouldering will occur in joints and interfaces for days after the decay of flames and requires firefighting intervention to bring under control.

The outcomes from the experimental series have informed this Guide and will assist in developing robust design fires for building designs. A summary of the key findings of the experiments is provided in Appendix A4. The published papers from this work and videos taken during the tests are available in the table below. Other papers published are included in the references section (Kotsovinos et al., 2021 a-d).

Table 2: Arup large scale compartment experiments

Experiment	Title	Paper	Video
CodeRed #01	Fire dynamics inside a large and open-plan compartment with exposed timber ceiling and columns.	Link	Link
CodeRed #02	Impact of ventilation of the fire dynamics of an open-plan compartment with exposed timber ceiling and columns.	Link	Link
CodeRed #03	The effectiveness of a water mist system in a an open-plan compartment with an exposed timber ceiling.	Link	Link
CodeRed #04	Impact of partial encapsulation on the fire dynamics of an open-plan compartment with exposed timber ceiling and columns.	Link	Link

Figure 2: CodeRed - Experiment 1 with a fully exposed CLT ceiling

3.5 Supporting technical information

This Guide includes appendices to provide supplementary background information from literature and research experiments that substantiates the basis for the risk-based methodology and proposed fire safety features. The appendices are as follows:

- A1 – Hazard and consequence-based approach to fire safety of mass timber buildings
- A2 – Introduction to the fire behaviour of mass timber
- A3 – Review of compartment fire experiments with protected and exposed mass timber surfaces
- A4 – Arup large scale mass timber compartment experiments - CodeRed
- A5 – Influence of compartment size and ventilation openings on fire involving mass timber construction
- A6 – Influence of exposed mass timber on external fire spread hazards

If the fire safety engineer using this Guide chooses to propose design solutions that deviate from the proposed solutions in Section 4 they should consider the findings presented within these appendices when forming their engineering justification.

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4. Design Guidance

This Guide is risk-based and may be used in any statutory jurisdiction. Where local codes and regulations require a higher standard of performance they take precedence. If a project does not fit within the scope of this Guide, it should be addressed through a performance-based approach.

4.1 Types of occupancy and building use

This Guide has been expressly developed to address the potential fire hazard that mass timber structures can pose to occupancy types where there is the highest demand for mass timber, namely residential, business and education. For occupancies not listed, a performance-based approach is recommended, based on the fire safety design goals of this Guide and other compensatory features as needed. For mixed-use buildings or buildings with ancillary accommodation (e.g. mixed office and hotel buildings), the occupancy type resulting in the more onerous requirements of this Guide can be adopted.

Table 3: Occupancy types / building uses within the scope of this Guide

Occupancy Type	Description (Based on UK Approved Document B 2019 descriptions)
Business	Offices or premises used for normal day-to-day business activities.
Residential	Dwellings – Apartment, block of apartments, dwelling houses, condominium, school or other similar establishment used as living accommodation, where persons sleep on the premises. Other – Hotel, boarding house, residential college, hall of residence, hostel and any other residential purpose not described above. Note – Healthcare and institutional residential premises (e.g. aged care homes) are not within the scope of this Guide.
Education	Education establishments, schools for students under the age of 18 years. Note – Higher-education (over 18 years old) premises should be assessed on an individual basis to determine which category the buildings most closely align with (e.g. a faculty staff building could align with ‘business’ use whereas lecture theatres may better align with ‘education’).

4.2 Risk-based methodology framework

4.2.1 Methodology for determining design goals and recommendations

The methodology for determining the appropriate design goals and recommendations is outlined in detail in the following sections, and comprises:

(i) Determination of the consequence of a fire on the building occupants, firefighters and neighbouring properties, considering:

– Occupancy type

– Height of the building

– Evacuation strategy, number of exits, protection of stairwells

(ii) Determination of the likelihood that the fires in the building may be of greater severity than the prescribed duration of fire resistance of the structure (i.e. by the applicable local codes) by considering:

– Whether an automatic fire suppression system is provided

– The extent of exposed area of mass timber structure in a room

– If the mass timber elements used can maintain bond line integrity in fire

(iii) Determination of the acceptable level of risk:

– Check the risk matrix (Table 4) against the tables of design limits for the applicable building occupancy.

– Accept the design if the risk is Trivial or Tolerable. Modify the design if the risk is higher.

A check to ensure that other local regulations are met will also need to be done.

4.2.2 Definition of risk

For the purpose of this Guide, “risk” is defined in line with widely adopted principles for risk-based design:

Risk = Likelihood × Consequence

Where:

– Likelihood is the probability of the proposed timber design resulting in a fire scenario that is more severe than the prescribed fire resistance period of the structure (i.e. by the applicable codes);

– Consequence is the possible outcomes of a severe fire for the building occupants, firefighters and neighbouring properties.

4.2.3 Acceptable levels of risk

This Guide uses five risk rankings, as presented in Figure 3. The risk rankings are classified as either acceptable or unacceptable under this guide and this informs what safety solutions are required.

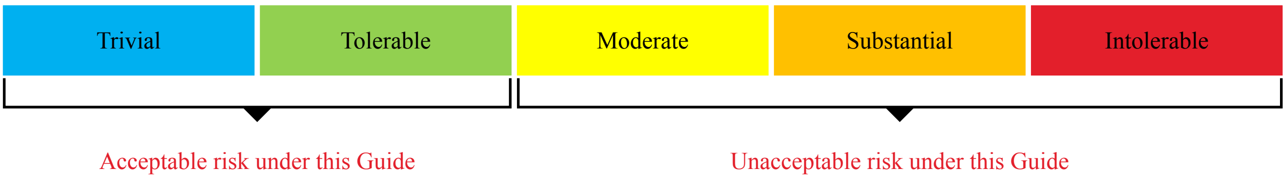


Figure 3: Risk rankings used by this Guide

The combination of hazard likelihood and consequence has been assessed and results in each of the fire risk rankings presented in the form of a matrix in Table 4. The black line separates the acceptable and unacceptable risk within this Guide (with Tolerable and Trivial being acceptable)

Table 4: Occupancy types / building uses within the scope of this Guide

Consequence category → (see Section 4.3.2.4)	Very low	Low	Medium	High	Very high
Extreme	Moderate	Substantial	Substantial	Intolerable	Intolerable
Moderate-extreme	Tolerable	Moderate	Substantial	Substantial	Intolerable
Moderate	Tolerable	Tolerable	Moderate	Substantial	Substantial
Slight-moderate	Trivial	Tolerable	Tolerable	Moderate	Substantial
Slight	Trivial	Trivial	Tolerable	Tolerable	Moderate
Very slight	Trivial	Trivial	Trivial	Tolerable	Tolerable

Likelihood category → (See Section 4.3.3)

4.3 Application of the framework on projects

4.3.1 Application of the framework

The risk methodology follows four parts:

1. First define the consequence category for the building. The life safety consequence of a severe fire for building occupants, firefighters and neighbouring properties is informed by the following:
   - Building use (Section 4.3.2.1)
   - The evacuation strategy (Section 4.3.2.2)
   - Building height (Section 4.3.2.3) and the required structural fire safety goals (Section 4.3.2.4)
2. Establish the maximum allowable likelihood category for the building, using the risk matrix and acceptable risk rankings set out in Section 4.3.3.
3. Identify the design features required to achieve the maximum permissible likelihood category; in some instances, there are different options listed that could be implemented (Section 4.3.4).
4. As a last step, the design features recommended by the guide need to be reviewed in the context of the project, and any country specific requirements (Section 4.3.5).

The process is outlined below in more detail.

4.3.2 Part 1: Define the Consequence Category

4.3.2.1 Step 1: Define the building use (occupancy type)

The potential consequences of fire vary between building use or occupancy type, for the following reasons:

- Pre-movement times (e.g. longer where there is a sleeping risk)
- Familiarity with the building (e.g. hotel guests would be less familiar)
- Greater assistance required in evacuation (e.g. young children in schools)

Table 5 summarises the typical occupant characteristics associated with the different occupancy types or building uses covered by this Guide. Descriptions of the occupancy and building types covered by this Guide are provided in Section 4.1.

Table 5: Occupant characteristics for different occupancy types

Occupancy Type	Occupant Characteristics			
	Age	Sleeping-risk	Likely to be familiar with the building	Persons who may require assistance
Business	Working-age adults	No	Yes	Assume to be present
Residential	All ages	Yes	Yes, for apartments No for hotels	Assume to be present
Education (< 18 years old)	Large proportion of children. Could have some very young children	No	Yes, but might need instructions so may not evacuate immediately. Evacuations are usually heavily managed	Assume to be present. Very young children also need assistance

4.3.2.2 Step 2: Consideration of the evacuation strategy

The evacuation strategy for a building can influence the life safety consequences associated with the building. Evacuation strategies that result in longer evacuation times could present higher risks to persons still in the building.

The evacuation strategies within the scope of this Guide are summarised in Table 6 and this Guide has been developed for simultaneous and phased evacuation strategies only. These two approaches make up most evacuation strategies globally.

Table 6: Evacuation strategies within and outside the scope of this Guide

Evacuation Strategy	Within the Scope of Guide	Brief Description
Simultaneous	✓	The premises form a single evacuation zone. All parts of the premises are evacuated at the same time. For residential, occupants of the dwelling of fire origin only can be alerted to evacuate initially, provided there is an automatic detection and fire alarm system that cascades to simultaneous evacuation strategy as smoke spreads to activate more than one smoke detector inside or outside the initial dwelling.
Phased	✓	The premises is divided into zones separated by fire compartmentation. Zones are evacuated in a controlled sequence of phases, with those zones expected to be at greatest risk being evacuated first.
'Stay put' (e.g. for residential apartments in some countries)	X	Occupants of the dwelling of fire origin are alerted to evacuate, but occupants of all other dwellings are intended to safely remain in their dwellings unless directly affected by heat and smoke. There is no automatic means in place to escalate the alarm to simultaneously evacuate.
Progressive Horizontal Evacuation (e.g. for hospitals, care homes)	X	Patients / occupants are moved into adjoining fire compartments or sub-compartments where they are protected from the immediate threat of fire. From there, further evacuation can be made.

4.3.2.3 Step 3: Determine the building height

The life safety consequences for building occupants, firefighters and neighbouring properties can be considered to increase with building height. This is for various reasons, including:

- More people being within the building.
- Longer evacuation times (due to increased travel distances, queuing or a phased evacuation approach)
- Complex firefighting operations (i.e. more internal operations required where beyond the limits of high-reach external appliances)
- Longer search and rescue times (i.e. more floors, more people to try to find)
- Greater consequence of collapse for surrounding buildings, infrastructure, firefighters and public

For these reasons, prescriptive codes and standards commonly prescribe fire safety measures as a function of building height. The measurement of building height should follow the method outlined in local codes. Table 7 provides five height categories with descriptions for evacuation and firefighting for each category.

The height categories broadly represent the heights at which firefighting techniques and evacuation strategies change, as per the high-level descriptions in the table. A global exercise has been undertaken across the regions in which Arup operates to identify the relevant height categories which correlate to these descriptions.

► Macquarie University Innovation Hub, Sydney, Australia © Murray Frederick

Table 7: Building height, evacuation expectations and firefighting tactics

Building Height	Evacuation Time	Firefighting and rescue tactics
Low-rise ≤ 12m	Evacuation times are short. There will be fewer people who require assistance to evacuate down stairs.	External firefighting effective and often preferred. Internal firefighting provisions may be limited to protected egress stairs.
Medium-rise 12m < H ≤ 25m	Evacuation times are relatively short. Some people will require assistance to evacuate down stairs. Phased evacuation may be adopted in limited circumstances, that can readily be escalated to a full building evacuation where evacuation times remain relatively short.	External firefighting effective and often preferred. Internal firefighting provisions may be limited to fire mains (often dry) and protected egress stairs.
High-rise 25m < H ≤ 35m	Evacuation times increase. Phased evacuation may be adopted. More people will require assistance to evacuate down stairs.	External firefighting usually still possible for the upper floors but may be constrained. Additional internal firefighting provisions such as dedicated firefighting lifts typically provided.
Very high-rise 35m < H ≤ 50m	Evacuation times are relatively long. Phased evacuation likely to be necessary to meet occupancy demands. More people will require assistance to evacuate down stairs.	External firefighting generally ineffective for the upper floors. Reliance on internal firefighting provisions.
Super high-rise [Note 1] > 50m (not covered in this Guide)	Evacuation times are long. Phased evacuation is typical. Total building evacuation may not be instigated. Many people may require assistance to evacuate down stairs.	External firefighting not usually possible for the upper floors. Reliance on internal firefighting provisions.

Note 1: Super high-rise buildings over 50m are outside the scope of this Guide and need to be assessed using performance-based design approaches.

4.3.2.4 Step 4: Determine the building consequence category

The consequence category of a building is defined in Section 4.2.2 as "the possible outcomes of a severe fire for the building occupants, firefighters and neighbouring properties".

To calculate the consequence category for a building, the height is first determined from Table 7. The consequence category for that height is defined as a function of the occupancy type for the building and the evacuation strategy in place as shown in Table 8.

Table 8: Building consequence categories for different building heights and different occupancy types

Occupancy Type	Building consequence category for different building heights			
	Low-rise	**Medium-rise**	**High-rise**	**Very high-rise**
Business	Very slight	Slight-moderate	Moderate	Moderate
Residential Note 1	Slight	Slight-moderate	Moderate	Moderate-extreme
Education (< 18 years old)	Slight	Slight-moderate	N/A Note 2	N/A Note 2

Note 1: Per Table 6, buildings with a 'Stay Put' evacuation strategy are not within the scope of this Guide.

Note 2: This Guide is limited to very high-rise residential and business buildings, and to medium-rise education buildings.

4.3.3 Part 2: Determine the maximum permissible likelihood category

The likelihood category is defined in Section 4.2.2 as "the probability of the proposed timber design resulting in a fire scenario that is more severe than the prescribed fire resistance period of the structure".

The likelihood that the fire might be more severe than the prescribed fire resistance period of the structure is related to the characteristics of the building. Under this Guide, the likelihood is taken to be a function of the following design features:

– Whether an automatic fire suppression system is provided.

– The exposed area of mass timber structure.

– Whether the mass timber elements used can maintain bond line integrity in fire.

Table 9 outlines the five categories used for likelihood under this Guide and explains the different combinations of the above-mentioned design features which bring about the different likelihood categories.

The selection of influencing design controls, and the thresholds and transitions between the different likelihood categories, have been informed by the available standard and compartment fire experiment data involving mass timber construction.

As outlined in Section 4.2.2 the level of risk is defined as a function of:

Risk = Likelihood × Consequence

To achieve a 'trivial' or 'tolerable' risk ranking in a building that has a particular consequence category, fire safety measures need to be in place to reduce the likelihood of a fire that is more severe than the prescribed fire resistance of the structure.

The likelihood category is determined by correlating the consequence category determined from Table 8, with the 'trivial' and 'tolerable' risk levels in Table 4. For a given consequence category, the likelihood is the category (i.e. from 'very low' to 'very high') that correlates with a 'trivial' or 'tolerable' risk ranking.

4.3.4 Part 3: Identify the appropriate fire safety design features

To achieve a 'trivial' or 'tolerable' risk ranking in a building with a particular consequence category, this Guide recommends design features related to likelihood categories.

For business, residential and education use respectively, Table 10, Table 11 and Table 12 summarise the appropriate design features to achieve a 'tolerable' risk ranking.

The design features are interdependent, so all of them are to be adhered to when applying this Guide. The tables include several options for combinations of fire safety features that could be used.

Other fire safety design features are also defined, such as the materiality of external walls and the number of protected egress stairs, as they impact on the overall fire safety solution.

4.3.5 Part 4: Review the design goals in the context of the project

The design goals for fire safety solutions are defined in Section 3.1.

It is important that the practitioner using this Guide to develop fire strategy solutions reviews the design goals within the context of the specific project to check if these are being met by the combination of design features recommend using the risk-based approach.

A check should also be undertaken against local codes and regulations in the jurisdiction the project is located. Where local codes and regulations exceed the recommendations in this Guide they will take precedence.

Table 9: Summary of likelihood categories for mass timber construction with different design controls

Likelihood category	Automatic fire suppression provided throughout the building (Note 1)	Max. number of exposed timber surfaces (wall / ceiling) of compartment (Note 2)	CLT needs to maintain bond line integrity in fire (no char debonding)	Description of the impact of different design aspects on the likelihood category. A(+) denotes design aspects (or combinations thereof) which should reduce the likelihood of timber contributing adversely to fire severity. A(-) denotes design aspects (or combinations thereof) which could lead to increased likelihood of timber contributing adversely to fire severity.
Very low	X	0	X	(-) WITHOUT automatic fire suppression it is likely that a severe fire will develop within the compartment. (+) BUT all mass timber surfaces being encapsulated will reduce the likelihood of the timber reaching elevated temperatures or contributing to the fire.
	✓	0	X	(+) WITH automatic fire suppression it is unlikely that a severe fire will develop, i.e. the suppression system would have to fail for a severe fire to develop. (+) AND all mass timber surfaces being encapsulated will reduce the likelihood of the timber reaching elevated temperatures or contributing to the fire.
Low	✓	30% of 1 surface	✓	(+) WITH automatic fire suppression it is unlikely that a severe fire will develop, i.e. the suppression system would have to fail for a severe fire to develop. (+) AND allowing a limited area of exposed mass timber surfaces (one half d of the area of one face) will reduce the likelihood of the exposed timber significantly contributing to the fire. (+) AND with CLT that exhibits bond line integrity in fire results in predictable HRR decay.
Medium	X	30% of 1 surface	✓	(-) WITHOUT automatic fire suppression it is likely that a severe fire will develop within the compartment. (-) AND without suppression there is increased likelihood of the single exposed mass timber surfaces re-radiating and causing sustained burning. (+) BUT with CLT that exhibits bond line integrity in fire results in predictable HRR decay.
	✓	1 (ceiling or single wall)	✓	(+) WITH automatic fire suppression it is unlikely that a severe fire will develop, i.e. the suppression system would have to fail for a severe fire to develop. (-) AND although there may be a single exposed mass timber surface in a compartment, suppression should adequately reduce the likelihood of timber impacting the required fire resistance. (+) AND with CLT that exhibits bond line integrity in fire results in predictable HRR decay. (-) AND considering the impact of timber external walls and exposed timber within egress and firefighting cores.
High	X	30% of 1 surface	X	(-) WITHOUT automatic fire suppression it is likely that a severe fire will develop within the compartment. (-) AND without suppression there is increased likelihood of the single exposed mass timber surface re-radiating and causing sustained burning. (-) AND considering the impact of timber external walls and exposed timber within egress and firefighting cores.
	✓	All (ceiling and all walls)	✓	(+) WITH automatic fire suppression it is unlikely that a severe fire will develop, i.e. the suppression system would have to fail for a severe fire to develop. (-) BUT with multiple surfaces exposed resulting a greater likelihood of re-growth or very slow HRR decay (+) AND with CLT that exhibits bond line integrity in fire results in predictable HRR decay.
	✓	1 (ceiling or single wall)	X	(+) WITH automatic fire suppression it is unlikely that a severe fire will develop, i.e. the suppression system would have to fail for a severe fire to develop. (-) BUT with CLT susceptible to char debonding results in potential re-growth or unpredictable HRR decay.
Very High	X	All (ceiling and all walls)	X	(-) WITHOUT automatic fire suppression it is likely that a severe fire will develop within the compartment (-) AND with CLT susceptible to char debonding results in potential re-growth or unpredictable HRR decay.
	✓	All (ceiling and all walls)	X	(+) WITH automatic fire suppression it is unlikely that a severe fire will develop, i.e. the suppression system would have to fail for a severe fire to develop. (-) AND due to the multiple exposed mass timber surfaces, re-radiation and sustained burning is likely. (-) BUT with CLT susceptible to char debonding results in potential re-growth or unpredictable HRR decay.
	X	All (ceiling and all walls)	✓	(-) WITHOUT automatic fire suppression it is likely that a severe fire will develop within the compartment. (-) AND unlimited compartment size / ventilation increases the likelihood of fire severities / durations outside those which have been assessed for mass timber.

Note 1: See 6.3.2 for an explanation for what constitutes appropriate automatic fire suppression for the purpose of this Guide.

Note 2: Exposed timber surfaces are any wall or ceiling surfaces in a fire compartment which are not provided with effective encapsulation. Current information and data shows that a single exposed surface, of limited area in larger compartments, can lead to compartment fire decay, if the CLT maintains bond line integrity in fire. Current data also shows that for multiple exposed mass timber surfaces, once the moveable contents have been consumed, the fire does not always decay. The top surface of the floor must always be protected.

4.4 Design guidance

Following the methodology presented in Section 4.3, the following tables outline the design guidance for each of the three building types covered by this Guide (business, residential and education)

Summary of Design Guidance - Business

Table 10: Summary of Design Guidance - Business Use

Building and consequence category (from Table 8 correlating building height and occupancy type)		Risk ranking (from Table 4 likelihood X consequence matrix)					Summary of design features (see Section 3.1 for details of the design goals)					
		Likelihood categories					Design features required to achieve 'trivial' or 'tolerable' risk ranking					
Height	Consequence category	Very low	Low	Medium	High	Very high	Appropriate automatic fire suppression provided throughout the building	Maximum number of exposed timber surfaces (wall / ceiling)	CLT that exhibits bond line integrity in fire	External walls may include timber	Minimum number of protected egress stairs	Exposed timber construction forming egress or firefighting cores
From Table 7	From Table 8	Unacceptable risk rankings under this Guide are shaded in grey					Section 6.3.2	Section 6.3.2	Section 6.3.2	Section 6.5.2	Section 6.2.2	Section 6.2.2
Low-rise H ≤ 12m	Very Slight	Trivial	Trivial	Tolerable	Tolerable	Tolerable	No limits			✓ (Note 2)	1	✓
Medium-rise 12m < H ≤ 25m (see Note 1)	Slight-moderate	Trivial	Tolerable	Tolerable	Moderate	Substantial	✓	1	✓	X	2	✓
							X	30% of 1 surface	✓	X	2	X
High-rise 25m < H ≤ 35m	Moderate	Tolerable	Tolerable	Moderate	Substantial	Substantial	✓	0	X	X	2	X
							✓	30% of 1 surface	✓	X	2	X
Very high-rise 35m < H ≤ 50m	Moderate-extreme	Tolerable	Tolerable	Moderate	Substantial	Substantial	✓	0	X	X	2	X
							✓	30% of 1 surface	✓	X	2	X

Note 1: Medium-rise business use buildings will typically adopt a simultaneous evacuation strategy (as defined in Table 4). The recommendations for this use and height category are based upon a simultaneous evacuation strategy being adopted. If a phased evacuation strategy is adopted, the designer should consider the impact of increased evacuation times when deciding which design features are appropriate.

Note 2: Timber external walls should not be used in buildings requiring compartment walls and floors. However, timber may be used in external walls where the building does not require compartment walls or floors.

Summary of Design Guidance - Residential

Table 11: Summary of Design Guidance - Residential Use

<table>
<tr><th colspan="2">Building and consequence category (from Table 8 correlating building height and occupancy type)</th><th colspan="5">Risk ranking (from Table 4 likelihood X consequence matrix)</th><th colspan="6">Summary of design features (see Section 3.1 for details of the design goals)</th></tr>
<tr><th colspan="2"></th><th colspan="5">Likelihood categories</th><th colspan="6">Design features required to achieve ‘trivial’ or ‘tolerable’ risk ranking</th></tr>
<tr><td>Height</td><td>Consequence category</td><td>Very low</td><td>Low</td><td>Medium</td><td>High</td><td>Very high</td><td>Appropriate automatic fire suppression provided throughout the building</td><td>Maximum number of exposed timber surfaces (wall / ceiling)</td><td>CLT that exhibits bond line integrity in fire</td><td>External walls may include timber</td><td>Minimum number of protected egress stairs</td><td>Exposed timber construction forming egress or firefighting cores</td></tr>
<tr><td>From Table 7</td><td>From Table 8</td><td colspan="5">Unacceptable risk rankings under this Guide are shaded in grey</td><td>Section 6.3.2</td><td>Section 6.3.2</td><td>Section 6.3.2</td><td>Section 6.5.2</td><td>Section 6.2.2</td><td>Section 6.2.2</td></tr>
<tr><td rowspan="3">Low-rise
H ≤ 12m</td><td rowspan="3">Very Slight</td><td rowspan="3">Trivial</td><td rowspan="3">Trivial</td><td rowspan="3">Tolerable</td><td rowspan="3">Tolerable</td><td rowspan="3">Moderate</td><td>✓</td><td>All
(ceiling and all walls)</td><td>✓</td><td rowspan="3">X
Note 1</td><td rowspan="3">1</td><td rowspan="3">✓</td></tr>
<tr><td>✓</td><td>1
(ceiling or single wall)</td><td>X</td></tr>
<tr><td>X</td><td>30% of 1 surface</td><td>X</td></tr>
<tr><td rowspan="2">Medium-rise
12m < H ≤ 25m</td><td rowspan="2">Slight-moderate</td><td rowspan="2">Trivial</td><td rowspan="2">Tolerable</td><td rowspan="2">Tolerable</td><td rowspan="2">Moderate</td><td rowspan="2">Substantial</td><td>X</td><td>30% of 1 surface</td><td>✓</td><td rowspan="2">X</td><td rowspan="2">2</td><td rowspan="2">X</td></tr>
<tr><td>✓</td><td>1
(ceiling or single wall)</td><td>✓</td></tr>
<tr><td rowspan="2">High-rise
25m < H ≤ 35m</td><td rowspan="2">Moderate</td><td rowspan="2">Tolerable</td><td rowspan="2">Tolerable</td><td rowspan="2">Moderate</td><td rowspan="2">Substantial</td><td rowspan="2">Substantial</td><td>✓</td><td>0</td><td>X</td><td rowspan="2">X</td><td rowspan="2">2</td><td rowspan="2">X</td></tr>
<tr><td>✓</td><td>30% of 1 surface</td><td>✓</td></tr>
<tr><td>Very high-rise
35m < H ≤ 50m</td><td>Moderate-extreme</td><td>Tolerable</td><td>Moderate</td><td>Substantial</td><td>Substantial</td><td>Substantial</td><td>✓</td><td>0</td><td>X</td><td>X</td><td>2</td><td>X</td></tr>
<tr><td colspan="13">Note 1: Timber external walls should not be used in residential buildings requiring compartment walls and floors. However, timber may be used in external walls where the building does not require compartment walls or floors (e.g. single dwelling houses).</td></tr>
</table>

Summary of Design Guidance - Education

Table 12: Summary of Design Guidance - Education Use

Building and consequence category (from Table 8 correlating building height and occupancy type)		Risk ranking (from Table 4 likelihood X consequence matrix)					Summary of design features (see Section 3.1 for details of the design goals)					
		Likelihood categories					Design features required to achieve 'trivial' or 'tolerable' risk ranking					
Height	Consequence category	Very low	Low	Medium	High	Very high	Appropriate automatic fire suppression provided throughout the building	Maximum number of exposed timber surfaces (wall / ceiling)	CLT that exhibits bond line integrity in fire	External walls may include timber	Minimum number of protected egress stairs	Exposed timber construction forming egress or firefighting cores
From Table 7	From Table 8	Unacceptable risk rankings under this Guide are shaded in grey					Section 6.3.2	Section 6.3.2	Section 6.3.2	Section 6.5.2	Section 6.2.2	Section 6.2.2
Low-rise H ≤ 12m	Slight	Trivial	Trivial	Tolerable	Tolerable	Moderate	✓	All (ceiling and all walls)	✓	X	1	✓
							✓	1 (ceiling or single wall)	X			
							X	30% of 1 surface	X			
Medium-rise 12m < H ≤ 25m	Slight-moderate	Trivial	Tolerable	Tolerable	Moderate	Substantial	✓	1 (ceiling or single wall)	✓	X	2	✓
							X	30% of 1 surface	✓	X	2	X
High-rise 25m < H ≤ 35m	This Guide is limited to medium-rise education buildings.											
Very high-rise 35m < H ≤ 50m												

5. Worked Examples

This section presents two worked examples using the risk-based methodology presented in Section 4.

5.1 Example 1 – 30m tall office building

Example building: A 30m tall office building with a phased evacuation strategy.

5.1.1 Part 1: Determine consequence category

Step 1: Define the building use (occupancy types)

Using Table 3 it can be established that an office building is classified as '**Business**' use.

Occupancy Type	Description (Based on UK Approved Document B 2019 descriptions)
Business	Offices or premises used for normal day-to-day business activities.

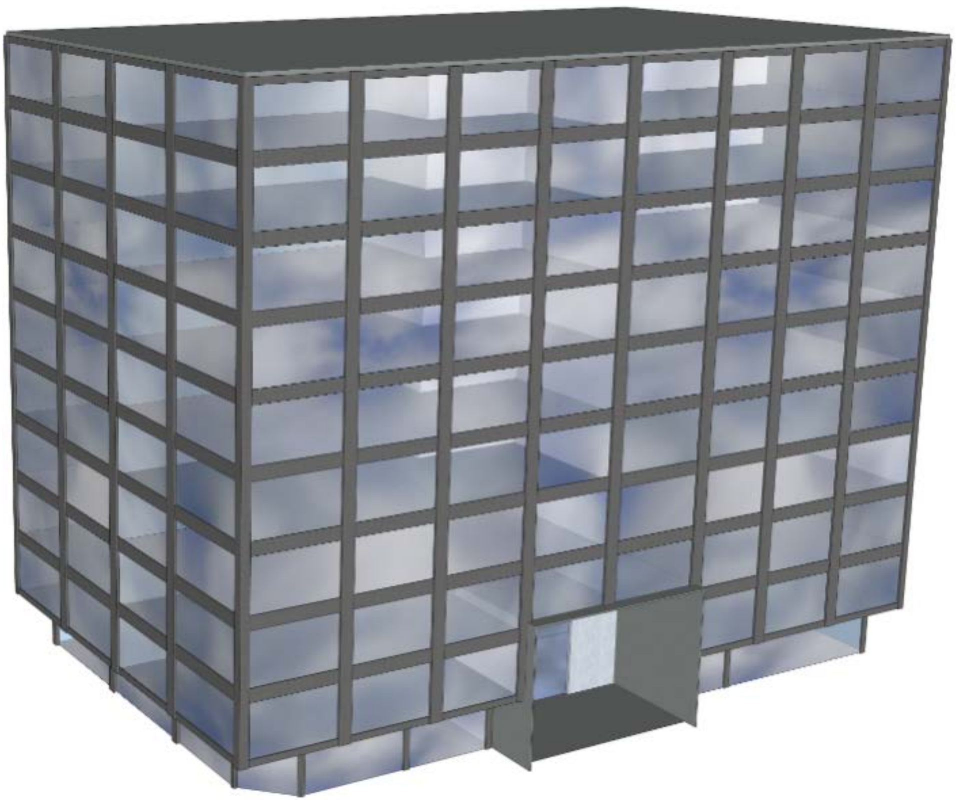


Figure 4: Render of a 30m tall office building

Using Table 5, the building is assumed to have the following occupancy characteristics:

Occupancy Type	Occupant Characteristics			
	Age	Sleeping-risk	Likely to be familiar with the building	Persons who may require assistance
Business	Working-age adults	No	Yes	Assume to be present

Step 2: Consideration of the evacuation strategy

Using Table 6, the phased evacuation strategy adopted is within the scope of the Guide.

Evacuation Strategy	Within the Scope of Guide	Brief Description
Phased	✓	The premises is divided into zones separated by fire compartmentation. Zones are evacuated in a controlled sequence of phases, with those zones expected to be at greatest risk being evacuated first.

Step 3: Determine the building height

Using Table 7, the building height of 30m falls within the '**High-rise**' category.

Building Height	Evacuation Time	Firefighting and rescue tactics
High-rise $25m < H \leq 35m$	Evacuation times increase. Phased evacuation may be adopted. More people will require assistance to evacuate down stairs.	External firefighting usually still possible for the upper floors but may be constrained. Additional internal firefighting provisions such as dedicated firefighting lifts typically provided.

Step 4: Determine the building consequence category

Using Table 8, the consequence category for a 'Business' use building in the 'High-rise' height category is '**Moderate**'.

Occupancy Type	Building consequence category for different building heights			
	Low-rise	Medium-rise	High-rise	Very high-rise
Business	Very Slight	Slight-moderate	Moderate	Moderate

5.1.2 Part 2: Determine maximum permissible likelihood category

The likelihood category is determined by correlating the consequence category determined from Table 8, with the 'trivial' and 'tolerable' risk levels in Table 4. For a 'Moderate' consequence category the required likelihood category is '**Low**'.

Consequence category → (see Section 4.3.2.4)					
Extreme	Moderate	Substantial	Substantial	Intolerable	Intolerable
Moderate-extreme	Tolerable	Moderate	Substantial	Substantial	Intolerable
Moderate	Tolerable	Tolerable	Moderate	Substantial	Substantial
Slight-moderate	Trivial	Tolerable	Tolerable	Moderate	Substantial
Slight	Trivial	Trivial	Tolerable	Tolerable	Moderate
Very slight	Trivial	Trivial	Trivial	Tolerable	Tolerable
	Very low	Low	Medium	High	Very high

Likelihood category → (See Section 4.3.3)

5.1.3 Part 3: Identify the appropriate fire safety design features

Using Table 10, the following combinations of fire safety design features are suggested by the Guide to achieve a 'tolerable' risk ranking.

Table 13: Design features for example case study #1

Design features	Combination 1	Combination 2
Appropriate automatic fire suppression provided throughout the building	✓	✓
Maximum number of exposed timber surfaces (wall / ceiling)	0	30% of 1 surface
CLT that exhibits bond line integrity in fire	X	✓
External walls include timber	X	X
Number of protected egress stairs	2	2
Exposed timber construction forming egress or firefighting cores	X	X

5.1.4 Part 4: Review the design goals in the context of the project

A review of the design goals within the context of the specific project should be undertaken to confirm they are being met by the design features determined in Part 3.

A check should be undertaken against local codes and regulations in the jurisdiction the project is located. Where local codes and regulations exceed the recommendations in this Guide they will take precedence.

5.2 Example 2 – 24m tall apartment block

Example building: A 24m tall apartment block with facilities provided to initiate a simultaneous evacuation of the building if required.

5.2.1 Part 1: Determine consequence category

Step 1: Define the building use (occupancy types)

Using Table 3 it can be established that an apartment block is classified as '**Residential**' use.

Occupancy Type	Description (Based on UK Approved Document B 2019 descriptions)
Residential	Dwellings – Apartment, block of apartments, dwelling houses, condominium, school or other similar establishment used as living accommodation, where persons sleep on the premises. Other – Hotel, boarding house, residential college, hall of residence, hostel and any other residential purpose not described above. Note – Healthcare and institutional residential premises (e.g. aged care homes) are not within the scope of this Guide.

Figure 5: Render of a 24m tall apartment block

Using Table 5, the building is assumed to have the following occupancy characteristics.

Occupancy Type	Occupant Characteristics			
	Age	Sleeping-risk	Likely to be familiar with the building	Persons who may require assistance
Residential	All ages	Yes	Yes, for apartments No for hotels	Assume to be present

Step 2: Consideration of the evacuation strategy

Using Table 6, the evacuation strategy adopted is within the scope of the Guide on the basis that facilities are provided to initiate a simultaneous evacuation of the building if required.

Evacuation Strategy	Within the Scope of Guide	Brief Description
Simultaneous	✓	The premises form a single evacuation zone. All parts of the premises are evacuated at the same time. Occupants of the dwelling of fire origin only can be alerted to evacuate initially, provided there is an automatic detection and fire alarm system that cascades to simultaneous evacuation strategy as smoke spreads to activate more than one smoke detector inside or outside the initial dwelling, as defined in Table 6.

Step 3: Determine the building height

Using Table 7, the building height of 24m falls within the '**Medium-rise**' category as defined below.

Building Height	Evacuation Time	Firefighting and rescue tactics
Medium-rise $12m < H \leq 25m$	Evacuation times are relatively short. Some people will require assistance to evacuate down stairs.	External firefighting effective and often preferred. Internal firefighting provisions may be limited to fire mains (often dry) and protected egress stairs.

Step 4: Determine the building consequence category

Using Table 8, the consequence category for a 'Residential' use building in the 'Medium-rise' height category is '**Moderate**'.

Occupancy Type	Building consequence category for different building heights			
	Low-rise	Medium-rise	High-rise	Very high-rise
Residential	Slight	Moderate	Moderate	Moderate-extreme

5.2.2 Part 2: Determine maximum permissible likelihood category

The likelihood category is determined by correlating the consequence category determined from Table 8, with the 'trivial' and 'tolerable' risk levels in Table 4. For a 'Moderate' consequence category the required likelihood category is '**Low**'.

Consequence category → (see Section 4.3.2.4)

Extreme	Moderate	Substantial	Substantial	Intolerable	Intolerable
Moderate-extreme	Tolerable	Moderate	Substantial	Substantial	Intolerable
Moderate	Tolerable	Tolerable	Moderate	Substantial	Substantial
Slight-moderate	Trivial	Tolerable	Tolerable	Moderate	Substantial
Slight	Trivial	Trivial	Tolerable	Tolerable	Moderate
Very slight	Trivial	Trivial	Trivial	Tolerable	Tolerable
	Very low	Low	Medium	High	Very high

Likelihood category → (See Section 4.3.3)

5.2.3 Part 3: Identify the appropriate fire safety design features

Using Table 11, the following combinations of fire safety design features are suggested by the Guide to achieve a 'tolerable' risk ranking.

Table 14: Design features for example case study #2

Design features	Combination 1	Combination 2
Appropriate automatic fire suppression provided throughout the building	X	✓
Maximum number of exposed timber surfaces (wall / ceiling)	30% of 1 surface	1
CLT that exhibits bond line integrity in fire	✓	✓
External walls include timber	X	X
Number of protected egress stairs	2	2
Exposed timber construction forming egress or firefighting cores	X	X

5.2.4 Part 4: Review the design goals in the context of the project

A review of the design goals within the context of the specific project should be undertaken to confirm they are being met by the design features determined in Part 3.

A check should be undertaken against local codes and regulations in the jurisdiction the project is located. Where local codes and regulations exceed the recommendations in this Guide they will take precedence.

6. Background to Fire Safety Design Goals

6.1 Fire safety goals covered in this Guide

This section of the Guide sets out the fire safety design goals that underpin the Guide which need to be considered when developing the fire safety strategy for a building:

- Supporting safe evacuation and firefighting access
- Limiting fire growth within the fire compartment (slowing or preventing rapid fire growth)
- Delivering a suitable period of structural fire resistance (based on the height and use of the building)
- Limiting fire spread beyond the fire compartment (both to other areas of the building or to adjacent buildings)

The goals and design features to help achieve them are formulated to be globally applicable.

Examples of possible codes that could be adopted for design features are included to provide guidance on where to find more detailed recommendations.

6.2 Supporting safe evacuation and firefighting access

6.2.1 Design Goal – Supporting safe evacuation and firefighting access

In the event of a fire, it is important that suitable design features are provided such that occupants within the building are alerted to a fire and have enough escape routes to safely and efficiently escape from the building. The escape routes need to remain available at all times.

In addition to providing means of escape for building occupants, reasonable provisions need to be made available to allow the fire service access to the building in the event of a fire so that firefighting activities are not delayed.

6.2.2 Design features to support safe evacuation and firefighting access

The following design features can be incorporated to support safe evacuation and firefighting access:

Evacuation strategy

The evacuation strategy selected directly impacts the time for all occupants within the building to escape to a place of ultimate safety (outside the building).

Either a simultaneous or phased evacuation can be used for all occupancy types covered by this Guide, provided that an automatic building-wide fire alarm is provided to facilitate an ‘all-out’ evacuation if necessary.

The signal(s) to initiate either the building-wide simultaneous evacuation or the separate phases of a phased evacuation should be automatic (and be under firefighter control).

This Guide has been developed for simultaneous and phased evacuation strategies only. These two approaches make up the majority of building evacuation strategies globally. For the purposes of implementing this Guide, the following definitions for these evacuation strategies are used:

Simultaneous evacuation – a system of evacuation in which all parts of the premises are evacuated at once:

- The building is a single evacuation zone.
- All occupants in the building are alerted to the need to evacuate once fire or smoke has been detected.
- The method of fire detection and alarm is automatic.
- Investigation periods can be used to avoid unnecessary disruption in the event of nuisance alarms caused by smoke detectors (subject to local codes). In buildings where there is a sleeping risk, the unit (e.g. apartment or hotel room) of fire origin should be alerted to evacuate on activation of the first smoke detector. Activation of a second smoke detector initiates evacuation of the whole building.
- The stairs have sufficient egress capacity for simultaneous evacuation of all occupants in the building (as per the relevant local codes).

Phased evacuation – a system of evacuation in which different parts of the premises are evacuated in a controlled sequence of phases, with those areas expected to be at greatest risk being evacuated first:

- The building is subdivided into evacuation zones (e.g. groups of floors).
- Compartmentation equal to the required fire resistance for the building is provided between evacuation zones.
- All occupants in the evacuation zone affected by fire are alerted to the need to evacuate once a fire or smoke has been detected.
- The method of fire detection and alarm is automatic (see below).
- Investigation periods can be used to avoid unnecessary disruption in the event of nuisance alarms caused by smoke detectors (subject to local codes). In buildings where there is a sleeping risk, the unit (e.g. apartment or hotel room) of fire origin should be alerted to evacuate on activation of the first smoke detector. Activation of a second smoke detector initiates evacuation of the whole building.
- The stairs have sufficient egress capacity for simultaneous evacuation of all occupants in the affected evacuation zone(s) (as per the relevant local codes).

