Article:

Hopkin, D. orcid.org/0000-0002-2559-3581, Węgrzyński, W., Gorska, C. et al. (6 more authors) (2024) Full-scale fire experiments on cross-laminated timber residential enclosures featuring different lining protection configurations. Fire Technology, 60 (6). pp. 3771-3803. ISSN 0015-2684

https://doi.org/10.1007/s10694-024-01581-1

Fire Technology, 60, 3771–3803, 2024

Manufactured in The United States
https://doi.org/10.1007/s10694-024-01581-1

Full-Scale Fire Experiments on Cross-Laminated Timber Residential Enclosures Featuring Different Lining Protection Configurations

Danny Hopkin, OFR Consultants, Sevendale House, Lever St, Manchester M1 1JA, UK; Department of Civil and Structural Engineering, Sir Frederick Mappin Building, Mappin Street (via Broad Lane), Sheffield S1 3JD, UK*
Wojciech Węgrzyński, Instytut Techniki Budowlanej (ITB), Filtrowa 1, 00-611 Warsaw, Poland
Carmen Gorska and Michael Spearpoint, OFR Consultants, Sevendale House, Lever St, Manchester M1 1JA, UK
Jakub Bielawski, Instytut Techniki Budowlanej (ITB), Filtrowa 1, 00-611 Warsaw, Poland
Harald Krenn, KLH Massivholz GmbH, Gewerbestraße 4, 8842 Teufenbach-Katsch, Austria
Tim Sleik, Binder Holz GmbH, Zillertal Straße 39A, 6263 Fugen, Austria
Renaud Blondeau, Stora Enso Oyj, Wood Product-Building Solutions, PL 309, 00101 Helsinki, Finland
Gordian Stapf, Henkel and Cie. AG, Industriestrasse 17a, Sempach Station, 6203 Neuenkirch, Switzerland

Received: 9 August 2023/**Accepted:** 19 March 2024/**Published online:** 3 May 2024

Abstract. The adoption of timber, specifically cross-laminated timber (CLT), as a primary construction material is gaining traction due to its carbon sequestration capabilities, environmental advantages, and potential for precision manufacturing. However, the combustibility of wood raises legitimate concerns about fire safety in timber-based residential buildings. This paper investigates the fire performance of timber in a residential context, attempting to fill knowledge gaps and outline strategies for improving fire robustness in timber-built dwellings. Through comprehensive experimental studies on residential-type enclosures constructed with CLT panels, this research explores different configurations and the effects of varying degrees of non-combustible protective lining. The findings underscore the significance of considering timber surface exposure and adopting effective encapsulation strategies in CLT buildings. It has been estimated that the exposure of timber walls leads to a proportional increase in heat release rate, corresponding to the area of exposed timber surfaces and their charring rates. Consequently, the external flame has a larger projection,

* Correspondence should be addressed to: Danny Hopkin, E-mail: D.J.Hopkin@Sheffield.ac.uk, danny.hopkin@ofrconsultants.com

resulting in a much greater heat flux to the façade. Furthermore, threshold conditions for initial flaming self-extinguishment of timber defined in literature of 44.5 ± 1.2 kW/m^2 have been found to be applicable to the experiments conducted in this research. Finally, it has been observed that partial encapsulation, where the protective lining will likely fall off during a fire, may hinder rather than increase the likelihood of self-extinguishment. This work contributes towards a nuanced understanding of fire dynamics in timber structures, offering insights for safer and more effective design strategies for CLT-based construction.

Keywords: Self-extinguishment of timber, Flaming, Residential buildings, Large-scale timber enclosures fires, Linings

1. Introduction

The United Nations [1] predicts that 68% of the world's population will be residents of urban areas by 2055, necessitating the construction of a vast number of dwellings to accommodate this growth. Concurrently, the climate emergency poses an unprecedented challenge, requiring urgent action to reduce greenhouse gas emissions and promote sustainable development [2]. In this context, the use of timber as a primary building material for residential construction offers several compelling advantages over conventional materials, such as concrete and steel.

