Structural Fire Modelling Strategies for Exposed Mass Timber Compartments and Experimental Gaps for Model Validation

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(Manuscript Author order: Philion, Chorlton, Gales, Kotsovinos)

John Gales PhD, P.Eng (Principal Investigator, York University)
Ethan Philion (Graduate Student, York University)
Bronwyn Chorlton PhD (Graduate Student, York University)
Panagiotis Kotsovinos PhD (Arup)

Abstract

Exposed mass timber is being increasingly used for tall hybrid structures due to its sustainability features, rapid construction time, and the aesthetic desire to see exposed timber. However, there are currently many knowledge gaps in timber's performance in fire. Current prescriptive methods can be limiting, and designers are therefore required to develop alternative solutions to design tall and/or exposed timber structures. One approach which can be used to better evaluate timber's performance in fire is numerical modelling, which is often used in synergy with some form of fire testing. The authors have reviewed literature primarily published over the past five years to determine the state of the art of modelling timber at elevated temperatures. Following this review, an a priori model of a cross-laminated timber (CLT) ceiling subjected to a localized fire was developed in LS-DYNA to determine what datasets are currently required to better calibrate a thermal model of timber at elevated temperatures. Datasets include the flame spread rate of CLT, the heat flux produced by CLT, charring rates at high heat fluxes, and criteria for the extinction of timber.

Author keywords: Exposed timber; Fire Safety; Numerical modeling; LS-DYNA

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1.0 INTRODUCTION

While timber itself is not a new structural material, mass timber structural systems are being used in increasingly taller and complex building designs (Perkins&Will n.d.). Building with timber has several advantages, such as its biophilia effects (Ikei et al. 2017), environmental benefits (Oliver et al. 2014), as well as architectural appeal. These contemporary designs are often concentrated on either the residential (small compartments) or commercial (large open-plan spaces) sectors. In large open compartments, it has been observed in non-combustible structures that non simultaneous fire propagation across the floorplate is possible which is in disagreement with traditional approaches to fire dynamics for small enclosures (Rackauskaite et al. 2021a). Timber is a combustible material, and the presence of exposed timber will add a fuel source and allow flame spread through the compartment further complicating fire dynamics in exposed timber compartments. Therefore, it is important to have suitable design methods for exposed mass timber compartments.

A prescriptive approach to ensure safety in design is to completely encapsulate all mass timber members. However, often there is a desire in design for the timber to be left exposed. In some cases, the timber can be overdesigned using the Reduced Cross-Section Method. This method accounts for the reduction of the cross-section of a timber member due to charring based on the time exposed to fire. The method assumes that the charred region (plus an additional allowance) will lose all strength while the remaining portion of the cross-section retains its full strength (CSA Group 2014). It should be noted, however, that the reduced cross-section method only accounts for the lower capacity of a timber member after being exposed to a fire. This method does not address elements such as the fire dynamics of having an exposed, combustible surface in a compartment. Therefore, additional criteria, other than only the remaining capacity, should be examined to determine if the timber member should be exposed.

Encapsulation of a timber member with a fire-rated material typically takes the form of a Type X gypsum (CSA Group 2014). Adequate fire testing and correct implementation on-site are necessary to avoid premature failure of the material (Law and Hadden 2020). In the event of encapsulation failure, the combustible structure would become exposed to the fire which can impact the stability of the building. Building designs that have both encapsulated and exposed timber structure in the same compartment would need to consider the impact of the exposed timber on fire dynamics and the fire resistance requirements of both the structure and the encapsulation.

Additionally, current design proposals consider high-rise mass timber buildings. Questions have been posed by researchers and designers that current building and fire codes may not be designed with such structures in their scope (Cowlard et al. 2013). Several of these tall timber buildings are designed to be a hybrid of several structural materials, using each material to its advantage. For example, Brock Commons is an 18-storey timber-concrete hybrid structure. The timber components make up the floor slab and columns, whereas the concrete is used to construct the core of the structure (Think Wood n.d.). Other hybrid designs such as a CLT slab with steel beams are also being used due to the environmental and speed of construction advantages (Hagan 2021).

For the design of buildings which may not fall within the parameters of current prescriptive methods, alternative solutions are required. A common approach to verifying the performance of an alternative solution is to perform a comparative risk-based analysis to a non-combustible building (Ministry of Natural Resources and Forestry 2017). Other approaches include a semi-qualitative method in which either the consequence of an unwanted event or the frequency of these events is quantified. Finally, quantitative approaches also exist. These approaches often require computational tools and can consider both the consequence and frequency of unwanted events and are more robust. If the risk of an alternative solution can be shown to have a risk no greater than a current acceptable solution, then the proposed alternative solution may be considered acceptable (Craft 2018).

A typical approach that, when properly validated, can be used to analyze an alternative solution is numerical modelling and more specifically finite element modelling. Finite element modelling can allow practitioners to analyze proposed alternative solutions for designs that include irregular geometries and unusual boundary conditions. Furthermore, after a model has been validated against experimental data, the model can be used to analyze the effects of minor changes to determine what criteria govern the design. Once the behaviour and governing criteria of the systems and materials are better understood, generalized solutions can be developed for these complex designs. Numerical modelling can also be used to guide the development of an experimental program.

The purpose of this study is 1) to perform an in-depth review of the current state of modelling of the fire performance of mass timber structures and 2) present an a priori finite element model that helps to identify knowledge gaps that are required to be addressed to develop numerical models capable of being used in the design of modern mass timber designs. As engineered timber is being used with newer design constraints, such as leaving it exposed, additional knowledge about the performance and behaviour of timber in these designs is required to ensure safety in the event of a fire. As these applications of timber are new, there have not yet been many research programs to address the performance of timber. While the use of a validated model can be a method of addressing these knowledge gaps, due to the lack of research programs there are not many data sets to validate the model against. Therefore, these knowledge gaps must be addressed through experimental study, at least until models will be able to be validated with confidence. The results of this review will highlight current gaps in the knowledge base which are preventing more accurate models from being validated so that can be extensively used by practitioners as another tool to analyze the performance of an alternative solution when prescriptive routes are not desirable.

2.0 CURRENT METHODOLOGIES OF TIMBER DESIGN

Regarding modelling timber in fire, two knowledge areas need to be understood that are interlinked due to the combustible nature of the timber. The first is compartment fire dynamics and the thermal exposure to the structure. Secondly, the thermal and mechanical response of the structure.

2.1 COMPARTMENT FIRE DYNAMICS

As opposed to other contemporary structural materials, timber is combustible. Therefore, when timber is exposed to a fire, it will contribute fuel to its own burning as well as allow the flames to propagate and overall increase the severity of a fire (Hopkin et al. 2020; Lange et al. 2020; Węgrzyński et al. 2020).

For a conventional compartment fire, there are three main phases the fire can experience, the growth phase, fully developed phase, and decay phase. All fires begin with a growth phase. During this phase, the fire first begins and starts to spread throughout a compartment. If the flames are not extinguished (by means of either suppression or auto-extinction due to lack of sustained burning), the fire may reach flashover. A definition of flashover describes it as being the point when all temperatures within the compartment achieve at least 600 ^oC, or the radiation to the floor of the compartment reaches 15 – 20 kW/m^2 (Karlsson and Quintiere 1999). Regarding the auto-extinction of a fire involving timber, researchers have several opinions on the exact definition. This is because timber will continue to combust, in the form of smouldering, after the end of flaming. Smouldering is a phenomenon that can occur post-burnout of a compartment and is a slow and low-temperature form of flameless combustion that involves surface oxidation of the char layer (Drysdale 2011; Rein 2009). Due to the presence of multiple forms of combustion, some researchers consider auto-extinction to mean when the flames have been extinguished (Bartlett et al. 2016; Emberley et al. 2017), whereas others consider it to be the termination of any combustion process including smouldering (Crielaard et al. 2019). Wiesner et al. (2019) have noted that once in the decay phase of a conventional compartment fire, exposed timber members will continue to deteriorate due to a "… continued propagation of a thermal wave beneath the char layer (Wiesner et al. 2019)." Furthermore, Wiesner et al. (2019) recommend that designs for tall timber buildings should consider the decay phase of fire when sizing members, even though local prescriptive design methods may not explicitly state to do so (Wiesner et al. 2019).

