World Conference on
Timber Engineering
Oslo 2023

EXPLICIT FIRE SAFETY FOR MODERN MASS TIMBER STRUCTURES – FROM THEORY TO PRACTICE

Laura Schmidt[1,2], Ryan Hilditch[1], Adam Ervine[1], Joshua Madden[1]

ABSTRACT: A holistic methodology for explicit fire safety strategies for buildings with mass timber structures has been developed based on theoretical frameworks outlined in the literature and the current state of published research on the fire behaviour and safety of mass timber structures. This paper presents the four main pillars of this methodology: tenability for occupant evacuation; heating of the mass timber structure and loss of loadbearing capacity; external flaming; and assessment of the potential for self-extinction of the mass timber structure after burnout of the movable fuel load. The application of the methodology to three case study buildings showed the need for interdisciplinary collaboration throughout the design and planning of mass timber buildings. Engineering and design decisions including structural design options, the extent of exposure of the timber, façade type and construction and general building layout influence the resultant level of fire safety to an even greater extent for buildings utilising structural mass timber elements than for buildings with non-combustible structures. All practitioners collaborating on design projects with mass timber structural elements require a contemporary understanding of the persisting limitations around timber fire safety strategies and research as anyone whose work affects or limits the fire safety measures on such a project will carry a certain ethical or legal responsibility for the outcomes and consequences of a fire.

KEYWORDS: Mass timber structures, exposed engineered timber, fire safety strategy, holistic fire engineering

1 INTRODUCTION

The construction industry is faced with increasing pressure from different stakeholders to integrate mass timber structures into modern designs. Specifically, fire engineers are expected to support these designs in their many forms. The main hazard of mass timber structures is the potential for the structure itself to contribute to the fuel load in a fire, potentially affecting the fire severity and duration. Exposure to fire and heat will also result in reduced structural capacity of structural mass timber elements. The consequence associated with loss of structural capacity is a local or global structural failure, leading not least to breach of compartmentation, potentially endangering occupants by not providing sufficient time to safely evacuate the building and fire brigade personnel by not providing sound structural conditions for search and rescue operations and intervention.

Fire safety strategies must consider the inherently different fire performance of combustible structures: from the ignition of the timber structure, fuel contribution, and altered fire dynamics to self-extinction. However, traditional frameworks and calculation methods currently available for fire and structural engineering have been originally developed for non-combustible structural materials.

This paper presents a theoretical methodology developed for fire engineering practice. It will discuss the shortcomings and knowledge gaps hindering the application of the developed methodology and report further challenges encountered in the practical realisation of real-life timber building designs.

Fire safety engineers must carefully assess which tools originally developed for non-combustible structures, like reinforced concrete or steel structures, remain applicable and where new frameworks and methodologies are required when materials and geometries change. Historically, most research has been focused on small compartments in the order of 10 m2 [1]. Consequently, most existing frameworks for assessing fire safety have been developed for small compartments. Research into the fire dynamics governing fire evolution in large, open-plan compartments has only begun to receive focus in the last few decades [2]. Until very recently [3], this work again assumed the use of non-combustible structures.

The characteristics of the local temperature profiles and fire dynamics become more complex in fires that involve combustible structures [4]. This complexity is especially due to the in-depth heating affecting both the loss of loadbearing capacity and production of flammable pyrolysis gases for combustible structures: The energy released by the combustion of the movable fuel load causes heat transfer into the timber structure. At elevated temperatures, pyrolysis of the timber structure results in combustible gases adding additional fuel to the combustion reaction. A char layer may form on the timber surface. The production and combustion of combustible gases contributed by the structure itself affect the local and global energy balance, which, in turn, has an impact on the pyrolysis reaction within the timber. In summary, the burning of the movable fuel load and the thermomechanical degradation and burning of the combustible structural elements are coupled [5].

[1]WSP Australia Pty Limited, Australia
[2] WSP UK Limited, United Kingdom,
laura.schmidt@wsp.com

https://doi.org/10.52202/069179-0232

The complexity of assessing combustible timber elements' degradation and fuel contribution is further increased since the degradation is thermomechanical, i.e. it depends on the mechanical and thermal loading. Phenomena like char fall-off have the potential to further weaken the structure [6] [7].

The possible impact of the burning of the timber structure itself on the fire growth is presented in Figure 1, in direct comparison with the fire development expected in a compartment with a non-combustible structure. The fire could grow more rapidly following the onset of pyrolysis and ignition of mass timber elements as they contribute additional fuel to the fire. The additional fuel may lead to higher heat release rates inside the compartment of origin, causing a faster transition to flashover, i.e. a fire involving all available fuel. Moreover, external flaming is expected to become more severe if an increased amount of gaseous fuel burns outside the compartment openings [3].