The cement-making process, a prerequisite of conventional concrete construction, contributes to 6% of the world's carbon emissions. This is second only to steel production, with half of the steel produced going into buildings [3]. In contrast, as trees grow, they sequester carbon dioxide from the atmosphere, effectively acting as natural carbon sinks. Building with timber has the potential to save an average of 40 tonnes of CO_2 per dwelling, when compared to concrete or steel construction, significantly reducing the carbon footprint of new residential construction [4].

In addition to its carbon sequestration properties, timber can be sourced from sustainably managed forests, encouraging responsible forestry practices and increasing overall afforestation. This, in turn, contributes to the preservation of ecosystems and biodiversity, and promotes a circular economy using renewable resources [4].

The lightweight nature of timber reduces the number of deliveries to the construction site and the reliance on heavy machinery such as cranes, further minimising the environmental impact of construction [5]. Building with timber can also accelerate construction times due to its ease of assembly and the possibility of prefabrication, allowing for more rapid delivery of new housing units to meet growing demands.

Lastly, the use of timber in residential buildings has biophilic benefits, as human interaction with natural materials is shown to improve well-being. Incorporating wood into residential design (e.g., Figure 1) can foster a connection with nature, creating living spaces that are not only more sustainable but also more conducive to human health and happiness [6].

Figure 1. View of the Murray Grove nine-storey timber tower [7].

Despite the many advantages of wood as a primary construction material, fire safety is a concern for many stakeholders [8, 9]. As a combustible material, if wood can contribute as a source of fuel in the event of a fire, this presents challenges in developing a robust fire safety strategy for a building. Engineers need to address the hazards that come with the contribution of the structure to enclosure fire dynamics and the relevance of the status quo fire resistance approach [10].

This paper, therefore, aims to investigate the fire performance of mass timber structures in a residential context, addressing knowledge gaps about the safety of using wood as a primary construction material and exploring potential strategies for enhancing fire robustness in timber-built dwellings. This is through an extensive experimental study on residential-type enclosures constructed from cross-laminated-timber (CLT) panels. The enclosures adopt several configurations by protecting the timber structure with different amounts of non-combustible protection linings and exposing different surfaces of the enclosure (walls, ceiling) to the fire.

2. Fire Safety, Residential Buildings and Mass Timber in the UK

The UK was an early adopter of CLT in residential buildings, with Murray Grove, completed in 2009, said to be the first tall urban housing project to be constructed entirely from prefabricated solid timber (CLT) and, in the process, becoming the then tallest mass timber building in the world. Subsequently, upon completion in 2017, Dalston Works (also in the UK) was said to be the world's largest CLT building when considering the volume of timber utilised.

2.1. The Grenfell Tower Fire and the Implications for Mass Timber

After the initial proliferation of mass timber residential buildings in the UK, the Grenfell Tower tragedy occurred, a significant fire in a concrete high-rise residential building [11]. This fire led to changes in technical policy by the government of England and the devolved nations of the UK. One of the more significant changes is the 'in-effect ban' on combustible materials in the external wall zone of relevant buildings in England. The Building (Amendment) Regulations [12] primarily focus on the fire safety of external wall systems, including cladding and insulation materials, for residential buildings above 18 m in height. These regulatory changes have had a notable impact on the use of timber in residential buildings, particularly in high-rise constructions. The revisions to the Building Regulations imposed stricter requirements on the fire performance of materials used in the external envelope of residential buildings, limiting the use of combustible materials to those with a European fire classification of Class A1 or A2-s1, d0 according to BS EN 13501-1 [13]. As a combustible primary framing material, timber cannot achieve the stated fire classification and, thus, is not permissible within the external wall zone of relevant buildings. This does not amount to in-effect ban on the use of timber as a framing material in relevant buildings, but it does introduce challenges as to how timber can be used effectively whilst not interfacing with the external wall zone. Based on observations of the government's impact study at the time of considering the implementation of the 'in-effect ban', Law and Butterworth [14] imply that the government may be using the Grenfell Tower incident as a reason to prohibit this increasingly popular construction method or, at least, slow its proliferation.