For a typical compartment when flashover is reached, the fire will have moved into the fully developed phase in which the highest temperatures will be met. Afterwards, the fire will enter the decay phase in which the temperatures and energy release rates will decrease (Karlsson and Quintiere 1999). Although this method alongside a standardized time-temperature curve has been commonplace, designers have recently been utilizing newer, time-temperature curves to better capture the behaviour of fires being observed in compartments which the standard time-temperature heating curve was not necessarily intended to represent (Gales et al. 2021).

The use of alternative time-temperature curves acknowledges that the standard curve does not represent real fire. Particularly, the standard time-temperature curve does not account for the lowering temperatures of the decay phase of a fire. This impacts contemporary building designs, which are incorporating large open spaces. It has been observed that in large compartments of steel and concrete structures, a fire behaves differently than what is proposed by conventional flashover fire dynamics and the standard time-temperature curve (Zhang et al. 2013). Rather than an instance where the entirety of the compartment is involved in the fire simultaneously, the fire will grow non-uniformly across the floor plate and/or stories (Rackauskaite et al. 2015). For longer duration fires, if a model uses uniform gas temperatures there could be significant errors in the thermal and structural analysis (Rackauskaite et al. 2015). Figure 1 illustrates an arbitrary comparison of the standard time-temperature curve, calculated parametric curves, and travelling fires. The parametric curves are meant to include the heating and cooling phases of different compartment fires. The travelling fire time-temperature curves are meant to represent a localized fire travelling through a compartment. In this scenario, different locations in a compartment will be heating and cooling at different times during the fire.

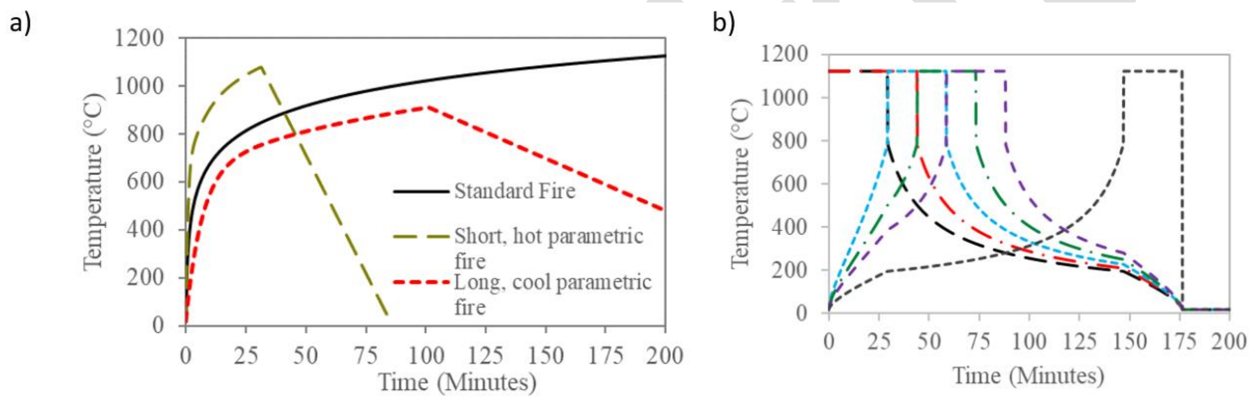


Figure 1:Different design fire examples including a) the standard fire, two-sample parametric fires and b) a sample travelling fire as it progresses through a fixed dimensioned compartment of 20 x 20m. Calculated design heating curves utilized arbitrary inputs for illustrative purposes.

For non-combustible materials such as steel and concrete, simplified methods have been developed to assess the effects of these non-uniform (travelling) fires (Dai et al. 2020; Heidari et al. 2019; Rackauskaite et al. 2015). Through past experimental and computational research, there has been evidence that during a localized fire the peak temperatures in materials can exceed that of a post-flashover fire (Rackauskaite et al. 2017). Furthermore, the localized fires can create non-uniform temperature distributions in which simultaneous heating and cooling is occurring (Zhang et al. 2013).

While research is currently being conducted on non-uniform fires, very little has focused on the use of combustible materials. The use of exposed timber in large compartments creates several complications in a design. As outlined in Rackauskaite et al. (2021) these challenges involve a lack of data for combustible materials including fire sizes, fuel load, heat release rate, near field heat flux, and far field thermal exposure (Rackauskaite et al. 2021b). In the context of this study, near field represents flames directly impinging on the ceiling from an external source, whereas far field represents the cooler temperatures away from the direct impingement.

Convection effects in compartment fires are associated with the transfer of heat by the motion of a fluid, which often arises naturally, or is forced when external factors are present, and is the primary mode of heat transfer in the early stages of a fire. The heat transfer convection heat transfer coefficient is related to the heat flux and the difference in temperature between a solid and the surrounding fluid. Most of the available literature regarding timber fire modelling has considered a convection coefficient of 25 W/m^{2}K, aligning with the standard temperature time curves which are being modelled. Eurocode 1 Part 1-2 recommends a convection heat transfer coefficient of 25-50 W/m^{2}K depending on the temperature time curve considered (European Committee for Standardization 2002).

Additionally, another approach used in fire design is compartmentation, which is to contain a fire in its room of origin. This approach intends to ensure the fire will decay even if not suppressed. This will allow for safe egress, firefighting access, and resilience to the structure. However, due to smouldering induced by the combustible nature of timber, during what would be the traditional decay phase of a compartment fire, the structure may continue to lose strength and resilience.

2.2 PERFORMANCE OF TIMBER IN ELEVATED TEMPERATURES

When designing timber structures, additional considerations are required to account for timber's combustible nature. Currently, there are a limited number of prescriptive methods to design for timber in elevated temperatures. These methods such as calculating a char depth (CSA Group 2014) have the potential to be overly or under-conservative, depending on the impact of timber on fire dynamics. Within the method of calculating a char depth, typically an additional layer referred to as a zero-strength layer is added to the char depth to account for the possible reduction in strength of cross-section which may have been exposed to high temperatures (CSA Group 2014). While the zero-strength layer does acknowledge that timber will lose strength before reaching 300°C and charring, it does not account for the fact during cooling, heat will penetrate further into the cross-section and potentially reduce the strength of the entire cross-section (Gernay 2021). Until further research is performed to deepen the understanding of the performance of timber, current prescriptive design methods may not be adequate to account for these uncertainties for exposed timber structures, particularly large compartments where a long decay period is likely.

One important characteristic of timber is that it retains moisture (Werther et al. 2012). Once temperatures of a timber member reach 100°C the moisture will begin to evaporate which consumes thermal energy and delays the heating of the timber. Difficulties arise to account for this as once the timber member heats up some of the moisture will migrate making it difficult to identify the amount of moisture evaporation occurring in a given moment. One approach is to increase the specific heat of timber within the range of 99°C to 120°C as described in the Eurocode 5 (European Committee for Standardization 2004). The increase in specific heat accounts for a greater amount of energy required to increase the temperature of the timber member. After 120^{o}C it is assumed that all moisture has evaporated and the artificial increase in specific heat is taken away. Alternatively, designers can follow a latent heat/enthalpy approach (Werther et al. 2012). For this, a user-defined moisture content is modelled as latent heat. This allows for a model of the timber element to non-explicitly account for moisture within a member and does not require a peak in specific heat values. Some commercial software can automatically follow this latent heat method while most other packages can have this method be implemented.

Due to the smouldering of timber, additional design considerations are required. Design procedures do not typically account for the performance of timber while it smoulders during the decay phase. When timber burns, it creates its own heat, which in turn has the potential to heat material found deeper in the member. This in turn can cause more material to be included in the combustion process even after flaming combustion has been extinguished. Therefore, timber can continue to combust and potentially fail long after a fire has been considered extinguished in a compartment (Gernay 2021). While smouldering, the effective cross-section will continue to decrease as the material degrades during combustion until it finally has an assumed zero strength when charred. Additionally, during or after a fire, sections of char can fall off or delaminate from the timber member. Without this protective layer, portions of the cross-section which may have previously not been involved in the fire may now combust due to either a continuing fire or smouldering depending on the current state of the compartment fire (Medina 2014; Su et al. 2018). Current prescriptive methods, such as the Reduced Cross-Section Approach from Annex B of the CSA O-86 (CSA Group 2014), do not explicitly consider the decay phase of a fire. It has been shown that timber members can fail post-burnout due to the continued combustion via smouldering (Gernay 2021).