Fire detection and alarm

The detection of fire throughout the building should be by automatic sensors (e.g. heat detection, smoke detection, sprinklers). Manual-only detection is not recommended due to the potential for this to result in delayed alert times for occupants.

In buildings implementing a phased / zoned evacuation strategy the detection and alarm system should be networked such that an alarm may be sounded in all parts of the premises to instigate an 'all-out' evacuation, if required. The activation of the alarm in the zone of fire origin should be automatic.

Residential buildings provided with an alarm system capable of only alerting the flat of fire origin (often called 'Stay put') are not covered by the Guide, unless there is an automatic detection and fire alarm system that cascades to a simultaneous evacuation strategy as smoke spreads to activate more than one smoke detector inside or outside the initial dwelling.

Number of protected egress stairs

The minimum number of egress stairs has a direct impact on the time required to evacuate a building.

A single protected egress stair can be used in a limited number of situations, such as low-rise buildings where the expected number of occupants is low. Even in low-rise buildings, multiple stairs may be required to support travel distance requirements and desired occupancy numbers.

In some regions, local prescriptive fire safety codes may permit single-stair designs for buildings sitting in higher consequence categories than those considered to have single-stairs under this Guide. It is recommended that the minimum number of stairs recommended in this Guide is followed.

Timber construction forming egress / firefighting cores

The enclosure, internal linings and structure supporting vertical egress routes and firefighting cores (i.e. stairs and lifts) can be exposed timber in some building situations. The timber construction is to comply with any other relevant material classification requirements of local fire codes.

In higher consequence buildings, restricting the construction material of the escape and firefighting cores to non-combustible materials can increase the likelihood that they will not be compromised in a fire scenario. Non-combustible construction includes reinforced concrete, blockwork, masonry, gypsum board on metallic frames, etc.

Measures to assist mobility-impaired occupants to escape

Buildings need to be designed such that those with mobility impairments, who are unable to self-evacuate using the stairs, are still able to evacuate (either via self-evacuation or with assistance from building management).

At a minimum, suitable provisions and / or management procedures should be put in place for assisted evacuation, including refuge positions within protected enclosures (i.e. protected egress stairs or associated lobbies) on all floors above-ground. Refuge positions should be provided with a two-way handsfree emergency voice communication system linked to a 24/7 occupied facility (e.g. building security room) or remote monitoring facility.

Where evacuation lifts are proposed (either for self-evacuation or assisted evacuation), the lifts and associated design features should meet the requirements of the local prescriptive codes.

6.3 Limiting fire growth within the compartment

6.3.1 Design Goal – Limiting fire growth within the compartment

It is important to limit fire growth within the compartment. The larger a fire grows the greater the impact it will have on several aspects of the fire strategy, including:

- The availability of escape routes (faster growing fires can compromise exits and exit access routes, and larger fires can compromise multiple exits).
- The ability of fire to be contained to one compartment in one building (increased external flaming via external windows can result in fire spread to other floors of the building or to neighbouring buildings).
- The ability of the fire service to bring the fire under control (a larger fire requires more resources and will create greater damage)
- The ability of the structure to withstand the impacts of fire (a larger fire may threaten the structural stability of the building).

Previous large open-plan experiments (Appendix A.4.3.1) have shown that ignition and spread of flames over exposed timber surfaces can increase the rate of growth of a fire.

6.3.2 Design features to limit fire growth within the building

The following design features can be incorporated to limit the fire growth within the building:

Appropriate automatic fire suppression provided throughout the building

Automatic fire suppression systems can significantly reduce the likelihood of a fire growing to a sufficient size to ignite combustible timber structures. To be considered as a mitigation for the fire hazard posed by mass timber construction, this Guide requires suppression systems to be designed to a high degree of reliability. CodeRed #03, as discussed in appendix A.4.2, showed that water mist sprinkler systems can be effective at preventing timber ceiling ignition by ensuring the compartment fire size does not reach a sufficient severity.

The reliability of automatic sprinkler systems and their effectiveness in timber compartments have been investigated by Arup, including collation and review of relevant test.

Statistical Analysis of Fires in Timber Structures by Brandon, D., Vermina Lundström, F., Mikkola, E. in 2021 concluded that "Statistically, the extent of fire spread is significantly limited by sprinklers. A comparison of property loss expressed in US dollars indicated that the losses of large-spread fires can vastly exceed the costs of potential water damage caused by sprinklers. In addition, there is no evidence of a difference between losses caused by water of sprinklers or water of the fire brigade." Fedøy and Verma, 2019 analysed reliability data on sprinklers and presented an overview of studies after 1990 with reliabilities of over 90%.

Based on this review, sprinkler systems meeting the international standards listed below are considered sufficiently reliable to provide mitigation against the fire hazard posed by mass timber construction.

– UK and Europe: National implementation of EN 12845 Fixed firefighting systems – Automatic sprinkler systems – Design, installation and maintenance, including the additional measures listed in Annex F of the same document, and any insurance requirements (e.g. LPC Rules for Automatic Sprinkler Installations in the UK).

– USA: NFPA 13 Standard for the installation of sprinkler systems.

– Australia: AS 2118.1 Automatic fire sprinkler systems – general requirements.

– Germany: VdS CEA 4001 - VdS CEA-Richtlinien für Sprinkleranlagen, Planung und Einbau.

Alternative suppression systems or sprinkler systems that include variations from these standards should be reviewed to establish whether they can be considered sufficiently reliable to provide suitable mitigation under this Guide. The suitability of water-mist suppression systems for a mass timber building should be reviewed in the context of the particular project.

The guaranteed stored water supply for the suppression system is to be in line with the fire resistance period required by local prescriptive codes, unless another maximum expected fire duration is supported by fire engineering analysis.

Automatic fire suppression can be included in the design to help reduce the likelihood category or permit some mass timber wall or ceiling surfaces to be exposed.

Where the risk-based design relies on the provision of automatic fire suppression to achieve the likelihood category, the following are not appropriate when following this Guide:

– Reductions in structural fire resistance or compartmentation fire rating requirements allowed by codes due to suppression provision.

– Increases to or removal of fire compartment size limits due to suppression provision, where mass timber is exposed (increasing compartment area also increases the volume of exposed timber included in the compartment).

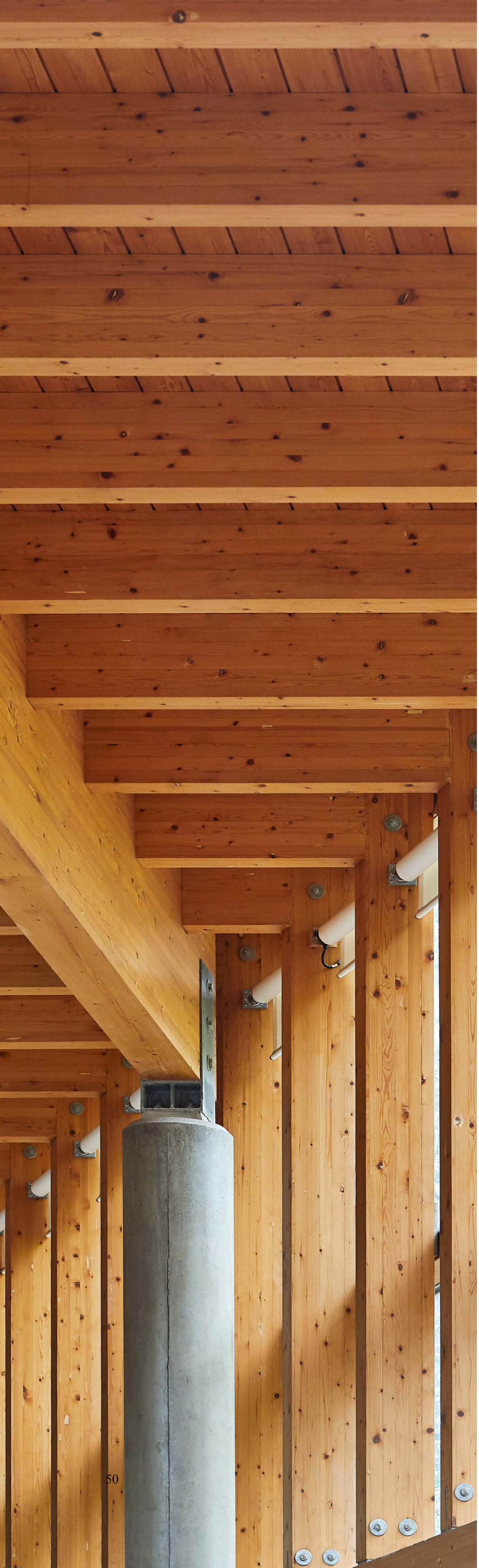
– The suitability of any other relaxations allowed by local codes should be reviewed with cognisance of the additional fire risk posed by the exposed mass timber and building height and use.

Maximum number of timber surfaces exposed within a room

The number of timber surfaces exposed within a room has a direct impact on the fire growth, as exposed timber surfaces provide additional fuel to the fire which can result in larger fires as well as a prolonged duration of burning.

By limiting the amount of exposed timber within a room, the fire growth and duration can be controlled. A review of 60 experiments studying the impact of the extent of exposed mass timber on fire behaviour is provided in Appendix A3.

For the design recommendations given in this Guide, the amount of timber that can be exposed has a direct impact on the likelihood classification which is “the probability of the proposed timber design resulting in a fire scenario that is more severe than the prescribed fire resistance period of the structure”. The type of CLT specified for use is also important and this Guide emphasises the use of CLT that exhibits bond line integrity in fire.



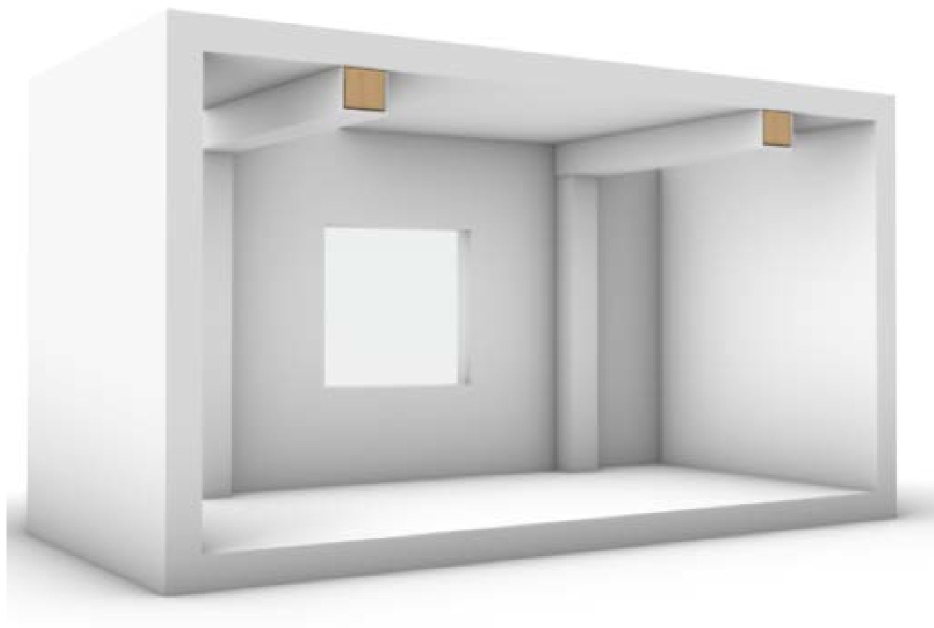
Therefore, within the design tables in Section 4, the amount of exposed timber is limited to the following depending on the specific design scenario:

- All surfaces can be exposed (no restrictions).
- A single surface within a room can be exposed (the remaining surfaces should be encapsulated or constructed of a non-combustible material).
- 30% of a single surface within a room can be exposed (the remaining surfaces should be encapsulated or constructed of a non-combustible material).
- All surfaces within a room should be encapsulated or constructed of a non-combustible material (no exposed timber)
- A single surface is defined as:
  - For a ceiling (underside of a floor), this includes all beams supporting that floor and the columns supporting those beams.
  - For a wall, this includes the wall and all columns attached or supporting that wall.

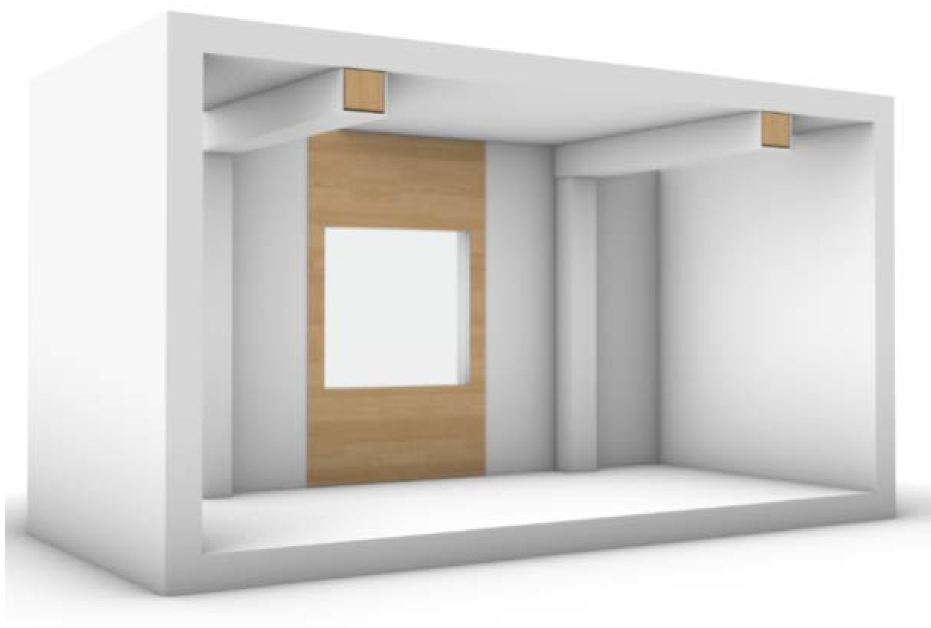
The different degrees of exposed timber are illustrated in Figure 6.

For all buildings in the Guide, the CLT is assumed to be covered on the top side (walking surface / floor of a compartment) with non-combustible protection that prevents the top-side of the CLT becoming part of the fire fuel, i.e. it is fully encapsulated. This can be achieved by differing top-side materials such as concrete, lightweight concrete or build-ups of non-combustible boards.

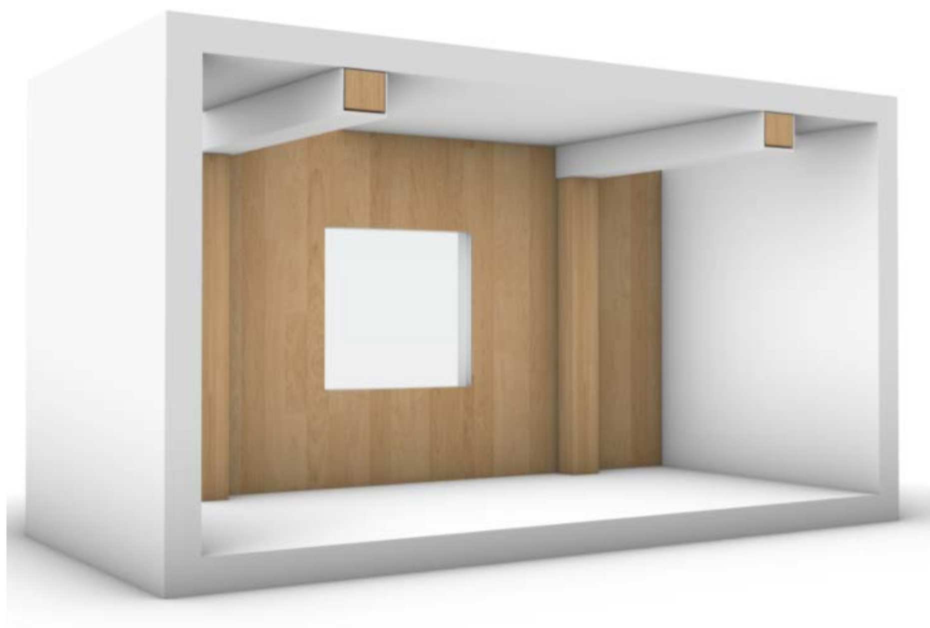
◄The Burrell Collection, Glasgow © Hufton+Crow



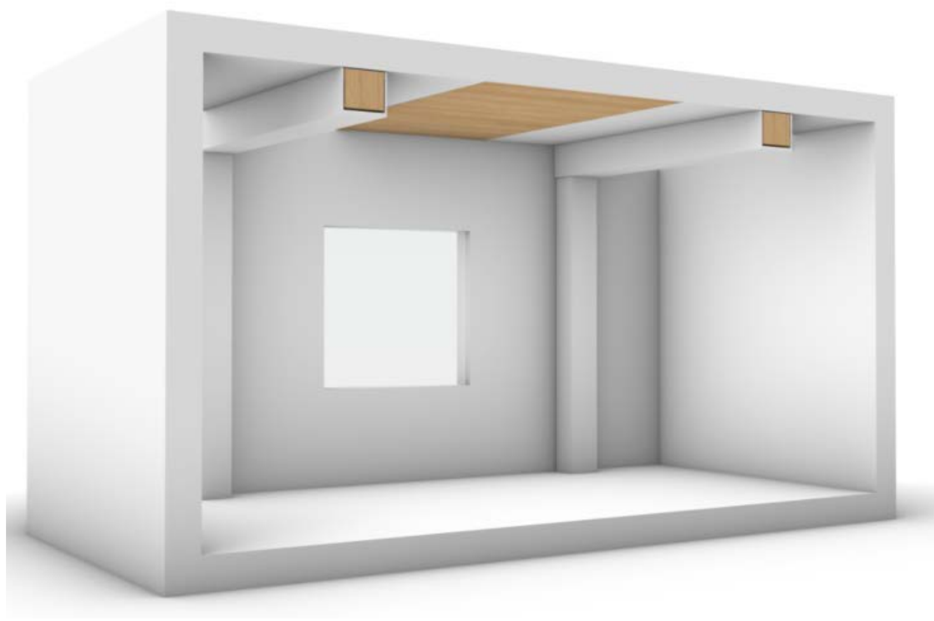
No exposed timber (fully encapsulated)



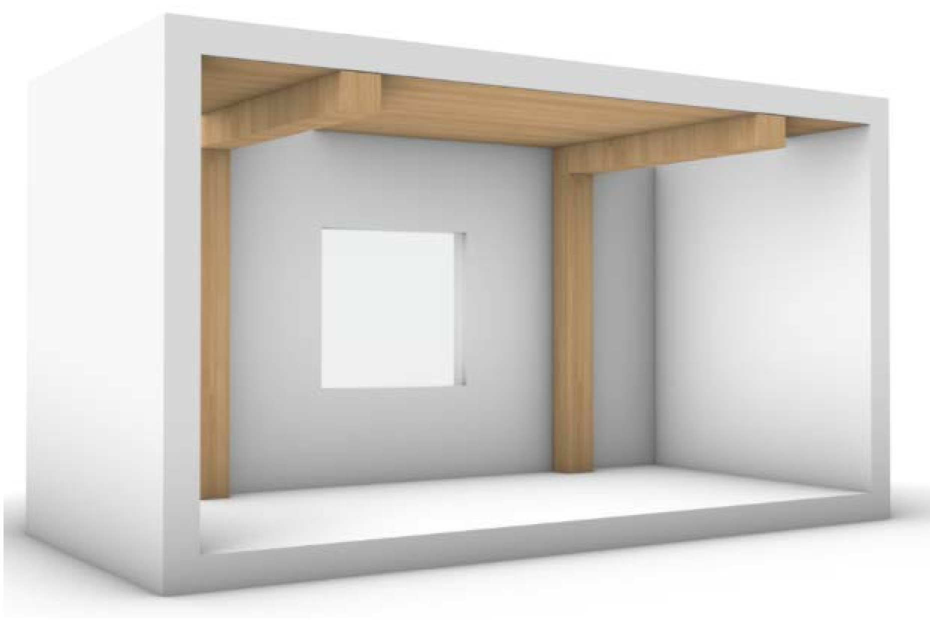
30% of a single surface (wall) exposed



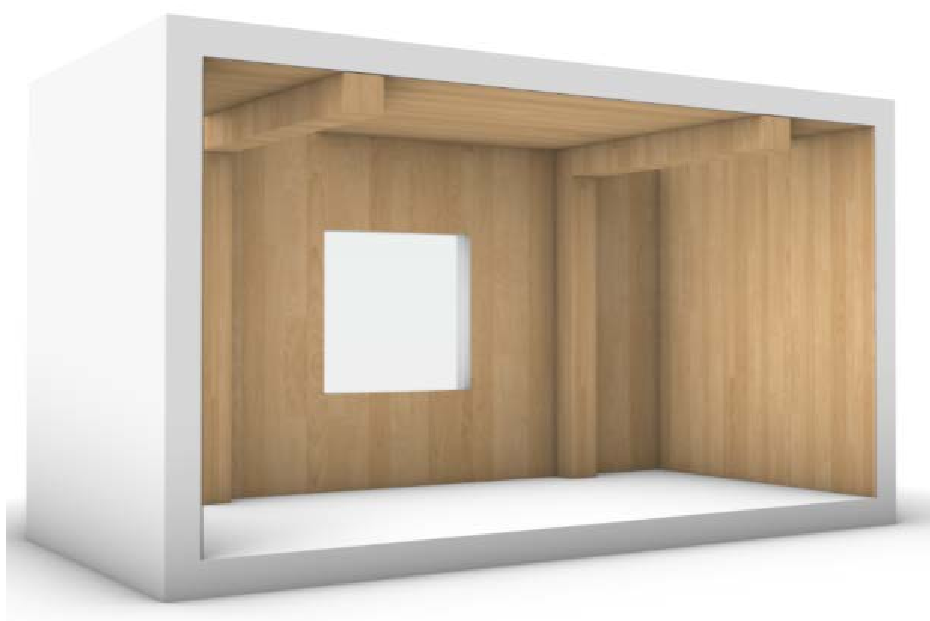
Single surface (wall) exposed



30% of a single surface (ceiling) exposed



Single surface (ceiling exposed)



Fully exposed timber (no encapsulation)

Figure 6: Maximum number of timber surfaces exposed within a room

Bond line integrity in fire

This Guide places an emphasis on specifying timber that maintains bond line integrity in fire (Appendix A.2.1.4) as one of the measures to enhance fire decay predictability. Maintaining bond line integrity in fire prevents char debonding from occurring. This is where charring occurs through the bond line allowing the char layer to separate from the element, exposing fresh virgin timber beneath. This results in increased charring rates and the supply of additional fuel to the fire.

Propensity for char debonding is primarily influenced by the adhesives used during manufacture to bond the lamella together. Standard fire testing and compartment experiments have shown that certain CLT panel adhesives are less susceptible to char debonding.

A new test method to verify char debonding is expected to be documented in the upcoming revision of pr EN 1995-1-2 2025, based on bond line integrity research undertaken by RISE (Brandon, Klippel, & Frangi, 2021). Until that method is fully published, to verify no char debonding, a CLT panel should exhibit a char rate of no more than 0.7 mm/min for exposure to standard fire furnace test heating, of sufficient duration to burn through more than three lamellae (plys) or 120 minutes. The char rate should be similar to that of the same wood if it were solid (i.e. no lamellae). Other methods, such as mass loss measurement may also be applicable based on the appropriately referenced test approach, or specifying CLT that meets the product performance standards used in the US (ANSI/ APA PRG-320), which does not permit CLT that displays bond line integrity failure.

Glulam elements typically use glue that maintains bond line integrity in fire. The guide assumes that this is the case.

Limiting surface flame spread

It is important to limit the rate that fire spread can occur across a surface. Rapid fire spread across surfaces can result in larger fires and increases the likelihood of multiple escape routes being obstructed.

Where exposed timber is used as the wall and ceiling linings within a compartment, they should have a reaction to fire classification as per local prescriptive codes. Reaction to fire performance describes one or a combination of a materials' or product's combustibility, flame spread behaviour and rate of fire growth (smoke production and production of flaming droplets may also be measured).

Where timber is exposed, local codes may require the timber to be protected with a proprietary surface treatment to improve the reaction to fire performance in terms of surface spread of flame only. Care should be taken when specifying such products that a valid fire test report or relevant certificate is available and applicable to the design scenario. Such products or treatments also have a limited life span. Specification of such treatments or products will impose an ongoing maintenance requirement. The feasibility of such maintenance commitments should be reviewed before specification.

Recent experimental research at Brandforsk (Brandon et al., 2024) investigated the impact of surface treatments on flame spread over mass timber ceilings. This research found that, although surface treatments can be effective at lower thermal exposures (e.g. away from the fire source), they can have minimal impact in the performance of exposed timber surfaces closer to the fire source. Therefore, in post-flashover compartments, surface treatments may have a negligible effect. But pre-flashover, they should be considered to reduce lateral timber surface flame spread.

► Macquarie University Ainsworth Building, New South Wales © Brett Boardman

Other key considerations regarding the inclusion of timber surface treatments include:

- Durability
- Compatibility with other treatments present in the timber
- Maintenance requirements
- Implications for timber moisture control

Firefighting water supply

Firefighting intervention is one way to limit fire growth within the compartment. However, this cannot be relied upon and should be considered in addition to the other features outlined above to achieve this design goal.

It is essential that sufficient sources of water supply are available to allow the fire-brigade to fight a fire at any location within the building. Current practice when designing a building is to consider that a fire can only originate in a single location at one time. Fires originating simultaneously in several locations throughout the building at the same time are not considered. Therefore, when providing water supply facilities for the fire brigade it is only necessary to provide supply for firefighting activities in a single location.

However, for mass timber buildings more than 25m in height with exposed timber surfaces, it may be appropriate to provide enhanced firefighting facilities to fight two fires in different locations simultaneously. This is for the following reasons:

- For high-rise buildings external fire-fighting activities will not be sufficient due to the limitations of current equipment in accessing the upper levels. Firefighting activities need to therefore be undertaken internally, where provisions of water supply will be required.
- Where there are exposed timber surfaces within the compartment, initial experimental results have demonstrated that the protruding flame temperature from openings is significantly higher. This increases the likelihood of fire spread to adjacent levels and subsequently the probability that a fire may need to be fought on two levels simultaneously should automatic suppression not be effective.

6.4 Delivering a suitable period of structural fire resistance

6.4.1 Design Goal – Delivering a suitable period of structural fire resistance

The fire scenarios, or design fires, that a mass timber structure needs to withstand have to take into consideration the relevant building code fire safety goals, as a function of the use of the building, number of occupants, height, if the mass timber structure is exposed and where appropriate, the possibility of a fully developed fire (assuming the sprinklers (if present) are not operational and there is no firefighting intervention).

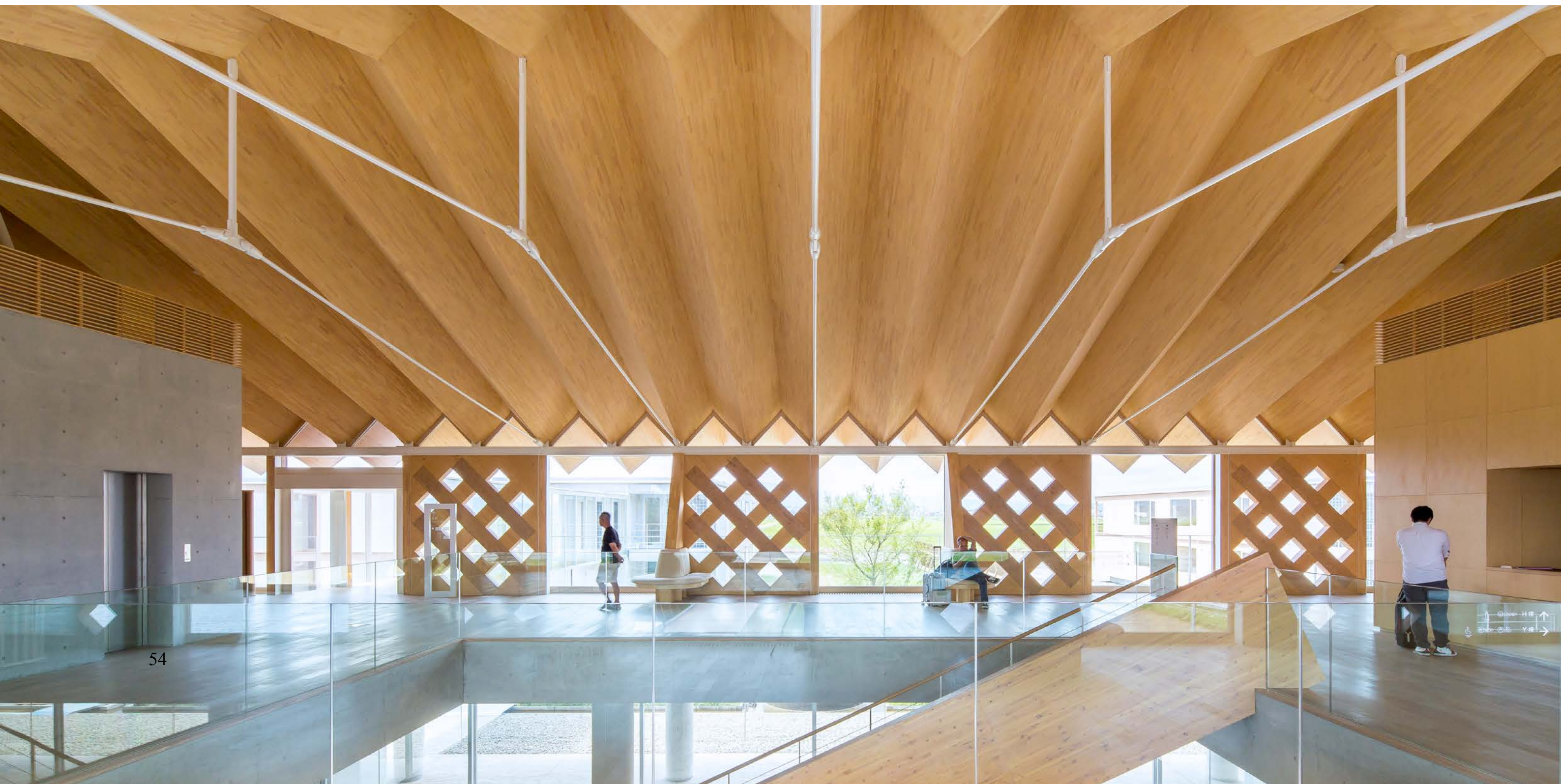
For high rise buildings, a range of credible worst case, fully developed fires may need to be defined to assess the fire performance of the structure in those scenarios, regardless of structural material and demonstrate that the structure can survive these possible fires with a high degree of reliability.

For low and medium-rise buildings, structure survival through all credible design fire scenarios may not be a fire safety goal. For most medium-rise buildings, this will need to be agreed between the approval authorities and the project team, so that an informed determination of fire protection and fire safety can be made.

All fire resistive elements of construction (walls, floors, doors, penetration seals etc) are tested and designed to resist only one peak in fire growth and are not normally able to resist fire growth, decay and then fire re-growth. Some buildings will require the structure (of any material) to provide stability through fire decay and burnout.

Fire resistance ratings for the structure are not specified in this Guide, but minimum fire resistance ratings are required to comply with the Guide, based on building height and are shown below. Fire resistance ratings should follow local codes and guidance alongside the minimum applicable fire resistance ratings outlined below.

– Low-rise (≤ 12m): zero minutes
– Medium-rise (12m < H ≤ 25m): 60 minutes
– High-rise (25m < H ≤ 35m): 90 minutes
– Very high-rise (35m < H ≤ 50m): 120 minutes



6.4.2 Design features to deliver a suitable period of structural fire resistance

The following design features can be incorporated to design mass timber buildings to achieve the required period of structural fire resistance.

Exposed timber – fire resistance by charring

The fire resistance of elements of structure can be determined by calculating the expected charring depth and from that, the residual loadbearing cross section of the timber when exposed to a specified period of standard fire exposure that the building is expected to achieve to demonstrate compliance. There are two main routes to compliance:

– Verification by testing – Mass timber building elements can be shown to have an inherent fire resistance by charring under standard fire testing, e.g. EN 13501-2 and test regime as described by EN 1365-3 for a beam. Demonstrating fire resistance by charring through standard fire testing is suitable for any type of timber construction. The test and classification standards should align with those outlined in the applicable national code.

– Verification by calculation – For example the version of EN 1995-1-2 current at the time of publication of this Guide provides the reduced cross-section method for calculating the fire resistance of timber elements. A depth of char and a zero strength layer is calculated to determine the remaining structural effective cross section of wood. This method of calculation was primarily developed for glulam and LVL. The version of EN 1995-1-2 current at the time of publication of this Guide does not state that CLT is included for any calculation methods.

Design approaches

Various national standards and guides provide guidance on how to calculate expected char depth (National Design Specification for Wood Construction (NDS), AS1720.4, CSAO86, EN 1995-1-2, for example).

The 2004 version of EN 1995-1-2 current at the time of publication of this Guide outlines a reduced cross-section method for calculating fire resistance achieved by charring. EN 1995-1-2 is in the process of being revised and the design basis in this Guide refers to the current version.

The reduced cross-section method in the version of EN 1995-1-2 current at publication of this Guide (in the new EN 1995-1-2 the method name will be changed to “effective cross-section method”) is suitable for application to LVL, glulam or solid timber members. The char rates are based on exposure to standard fires only.

For analysis that requires assessment of non-standard (natural) fires, a constant char rate cannot be used. Char rates must be based on the expected fire dynamics as influenced by the exposed timber, the fuel available in furnishings and fittings and the anticipated compartment ventilation.

The reduced cross-section method in the version of EN 1995-1-2 current at publication of this Guide to verify the fire resistance of CLT panels should not be used. Where a calculation method is not accepted, it is recommended that CLT panel fire resistance testing is specified as the means of demonstrating fire resistance, or advanced calculations based on fire resistance test results are applied by experienced fire safety and structural engineers.

The proposed update to EN 1995-1-2 will explicitly consider CLT, including tabulated data and calculation methods based on design specifics such as bond line integrity in fire.

◄ Macquarie University Ainsworth Building, New South Wales © Brett Boardman

Specification of the mass timber

From the design guidance presented in Section 4, CLT which has no char debonding is required for certain design scenarios. This is necessary to increase the likelihood that the required structural fire resistance will be achieved by the CLT.

Where char debonding occurs, this results in an increased char rate, when compared to an identical panel with more heat resistant adhesives. The char debonding can also result in fire regrowth where there are large areas of CLT exposed, preventing compartment fire decay. Increased char rates caused by char debonding can also result in the structural fire performance of the element not being achieved due to an increase in the thermal penetration depth, reducing the residual cross section.

Given the desire to expose mass timber as part of building design, one method to provide more predictability in overall compartment fire performance is to control the CLT influence to a growing and decaying fire. This Guide therefore places an emphasis on the choice of CLT and is strongly orientated towards CLT that does not exhibit char debonding and has proven bond line integrity in fire. By doing so, designers can remove one unpredictable variable in the assessment of a compartment fire.

Glulam elements typically use glue that maintains bond line integrity in fire. The guide is based on the assumption that this is the case.

Fire resistance design for exposed timber members to survive burnout

For high-rise buildings and some high-consequence buildings, the fire resistance of the exposed mass timber structure may be required to have a proven structural stability for the full development of the fire, through decay and to burnout (where burnout needs to be defined by the fire safety engineer and authorities, refer to the Glossary in Section 2 for further detail).

The very large experiments with exposed mass timber ceilings undertaken by Arup, CERIB and Imperial College London (CodeRed, Appendix A4) have shown that mass timber structures may be vulnerable in the fire decay phase unless certain protective measures are implemented. It is important that the following design issues are addressed:

- Transient heating: Needs to be addressed given the peak temperature in a timber member can occur well after the fire has reached its peak.
- Exposed columns: The lower portion of exposed columns are vulnerable in the decay phase of a fire, due to the smouldering that occurs in the combusted fuel at the floor.
- Smouldering: Can occur in joints, connections, interfaces, local to insulating materials, and behind encapsulation for days after the end of flaming and potentially transition back to flaming. Therefore, post-fire firefighting inspection and intervention is necessary to prevent the progression of smouldering.

These issues should be considered by the design team and can be addressed by careful consideration of material choices in the structural design through which some hazards could be eliminated, or additional protective measures such as applying extra protection or oversizing structural elements, accounting for the relevant heating regimes in design analysis.

Fire resistance design of timber connections

The performance of timber connections in fire, which typically involve metal components, is of critical importance to maintaining structural stability.

Connections of mass timber members are required to achieve a fire resistance rating equal to that required of the connecting members (the same as for connections involving non-combustible structural elements). All connections will need to have fire resistance proven through fire testing or detailed analysis (such as finite element assessment of temperature profiles through protection).

CLT suppliers who do not have a fire tested panel-to-panel connection should be viewed with caution, given the weak point in a fire test is the connection.

Glulam and LVL beam-to-column connections have few standard fire tests available for 90 minutes' or 120 minutes' fire resistance, given most connectors are proprietary. Non-proprietary connection design is available through various research papers, based on dowels combined with concealed steel plates.

Where possible, connections should be fully concealed and if not, additional fire protection such as non-combustible boards will be needed to achieve a fire resistance rating.

Exposed timber-to-steel connectors with intumescent paint will not achieve the required fire resistance required and should be avoided, because the exposed timber has already started to char before the intumescent reacts due to heat transfer through the steel. Even after the intumescent paint reacts and forms its protection around the connection, the temperature of the steel will likely still exceed the temperature required for the charring of timber (approximately 270-300^{o}C).

Beam widths, and potentially depths, can be governed by the fire resistance requirements for the connections and it is therefore important to consider the connection design at an early stage.

Protected timber – fire resistance by encapsulation

The purpose of encapsulating timber elements of a structure is to prevent charring of the timber for the duration of the building's required fire resistance period, or through to fire decay, and, therefore, decouple the fire dynamics of combustible construction from the compartment fire dynamics. This is important for buildings where the determination of a fully developed fire and the decay of the fire needs to occur. For low and medium-rise buildings, mass timber encapsulation may not be necessary.

The most commonly used encapsulation material is a fire-specific plasterboard lining mechanically fixed to the underlying timber in accordance with the supporting test documentation.

The performance of the encapsulation system is measured by how the encapsulation to the mass timber meets certain criteria. The criteria differ country to country but are typically related to temperature and preventing the underlying timber from charring.

The performance of any encapsulation system should be verified by appropriate standard fire testing.

Demonstrating the performance of encapsulation systems

The following summarises some typical current approaches to verifying the performance of timber encapsulation systems globally.

Europe: The performance criteria in BS EN 13501-2 Clause 7.6.4.2 should be achieved when tested in accordance with EN 14135, assuming a K_2 covering. The performance criteria are as follows:

- There should be no collapse of the covering or parts of it.
- During the test, the mean temperature measured on the lower side (i.e. between the encapsulation and the timber) of the substrate shall not exceed the initial temperature by more than 250°C and the maximum temperature measured at any point of this side shall not exceed the initial temperature by more than 270°C.
- After the test there shall be no burnt material or charred material at any point on the substrate.

BS EN 13501-2 currently permits a K_2 classification up to 60 minutes only. Where the required period of fire resistance for the timber exceeds 60 minutes, it is recommended that an assessment is carried out by an 'EGOLF' member (European Group of Organisations for Fire Testing, Inspection and Certification). This should be supported by an extended test to EN 14135 with duration at least equal to the required fire resistance (i.e. 90 or 120 minutes).

US: In the US the performance of an encapsulation system is measured by standard fire testing whereby an underlying mass timber element is tested with the encapsulation material and without, and the difference in fire resistance time is reported. The performance criteria for the encapsulation of mass timber are therefore not related to preventing charring. The IBC also prescribe specific protection to mass timber elements for certain building heights, so that the mass timber can be considered as equivalent to non-combustible construction, with two or three layers of 16 mm fire rated plasterboard required. This protection may not prevent charring behind the plasterboard in some designs.

Canada: The country introduced a new test standard (CAN / ULC-S146 in 2019) to determine an encapsulation rating of not less than 50 minutes and the 2020 NBC is based on the specified encapsulation.

Australia: Code requirements are based on plasterboard protection that prevents the timber charring for a deemed period, typically 30 minutes. The fire duration is most likely to be longer and therefore charring is not prevented in all building designs and all timber may be involved in a longer duration fire.

6.5 Limiting fire spread beyond the fire compartment

6.5.1 Design Goal – Limiting fire spread beyond the fire compartment

It is important to limit the fire spread beyond the compartment of fire origin as this can put other persons at undue danger from the fire. This is especially important in buildings where a 'phased' or 'zoned' evacuation strategy is adopted as these strategies rely on the fire being contained to its compartment of origin.

Fire spread beyond the compartment can be classified into two separate scenarios:

- Fire spread to other areas of the same building via the external wall; and
- Fire spread to adjacent buildings.

Each of these scenarios needs to be addressed by the fire safety design for the building.

6.5.2 Design features to limit fire spread beyond the fire compartment

The following design features can be incorporated to limit fire spread beyond the compartment.