Whilst no comment has been made by the government on the consequence of the ban for timber construction, clarifications through recently published 'Frequently asked questions' [15] on the routes to fire safety compliance of mass timber buildings and the relationship with statutory fire safety guidance (Approved Document B) suggest concerns existed and continue to exist regarding design philosophies for buildings adopting timber as the primary framing material. These concerns build on articles either published by or containing interviews of fire safety engineers [8, 10], where it has been noted that many mass timber buildings are conceived and developed without great cognisance or consideration of the additional hazards that the involvement of the structure as a source of fuel brings.

The in-effect ban on combustible materials in the external wall zone, allied to uncertainty in its future scope and safety concerns about the use of combustible primary framing materials has led to a reduction in residential construction that utilises CLT in the UK. In lieu of seeking to find ways of working around the in-effect ban, Law and Butterworth [14] note that "*a key motivation for the engineered timber industry should therefore be to provide evidence to the government that this form of construction should be one of the exempted products—by spending time to address safety concerns*".

2.2. Compliance and Structural Fire Design Approaches

Recently published guidance [16] has provided clarification on the design evidence that designers should develop to demonstrate that a sufficient level of structural fire performance will be achieved when using combustible structural framing solutions. In buildings with higher consequences of failure, such as medium- to high-rise residential buildings, it is essential for the structure to be designed in a way that ensures a reasonable probability of withstanding the entire duration of a fire. This requirement implies that if the structure becomes a fuel source during a fire, it must be able to self-extinguish and maintain its load-bearing capacity both during and after the fire event.

A relatively simple solution to ensuring a mass timber structure has a reasonable probability of withstanding the entire duration of a fire is to prevent the involvement of the structure as a source of fuel in the first place. This can be achieved through the specification of protective linings that prevent the pyrolysis of the underlying combustible substrate. This approach is conventionally termed encapsulation. Adopting such a solution, subject to appropriate specification and detailing of linings, at least in-principle, results in an enclosure fire that is only influenced by the contents, i.e., the moveable fire load. Thus, traditional routes to compliance in seeking to demonstrate adequate performance in the event of a fire can apply, i.e., the structural elements, inclusive of their protection, should achieve a fire resistance rating. The key difference being that the lining's performance criteria should be such that it facilitates the prevention of the pyrolysis of the combustible substrate. For such a purpose, the fire protection ability (K_2) as described in [17] is commonly adopted, where the surface temperature of a combustible substrate must remain suitably low and visual observation of the substrate should not indicate discolouration. The notable downside of preventing the involvement of a combustible structure via encapsulation is the amount of protection material required, particularly for high consequence of failure buildings, which typically have high fire resistance demands. Such an amount of protection is detrimental to the commercial appeal of CLT in residential buildings, but also can serve to undermine the reduced carbon credentials given the amount of (typically gypsum based) lining material required and impact on the net internal area.

2.3. Protective Lining Strategies

Given the trade-offs of adopting encapsulation as a fire protection strategy and, perhaps, through a lack of understanding of the role of fire resistance in conferring compliance with the Building Regulations for mass timber buildings, designers have sought to reduce the amount of fire protection in mass timber buildings. In referencing the structural fire safety strategy for Dalston Works, the project's structural engineer stated: "'*the plasterboard gives 49 min of fire protection, after that the timber chars at 0.7 mm per minute, so we have to ensure we have enough timber remaining to carry the loads after 120 min*" [18], surmising what is traditionally known as a partial-protection strategy. That is, the design is premised on the explicit assumption that the fire protection falls away from the timber at some point in a fire, thus likely exposing the combustible substrate and allowing its contribution as a source of fuel. The motivations for 'partial protection' are clear. It has the potential to reduce costs and the CO_2 footprint, while allowing for larger floor areas when compared to the fully encapsulated alternative.