Designers have utilized various fire safety strategies which either reduce the risk of a fire growing to the point where it poses a threat to the structure or prevent timber and other combustible materials from becoming involved in the fire. A common approach is to use a fire-rated Type X gypsum to encapsulate any combustible surface (Law and Hadden 2020). While these methods can prevent the underlying material from becoming involved in a fire, the encapsulation could still fail in a fire if its performance is not adequately tested, or if it is not implemented properly during construction (Chorlton et al. 2021). The drawbacks of encapsulation are its larger environmental footprints due to the use of redundant layers of protection, covering the timber, as well as increasing the time of construction. These drawbacks are opposing the benefits of timber which are its environmental strength, the desire for exposed timber, and its rapid rate of construction. By having a deeper understanding of timber's behaviour and performance in fire, solutions can be developed which allow for complete or partial exposure of the timber surfaces.

3.0 CURRENT STATE OF TIMBER MODELLING

The use of numerical models to assess the performance of timber in fire is a topic of current interest and several studies have been performed to validate this ability of current software packages. In one of the earliest studies, Werther et al. (2012) found that finite element software such as ANSYS, SAFIR, and ABAQUS are capable of modelling timber, however, some accounted for the moisture content of wood more intuitively than others. Where some software could automatically account for moisture as a latent heat, others would have to be manually set to account for moisture in this method. Otherwise, when accounting for moisture with a discontinuity in the specific heat of wood as prescribed by Eurocode 5 it was found that smaller timesteps (greater computational time) were required to avoid divergence (Werther et al. 2012). While accounting for latent heat may produce a less conservative design, it may be more representative of the actual performance of the timber assuming the moisture content used is realistic. From a designer's perspective, accounting for latent heat can lead to more efficient use of the material as there will not be a need to overdesign to account for the unknown heat flowing through the members. From a modeller's viewpoint, accounting for latent heat can reduce discrepancies from the model results to experimental data (i.e., model producing overly conservative results.

The capabilities of modelling the rate of pyrolysis and charring when a timber member is exposed to high temperatures have also been researched. Thi et al. (2017) utilized a user-defined subroutine, UMATHT, in ABAQUS to model heat transfer through structural timber members. The model developed by the researchers was capable of identifying the locations of the char layer, pyrolyzed wood, dried wood, and wood at ambient temperatures (Thi et al. 2017). Geometric configurations included a small-scale laminated veneer lumber (LVL) sample and a large-scale cross-laminated timber (CLT) beam.

Xing et al. (2021) developed a model to determine the char depth and zero strength layer of a CLT panel for both when the char layer remains intact and when there is char fall off under the ISO 834 standard fire (International Organization for Standardization 2014) or natural fire. The natural fire is based on previous experimental data collected by Wang (2019). Xing et al. (2021) found that in most cases the results of the model were in good agreement with charring rates stated from Eurocode 5 (European Committee for Standardization 2004). Overall, the model was considered to adequately capture the performance of the CLT panels.

Quiquero et al. (2020) used ABAQUS to develop a finite element model of post-tensioned timber beams under both ambient and fire conditions. In terms of thermal analysis, the temperature gradients and char depths aligned with the results of other experimental studies. A main challenge encountered in the thermal modelling was to adequately capture the effects of moisture evaporation (Quiquero et al. 2020). It was noted that discrepancies at the end of the trials may be due to the model not accounting for the continued combustion due to smouldering of the timber member. Additional studies into complex timber members have been performed by Kleinhenz et al. (2021). This study investigated temperature-dependent thermal properties of "CLT rib panels". The rib panels are composed of glulam columns (the rib) which are evenly spaced out and sandwiched by two CLT panels. Additionally, work has been performed to develop models capable of analyzing timber-concrete composites (TCC). Bedon et al. (2018) tested the capabilities of analyzing a TCC beam-type slab with in-house finite-element software, COMP-WOOD.

Chen et al. (2020) developed a constitutive model which was able to simulate the temperature gradient, deformation, and failure mode of an LVL beam and a glulam bolted connection which were loaded and subjected to elevated temperatures. This model accounts for the post-peak softening of timber in tension and shear, the plastic flow and hardening of timber in compression, as well as a second hardening in compression. Gernay (2021) developed a numerical model within SAFIR to assess the response of timber columns that experience a "standardized natural fire". This standardized natural fire follows the Eurocode parametric fire model (European Committee for Standardization 2002), where the heating phase is similar to that of the standard ISO 834 curve (International Organization for Standardization 2014).

There have also been researchers who have approached thermal modelling of timber with different methods other than finite element analysis. Examples of such attempts include modelling the chemical kinetics of timber combustion. Recent studies of kinetic modelling can be found in (Richter et al. 2019, 2021; Richter and Rein 2020). In addition to the finite element and chemical kinetic models previously described, studies have been performed using a fundamental mechanics approach such as by Wiesner et al. (2021), in which they analyzed the capacity of one-way CLT panels in standard and natural fires.

Table 1 provides a brief summary of the literature discussed. As illustrated in Table 1, most studies discussed are not applying their models to natural fire exposures. Additionally, it can be seen that there is little done to account for the smouldering of timber within a timber model.

While there have been several research studies to investigate the capabilities of modelling timber, they typically follow conventional compartment fire dynamic theories. With the current demand to construct timber buildings with open plan, well-ventilated spaces, these models and their results may not be robust enough in considering all possible fires. However, at this time further data and research are needed to understand the fire dynamics for these types of compartments. The current lack of experimental data should be noted when comparing the current state of timber modelling when compared to that of other materials. Materials such as concrete and steel have had large experimental studies such as the fire experiments performed at Cardington (Kirby et al. 1999; Rackauskaite et al. 2021a, b), whereas exposed timber construction is only currently receiving attention with regard to large-scale compartment experiments such as those performed recently as part of the CodeRed series of experiments (Kotsovinos et al. 2022 a, b). This lack of experimental data for timber is likely because steel and concrete are being used in complex applications for a very long period of time, allowing researchers to undertake experiments and develop and validate numerical models.

Table 1: Literature Review Summary

Year	Author	Primary Focus	Thermal Exposure	Thermal Model	Mechanical Model	Pyrolysis	Moisture (Specific Heat)	Moisture (Latent Heat)	Smouldering
2012	Werther et al.	Modelling Heat Transfer	Standard Fire	X			X	X	
2017	Thi et al.	Modelling Heat Transfer	Standard Fire	X		X	X		
2018	Bedon et al.	Timber-Concrete Composite	Standard Fire	X	X		X		
2019	Richter et al.	Chemical Kinetic Model of Timber Charing	Constant Heating Rate	X		X			
2020	Richter and Rein	Chemical Kinetic Model of Timber Pyrolysis	Steady Heat Flux	X		X	X		

2020	Quiquero et al.	Numerical Model of Complex Timber Elements	Standard Fire	X	X			X	
2020	Chen et al.	Constitutive Model	Standard Fire	X	X		X		
2021	Gernay	Fire and Burnout Resistance	Standard and Natural Fires with Cooling Phases	X			X		X
2021	Xing et al.	Modelling CLT in natural and standard fires	Standard and Natural Fires	X	X	X			
2021	Kleihenz et al.	Temperature dependant thermal properties	Standard Fires	X		X	X		
2021	Wiesner et al.	Semi-Probabilistic Model of CLT	Standard and Natural Fires		X				X

4.0 DEVELOPMENT OF AN A PRIORI MODEL

From the previous sections, it is clear that there is an absence of models regarding the performance of timber in open-plan, well-ventilated spaces and the lack of experimental data that would help validate such models. In order to determine which data gaps have the greatest impact on a numerical model being able to provide an accurate representation of timber's performance in these spaces, a finite element model was developed, by the authors, with such purpose in mind. The purpose of the model considered herein is to identify datasets that should be collected experimentally that will allow for model calibration. The intent is not to precisely calibrate a thermo-mechanical model, but rather to understand which data sets are needed for calibration and recommend instrumentation for future experimental studies. Future research (not included within the scope of this paper) could then perform the appropriate experiments and develop a calibrated model and simplified analytical methodologies for understanding the fire performance of open plan, well-ventilated timber structures.