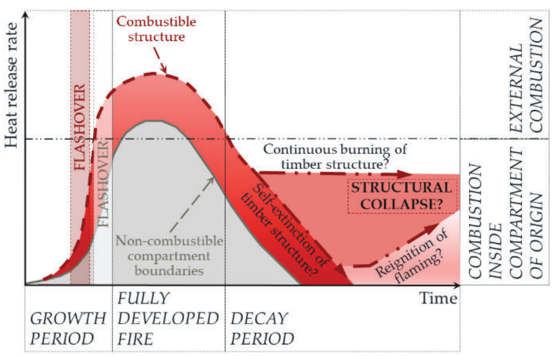

Figure 1: *The expected impact of a combustible structure (dashed red curve) on the fire development following ignition of the structure in comparison to non-combustible compartment boundaries (solid grey curve) in small compartments: increased total heat release and faster transition to flashover, changed heating conditions and thermo-mechanical degradation of the structure, potential for more severe external flaming and the possibilities of continued burning of the structure until collapse or self-extinction (adapted from Drysdale [8] and Hidalgo [9]).*

Fire safety strategies for high-rise buildings generally rely on structural integrity being maintained for longer than the duration of a fire. High-rise buildings require extended evacuation periods, during which occupants must be provided with adequately safe conditions. Moreover, the structural capacity must be sufficient to provide safe conditions for emergency personnel, who may need to enter the building for search-and-rescue operations or internal firefighting. The fire – referring to the combustion of the moveable fuel load (building contents) as well as the combustible structure itself – must eventually cease if sufficient structural capacity is to be retained.

A sound fire engineering methodology must assess if a given design (geometry, ventilation, exposed timber surface area, engineered timber products and other factors) allows for self-extinction to be achieved. In this context, self-extinction refers to the total burnout of the structural fuel. Self-extinction of the mass timber structure shortly after burnout of the movable fuel load is critical to avoid loss of load-bearing capacity until structural collapse [4].

It is important to differentiate between the extinction of flaming combustion and the extinction of smouldering combustion. Smouldering combustion may occur after flaming combustion [10]. While the heat generation of smouldering combustion is generally lower than flaming combustion, smouldering has been seen to continue for hours with prolonged heating leading to structural collapse hours after the extinction of visible flaming combustion [11] [12].

Most existing frameworks, including standard fire resistance tests, were originally developed for non-combustible structural materials, products, and elements. The additional energy generation from exposed combustible members is not accounted for [13]. Standard methods and calculations have been shown to potentially underpredict the loss of structural capacity [11] [14]. Moreover, calculating a Fire Resistance Level (FRL) using the existing frameworks does not allow a holistic assessment of fire safety and in no way supports the prediction of the potential for self-extinction of the combustible structural elements. For timber, some guidance documents describe so-called char depth or zero strength layer calculations to assign FRL to building elements. However, these calculations generally do not consider the fire dynamics and the importance of the incident heat flux. Therefore, existing frameworks are not able to assess the fire safety of mass timber structures to the level of existing knowledge around the complexities and relevance of the critical phenomena.

This paper aims to present the four key areas of fire safety that need to be addressed in the design of any building with combustible structural elements through a holistic fire safety strategy:

1. Influence of the burning of combustible structural elements on fire growth and tenability conditions;
2. Loss of loadbearing capacity of the heated combustible structural elements, considering the impact on the fire intensity and duration;
3. Potential impact on external flaming;
4. Self-extinction of the combustible structure after burnout of the movable fuel load.

The boundary conditions, compartment configuration, ventilation and other design decisions greatly influence the fire behaviour of combustible structures but vary considerably between buildings. Therefore, any fire safety strategy for buildings with mass timber elements needs to be performance-based. However, to the knowledge of the authors, currently, no prescriptive framework exists that addresses all of the above.

A holistic methodology based on concept steps proposed in previous literature [4] has been developed. Through practical application to several real building designs, critical knowledge gaps and limitations around key design variables have been identified and will be discussed in the following. In practice, a collaborative approach between all involved disciplines and stakeholders has proven critical to the development of fire-safe mass timber buildings.

 https://doi.org/10.52202/069179-0232

2 PROPOSED METHODOLOGY

A four-part methodology is proposed to enable a holistic review and assessment of mass timber structures (see Figure 2). This methodology addresses the key elements of any fire safety strategy (fire growth and extinction; evacuation and tenability; heating of structural elements and structural stability; smoke spread and external flaming) with a special focus on the hazards introduced by the use of combustible structural timber.

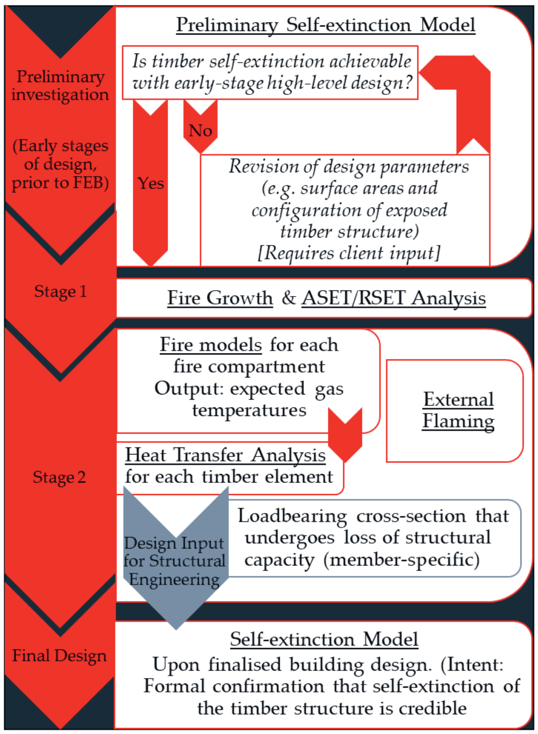

Figure 2: *Proposed fire engineering analysis of mass timber structures in the context of performance-based design.*

The order in which the different assessments are performed is based on the flow of projects encountered in construction practice, involving several stakeholders and interdisciplinary design decisions influencing the fire safety strategy, as well as the outputs of certain frameworks feeding into the calculations performed thereafter. The assessment of self-extinction is performed in the conceptual stage and informs important design decisions. The refined design is then assessed with different design fires regarding evacuation and tenability criteria.