Whilst this reference is made to one project, anecdotally and from the authors' experience, partial protection has been widely adopted as part of structural fire safety strategies for timber buildings in the UK, particularly for those buildings that were early adopters of CLT. Partial protection strategies present a challenge to the fire safety strategy of higher consequence of failure buildings, such as medium- and high-rise residential buildings. In these buildings the explicit acceptance of the combustible structure becoming involved as a source of fuel must go together with a demonstration that the structure can stop burning and have a reasonable probability of surviving the full duration of fire, without reliance upon external intervention. Operating within the fire resistance paradigm provides no assurance, nor any evidence of this and, thus, is a weak basis for compliance with the Building Regulations. Instead, such a demonstration of self-extinction would fall within the remit of performance-based fire safety engineering, with the corresponding analysis/evidence supporting the case for compliance. To this point (and within this paper), much of the design narrative surrounding self-extinction has focussed on the ability of timber to initially cease flaming combustion under certain conditions, without external intervention. These conditions are usually expressed in terms of mass loss rate and external incident heat flux to the timber surface [19], and are further described in Sect. 6.4. Demonstrating that these conditions can be met requires some knowledge of how linings are likely to perform, how they might fail/detach and what this ultimately means for the enclosure fire, and the ability of the timber substrate to stop burning.

To add further nuance to the possible protection strategies, both encapsulation and partial protection can be considered at the surface scale, with enclosures formed from a collection of surfaces. This may mean some surfaces comprise of exposed structure, while other surfaces may be either encapsulated or partially protected. This could be driven by reasons unrelated to fire, such as acoustic attenuation, structural dynamics and the provision of building services. To this end, when communicating about fire protection strategies for mass timber buildings, this paper introduces the following terminology and is used henceforth:

- Partial protection: passive fire protection is adopted within the enclosure, but any protected surfaces are knowingly designed in such a manner that they may become involved as a source of fuel during a fire event;
- Partial encapsulation: some surfaces within the enclosure are explicitly designed to not become involved as a source of fuel during a fire event;
- Full encapsulation: all surfaces within the enclosure are explicitly designed to not become involved as a source of fuel throughout a fire event.

3. Existing Research, Motivation and Research Strategy

Large-scale fire experiments on mass timber enclosures have developed into an area of significant study given the global proliferation of buildings using wood as the primary framing material. It is not the intent in this paper to undertake an extensive review of existing literature on the topic, with several review studies having been undertaken in the last decade, by Buchanan et al. [20], Brandon and Östman [21], Ronquillo et al. [22], Liu and Fischer [23], Mitchell et al. [24], Bøe et al. [25, 26] and Su et al. [27]. However, what these review papers collectively highlight is a lack of knowledge on the role of different lining protection strategies for CLT residential buildings on the prospect of self-extinction and, in the authors' opinion, a conflating of fire dynamics behaviours that arise due to fire induced delamination versus failure/fall-off of fire protection materials, such as secondary or tertiary flashovers. Further, little attention has been given to partial protection as part of a fire safety strategy for a mass timber building, despite its apparent prevalence as a solution in practice.

Given the discussion provided in Sect. 1, the case for building more with mass timber is compelling and, when faced with housing shortages, this case is potentially strongest in the residential sector [28], where urban development limitations will necessitate taller buildings. This will place the need within the domain of higher consequence of failure buildings and within the constraints of the in-effect ban on combustible materials in the external wall zone of relevant buildings. Precedent from early adopters of CLT suggests that fire protection by way of lining materials will form part of the design, often for reasons unrelated to fire safety. However, minimising the extent of this offers both commercial and environmental benefits, meaning partial encapsulation and partial protection are attractive options, subject to them being able to deliver the intended regulatory/life safety outcome. Existing literature reviews on large-scale mass timber fire experiments highlight a lack of knowledge has been generated on the viability of partial encapsulation and partial protection solutions (Sect. 3). There is also an apparent misappropriation of fire induced delamination as the basis for observed fire dynamics phenomenon, such as cyclical flashover, when counter arguments can be made that a high degree of uncertainty in the ability of a mass timber enclosure to self-extinguish arises from the failure of fire protective linings. Research that has focussed on partial encapsulation, such as that by Kotsovinos et al. [29], aimed to explore commercial type enclosures, meaning the scale was not representative of typical apartment construction, nor were there multiple combustible internal surfaces that could interact in the event of exposure/fire protection failure. There are other studies intended for the USA market that investigate the effect of partial encapsulation [30]. In this US study the timber elements are manufactured with an enhanced adhesive which is less prone to delamination when compared to adhesives commonly used in England, e.g., standard polyurethane, which are the focus of this study.