4.1 METHODOLOGY OF MODEL

The a priori model was created using LS DYNA, a general-purpose nonlinear finite element program that accommodates changing boundary conditions, large deformations, nonlinear materials, and transient dynamic events (LS-DYNA 2020). The mathematical theory of the heat transfer equations used in the LS-DYNA solver is based on the assumption that the change in internal energy is equal to the change in conduction in and out of the system, plus any heat sources/sinks present (Shapiro 2012). LS DYNA is capable of modelling both the thermal and structural response and therefore this model could be expanded in the future to include structural aspects, after relevant validation against experimental data.

Solidworks was used to create the geometry whereas Altair Hypermesh generated the mesh. Oasys Primer was for the preprocessing which involved defining the boundary conditions, initial conditions, material properties, solution control, and output parameters. Finally, Oasys D3Plot was used for the postprocessing which involved plotting the results of the parameters with respect to time.

4.1.1 MATERIAL PROPERTIES USED FOR MODEL

The CLT panel modelled as a ceiling will be designed under the assumption of future experiments that will be undertaken following the results of this analysis for model validation. Therefore, the moisture content of the CLT is assumed to be 8% which is a typical value if the panel were to be stored in a laboratory setting (Williams 1999). The emissivity of the timber was taken as 0.8 as per Eurocode 5 (European Committee for Standardization 2004), and the coefficient of heat transfer by convection was taken as 25 W/m^{2}K as per Eurocode 1 part 1-2 (European Committee for Standardization 2002). It should be noted herein that the convective heat transfer coefficient of 25 W/m^{2}K is specified for standard temperature time curves (e.g. as defined by EC 1 1-2 (European Committee for Standardization 2002)), and has been widely used for the purposes of modelling timber subject to standard temperature time curves. However, in this case, a nonstandard fire is considered, and there is little available information regarding the most appropriate parameters and inputs for nonstandard fires. The objective of this model, however, was to create a starting point using readily available parameters that can be used to identify data sets needed for collection. The convection coefficient of 25 W/m^{2}K is therefore adequate for this purpose. This value is also in line with previous research that has shown the convection coefficient to be between 10-40 W/m^{2}K for compartment fires (Tanaka and Yamada 1999). Additionally, values for thermal conductivity were taken from Eurocode 5 Annex B (European Committee for Standardization 2004) and are summarized in the paper's supplemental data (Table S1). Within LS DYNA the timber was modelled as thermal material type 10; characterized as being thermally isotropic, with properties that are temperature dependent and can be defined by load curves. These features allow for properties such as specific heat capacity and thermal conductivity to be defined as a function of temperature.

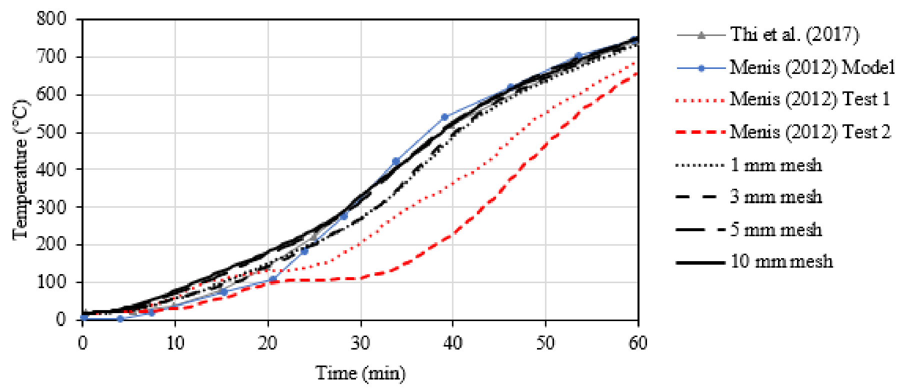
The specific heat capacity was also determined from Eurocode 5 Annex B (European Committee for Standardization 2004), however, the discontinuity between 99^{o}C and 120^{o}C (372 K and 393 K) were omitted. This was done to account for the moisture via a latent heat approach rather than through the discontinuity as described by Werther et al. (2012). Taking the heat of evaporation of water to be 2260 kJ/kg and with the moisture content being 8%, the latent energy of the moisture in the CLT panels can be calculated to be 180 kJ/kg_{wood} following Equation S1 in the paper's supplemental materials.

4.1.2 DETERMINATION OF SUITABLE MESH SIZE

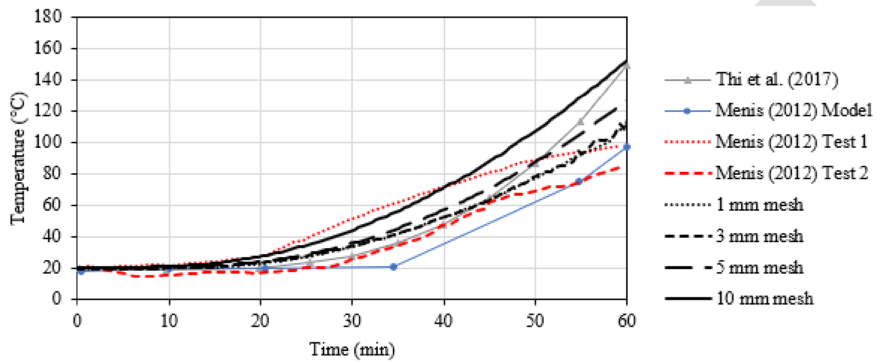
A sensitivity study was completed to determine an appropriate mesh size. This mesh sensitivity analysis considered mesh sizes of 3 mm, 5 mm, and 10 mm as these sizes align with previous studies while also aligning with the dimensions of the CLT panels. Additionally, a mesh size of 1 mm was examined to verify that the larger meshes converge. The dimensioning for this verification analysis is based on the heat transfer model outlined by Thi et al. (2017) and the tests performed by Menis (2012), which involve a 150 mm thick CLT panel, with a moisture content of 12%, a density of 460 kg/m^3, and subjected to ISO 834 (International Organization for Standardization 2014) thermal exposure. The test performed by Menis (2012) was used as a reference as this test series is similar to the purpose of this model (i.e. CLT panels exposed to fire from their soffit). This test series was also selected as it clearly reported the temperatures throughout the test duration at several depths of the CLT panel. While the data collected was able to provide a temperature gradient through the CLT panels, there are some limitations. Primarily the experiment was not instrumented to capture the heat fluxes at the soffits of the panels, or flame spread along the panels. Experimental data relating to the heat fluxes along the soffit of the panels and the flame spread along the panels would be useful in calibrating a model to better estimate the impact of a burning CLT panel on a compartment. Secondly, due to safety concerns, some tests concluded early and the resulting data do not reflect the entire test.

Figure 2 illustrates the results of the mesh analysis. The results are compared to the modelling results of both Thi et al. (2017) and Menis (2012), as well as the data from two experimental tests performed by Menis (2012). From the mesh sensitivity analysis, it was determined that a 3 mm mesh size would be adequate for this modelling endeavour of identifying data sets needed for future model calibrations. Through the analysis, it was found that the 3 mm mesh size produced nearly identical results to that of the 1 mm mesh size while only requiring 4% of the computational time. For comparison, the final temperature difference at 60 minutes between the 3 mm and 1 mm mesh size was 1% at 21 mm depth, and 2% at 52 mm. Thus, the increased computational time to continue using the 1 mm mesh size is not justified for such a small discrepancy in results. Although the 5 mm and 10 mm mesh sizes had faster computational times, they did not readily converge with the 1 mm and 3 mm meshes and were discarded.

As stated earlier, the soffit of the CLT panels will be exposed to the fire in this model. As a baseline, the thermal boundary conditions of the area of CLT directly above the localized fire were characterized as radiation and convective contributions from the pool fire. The pool fire will consist of 14.3 L of methanol in a pan which measures 0.48 m x 0.6 m. This boundary condition does not account for the contribution of the timber, and therefore experimental results could expect to see different temperatures or heat fluxes.



a)



b)

Figure 2: Comparison between predicted temperatures of different mesh sizes, with measured temperatures and previous studies by other authors at a) a depth of 21 mm and b) a depth of 52 mm.