It is not possible to accurately predict the nature of an accidental fire (fire source, spread directions, spread rate, etc.). This is especially true for large, open-plan compartments since the boundary conditions play a significant role in the fire development. Therefore, design fires for the assessments of tenability and heat transfer to the structure (see below) need to be chosen to provide upper and lower bounds, possibly working backwards using a worst-outcome approach.

The evacuation and tenability criteria are mostly identical to those that would be used in a building of the same occupancy and design but with a non-combustible structure. However, for the analysis of a mass timber structure, an additional criterion considering the ignition of the combustible structure needs to be considered. The structure's loss of loadbearing capacity due to heating is then assessed considering the thermal environment inside the compartment during different design fires. The output feeds into the structural design which can then provide sufficient sacrificial depth for the considered design fires on the one hand and optimise the material use on the other hand.

2.1 SELF-EXTINCTION

The potential of a proposed design to achieve self-extinction is the most critical design parameter and hence is suggested as the first step in the early design stages. Structural collapse will occur eventually if extinction of all combustible structural elements is not achieved. Once the continuous heat transfer from self-sustained combustion of the structure has reduced the structural capacity sufficiently to cause local collapse, the loss of compartmentation is a likely consequence, allowing for fire to spread outside the compartment of origin and violating the basic principles of most fire safety strategies. Therefore, the potential for self-extinction must be assessed by any fire safety strategy relying on the integrity of combustible structural elements. The framework for self-extinction of the timber structure is therefore proposed to assess indirectly the potential to retain adequate structural stability after burnout of the movable fuel load, for which self-extinction of the combustible structure is critical.

The term *self-extinction* must refer to the complete cessation of both flaming and smouldering combustion in this context. It is important to note that many publications report *self-extinction* as the cessation of flaming, regardless of smouldering combustion. As such, most of the criteria presented in literature which can be used as a design basis are limited to flaming extinction alone. Only after all combustion and therefore heat generation has stopped, the transfer of additional heat into the structure will cease and the elements can begin to cool down. Therefore, both flaming and smouldering combustion must self-extinguish or be actively extinguished and not continue self-sustained after burnout of the movable fuel load. Continued smouldering can also lead to the reignition of flaming. However, significant knowledge gaps around the smouldering of solid timber persist, especially with regard to its self-extinction.

The period of interest for consideration of timber self-extinction is during the fire decay phase after the flaming combustion of the moveable fuel has ceased within the compartment. Numerous focused studies [5] [15] [16] have observed that self-extinction of exposed timber, i.e. cessation of flaming combustion involving the exposed timber itself, can occur gradually within a compartment if well-ventilated conditions are present after the burnout of the moveable fuel load.

The proposed framework assesses a design fire scenario in which flashover has resulted in the ignition of all exposed mass timber elements which continue to combust and emit heat simultaneously immediately after the movable fuel load has burned out. At this point, it is critical to understand the energy balance across the compartment, and whether the heat losses from each structural timber element are sufficient to result in the self-extinction of the member in this worst-case scenario in terms of ignition of available combustible structural fuel load. Adequate assumptions regarding the boundary conditions are critical as they impact the global energy balance of the compartment.

If the model shows that the incident heat flux into the timber is lower than the critical heat flux for sustained combustion while all surrounding mass timber elements are radiating, this means that these conditions cannot be self-sustained, i.e. permitting eventual self-extinction. If the received heat feedback results in a local positive energy balance sufficient to promote further pyrolysis beyond the char layer, the timber element can continue to undergo and promote combustion and will eventually lose structural integrity.

Computational Fluid Dynamics (CFD) modelling of each fire compartment can determine the theoretical potential heat feedback between burning timber surfaces. Therefore, each fire compartment is modelled with the proposed dimensions and other relevant characteristics. For the assessment, the surfaces of the remaining timber members are considered to be at elevated temperature and continuously undergoing exothermic reactions transferring heat into the compartment. A burning rate per unit area and temperature are assigned to the surface of each combustible structural element as proposed by Sahoo et al. [17]. Radiation modelling in CFD models is very sensitive to input parameters such as the soot yield, radiative fraction, radiation solid angles and path length. The incident heat received by each exposed mass timber surface as feedback from the other radiating timber surfaces must be below the critical incident heat flux for self-sustained burning. Otherwise, design parameters like the orientation and extent of exposed timber members need to be adjusted. The factors affecting the potential for self-extinction of the mass timber structural elements (geometry, configuration and view factors between timber surfaces, choice of materials, compartmentation, ventilation, etc.) must be considered in major design decisions, which are generally made in the early stages of a project. It is therefore advisable to perform a preliminary self-extinction assessment including a sensibility study in the early conceptual design stage to ascertain the credibility of timber self-extinction. The design limitations posed by the need for self-extinction can then inform the project going forward. The final self-extinction assessment can be carried out as the last step of the holistic fire safety assessment of the refined design.