Owing to the in-effect ban on combustible materials in the external wall zone of relevant buildings in England, there is some inherent limiting of the surfaces of a CLT residential structure that can contribute as a source of fuel, i.e., CLT could not be contained in the external wall zone of relevant buildings. Given this, this research positions itself to provide data in support of the design of partially encapsulated or partially protected CLT residential buildings, falling within the scope of the in-effect ban. The aim is to support the industry in progressing towards a design envelope that is defensible, whilst also identifying design solutions that may not be appropriate or present large uncertainties when seeking to demonstrate a given building's structure can have an adequate likelihood of surviving burn-out.

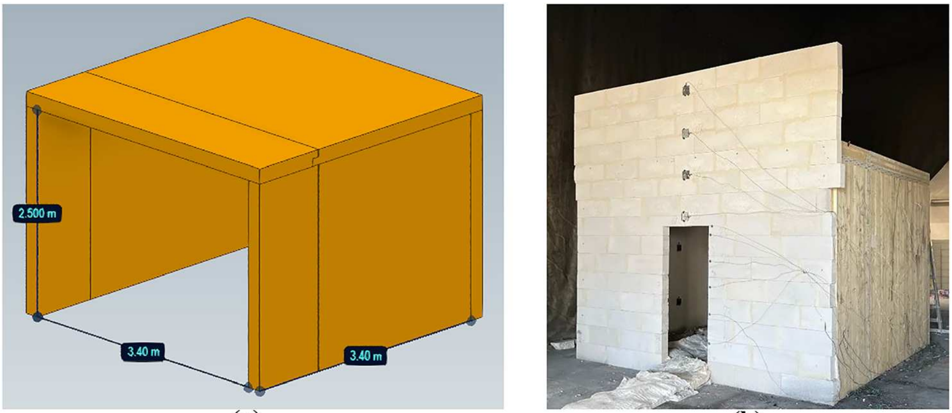
It is established that the primary goal of the research is to generate data to support the construction industry in the development of mass timber residential buildings that fall within the scope of the in-effect ban, by identifying a design envelope that can support the attainment of an adequate level of life safety performance and highlighting design solutions that might be inadequate. The emphasis is, therefore, on the influence of different partial protection or partial encapsulation strategies on the structure's ability to initially self-extinguish, which is a prerequisite for surviving the full duration of a fire. Given, as yet, limited computational tools exist that are capable of reliably simulating the fire dynamics within a combustible enclosure and given large uncertainties regarding the prediction of both passive fire protection failure/detachment and fire induced delamination, it has been decided to address the research goal experimentally. Owing to the potential impact of scale, particularly in respect of enclosure surface interactions and the detachment of passive fire protection, experiments have been conducted at large-scale, on enclosures broadly representative of that of rooms within dwellings. In total eleven experiments have been undertaken, representing different types and configurations of partial protection and partial encapsulation solutions. These range from a fully-encapsulated enclosure (i.e., as advocated within a recently developed "new model building" [31]), with the express goal of mitigating the involvement of the CLT substrate as source of fuel, through to enclosures that feature a relatively high surface area of exposed CLT. The enclosure characteristics and configurations are discussed further in Sect. 4.

4. Experimental Methodology

4.1. Experimental Set-up

The key dimensions of the enclosure geometry adopted are given Figure 2. The enclosure had a floor area of 3.4 3.4 m and a ceiling height of 2.5 m. The front most wall that featured the opening was formed of concrete blocks. This extended to a height of ca. 3.9 m above ground level. Ventilation to the enclosure was provided by way of a door opening at the front of the enclosure, which measured 700 mm wide by 1800 mm high. These door dimensions were chosen to ensure that the fire would reach a post-flashover state for the maximum heat release rate that could be achieved by the available gas burners. In addition, the height of the opening is comparable to that of a door and provided a means of entry.