4.1.3 STUDIES USED FOR VERIFICATION STUDY

To verify that the model works as intended, two previous experimental studies (Chorlton 2021; Quiquero et al. 2018) were also modelled. In this context, verification indicates testing that the model meets the requirements at this stage of development, whereas validation would ensure a final model meets the needs and expectations of the model. The first experimental study (Quiquero et al. 2018) considers five Glulam beams with cross-sectional dimensions of 45 mm x 195 mm. These beams were exposed to a kerosene pool fire for 10 minutes on each of the longer sides of the beams (i.e., one of the 195 mm sides was exposed to the pool fire, then the member was flipped to allow the opposite side to be exposed to the pool fire). The char depth was found to be 5 mm +/- 1 mm (Quiquero et al. 2018). The second experimental study involves two heritage timber members (Chorlton 2021). These members had an average density of 657 kg/m^3 and a moisture content of 10%. The heritage members were exposed to a 30-minute methanol pool fire. The maximum char depths on the soffit of 25 mm and 21 mm for the first and second trials.

For the model verification, the heat flux was calculated from the fuel, based on the burning rate and the heat of combustion of the fuel (Drysdale 2011). The mass burning rate was taken as 0.039 kg/m^{2}s for kerosene and 0.017 kg/m^{2}s for methanol, while the heat of combustion for the fuels was taken as 43,200 kJ/kg and 20,000 kJ/kg respectfully (Society of Fire Protection Engineers 2016). The empirical constant was further used for heat release rate calculations of the fuel representing the product of the extinction absorption coefficient and the beam-length corrector was taken as 3.5 m^{-1} for kerosene (Babrauskas 2015). Heat release rates were calculated following Equation S2 (Babrauskas 2015) in the paper's supplemental materials.

The incident heat flux on the members was taken as the heat release rate of the fuel due to the proximity of the fuel. The incident heat flux on the soffit of the members was therefore taken as 52.6 kW/m^2 for the glulam members (kerosine pool fire) and 24.2 kW/m^2 for the heritage members (methanol pool fire).

4.1.4 DETERMINING UNCERTAIN FIRE PARAMETERS

Current methodologies for non-combustible compartments consider several parameters for the design of non-uniform fires. These include flame length (as a function of ceiling height and heat release rate), incident heat flux on the ceiling relative to the location of localized fire flames, fire spread rate, time for fuel to auto-extinguish, and ambient room temperature, among other parameters (Heidari et al. 2019). As previously mentioned, adapting existing methods for timber structures becomes challenging due to the contribution of the timber to the fire, as well as the lack of existing data regarding the thermal performance of CLT ceilings. There is limited experimental evidence available regarding the fire spread and extinction rates of CLT ceilings, as well as expected heat fluxes or temperatures in the near and far field regions.

In terms of available information regarding fire spread and extinction rates, there has been some investigation regarding non-combustible structures, as well as flame spread/extinction along the top of wood cribs. Gupta et al. (2021) looked at the flame spread characteristics of wood cribs, considering the experimental setup and results of the Malveira Fire Test, from which the location and velocity of the flame front were determined (Gupta et al. 2021; Hidalgo et al. 2019). Additionally, there are recent fire tests with the purpose of examining natural fires in open-plan compartments. An example of which are the x-ONE and x-TWO experiments also considered full-scale experimental tests of large-scale, open plan non-combustible structures, in which it was found that the fire was observed to travel with clear leading and trailing edges (Heidari 2021; Heidari et al. 2020).

From a review of the literature, it was found that the parameters of incident heat flux, flame spread rate, and extinction rate are lacking detail as to what might be expected when considering CLT ceilings. Additionally, there is a lack of knowledge of the impact a burning CLT ceiling has on the rest of a compartment such as the vertical temperature gradient or heat flux experienced at the floor level. There is a need to understand likely heat fluxes and flame temperatures of CLT ceilings in the near-field region. For this, a localized fire underneath the ceiling will be considered, with two incident heat fluxes. These heat fluxes will be taken as 23.9 kW/m^2 (Tewarson and Pion 1976) and 77.5 kW/m^2 (Petrella 1979), meant to represent the high and low end of heat fluxes provided by timber flames as observed in literature. In the studies by Tewarson and Pion (1976), as well as by Petrella (1979), the researchers examined the ideal burning rate in which small samples of various combustible materials, including several timber species, were exposed to radiant heat. The heat flux provided by the materials' flames was then calculated. It should be noted that the heat fluxes considered are meant to represent a range of values, more than accurate values that would be expected, as expected heat fluxes and flame temperatures specific to the soffit of CLT ceilings have yet to be experimentally collected. It should also be noted that these heat fluxes consider only contributions from the timber ceiling and not from external fuel sources. From this analysis, parameters needed for calibration will be explored.

Dimensions of the ceiling strip were selected as 0.5 m x 0.1 m x 2.4 m, chosen as large enough to observe heat transfer through the depth of the ceiling and along the length, but not so large as to cause unnecessary computational expense. The thickness of 0.1 m is aligned with available CLT thicknesses, and the length of 2.4 m is a scaled-down version of what could potentially be considered in experimental tests.

In terms of relevant information to use as a starting point for horizontal flame spread and extinction rates of CLT ceilings, to the authors' awareness, there is no readily available data. Data in general regarding fire spread rate in realistic fires is limited, though some data has been reviewed by Rackauskaite et al. (2015) based on a review of available experimental data and by Grimwood (2018) based on fire-fighter collective experience. Collected fire spread rates include the reconstruction of the World Trade Centre Fired, tests on natural fires in large scale (non-combustible) compartments, the St. Lawrence burn tests from 1958, and the First Interstate Bank fire from 1988. Of these, fire spread rates ranged from 1.5 mm/s to 19.3 mm/s (Rackauskaite et al. 2015), however, all of the experiments examined considered non-combustible structures. Both the maximum and minimum flame spread rates are derived from tests by Kirby et al. (1999) which considered nine compartment fire tests at the Cardington lab. The structure was primarily concrete with insulated lining (ceramic fibre or plasterboard) with fuel provided by wooden cribs. Given the lack of data related to flame spread rates of combustible compartments, these data will be considered as a starting point for the a priori model considered in this study however, these setups are notably different from solid CLT members for several reasons, including that the flame is propagating along the porous crib, where in a CLT compartment it could be propagating along a solid ceiling. This again reinforces the need for experimentally collected data to understand the potential rates of fire spread and extinction of CLT ceilings.

Regarding appropriate extinction rates, to the authors' awareness, even less data has been collected than for flame spread. Of those that have considered the rate of the trailing edge are the aforementioned x-ONE and x-TWO experiments, in which a concrete building was fitted with wood cribs throughout the length of the building, and flame spread and the rate of the trailing edge were observed (Heidari et al. 2020). Two trials were performed with varying fuel load densities, the first with a higher fuel load density that had a non-constant rate of the trailing edge, and the second that had a lower fuel load density that did reach a steady-state rate of travel. For the purposes of this model, the steady-state rate of the trailing edge will be considered, which was evaluated to be 0.02 m/min (0.33 mm/s) less than the flame spread rate of the leading edge. This value again stems from experiments in non-combustible structures, highlighting the need for this data to be collected in combustible structures. Nevertheless, the values selected should be reasonable in achieving the objective of this study, recommending data sets for experimental collection using an a priori model. A summary of parameter values used within the a priori model is provided in Table 2.

Table 2: Summary of parameters used for the a priori model

Parameter	Value	Source
Moisture content of CLT	8%	Williams (1999)
Emissivity of timber	0.8	Eurocode 5
Coefficient of heat transfer	25 W/m^2K	Eurocode 1 Part 1-2
Mesh size of elements	3 mm	Through a sensitivity analysis with comparison to Menis (2012) and Thi et al. (2017)
Incident heat flux	Lower: 23.9 kW/m^2 Upper: 77.5 kW/m^2	Tewarson and Pion (1976) Petrella (1979)
CLT dimensions	0.5 m x 0.1 m x 2.4 m	Selected as it can be replicated in future experiments
Fire spread rates	Lower: 1.5 mm/s Upper: 19.3 mm/s	Rackauskaite et al. (2015) and Kirby et al. (1999)
Trailing edge rate	Lower: 1.17 mm/s Upper: 19 mm/s	Heidari et al (2020)

Important assumptions made in the creation of this model are assumptions related to delamination and char fall off, as well as assumptions related to auto-extinction. This model assumes that the adhesives do not allow for delamination, and char fall off is insignificant. Otherwise, additional fresh timber would be exposed to the thermal exposure following the delamination or char fall off, providing additional fuel to the fire impacting the severity of the thermal exposure. If the timber being modelled were to delaminate, several aspects of its fire performance would be altered, including its char depth. However, the current practice in many countries is to avoid char-fall off by adopting a CLT ceiling that their adhesive has been appropriately tested. Further, the current model assumes timber will auto-extinguish in that the timber will not experience continued flaming or smouldering combustion. These considerations need to be addressed by designers in addition to any numerical models.