Limiting fire spread via external walls

Limiting fire spread via the external envelope of buildings is a common feature of fire safety design globally. Prescriptive requirements for exterior walls, external walls and façade fire safety typically varies based on building height, with increased restrictions depending on occupancy type and as buildings get taller.

Limiting fire spread is important where the building relies on high degrees of fire compartmentation because if the wall is designed incorrectly the external wall can provide a route to bypass fire rated floors and walls.

Designers typically have two options for limiting fire spread over the façade of the building of fire origin:

1. Selecting materials which meet prescriptive reaction-to-fire performance requirements; or
2. Conducting a large-scale 'standard' façade fire test and passing specified performance criteria governed by the test standard used.

When large-scale fire tests are used to assess the performance of a façade in limiting fire spread, it is important to consider the impact that exposed mass timber within the fire compartment will have on the temperatures the test specimen is subjected to during the test.

Exposing large areas of mass timber introduces additional fuel load to a compartment. Fire compartment experiments conducted to date have shown that this can result in larger external flames (Glew, et al., 2023) and increased heat flux to the building of fire origin and neighbouring buildings.

A review (Glew, et al., 2023) comparing large-scale compartment tests with exposed timber against three existing industry standard façade fire tests found that:

- The proposed large scale harmonised European test and BS 8414: Fire performance of external cladding systems tests generally enveloped the data points from experiments with exposed mass timber well. These large-scale tests therefore are reasonable tests to use for façade systems of buildings with large areas of exposed mass timber.
- The NFPA 285: Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components was shown to have a lower external flame severity than those observed during the compartment fire tests with exposed mass timber. Its use on projects with exposed mass timber should therefore be approached with caution.

The above should be considered by designers when specifying any large-scale façade experiments to be undertaken on a project with exposed mass timber compartments.

Using mass timber in external walls requires careful consideration, as there are usually many fire safety performance requirements to resolve, including fire spread over the external wall, fire spread in cavities, fire spread via fire resisting floor and wall junctions, protection of loadbearing structure, and fire spread to and from neighbouring buildings.

More details on the impact of exposed mass timber on external fire spread are presented in Appendix A6. The correct detailing and application of timber in external walls is subject to extensive ongoing research and not within the scope of this Guide.

Limiting the impact of fire spread above the fire floor via exterior flaming

Fire spread can occur to floors above the fire floor through external flaming. All buildings where a post-flashover fully developed fire must be assessed need to be checked to determine if vertical exterior fire spread is acceptable.

Several large and very large compartment experiments have shown that external flaming is increased in height where mass timber ceilings are exposed, which can result in fire spread occurring via radiation to the floor above the fire floor. Current calculation methods for vertical flame height and temperatures may not be valid and therefore care needs to be taken in the assessment of vertical flame spread. Vertical fire spread between floors in a fully developed fire may not be preventable through architectural means, such as spandrels or setbacks.

Mitigation measures can include additional firefighting water to allow firefighting to occur on at least two floors simultaneously. If a phased evacuation strategy is adopted it should be considered if the floor directly above the fire floor should evacuate as part of the first evacuation zone (fire floor + floor above). Consideration should also be given to the building structure if a fully developed fire were to occur on two floors.

Limiting fire spread via fire compartmentation

The walls and ceiling forming a fire compartment should be specified to achieve the required fire resistance period outlined in local prescriptive fire safety codes.

The build-up of the walls and ceilings should have a demonstrated fire resistance period via appropriate fire testing as required by local codes.

Limiting fire spread via service penetrations

Where services penetrate the walls and ceiling of a compartment they should be fire stopped to maintain the fire resistance period of the element they penetrate. Fire-stopping and opening protection (e.g. fire dampers, fire-and-smoke dampers, etc) are to be provided in line with local prescriptive codes.

Fire-stopping and opening protection products which are to be installed in a fire resisting mass timber walls and floors, should be tested and certified for application within the timber construction build-ups proposed.

The performance of fire stopping and opening protection should be demonstrated by appropriate fire testing as required by local codes.

Limiting fire spread to neighbouring buildings via radiation

The risk of fire spread between buildings via radiation is typically mitigated in the prescriptive fire safety codes by either reducing the area of unprotected openings in the external walls or by increasing the separation distance between the buildings.

Various fire engineering calculation methods exist for assessing the radiation received at a certain point from a compartment fire in a building. The methods typically assume a post-flashover fire in the compartment with all façade openings treated as simultaneously radiating emitters. The temperature or radiation intensity of the emitters in the methods are commonly linked to the expected fire severity within the compartment.

Research (Glew, et al., 2023) has shown that radiation received from compartment fires with exposed mass timber linings was greater when compared to those without exposed mass timber. To better represent this, one possible way is to increase the emitter temperature in external fire spread radiation calculations to 1200°C (Glew, et al., 2023).

Where compartments have one or more exposed mass timber surfaces, the suitability of local prescriptive codes / assessment methods for external fire spread via radiation should be reviewed and appropriate adjustments made to accurately reflect the additional hazard posed.

Limiting fire spread to neighbouring buildings via burning firebrands

Firebrands (or embers) are burning fragments of fuel produced when buildings, trees and other vegetation burn and then are transported by the flame plume and local wind away from the original source of the fire. They can travel long distances and ignite features on the outside of buildings or enter the building through openings such as eaves, vents, and windows, potentially igniting materials within the building. This is of particular concern with the presence of ignitable exposed timber surfaces.

Firebrands are implicitly considered as a hazard in combination with radiation in some countries, e.g. where acceptable limits for incident radiation are defined using piloted ignition thresholds ($12.6kW/m^2$).

Firebrands as a fire spread mechanism in isolation (e.g. not in combination with radiation) has not traditionally been considered to represent a significant fire hazard in the context of limiting fire spread between buildings. However, there have been several case studies where firebrands produced by a building fire have caused secondary ignition of neighbouring buildings. Therefore, as research in this area progresses this hazard should be considered.

Wildland Urban Interface (WUI) guidance is available in countries such as the USA, Canada and Australia which sets out recommended design features to help control the risk of burning firebrands, which exist in large quantities in wildfires, leading to buildings catching fire. One of the main objectives of current guidance is to prevent areas where firebrands can accumulate, leading to higher localised heat fluxes that can result in the ignition of combustible materials inside or outside the building. Protection measures include, for example:

- Definition of protective zones around buildings where combustible items (e.g. trees, chipping, ancillary structures, bins etc.) are progressively more controlled the closer the zone is to the building that is to be protected from fire.
- Controlling building details where brands could cause ignition, e.g. for gutters and downspouts, as well as eaves and other openings (e.g. vents, flues, pipes)

The designer should consider if additional safety measures in line with WUI guidance should be incorporated on their project.

Appendix 1.

Hazard and consequence-based approach to fire safety of mass timber buildings

A method to determine an appropriate approach to fire safety for a mass timber building based on building height, guidance and recommendations for fire protection and area of exposed timber has been developed within this Guide.

The method of assessing hazards and consequences for mass timber buildings was first proposed by Buchanan, Östman and Frangi (Buchanan, Östman & Frangi, 2014), and further developed by Buchanan (Buchanan, 2015). The methodology proposed in their papers is based on studying the implications of building height and use and area of exposed mass timber on fire safety and providing appropriate fire safety measures. This includes combinations of active measures, fire resistance ratings and additional measures to improve the reliability of sprinkler protection.

However, the approach of Buchanan, Östman and Frangi does not currently account for the impact of the size and geometry of the fire compartment on fire behaviour. As noted in earlier sections, there are numerous small- and medium-scale compartment natural fire experiments with exposed mass timber that provide fire behaviour representative of residential (and hotel, student accommodation) compartments. However, due to the differing fire behaviour and lack of representation of large compartments in the aforementioned approach, application of this guidance to a larger open-plan building, particularly mid- and high-rise office buildings, should be used with a greater degree of caution.

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Appendix 2.

Introduction to the fire behaviour of mass timber

The dynamics and behaviour of fires within a non-combustible compartment is relatively well understood and underpins fire safety guidance globally; including prescribed structural fire resistance periods and performance-based approaches to structural fire design.

The behaviour of fire within a compartment constructed in part, or in full, from mass timber (e.g. CLT walls, floors) is directly influenced by the burning of the timber elements (Hadden et al., 2017). The interaction between the compartment fire and the timber structure can invalidate underlying assumptions about fire duration and severity that underpin fire safety guidance for structural fire resistance as well as internal and external fire spread in current Building Codes and design guidance. Prescriptive fire resistance ratings may not be appropriate and traditional methods for determining fire resistance periods will also not be valid.

A2.1 Fundamentals of timber behaviour in fire

A2.1.1 Thermophysical behaviour in fire

Understanding the thermal and chemical behaviour of timber under heating is important when assessing the structural impact of fire on a mass timber element, particularly with exposed surfaces. Timber will undergo a range of both chemical and thermal processes when subjected to elevated temperatures, the most severe of which will typically occur during a fire. These processes will directly impact the structural capacity of a mass timber member, as discussed in the later section. At elevated temperatures, the mechanical properties of the timber are reduced and subsequently the structural performance of the member. At elevated temperatures, the key processes discussed by this section are preheating, drying, charring (pyrolysis), flaming (combustion), and smouldering. Each of these processes is influenced by a range of factors both intrinsic (density, thickness, type of timber, glue type) and extrinsic (location in compartment, fire behaviour, encapsulation, ventilation) to the mass timber element.

When subjected to increased temperatures (e.g. due to an external fire source), timber will initially undergo preheating. The mode of heat transfer through the solid timber is primarily by conduction (as timber is a solid) and heat is transferred from the fire by radiation and convection. The structural performance of timber already starts to decline during the preheating phase.

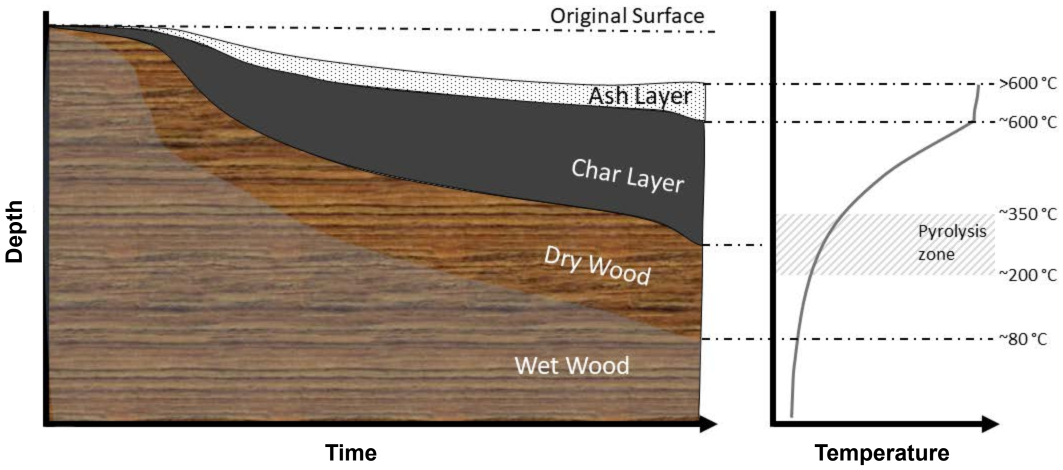


Figure 7: Sketch of different physical states timber undergoes during heating (left), with typical threshold isotherms (right) for each process. Figure developed from Richter et al. (2021).

Once the temperature of the timber reaches between 80-100°C, as shown in Figure 7, the moisture content present in the porous timber transitions to a vapour, diffusing through and leaving the timber element via exposed surfaces. The greater the moisture content, the more energy is required to progress the drying phase, delaying the onset of charring.

As timber heats beyond the drying phase, it chars or pyrolyses, producing flammable gases and a brittle carbon-rich layer of char at the exposed surface. Pyrolysis is the thermal decomposition of organic matter at elevated temperatures that leads to the production of volatiles (or flammable gases), tar, and char. Bench-scale experiments have demonstrated that prior to the timber reaching 300°C, the pyrolysis process is fairly slow. However, once the temperatures exceed 300°C, this indicates the onset of rapid pyrolysis and the formation of a char layer at the surface of the timber. This process signifies the chemical breakdown of the three polymers timber is typically comprised of (cellulose, hemicellulose, and lignin) which influence the mechanical properties of the timber.

The layer of char has no loadbearing strength or stiffness. As a result, a temperature increase to 300°C corresponds to the complete loss of structural strength of the timber. However, the char is highly insulating and so, reduces the heat which is conducted into the remaining timber. Therefore, pyrolysis of wood simultaneously produces fuel to sustain a fire, reduces the strength of the timber and produces char which insulates the underlying timber from the pyrolysis process. Figure 8 and Figure 9 illustrate charred structural mass timber elements.

If enough pyrolysate is produced by the charring process under sufficient conditions (literature typically signifies either a threshold temperature or heat flux at the timber surface), this gas will react with oxygen local to the char surface and ignite, leading to flaming combustion. Flaming combustion produces heat, which can not only contribute to the fire load of a compartment, but also supply the flaming timber element with additional heat, increasing the rate of charring.

Where timber is exposed to a constant radiant heat flux, initially the rate of pyrolysis is high, leading to the release of flammable gas fuel. However, as the char layer increases in thickness, this rate slows until such point that the heat transfer to the underlying timber is insufficient to sustain further pyrolysis. As a result, in some cases if the heat flux is removed, the pyrolysis will cease.

Following flaming of the mass timber surface, the char produced during the fire will oxidise, more commonly known as smouldering (Rein et al., 2016). As smouldering occurs, char reacts with oxygen, producing heat, ash at the exposed char surface, and other products. Smouldering can cause recession of the char surface during flaming combustion and continue after flaming of the timber surface has ended.

The heat produced by smouldering can transfer through the char layer, facilitating further timber charring, providing more char to smoulder, and perpetuating the smouldering process. Smouldering combustion is a flameless process, occurring at typically lower temperatures than flaming combustion, and is typically only visible by glowing of the solid media (although as smouldering is a process within the solid media, this is not always directly visible).

The rate and propensity of smouldering is highly influenced by airflow and the presence of an external heat flux. Both an increase in airflow and external heat flux will increase the spread rate of smouldering. In simple geometries without external heat flux or airflow, a smouldering timber surface will often reach self-extinction due to heat losses exceeding the heat produced by smouldering, preventing further charring. However, in complex geometries, smouldering surfaces can exert a radiative heat flux on each other, resulting in self-sustained smouldering.

Given appropriate conditions, the flammable gases produced by charring during the smouldering process can reignite, resulting in transition from smouldering to flaming. A transition to flaming can occur due to an increase in airflow local to the smouldering surface.

All of the aforementioned processes have a direct impact on both the mechanical properties of timber, and the available timber cross-section that can still contribute to the overall structural capacity, as shown in Figure 8 and Figure 9. This is discussed further in A.2.2.

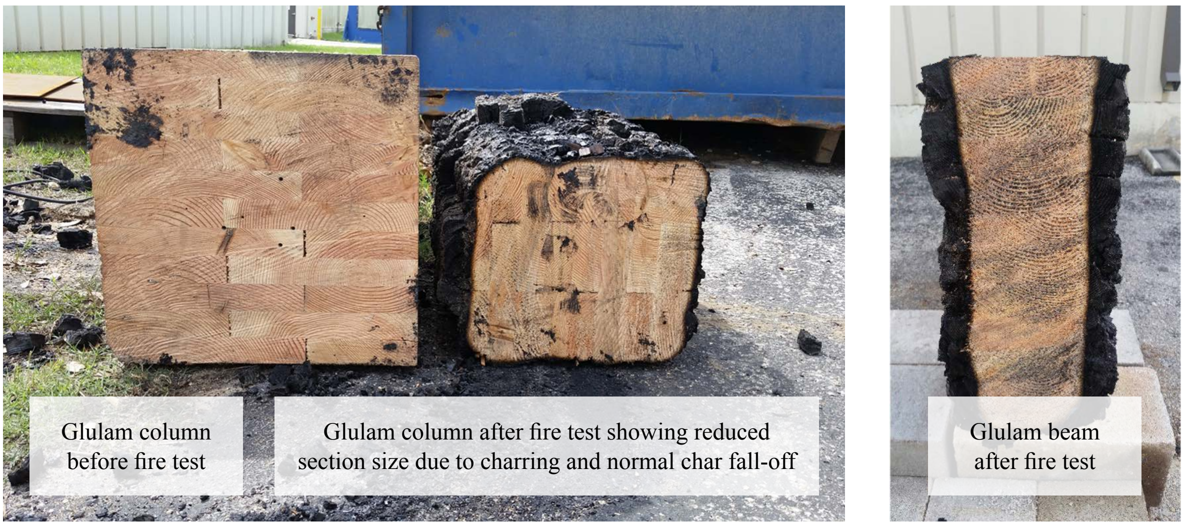


Figure 8: Cross-sections through glulam column (left) and beam (right) following fire experiments showing char layer and reduced cross-sectional area

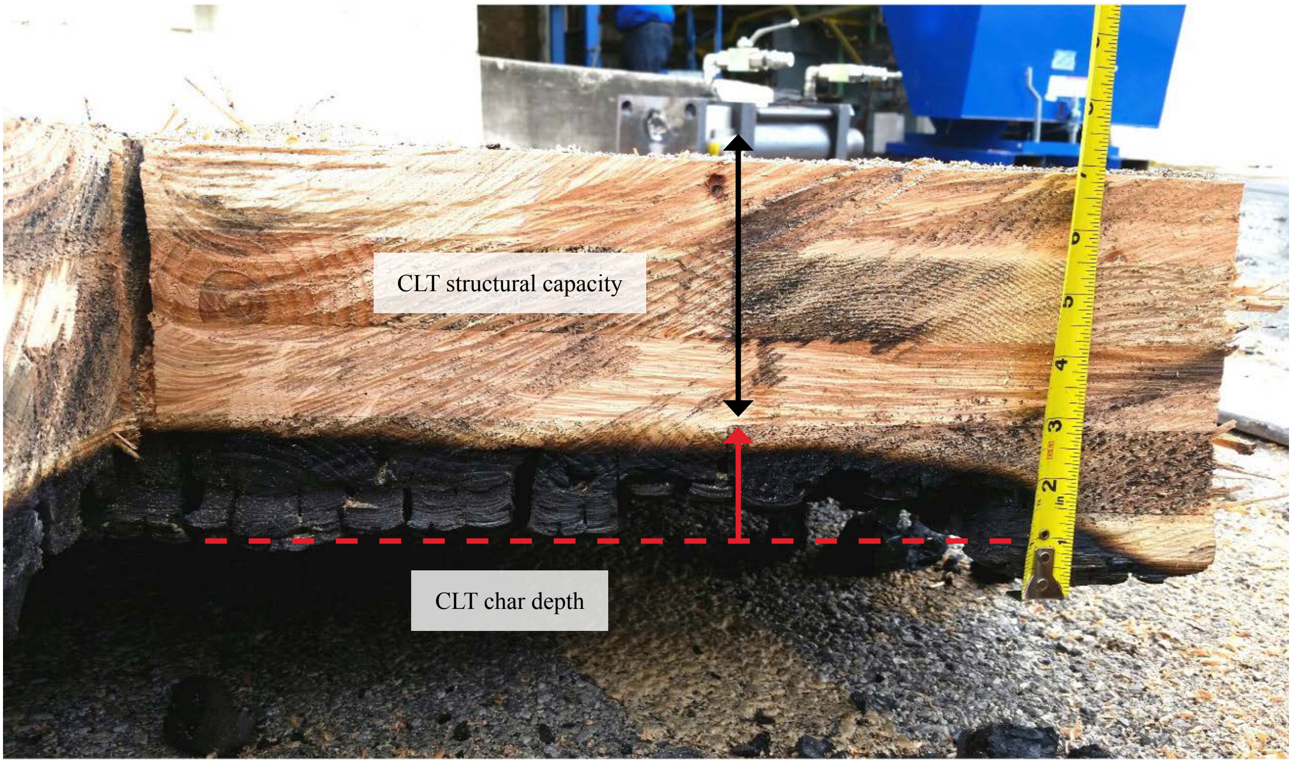


Figure 9: Cross-section through CLT panel following a fire experiment showing char depth and residual uncharred timber depth

A2.1.2 Mechanical behaviour in fire

There are three primary polymers which timber is comprised of – cellulose, hemicellulose and lignin. The proportion of each of these polymers will vary between different timber species. These polymers influence the mechanical properties of the timber, with the cellulose contributing to the tensile strength of the timber while lignin contributes to the compressive and shear strength. The hemicellulose links the cellulose and lignin, thereby affecting the mechanical behaviour and stability of the timber. Each of these polymers begins to degrade at a different temperature and this contributes to the charring behaviour of timber under heating.

Timber is frequently assumed to only lose mechanical strength at the onset of charring. However, as exhibited by Figure 10 and Figure 11, the loss of strength of timber under relatively low temperatures also needs to be recognised and considered, as preheating and drying occur at lower temperatures than charring temperatures but can still reduce the strength of a timber element. In practice, the loss of structural strength is typically accounted for with a 'zero strength layer', being the thermally impacted zone behind the char. The assumption of using 7mm (as recommended by the version of EN 1995-1-2 current at the time of publication of this Guide) is simplistic and applies to standard fire exposure only. The temperature-dependent loss of strength in timber is shown in the graphs below, from the version of EN 1995-1-2 current at the time of publication of this Guide.

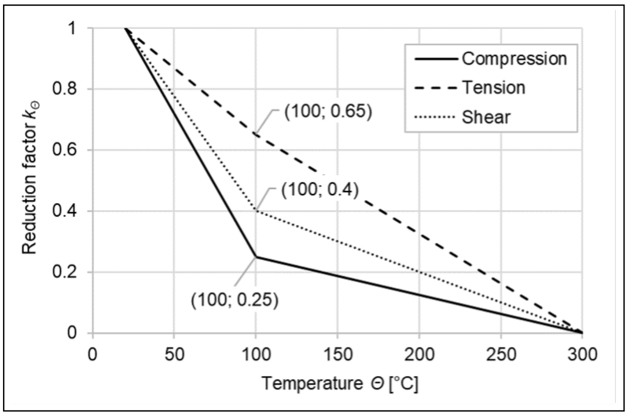


Figure 10: Reduction in strength parallel to grain for softwoods. Note compressive strength reduces to 25% of ambient strength at 100ºC (from version of EN 1995-1-2 current at the time of publication of this Guide)

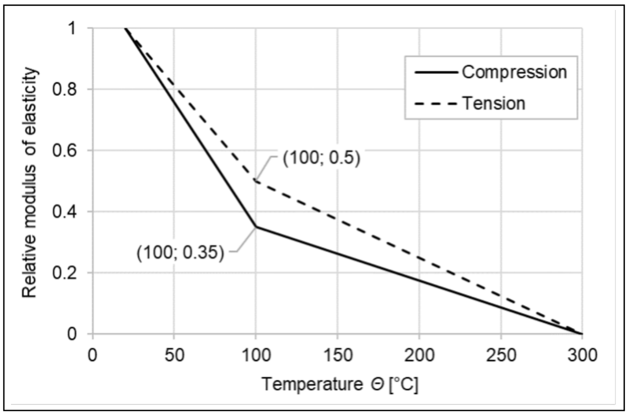


Figure 11: Reduction in modulus of elasticity parallel to grain for softwoods (from the version of EN 1995-1-2 current at the time of publication of this Guide)

A2.1.3 Exposed timber - Determining structural capacity

Timber structural design for fire has historically, and remains so generally, been based on sizing sections to allow for a constant charring rate over the prescribed period of fire resistance, with the residual section relied upon for stability. These charring rates and the fire resistance of timber structures are based on a long history of standard fire tests (furnace testing) of single elements to determine char rates. Codes/Standards such as EN 1995-1-2, NDS, CSA O86, AS 1720.4 provide guidance on determining the capacity of a structural member, for a prescribed fire resistance period, through the reduced cross section method. The reduced cross section method based on a constant char rate is appropriate for use when assessing standard fires, but cannot be used when assessing non-standard fires, which will have a variable char rate.

Where there is exposed timber within a compartment, the additional fuel produced by the pyrolysis of the timber will influence the fire heat release rate (HRR) and the fire duration. With the increase in heat release and fire duration, the structural capacity of the load-bearing mass timber members needs to be determined based on both heating and cooling of the compartment fire. Charring is directly proportional to temperature, in that the heat flux received determines a char rate. Once the combustible fuel of the furniture, fixtures and contents are consumed by the fire, understanding of the radiative heat from the growing, fully developed and decaying fire is required to then determine a char rate. How the compartment fire grows and decays to keep the timber pyrolyzing or leads to fire decay is vital for this assessment of char rate.

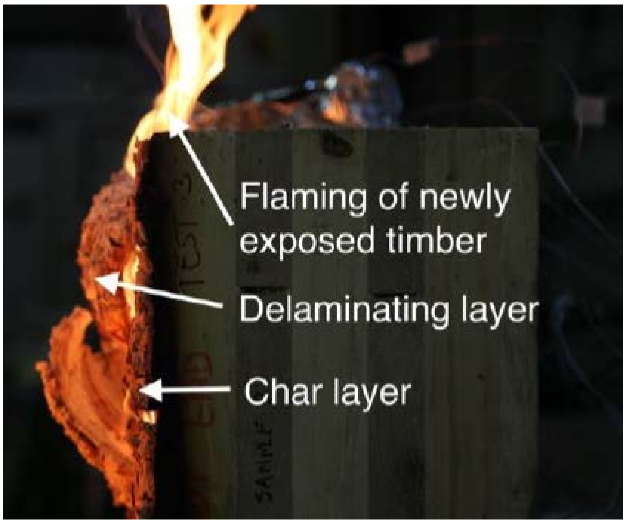
For a high-rise or high consequence building, the structure is required to remain intact and resist the applied forces while the fully developed fire decays. To determine the structural capacity of a member requires the reduced cross section to be determined, but based on a variable char rate, that is dependent on the compartment fire where that fire has been determined from growth through to decay.

The problem becomes further complicated by other aspects such as changing available ventilation into the compartment, if the timber encapsulation fails during the fire, or the material properties of the timber change due to bond line integrity failure. Thus, to determine the structural capacity, the following is required:

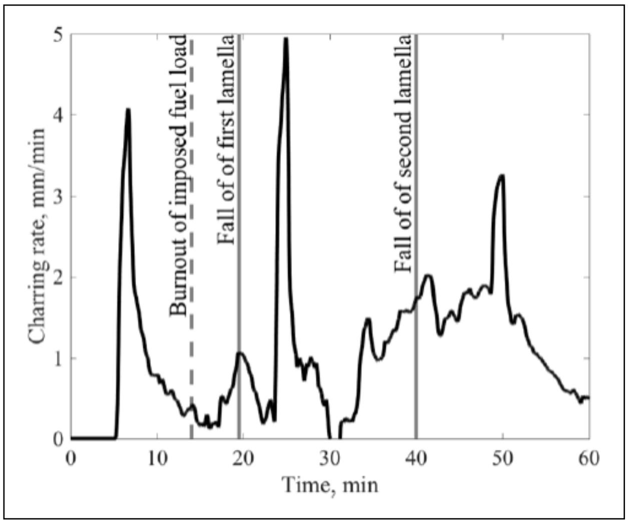
- Understanding of the extent of timber that is exposed and its location
- Reliability of the encapsulation
- Type of timber that is exposed (CLT, glulam etc.)
- Having a predictable compartment model for the HRR of the fire, based on the fire load and available timber fuel
- Understanding the ventilation available and the influence
- Determining the influence of the timber on the fire decay
- Structural loading conditions, structural connections and type of connection.

A2.1.4 Bond line integrity in fire

Bench scale (Figure 12a), standardised furnace, and natural fire experiments have shown a general consistency in how CLT reacts to fire. When a CLT panel is exposed to the heat of a fire, the reaction will depend on the thickness of the panel, type of adhesive used in the manufacture, and thickness of the plys (lamella). Also, to a much lesser degree, the fire performance is influenced by the species of the timber, the width of the timber used, the method of adhesive application (face application only, or face and edge application), and the stress induced by the application of any load.



(a)



(b)

Figure 12: Effect of bond line integrity failure (referred to as delamination in figure) for the rate of char in a CLT panel: (a) observed bond line integrity failure in a small-scale test, (b) calculated rate of char of CLT in a real-scale compartment fire experiment

When a CLT panel is exposed to fire the initial charring behaviour in the first ply is identical to that of timber or glulam. As the charring reaches the adhesive line, one of two events will occur:

– The charring continues consistently through the adhesive line.

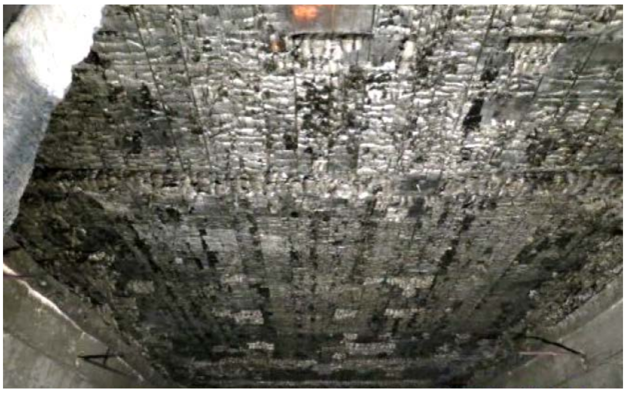
– The protective char will dislodge due to lack of adhesive strength under heating, exposing the unburnt wood below, referred to as bond line integrity failure.

The behaviour of bond line integrity failure at the adhesive line when a CLT panel is exposed to fire is also called delamination, char fall-off or char stickability.

Bond line integrity in fire is a desired outcome. Glue line failure is the process where small pieces of mostly charred wood separate from the unburnt CLT base, as the charring reaches the ply interface (adhesive line). The separation of the char occurs due to the ply adhesive losing its strength under increased temperatures. CLT panels located horizontally (underside of floors) are more susceptible to glue line failure than panels located vertically (walls). The process of glue line failure has been shown to be dependent on adhesive type and behaviour and is an excessive amount of char fall off or larger areas of unburnt wood that does not stay in place (due to the adhesive failure). This is different from natural char fall off.

The issue with a CLT panel that does not have bond line integrity in fire is that when glue line failure occurs, the heat insulating function of the char is lost. The unburnt timber below the char then becomes exposed to the heat of the fire and there is a rapid localised increase in the pyrolysis and charring rate. This increased burning occurs until a new char layer is formed, which then insulates the remainder of the timber and the normal char rate returns. Not all CLT panels are susceptible to glue line failure, as this behaviour is influenced by their design characteristics, including choice of adhesive, number of lamellas, and thickness of lamellas.

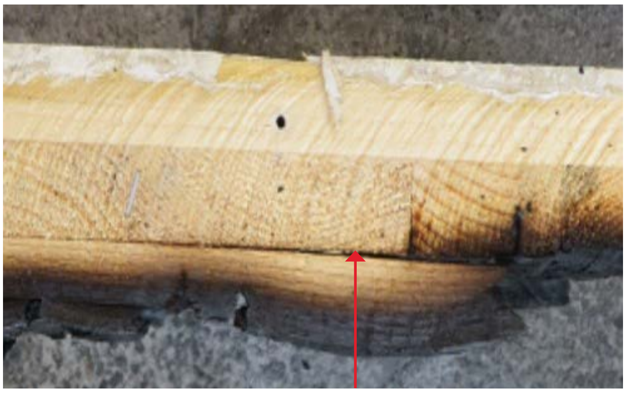
This effect is illustrated in Figure 12, which shows the glue line failure of a charred CLT section causing new flaming of the underlying timber. The post fire test images in Figure 13 and Figure 14 demonstrate the difference between CLT with so called "non-delaminating" adhesives (right) and CLT with adhesives that are prone to glue line failure (left). Glue line failure in fire is an important issue for a compartment with large areas of exposed CLT as it impacts the panel fire resistance and more importantly, how the compartment fire will behave. It is therefore a critical phenomenon to be addressed.



CLT panel post fire test without bond line integrity in fire.

CLT panel post test with bond line integrity in fire.

Figure 13: Post ASTM E119 fire tests showing two different CLT panels with and without bond line integrity in fire



CLT panel post fire test with adhesive that debonded upon heating

CLT panel post fire test with non-debonding adhesive

Figure 14: Post ASTM E119 fire tests showing two different CLT panels with and without bond line integrity in fire (in section after cutting through panel)

A2.2 Test method determination of CLT bond line integrity in fire

Research at the Swiss Federal Institute of Technology, ETH, has shown that where a CLT panel is exposed to a standard fire curve for a period in excess of 120 minutes and multiple adhesive lines are charred through, the susceptibility of the panel to glue line failure in fire can be proven. Currently, ANSI / APA PRG320:2018 is the only national standard with a methodology for confirming glue line failure in fire for CLT.

If a panel is exposed to the standard fire and has a consistent char rate through the plys as the char front progresses, then the panel is not susceptible to glue line failure. Where glue line failure occurs, there are spikes in char rates, as the underlying timber is exposed to the heat of the fire (furnace). There is also a corresponding increase in mass loss. Thus, exposing a panel to a standard fire and measuring the char rate or mass loss as the char front progresses can provide confirmation of adhesive behaviour.

A second check is the final char rate. In CLT that is not susceptible to glue line failure, the char rate will be at or below 0.7mm/min, after exposure of more than 120 minutes and consumption of multiple plys. For CLT panels that are susceptible to glue line failure, the char rate at the end of the test is normally in the order of 0.8mm/min to 0.9mm/min, depending on the number of plys and their thickness.

By exposing a CLT panel in a horizontal plane to the standard fire with extra temperature measurements to determine char depth and rate, the susceptibility to glue line failure in fire can be verified. A new test method to verify bond line integrity in fire will be documented within the revised EN 1995-1-2 (see https://www.ri.se/en/what-we-do/projects/glue-line-integrity-in-fire). The char rate will continue to increase as the standard fire progresses, given the temperature continues to increase over time. A higher char rate is expected for a 120 minute test, when compared to a 90 minute test.

A2.3 The fire hazards associated with exposed mass timber construction

In a non-combustible compartment the fire size and duration are governed by the fuel load available, the availability of oxygen (through ventilation openings) and the thermal properties of the enclosure. Most fires within small and medium-scale non-combustible compartments will experience four distinct phases of fire behaviour from ignition to burnout, as illustrated in Figure 15, where sprinkler protection and firefighting intervention are not included. Heat output is a measure of the size of a fire. It should be noted that in large open-plan non-combustible compartments, fuel distributed throughout the compartment often does not burn simultaneously, instead a travelling fire can progress through a compartment as a localised region of fire (Stern-gottfried et al., 2012, Rackauskaite et al., 2021, Heidari et al., 2020), typically known as a travelling fire.

In a compartment where the mass timber is exposed or is not protected with reliably specified encapsulation, the additional fuel produced by the pyrolysis of the timber structure will change the overall fire behaviour in each regime, due to the contribution of timber surfaces to flame spread during the incipient and growth phase, the addition of flaming timber surfaces to the fire load during the fully-developed stage, and continued smouldering of timber surfaces and connections during and after the decay phase. Each of these impacting factors is described within the following sections.

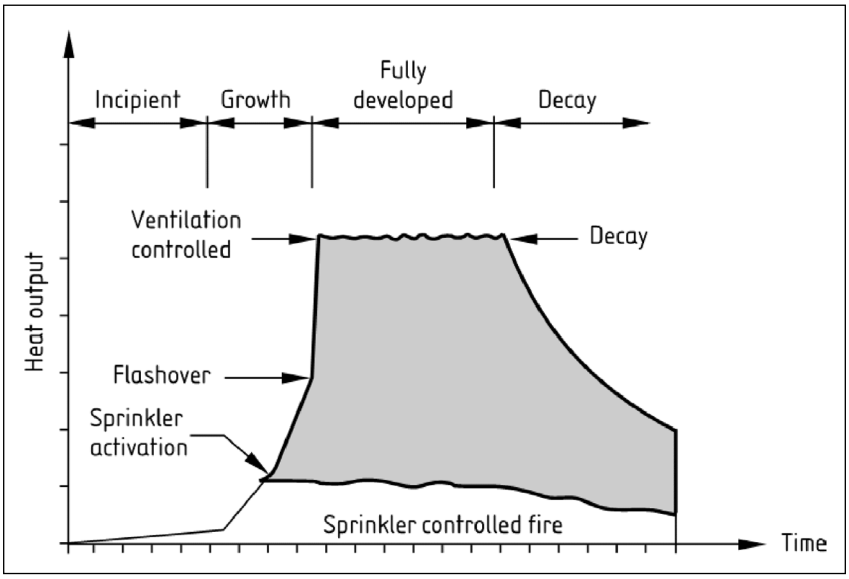


Figure 15: Phases of fire development and decay in non-combustible compartments (BS 7974 (BSI, 2019))

A2.3.1 The impact of additional mass timber fuel

The primary hazard mass timber structures present is the potential for increased fire duration and severity due to the additional energy released as exposed timber elements burn. The CodeRed experiments (Kotsovinos et al., 2023a, 2023b, 2023c, 2023d) showed that the addition of a mass timber surface can increase the total heat release rate of the compartment by up to 50% compared to an equivalent concrete compartment fire. Furthermore, flame spread along exposed timber surfaces was showed to accelerate flame spread along flammable compartment contents.

A prescriptive code design that includes exposed mass timber may not be appropriate, given the significant variation in underlying fire behaviour depending on timber performance (e.g. CLT glue line failure, external vertical flame spread).

The fire safety protection measures (active and passive) need to be adequate to mitigate the potential fire hazards posed by the increased fire duration and severity, or the exposed mass timber must be reduced in area through reliable encapsulation to reduce the fire duration and severity.

There are broadly three potential outcomes for a fire in a compartment with exposed mass timber. These have been illustrated in an indicative graph of heat release rate (HRR) vs time in Figure 16. The behaviours, the conditions which cause them and the impact for design are summarised in Table 15. Refer also to Appendix A3 where the literature review of available compartment fire experiments is presented.

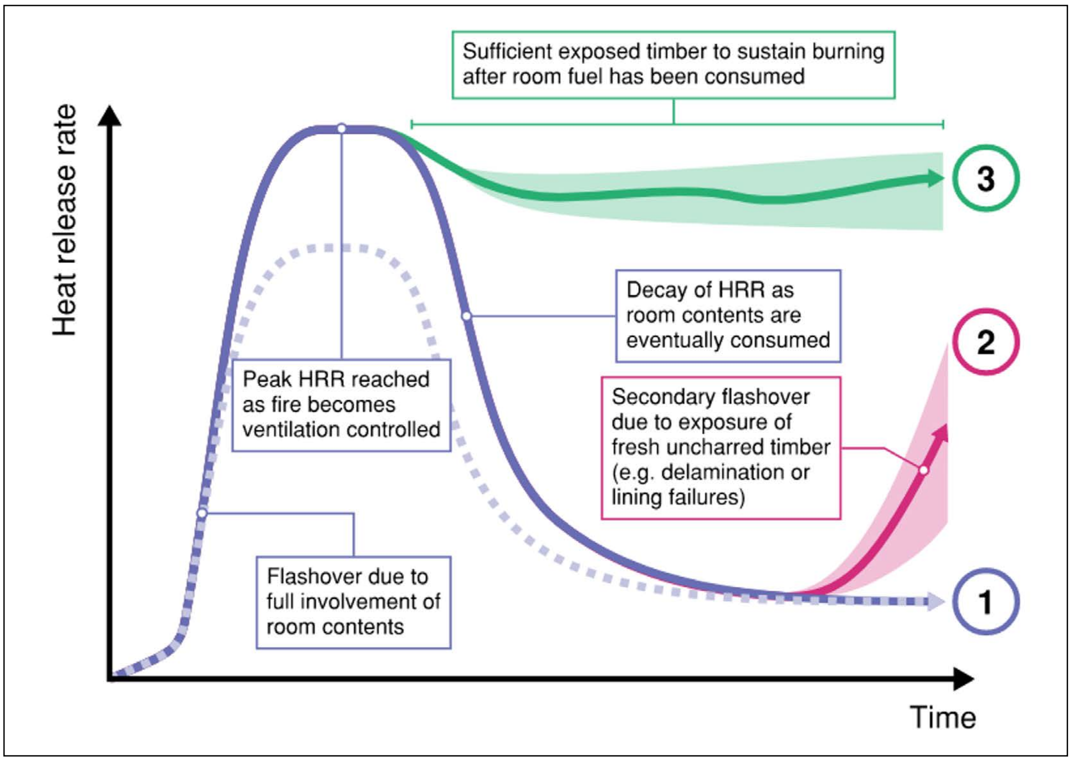


Figure 16: General trendlines of heat release rate (HRR) vs time plots from experimental data of ventilation-controlled fires within CLT compartments. Fires that do not decay require firefighting intervention for suppression.