2.2 EVACUATION AND TENABILITY

Life safety is the underpinning principle of any fire safety engineering effort. Safe conditions must be maintained for the required evacuation duration. Evacuation and tenability are often quantitatively assessed through a comparison of the Available Safe Egress Time (ASET) with the Required Safe Egress Time (RSET) with adequate safety factors for a range of primary and secondary fire scenarios.

The onset of untenable conditions for evacuating occupants, i.e., the end of the ASET, can be defined as and assessed via a range of criteria, e.g. sufficiently low temperatures not endangering human life, visibility levels that allow identification and navigation of evacuation routes, and adequate toxicity levels. These criteria can be applied to buildings with and without combustible structural materials.

In buildings with combustible mass timber structures, the ignition of the mass timber elements must be introduced as a further criterion to mark the potential onset of untenable conditions. The time between the initial onset of the burning of the movable fuel load and the ignition of the mass timber structure will vary between different fire scenarios and fire compartments.

In the context of tenability and evacuation, the expected critical impact of the burning of the timber structure is a potential decrease in the time until the onset of flashover conditions and a potential increase in the heat release rate within the compartment. All these effects can negatively impact the ASET.

Once a timber ceiling has ignited, it is expected that fire spread across the ceiling will occur rapidly [3] [12] [18]. The fire spread across combustible ceilings has been experimentally observed to support a rapid transition to flashover conditions [3] [12] [18], the rate of which is also affected by the ceiling profile. During flashover, all combustible materials within the compartment are on fire and more combustible gases are released than can burn within the compartment, which leads to combustion occurring outside the openings of the compartment. Occupant survival within a flashover compartment is considered impossible. Notably, the fire compartments with timber ceilings in our case studies were up to three times larger than the compartments in the subject experimental studies (see Section 4).

2.3 HEATING OF THE STRUCTURE

The temperature evolution within each structural mass timber element affects its loss of loadbearing capacity throughout the fire growth, fully developed fire, and decay phase. The remaining structural capacity needs to adequately support at least the design loads in the fire case which must be assessed in collaboration with the structural engineer. The selection of temperature criteria for the reduction of loadbearing capacity of heated timber members needs to be well documented to provide transparency and be based on relevant literature.

Heat transfer modelling to theoretically determine the in-depth temperature of the mass timber structure requires knowledge of the boundary conditions, including the incident heat flux or surface temperature of the timber element over time, as well as material properties. Expected maximum timber surface temperatures during the fully developed fire could theoretically be obtained from the modelling of a set of fire scenarios. The burning of the movable fuel load and combustible structural elements are coupled, as

https://doi.org/10.52202/069179-0232

explained previously [5]. Hence estimations of the expected burning duration must consider the coupled burning of the movable fuel load and mass timber structure, the compartment geometry, and ventilation.

If fire-protective layers are installed, it must be assessed when critical temperatures are reached within the timber underneath, causing loss of loadbearing capacity and contribution of combustible gases to the global fuel load (pyrolysis). Passive fire protection like protective non-combustible layers (e.g. plasterboard) are sometimes installed to delay the heating in depth of the timber and prevent involvement of the combustible structure in the fire. It is important to recognise the duration of the protective function provided and to consider the possibility of plasterboard failure as observed in large-scale experiments after which the formerly protected timber surfaces experience significant heat transfer [5] [10].

In the context of structural heating, the potential impact of the burning of the timber structure is firstly to increase the heat release and heat release rate and secondly to extend the burning duration by increasing the total available fuel load. Not only the increased total energy release but also the extended duration of heating can increase the in-depth heating of the timber structure, which is expected to result in increased and prolonged thermal degradation. Given the coupling of the combustible structure's thermal degradation and the fire dynamics, increased in-depth heating of the timber results in increased fuel contribution to the fire, which results in a feedback loop between the structure and the ongoing fire. This process can theoretically continue until all combustibles are consumed, unless sufficient char is formed and retained to allow for self-extinction of the timber, or firefighting intervention occurs.

Numerical models of burning timber must consider complex temperature-dependent processes like drying, pyrolysis and char oxidation. A finite difference model that accounts for the change in properties between virgin timber, dried timber and char was presented by Osorio [19] together with a review of existing models. Models like this can be used to estimate the in-depth temperatures in timber using a simplified energy balance accounting for the incident heat flux at the surface by summing the external heat flux and heat losses based on material properties and the thermal environment [7]. Heat transfer modelling to determine the temperature profiles within the timber complement the calculations performed by the structural engineers.

Due to the laminated nature of engineered timber, parts of the timber product can detach from the underlying structure [5] [6] [7]. In a fire, this phenomenon can add fuel, delay or prevent self-extinction and decrease residual structural capacity.

To account for the possible separation of lamella or loss of charred sections, it is proposed to consider the material properties of the proposed timber type and species, and to define failure, i.e. fall-off of lamellae and subsequent exposure of the underlying timber sections in the heat transfer model.

Prediction of debonding in heated engineered timber would require further research on the combined thermal and mechanical loading, and presents a highly complex problem. Publications that investigate the loss of charred sections from burning timber [6] [7] report no direct correlation between temperatures at the adhesive-timber interface and char fall-off. Therefore, it must be assumed that charring as well as char loss may occur.