4.2 RESULTS OF THE MODEL

4.2.1 RESULTS OF VERIFICATION STUDY

The temperature distributions of the Glulam as well as the heritage members used for verification are seen in Figure 3. In Figure 3, the red line at 300°C is used to visualize when a certain depth of timber might char. It can be seen in Figure 3 a) which considers the Glulam beams, that the beam chars to a depth of 3 mm at approximately 7 minutes and 9 seconds, and the peak temperature at a depth of 6 mm is 262°C after 10 minutes. From the experiments, it was recorded that the beams charred to a depth of 5 mm +/- 1 mm. Through interpolation, it is expected that after 10 minutes, the timber would be at a temperature of 308°C at 5 mm from the soffit (and would be considered charred). The percent difference between the modelled char depth and the experimental char depth is 3.5%. The charring rate observed in the model is on average 0.52 mm/min over the 10-minute period. Figure 4 shows a comparison of the cross-section of the Glulam members post-fire, as well as the results of the numerical model. The cracking shown in the photograph was induced by the mechanical loading during post-heating experimental testing, and the projected initial areas as outlined in red are adjusted to account for these cracks.

Similarly, in Figure 3 b), the heritage members are considered. The experimental tests of these members showed a char depth of 21 mm and 25 mm in the two trials. From the figure, it can be seen that the depth of 24 mm reaches a peak temperature of 292°C after 30 minutes. Interpolation between 24 mm and 21 mm shows that the depth which would reach 300°C after 30 minutes and would therefore be considered charred is found at 23.85 mm, well within the range observed in the experimental trials. The percent difference between the modelled char depth and the experimental char depth is 3.7%. The charring rate observed in the model is on average 0.80 mm/min over the 30-minute period. Figure 4 shows a visual comparison of the char depths at the end of the heat exposure of the experimental trial that showed a maximum char depth of 25 mm, and the numerical model. Note that in Figure 4, a heritage member is shown rather than an engineered member – the initial surface of the member was not perfectly even prior to fire exposure.

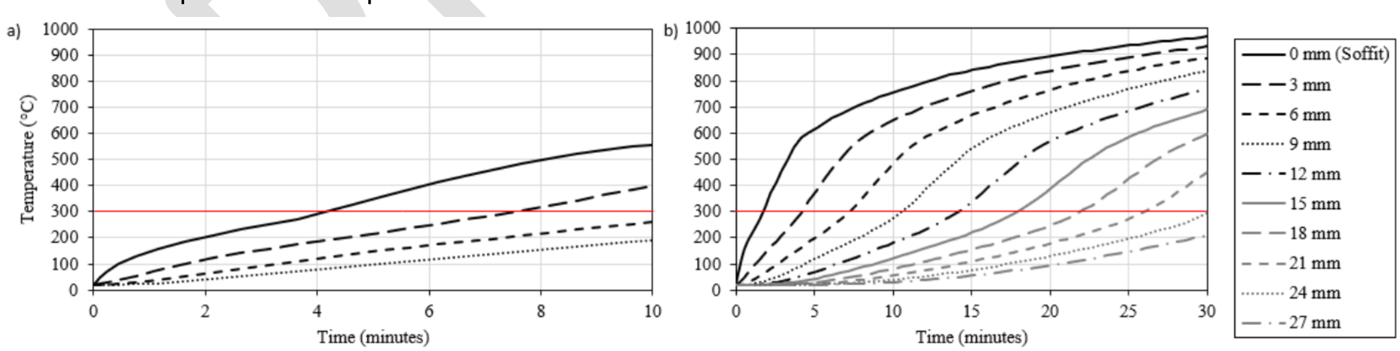
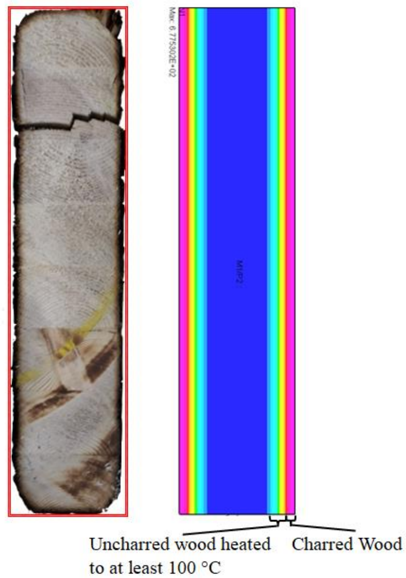


Figure 3: Temperature distributions of a) the Glulam members and b) the heritage members. Depths in the legend represent the distance from the soffit of the member, red horizontal line indicates the anticipated charring temperature

a)



b)

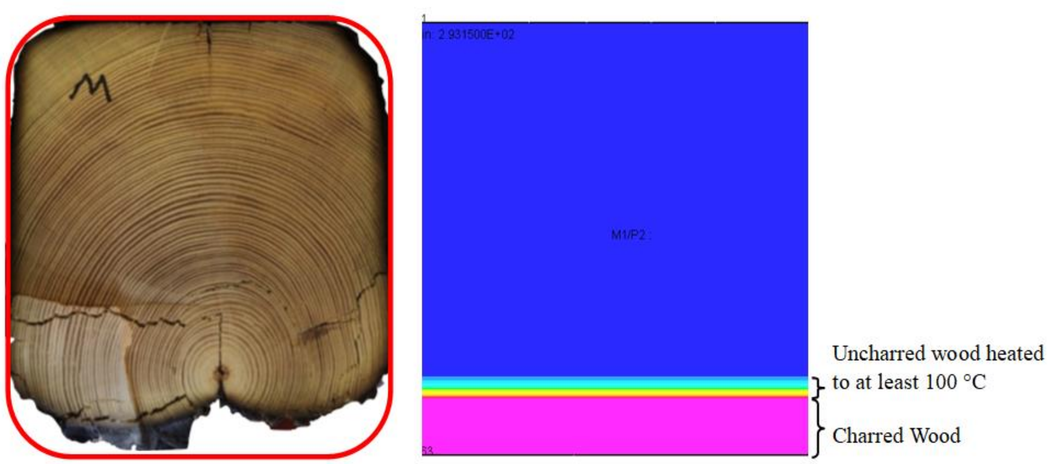


Figure 4: Comparison of the charred member and numerical model of a) the Glulam members and b) the heritage members

Though the results of verification models showed good alignment with the experimental studies, it should be noted that in these models the thermal properties of timber were input as being reversible i.e. they will return to their original strength when the member is cooled down to ambient. This was done following the material properties outlined in Annex B of Eurocode 5 (European Committee for Standardization 2004) even though nonstandard fires were considered in this model, in an attempt to develop a modelling procedure that was accessible and straightforward. The Eurocode properties do not inherently consider cooling as they were developed with a standard fire in mind. However, the models considered for verification were short in duration, and cooling and auto-extinction were not considered. Had other heat exposures been considered, including those that have a cooling phase, the models may not have aligned as well with the experimental results. The choice of convection coefficient is one parameter that will impact the results. Though radiation may be the dominant mode of heat flux in compartment fires (Drysdale 2011), altering the convection coefficient (along with other parameters as outlined in Section 4.1.4) will impact the results as more experimental information becomes available, and the results will change (e.g., the temperature profiles and temperature distributions may be hotter as the parameters are changed). However, much of the discussion herein relates to identifying knowledge gaps and research needs required for model calibration, the current parameters including the convection coefficient are sufficient for this purpose.