Table 15: Potential outcomes for fire behaviour and duration in a compartment with exposed timber

Potential outcomes	Description of behaviour	Conditions where this outcome is observed	Impact for design
1. Decay	The fire grows and reaches steady-state burning. Any burning timber contributes to the total HRR during these phases. Once most of the fuel within the room is consumed the fire decays. If exposed timber is present, the pyrolysis slows and stops as the fire within the compartment does. Smouldering of the timber at the char surface may still occur, but ideally will slowly cease during the decay phase.	Where the area of exposed mass timber is limited. When using CLT that is susceptible to bond line integrity failure, the amount of CLT that can be exposed is less than when using CLT that maintains bond line integrity in fire. For example, in one of the USFS fire experiments, ceilings with 20% exposed and debonding CLT had fire decay (see Appendix A.3.3.10).	In this scenario the timber has limited effect on the overall duration of the fire and, therefore, the fire is not likely to exceed the fire resistance expectations inherent in fire safety guidance. Intervention by fire fighters may be needed to identify and extinguish any residual smouldering.
2. Secondary regrowth during decay phase	The fire grows, achieves steady-state burning and starts to decay in the normal manner. Exposed timber contributes to the total HRR in these phases. Either during or after a period of decay, exposed timber surfaces reignite and flames spread, often quite rapidly.	The change in conditions which leads to regrowth is most commonly observed to be either a failure of encapsulation, CLT glue line failure, or transition from localised smouldering to flaming. CLT glue line failure or encapsulation failure have been shown to result in secondary regrowth similar to the initial flashover. While glue line failure is typically observed before or during the decay phase, smouldering transition to flaming can occur hours after the initial fire, after the decay phase.	In this scenario the timber does affect the overall duration of the fire and, therefore, may exceed the fire resistance expectations inherent in fire safety guidance. The re-growth is unpredictable. Fire rated elements of construction are specified for only one peak temperature rise and a secondary temperature peak, such as flashover, will likely result in failure. Intervention by fire fighters may be needed to identify and extinguish any residual smouldering.
3. Quasi steady-state burning	The exposed timber continues to burn at a quasi-steady state after consumption of all the typical fuel (furnishings, etc.) within the room, due to the area of exposed mass timber. In the fire experiments where this behaviour was observed, no decay phase was recorded as the experiments were typically terminated for safety. Failure of the compartment separation walls or structure may occur before decay.	Where there are multiple surfaces of mass timber exposed, there can be long periods of fully developed fire behaviour due to the timber fuel available and the impacts of re-radiation between surfaces. The prolonged burning can also be influenced by bond line integrity failure. For example, see FPRF 1-6 in Appendix A.3.3.8.	In this scenario the timber does affect the overall duration of the fire and, therefore, the fire may exceed the fire resistance expectations inherent in fire safety guidance.

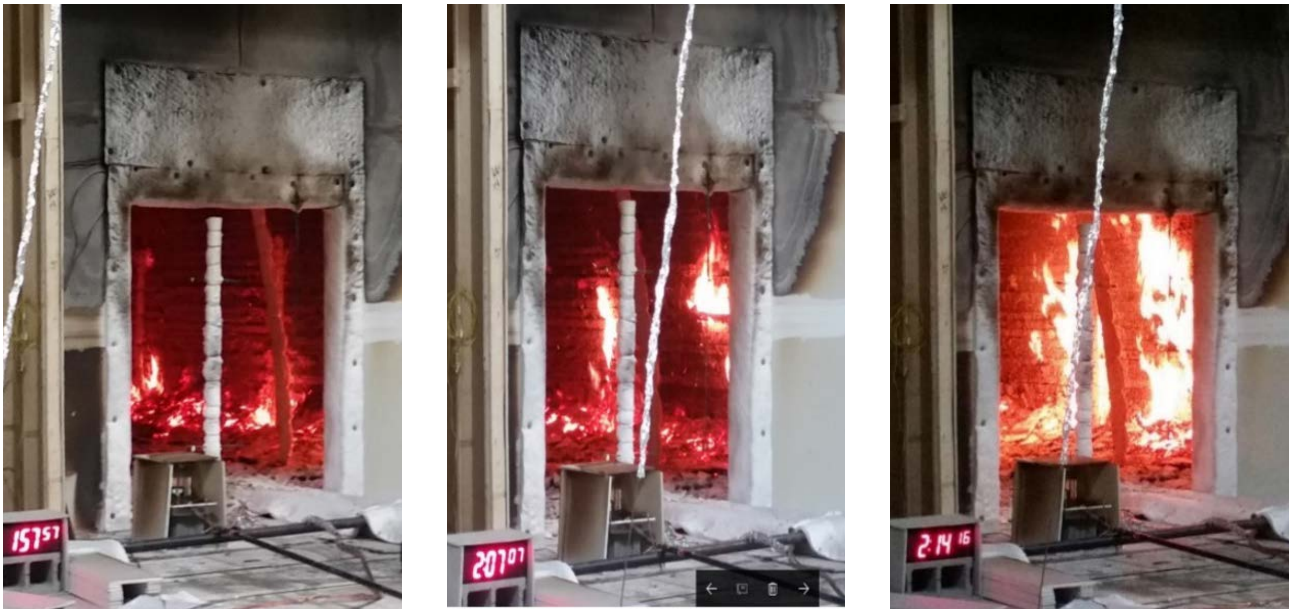


Figure 17: CLT compartment fire experiment with timestamps showing an example of secondary regrowth (Su et al., 2018b).

A2.3.2 The impacts of compartment size and ventilation

Fire dynamics within a space are influenced by the size of the space. In larger spaces, fire dynamics are commonly characterised by fuel-limited rather than ventilation-limited conditions and this can result in longer duration fires. As outlined in Section A.2.1.1, the likelihood and implications of longer duration fires can be exacerbated in compartments with exposed timber structure.

The observed fire behaviour in these smaller timber compartment fire experiments is not applicable to larger compartments, particularly considering that the fire dynamics will change from ventilation-limited to fuel-limited fires (see Appendix A4 on the findings from the large compartment fire experiments). Further to this, in larger compartments flame spread over timber surfaces is instrumental in fire growth. For further details on the impact of compartment size and ventilation, please refer to A5.

There is an increasing body of evidence of fire experiment data for large compartments with exposed timber surfaces, (refer to A4).

A2.3.3 Importance of type of CLT

Due to the varying manufacturing techniques and diverse sources of timber worldwide, there are a range of different choices in CLT supply in the marketplace, and therefore differences in CLT performance when exposed to fire. CLT material properties have a significant impact on charring. This includes density, thickness, moisture content, porosity, and as previously mentioned, species (changes proportion of cellulose, hemicellulose, and lignin).

Specifying CLT with bond line integrity in fire is an important fire safety control measure for designers for medium and high-rise buildings. Where large areas of CLT are exposed, specifying CLT with bond line integrity in fire the engineer can assume reliable fire decay and therefore more predictable fire behaviour for design.

For high-rise and medium-rise buildings where fire safety goals require a design to provide for fire decay, the exposed CLT needs to perform in a predictable manner in fire conditions. Fire testing and compartment experiments to date (see Appendix A.3) have proven that panels that are susceptible to bond line failure result in unpredictable fire conditions.

The influence of glue line failure either occurring or not occurring has been demonstrated by compartment fire experiments by NRC, Canada (See Appendix A3.3.9, Figure 20). These experiments included CLT that was proven to have bond line integrity in fire with two different configurations of exposed glulam beams and columns. The experiments showed a much slower decay than non-combustible compartments, when large areas of timber are exposed.

From a fire decay point of view, tracking the 300°C compartment temperature threshold shows a significant change in fire performance with the timber exposed (see Figure 18). These experiments show, that with low ventilation and relatively large areas of timber exposed, the fire decays very slowly, or not at all. The ventilation has a significant impact on the decay, but there is yet to be a correlation developed to link ventilation, exposed timber and how the fire decay occurs. The NRC experiments also showed the impact of charring occurring behind the two layers of fire rated plasterboard (2 x 12.5mm), which is most evident in Test 5 where compartment re-growth occurred due to the protection failure.

Exposed timber slowing fire decay was also seen in the FPRF experiments before the impact of CLT bond glue failure (Tests 1-4 and 1-5). On the other hand, the USFS compartment experiments included a limited area of exposed timber (Test 2 and Test 3), with a larger proportion of available ventilation, resulting in a decay phase generally unchanged from the compartment without timber.

Thus, to assess structural capacity of a timber member within a compartment with exposed CLT, the compartment fire needs to be reliably assessed and to do this requires CLT that also performs reliably when exposed to a growing, fully developed and decaying fire. In this Guide, the specification of CLT for certain building types is based on panels that that have been proven to have bond line integrity in fire and will char through the adhesive line at a consistent rate.

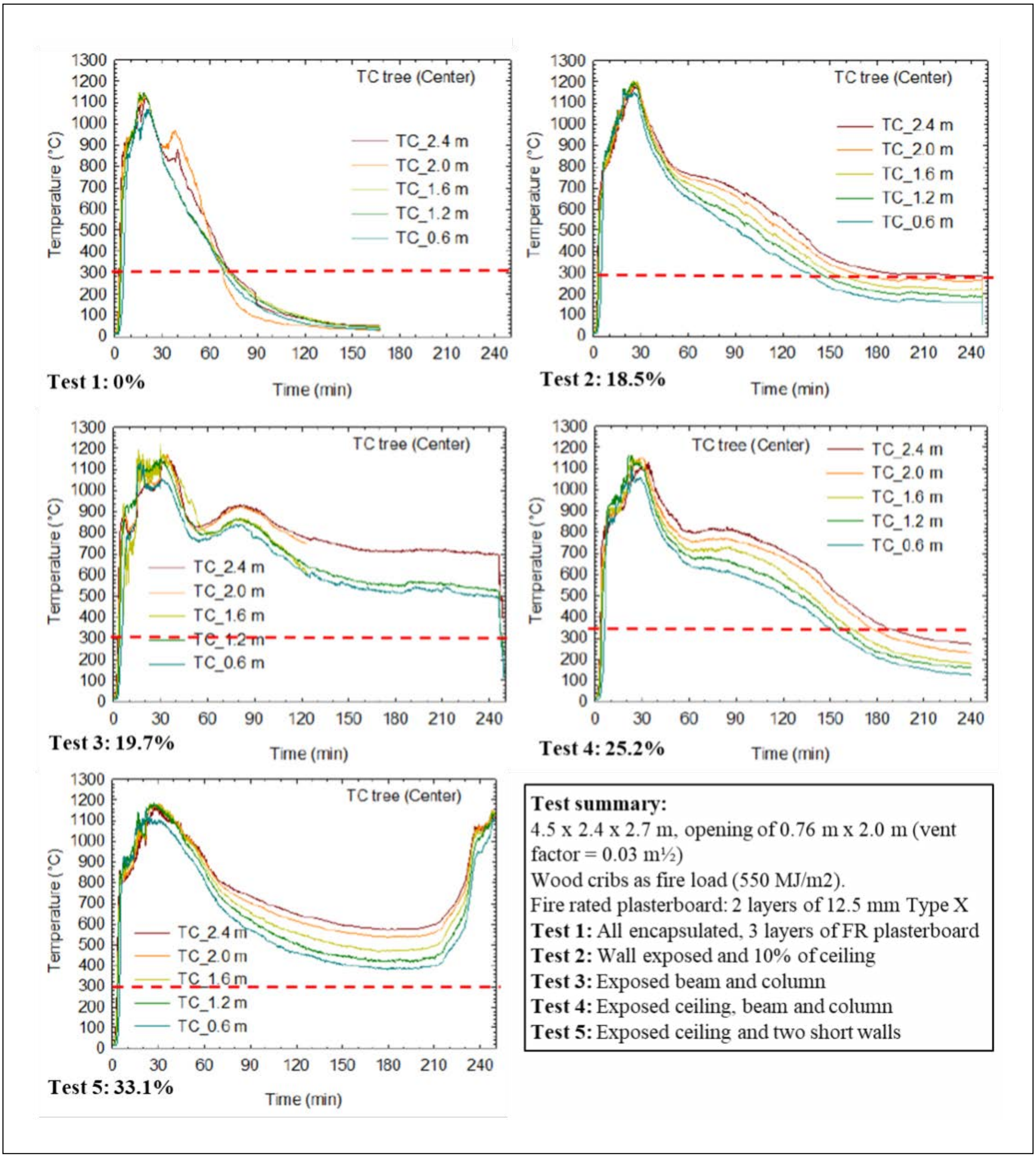


Figure 18: Summary of NRC Canada fire experiments (Su et al., 2018b) with areas of exposed mass timber, showing 300°C isotherm compartment temperature, compared with room temperatures. Experiment summary and percentage exposed timber area provided.

A2.3.4 Decay and post-decay behaviour

A predictable decay phase is necessary to enable estimating both the final char depth and the 'zero strength layer', and hence the residual structural loadbearing capacity of loadbearing timber elements following a severe fire. Effective prediction of the decay phase relies on estimating the rate of temperature decay inside the compartment, and therefore also the complete burn out of all available fuel present in the compartment, including movable contents and the timber structure. Prediction of decay phase behaviour will inform the thermal degradation behind the char layer during the decay phase.

As the fire intensity of both the fuel load and exposed timber decays, exposed timber will slow in char progression due to the lowering of received heat flux by convection and radiation as the compartment temperatures cool and the removal of direct flame impingement. There are several impacts during the decay phase:

- During the decay phase, smouldering on exposed timber surfaces can continue to contribute heat to the compartment and timber elements, providing heat to continue the charring of timber elements.
- During and after the decay phase, smouldering can occur in localised regions of timber elements, continuing to provide heat to char timber and potentially transition back to flaming.
- The decaying fire will continue to heat the timber and there is a residual heat 'wave' that will propagate through the timber, continuing to reduce structural capacity.

The available ventilation will also significantly impact HRR decay, with the decay rate being slower in ventilation-controlled fires (as evidenced by CodeRed #02, see A.4.3.2.).

The result of these factors is the reduction of timber structural capacity, by both the reduction in cross-section to the member and the on-going reduction in strength of the timber in the heat affected zone, ahead of the char layer. In simple geometries with no air flow present, the heat flux when flaming transitions to smouldering during decay has been determined to be in the order of 32kW/m^2 (Bartlett et al., 2017). As this received heat flux is reached, it does not mean that charring instantly ceases, or that the timber is at a point of maximum reduced capacity. During this phase charring still occurs, though typically at a slower rate. This is due to both residual heat that will impact the heat affected zone, and smouldering generating heat that can continue to sustain the progression of charring. This continued heating of the timber will result in a continuing reduction in timber strength, though typically at a slower rate. The continued heating of the timber will also continue to propagate behind the char layer, so it is important to determine the minimum residual structural capacity of structural timber due to these three processes.

As the internal temperature of the timber exceeds the temperature of the compartment, the residual temperature in the timber will transfer heat back into the compartment. However, after a sufficiently severe fire there will be a point where the char stops protecting the timber from the compartment heating, and instead acts as an insulator that keeps timber at elevated temperatures for longer, slowing the heat transfer from the timber back into the cooling compartment. Any char that continues to smoulder becomes a source of on-going heating for any neighbouring timber or unburnt fuel, and will be losing heat in two directions – to the compartment (convection) and through to the residual timber section (conduction).

Smouldering in simple geometries (i.e. a flat surface) will typically cease without an external heat flux or sufficient airflow (Rein, 2016). However, in locations where smouldering surfaces may re-radiate onto each other or gaps where increased airflows may form (e.g. slab-slab connection gaps, wall-ceiling interfaces), smouldering can continue to be sustained, generating heat and facilitating further charring in localised regions of timber. This can be of particular concern in structural elements local to regions of high stress-concentrations (e.g. connections), that may potentially lead to structural failures hours after the end of flaming. Details on the hazards of smouldering are detailed in A.2.1.1 and in the context of CodeRed in A.4.3.5.

Whilst relatively small, this increase in char depth could influence failure of the structure and is important enough to impact safety margins. Hence, modelling compartment fires with exposed timber has to be carried out to include the full decay period and the residual heat wave and the impact of the decay period needs to be included in the structural assessment.

Experiments that have run for a sufficiently long period have observed smouldering behind boarding or at junctions to continue (e.g. Brandon et al., 2021, CodeRed #04, 2021), as was observed also in cavities containing timber such as the TF2000 experiments on multi-storey lightweight timber frame construction (Lennon, 2003) and many fire incidents in timber framed buildings.

There is hence a residual risk of ongoing smouldering combustion consuming the timber which may be hidden from view. Smouldering needs to be identified by fire fighters to enable them to access and apply water to extinguish the smouldering combustion.

Brandon et al. (2021) and ongoing research studies by the fire and rescue service in Hamburg, Germany HoBraTec (2022), noted that encapsulation may need to be removed manually to expose localised smouldering and allow effective suppression, and that smouldering cannot always be detected using infrared cameras if deep seated.

A2.3.5 ETAs and other technical documents

European CLT suppliers have European Technical Approvals (ETA) and other CLT suppliers have their own technical documents, which typically provide material and structural properties, and most also include reaction to fire and fire resisting performance. Often, statements related to fire in the CLT supplier ETA's and technical documents can be incomplete. Where an ETA or some other technical document is being used to justify a char rate or fire resistance rating for a CLT panel, the information upon which it is based should be verified.

A2.4 Design methods for assessing limited areas of exposed timber

There is a limit to how much timber can be exposed before the timber significantly affects the HRR and duration of the fire. Determining that limit is key to the design for permitting a safe amount of timber to be exposed within a compartment, especially larger compartments over 500m^2.

As noted in previous sections, the design for a building that includes an exposed mass timber structure requires the determination of the depth of charring and the depth of thermal impact behind the char, for the full duration of the fire. The full duration of the fire includes the decay phase of the fire and the period of transient heating that occurs within the timber structure well after the compartment has cooled to ambient conditions. For example, within the CodeRed experiments, the glulam columns had elevated temperatures behind the char layer for periods of at least 60 minutes after the building had cooled to ambient temperatures (see Section A4)

For engineers, there is a very limited number of methodologies available for assessing the char depth of timber, based on compartment fires that have been derived to account for the impact of the exposed timber. This is very relevant for high-rise and more complex buildings where a performance-based design is required for the exposed mass timber.

For large compartments such as open plan offices of floor area greater than 500m^2 there is currently no assessment methodology available to determine char depth and heat impacted layer behind the char, for the full duration of a fire through to the point where the thermal degradation stops in the timber members. The current research on how exposed mass timber impacts post-flashover or large scale fully developed fires is limited to smaller compartments, typically in the order of up to 100m^2. Published data for larger compartments where travelling fires will occur is limited, with only three large scale experiments published – CodeRed (See section A4), FRIC #01 and #02 (Bøe et al., 2023) and Canadian MTDFTP (Su et al., 2023). To date no predictive model for determining the full extent of charring and heat impact in the exposed mass timber have been developed that have been validated against large scale experiments.

The published methods available include:

- Basic parametric iterative method developed by Arup (Barber, 2016)
- Method developed by Wade (Wade, 2019)
- Method developed by Schmid (Schmid and Frangi, 2021)
- Complex pyrolysis model developed by Richter (Richter et al., 2019)
- Method developed by RISE (Brandon et al., 2021).
- Method developed by FPInnovations (Girompaire et al., 2024).

The most widely used methodology for estimating the char depth for exposed timber and an acceptable area of exposed mass timber is that published by RISE (Brandon et al., 2021), which adapts the BS EN 1991-1-2 (Eurocode 1) Parametric temperature-time curves and uses an iterative method and is an approximation tool only. The RISE methodology has been continually revised and updated based on fire experiments and is considered the most up to date method. It does have limits on how it can be used, which include:

- Compartment limits up to 500m^2 (based on the parametric temperature time methodology).
- CLT must have proven bond line integrity in fire. The method is not valid where the exposed timber includes CLT that does not have bond line integrity in fire.
- The compartment cannot be interconnected to another compartment via an open stair void.
- Limits on input ventilation assumptions.

Given the lack of verified methods for predicting post-flashover or travelling fires within larger compartments, realistically those more than 500m^2, high-rise or complex buildings with larger compartments that include significant areas of exposed mass timber structure should be approached with an abundance of caution. Engineers and building authorities need to recognise that estimates of char depth and heat impacted layer using existing methods (listed above) may not be in any way accurate for larger compartments that include significant areas of exposed mass timber.

For further reading and information, Chapter 3 of the Fire Safe Use of Wood in Buildings – Global Design Guide (Buchanan and Ostman, 2022) provides a useful review and recommendations.

► Canary Wharf, Elizabeth Line Station, London © Arup

Appendix 3.

Review of compartment fire experiments with protected and exposed mass timber surfaces

A3.1 Overview

As this Guide is risk-based, it is necessary to define the likelihood of timber impacting the required fire resistance and substantiate this with available relevant experimental fire test literature and data.

For this Guide, the likelihood of the timber impacting on the required fire resistance is broadly influenced by the extent of timber exposed, and therefore, able to participate in, and contribute to, the compartment fire.

The likelihood of mass timber impacting the required fire resistance for a structure is also affected by the presence and performance of automatic suppression. Automatic fire suppression does not increase the fire resistance of the timber, but instead should suppress, if not extinguish, a fire before a structurally significant fire is able to develop, ideally preventing the ignition of mass timber elements entirely. Through this, the likelihood of structural failure can be substantially mitigated.

A3.2 Literature review methodology

The empirical experiment data reviewed relevant to mass timber compartment fires can broadly be grouped into three separate categories of compartment fire designs:

– Completely protected or encapsulated timber surfaces

– Single exposed surface (e.g. a single wall or ceiling either fully or partially exposed)

– Two or more surfaces exposed (e.g. multiple walls and/or ceiling either fully or partially exposed)

Note that discussion of the behaviour of exposed mass timber columns or beams is omitted from this analysis. The range of compartment floor areas and percentage of compartment surface area comprised of exposed timber is depicted in Figure 20. Each of the available compartment fire experiment series, listed in Table 19, have been reviewed and categorised into the above groupings to reflect current design aspirations. It is also important to note that most fire experiment data is on medium- and small-scale compartments (defined as < $100m^2$ for the purposes of this review) representative of a single bedroom or one bedroom apartment. By comparison, large open-plan compartments used in office buildings can span floor areas of >$1500m^2$.

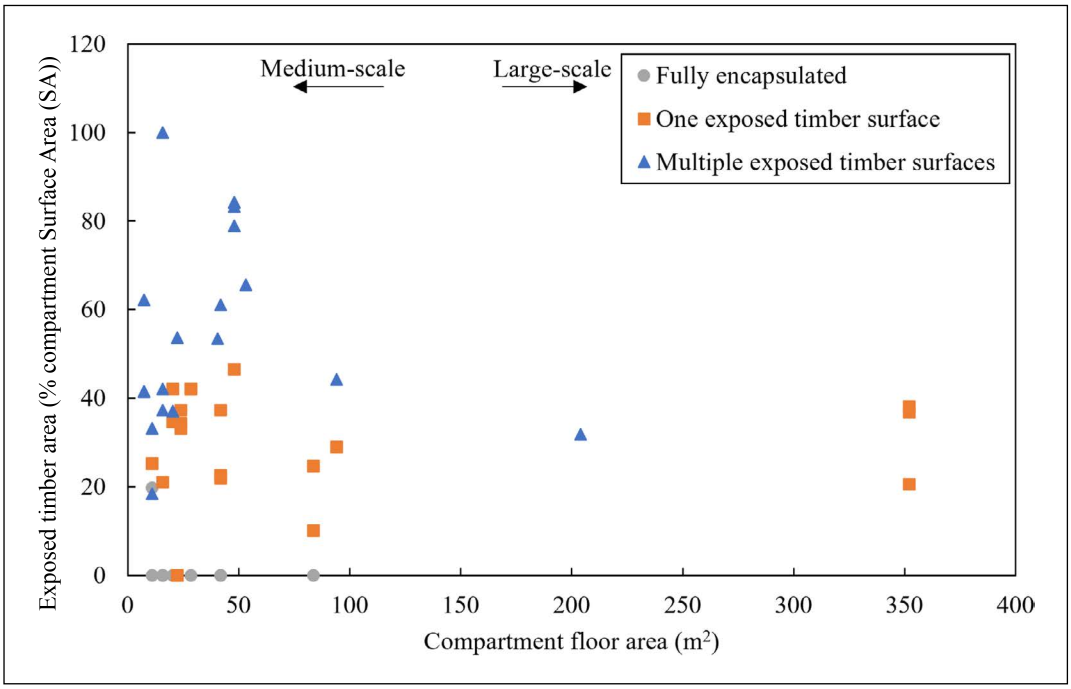


Figure 19: Plot of compartment floor area versus percentage of internal compartment area (walls and ceiling) comprising exposed mass timber for all reviewed experiments.

A3.3 Fire experiment information and data reviewed

The effect of exposed mass timber elements on compartment fire behaviour is now well-documented by a series of small and medium-scale research programmes conducted by multiple international institutions. A common finding from this research is the effect of increased area of exposed timber on increasing the heat release rate of the compartment fire, due to the contribution of flaming mass timber surfaces. Further, the fire experiment data has shown that in cases where CLT exhibits glue line failure and there are larger areas of CLT exposed, the onset of decay of the fire can be delayed. A result of delayed decay is an increased likelihood of exceeding the design basis fire duration, and so, the fire resistance period of structure. This has consequences for occupant and firefighter life safety in tall buildings, or high-risk buildings (e.g. care homes) where fire safety strategies are reliant on the structure maintaining stability for longer or where collapse is not acceptable.

Therefore, as designers, it is important to control the area of exposed timber in these types of buildings such that inclusion of exposed timber does not unreasonably extend the fire decay. However, no validated design methodology for predicting or quantifying the effect of exposed mass timber elements on fire duration has yet been established and accepted. Beyond this review, a range of reviews of timber compartment fire experiments have also been conducted by various institutions to identify research gaps and trends in fire behaviour (Mitchell et al., 2023; Buchanan, Östman & Frangi, 2014; Brandon & Östman, 2016; Ronquillo, Hopkin & Spearpoint, 2021; Liu & Fischer, 2022).

Table 16 below summarises the experiment series reviewed, and the number of experiments undertaken for varying amounts of exposed timber which is used to inform the likelihood definitions. Following Table 13, a summary of the design and key findings of each experiment series is provided.

Arup has undertaken four large-scale experiments of approx. 352m^2 with partners CERIB and Imperial College London. These are included in Table 19 and summarised in full in Appendix A4.

Table 16: Summary of the 59 fire compartment experiments reviewed

Experiment series	No. experiments undertaken		
	Fully encapsulated (i.e. no exposed timber)	Single exposed surface	Multiple exposed surfaces
ETH Zurich (Frangi et al., 2008)	1	0	0
Carleton University:			
McGregor (McGregor, 2013)	3	0	2
Medina Hevia (Medina-Hevia, 2014)	0	1	2
NRC (Su and Lougheed., 2014)	1	0	0
NRC (Su and Muradori., 2014)	1	0	0
National Technical University Athens (Kolaitis et al., 2014)	1	0	0
SP Fire Research (Hox, 2015)	0	0	1
Arup-Edinburgh University (Hadden et al., 2017)	0	0	5
NFPA Fire Protection Research Foundation (NRC, Canada and SP, Sweden) (Su et al., 2018a)	2	3	1
NRC (Su et al., 2018b)	2	1	2
US Forest Service – ICC (Zelinka et al., 2018)	1	2	2 [Note 1]
Epernon Programme phase 1 (McNamee et al, 2021; Wiesner et al, 2021)	0	3	0
RISE (Brandon et al., 2021, (Sjöström et al., 2023)	0	1	4
TIMpuls (Brunkhorst et al., 2021, Engel et al., 2022)	1	2	2
CodeRed (Arup, CERIB, Imperial College London) (Kotsovinos et al., 2022a, 2022b, 2022c)	0	3	0
STA (Hopkin et al., 2022, 2023)	1	2	0
FRIC (Sæter Bøe et al., 2023a, 2023b)	0	1	1
NRC (Su et al., 2023)	1	1	3
Sub-total:	15	20	24

Note 1: These experiments have not been included in this section of the literature review as automatic fire suppression was provided.

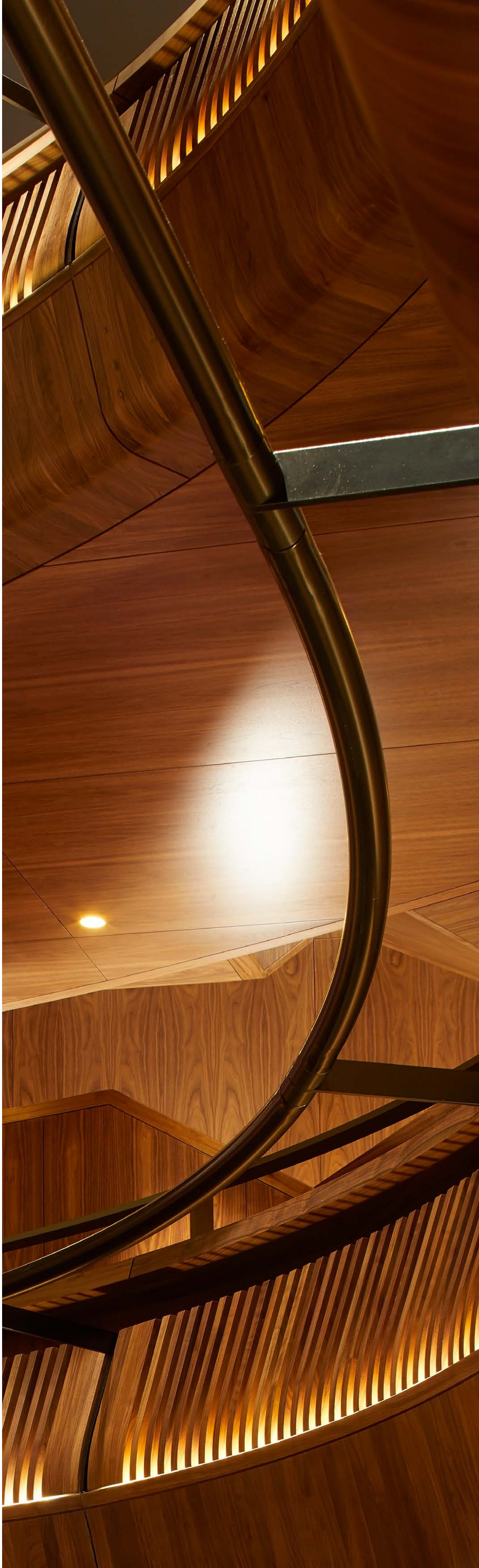
A3.3.1 ETH Zurich (Frangi et al., 2008)

A natural fire experiment in a three-storey timber building was conducted in Tsukuba, Japan, in 2006 (following strutural vibration testing), as a part of the SOFIE research project sponsored by the Italian Province of Trento, in a collaboration led by ETH Zurich.

The aims of these experiments were to analyze the performance and behaviour of cross-laminated (in the paper called XLam) timber structures, to support further numerical and experimental analysis in the SOFIE project.

Experiments were undertaken in a three-storey building of outer dimensions 7x7m and 10m in height. The fire compartment was on the middle floor, with dimensions of 3.34m wide, 3.34m deep, and 2.95m tall. The experiment had two permanent ventilation openings of 1.0m wide by 1.0m tall, with a window opened slightly to an opening size of 0.26m wide by 0.94m tall. The wall and ceiling slabs were comprised of five-ply CLT elements of 85mm thickness.

All surfaces were encapsulated by multi-layer protection comprising 12mm standard gypsum board, 12mm fireproof gypsum, and 27mm mineral wool. The natural fuel load was supplied by wood cribs, and residential furniture (beds, mattresses, cabinets, and retail electronics) of fuel load density 790MJ/m^2.



► The Royal Opera House, Linbury Theatre, London © Hufton+Crow

A3.3.2 Carleton University (McGregor and Medina-Hevia, 2012 – 2014)

A series of medium-scale fire compartment experiments were undertaken at Carleton University, Canada, between 2012 and 2013. The findings of which are summarised in theses prepared by McGregor (McGregor, 2013) and Medina-Hevia (Medina-Hevia, 2014), and also discussed by Li (Li et al., 2016).

The objective of the research was to study the behaviour of fully and partially protected CLT compartments in a non-standard (i.e. propane burner) and typical room fire (i.e. natural fuel load), and to investigate how the heat release rates, temperature, fire duration, and charring differ depending on how many CLT surfaces are protected. The experiments were undertaken in a single compartment of dimensions 3.5m wide, 4.5m deep, and 2.5m tall. The compartment was provided with a permanent opening for each experiment of 1.1m wide and 2.0m tall.

The compartments were constructed from three-ply cross-laminated timber panels with an overall thickness of 105mm and an individual ply thickness of 35mm. The lamella was bonded using PUR adhesive. The experiments outlined by Medina-Hevia investigated the impact of varying the number of exposed mass timber surfaces, having a single wall exposed in one experiment, and two walls exposed in the subsequent two experiments. Type Note 1 gypsum was used for those experiments where the surfaces were required to be encapsulated to protect the underlying timber.

The experiments with a natural fuel load were intended to reflect the average fire load density for a Canadian multi-family dwelling with a value of 534MJ/m^2. The experiment series described by McGregor not only varied the amount of exposed mass timber surfaces (either fully exposed walls and ceiling or completely protected by 2 x 12.7mm gypsum board), but also studied the impact of varying the fire load type between a propane gas burner and furniture. In the experiments which utilised a propane burner, the heat release rate curve was intended to represent a hotel room with a queen size bed fire.

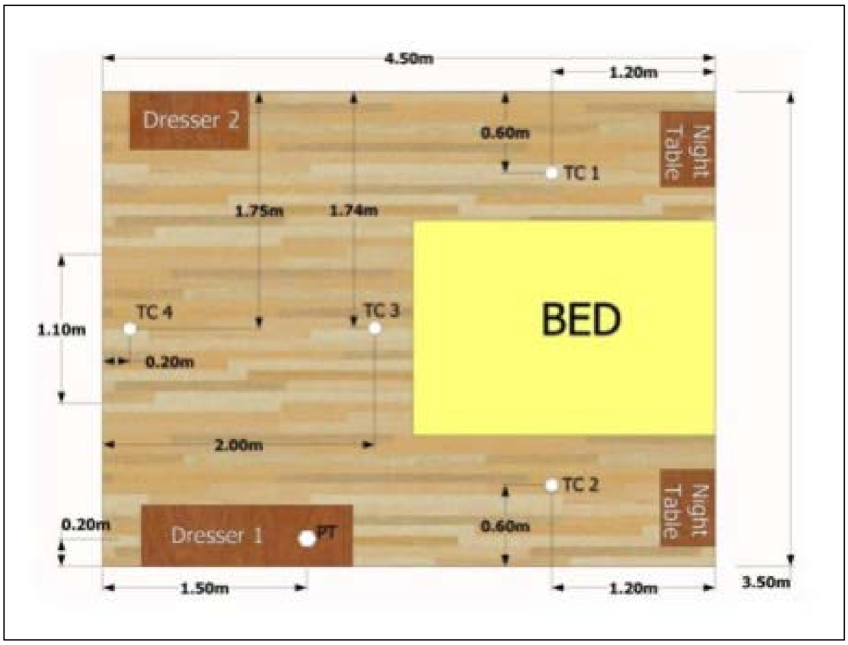


Figure 20: Image of Carleton University experiments

Note 1: Type X fire resistant gypsum per ASTM C1396

A3.3.3 NRC (Su and Lougheed, 2014)

As a part of a larger experimental series studying the fire performance of timber-framed and steel-framed compartments, a single CLT compartment experiment was conducted by the National Research Council Canada (NRC, Su and Lougheed, 2014). The main objective of the experiment was to support technical solutions for mid-rise timber buildings.

The experiment was undertaken for a compartment size or 6.3m wide, 8.3m deep, and 2.4m tall. The experiment had two permanent ventilation openings each of 1.5m wide by 1.5m tall.

The wall and ceiling slabs comprised of three-ply CLT elements of 105mm thickness.

CLT elements were encapsulated in two layers of 12.7mm Type X gypsum board. The natural fuel load was supplied by fully furnishing the compartment as a residential apartment, including a bed, hardwood flooring, tables and kitchen units, providing an average fuel load density of 550MJ/m^2.

Figure 21: Layout and residential fuel load in the experiments of Su and Lougheed, 2014.

A3.3.4 NRC (Su and Muradori, 2014)

A single compartment experiment comprising a timber compartment and lift shaft was conducted by the National Research Council Canada (NRC, Su and Muradori, 2014). The main objective of the experiment was to show that if a fire occurred in the compartment, the adjacent lift shaft would remain unaffected.

The experiment was undertaken for a compartment size of 4.6m wide, 5.2m deep, and 3.0m tall, and shared a wall with a lift shaft 9m in height. The experiment had a permanent ventilation opening of 2.5m wide by 1.8m tall.

The wall and ceiling slabs comprised of five-ply CLT elements of 175mm thickness. CLT elements were encapsulated in two layers of 16mm Type X gypsum board. The natural fuel load was supplied by an array of wood cribs and furniture (furnished bed, sofas, and drawers) with a fuel load density of 790MJ/m^2, to represent a typical residential bedroom.

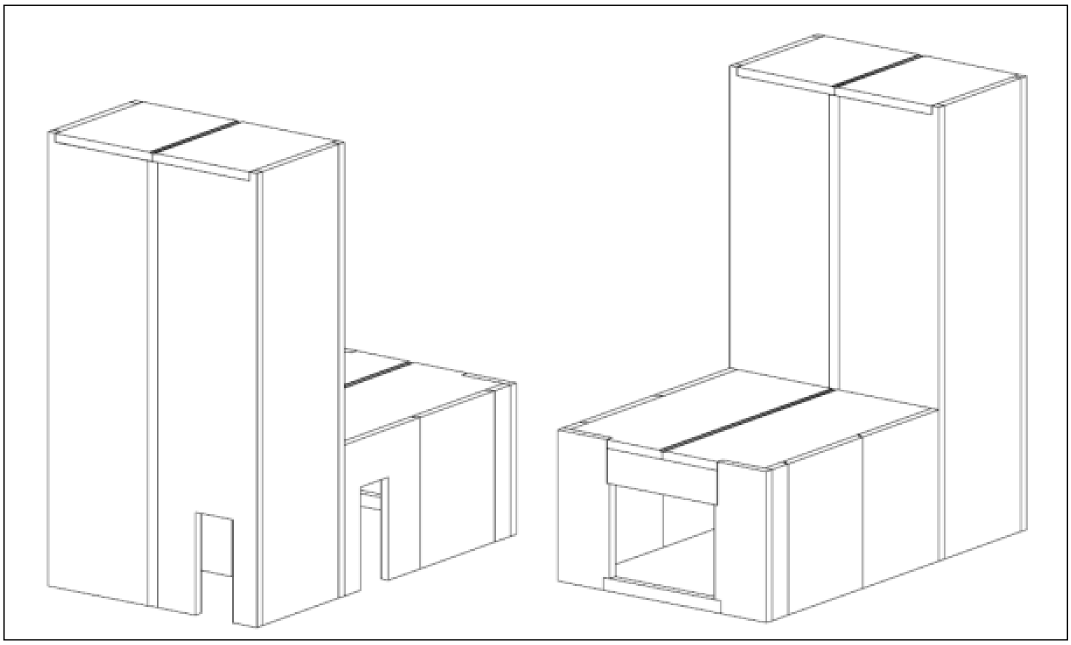


Figure 22: Layout of fire compartment and neighbouring lift shaft in Su and Muradori, 2014.

A3.3.5 National Technical University Athens (Kolaitis et al., 2014)

A single compartment experiment was conducted by the Greek Fire Academy, funded by the Greek Wood Association and in collaboration with the National Technical University of Athens (Kolaitis et al., 2014). The aim of the experiment was to evaluate the performance of gypsum plasterboards and wood panels in protecting both mass timber and light timber elements from fire.

Experiments were undertaken for a compartment size of 2.22m wide, 2.22m deep, and 2.11m tall. The experiment had a permanent ventilation opening of 0.43m wide by 0.98m tall.

The wall and ceiling slabs comprised of five-ply CLT elements of 95mm thickness. CLT elements were encapsulated in 40mm of rockwool, and two layers of 12.5mm Type DF gypsum board. The natural fuel load was supplied by an array of wood cribs with a fuel load density of 420MJ/m², to represent a typical office space.

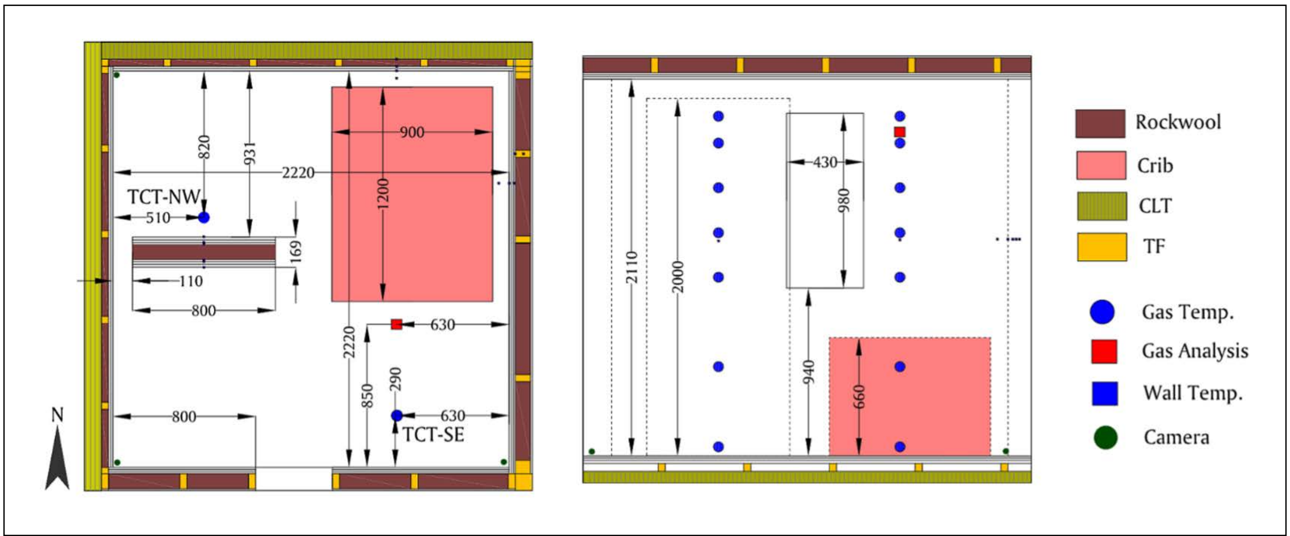


Figure 23: Compartment and instrumentation layout of the experiment by Kolaitis et al., 2014.