CLT slabs of walls and ceiling were 180 mm thick of lamella configuration 40–30–40–30–40 mm. Each surface was formed of two panels, joined in a half-lap



(a) (b)

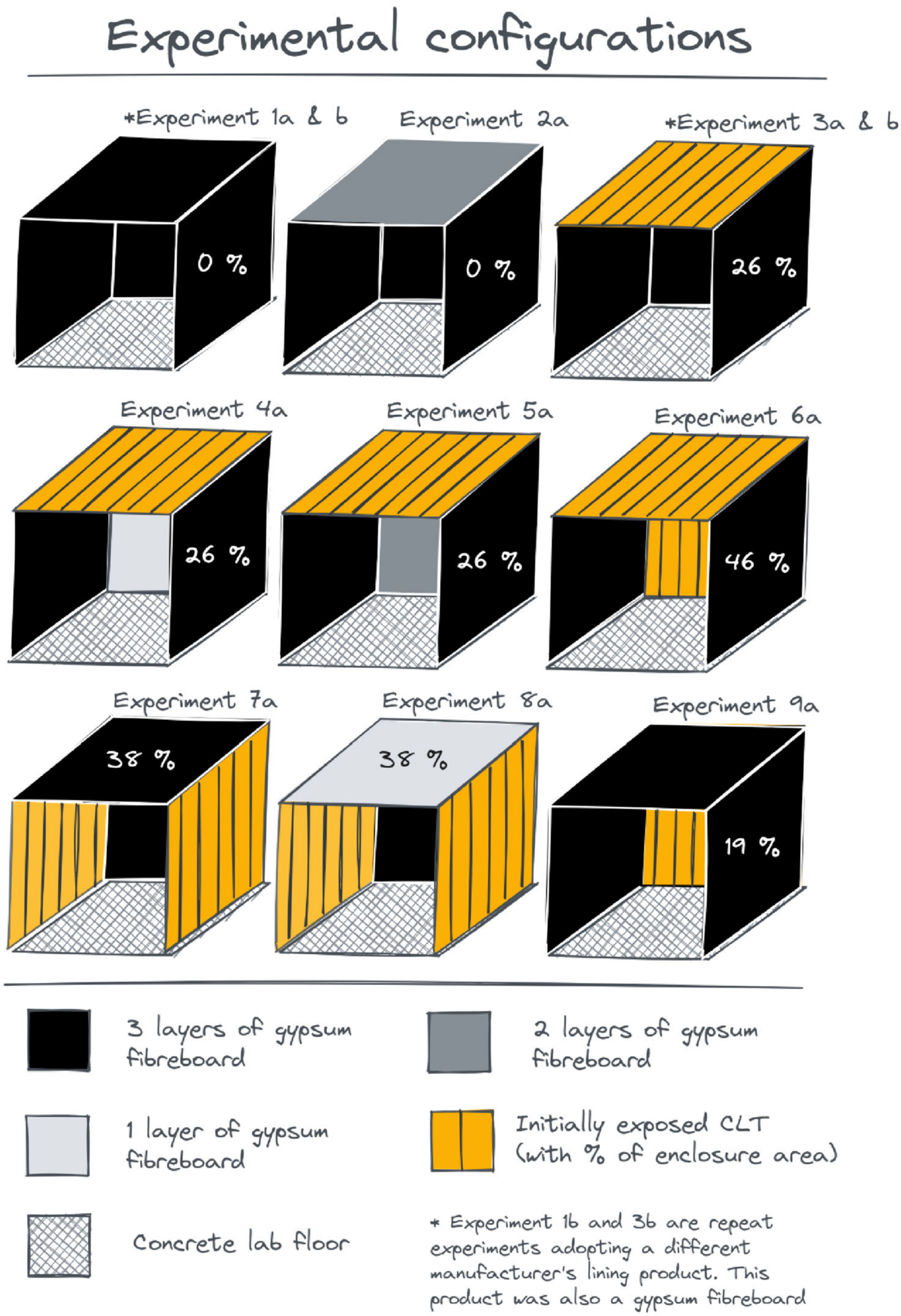
Figure 2. (a) Enclosure isometric with front wall omitted and (b) Picture of the experimental setup with the front wall and vertical façade extension.

configuration. Compressed mineral wool fire stopping was provided between the CLT walls/ceiling, and the blockwork elevation. The CLT lamellae were glued using a standard polyurethane adhesive (PU) that has been observed to suffer heat-induced delamination in other experiments of this research program [32], as well as in [25, 26].