A sensitivity study could be employed to assess the potential impact of the volume of charred lamella detaching from the exposed mass timber structure on the heat release within the compartment. Additional heat release from smouldering or flaming combustion of the detached char and partly charred sections needs to be considered as additional fuel load after falling to the compartment floor. The impact of the heat release of these materials on the potential for self-extinction of the mass timber structure after burnout of the movable fuel load must also be analysed as heat generation from smouldering combustion of charred timber has been observed to possibly continue for extended durations [12]. This additional heat release may have the potential to increase the incident heat to the exposed combustible structural elements beyond the critical limits for self-extinction.

For structural purposes, it is proposed to fully discard the depth of the cross-section that heats above a critical temperature. The additional required depth of timber has to be added to the cross-sectional depth of any load-bearing timber member as required for structural purposes.

2.4 EXTERNAL FLAMING

The potential for external flame spread to other floors, fire compartments, and neighbouring buildings must be assessed. External flaming radiates heat back at the façade of the building. Sufficiently high incident radiant heat received by other floors above and below the floor of fire origin can result in glazing breakage and ignite combustible materials within adjacent fire compartments, potentially resulting in uncontrolled vertical fire spread throughout the building, as seen in fires like the Grenfell Tower Fire in 2017 [20].

The potential severity of external flaming is expected to initially increase with increasing fuel load. Governed by the ventilation conditions, the combustible gases will partly burn inside and partly outside the fire compartment after partial or full window glazing failure. Increased heat release within the compartment can result in a larger effective height of the flames external to ventilation-controlled compartments. The assessment of external flaming must therefore consider the contribution of fuel provided by the timber structure itself over time, as well as several other factors such as available ventilation, opening orientation, compartment layout and the like.

Some local boundary conditions are especially difficult to predict and account for, yet could have an impact on the external flaming in a real fire. For example, wind conditions or the burning of a column located at the external compartment boundary are qualitatively understood to influence the intensity of the flame protruding but are difficult to quantify based on existing knowledge. Published scientific literature currently

https://doi.org/10.52202/069179-0232

lacks experiments assessing flame extension from uncontrolled fires in very large compartments of 100 m² or more, especially for buildings with mass timber structures [2] [8]. For example, the experimental work that underpins the Eurocode flame extension calculation was based on compartments with an area of less than 100 m². However, many modern designs aim for compartment areas in the order of 1000 m². This introduces further uncertainty into the external flame length calculation for such complex spaces.

When using the Eurocode calculation method to evaluate the impact of increasing the quantity of available fuel, a fuel load density quantity is reached after which increasing the fuel load density further ceases to increase the external flame height. This is understood to be because once a constant/maximum temperature is reached inside the compartment, the production of pyrolysis gases is then considered limited by the surface area of available fuel, and the combustion by the availability of oxygen based on the size of the compartment openings. These complex mechanisms bound the rate of combustion internally and, to some degree, control the impact of the contribution of the timber fuel to the internal combustion. The complex compartment fire dynamics that the combustible timber contributes to are responsible for affecting the resultant heat fluxes within the compartment and, by extension, the pyrolysis of the timber throughout the fire duration. These complex actions contribute to the resultant quantity of unburnt combustible gases escaping the compartment, and upon reaching fresh oxygen, undergoing flaming combustion externally.

3 CASE STUDIES

The methodology presented above was applied theoretically to three buildings with exposed mass timber structures, following the sequence as presented in Figure 2. Detailed design plans were attained and the buildings were assessed in line with Australian national building codes and regulations. Application of the methodology to the theoretical projects emphasised the limitations of existing guidance documents and persisting knowledge gaps around most of the design variables discussed previously.

3.1 DESCRIPTION OF THE BUILDINGS

The design plans utilised for the case study assessment represented three buildings with varying degrees of open-plan compartmentation; two were office buildings with typical open floor plates in the order of 1,000 m^2, one with seven and the other with three storeys, and an education building with large open areas adjacent to a series of smaller classroom configurations (total floor plate also in the order of 1,000 m^2, four storeys).

The designs of the mass timber structures of each building were seen to be generally similar: glulam columns, cross-laminated timber (CLT) beams and floor slabs, non-combustible internal partition walls (typically stud walls finished with plasterboard), and slab-to-slab height in the order of 3.8 m. Each building included storeys interconnected via an open stair or atrium configuration (never more than two storeys at a time). All buildings were provided with fire-isolated stairs and fire sprinklers. Other safety systems were provided in accordance with the prescriptive requirements of the Australian National Construction Code. The undersides of the CLT floor slabs were exposed in most areas (no suspended ceilings). The floors were provided with non-combustible, raised floor systems. Some exposed timber floors were also proposed in isolated locations.

The extent of glazing in the external walls in the case studies differed substantially from the compartments in studies published to date. Each case study building included 50-70 % glazed curtain wall, generally in a slab-to-slab design, whereas the majority of timber structure fire research to date has utilised external walls with a series of smaller windows, normally occupying the upper half of the wall [2] [3] [10] [12].

3.2 FIRE GROWTH & TENABILITY

The Stage 1 model assessed the onset of untenable conditions during occupant evacuation using CFD fire/smoke modelling and an empirical evacuation model to compare the Available Safe Egress Time (ASET) until untenable conditions were reached with the Required Safe Egress Time (RSET) for occupants to safely evacuate.