4.2.2 RESULTS OF THE CLT FLAME SPREAD MODEL

Once the model was validated it was used to simulate the CLT panels being exposed to the two heat fluxes. The results of the heat transfer of the two heat flux models are shown in Figure 5, where the legend shows the distance from the soffit (the application of the heat flux). Figure 6 also shows the temperature distributions within the CLT ceiling at 15, 30 and 60 minutes. Further, the flame spread models were used to highlight the needs for data collection. The temperature distribution of the flame spread models is seen in Figure 7. It is seen that the temperatures, as expected, are highly dependant on the rate of flame spread and the rate of extinction. Figure 5 and Figure 6 highlight the importance of having a clear understanding of incident heat flux of the soffit of the CLT ceiling and its effect on temperature distribution throughout the depth of the ceiling. It was found that the maximum char depth of the models was 2.32 mm for the model with a flame spread rate of 19.3 mm/s, and 11.88 mm for the model with the flame spread rate of 1.5 mm/s (assuming that there is no residual smouldering on the member). The slower flame spread rate, therefore, had a maximum char depth of over 5 times the quicker flame spread rate, emphasizing the importance of flame spread rate in determining the damaged area of a timber member, and resultantly, the residual strength. Figure 7 further demonstrates the uncertainty related to flame spread rate, extinction rate, and the impact of these metrics on the temperature distribution of the ceiling, and as a result, the structural capacity of the ceiling.

In order to calibrate these models precisely, several datasets are recommended for experimental collection. The first being the heat flux distribution on the soffit of the ceiling, in relation to the position of the ignition source below the ceiling. Understanding the incident heat flux on the ceiling will allow for a better determination of the expected temperature profiles. The next required dataset is an assessment of flame spread rates, along the ceiling, if any. With an exposed timber ceiling, there is the potential for the ceiling to ignite and for the flame to propagate along the ceiling at a different rate of any fuel at the floor level. This flame spread rate may be non-constant throughout the fire. Following this, an assessment of burn-out rates/speed of the trailing edge of the fire, if any, is required. An understanding of the burn-out rate of the timber (if burn-out occurs) will give a better idea as to the overall projected size of the fire. The final dataset is the flame extension of the fire below the ceiling and its impact of flame spread across the ceiling and the fuel bed.

One aspect that was not considered within the model was the iterative nature of the timber's contributions to the thermal exposure. When timber burns, it creates its own heat, which in turn has the potential to induce additional charring. The primary reason that the iterative contributions of the timber to the thermal exposure were not considered was due to the limited information available for inputs. These missing inputs can be used to identify datasets that should be collected experimentally, along with the datasets needed for model calibration.

To gather the required datasets, some instrumentation is recommended for future experimental studies of flame spread along CLT ceilings. The first is an array of cameras positioned along the length of the ceiling. Cameras could help to determine flame spread rates, and potentially extinction rates of the ceiling. These can be used as model inputs. Further, cameras could further allow for qualitative observation. Next, thermocouples along the length of the CLT ceiling are recommended. At a minimum, these should include thermocouples on the top and soffit of the CLT at regularly spaced intervals. Intervals could be dependent on the length of the ceiling in the experiment in consideration. Recording temperatures along the top and soffit of the CLT will allow for an assessment regarding if the model is working as intended. Further, assessing the ceilings after the experiments for the undamaged depth of timber will give an idea of the depth of timber that reached 300 °C which could be further compared to the model. Measuring the temperature of the ceiling will be vital for model calibration. Finally, in order to measure the heat flux incident on the soffit of the CLT ceiling, plate thermometers are recommended. The incident heat flux should be measured directly above a potential ignition source (e.g., radiant heater or pool fire), and at periodic intervals along the length of the ceiling (e.g., every 300 mm or as is deemed appropriate).

In terms of data sets needed to incorporate the contribution of timber into the thermal exposure, several data sets should be collected experimentally. The first data set is the charring rates of timber at extreme heat fluxes. While charring data of timber is available, many tests accommodate lower heat fluxes as available through traditional apparatuses. Charring rates may be greater under larger heat fluxes, as might be expected in large fires. An accurate assessment of the charring rate will help to determine the amount of char formed during a given thermal exposure, and better estimate the contributions of the timber to the overall thermal exposure. Additionally, data about the heat flux generated by the timber itself should also be collected. While again there is some data available to this extent, the data is limited. It would also be useful to understand expected heat flux when flaming is present, and when smouldering is present. These datasets would also help to better determine the contributions of the timber to the overall thermal exposure. Furthermore, the criteria for extinction, if extinction is to be considered within the model, should be determined. This includes both flaming extinction and smouldering extinction. This will help to better understand the thermal environment predicted at a given heating or cooling state. Finally, data about the heat flux experienced at the floor level along with the thermal gradient along the height of a compartment should be collected. These datasets would help determine the impact of a burning timber ceiling on the rest of the compartment.

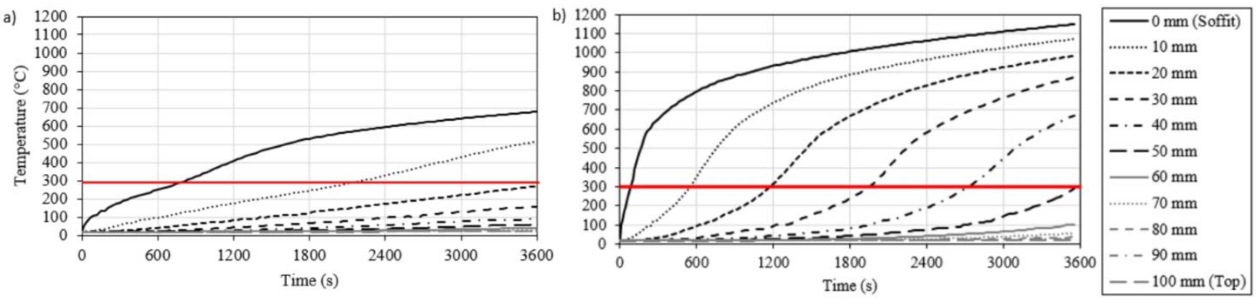


Figure 5: Distribution of temperatures based on heat fluxes applied at the soffit of a) 23.9 kW/m^2, and b) 77.5 kW/m^2. Depths in the legend represent the distance from the soffit of the member, red horizontal line indicates the anticipated charring temperature

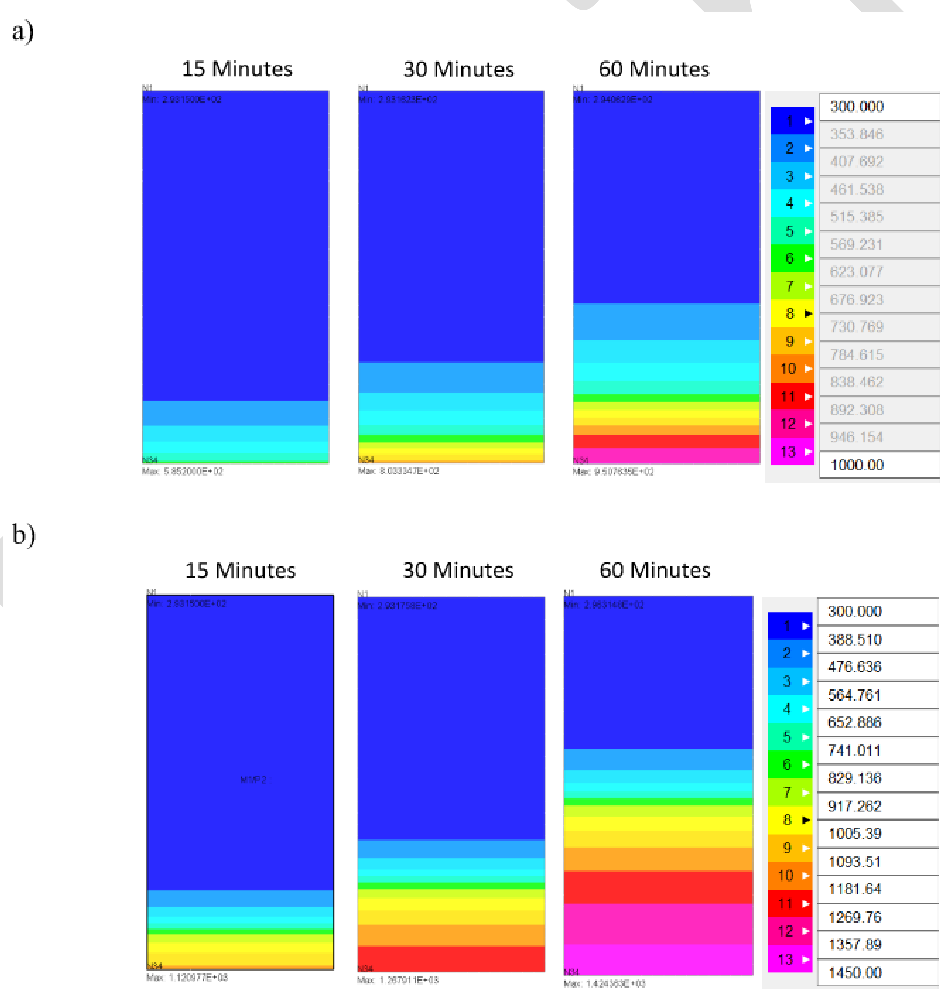
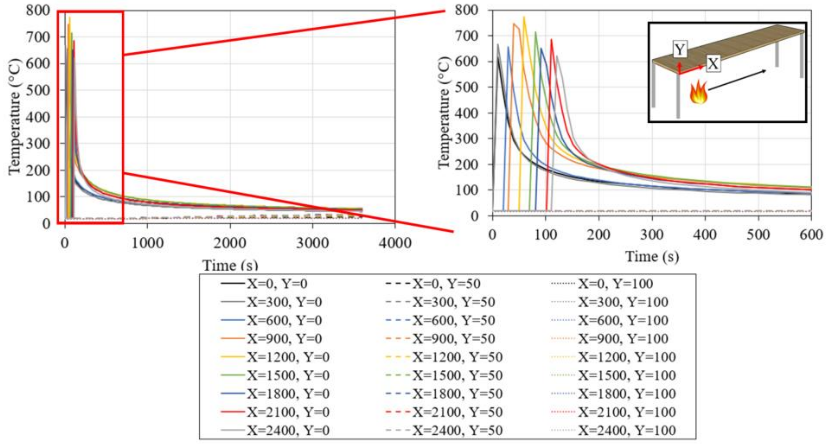