The lining adopted within the enclosures varied between experiments, as discussed further in Sect. 4.2. However, the lining was consistently formed from a gypsum product that measured 18 mm in thickness. This was adopted in one of a single, double or triple lined configuration, broadly aligning with performance corresponding to $K_2 30$, $K_2 60$ and $K_2 90$ classification [33] according to the information provided by the manufacturers, although $k_2 90$ is not an official classification and is introduced here for the purpose of this study by applying the same performance criteria. The supplier of the gypsum fibreboard was consistent through Experiments 1a to 9a. As an extension of the study, Experiments 1b and 3b adopt the same thickness of gypsum board albeit they used a plasterboard product from a different supplier but with the same classifications corresponding to $K_2 30$, $K_2 60$ and $K_2 90$.

4.2. Experimental Configurations

Eleven experiments in total were completed, with configurations as shown in Figure 3. Experiment 1a was configured to represent an inert reference experiment, i.e., where the involvement of the CLT substrate was prevented. This was subsequently repeated using the second lining product and is referenced as Experiment 1b. Averting the involvement of the CLT substrate was achieved by specifying a lining configuration of classification K_2,90. The remaining configurations, either from the outset, or through the course of the fire, anticipated the involvement of the CLT.


Experimental configurations
*Experiment 1a & b
0 %
Experiment 2a
0 %
*Experiment 3a & b
26 %
Experiment 4a
26 %
Experiment 5a
26 %
Experiment 6a
46 %
Experiment 7a
38 %
Experiment 8a
38 %
Experiment 9a
19 %
3 layers of gypsum fibreboard
2 layers of gypsum fibreboard
1 layer of gypsum fibreboard
Initially exposed CLT (with % of enclosure area)
Concrete lab floor
* Experiment 1b and 3b are repeat experiments adopting a different manufacturer's lining product. This product was also a gypsum fibreboard

◂**Figure 3. Experimental configurations, front wall omitted for clarity. The percentages indicated at each configuration show the percentage of internal exposed CLT area at the beginning of the test.**

4.3. Fire Source

The fire source comprised six propane burners located on the floor of the enclosure, arranged in two rows of three burners. The burners were oriented perpendicular to the door opening, 775 mm from the nearest parallel side wall. Provisional calibration burns for the opening size suggested external flaming occurred once the propane heat release rate (HRR) reached ca. 1800 kW. Given this, 1800 kW was chosen as the upper bound of the HRR curve to limit excess fuel burning outside of the opening in the reference cases (Experiment 1a and 1b).

The fire was idealised as following a fast t-squared growth rate, with the mass flow rate of the propane stepped to align with this. The growth and steady phases of the fire development lasted 60 min. Thereafter followed a decay phase, resulting in a fire severity broadly aligning with 90 min of ISO 834 exposure [34], based upon a time equivalency methodology which estimates an equal cumulative radiant energy exposure, as explained in [35]. An equivalent duration of 90 min of ISO 834 exposure from the propane supply was chosen to align with English fire resistance guidance for residential buildings [36] with a top floor of between 18 m and 30 m above lowest ground level. This was considered to be the most probable market for CLT residential buildings falling within the scope of the in-effect ban.

The resulting relationship between the propane HRR and time is shown in Figure 4.

In total, the propane contributed to an experiment's HRR for 90 min, after which time the burners were turned off. In cases where the CLT contributed as a source of fuel, the total HRR increased, with the fire duration often extended beyond 90 min.

4.4. Instrumentation

Figure 5 indicates the location of instrumentation with associated surface and location references. These locations result in nine instrument groupings per wall or ceiling, corresponding with the half and quarter points of the surface's width and height. At each location, e.g., A, B, C, etc., thermocouples were located for the purposes of estimating key metrics. Namely:

- Radiative heat flux to the internal bounding surfaces, estimated from plate thermometer (PT) measurements facing to the compartment distributed as per Figure 5.
- Radiative heat flux to the façade extension above the frontal opening, measured with PTs, at different offsets from the opening soffit, in line with the façade plane as presented in Figure 5.
- Charring depths to initially exposed CLT surfaces within the enclosure. These are estimated from the position of the 300°C isotherm measured with Type K

thermocouples installed at different depths of the CLT panel (20, 40, 60 and 80 mm from the CLT surface). The error induced by placing the thermocouples perpendicular to the thermal gradient was not assessed as it was assumed that this error was consistent across all the locations.