The fire scenarios modelled the movable fuel load with an initial t-squared fire growth rate based on the subject project and took account of the impact of the involvement of any of the exposed mass timber by conservatively assuming that rapid fire spread across the ceiling would occur should the timber ceiling reach the critical temperature for ignition (taken as 300°C [8]) in any location. This also accounts for the variable ceiling spread rate observed across experimental works.

Research [3] [12] has shown rapid fire spread horizontally under combustible ceilings where fire sprinklers are generally deemed ineffective and vertically on combustible walls. It is understood that flashover conditions occur soon after ignition of the combustible surfaces where significant or sustained pre-heating has taken place prior. Therefore, ignition of the exposed timber was considered as a failure criterion, meaning occupants must evacuate the fire floor before timber ignition.

It is important to note that the fire sprinkler system was considered to have failed on demand for all fire scenarios. This is considered to be reasonable based on our internal review of the available sprinkler statistics. Broadly speaking, it is prudent to assume that one out of ten fires results in an uncontrolled fire scenario, meaning that sprinkler failure must be considered as part of a holistic fire engineering assessment.

The impact of setting timber ignition as 300°C versus a traditional t-squared fire was significant. The available safe egress time is normally assessed with criteria such as the smoke temperature at a given height and the resultant radiant flux to the floor with the capacity to cause injury to occupants, with the time required for smoke layer build-up being the mechanism of interest. By contrast, the exposed timber ceiling, most likely directly above the fire plume, is at risk of igniting in a

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fraction of the time of unacceptable smoke layer build-up. Across our models, this time was in the order of half. However, the time to timber ignition depends on the building layout, structural member configuration and orientation, slab-to-slab height, beam layout and opening location.

3.3 HEAT TRANSFER & CHAR DEPTH

Different design fire scenarios were developed to attain temperature curves near the ceiling that were then used as inputs for the heat transfer model. The aim was to develop temperature curves representative of a fire involving the structural timber in the real space as designed. Different bounding fire growth scenarios were developed, including rapid growth to a high HRR resulting in a shorter burning duration, to assess short hot fires, and slow fire development with extended fully developed and a decay phase. Various opening configurations, building layouts and exposed timber configurations were considered, and could be similarly assessed as part of a collaborative design approach with the architect and structural engineer in real projects.

The finite difference heat transfer model [7] [19] with the estimated heating curves in the subject compartments was then applied to a range of timber members with different lamella layups to estimate the thermal gradients in depth of the CLT or glulam. The model attempted to account for the potential impact of loss of charred section on CLT members by assuming failure at consecutive glue lines, which is understood to be an oversimplification. However, no methodology exists which can account for all relevant coupled causal factors such as mechanical and thermal loads throughout the timber and in particular affecting the bond between lamellae. Thicker outer lamella were generally understood to provide preferable outcomes as the glue lines were seen to receive less heat later. However, failure of heated bonded lamellae and various adhesive types is not well understood (also see Section 4.5) [6].

Uncertainty persists around required input values such as thermal conductivity, specific heat capacity, and heat transfer coefficients that are functions of temperature, species and other factors. Assumptions for these variables were made based on available scientific literature. However, the available data does not support rapid and robust application of this approach to real timber designs.

This theoretical approach assesses the heat transfer for compartment-specific design fire scenarios. The in-depth heating rate depends on a range of variables including the compartment design and ventilation. The incident heat may be less, similarly or significantly more onerous than that from a standard fire curve.

3.4 EXTERNAL FLAME HEIGHT

The fully-developed design fire could amount to a ventilation-controlled or fuel-controlled fire, depending on the available ventilation through compartment openings. In a ventilation-controlled fire (A), the expected impact of adding more fuel gas is to prolong or increase the intensity of the external flaming, i.e. the combustion of unburnt fuel gases that exit the compartment. The addition of the mass timber fuel possibly has little impact upon the HRR achieved within the compartment if all of the available oxygen is already consumed by the moveable fuel combustion. If the burning of the moveable fuel load is not ventilation-limited but fuel-controlled (B), some of the additional mass timber fuel is considered to burn within the compartment, up to the limit permitted by the available ventilation, and increase the heat released within the compartment.

While modelling the range of buildings and various compartments, both ventilation-controlled (A) and fuel-controlled (B) cases were observed. During the case studies, a flame extensions review was undertaken in accordance with BS EN1995-1-2 to assess the impact of the additional fuel load provided by the timber structure on external vertical flaming. A range of fuel load densities was assessed and the fuel provided by the mass timber structure was added. The calculation assessed a scenario in which an uncontrolled fire had occurred (sprinkler failure) and enough glazing broke to sustain a post-flashover fire. The external heat release rate increased by 15-17 % when the timber fuel was added to each fire scenario. The ratio of the maximum HRR attributable to the moveable and timber fuel in each scenario varied, as did the number of available openings. Experiments assessing flame extension from uncontrolled fires in very large compartments are lacking from the scientific literature, especially for the case of a building with a mass timber structure. The experimental work that underpins the Eurocode flame extension calculation studied compartments with an area of less than 100 m^2. Therefore, the case study calculations were run for typical small compartments in the order of 3 x 3 m and also at the limits of applicability of the calculation method (ca. 100 m^2), despite the floor plate of the case study building compartments generally were in the order of 1,000 m^2. The impact of increasing the room size from 9 m^2 to 100 m^2 (i.e. one order of magnitude) was to increase the incident flux by 0.5 kW/m^2 to ca. 16.5 kW/m^2.