A3.3.6 SP Fire Research (Hox, 2015)

Two experiments were conducted by SP Fire Research (Hox, 2015), in collaboration with The Student Union in Trondheim (SIT) and Rambøll Norge AS. The aim of these experiments was to support construction of a mass timber residential student accomodation consisting of 632 dormitory-style rooms. The first experiment successfully implemented a sprinkler system, and is therefore not discussed by this review.

Experiments were undertaken for a compartment size of 2.3m wide, 5.75m deep, and 2.75m tall. All experiments had a permanent window opening of 1.2m wide by 1.6m tall, and a door of 0.9m wide by 2.0m tall, both of which were closed at the beginning of the experiment.

The wall and ceiling slabs comprised of five-ply CLT elements of 100mm thickness. Protected timber surfaces were encapsulated in a 13mm layer of standard gypsum board and a 15mm layer of fire resistant gypsum board. The natural fuel load was supplied by a combination of wood crib, and residential furniture (mattress, desk, and bed), to represent a fuel load density of 658MJ/m^2, typical of a student dormitory.

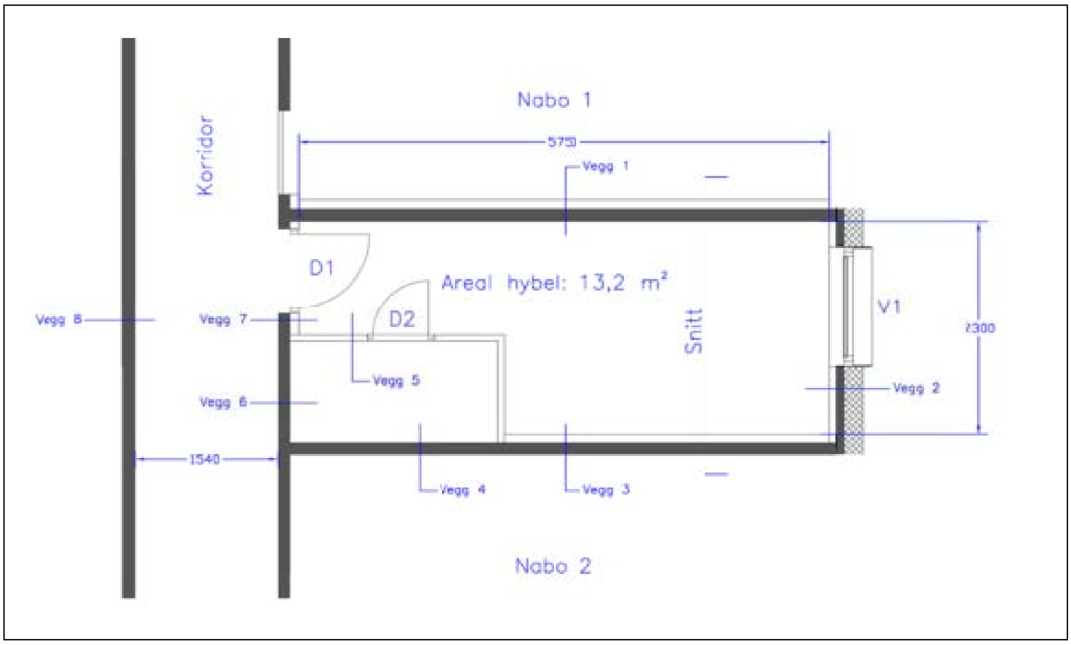


Figure 24: Compartment and attached corridor layout in the experiments of Hox, 2015.

A3.3.7 Arup and University of Edinburgh (Hadden et al., 2017)

Five fire compartment experiments were undertaken by Arup and the University of Edinburgh at the Building Research Establishment laboratory to assess the fire dynamics and charring behaviour of cross-laminated timber when varying amounts of timber are left exposed. The experiments also sought to establish the conditions required for the compartment to achieve auto-extinction. The findings were subsequently published in the Fire Safety Journal (Hadden et al., 2017).

The fire compartments were cubic with principal dimensions of 2.72m and formed from five-ply cross-laminated timber. Each lamella had a thickness of 20mm and were bound using polyurethane adhesive. A permanent opening 0.76m wide and 1.74m tall was provided.

Wooden cribs were used as the fuel load in the compartment with a fuel load density of 132MJ/m^2. The fire load density was chosen based on the heat release rate required for flashover. The fire load was also intentionally limited, based on the burning rate, to ensure that the wooden cribs would burn out within a short period of flashover. So, allowing the contribution of the CLT to the fire dynamics to be investigated. For the first experiment, the timber was encapsulated using Type F plasterboard (per BS EN 520). However, for the subsequent experiments, Type F plasterboard and high-density stone wool insulation were used. This change was implemented following failure of the encapsulation in the first experiment.

The encapsulation was intended to fully protect the CLT. In two experiments, two timber walls were exposed; in another two experiments, one wall and timber ceiling were exposed, and in the final experiment two walls and the ceiling were left exposed.

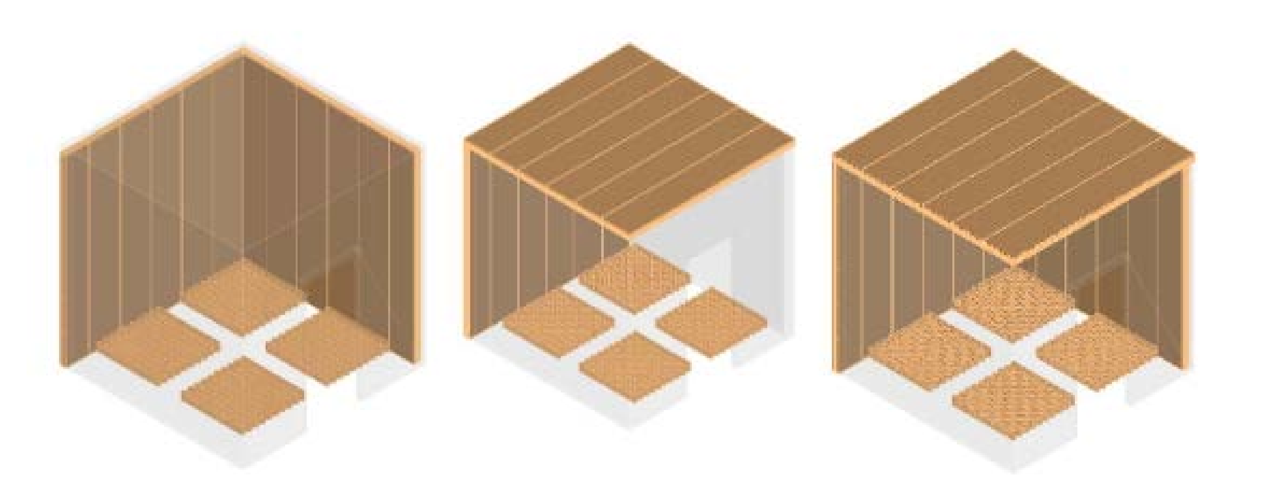


Figure 25: Image of CLT and wood crib configuration of Arup – Edinburgh University experiments

A3.3.8 The Fire Protection Research Foundation (National Research Council, Canada and SP Sweden, 2017-2018)

The Fire Protection Research Foundation undertook a research programme to assess the fire safety challenges of tall wooden buildings. As part of this programme, a series of compartment fire experiments were undertaken to quantify the contribution of exposed timber room fires on metrics such as charring rate, visibility, temperature and toxicity. The report states that its aim is to allow designers to quantify the contribution exposed timber may have so that they can adequately specify fire protection measures to mitigate the level of risk to occupants and the fire service. The findings of this are summarised in a technical report (Su et al., 2018a).

In total, six experiments were undertaken for a compartment size of 4.6m wide, 9.1m deep, and 2.7m tall. Four experiments had a permanent ventilation opening of 1.8m wide by 2.0m tall, whilst the remaining two experiments had a permanent ventilation opening of 3.6m wide and 2.0m tall.

The compartments were constructed from five-ply cross-laminated timber panels with an overall thickness of 175mm and a ply thickness of 35mm each. The plys were bonded using polyurethane adhesive, manufactured in Canada. Type X gypsum was used for those experiments where the surfaces were required to be encapsulated. Two experiments encapsulated all timber surfaces (either opting for two or three layers of Type X gypsum), and the remaining experiments either exposed a single timber wall, the timber ceiling, or a combination of both.

In all experiments, a natural fire load was provided, with a target fire load density of 550MJ/m^2. The fire load density was selected to reflect the average for a bedroom, living room and kitchen based on a survey on residential buildings. Figure 26 depicts the fire load distribution within the compartment.

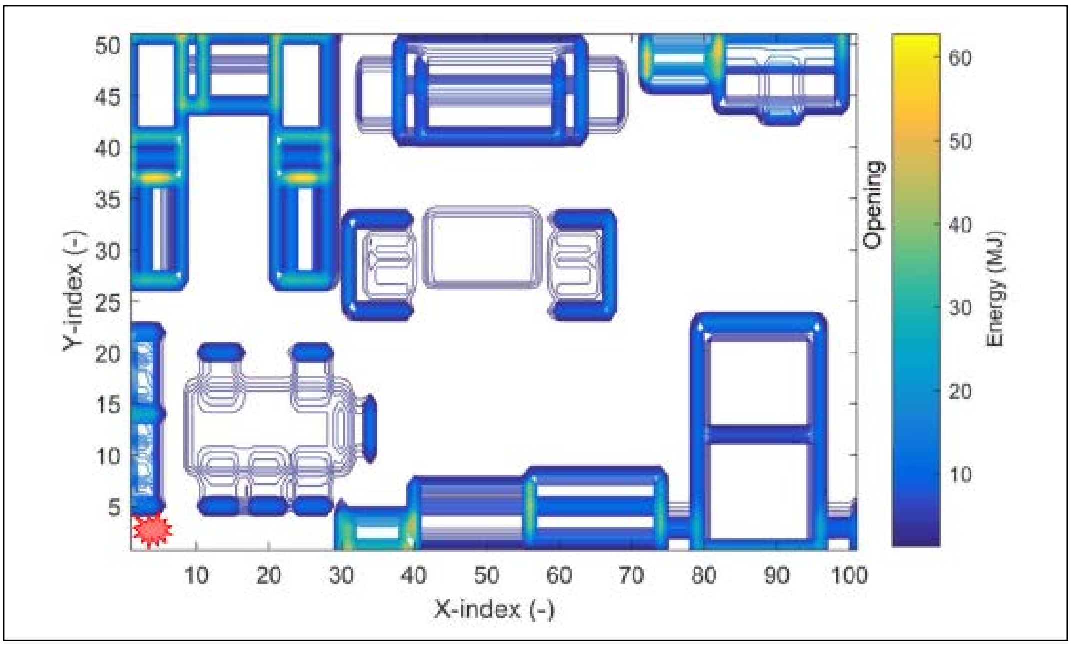


Figure 26: Fire load distribution in the compartment experiments of Su et al., 2018a

A3.3.9 NRC (Su et al., 2018b)

The second NRC 2018 experimental series, as described by Su et al., 2018b, were conducted in collaboration between the Natural Resources Canada and the Province of Ontario, and the National Research Council Canada. The aim of these experiments was "to further quantify the contribution of mass timber elements to fires and provide additional data for forming the technical basis for exposed mass timber elements in EMTC buildings without significantly increasing fire risks to life and property".

Five experiments were undertaken for a compartment size of 4.53m wide, 2.44m deep, and 2.78m tall. All experiments had a permanent ventilation opening of 0.76m wide by 2.0m tall. The wall and ceiling slabs comprised of five-ply CLT elements of 175mm thickness. Protected timber surfaces (varied throughout the experiments) were encapsulated in Type X gypsum board.

The fuel load was constructed as a uniform crib spanning the length of the compartment with a fuel load density of 550MJ/m^2, representative of a typical residential space.

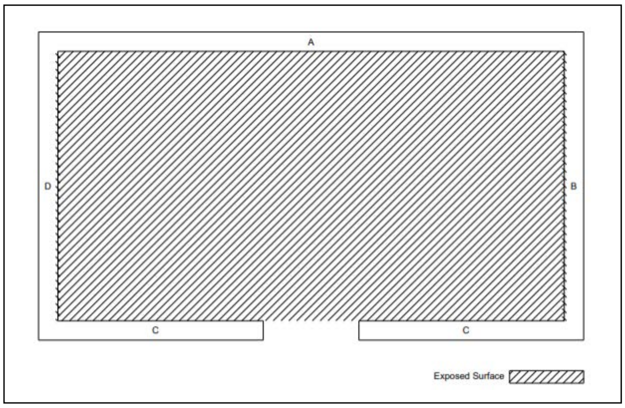


Figure 27: Layout of test 5 in the experiments of Su et al., 2018b.

A3.3.10 US Forest Service for ICC (Zelinka et al., 2018)

The US Forest Service (USFS) funded experiments to support the International Code Council (ICC), which publishes the International Building Code (IBC), who established a committee to explore the building science of tall wooden buildings with the scope being to investigate the feasibility of and take action on developing code changes for tall wooden buildings. To work toward achieving this objective, the ICC commissioned the USFS to undertake a series of compartment experiments at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF), managed by the Forest Products Laboratory. The findings of which were subsequently published by the USFS (Zelinka et al., 2018).

The aim was to examine the effect of exposed timber walls and ceilings, on a realistic, full size apartment and understand the contribution of CLT to a compartment fire. As the experiments commissioned by the USFS had the objective of supporting prescriptive design guidance, the report provided does not carry out the same scientific investigations when compared to the other experiments reviewed in this report.

The compartments had overall dimensions of 9.14m wide, by 9.14m deep (84m^2), and 2.7m tall and were divided internally with non-fire resisting construction to represent a one-bedroom apartment (see Figure 29). The three experiments reviewed in this section had two permanent openings, each 3.66m wide and 2.44m tall.

The compartments were constructed from five-ply cross-laminated timber with an overall thickness of 175mm. Each lamella had a thickness of 35mm and were bound using polyurethane adhesive, manufactured in the US. Type X gypsum was used for those experiments where the surfaces were required to be encapsulated.

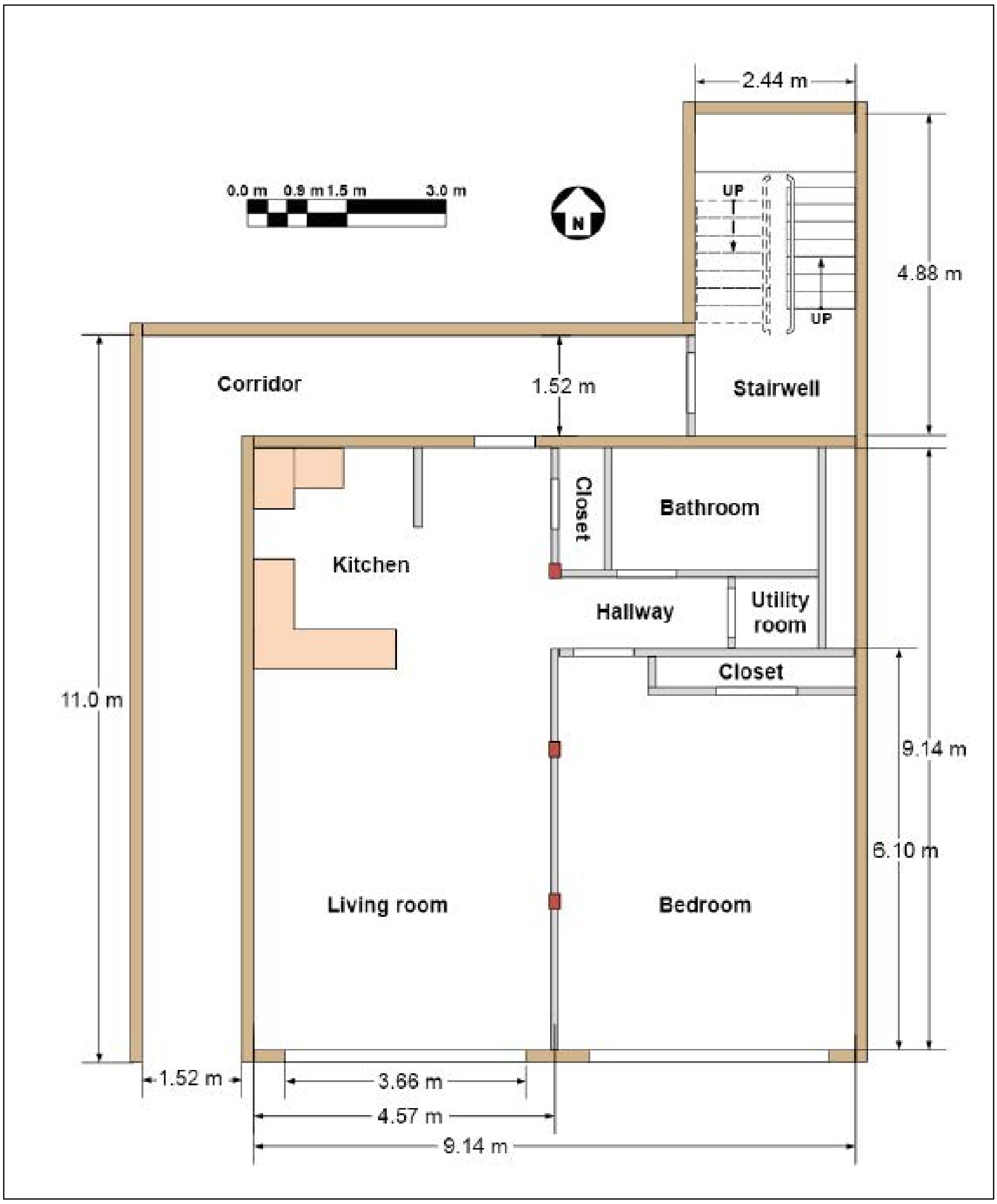


Figure 28: USFS compartment layout

A3.3.11 Epernon Programme: Phase 1 (Wiesner et al., 2021)

As stated on their website[2]:

"The Épernon Fire Experiments Programme is a multi-partner collaborative research project launched in 2017. The project seeks to understand the links between normative fire resistance ratings and real fire performance in buildings. The project has several objectives, such as quantification of the energy participation of combustible materials in standard furnace tests, the influence of combustible surfaces and ventilation factors on the dynamics of compartment fires (including external flaming), and the thermomechanical behaviour of structures under standard and natural fires."

As part of the Epernon Fire Test Programme, three compartment fire experiments were undertaken using wooden cribs as fuel with a fuel load density of 891MJ/m^2. The ventilation to the compartments was varied to reflect fuel controlled and ventilation controlled scenarios.

For the compartment fire experiments, the compartment walls were constructed from aerated concrete with the ceiling comprising exposed cross laminated timber. The floor consisted of calcium silicate boards on top of mineral wool.

The CLT had an overall thickness of 165mm comprised of five layers each 33mm in thickness and bonded using a single component polyurethane adhesive (PURBOND HB S709) (Wiesner et al., 2021).

The compartment dimensions were 6m width, 4m deep, and 2.52m in height.

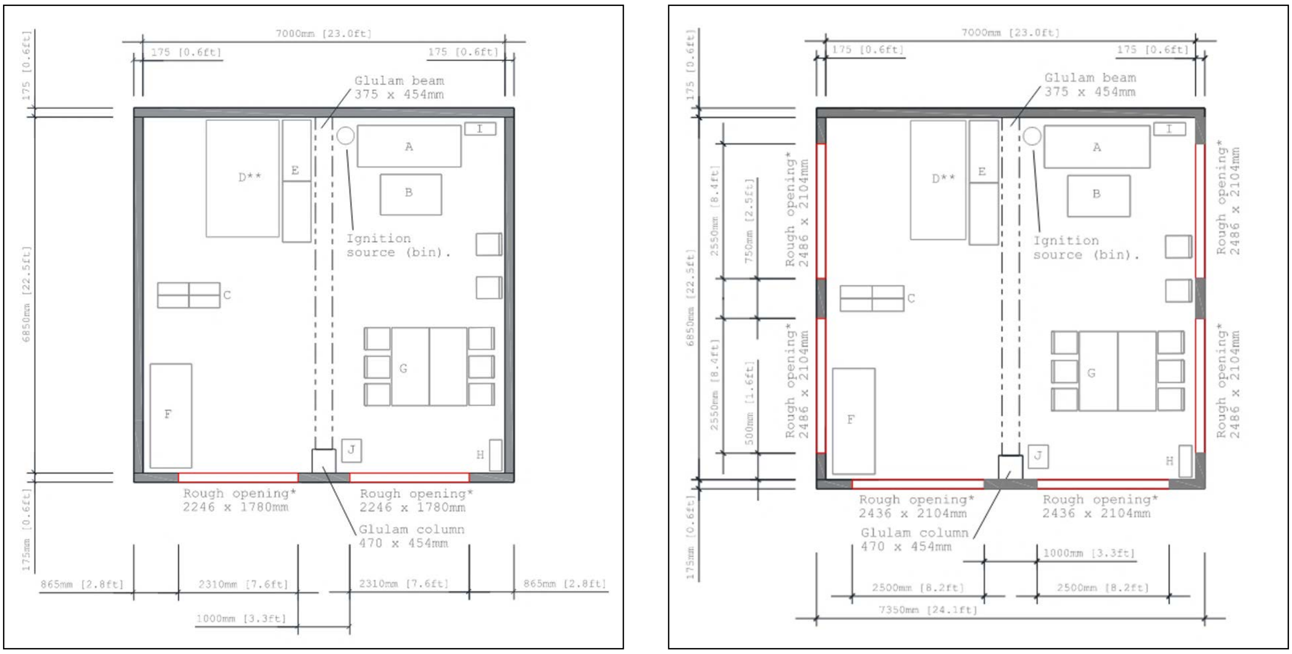
A3.3.12 RISE (Brandon et al., 2021)

A series of compartment fire experiments were undertaken by the Research Institutes of Sweden (RISE) for the American Wood Council as part of research on the "fire safe implementation of visible wood in tall timber buildings" (Brandon et al., 2021).

The specific objectives of the research by RISE are stated as:

- Perform a series of compartment fire experiments in structures constructed of PRG 320-2018 compliant CLT with varying amounts of exposed mass timber areas (CLT with proven bond line integrity in fire);
- Provide background for possible changes to code-prescribed limits of exposed mass timber surfaces consistent with the fire performance criterion used for changes to the International Building Code;
- Identify additional measures necessary (if any) to ensure the fire performance criteria established by the International Code Council (ICC) Ad-Hoc Committee on Tall Wood Buildings (TWB) and additional criteria discussed in Section 5 are met.

2: Epernon Fire tests programme – The Epernon Fire Tests Programme is seeking to understand the links between normative fire resistance ratings and real fire performance in buildings (epernon-fire-tests.eu). Accessed 12th January 2022.



(a) Two openings in front elevation

(b) Six opening across three elevations

Figure 29: RISE compartment fire experiments layout

The moveable fuel load comprised furniture, particle board sheets on the floor to represent a wood floor covering, and additional wood cribs to represent fuel in storage spaces; the target fuel load density was 560MJ/m^2. One experiment had a single timber surface (ceiling) exposed (see Table 19), and four of the five experiments had multiple timber surfaces exposed (see Table 20, below).

A3.3.13 TIMpuls (Brunkhorst et al., 2021)

A series of compartment fire experiments were undertaken as part of a joint research project by the Technical University of Munich, the Technical University of Braunschweig Magdeburg-Stendal and the Institute for Fire and Disaster Protection Heyrothsberge. The project was funded by the German Federal Ministry of Food and Agriculture, with co-financing from the Bavarian Carpenters' Guild Association (Brunkhorst et al., 2021).

The aims of the research were to understand the fire dynamics in compartments with unprotected solid wood components; influence of three fire phases (development, fully developed fire, and decay phase); post fire behaviour; external flaming from openings; fire protection behaviour; and smouldering. The research was undertaken to inform the development of building codes in Germany.

A total of five fire compartment experiments were undertaken, with the compartment wall and ceiling construction outlined below:

Table 17: Summary of TIMpuls compartment experiments

Experiment	V0	V1	V2	V3	V4
Wall 01	100mm CLT + 2x25mm GKF	100mm CLT + 18mm GF	150mm CLT	140mm HTB + 2×12.5mm GF	150mm CLT
Wall 02	100mm CLT + 2x25mm GKF	100mm CLT + 18mm GF	140mm HTB + 2×18mm GF	140mm HTB + 2×18mm GF	140mm HTB + 2×18mm GF
Wall 03	100mm CLT + 2x25mm GKF	100mm CLT + 18mm GF	150mm CLT	140mm HTB + 2×18mm GF	140mm HTB + 2×18mm GF
Wall 04	100mm CLT + 2x25mm GKF	100mm CLT + 18mm GF	140mm HTB + 2×18mm GF	140mm HTB + 2×18mm GF	140mm HTB + 2×18mm GF
Ceiling	180mm Glulam + 2x25mm GKF	180mm Glulam	220mm HTB + 2x18mm GF	180mm Glulam	180mm Glulam
Compartment dimensions (W, B, H)	4.5m x 4.5m x 2.4m	4.5m x 4.5m x 2.4m	4.5m x 4.5m x 2.4m	9m x 4.5m x 2.4m	9m x 4.5m x 2.4m
Additional timber elements					2 Columns 1 Beam

Notes: GKF – Gypsum fireboard ; GF – Gypsum board ; HTB – Timber stud element with mineral wool insulation

The opening factor for both compartment sizes was 0.094m$^{0.5}$ and selected to be representative of natural fire curves. The fuel load for all experiments is stated as being based on the 90th percentile for residential use with a value of 1,085MJ/m^2.

From Table 17, the compartments were constructed from a mixture of cross-laminated timber, glulaminated timber and timber stud constructions. Whilst this Guide focuses specifically on mass timber only, the TIMpuls experiments are still considered relevant as these featured exposed mass timber surfaces.

A3.3.14 STA (Hopkin et al., 2022, 2023)

A series of three experiments were conducted in Warsaw, Poland, at Instytut Techniki Budowlanej (ITB), in collaboration between OFR Consultants, KLH Massivholz, Binder Holz, Stora Enso, and Henkel & Cie (Hopkin et al., 2022).

The aims of these experiments were to understand ceiling jet and flame extension behaviour in compartments with a mass timber ceiling, the implications of glue line failure on self-extinction (cessation of flaming combustion), and the influence of a down-stand beam on flame extension along the ceiling.

Three experiments were undertaken for a compartment size of 3.75m wide, 7.6m deep and 2.4m tall. All experiments had a permanent ventilation opening of 7.6m wide by 2.0m tall. The wall and ceiling slabs comprised of five-ply CLT elements of 160mm thickness. In the first experiment, the ceiling was encapsulated in Type F gypsum board.

The fuel load was supplied by a gas burner at the mid-point of the compartment with a controlled flow-rate, which was controlled to a peak of 1250kW for the three experiments, maintained over a duration of approximately 80 minutes.

A3.3.15 FRIC (Sæter Bøe et al., 2023)

The FRIC experiment series, as described by Sæter Bøe et al., 2023a, 2023b, were conducted in a collaboration between the Norwegian University of Science and Technology and RISE Fire Research. The aim of these experiments was to study the impact of timber ceilings and walls on flame spread and overall fire behaviour in compartments representative of a modern office space.

Two experiments were undertaken for a compartment size of 5.0m wide, 18.8m deep, and 2.52m tall. Both experiments had a permanent ventilation opening of 18.8m wide by 2.2m tall. The ceiling and longest wall comprised of five-ply CLT elements of 140mm thickness, whereas the two side walls were three-ply of 80mm thickness.

Protected timber surfaces (side and back walls in the first experiment, side walls in the second experiment) were encapsulated in Type F gypsum board.

The fuel load was constructed as a uniform crib spanning the length of the compartment with a fuel load density of 353MJ/m², representative of an office space. The adhesive used for the CLT lacked a demonstrated resistance against glue-line failure. The compartment was observed for a total of four hours.

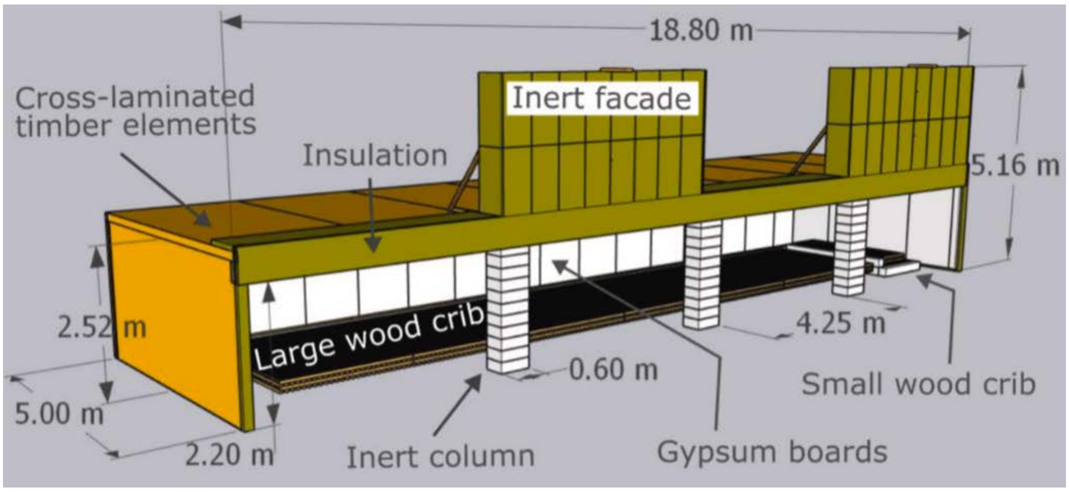


Figure 30: Experimental design of #FRIC-01, reported by Sæter Bøe et al., 2023a.

A3.3.16 NRC (Su et al., 2023)

The 2023 NRC experiment series, as described by Su et al., 2023, were conducted in a collaboration between the Natural Resources Canada and the Province of Ontario, and the National Research Council Canada. The aim of the five experiments was to characterise the fire dynamics and severity of a variety of mass timber structures, including both office and residential units, and construction fires, without taking account of automatic suppression or firefighting intervention over a period of four hours.

Test 1 represented a baseline test with code compliant combustible linings on walls and ceilings in a residential arrangement, equivalent to a total surface area of $72.2m^2$.

Test 2 represented a residential arrangement with exposed mass timber columns, beams and ceiling, equivalent to a surface area of $29.7m^2$.

Test 3 represented a garbage bin fire on a construction site, with a partially constructed mass timber building.

Test 4 represented a partially constructed mass timber building, with all surfaces exposed.

Test 5 represented a fully furnished open plan office.

The three experiments in residential units were 3.2m wide, 7.3m deep, and 2.2m tall, with a single opening 2.2m in width and 2.2m in height. Test 1 and 2 had a wood crib with a fuel load of $613MJ/m^2$ to represent a residential space, while Test 3 had a garbage bin containing a wood crib, providing a fuel load density of $15MJ/m^2$ to represent a fire on a construction site, with 100% exposed CLT ceiling, CLT floor and CLT wall totalling $55.2m^2$ of exposed timber surfaces.

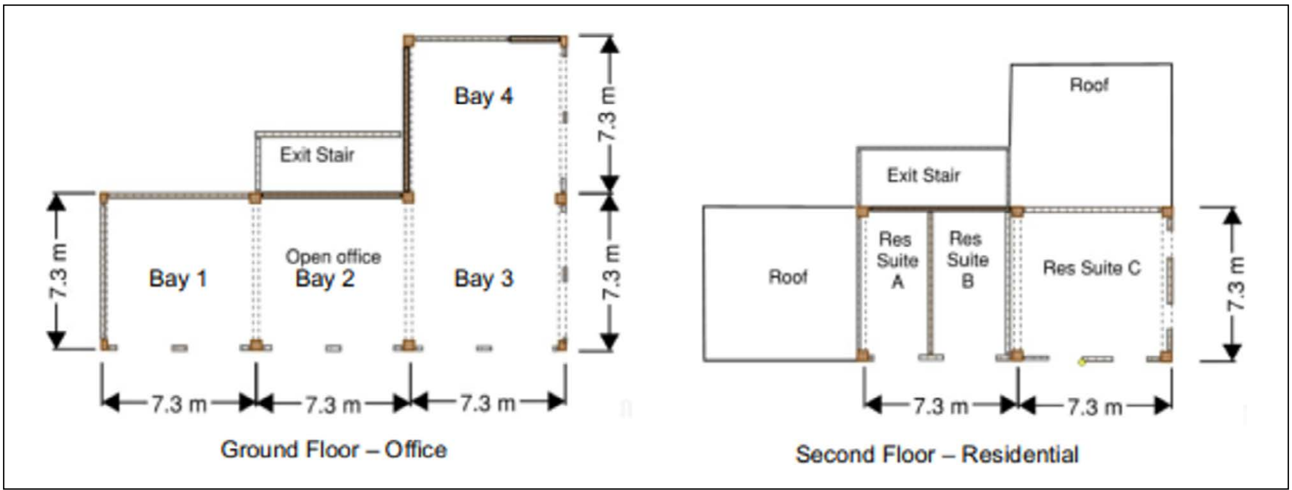


Figure 31: (a): Layout and 3D model of each compartment on the first and second floor of the 2023 NRC experiments.

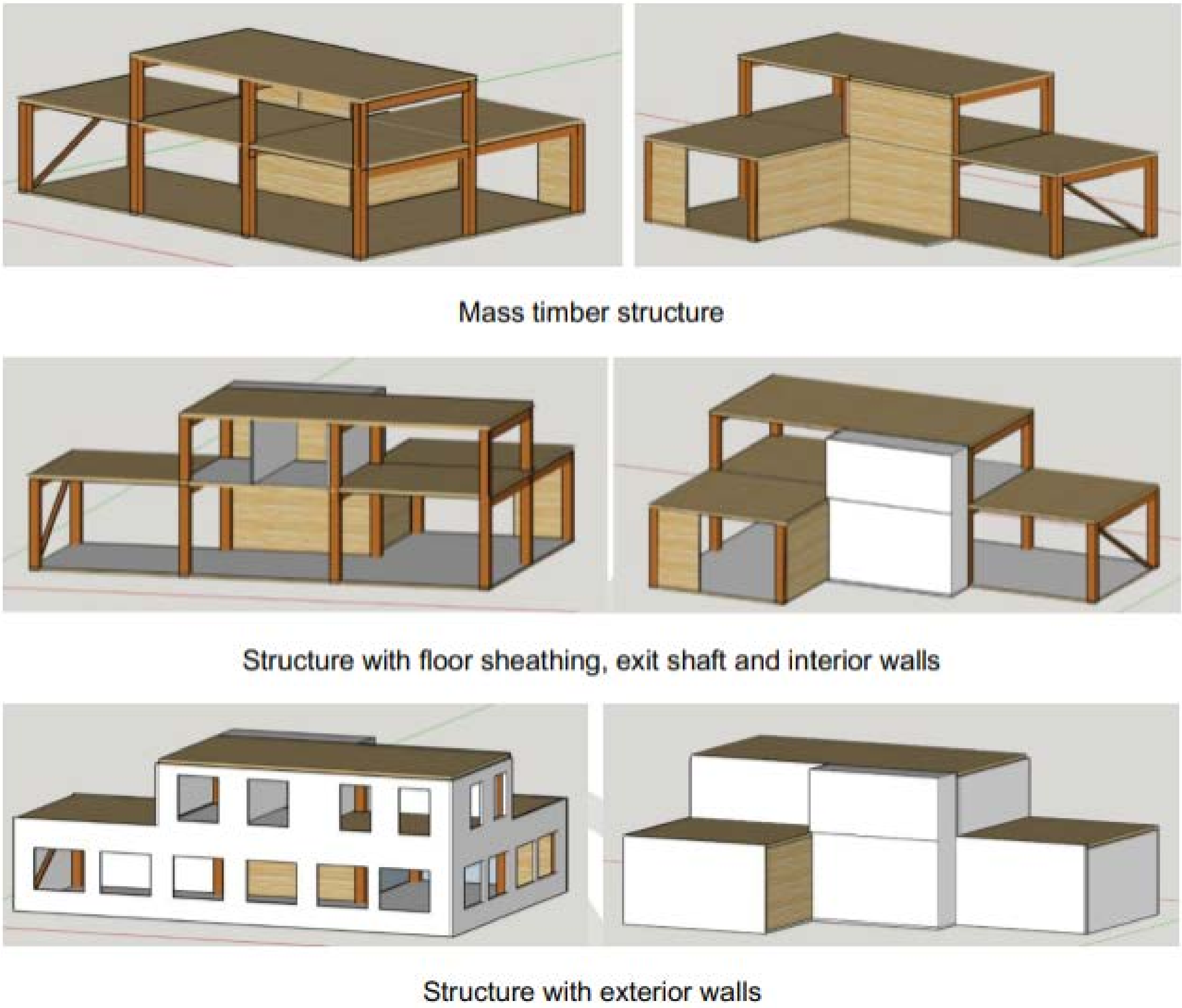


Figure 31 (b): Layout and 3D model of each compartment on the first and second floor of the 2023 NRC experiments.

Test 4 had dimensions 7.1m wide, 7.3m deep, and 3.0m tall, with four openings of 1.6m width and 2.2m height. The fuel load comprised of exposed light timber framing and wood cribs of fuel load density of 224MJ/m^2, with exposed DLT (Dowel-Laminated Timber) ceiling, CLT floor, and glulam columns and beams totalling 124.6m^2 exposed timber surfaces. This test lasted for 2.5 hours, with strong winds on the test day.

Test 5 was set up as an office space with a non-quadrilateral floor space of 204m^2 and height 4.3m, with 10 openings of 2.6m width and 2.0m height each. The fuel load was constructed as a uniform crib spanning the length of the compartment with a fuel load density of 362MJ/m^2. The ceiling was 100% exposed, as were timber columns, beams and walls (total of 291m^2 exposed timber).

The experiment structure was constructed using a variety of mass timber elements from several manufacturers. Ceiling and floor slabs were constructed using either:

- CLT, E1 grade, 7 ply, 213mm thickness, PUR adhesive compliant with manufacturing standard ANSI/APA PRG 320 that prohibits CLT displaying glue line failure;
- CLT, E1M5 grade, 7 ply, 245mm thickness, PUR adhesive compliant with ANSI/APA PRG 320, that prohibits CLT displaying glue line failure;
- GLT, 215mm thickness, melamine adhesive compliant with CSA O177 and ANSI/APA PRG 320;
- DLT (dowel-laminated timber), 230mm thickness, conforming to ICC-ES ESR 4069.

The inner shaft wall exposed in Test 5 was comprised of V2.1 grade CLT, comprised seven-ply 245mm total thickness, manufactured using a PUR adhesive.

Protected timber surfaces (varied throughout the experiments) were encapsulated in Type X gypsum board.

A3.4 All surfaces fully encapsulated

This section presents a summary of the 15 fully encapsulated compartment fire experiments. Eight compartments had a natural moveable fuel load with a fuel load density of 533-550MJ/m^2, which is reflective of the average (50th percentile) fuel load for a domestic type building based on research on Canadian dwellings. Other experiments had comparatively higher fuel loads, including the TIMpuls V0 experiment which had a fuel load density of 1,085MJ/m^2.

In the United Kingdom the average fuel load for a dwelling is quoted as 780MJ/m^2, and 970MJ/m^2 for the 95th percentile per PD 7974-1:2003.

In the Carleton University, NFPA, and US Forest Service experiments the CLT panels were manufactured with a lamella thickness of 35mm, however, the Carleton experiment had three layers (overall thickness of 105mm) whilst the NFPA and USFS experiments had five layers with an overall thickness of 175mm. The CLT layers were bonded using polyurethane adhesive in all experiments.

For the TIMpuls experiment (V0), the walls comprised CLT panels with an overall thickness of 100mm consisting of five layers of 20mm. The Glulam ceiling had an overall thickness of 180mm. All timber surfaces were encapsulated with two layers of 25mm gypsum plasterboards complying with DIN EN 520.

The Carleton University, NFPA, and US Forest Service experiments were encapsulated using bespoke arrangements of Type X gypsum wallboard and fixing details (i.e. the encapsulation systems were not fully tested and/or certified systems as would be required for design). For USFS Test 1, the entire front elevation was open to the hall, representative of an actual residential one bedroom apartment. For the Carleton and FPRF experiments, the permanent ventilation opening in the compartment was provided to be representative of a door opening and purposely under-ventilated.