Figure 6: Temperature distributions throughout the CLT at 15, 30 and 60 minutes of a) an applied heat flux of 23.9 kW/m^2 and b) and applied heat flux of 77.5 kW/m^2 (units of temperature are K)

a)



b)

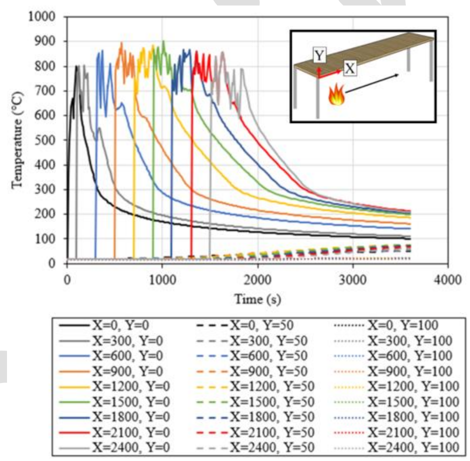


Figure 7: Temperatures at varying points along the ceiling considering flame spread rates of a) 19.3 mm/s and b) 1.5 mm/s

5.0 CONCLUSIONS

With the desire to construct mass timber structures with open plan, well-ventilated floor plans there is a need to gain a deeper understanding of the performance of timber in fire as well as the fire dynamics of these designs. Finite element modelling offers several advantages in the design and analysis of these types of spaces allowing a better understanding of the resilience of the structure under a range of realistic fire scenarios.

The purpose of this study was to identify current understanding with regards to modelling timber in fire as well as data sets recommended for experimental collection, to support the creation of future design methodologies which address open plan, well-ventilated timber structures. This was done by examining which data would be required for model input and calibration, using an a priori finite element model.

Reviewing the state of the art, it is observed that future research needs for the modelling of timber include the further development of thermal-structural models. These have begun to be addressed by other researchers (Quiquero et al. 2020; Gernay 2021; Chen et al. 2020), but additional modelling endeavours considering loaded thermal models could examine different thermal exposures (including nonstandard fires) and structural loading scenarios. This would help to make thermal-structural modelling of timber more established, contributing to the development of these models being used for design. Other properties unique to timber could be investigated through modelling. These include the effect of moisture content, including the effect of having varied localized moisture contents throughout the timber caused by moisture migration during heating. Current methods of accounting for moisture only account for the energy required to evaporate the moisture rather than simulate its movement throughout the timber member (Werther et al. 2012; European Committee for Standardization 2004b). Smouldering is also a phenomenon not seen in all structural materials, but that can affect the temperature profile of the section and in turn weaken the member after the flames are extinguished. The development of a model which considers smouldering through software currently used by industry members would contribute towards more accurately modelling the fire performance of timber structures.

LS DYNA was used to create the a priori finite element model. The results of the model, which considered a range of heat fluxes, flame spread rates, and extinction rates from literature highlighted the importance of future experiments related to the fire performance of CLT ceilings. Each of these areas greatly impacts the expected temperature distribution throughout the ceiling, and therefore the area of timber of which the structural capacity would be reduced. The results of this model indicate that more data is needed for charring rates of timber at extreme heat fluxes, the heat flux generated from the timber when both flaming is present and when smouldering, criteria for when to consider the extinction of timber, and data of the heat flux experienced along the floor level during a fire.

From the creation of this model, recommendations were made regarding the instrumentation of future experiments to gather these data sets. These recommendations include an array of cameras positioned along the length of the ceiling. The cameras can be used to determine flame spread rates as well as aid in determining an extinction rate of the fire. CLT samples should also be instrumented with thermocouples along their lengths. Each interval should at minimum have a thermocouple on the top and the soffit so that the temperature gradient of a model can be validated to that of the real temperature gradient. Finally, plate thermometers are recommended to be used to measure the heat flux experienced by the CLT from the source fire as well as the heat flux experienced by the floor from the ceiling. The collection of these data sets will help with providing model inputs, and data sets for model calibration.

As values for the applied heat flux and flame spread rate were taken at the far ends of accepted values (23.9 and 77.5 kW/m^2 for heat flux and 19.3 and 1.5 m/s for flame spread rate) the simulated results in turn have a large variability, demonstrating the need for further collection of experimental data for timber. It was observed that the char depth varied by approximately 20 mm (66% increase) when exposed to a higher heat flux. It was also observed that assuming a faster flame spread the fire was shorter in duration and reached lower temperatures.

Although several steps need to be taken before simplified design methodologies for open plan, well-ventilated timber structures can be created, the fire research community is beginning to mobilize and address some of these research gaps. Currently, in-progress experiments and analyses are anticipated to help better understand the expected fire dynamics of these types of spaces. By understanding how fires in well-ventilated, open plan spaces differ from compartment fires recently considered in experimental research, analysis of these types of fires becomes possible, and the creation of methodologies for the design of these spaces becomes more accessible.

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SUPPLEMENTAL MATERIALS

Table S1 and Equations S1 -S2 are available online in the ASCE Library (ascelibrary.org).

DATA AVAILABILITY

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPLEMENTAL MATERIALS

SUPPLEMENTAL TABLE

Table S1: Material properties according to Eurocode 5 Part 1-2 Annex B

Temperature (K)	Thermal Conductivity (W/mK)	Specific Heat (J/kgK)
293	0.12	1.53
372	-	1.77
372	-	13.60[a]
393	-	13.50[a]
393	-	2.12
473	0.15	2.00
523	-	1.62
573	-	0.71
623	0.07	0.85
673	-	1.00
773	0.09	-
873	-	1.40
1073	0.35	1.65
1473	1.5	1.65

[a] Data Points omitted due to latent heat method

SUPPLEMENTAL EQUATIONS

$$\Delta H_{vap,wood} = \Delta H_{vap,water} * \%MC \qquad (S1)$$

where $\Delta H_{vap,wood}$ is the latent energy of moisture within the CLT, $\Delta H_{vap,water}$ is the heat of evaporation of water, and *%MC* is the moisture content of the CLT.

$$q = \Delta h_c * \dot{m}_\infty * \left(1 - e^{-k\beta D}\right) \qquad (S2)$$

where q is the heat release rate, Δh_c is the heat of combustion, $\dot{m}_\infty$ is the mass burning rate, $k\beta$ is an empirical constant, and *D* is the diameter of the pool.