Upon review of the range of results, the external flame was evaluated as the radiant flux back to the building at 2.0 m above the opening. In the case studies, the incident radiant flux received by the glazing of the floor two storeys above the fire floor was deemed too low to induce thermal glazing failure. A review of the limited available literature on heat-induced glazing failure determined that laminated glazing is not likely to fail when exposed to an incident flux of up to 25 kW/m^2. The unknowns regarding extrapolation test results with specific designs to real design cases needs to be assessed in future work.

3.5 SELF-EXTINCTION

The assessment involved CFD modelling of fire compartments with dimensions as designed, and varying extent and configuration of exposed mass timber surfaces. The timber surfaces were assigned a burning rate per unit area (heat release rate per unit area) and temperature. The boundary conditions for the

https://doi.org/10.52202/069179-0232

compartment at the point of extinction of the moveable fuel load were defined to assess the scenario of minimum heat losses.

The incident flux received across all exposed timber surfaces calculated by the model was then compared with the critical incident heat flux for self-extinction reported in published research to determine if self-extinction was credible. The critical incident flux for flaming combustion reported in the literature is in the order of 30 to 42 kW/m2 for a series of lab and compartment experiments [15] [21]. However, the critical incident heat flux for self-extinction is a function of the experimental environment and conditions, including the char layer thickness [21]. Consequently, the critical heat flux for self-extinction will vary on a case-by-case basis depending on compartment boundary conditions, such as the available ventilation (quantity and size of openings) or the configuration and orientation of internal surfaces. The unknowns regarding extrapolation of experimental values for a range of compartment sizes and configurations needs to be assessed in future work.

4 DISCUSSION AND LIMITATIONS

The proposed methodology including the finite difference heat transfer model is a fundamental approach to mass timber design for fire safety. However persisting scientific knowledge gaps require to be filled to improve confidence and enable reduced inherent error in this fundamental approach. The key limitation of the proposed methodology relates to data availability and applicability, predominantly in the areas discussed in the following.

4.1 BURNING AND HEAT RELEASE RATES IN OPEN-PLAN COMPARTMENTS

The rate of energy released by the burning movable fuel load changes over time as a function of the thermal environment within the fire compartment. Higher heat feedback to the fuel increases the energy release rate and reduces the fire duration due to energy conservation.

The heat feedback to the fire changes with changing compartment geometries. The assumptions based on ventilation-controlled regimes no longer apply once the compartment becomes sufficiently large and well-ventilated. Spatial and temporal distributions of temperatures and incident heat fluxes on compartment boundaries are determined by the fire spread mode [2]. The heterogenous temperatures throughout a large compartment can lead to longer burning durations of the movable fuel load compared to compartments in which uniform burning of all fuel can be assumed [2]. As a consequence, the duration of thermal exposure to structural members increases.

Both the heat received over time and the burning duration affect the heat transfer into structural elements within the fire compartment. A high HRR over a short duration can be more favourable from a structural perspective than a longer lower HRR.

Different fire scenarios have to be assessed considering the movable fuel load and the burning rates expected for the compartment at hand. However, burning rates for large compartments, especially those with combustible compartment boundaries, form a critical research gap.

4.2 BURNING OF CEILINGS AND WALLS

The fire dynamics in a compartment with combustible boundaries are expected to differ once the compartment boundaries become involved in the fire. In traditional scenarios, all fuel is located on the compartment floor. The impact of burning combustible ceilings and walls on the fire dynamics are currently understudied.

4.3 THERMAL PROPERTIES AND EXTINCTION

The applicability of material properties required as input parameters for fire safety assessments of timber structures is uncertain and has not been sufficiently validated. Therefore, the results which can be obtained with any framework hold high uncertainty. Values determined in bench-scale experiments for a limited number of timber species may not scale up to full-scale applications and likely vary between timber species. The critical heat flux for self-extinction is conditional on the char layer thickness, which may differ substantially between timber species and application scales.

In addition, Sahoo et al. [17] determined best-fit results between a CFD model and an experimental study on small-scale compartments made of Radiata Pine CLT [16]. However, the modelling approach to assess self-extinction by Sahoo et al. [17] was not benchmarked against large-scale experiments. The incident heat flux obtained using fire CFDs are very sensitive to fuel (e.g. radiative fraction) and scale-dependent (e.g. path length) parameters from the radiation solver.

4.4 CONTINUOUS SMOULDERING

Numerous studies [5] [15] [16] have reported gradual self-extinction of flaming of exposed timber after the burnout of the moveable floor fuel load and following cessation of flaming combustion involving the exposed timber within well-ventilated compartments. However, large-scale experiments observed hotspots which continued smouldering for hours or days after flaming combustion was considered to have self-extinguished [12]. This is a fundamental safety problem for the long-term viability of timber building design that cannot be addressed with improved input parameters and calculations. A collective stakeholder approach involving the design team, first responders and other stakeholders must assess the potential consequences of continuous smouldering.

The methodology outlined in Section 2.1 allows qualitative identification of areas likely receiving increased heat feedback or losing insufficient heat critical for total self-extinction. However, the method cannot quantify the phenomenon or predict the consequence of these hotspots potentially undergoing self-sustained smouldering for extended periods of time. Critical heat fluxes and other critical variables (geometry, lamella thickness, air flows, etc.) regarding

https://doi.org/10.52202/069179-0232

the extinction of smouldering combustion of charred solid timber form a critical research gap.