Based on the experimental data summarised in Table 18, the following has been found regarding the protection of mass timber by means of encapsulation:

- In appropriate arrangements, Type X gypsum can be effective at preventing charring of the underlying timber. Nine of the 15 experiments reviewed exhibited no charring in encapsulated timber members. The effectiveness of the gypsum board at preventing charring depends on the number of layers and the duration of the fire.
- From the experimental data available, two layers of fire rated gypsum board have variable performance in preventing charring of timber elements, depending on the thickness of each layer and severity of the fire. The two 25mm gypsum plasterboard layers provided to the timber surfaces in the TIMpuls experiment were effective at protecting the timber from charring.
- By comparison, the two layers of 12.7mm Type X gypsum board in the Carleton McGregor Test 1 were ineffective at preventing charring, with gypsum board observed failing at approximately 40 minutes after ignition, Resulting in 40-60mm of char in the initially protected ceiling and rear wall.
- For the gypsum to be effective at preventing charring of the underlying timber, the gypsum is required to be installed correctly and remain in place for the period for which it is designed. Once the gypsum has failed, and the timber is exposed, the timber can contribute to the fire as a fuel source. Therefore, where the compartment is required to withstand complete burnout for a greater period (e.g. for high risk buildings), the encapsulation should be designed to remain in place for the design duration. As opposed to the fire resistance being provided as a combination of encapsulation and charring of the timber.
- From the experimental results, the gypsum board orientated horizontally (i.e. ceiling) was more prone to failure by fall-off when compared to the vertical orientated gypsum on the walls – with fall-off of ceiling encapsulation occurring in the majority of experiments where charring was observed.
- The authors of the reports do not provide justification for the gypsum board fall-off behaviour from the ceiling. However, this may be due to the gypsum board cracking and falling away due to its weight, and greater thermal exposures towards the ceiling. Thus, where encapsulation is used to protect a ceiling, the designer should ensure that the fixing details and gypsum board layup reflect exactly those which have been shown by fire test to be effective in supporting the protection when exposed to fire.
- Although Type X gypsum can prevent the timber from charring (i.e. maintain temperature in timber below 300ºC), timber begins to lose its strength much earlier than this. Therefore, whilst it may not be necessary to reduce the section size for charring, higher temperatures on the timber behind the encapsulation could result in reduced strength of the timber. So, further research is required to establish if the zero-strength layer principle should be applied to encapsulated timber.
- Of the 15 experiments reviewed, seven exhibited a natural decay to ambient temperatures without any intervention.
- In eleven of the experiments, manual firefighting intervention was used to fully extinguish the fire.

Where timber is encapsulated with fire rated Type X gypsum, the current fire experimental data supports the notion that the likelihood of the encapsulated timber adversely impacting the structural fire resistance is low. Figure 33 depicts the heat release rate of the seven experiments reviewed in this section imposed on a single plot.

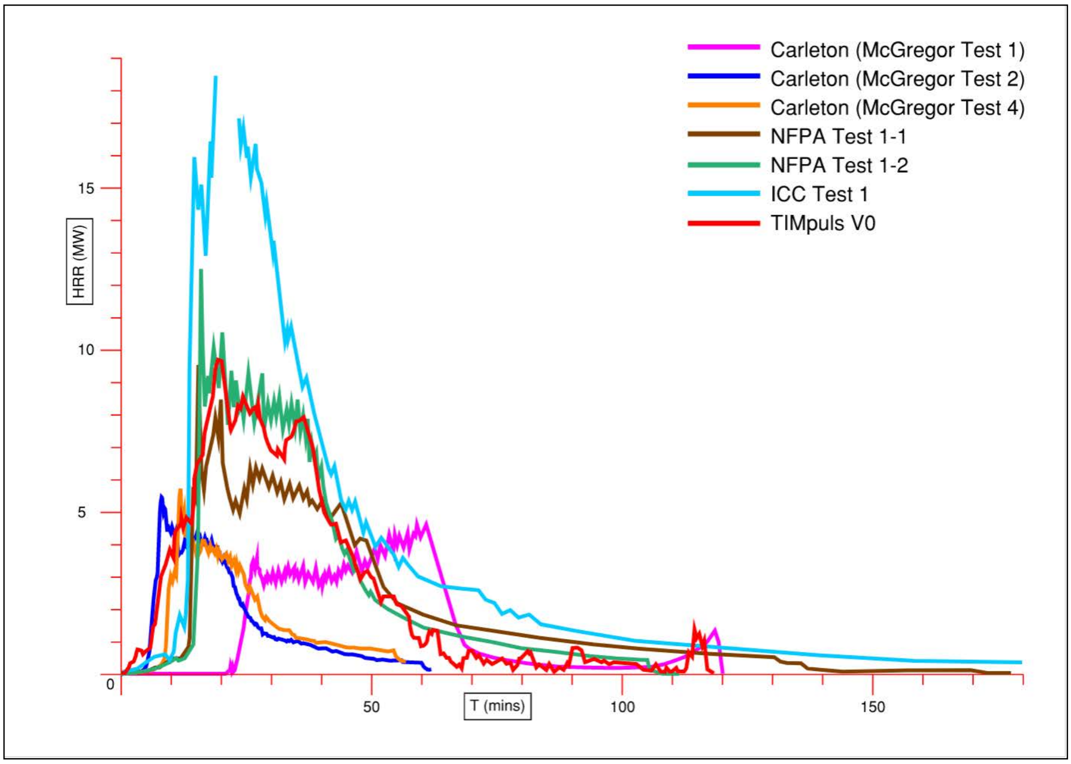


Figure 32: Fully encapsulated surfaces HRR combined

Table 18: Summary of fully encapsulated compartment experiment results

Experiment Series	Experiment No (Compartment Size L x B x H [m])	Internal surface area, A_T (m^2)	CLT Description	Protected surfaces	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	Fuel load density [MJ/m^2]	Peak temp [°C]	Fuel Type	Charring behind protection	Encapsulation failure/fall-off	Fire decay
ETH	Experiment 1 [3.34 x 3.34 x 2.95]	50.1	5-ply CLT, 85 mm thick	Multiple protection arrangements combining arrangements of 12 mm standard gypsum board, 12 mm fireproof gypsum, and 27 mm mineral wool	25.0	790	-	Wood crib	Yes, 2 – 14 mm in east wall	Yes, observed in post-fire investigation	Manual extinguishment after decrease in fire intensity
Carleton	McGregor - Test 1 [4.5 x 3.5 x 2.5]	53.6	3-ply CLT, each layer 35 mm thick, polyurethane adhesive	Two layers of 12.7 mm thick Type X gypsum board	17.7	The burner released energy equivalent to 486 MJ/m^2 overall. The burner was anticipated to represent the 95th percentile fuel load based on research for bedroom survey results (753 MJ/m^2).	1200	Propane burner	Where encapsulation remained in place, the char reached depths between 6 and 12 mm. The encapsulation to the ceiling and rear wall failed, the char reached a depth of 40-60 mm	40 minutes 10 seconds first layer of protection falls off ceiling	The exposed CLT had bond line integrity failure and contributed to the fire. Manual extinction at 119 minutes.
	McGregor - Test 2 [4.5 x 3.5 x 2.5]					533	1100	Furniture (residential)	No charring recorded	Ceiling: First layer at 21 minutes Second layer at 43 minutes	Fire decayed as moveable fuel load was consumed. Manual extinction at 60 minutes.
	McGregor - Test 4 [4.5 x 3.5 x 2.5]					553	1109	Furniture (residential)	No charring recorded	Ceiling: First layer at 22 minutes Second layer at 39 mins 34 seconds	Fire decayed as moveable fuel load was consumed. Manual extinction at 53 minutes 34 seconds.
NRC 2014	Su and Lougheed [6.3 x 8.3 x 2.4]	117.9	3-ply CLT, 105 mm thick	two layers of 12.7 mm of Type X gypsum board.	21.4	550	-	Furniture (residential)	Yes	Yes, 65-99 min for wall panels, 36-47 min for floor panels.	Manual extinguishment after failure of ceiling encapsulation during decay phase.
	Su and Muradori [4.6 x 5.2 x 3.0]	78.2	5-ply CLT, 175 mm thick	Two layers of 16 mm of Type X gypsum board.	13.0	790	-	Furniture (residential)	Yes, charring after ceiling encapsulation failure.	Yes, ceiling at 14 min	Manual extinguishment during decay phase.
NTUA	Experiment 1 [2.22 x 2.22 x 2.11]	23.2	5-ply CLT, 95 mm thick	40 mm of rockwool, and two layers of 12.5 mm Type DF gypsum board	66.7	420	831	Wood crib	None	None	Manual extinguishment after partial collapse of protected MDF wall
NFPA Fire Protection Research Foundation	Test 1-1 [9.1 x 4.6 x 2.7]	112.2	5 ply CLT, each layer 35 mm thick, polyurethane adhesive	3 x 15.9 mm thick Type X gypsum board.	22.05	549	1200	Furniture (residential)	No charring recorded	Ceiling: first layer at 34-44 minutes	Natural decay falling to 300kW at end when manually extinguished at 134 minutes.
	Test 1-2 [9.1 x 4.6 x 2.7]	108.6		2 x 15.9 mm thick Type X gypsum board.	10.67	548	1200	Furniture (residential)	No charring recorded on walls. Charring on ceiling: 0-15 mm	Ceiling: first layer at 36-40 minutes	Natural decay falling to 500 kW at end when manually extinguished at 104 minutes.

Table 18: Summary of fully encapsulated compartment experiment results (continued)

Experiment Series	Experiment No (Compartment Size L x B x H [m])	Internal surface area, A_T (m^2)	CLT Description	Protected surfaces	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	Fuel load density [MJ/m^2]	Peak temp [°C]	Fuel Type	Charring behind protection	Encapsulation failure/fall-off	Fire decay
NRC 2018	Test 1 [4.53 x 2.44 x 2.78]	71.7	5-ply CLT, 175 mm thick, PU adhesive	1 layer of 15.9 and 2 layers of 12.7 mm Type X gypsum board.	33.3	550	1200	Wood crib	None	None	Natural
	Test 3 [4.53 x 2.44 x 2.78]	71.7	5-ply CLT, 175 mm thick, PU adhesive	3 layers of 12.7 mm thick Type X gypsum board.	33.3	550	1200	Wood crib	Yes, all encapsulation eventually failed, charring to 28-66 mm.	Yes, first layer at 100 minutes.	Manual suppression after failure of encapsulation.
USFS - ICC	Test 1 [9.14 x 9.14 x 2.74]	165.9	5-ply CLT, each layer 35 mm thick, polyurethane adhesive	2 x 15.9 mm thick Type X gypsum board.	5.94	550	1080	Furniture and wooden cribs	No charring recorded	None recorded in report	Natural
TIMpuls	Test V0 [4.5 x 4.5 x 2.4]	58.2	Walls: 5 ply CLT, each layer 20mm thick, adhesive not stated Ceiling: glulam panel 180mm deep, adhesive not stated	Two layers of 25mm Type F gypsum plasterboard per DIN EN 520.	7.4	1,085	1280	Wood crib	No charring recorded	None recorded in report	Natural
STA	Experiment 1 [3.75 x 7.6 x 2.4]	67.7	5-ply CLT, 160 mm thick, PUR adhesive	Two layers 15 mm thick Type F plasterboard	3.15	Not provided	950	Gas burner	None	None	Natural after deactivation of gas burner
NRC 2023	Test 1 [3.2 x 7.0 x 2.2]	102.6	Multiple types used	Two layers of 15.9 mm thick Type X gypsum board, and 25 mm plywood on three interior walls, and two layers of 12.7mm thick fire retardant treated ply on the ceiling.	14.3	613	1200	Furniture (residential)	Localised near floor level of back wall	Plywood lining consumed. None of the Type X board fell off during the experiment.	Natural with firefighting operations after four hours to fully extinguish hot spots

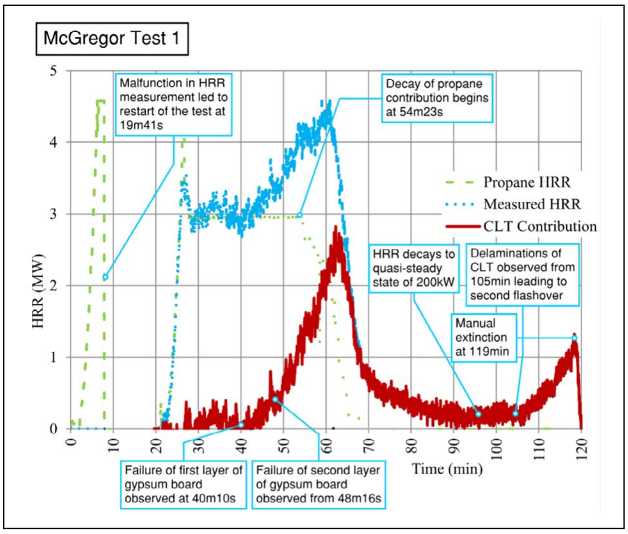


Figure 33: Carleton - McGregor Test 1 - Heat Release Rate

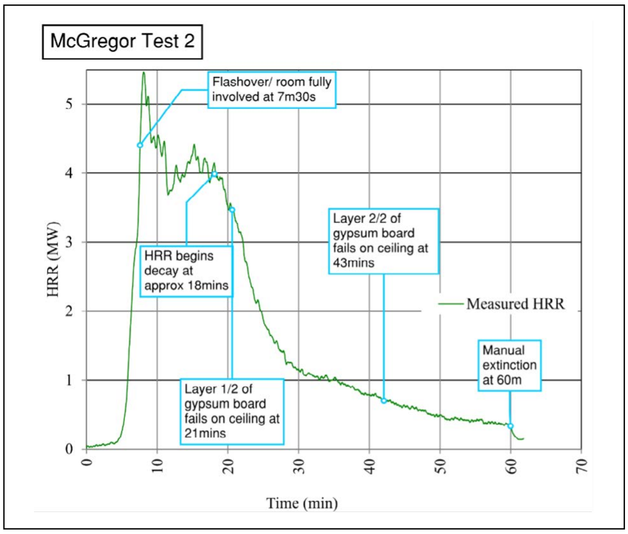


Figure 34: Carleton - McGregor Test 2 - Heat Release Rate

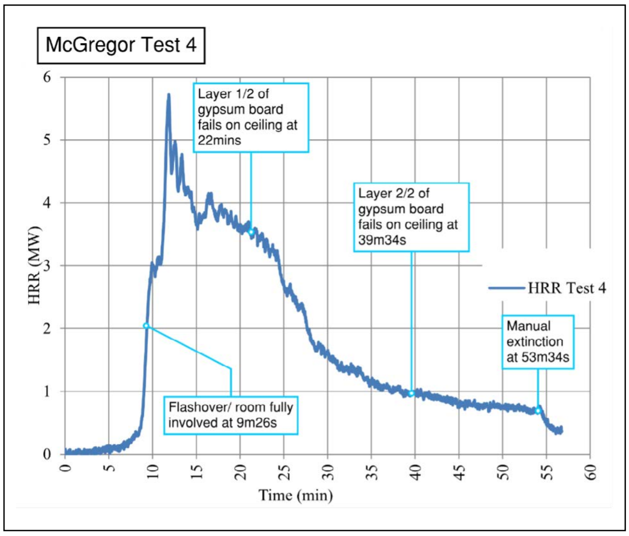


Figure 35: Carleton - McGregor Test 4 - Heat Release Rate

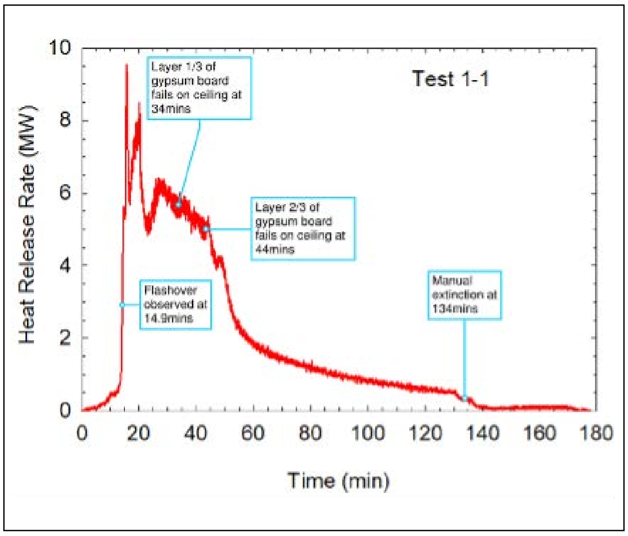


Figure 36: NFPA FPRF - Test 1-1 - Heat Release Rate

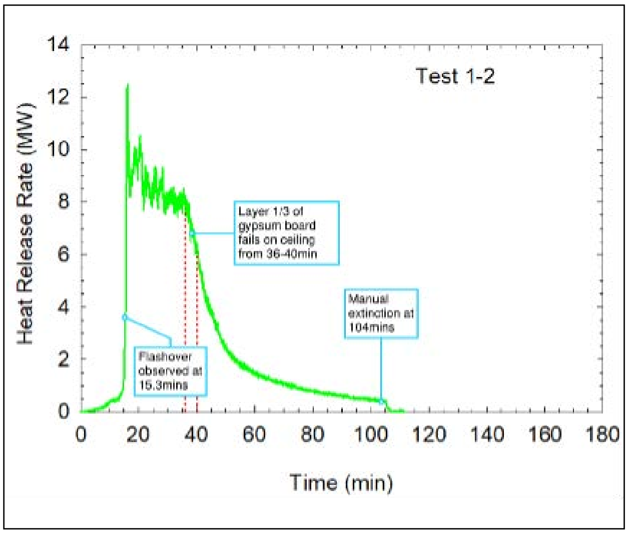


Figure 37: NFPA FPRF - Test 1-2 - Heat Release Rate

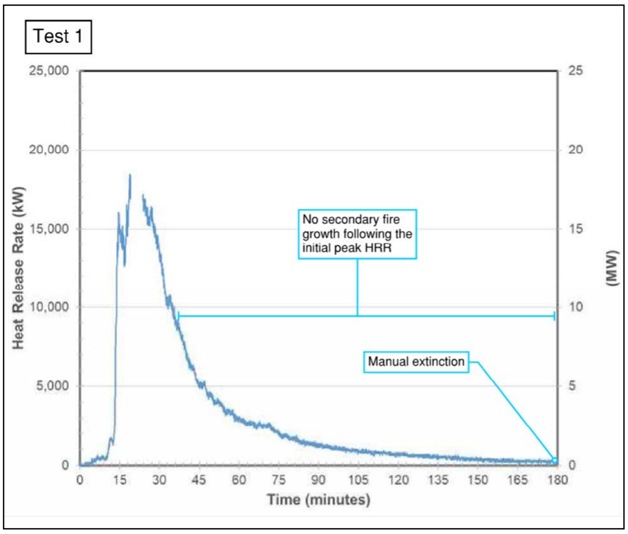


Figure 38: USFS -ICC - Test 1 - Heat Release Rate

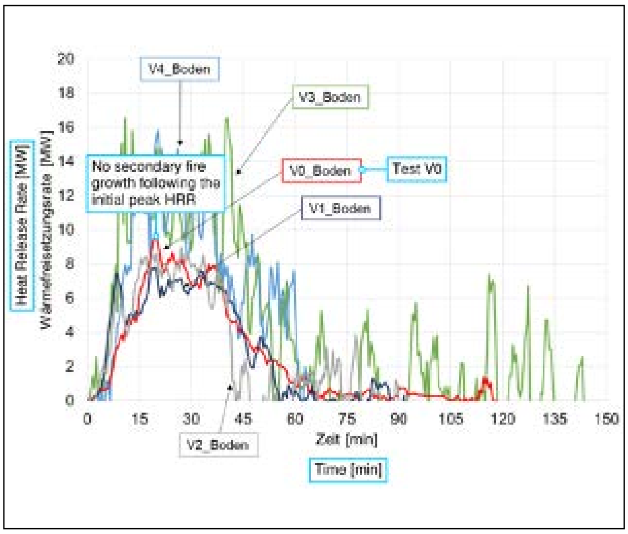


Figure 39: TIMpuls - Test V0 - Heat Release Rate

A3.5 Single exposed surface

This section presents a summary of 20 single-exposed surface compartment fire experiments.

Apart from FRIC that used Type F, the non-exposed timber surfaces were protected with Type X gypsum board or plasterboard in accordance with DIN 520. Note, for USFS-ICC Test 3, a portion of the CLT wall was exposed in the living room and the bedroom wall (i.e. more than one timber surface exposed in the compartment, but only one exposed surface per room).

The following list summarises the findings of the experimental research for the single exposed surface (see Table 16) and Figure 41 presents the HRR for each of the single exposed surface experiments. Note, in the public literature available for the Epernon Fire Test Programme series, heat release rate plots are not provided.

In all experiments, flashover occurred followed by a period of quasi-steady burning before beginning to decay. In these experiments:

- Sixteen of the experiments showed no full regrowth following natural decay of the fire. For the Carleton experiment, the author noted flaming combustion of timber ceased. However, following the decay phase the experiment was manually extinguished with water (see HRR curve in Figure 48).
- However, of these 16 experiments, 12 either involved manual suppression during the decay phase, or observed smouldering hotspots at connections and interfaces that required manual suppression after the decay phase. For example, the wall-ceiling interface in the Epernon experiment 2 continued to smoulder for 29 hours, resulting in structural collapse of the ceiling (McNamee et al., 2020).
- Following flashover, the USFS-ICC experiments began to decay and showed no re-growth. This is because the experiments with exposed timber were well ventilated, and the timber exposed was limited, thus, the heat could readily escape from the compartment. The USFS-ICC experiments were manually extinguished at four hours. The HRR curves for USFS-ICC series are presented in Figure 52 and Figure 53.
- One experiment, NFPA FPRF 1-3, showed small cyclical regrowth following the initial decay. From the report, this behaviour is understood to be due to CLT glue line failure and fresh timber being exposed which then contributes as fuel load to the fire. The cyclical HRR pattern can be seen in Figure 49.
- In two of the NFPA FPRF experiments (1-4 and 1-5), the fire re-grew following the initial decay causing secondary flashover.
  - For Test 1-4, the regrowth is understood to be due to the exposed timber exhibiting glue line failure and contributing to the fuel load. Following the secondary re-growth, the fire was manually extinguished to preserve the setup for future experiments. The heat release rate curve is shown in Figure 50.
  - In NFPA FPRF Test 1-5 where a greater amount of fire protection was provided to the encapsulated surfaces, and where the ventilation was reduced when compared to Test 1-3, the gypsum board ffell off the ceiling and walls exposing the underlying timber. The fall-off of gypsum board on the ceiling occurred when the sidewall began to exhibit bond line integrity failure. Consequently, as multiple timber surfaces were exposed, the fire began to grow after the initial decay – reaching a heat release rate of 9.5 MW before being manually extinguished. During this period of growth, the gypsum board began to fail and fall off. This highlights that where a single surface is exposed, but the fire burns for a prolonged period, the encapsulation can fail resulting in the freshly exposed timber surfaces becoming involved in the fire and re-radiating. The fire was then manually extinguished. The HRR for Test 1-5 is shown in Figure 51.

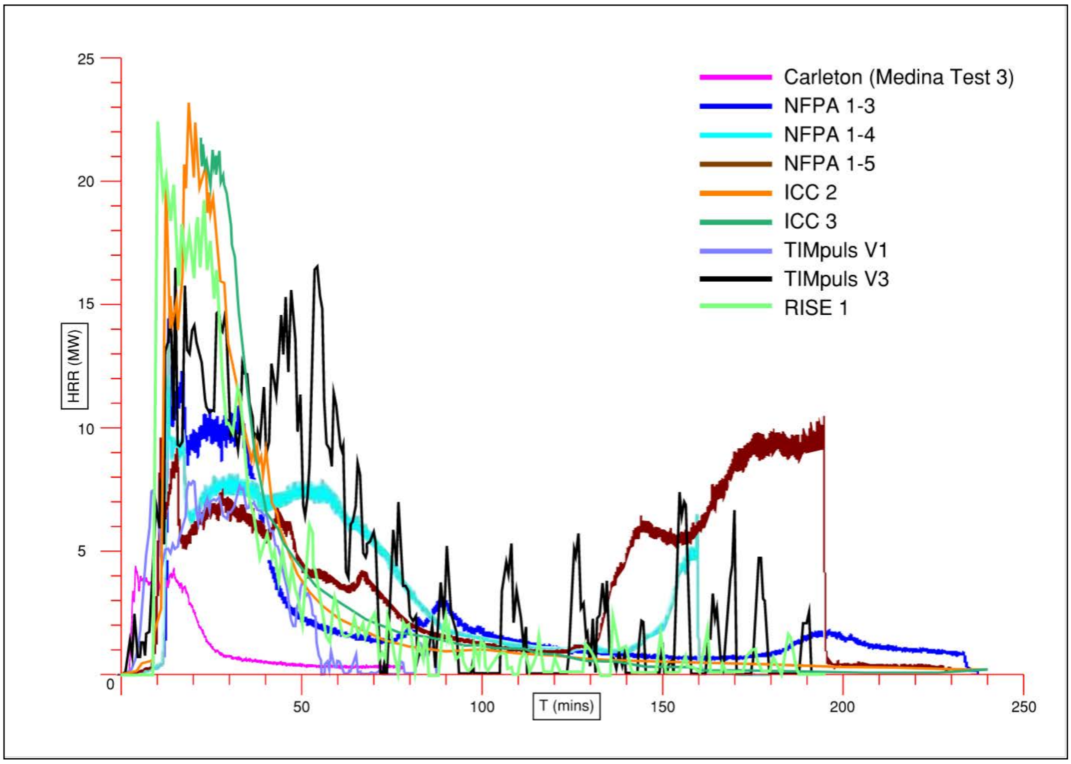


Figure 40: Single exposed surface HRR combined.

Table 19: Single surface summary experiments

Experiment series	Experiment no [Compartment size (L x B x H) in metres]	Internal surface area, A_T [m²]	Exposed surface	CLT description	Protected surfaces	Exposed CLT surface area [m²]	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	% of surface area exposed	Fuel load density [MJ/m²]	Peak temp [°C]	Fuel type	Charring behind protection	Max char depth at exposed surface at end of experiment [mm]	Failure of glue line in CLT observed	Fire decay	Avg. charring rate (mm/min)
Carleton	Medina - Test 3 [4.5 x 3.5 x 2.5]	53.6	Sidewall	3-ply CLT, each layer 35 mm thick, PU adhesive	Two layers of 12.7 mm thick Type X gypsum board	11.25	17.7	21.0	531.6	1097	Furniture (residential)	None	44 (0.71 mm/min)	None recorded	Natural decay with manual extinguishment	0.71
NFPA Fire Protection Research Foundation	1-3 [9.1 x 4.6 x 2.7]	108.6	Sidewall	5-ply CLT, each layer 35 mm thick, PU adhesive	Walls: 2 x 15.9 mm thick Type X gypsum board. Ceiling: 3 x 15.9 mm thick Type X gypsum board.	24.57	10.67	22.6	556	1200	Furniture (residential)	Yes: on opposing sidewall to 10 mm depth, and on ceiling to a depth of 10mm.	86	Yes	Natural decay with manual extinguishment	0.35
	1-4 [9.1 x 4.6 x 2.7]	112.2	(W1) Ceiling		Walls: 3 x 15.9 mm thick Type X gypsum board.	41.86	22.05	37.3	548	1200	Furniture (residential)	Yes: on opposing sidewalls to a depth of 9 mm for W1 and 10 mm for W3	90	Yes – two layers of ply	Re-growth with manual extinguishment	0.56
	1-5 [9.1 x 4.6 x 2.7]	112.2	Sidewall (W1)		Walls: 3 x 15.9 mm thick Type X gypsum board.	24.57	22.05	21.9	556	1200	Furniture (residential)	All protection failed. Max char depth: W1 – 141mm W3 – 52mm W4 – 51mm	79	Yes – two layers of ply	Significant re-growth with manual extinguishment	0.7
USFS-ICC	2 [9.14 x 9.14 x 2.74]	165.9	Ceiling	5-ply CLT, each layer 35 mm thick, PU adhesive	Walls and portion of ceiling protected (30% exposed): 2 x 15.9 mm thick Type X gypsum board	16.71	5.94	10.1	550	1130	Furniture and wood crib	No images with encapsulation removed provided in report. See Figure 42 of this report. Temperature data indicates that char depth did not reach 12mm based on 300ºC isotherm.	Living room: 23-35 mm from thermocouple data. Bedroom: not provided	None recorded	Natural decay with manual extinguishment at 4hrs	-
	3 [9.14 x 9.14 x 2.74]	165.9	Living room wall & Bedroom wall		2 x 15.9 mm thick Type X gypsum board	41.76	5.94	24.7	550	1170	Furniture and wood crib	No images with encapsulation removed provided. Temperature data indicates that char depth did not reach 12mm based on 300ºC isotherm.	Living room wall: 47-58 mm from thermocouple data	Yes. Localised glue line failure recorded on exposed living room wall	Natural decay with manual extinguishment of multiple flaming hotspots from 1.27-3.75hrs	-

Table 19: Single surface summary experiments (continued)

Experiment series	Experiment no [Compartment size (L x B x H) in metres]	Internal surface area, A_T [m²]	Exposed surface	CLT description	Protected surfaces	Exposed CLT surface area [m²]	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	% of surface area exposed	Fuel load density [MJ/m²]	Peak temp [°C]	Fuel type	Charring behind protection	Max char depth at exposed surface at end of experiment [mm]	Failure of glue line in CLT observed	Fire decay	Avg. charring rate (mm/min)
Epernon Fire Tests Programme	CLT Scenario 1 [6 x 4 x 2.52]	64.4	Ceiling	Ceiling: 165mm thick CLT, each layer 33mm thick, single component polyurethane adhesive Walls: aerated concrete with a nominal density of 350 kg/m³	No additional protection to walls provided.	24	4.6	37.3	891	1,200	Wood crib	N/A	45	Yes	Natural decay.	0.66
	CLT Scenario 2 [6 x 4 x 2.52]	69.9	Ceiling	Ceiling: 165mm thick CLT, each layer 33mm thick, single component polyurethane adhesive Walls: aerated concrete with a nominal density of 350 kg/m³	No additional protection to walls provided.	24	14.2	34.3	891	1,200	Wood crib	N/A	74	Yes	Natural decay. Continued to smoulder until collapse 29 hours after onset of heating	0.69
	CLT Scenario 3 [6 x 4 x 2.52]	72.2	Ceiling	Ceiling: 165mm thick CLT, each layer 33mm thick, single component polyurethane adhesive Walls: aerated concrete with a nominal density of 350 kg/m³	No additional protection to walls provided.	24	23.2	33.2	891	1,200	Wood crib	N/A	85	Yes	Natural decay.	0.79
NRC 2018b	Test 4 [4.53 x 2.44 x 2.78]	71.7	Ceiling, beam and column	5-ply CLT, 175 mm thick, PU adhesive	4 layers of 12.7 mm thick Type X gypsum board	18.07	33.3	25.2	550	1,170	Wood crib	Yes: All encapsulation eventually failed, charring to 22-45 mm	66	No	Natural decay	0.4-0.8
RISE	Test 1 [7 x 6.85 x 2.73]	115.6	Ceiling and beam	Ceiling and walls: 175mm thick CLT, each layer 35mm thick, phenolic adhesive	Two layers of 15.9mm thick Type X gypsum.	53.8 (including exposed surfaces of glulam beam)	10.8	46.5	560	1,200	Furniture and wood crib	No gypsum board fall-off observed, however, in one location (low level of back wall) the temperature between the gypsum and CLT exceeded 300°C with localised charring observed. Discolouration of timber observed in location of gypsum board joints also.	45	No	Natural decay, manually extinguished at 4 hours.	-

Table 19: Single surface summary experiments (continued)

Experiment series	Experiment no [Compartment size (L x B x H) in metres]	Internal surface area, A_T [m²]	Exposed surface	CLT description	Protected surfaces	Exposed CLT surface area [m²]	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	% of surface area exposed	Fuel load density [MJ/m²]	Peak temp [°C]	Fuel type	Charring behind protection	Max char depth at exposed surface at end of experiment [mm]	Failure of glue line in CLT observed	Fire decay	Avg. charring rate (mm/min)
TIMpuls	V1 [4.5 x 4.5 x 2.4]	58.2	Ceiling	Walls: 5-ply CLT, each layer 20mm thick, adhesive not stated Ceiling: glue-laminated panel 180mm deep, adhesive not stated	Single layer of 18mm gypsum plasterboard per DIN EN 520. Type not stated.	20.25	7.4	34.7	1,085	1,210	Wood crib	No images provided in report. No char depths or in panel temperature stated.	Not stated.	No	Manually extinguished at 92 minutes. Smouldering in joint observed up to 202 minutes after ignition.	0.87
	V3 [4.5 x 4.5 x 2.4]	96.1	Ceiling	Walls: Timber stud partition, 140mm deep, 60mm wide studs, with mineral wool insulation Ceiling: glue-laminated panel 180mm deep, adhesive not stated	One wall: 12mm of OSB with two layers of 12.5mm plasterboard per DIN EN 520. Type not stated. Remaining three walls: 2 layers of 18mm plasterboard per DIN EN 520. Type not stated.	20.25	7.0	42	1,085	1,250	Wood crib	No images provided in report. No char depths or in panel temperature stated. Protection to walls did fail.	Not stated.	No	Manually extinguished at 150 minutes; no visible flaming of exposed glulam ceiling at this time. Smouldering observed up to 24 hrs later.	0.6
CodeRed	CodeRed #01 [34.27 x 10.27 x 3.1]	925	Ceiling	5-ply CLT, 140mm thick, MUF adhesive	None	352	14.1	38.1	374	1,030	Wood crib	No protection present	35	No	Natural decay, smouldering hotspots observed up to 48 hrs.	2.38
	CodeRed #02 [34.27 x 10.27 x 3.1]	956	Ceiling	5-ply CLT, 140mm thick, MUF adhesive	None	352	25.6	36.8	377	1,058	Wood crib	No protection present	32	No	Natural decay, smouldering hotspots observed up to 60 hrs	1.4
	CodeRed #04 [34.27 x 10.27 x 3.1]	925	Outer 50% of ceiling	5-ply CLT, 140mm thick, MUF adhesive	Three layers of 12.5mm plasterboard	191	14.1	20.6	394	1,007	Wood crib	None	34	No	Natural decay, smouldering hotspots observed up to 60 hrs	2

Table 19: Single surface summary experiments (continued)

Experiment series	Experiment no [Compartment size (L x B x H) in metres]	Internal surface area, A_T [m²]	Exposed surface	CLT description	Protected surfaces	Exposed CLT surface area [m²]	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	% of surface area exposed	Fuel load density [MJ/m²]	Peak temp [°C]	Fuel type	Charring behind protection	Max char depth at exposed surface at end of experiment [mm]	Failure of glue line in CLT observed	Fire decay	Avg. charring rate (mm/min)
STA	Experiment 2 [3.75 x 7.6 x 2.4]	67.7	Ceiling	5-ply CLT, 160mm thick, PUR adhesive	None	28.5	3.15	42.1	N/A	1,000	Gas burner	No protection present	67	Yes Multiple instances of glueline failure observed	Natural decay after deactivation of gas burner	0.43
	Experiment 3 [3.75 x 7.6 x 2.4]	67.7	Ceiling	5-ply CLT, 160 mm thick, PUR adhesive	None	28.5	3.15	42.1	N/A	980	Gas burner	No protection present	65	Multiple instances of glue-line failure observed	Natural decay after deactivation of gas burner	0.43
FRIC 2023	#FRIC-01 [18.8 x 5.0 x 2.52]	308.2	Ceiling	Back wall and ceiling: 5-ply CLT, 40-20-20-20-40 mm thick, PU adhesive	Two layers of 15 mm thick Type F gypsum board	89.3	5.56	29.0	353	1,040	Wood crib	Not reported	40	Yes	Natural decay with manual suppression of smouldering hotspots. Experiment ended after 4hrs.	1.13
NRC 2023	Test 2 [3.2 x 7.0 x 2.2]	102.6	Ceiling, beam and columns	Multiple types used	Two layers of 15.9 mm thick Type X gypsum board	22.4	14.3	21.8	613	1,200	Furniture and wood crib	Yes Rear wall corner with side wall, in ceiling corner, and over full rear wall height at approx. 1/3 points	Ave/ max Ceiling 40/48 Beam 70/90 Column C104 57/56 Column C201 67/95	Some localised glue line failure observed	Natural decay with fire fighting operations after 4 hours to fully extinguish hot spots	1.33

A_T = Internal surface area of walls and ceiling, excluding ventilation opening; Aw = Area of ventilation opening; H = height of ventilation opening

Figure 41: USFS-ICC – Test 2 – Post-test photo – 30% exposed ceiling

Figure 42: USFS-ICC – Test 3 – Post-test photo – bedroom ceiling

Figure 43: USFS-ICC – Test 3 – Post-test photo

Figure 44: USFS-ICC - Test 3 – Post-test photo – living room ceiling

Figure 45: USFS-ICC Partially exposed ceiling in Test 2 (30% exposed) – Post-test photo

Figure 46: NRC 2023 Test 2 (100% ceiling exposed, post-test after removal of protection to rear wall)