The qualitative consequence of localised hotspots that do not undergo self-extinction can be low but prolonged heat generation, gradually weakening nearby loadbearing elements and eventual re-transition to flaming combustion. Kotsovinos et al. [12] observed the smouldering burn-through of an exposed CLT ceiling over a 40-hour period in a large-scale open-plan compartment after a flaming fire that lasted under 23 minutes. In a real building, this would have resulted in the loss of compartmentation. Kotsovinos et al. observed hotspots primarily at the interface between the CLT ceiling and concrete beams, i.e. where the two surfaces radiated back and forth over a short distance.

The observations of local hot spots suggest that even with conditions that appear generally favourable for self-extinction of exposed mass timber, localised heat generation can continue and spread through the structural timber members. The impacts thereof that need to be considered in structural design in practice is, to date, unknown. Partial evacuation seems unadvisable in buildings with combustible structural elements as delayed structural collapse and compartmentation by smouldering cannot be quantitatively assessed. Furthermore, it emphasises the importance and complexity of fire brigade intervention to ensure the complete extinction of structural timber members. The practical considerations of fire brigade intervention in post-flashover compartments with load-bearing timber are beyond the scope of this paper but must urgently be addressed in an open dialogue between the fire brigade, building authorities, researchers and fire engineers.

4.5 LOSS OF CHARRED CROSS-SECTION

Loss of charred timber section due to fall-off is a complex, currently unpredictable phenomenon that can cause iterative self-enhancing loss of loadbearing cross-section and affect compartment fire dynamics. It can delay or prevent self-extinction and enhance the in-depth heating of the timber structure [7].

The laminated nature of engineered timber products results in a potential for lamellae detaching once the capacity of their bond is exceeded. Temperatures like those expected in compartment fires can negatively affect the bond strength. The loss of charred timber sections through phenomena like delamination or char fall-off exposes the underlying timber and adds additional fuel to the fire. Char fall-off was visually observed to be followed by flaming combustion of the newly exposed, previously protected timber surface in full-scale compartment experiments with mass timber walls, and temperature devices recorded a local temperature increase in local temperatures [22].

A theoretical possibility to account for the loss of load-bearing cross-section to char fall-off is to perform a heat transfer calculation and continuously discount lost cross-section exceeding a critical state. Experimental research has observed char fall-off to occur over a wide range of temperatures as low as 140 ºC [6] and to be a thermomechanical phenomenon, i.e. a function of the local absolute temperature and mechanical loading [7]. Therefore, current knowledge does not support the use of a critical temperature criterion for char fall-off.

4.6 HEAT TRANSFER & COOLING PHASE

Fire curves in real compartment fires do not resemble the standard curve. In fire safety engineering practice, the standard curve is generally assumed to encompass all most reasonably foreseeable fire cases. It is not the scope of this paper to discuss the adequacy of standard furnace testing for non-combustible structural members. However, for designs using combustible structural members, the fundamental difference between furnace tests of combustible versus non-combustible elements becomes problematic and the real timber-involved fire may in fact fall well outside of what was once considered the reasonably foreseeable fire cases, and this occurrence is lost by relying only upon the furnace test to support timber structural member design.

In a standard furnace test, structural members are tested against standard temperature-time curves with gas burners providing heat [13]. Unlike non-combustible members, combustible elements like structural timber members themselves add to the fuel load in a furnace test, leading to reduced heat supply from the gas burners [13]. The timber's energy contribution is effectively deleted by the furnace recalibration procedure.

The peak temperatures in-depth of mass timber elements can be reached later than peak compartment temperatures due to thermal lag. The temperature evolution within a compartment after burnout of the movable fuel load depends on the heat losses from the compartment through compartment boundaries and openings and is influenced by fluid flows and, in the case of mass timber, the additional heat generation from combustible elements and their self-extinction.

4.7 WINDOW GLAZING FAILURE

Currently existing knowledge does not allow prediction of the timing, amount and locations of glazing breakage in compartment fires, especially in open-plan compartments. However, the amount of glass breakage can have critical importance regarding the energy balance in a post-flashover compartment, which can be especially critical for self-extinction of combustible structures. Therefore, the sensitivity of the assessments to varying amounts and configurations of intact and broken glazing must be analysed for the design at hand.

5 CONCLUSIONS

An explicit fire safety strategy for mass timber buildings with different compartment geometries has been developed based on theoretical frameworks proposed in existing literature. The four frameworks address self-extinction, tenability, adequate structural capacity in fire and external flaming. A review presented the applicability of available research as well as the remaining knowledge gaps. This approach highlights the need for research that addresses the fundamental questions including self-extinction, compartment fire dynamics and the material response to fire required for the safe design of modern mass timber structures.

A lot of responsibility lies with fire safety engineers to determine whether the existing knowledge of the profession, the design tools available and their individual knowledge and skills are sufficient to deliver a holistically adequate fire-safe design when faced with the challenge of a project that is proposed to include a mass timber structure. It is critical to clearly communicate limitations and potential consequences related to fire safety in mass timber buildings with all stakeholders as a part of executing due diligence.

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