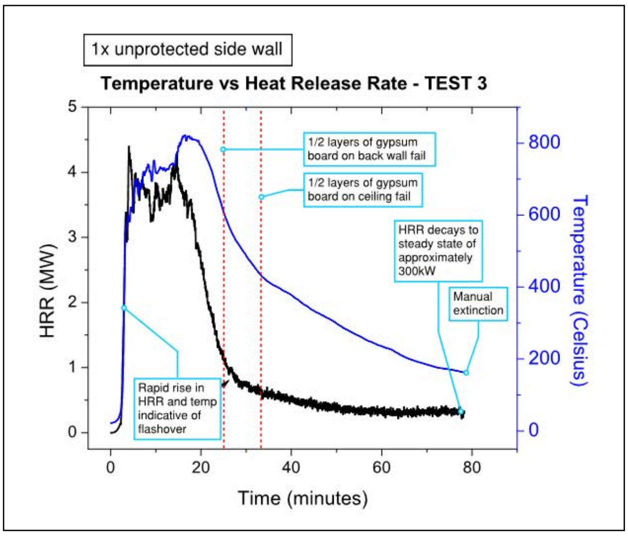


Figure 47: Carleton - Medina Test 3 – Heat Release Rate

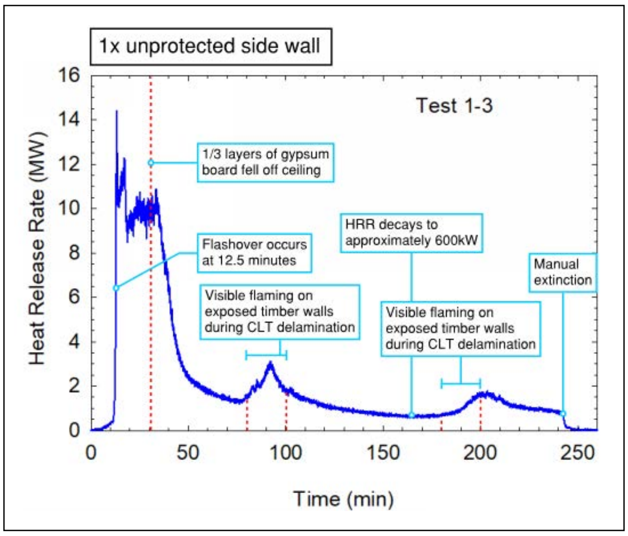


Figure 48: NFPA FPRF - Test 1-3 – Heat Release Rate

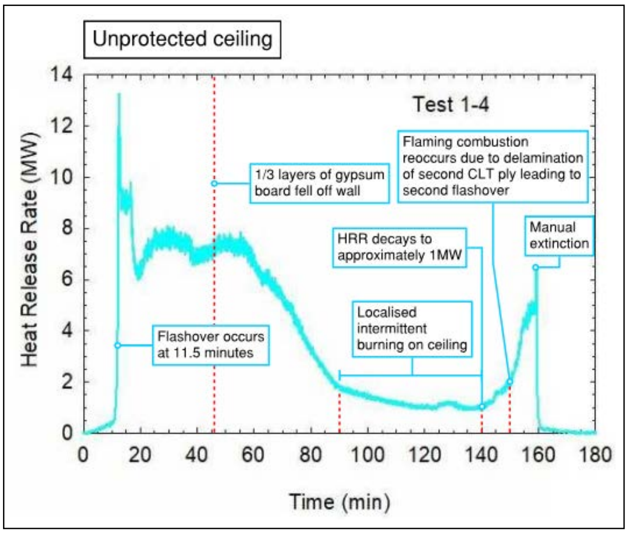


Figure 49: NFPA FPRF –Test 1-4 – Heat Release Rate

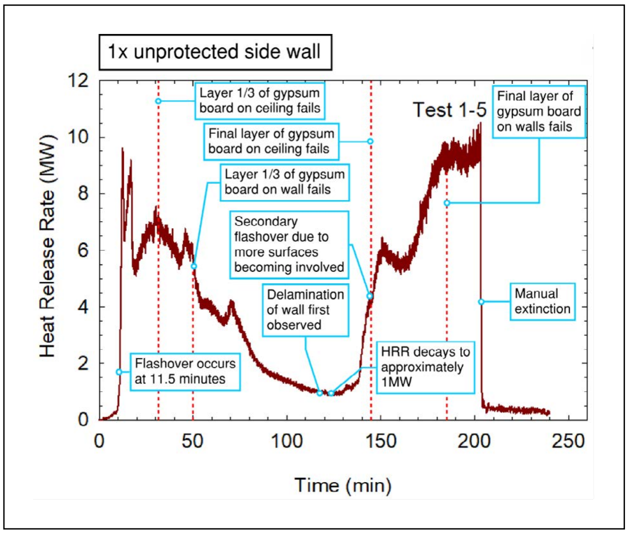


Figure 50: NFPA FPRF – Test 1-5 – Heat Release Rate

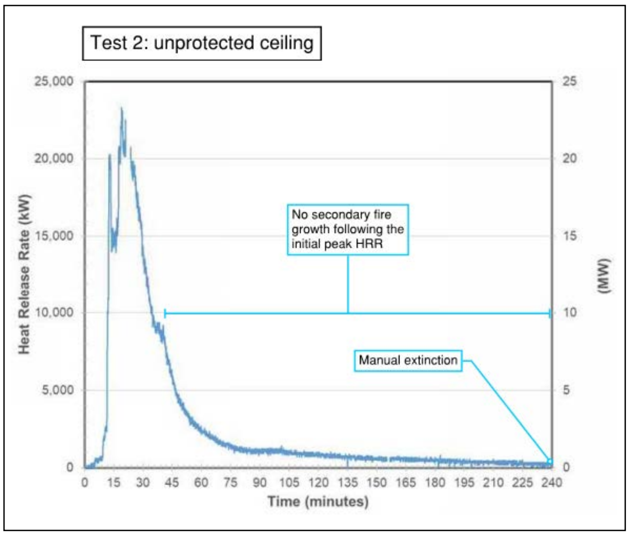


Figure 51: USFS-ICC - Test 2 – Heat Release Rate

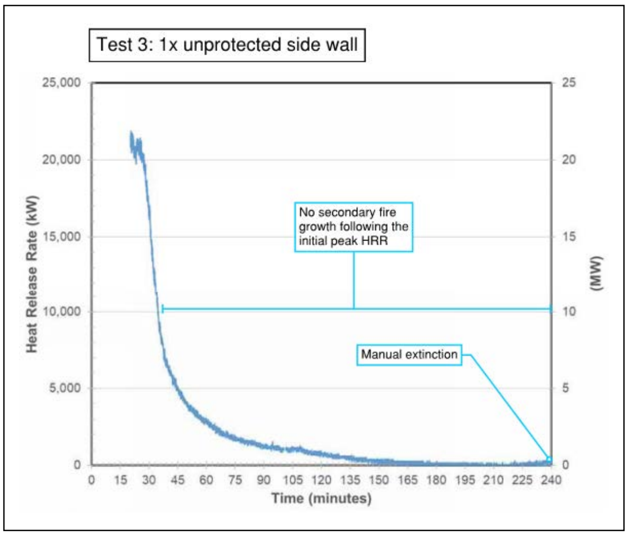


Figure 52: USFS-ICC - Test 3 – Heat Release Rate

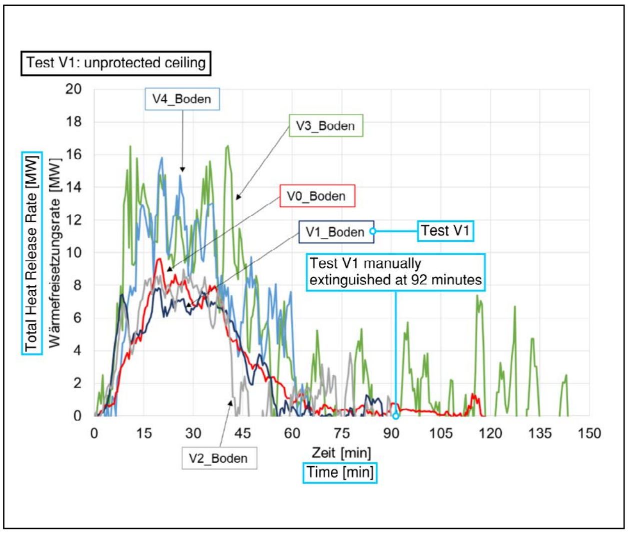


Figure 53: TIMpuls Test V1

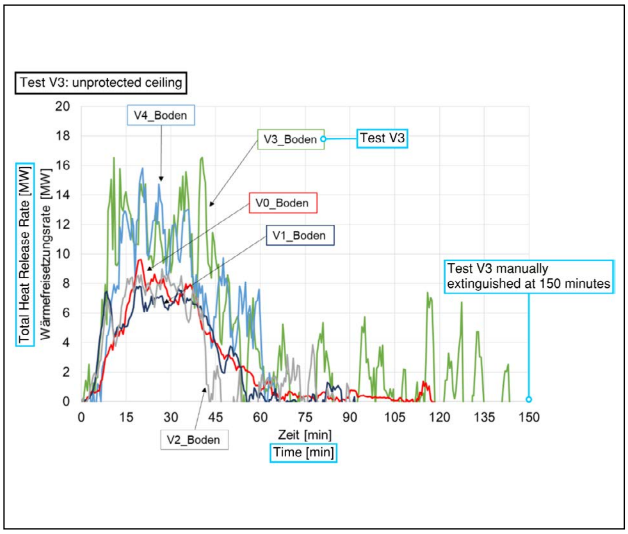


Figure 54: TIMpuls Test V3

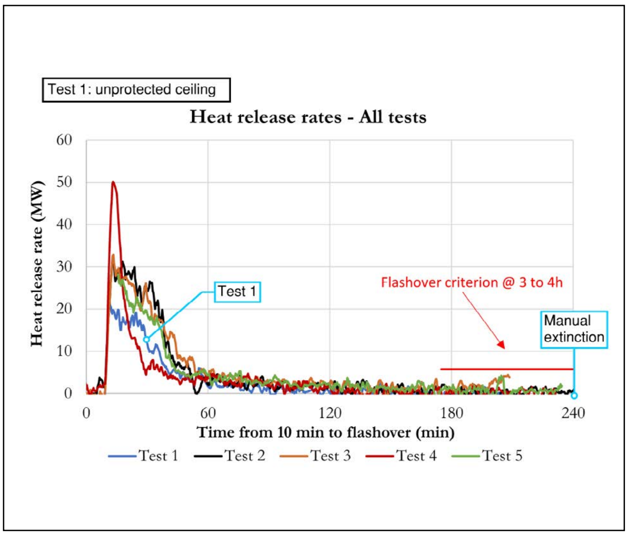


Figure 55: RISE Test 1

A3.6 Multiple exposed surfaces

This section presents a summary of 24 fire compartment experiments with multiple exposed timber surfaces.

From the compartment fire experiments reviewed in Table 20 below, where more than one timber surface is exposed, the following is evident:

- In nine experiments, natural decay occurred (including those that included manual suppression during decay phase and suppression of hotspots afterwards). For example, all NRC 2023 experiments exhibited natural decay, but also included manual suppression after the decay phase to extinguish any remaining smouldering.
- In 14 of the multi exposed surface experiments, the CLT had glue line failure. Of these, re-growth of the fire was witnessed in eight experiments. The remaining four experiments maintained steady-state burning following flashover until being manually suppressed.
- In one experiment flaming ceased at the CLT surface (Figure 63, Beta 1), however, when this arrangement was repeated (Beta 2), flaming did not cease and a cyclical heat release rate pattern was observed as the CLT exhibited glue line failure and exposed the timber which contributed to the fire as fuel (see Figure 63).
- The exposed timber contributed to the fuel load, resulting in longer duration fires when compared to a compartment with non-combustible construction – but with the same moveable fuel. This, in turn, provided extended heating periods causing failure of the encapsulation. Following failure of the encapsulation, the remaining timber also became involved in the fire. This can be seen if the HRR in the same series in Figure 41 for the single exposed surface is compared with Figure 57 for the multiple-exposed surfaces (e.g. NFPA FPRF Test 1-6 with multiple exposed surfaces showed a quasi-steady heat release rate following flashover, whilst NFPA FPRF Tests 1-4 and 1-5 which had the same boundary conditions, except only a single exposed surface, demonstrated a cyclical heat release rate).
- The experiments undertaken were all on compartments of limited size – reflecting a single bedroom or studio apartment. As there is no available fire data for larger fire compartments, the applicability of these results to large compartments is unknown. Re-radiation is more likely to impact smaller compartments when compared to large due to the geometry. However, fire data is required to substantiate this.
- There is only one experiment series that has used a CLT adhesive that is not prone to glue line failure (NRC Canada 2018). These experiments show a likely fire decay when one surface is exposed.
- The two TIMpuls experiments (Test V2 and Test V4) were manually extinguished at 92 minutes and 65 minutes respectively. Before being manually extinguished, the heat release rate was decaying. The timber used was a glue laminated floor and not susceptible to glue line failure.
- Three of the four multi-exposed timber surface experiments by RISE (Tests 2, 4, and 5) showed natural decay before being manually extinguished at four hours (see Figure 68). In one RISE experiment (Test 3), regrowth was observed and manually extinguished due to failing predetermined criteria.
- In the #FRIC-02 experiment, the flaming died down 40-50 minutes after ignition. At 66-76 minutes small regions of flaming on the back exposed wall regrew to a second flashover, which was then manually extinguished at 175 minutes.

A3.6.1 Recorded char rates

The charring rates for the compartment experiments are presented in Table 20.

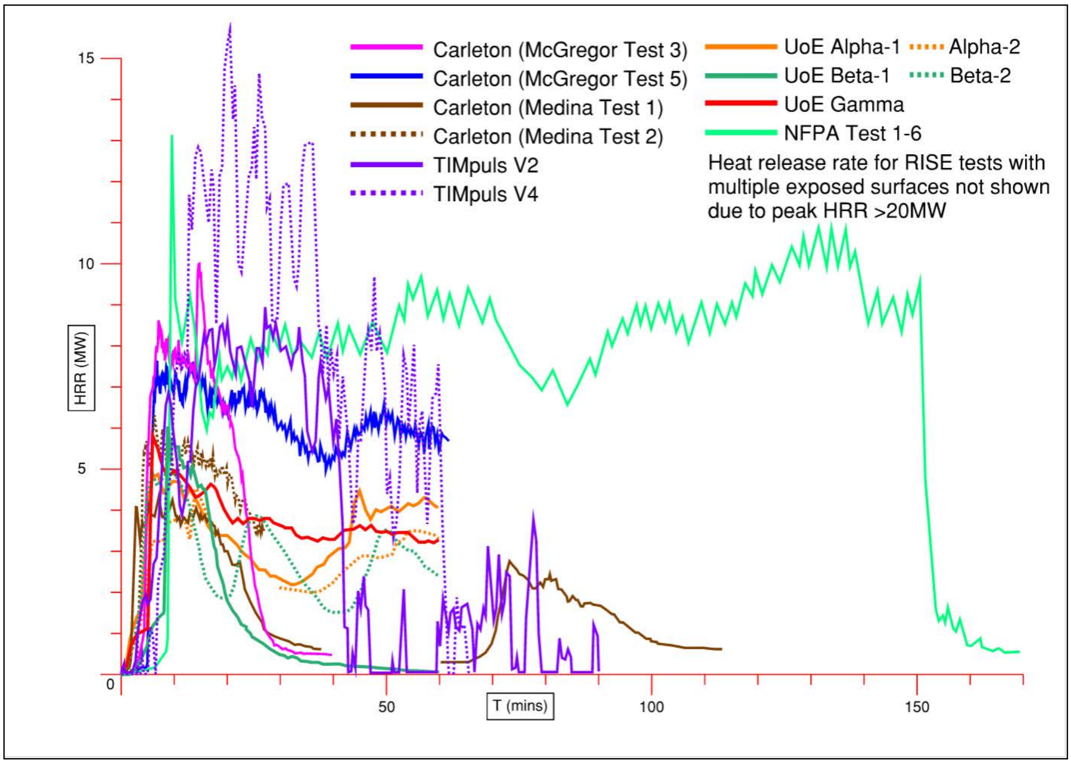


Figure 56: Multiple exposed surfaces HRR combined

Table 20: Multiple exposed surfaces

Experiment series	Experiment no	Compartment size (L x B x H) [m]	Internal surface area, A_T [m²]	Exposed surface	CLT description	Protected surfaces	Exposed CLT surface area [m²]	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	% of surface area exposed	Fuel load density [MJ/m²]	Peak temp [°C]	Fuel type	Max char depth at exposed surface at end of experiment [mm] Note 1	Char depth behind protection [mm]	Glueline failure of CLT observed	Fire decay	Avg. charring rate (mm/min)
Carleton	McGregor - Test 3	4.5 x 3.5 x 2.5	53.6	Fully unprotected	3-ply CLT, each layer 35mm thick, polyurethane adhesive	None	53.6	17.7	100	HRR curve to reflect fuel load density of 550	1140	Propane burner	20-30 mm (Char rate stated by author: 0.63 mm/min)	N/A	Minor bond line integrity failure noted	Tends to quasi-steady HRR of 0.45 MW at 35 minutes. Manual extinguishment after 60 minutes.	0.63
	McGregor - Test 5			Fully unprotected		None	53.6	17.7	100	529	1170	Furniture (residential)	60-70 mm (Char rate stated by author: 1.0 mm/min)	N/A	Yes	Tends to quasi-steady HRR of 5.7 MW at 57 minutes. Manual extinguishment at 63 minutes.	1
	Medina – Test 1			Back wall and one side wall		Ceiling and remaining walls: 2 layers of 12.7 mm Type X gypsum	20	17.7	37.3	532	1200	Furniture (residential)	71-80 mm (Char rate stated by author: 0.69 mm/ min)	12-25	Yes	Initial decay followed by glue line failure and re-growth. Manual extinguishment as last ply burning at 123 minutes.	0.69
	Medina – Test 2			Opposing sidewalls			22.5	17.7	42.0	532	1200	Furniture (residential)	53-60 mm (Char rate stated by author: 1.0 mm/min)	2-17	Yes	HRR measurement device failed. Initial decay followed by re-growth based on temperature data and observations. Manual extinguishment at 57 minutes.	Right wall: 0.75 Left wall: 1.0
SP Fire Research	Test 2	[2.3 x 5.75 x 2.75]	53.8	Left side wall and ceiling	5-ply CLT, 100 mm thick	13 mm layer of standard gypsum board and a 15 mm layer of fire resistant gypsum board	29.0	14.3	54.0	658	1025	Furniture and wood crib	Not recorded, but "burn-through" of full timber thickness observed		Yes	Manual extinguishment after structural failure of timber ceiling.	Wall: 0.7-1.4 Ceiling: 1

Table 20: Multiple exposed surfaces (continued)

Experiment series	Experiment no	Compartment size (L x B x H) [m]	Internal surface area, A_T [m^2]	Exposed surface	CLT description	Protected surfaces	Exposed CLT surface area [m^2]	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	% of surface area exposed	Fuel load density [MJ/m^2]	Peak temp [°C]	Fuel type	Max char depth at exposed surface at end of experiment [mm] Note 1	Char depth behind protection [mm]	Glueline failure of CLT observed	Fire decay	Avg. charring rate (mm/min)
	Alpha-1			Back wall and one side wall		Two layers of 12.5mm Type F gypsum	14.8		41.5		1236		53	Protection failed. Depth of char not provided.	Yes	Initial decay followed by glue line failure and re-growth. Manual extinguishment at 61.3 minutes.	0.83
	Alpha-2					Two layers of 12.5mm Type F gypsum + 25mm high-density stone wool	14.8				1150		53	Depth of char not provided	Yes	Initial decay followed by glue line failure and re-growth. Manual extinguishment after 60 minutes.	0.83
University of Edinburgh	Beta-1	2.72 x 2.72 x 2.72m	35.7	Back wall and ceiling	5-ply CLT, each layer 100mm thick, polyurethane adhesive		14.8	20.5		132		Wood crib	11	Depth of char not provided	Partial bond line integrity failure	Auto extinction observed	-
	Beta-2						14.8				1114		44	Depth of char not provided	Yes	Initial decay followed by glue line failure and re-growth. Manual extinguishment at 62.5 minutes.	0.73
	Gamma-1			Back wall, one side wall, and ceiling			22.2		62.2				58	Depth of char not provided	No description of bond line integrity failure	Following initial peak, quasi-steady HRR of 3.7 MW until manual extinguishment at 78 minutes.	0.97
NRC 2018b	Test 2	[4.53 x 2.44 x 2.78]	71.7	Back wall and 10% of ceiling	5-ply CLT, 175 mm thick, PU adhesive	Two layers of 12.7 mm thick Type X gypsum board	13.2	33.3	18.5	550	1200	Wood crib	95	Wall: 50-95 Ceiling: 45-63	None recorded	Manual suppression during decay phase.	Ceiling: 0.63-1.0 Wall: 0.63-1.0
	Test 5	[4.53 x 2.44 x 2.78]	71.7	Side walls and ceiling	5-ply CLT, 175 mm thick, PU adhesive	Two layers of 12.7 mm thick Type X gypsum board	23.8	33.3	18.5	550	1190	Wood crib	109	Walls: 81-109 Ceiling: 70-90	None recorded	Manual suppression after reignition of timber surfaces causing second flashover.	Ceiling: 0.8 Walls: 0.8
NFPA Fire Protection Research Foundation	Test 1-6	9.1 x 4.6 x 2.7	108.6	Sidewall and ceiling	5-ply CLT, each layer 35 mm thick, PU adhesive	3 x 15.9 mm thick Type X gypsum board.	66.4	22.05	61.1	550	1200	Furniture and wood crib	Ceiling: 116-154 Wall: 88-143	Protection failed. Sidewall: 5-66 Backwall: 25-68	Yes	Following initial peak, quasi-steady HRR of 9 MW until fire suppression activation at 160 minutes.	Ceiling: 0.72-0.96 Wall: 0.55-0.89

Table 20: Multiple exposed surfaces (continued)

Experiment series	Experiment no	Compartment size (L x B x H) [m]	Internal surface area, A_T [m²]	Exposed surface	CLT description	Protected surfaces	Exposed CLT surface area [m²]	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	% of surface area exposed	Fuel load density [MJ/m²]	Peak temp [°C]	Fuel type	Max char depth at exposed surface at end of experiment [mm] Note 1	Char depth behind protection [mm]	Glueline failure of CLT observed	Fire decay	Avg. charring rate (mm/min)
RISE	Test 2	7 x 6.85 x 2.73	115.6	Ceiling, beam, two walls (opposing)	Ceiling and walls: 175mm thick CLT, each layer 35mm thick, phenolic adhesive	Back wall and front wall protected with 3 x 15.9mm layers of Type X gypsum plasterboard	91.2	10.8	78.9	560	1,290	Furniture and wood crib	Wall: 36-86 Ceiling: 33-57	20	None observed.	Following the initial peak, natural decay was observed with the test manually extinguished at four hours.	-
	Test 3	7 x 6.85 x 2.73	115.6	Ceiling, beam, two full walls, and 78% of one wall	Ceiling and walls: 175mm thick CLT, each layer 35mm thick, phenolic adhesive	Back wall and 1.5m of adjoining right wall protected with 3 x 15.9mm layers of Type X gypsum plasterboard	96.2	10.8	83.2	560	1,250	Furniture and wood crib	Wall: 35-104 Ceiling: 40-58	0	None observed	Following the initial peak, natural decay was observed until the fire began to grow again at around 3.5 hours when the fire was then manually extinguished due to regrowth of the fire occurring in the corner where two exposed wall surfaces met.	-
	Test 4	7 x 6.85 x 2.73	92.4	Ceiling, beam, three walls, and one column	Ceiling and walls: 175mm thick CLT, each layer 35mm thick, phenolic adhesive	Back wall protected with 2 x 15.9mm layers of Type X gypsum plasterboard	77.9	2.0	84.3	560	1,140	Furniture and wood crib	Wall: 39-104 Ceiling: 19-45	0	None observed.	Following the initial peak, natural decay was observed with the test manually extinguished at four hours.	-
	Test 5	7 x 6.85 x 2.73	115.6	Ceiling, beam, three walls, and one column	Ceiling and walls: 175mm thick CLT, each layer 35mm thick, phenolic adhesive	Back wall and left and right corners of front wall protected with 3 x 15.9mm of Type X gypsum plasterboard	97.2	10.8	84.1	560	1,250	Furniture and wood crib	Wall: 34-89 Ceiling: 37-73	0	None observed	Following the initial peak, natural decay was observed with the test manually extinguished at four hours.	-

Table 20: Multiple exposed surfaces (continued)

Experiment series	Experiment no	Compartment size (L x B x H) [m]	Internal surface area, A_T [m²]	Exposed surface	CLT description	Protected surfaces	Exposed CLT surface area [m²]	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	% of surface area exposed	Fuel load density [MJ/m²]	Peak temp [°C]	Fuel type	Max char depth at exposed surface at end of experiment [mm] Note 1	Char depth behind protection [mm]	Glueline failure of CLT observed	Fire decay	Avg. charring rate (mm/min)
TIMpuls	Test V2	4.5 x 4.5 x 2.4	58.2	Two opposing sidewalls	Exposed CLT sidewalls: 150mm thick 5-ply panels with layup 34/24/34/24/34 Remaining walls and ceiling: timber stud construction	2 x 18mm thick gypsum plasterboard per DIN EN 5202. Type not stated.	21.6	7.4	37.1	1,085	1,250	Wood crib	Char depths not stated in report	Char depths not stated in report	Not stated in report	After initial peak, heat release rate began to decrease with sustained burning until manually extinguished at 92 minutes.	-
	Test V4	9 x 4.5 x 2.4	96.1	Ceiling and one sidewall	Exposed CLT sidewall: 150mm thick 5-ply panels with layup 34/24/34/24/34 Remaining walls: timber stud construction Ceiling: 180mm thick glulaminated timber	Two walls with 2 x 18mm thick gypsum plasterboard per DIN EN 5202. Type not stated. One wall with 2 x 18mm thick Type F gypsum plasterboard per DIN EN 5202.	51.3	7.0	53.4	1,085	1,230	Wood crib	Char depths not stated in report	Char depths not stated in report	Not stated in report	Manually extinguished at 65 minutes, when heat release rate was decaying.	-
FRIC	#FRIC-02	18.8 x 5.0 x 2.52	308.2	Ceiling and back side wall	Back wall and ceiling: 5-ply CLT, 40-20-20-20-40 mm thick, PU adhesive	Three layers of 15 mm thick Type F gypsum board	136.4	5.56	44.3	353	1172	Wood crib	Wall: 118 Ceiling: 140	0	Yes Multiple instances of glueline failure observed.	Manual suppression after reignition of timber surfaces causing second flashover.	Ceiling: 0.56 (0.22-2.64) Wall: 0.60 (0.32-2.71)

Table 20: Multiple exposed surfaces (continued)

Experiment series	Experiment no	Compartment size (L x B x H) [m]	Internal surface area, A_T [m²]	Exposed surface	CLT description	Protected surfaces	Exposed CLT surface area [m²]	Opening Factor ($A_T/A_wH^{1/2}$) [$m^{-1/2}$]	% of surface area exposed	Fuel load density [MJ/m²]	Peak temp [°C]	Fuel type	Max char depth at exposed surface at end of experiment [mm] Note 1	Char depth behind protection [mm]	Glueline failure of CLT observed	Fire decay	Avg. charring rate (mm/min)
NRC 2023	Test 3	[3.2 x 7.0 x 2.2]	102.6	Floor, ceiling, and glulam beams and columns	CLT ceiling Columns Beams CLT stair shaft wall	Two layers of 15.9 mm thick Type X gypsum board	55.1	14.3	53.7	12	1000	Wood crib	Shaft wall 5 Ceiling 2 Floor 10	None	No	Natural decay with manual suppression of smouldering hotspots.	-
	Test 4	[7.1 x 7.5 x 3.0]	189.9	Floor, ceiling, and glulam beams and columns	DLT Ceiling	Two layers of 15.9 mm thick Type X gypsum board	124.6	9.1	65.6	224	1100	Wood crib and lumber	Ave/max depths: DLT Ceiling: 70/89 CLT Floor: 59/75 Columns: 56-73/135 Beams: 34-53/68 Deeper near connections and junctions	None	No	Manual extinguishment during decay phase, followed by manual suppression of smouldering hotspots.	Ceiling: 3.33 Floor: 2.81
	Test 5	[Non-quadrilateral floor plan, 204 m2 x 4.3 m]	612.8	Columns, beams, ceiling, stair shaft wall	CLT ceiling CLT floor CLT shaft wall	Two layers of 12.7 mm thick Type X gypsum board	195	8.3	31.8	362	1200	Furniture (office) and wood crib	Ave/max depths: Ceiling 24/40 Beams 29/33 Columns 39/60 Stair shaft panels 42/56	None Deeper seated charring in joints	Some localised instances of delamination observed.	Natural decay with manual suppression of smouldering hotspots.	Ceiling: 1.38 Wall: 2.42

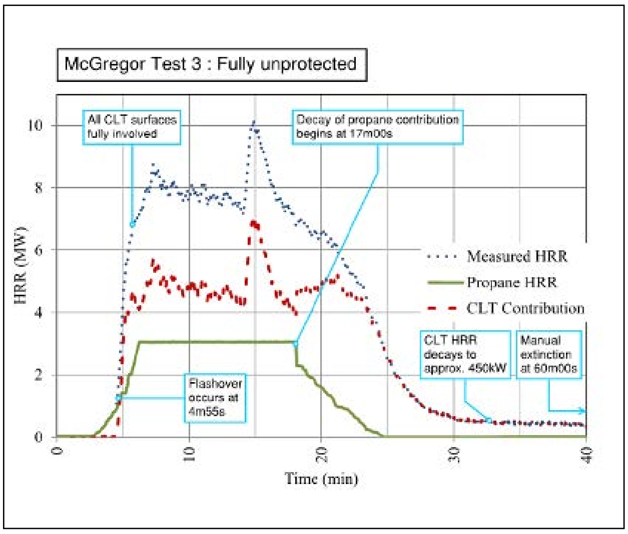


Figure 57: Carleton - McGregor Test 3

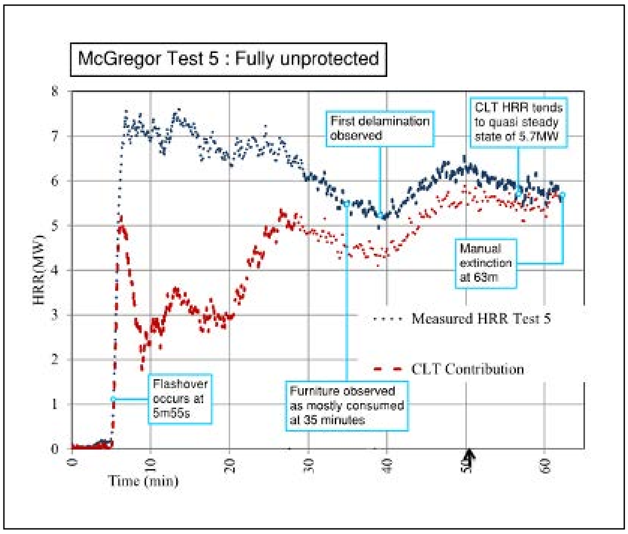


Figure 58: Carleton - McGregor - Test 5

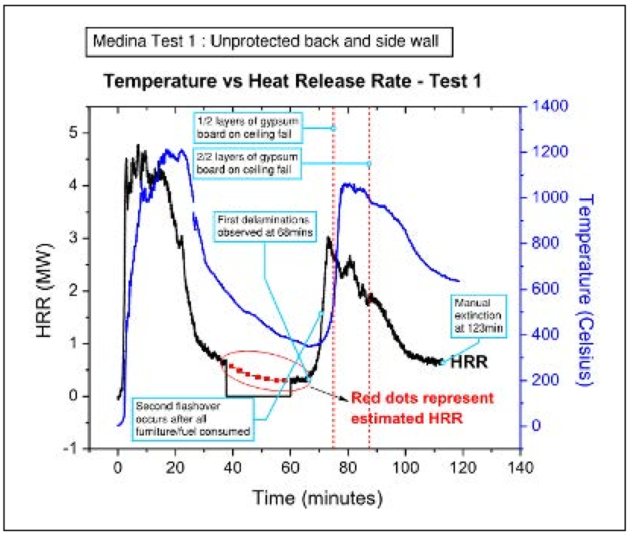


Figure 59: Carleton – Medina – Test 1

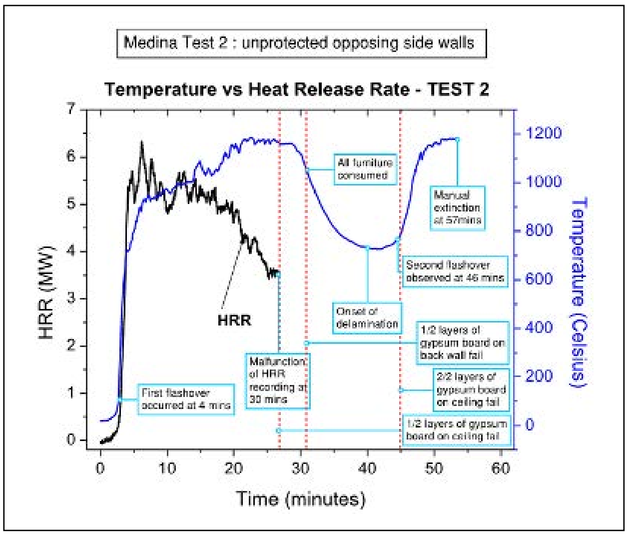


Figure 60: Carleton – Medina – Test 2

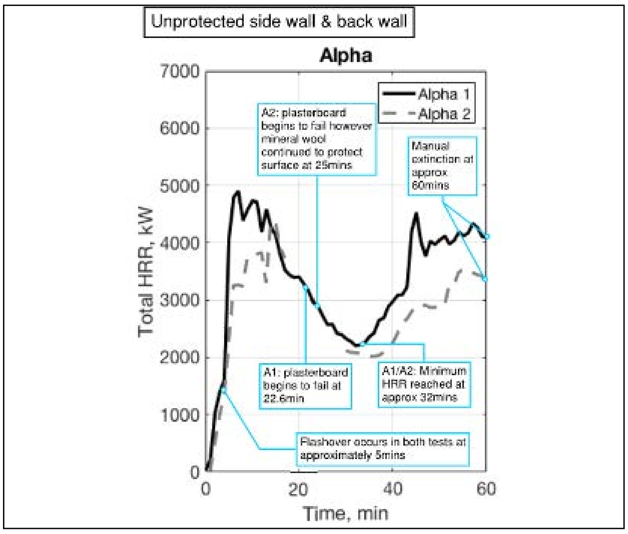


Figure 61: University of Edinburgh - Alpha Tests

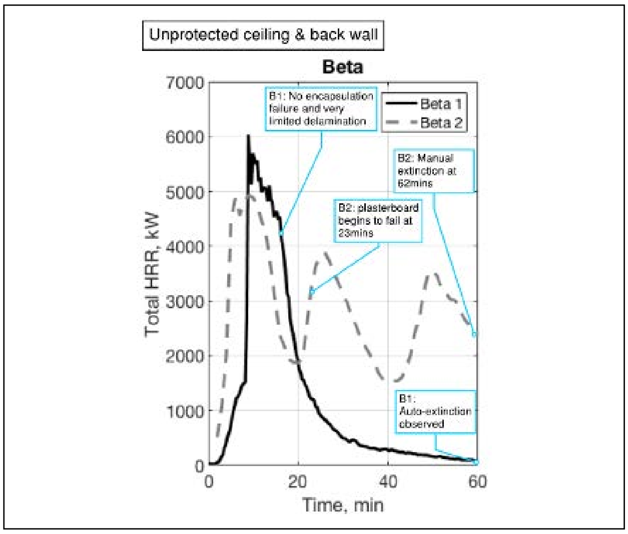


Figure 62: University of Edinburgh – Beta Tests

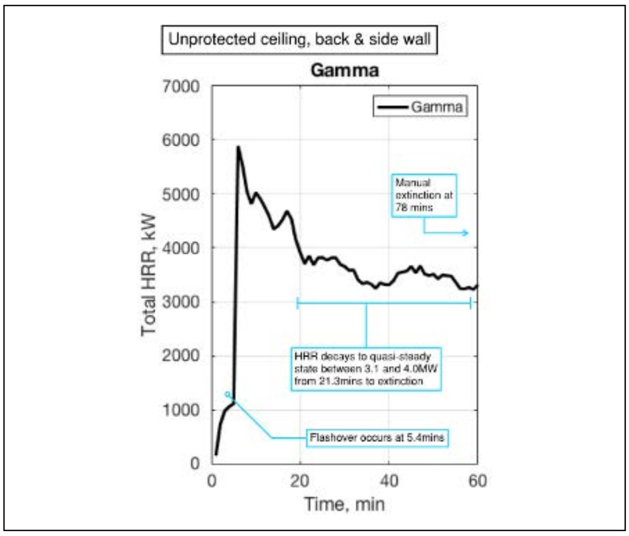


Figure 63: University of Edinburgh – Gamma Tests

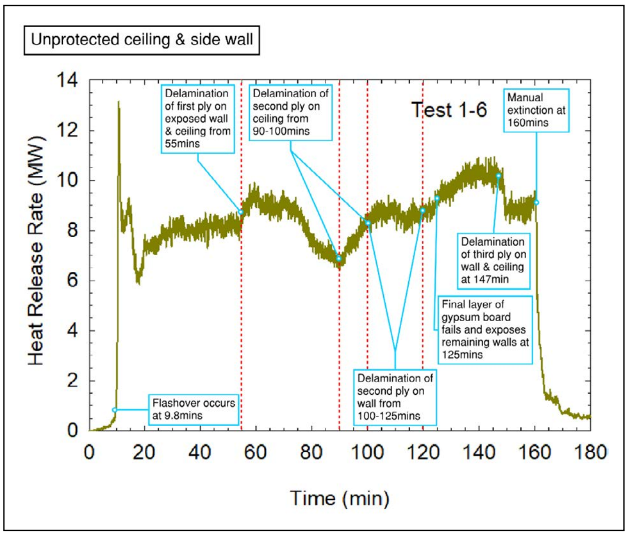


Figure 64: NFPA FPRF Test 1-6.

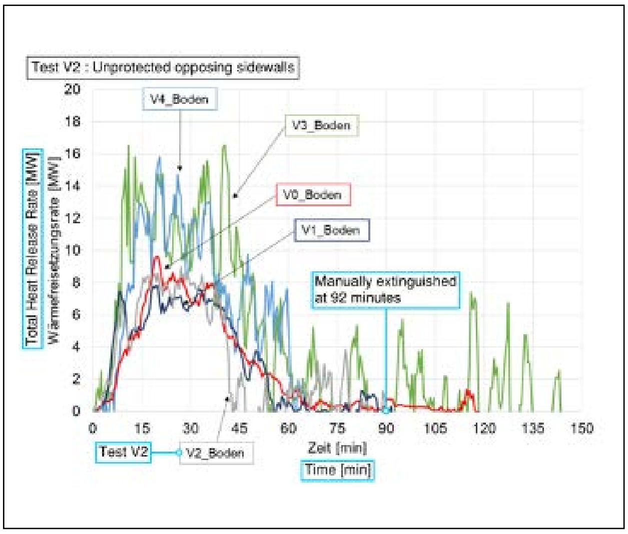


Figure 65: TIMpuls – Test V2

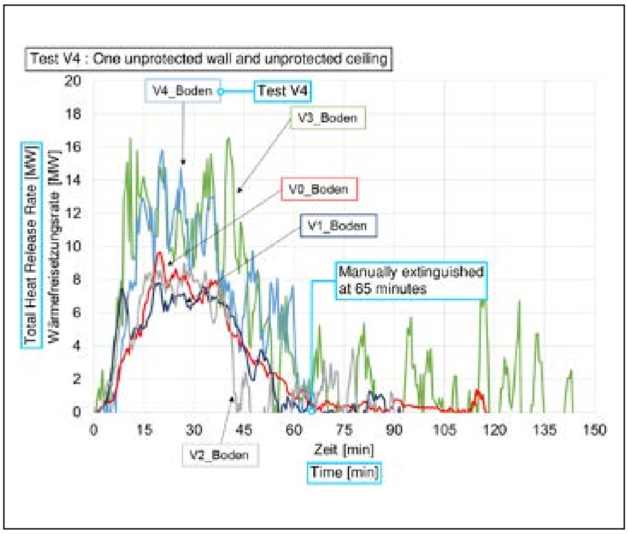


Figure 66: TIMpuls – Test V4

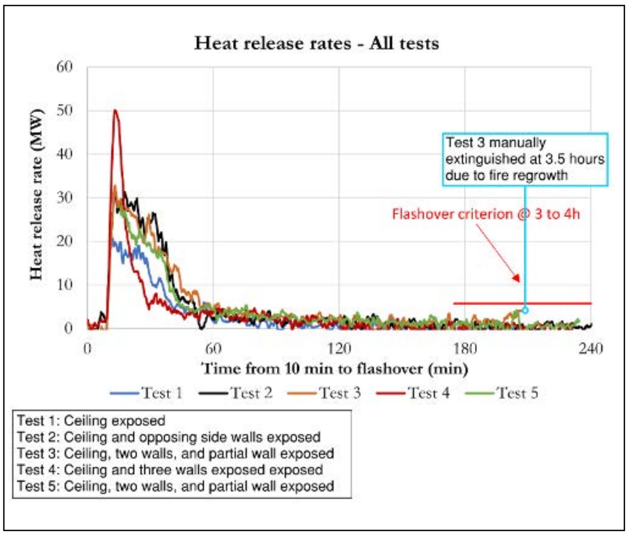


Figure 67: RISE – Heat release rate for all experiments

Appendix 4.

Large compartment fire experiments - CodeRed

This section presents an overview of the compartment fire experiments undertaken by Arup, CERIB and Imperial College London. This section is a summary only with all details and findings detailed within published papers (Kotsovinos et al., 2022a-d). The outcomes from these large compartment experiments have informed the recommendations in this Guide.

A4.1 Experiment set-up and goals

The series of full-scale fire experiments were carried out in a large purpose-built compartment of internal dimensions of 10.27 × 34.27 (352m^2) × 3.1m located at CERIB, France (Figure 68). The building consists primarily of masonry walls and a CLT ceiling. The layout of the structure closely follows a series of fire experiments with a similar design including a concrete ceiling (Rackauskaite et al., 2022, Heidari et al., 2021), allowing for direct comparison and understanding of the impact of the CLT ceiling. The CLT panels forming the ceiling are exposed and designed to replicate the aesthetic desired in modern timber office buildings. The CLT ceiling comprised of 14 individual five-ply CLT slabs with MUF adhesive, with a thickness of 140mm, with proven bond line integrity in fire. Two 400 × 400mm glulam columns were also included to allow research on the charring and thermal penetration behaviour of the columns and any interaction between CLT and exposed columns and the fire.

The CLT and glulam was purchased directly from a European supplier, specified against fire safety performance requirements set by Arup. The main fuel source for the experiment and the first fuel to be ignited was a uniform bed of wood cribs, as it allowed for a highly controlled fuel load that approximated the fuel load density of an open-plan office unit.

The goals for the fire experiments were to investigate the impact of large areas of exposed mass timber on the internal and external fire dynamics that occur in an open-plan compartment, to understand how exposed timber structures behave after the end of flames inside the compartment, including fire decay, cooling, and smouldering behaviour, and to develop robust fire scenario calculations as the basis for future designs. These design fire scenarios will enable future evacuation, structural design, and fire-fighting planning, all of which are critical components of the robust use of mass timber in buildings worldwide.

Figure 68: Large compartment experiment building

A4.2 Summary of experiments undertaken

Four experiments were undertaken in 2021. The findings of each are detailed in full by Kotsovinos et al., 2023a, 2023b, 2023c, 2023d. A summary of the design and findings of each experiment is included below:

CodeRed #01: Base case

For the first experiment, 20.5% of the compartment wall surface area was openings (34.4m^2 windows, 22.6m^2 doors) with an opening factor of 0.071m$^{1/2}$. The fuel used was a continuous wooden crib, covering a floor area of 174m^2 with an approximate fuel density of 374MJ/m^2. This fuel load was chosen to limit the risk of damage to the structure but to still be within the range of typical fuel load densities in office buildings. The crib was ignited at one end of the compartment length, resulting in flames spreading along the compartment length. Observations indicated that fire spread across the exposed CLT ceiling was faster than expected and analysis of the data has shown that the fire did spread across the exposed CLT ceiling slightly faster than across the wood-crib fuel on the floor. Directly after ignition of the ceiling, the speed of fire spread at the wood crib was enhanced by the radiative heating from the flaming CLT. Any increase in speed of fire spread impacts occupant evacuation options, and fire-fighting response scenarios.

Maximum temperatures occurred over a range of heights throughout the compartment, not just near the CLT ceiling, confirming previously published research on CLT fire behaviour. Temperatures within the timber columns showed a “thermal lag” where peak temperatures in the columns occurred after the fire had decayed. Following the end of flaming some hotspots in the CLT where observed, although the majority of the CLT had stopped burning. The following day, three hotspots were detected via thermal imaging and visual detection. One hotspot near the central beam continued to smoulder and burn through the thickness of the CLT, eventually being extinguished through rainfall.

CodeRed #02: 50% reduced ventilation from base case

The construction of the second experiment was identical to the first experiment, with all the CLT exposed. Two glulam columns were again included to allow for research on the thermal movement in the glulam, smouldering behaviour and the interaction with the adjacent exposed CLT. As with the first experiment, the fuel source for the experiment was a series of wooden cribs.

The window openings were reduced by half compared to the first experiment, to study fire dynamics of under-ventilated fires. Non-combustible protective boards were installed in sample locations on the floor to observe their ability to protect timber flooring against fire exposure from above. Devices to measure radiant heat at set distances were also installed directly outside windows in the second experiment. No fire-fighting intervention was undertaken within the building thereby enabling a detailed study of the long-term fire decay and smouldering behaviour of the CLT and glulam.

Observations from the experiment indicate the fire spreading across the CLT ceiling and the building at a similar speed to the first experiment, followed by a longer phase of intense burning compared to the first experiment. During this prolonged burning phase, flame extension from the available windows and doors was again significant. As occurred in the first experiment, after a period of time the fire in the wood-crib fuel reduced and flaming ceased at the CLT. Flaming was still visible at the columns for some time when there were only smouldering embers remaining on the floor. Without firefighting intervention, small pockets of CLT again continued to smoulder for hours, again breaching the CLT thickness.

CodeRed #03: Automatic water mist suppression

The construction of the third experiment was identical to the first experiment, with all the CLT exposed and the inclusion of an automatic water suppression system at the ceiling. The low-pressure mist system was designed to meet European standards for a typical office building, with nozzles with an activation temperature of 68ºC. The fuel was amended to reflect the configuration of a water mist corner test, comprising continuous wooden crib with a fuel load of 570MJ/m^2. Some of the window and door openings were left open to replicate the condition in a naturally ventilated office building where some of the windows may be open to allow fresh air in. There was a slight breeze during the experiment.

The sprinkler system activated five nozzles at approximately 1.5, 1.8, 2.7, 2.95, and 5.5 minutes respectively, maintaining an approximate discharge density of 2.88-3.0 litres/m/min. During this time, the fire reached heights of 2.5m, until rapidly decreasing in size at 3 minutes. This gave an approximate peak heat release rate of 762-1205kW.

The fire size was successfully controlled and eventually suppressed by the automatic suppression system, with minor smouldering of the crib extinguished fully through manual firefighting water application. There was only limited discoloration visible at the CLT ceiling in the immediate vicinity where the fire was ignited and no ignition of the CLT ceiling. Ceiling temperatures were recorded to reach a peak of 185ºC.

CodeRed #04: 50% partial ceiling encapsulation from base case

The construction of the fourth experiment was identical to the first experiment, using the same ventilation openings, wood crib, CLT slab and glulam columns. In this experiment the CLT was protected by 3x 12.5mm fire rated boards achieving a $K_2$60 classification, covering just under 50% of the area, to study the impact of part CLT protection on fire dynamics. Both screw and staple fixings were used.

In addition, it included eight 1m^2 samples of floor protection, and over 60 ceiling mounted fixings to replicate supports for ceiling mounted engineering services commonly found in office buildings (e.g. lights, fire safety systems etc.), half were fixed into the CLT directly and the other half into the protected CLT. A portion of the fixings were loaded with concrete blocks to replicate their expected design load.

Observations from the experiment indicate the fire spreading across the CLT ceiling and through the building at substantially slower speed compared to the first two experiments, followed by a longer phase of less intense burning compared to the first experiment. During this prolonged burning phase, flame extension from the available windows and doors was controlled both in extent and height. As occurred in the first two experiments, after a period of time the fire in the wood-crib fuel reduced and flaming ceased at the CLT, and flaming was still visible at the columns for some time when there were only smouldering embers remaining on the floor. As in CodeRed #02 there was no firefighting intervention, resulting in small pockets of CLT smouldering for hours, again breaching the CLT thickness. Localised failure of the outermost layer of the CLT protection was evident in the late stages of the fire, though the CLT remained protected as the residual layers remained intact. Most of the service's fixings loaded with concrete blocks that were fixed directly into the CLT failed during the fire.

A4.3 Experimental findings

Observations from the experiments have provided valuable data and informed the recommendations of this Guide. The experiments investigated the impact of large areas of exposed mass timber on the fire dynamics that occur in an open-plan compartment, and provided important information on how fires develop with large areas of exposed mass timber structure, and how the structures withstand fire decay and smouldering.

Further understanding of the speed and duration of the fire will enable robust design solutions to be developed. The data from the experiments will inform new numerical modelling methods for exposed structural timber, to predict fire behaviour.

Key findings from the series of experiments are as follows:

A4.3.1 Flame spread

Over the three experiments where the CLT ceiling became involved in the overall fire dynamics, it was shown that the flaming CLT had a significant impact on flame spread behaviour. Rapid flame spread along the wood crib and ceiling was observed directly following ignition of the CLT ceiling.

In CodeRed #01, the ceiling ignited at 2.8 minutes after ignition of the crib, shortly after crib flames began to impinge on the ceiling. Flames spread along the ceiling at an average rate of 0.2m/s before reaching the end of the compartment and burning steadily across the entire crib surface. Shortly after spread of flames across the ceiling, the rate of spread of crib flames increased significantly, as depicted in Figure 69.

Compared to experiments of a similar design with a concrete ceiling (x-ONE and x-TWO.1 in Figure 70, Rackauskaite et al., 2021 and Heidari et al., 2020), the maximum rate of spread of flames along the wood crib was three to eight times greater in CodeRed #01 (160mm/s), supported by the additional heat transferred to the crib by flaming of the CLT ceiling.

The reduction of ventilation in CodeRed #02 compared to #01 reduced the average flame spread rate across the ceiling by 23% (0.15m/s) and 8% in the crib.

The encapsulation of 50% of the timber ceiling in CodeRed #04 contributed to extending the time to ignition of the exposed region of CLT ceiling to 23.9 min, 21.1 min later than in CodeRed #01. However, once ignited the ceiling flames spread at an approximately 10% greater rate than in CodeRed #01 (222mm/s), attributed to the extended preheating time.

Fire spread across large areas of exposed timber is rapid, compared with non-combustible ceilings. Current models for travelling fires therefore need to be re-evaluated, with new input data and assumptions on fire spread modes.

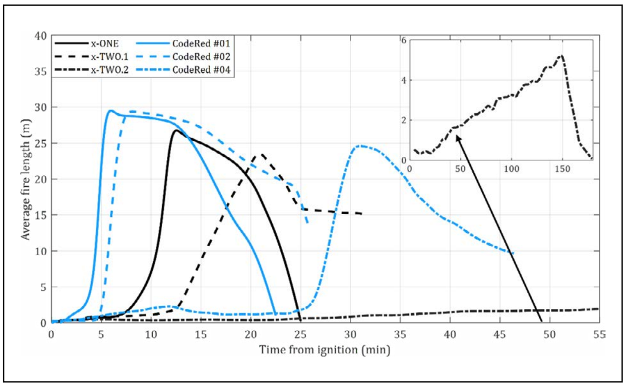


Figure 69: Comparison of crib fire length in the CodeRed and Obora (concrete ceiling) experiments. Gradient of curve before reaching peak is indicative of flame spread rate.

A4.3.2 Compartment temperatures

Peak gas phase temperatures inside the CodeRed #01 compartment were similar to those in non-combustible compartments (1030ºC). Changes in ventilation and ceiling encapsulation in CodeRed #02 and #04 had minimal impact on this peak temperature (1080 and 1000ºC). Peak temperatures were observed 0.7m below the ceiling. As shown in Figure 71, the temperature profile in the compartment was impacted significantly by the spread of flames along the crib and ceiling.

Large temperature distributions were observed across the compartment area and compartment height, such as in CodeRed #02 where in some instances compartment temperatures varied by up to 518ºC (reduced compared to #01 with a maximum variation of 673ºC). This suggests that the assumption of a uniform flashover in design may lead to unconservative structural performances.

After the end of flames, the rate of cooling inside CodeRed #01 and #02 was 11.2 and 9.7ºC/min, with the latter marginally slower cooling rate influenced by the reduction in ventilation.

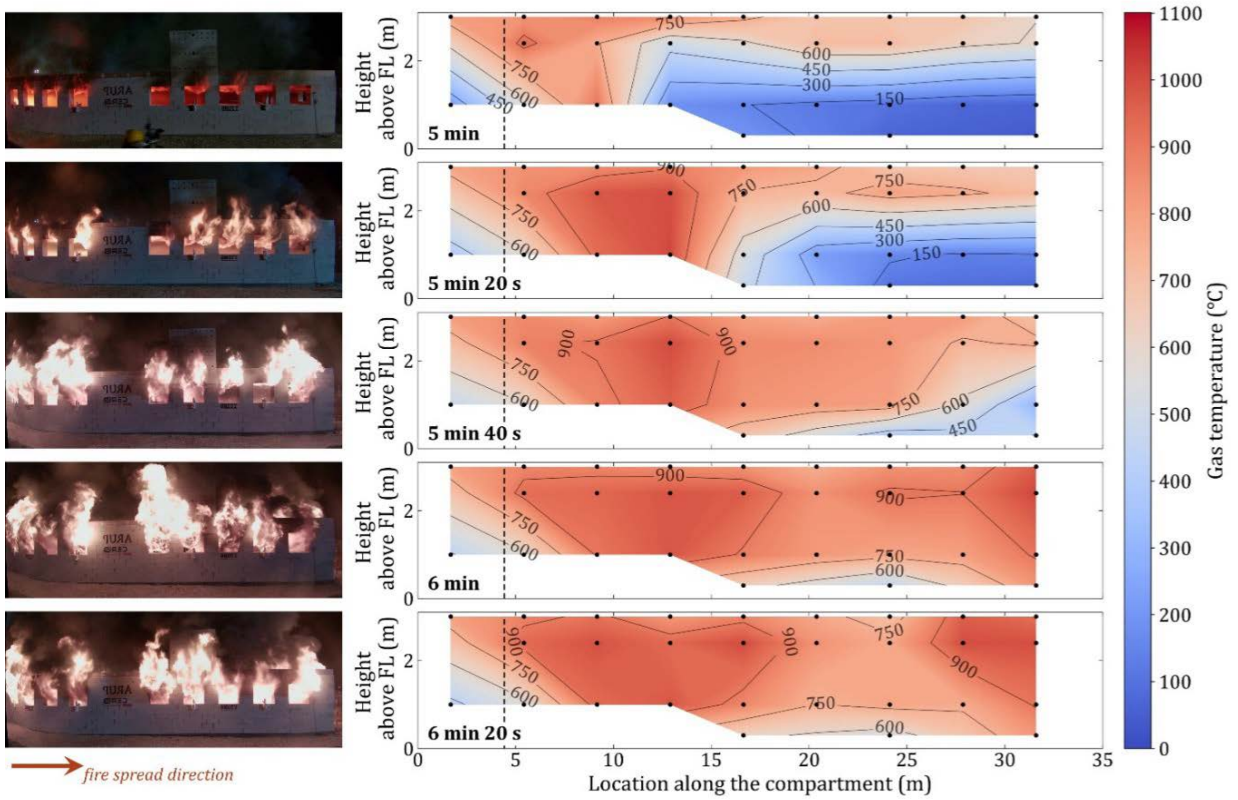


Figure 70: CodeRed 1 - Temperature Profile from 5 minutes to 6 minutes 20 seconds

A4.3.3 Heat release rate

Based on flame spread behaviour, heat release rates in the three full-developed CodeRed experiments were calculated considering the contribution of the wood crib, timber ceiling, and columns. As depicted in Figure 71, the total peak heat release rate of CodeRed #01 was in the order of magnitude of 121 MW, approximately double the heat release rate of an equivalent concrete compartment fire (x-ONE, 70MW), and compared to the growth rate of standard t^2 fires, experienced a greater initial increase in HRR than an "ultra-fast" fire growth rate.

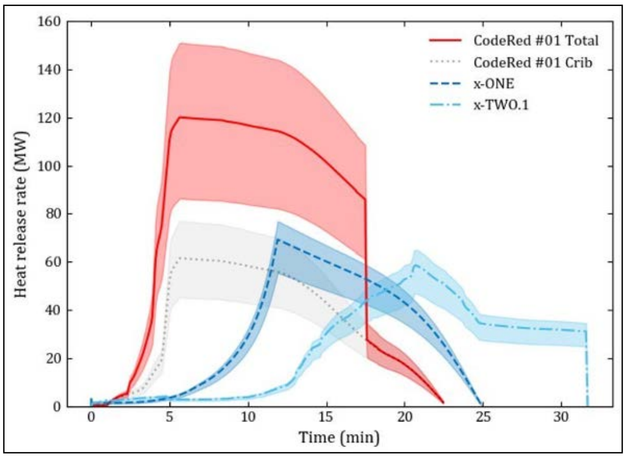


Figure 71: Comparison of heat release rate over time for the CodeRed #01 experiment and equivalent concrete compartment experiments (x-ONE and x-TWO.1).

CodeRed #02 experienced a peak heat release rate of 99MW, 21MW less than CodeRed #01, attributed to the longer duration of burning of the crib and ceiling in CodeRed #02.

The peak heat release rate in CodeRed #04 compared to CodeRed #01 was 17% less, attributed to the reduction in flaming timber surface area contributing to the fire. Furthermore, due to the delay in ceiling ignition and onset of rapid flame spread along the crib, the peak heat release rate was reached approximately 25 minutes later than in CodeRed #01.

A4.3.4 Timber element behaviour

Charring behaviour – ceiling

Peak temperatures in-depth in the CodeRed #01 exposed CLT were observed 36 minutes after ignition at 20mm, several minutes after the end of flaming in the crib and ceiling. This can be attributed to a combination of thermal lag of heat passing through the CLT thickness and additional heat produced by smouldering during the decay phase of the fire. Transient heating in timber members needs to be addressed as the peak temperature in a timber member can occur well after the fire has reached its peak. With similar observations of delayed peak temperatures in CodeRed #02 and #04, it is evident that the cessation of flaming cannot be used as a reliable point to determine structural capacity for exposed timber members.

In CodeRed #01, the charring depth of the ceiling was measured between 18-32mm, with lower char depths observed closer to the ignition line where there was a comparatively shorter duration of exposure to flames. In CodeRed #02, the reduction in ventilation increased the average char depth by 11% compared to CodeRed #01 (28mm), attributed to the 15.6% increase in total burning duration. In CodeRed #04, the encapsulation was effective at preventing charring of the protected region of CLT ceiling. However, the region of unprotected ceiling exhibited similar char depths to CodeRed #01, suggesting that the addition of encapsulation did not reduce the overall fire severity near the ceiling.

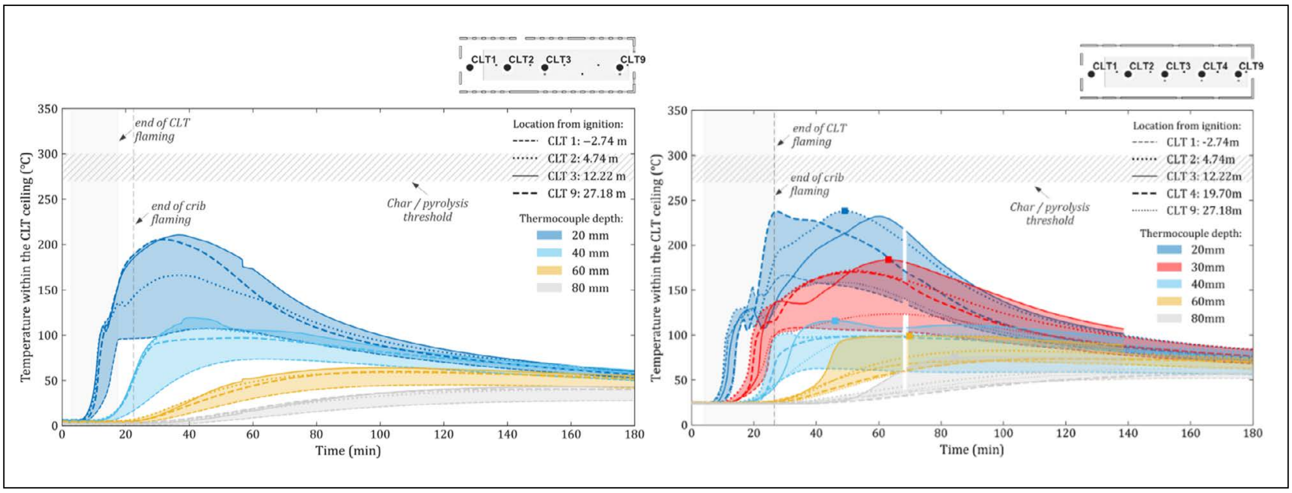


Figure 72: In-depth thermocouple temperatures after ignition in CodeRed #01 (left) and #02 (right).

Charring behaviour - columns

Thermal lag was also observed through the thickness of the Glulam columns in CodeRed #01 (Barber et al., 2023). Peak temperatures of 238-304ºC were reached 30mm in-depth in one column at 42-73 minutes after ignition, significantly after the end of flaming, see examples of this in Figure 72.

Char depths in the columns of CodeRed #04 (18.7 and 24.6mm) were significantly less than in CodeRed #01, which is attributed to the comparatively lower thermal exposure of the timber elements.

A4.3.5 Post-flaming smouldering behaviour

Directly following the end of flames along the timber ceiling and wood crib in CodeRed #01, #02, and #04, the entire exposed area of timber ceiling, now charred, continued to smoulder for approximately 40-45 minutes. Following this, 19 localised regions of smouldering were observed over the three experiments (Mitchell et al., 2023).

Hotspots were identifiable visually by glowing and the emission of smoke, although not in all cases, particularly for concealed (e.g. by encapsulation) or in-depth smouldering. Infrared imaging was significantly more effective at identifying hotspots, as they were indicated by regions of high IR intensity.

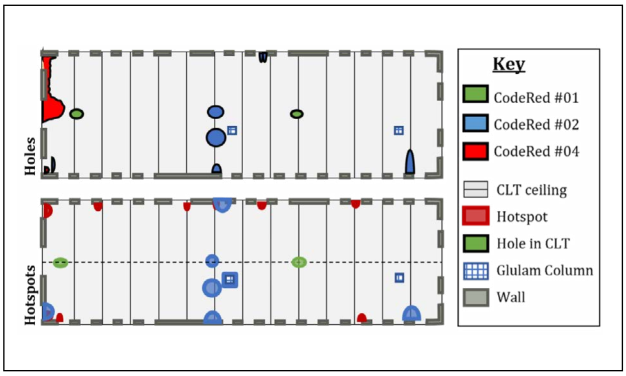


Figure 73: Location of smouldering hotspots and holes in the CLT ceiling over the three CodeRed experiments.

As shown in Figure 73, localised regions of smouldering in the ceiling were primarily observed at timber interfaces, including connection lines between individual CLT slabs, the location where ceiling slabs were supported by the masonry wall, and directly above where slabs were supported by the mid-span insulated concrete beam. Nine of the smouldering hotspots were observed to spread through the full thickness of the mass timber ceiling, forming holes through the ceiling slabs in several locations.

Transition to flaming was observed at several hotspots, in many cases due to the formation of a penetration in a mass timber element, as shown in Figure 74.

The lower portion of exposed columns are vulnerable in the decay phase of a fire, due to the smouldering that occurs in the combusted fuel at the floor. This was evidenced in CodeRed #02 where smouldering of a glulam column base caused the collapse of the column.

In summary, smouldering is a hazard that still needs quantification and appropriate design methods to mitigate its likelihood and severity.

Figure 74: Transition to flaming observed at a smouldering hole 37.5 h after the end of flames in CodeRed #01

A4.3.6 External flaming behaviour

The CodeRed experiments found that both ventilation and encapsulation of timber had significant impact on the duration and height of external flaming. External flaming in CodeRed #01 was initially observed at the ignition-end of the compartment at 3.3 minutes, shortly after ignition of the CLT ceiling. External flaming progressed along the length of the compartment, indicating it was linked to the internal spread of flames along the crib and ceiling, as indicated for an opening at the midpoint of the compartment in Figure 76. Extensive flaming was observed from all openings by 6 minutes, before decreasing in height from 15 minutes.

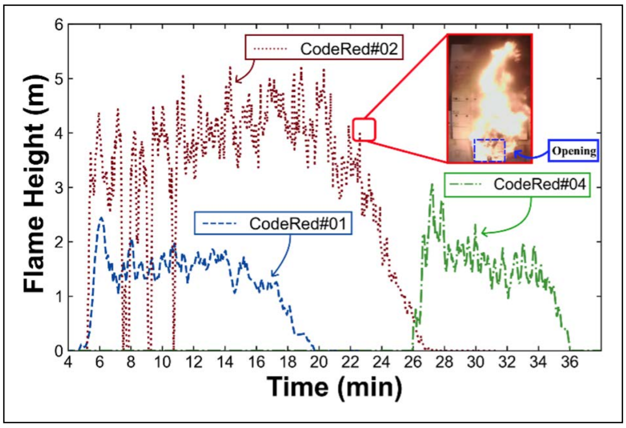


Figure 75: External flaming height over time for the three CodeRed experiments where external flaming was observed. (Amin, 2024)

Due to the reduced ventilation, CodeRed #02 observed peak external flaming heights of 3-3.5m, which were significantly taller than the 2.5-3m external flames in CodeRed #01. Comparatively, in CodeRed #04 encapsulation was found to reduce external flaming significantly in the ignition-end compartment openings (0.5m) and increase the time to the onset of external flaming at openings in the rest of the compartment (e.g., 22 min for the opening depicted in Figure 75).

External flaming is significantly influenced by the presence of exposed timber; therefore:

1. Fire spread occurring for two floors above the fire floor needs to be considered and addressed.
2. Fire spread to neighbouring properties also needs to take into account the external flaming.

Further details on the implications of timber on external flaming behaviour are discussed further in A6.

Figure 76: External flaming from various openings during the CodeRed #01 experiment.

Appendix 5.

Influence of compartment size and ventilation openings on fire involving mass timber construction

A5.1 Introduction

This section reviews the impact of compartment size and ventilation conditions on the overall fire behaviour of a compartment with exposed mass timber elements.

A5.2 Implications of large compartment fires for timber

In larger spaces, fires have been observed to be of limited size that travel over the fuel bed rather than engulf the entire room at once as is the case in smaller compartments (Stern-Gottfried et al., 2010). The travelling behaviour can result in longer duration fires.

Under-ventilated fire involving the whole space can also result in longer duration fires, as can smouldering fires which transition to secondary ignitions.

The above behaviours can result in longer thermal exposure for timber elements, potentially leading to more severe charring and structural implications. The resultant thermal exposure for structural elements is typically characterised by a period of preheating at relatively low temperatures (100-300°C), a period of peak heating (900~1200°C) and a post-peak low temperature exposure (100-300°C).

Performance of structural elements in fire is generally defined by the residual load-carrying capacity of the element, also considering the degradation of material properties (e.g., strength and stiffness) in the member. The level of degradation is characterised by the temperature profile within the element, with higher temperatures leading to increased degradation. Steel and concrete structures are also sensitive to the effects of induced thermal strains; this behaviour has been well researched, particularly in steel structures and to some extent in concrete structures. Previous research has indicated that thermal strains do not impact the overall structural performance of timber structures (Buchanan, Östman & Frangi, 2014).

Although fire duration does affect the temperature profile attained within steel and concrete sections, the peak fire temperature is typically the governing characteristic. As such, longer duration fires do not usually present uniquely onerous heating conditions. However, for timber elements, where the depth of charring and the depth of the heat impacted zone, and by extension the residual structural capacity, is determined by the duration of burning, longer duration fires and pre-heating of timber are critical factors in the structural performance of a timber element. Numerical models of timber slabs charring in longer duration fires, specifically travelling fires (Richter et al., 2021), have shown that smaller fires that travel over a longer duration can lead to longer preheating times, therefore resulting in potentially greater charring depths than larger, shorter fires. Longer fires can also result in a deeper heat impacted zone behind the char.

As shown in the CodeRed experiments, fire behaviour in large compartments is initially driven by flame spread, particularly in compartments with large exposed CLT ceilings where flames can spread beyond the initial fire source and radiate heat to unburnt fuel, accelerating flame spread.

Of importance for structural design is to determine the depth at which thermal degradation of the timber has stopped. Thermal degradation in timber includes the depth of char and the zone behind the char that has been impacted by the transient heating. The charring and transient heating will continue to occur after the flames have ceased on the timber surfaces.

A5.3 Fire experiment data – fire dynamics implications

Based on the above presentation of fire experiments, Table 21 provides a summary of the key compartment characteristics, including the opening factor and opening factor inverse, for easy comparison.

For each of the fire experiments listed in Table 21, the peak temperature is plotted against the opening factor in Figure 77. They are overlaid on a plot produced by Thomas and Heselden, 1972 (reproduced in Drysdale, Figure 10.6 (Drysdale, 2011)) which compared the maximum compartment temperature of a range of different model compartments with differing fuel characteristics, with the opening factor of those model compartments. It shows a trend split into two regimes, fuel control and ventilation control.

Based on the currently available CLT compartment fire experiment data, the peak compartment temperatures depicted in Figure 77 do not follow the trend of the Thomas and Heselden curve for traditional compartment behaviour and are in most instances higher in the CLT fire experiments than traditional compartment fire experiments with non-combustible construction. Peak temperatures were observed between 980 – 1290°C, and showed significant variation irrespective of inverse opening factor, likely also related to the movable fuel load characteristics, amount of exposed mass timber, and thermal resistance of compartment surfaces. Thomas and Heselden also identified that compartments with boundaries comprising higher thermal resistivity materials typically exhibit greater peak fire temperatures due to the reduction of heat lost via compartment boundaries.

Note that Figure 77 only shows peak temperatures. It does not describe the temperature-time progression in the compartments. For timber compartments, this may include sustained flashover or a second flashover. Furthermore, this plot does not include the spatial distribution of temperatures that will occur in a timber compartment, which can often vary depending on height, and proximity to openings, and flaming timber surfaces and fuel loads (particularly in large open-plan compartments where a near and far temperature field can develop). Temperatures in various experiments, including the CodeRed experiments, are shown to vary between 200-1200°C depending on the location of temperature measurement, including height in the compartment, and distance to the fuel load or flaming timber surfaces.

It is not known how the results for timber construction would vary from non-combustible construction in larger compartments or compartments with opening factors outside the range checked to date.

Table 21: Summary of medium scale fire experiments involving mass timber construction

Fire experiments by	Number of surfaces exposed			Compartment characteristics				
Organisation	Full encapsulation	Single surface exposed	Multiple surfaces exposed	Comp. size [m]	Plan area [m^2]	Total internal surface area [m^2]	Opening factor [$m^{-1/2}$]	Opening factor inverse [$m^{1/2}$]
ETH	1			3.34 x 3.34 x 2.95	11.2	50.1	25.0	0.04
Carleton University	3	1	4	4.5 x 3.5 x 2.5	15.8	53.6	17.70	0.056
NRC (2014a)	1			6.3 x 8.3 x 2.4	52.3	117.9	21.4	0.047
NRC (2014b)	1			4.6 x 5.2 x 3.0	23.9	78.2	13	0.077
NTUA	1			2.22 x 2.22 x 2.11	4.93	23.2	66.7	0.015
SP			1	2.3 x 5.75 x 2.75	13.2	53.8	14.3	0.07
University of Edinburgh-Arup			5	2.72 x 2.72 x 2.72	7.4	35.7	20.50	0.049
FPRF (NRC Canada + SP Sweden)	2	3	1	9.1 x 4.6 x 2.7	41.9	108.6	10.67	0.094
						112.2	22.05	0.045
NRC (2018)	2	1	2	4.53 x 2.44 x 2.78	11.1	71.7	33.3	0.03
USFS-ICC	1	2		9.14 x 9.14 x 2.74	83.5	165.9	5.94	0.168
Epernon Fire Test Programme		3		6 x 4 x 2.52	24	64.4 to 72.2	4.6 to 23.2	0.043 to 0.217
RISE		1	4	7 x 6.85 x 2.73	47.95	92.4-115.6	2 to 10.8	0.5 to 0.09
TIMpuls	1	2	2	4.5 x 4.5 x 2.4	20.25	58.2	7.4	0.135
				9 x 4.5 x 2.4	40.5	96.1	7.0	0.143
CodeRed (Arup + CERIB + Imperial Hazelab)		3		34.27 x 10.27 x 3.1	352	925-956	14.1-25.6	0.04-0.07
STA	1	2		3.75 x 7.6 x 2.4	28.5	67.7	3.15	0.32
FRIC		1	1	18.8 x 5.0 x 2.52	94	308.2	5.56	0.18
NRC (2023)	1	1	1	3.2 x 7.0 x 2.2	22.4	103	14.3	0.07
			1	7.1 x 7.5 x 3.0	53.3	190	9.1	0.11
			1	204 m^2 x 4.3 m	204	613	8.3	0.12

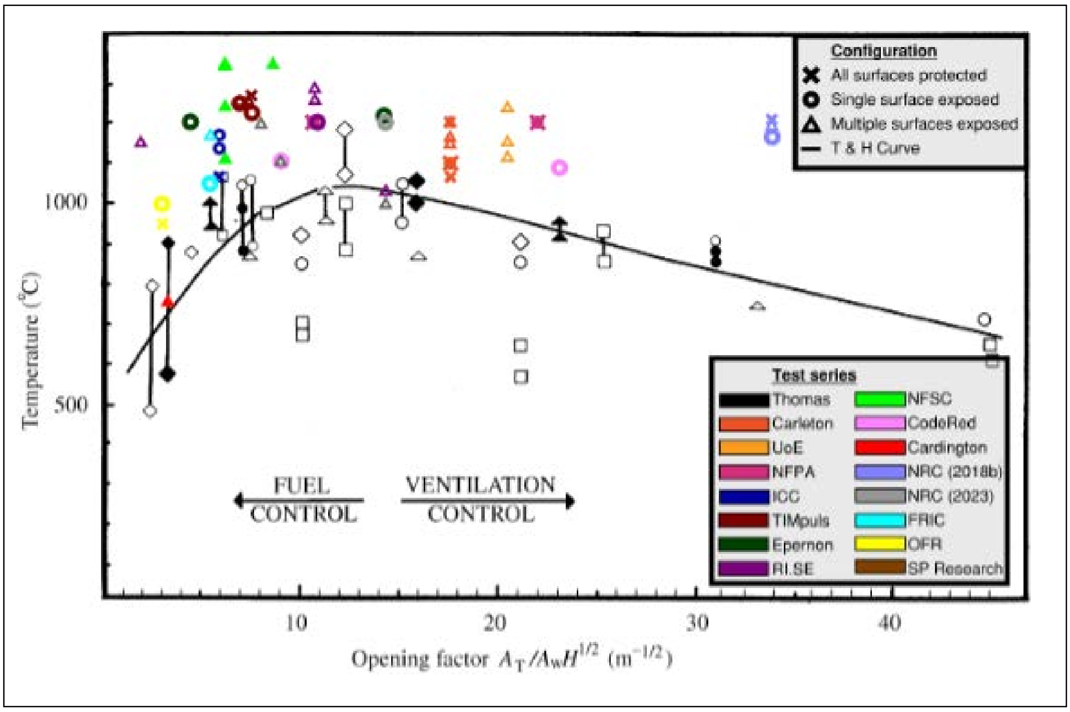


Figure 77: Overlay of results from full-scale fire experiments (see Table 16) involving mass timber construction on a comparison of maximum compartment temperature with opening factor by Thomas and Heselden, 1972. Non-combustible large compartment examples also included (NFSC and Cardington – Lennon, 2003 ; BRE, 1997).

Appendix 6.

Influence of exposed mass timber on external fire spread hazards

A6.1 Introduction

This section reviews the impact of exposed mass timber inside a compartment on external fire spread and additional considerations needed when assessing compartments with exposed mass timber.

A6.2 Implications of large compartment fires for timber

Compartments with exposed mass timber have been observed to have increased compartment temperatures and total heat release rate. Further to this, the under-ventilated behaviour exhibited by many timber building fires will tend to produce more severe external flaming from compartment openings (Sjöström et al., 2023).

The CodeRed experiments, as depicted in Figure 76, found that external flaming height, duration, and HRR were impacted significantly by ventilation and area of exposed timber (detailed further in A.4.3.6). Therefore, it is important to understand and quantify the implications of exposed mass timber surfaces on the height and temperature of external flaming.

The increase in compartment temperature is not reflected in the methods currently used for assessing external fire spread. When assessing external fire spread there is typically two performance objectives:

1. Prevent the ignition of an opposing building for a prescribed period of time in line with local codes and standards.
2. Prevent the ignition of the external wall of a nearby building for a prescribed period of time in line with local codes and standards.

There are a range of tools available to demonstrate the performance objectives are achieved by the design. These typically fall within the following groups:

– Prescriptive

– Calculation-based methodology

– Demonstrating the performance with testing

The calculation based and test based routes are discussed in more detail in the following sections.

A6.3 Fire spread to a building nearby

Fire spread to buildings nearby are generally mitigated using either a minimum distance in line with national building codes or via a radiation assessment in which the heat flux on the opposing building is calculated and compared to a predefined acceptance criterion.

The performance-based approach relies upon the user to identify the temperature of the compartment as well as input the appropriate geometry. For example, BR 187 (UK guidance document) recommends adopting 830°C for "low fire load" spaces (office, residential) and 1040°C for "high fire load" spaces (industrial, retail) when selecting the emitter temperature.

The original data from non-combustible compartments that these temperatures are based on has been reproduced in Figure 78 along with additional temperature measurements from mass timber compartments. This plot shows a noticeable inclination in the temperature towards higher compartment temperature and 1200°C has been indicated as a further "very high fuel load" bracket.

This indicates that the current "low fire load" and "high fire load" categories are not adequate to accurately represent buildings where structural timber is exposed.

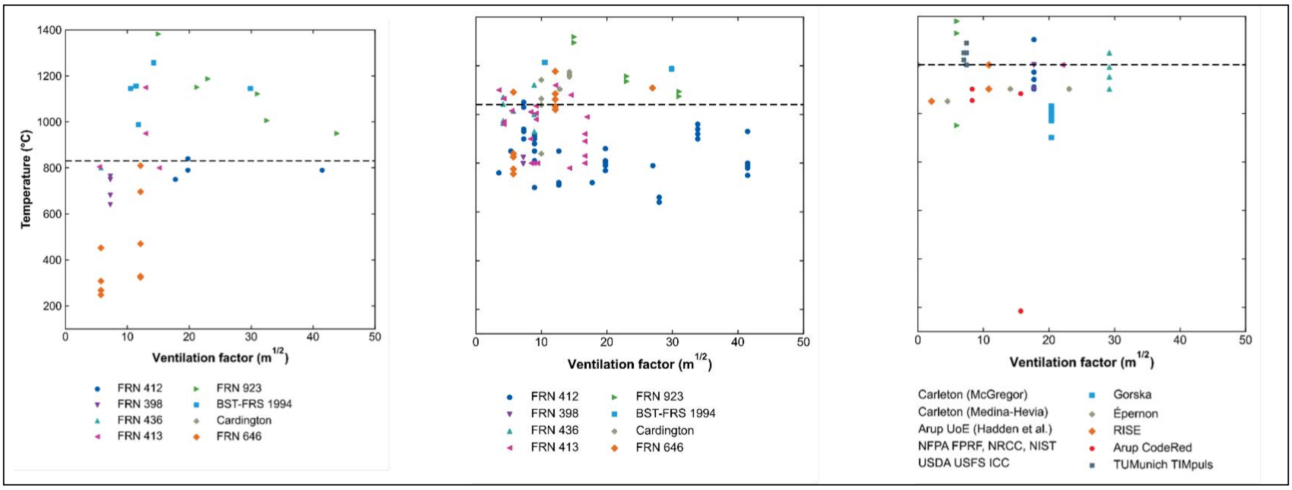


Figure 78: Maximum internal temperature versus ventilation factor for compartment experiments with (left) low fire load, (centre) high fire load, and (right) exposed mass timber structure.

The radiation assessment calculations often permit designers to take benefit of automatic suppression systems that have been designed and installed currently. The evidence gathered to date, both experimentally and from real fire events, suggests that automatic suppression such as sprinklers and water mist systems are effective in suppressing fire within timber buildings.

A6.4 Fire spread over the façade

Controlling the combustibility of the façade materials or demonstrating the performance using large-scale testing of façade systems are two primary routes to compliance for limiting external fire spread on the building of fire origin where combustible materials (such as insulation or cladding) form part of the system.

A6.5.3 Façade test severity

To understand whether the existing ‘standard’ test fires are severe enough to represent the external flaming observed in large scale experiments with exposed timber, the external temperature data from CodeRed and other notable mass timber experiments with external instrumentation has been compared to available data from large-scale industry ‘standard’ façade fire tests. Namely:

- The BS 8414 test.
- The NFPA 285 test.
- The proposed large-scale harmonised European (EU) test, which is broadly based on the BS 8414 test (Sjöström et al., 2021).

These tests were chosen as they are widely applicable, and data was available from tests which had either no façade system installed (Thomas Bell-Wright, 2019; Efectis, 2020, Sjöström et al., 2021) or a limited combustibility façade installation only (BRE Global Ltd, 2017), such that the façade system itself did not contribute to the temperature data.

Figure 79 plots the 'standard' façade fire test data on top of maximum temperatures recorded at different heights outside the openings of a range of small- to large-scale mass timber compartment fire experiments.

– The proposed EU test represents a relatively accurate upper bound of the external temperature data recorded during the mass timber compartment fire experiments. The only minor inaccuracy is at around 0.5 m above the top of the opening, which may be due to the thermocouple being placed outside the flaming region (e.g. if the flame did not adhere to the façade).

– The BS 8414 test performs similarly, however has slightly lower temperatures than the proposed EU test. Some timber compartment fire external flame temperatures slightly exceed the BS 8414 test temperatures, by approximately 50-100°C.

– The NFPA 285 test, on the other hand, exposes the façade to much lower temperatures than those seen during timber compartment fire experiments. The temperatures recorded during calibration of the NFPA 285 test are lower than all external temperatures recorded during the mass timber compartment experiments chosen for this analysis.

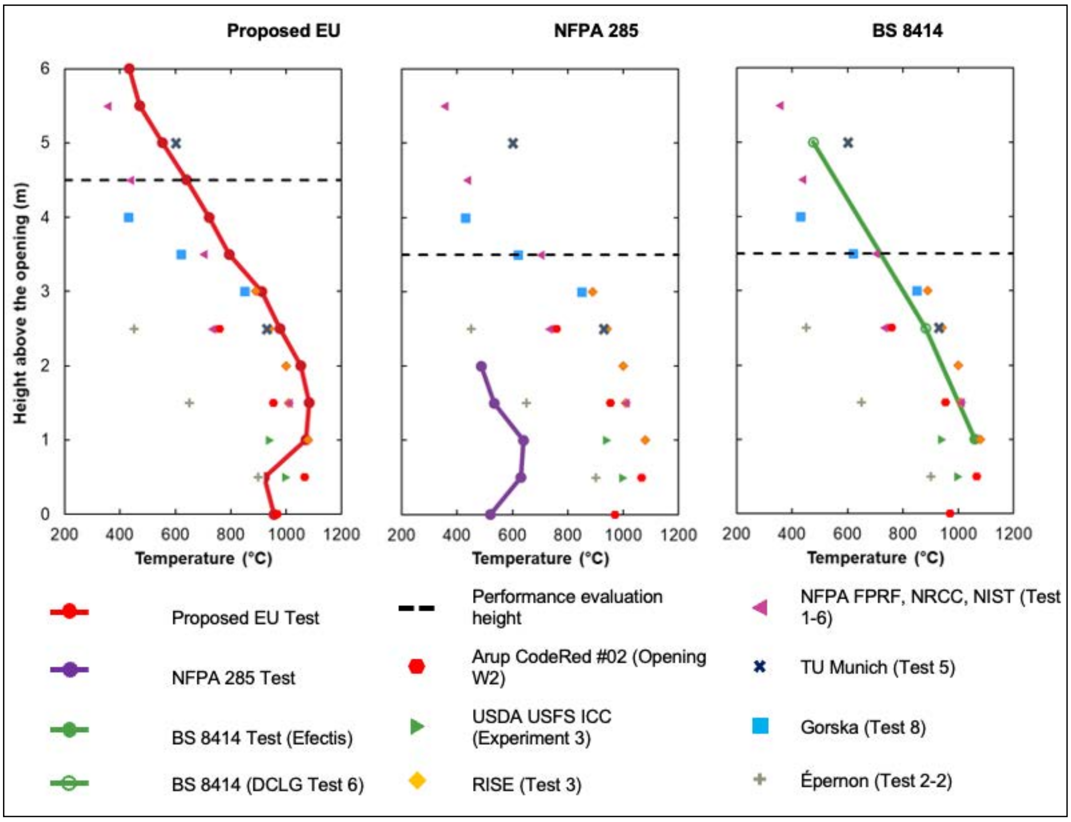


Figure 79: Temperatures recorded outside timber compartment fire experiments compared with those experienced by the façade during 'standard' large-scale tests.

A6.5.4 Study of CLT external walls to NFPA 285

Mass timber has the potential to be used for both walls, floors and where permitted by local codes as exterior wall elements. As part of the International Building Codes (IBC), CLT is an acceptable material for the external walls if the wall assembly is protected with a fire rated gypsum board. For buildings above 12.2m the wall assembly needs to be tested to NFPA 285.

A study conducted by Timberlab and Arup demonstrated that CLT based exterior walls can pass NFPA 285 when sufficiently encapsulated, as depicted in Figure 80. Further information available in Barber and Blomgren, 2023.

Figure 80: Timber wall subjected to an NFPA 285 test. Left to right: exposed; encapsulated with mineral wool and gypsum board; during fire test; after fire test (Barber and Blomgren, 2023).

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