- Charring rates and corresponding estimates of heat release rate contribution from exposed surfaces have been determined from in-depth temperatures.
- Where protected, interface temperatures at the surface of the CLT; behind the protective lining.

Elaboration on how radiative heat fluxes and heat release rate contributions from initially exposed surfaces are calculated is given in Sects. 4.5 and 4.6, respectively.

4.5. Estimation of Heat Fluxes

Façade, ceiling and wall mounted plate thermometers (PT) were utilised to estimate the radiative heat flux to the surfaces, adopting the correlations presented in Ingason and Wickstrom [37], as adopted by other researchers for similar applications, e.g., Su et al. [38].

The relevant correlation is given in Eq. (1) with key terms and values populated in Table 1.

$$\dot{q}_{inc} = \left(\varepsilon_{pt}\sigma T_{pt}^4 + \left(h_{pt} + K_{cond}\right)\left(T_{pt} - T_\infty\right) + \rho_{st}c_{st}\delta\left(\Delta T_{pt}/\Delta t\right)\right)/\varepsilon_{pt} \tag{1}$$

4.6. Estimation of Heat Release Rate from Initially Exposed Surfaces

Bartlett et al. [39], note that the charring rate of wood (β) can be correlated to its mass loss rate ($\dot{m}''$), according to Eq. (2), where ρ_w is the density of wood.

$$\beta = \dot{m}''/\rho_w \tag{2}$$

For an exposed surface, the heat release rate contribution ($\dot{Q}$) becomes:

$$\dot{Q}_s = A_s\beta\rho_w\Delta H_c \tag{3}$$

where A_s is the area of the initially exposed surface and ΔH_c is the effective heat of combustion.

The estimation of the heat release rate from initially exposed surfaces is calculated according to Eq. (3), adopting a mean density of CLT of $\rho_w = 433kg/m^3$ as reported in [40] and the mean effective heat of combustion of Radiata Pine of $\Delta H_c = 17.5MJ/kg$ in accordance with [39].

The charring rate was estimated from each experiment based on the in-depth thermocouples to each exposed surface, noting the char front to broadly coincide with the 300℃ isotherm. In-depth temperatures were measured in multiple loca-

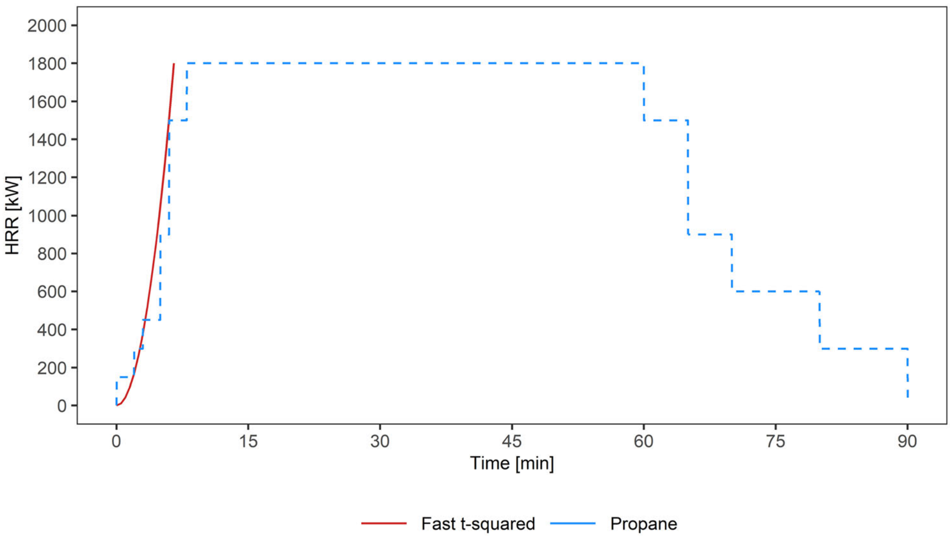


Figure 4. Propane HRR with time, alongside target fast t-squared growth rate.

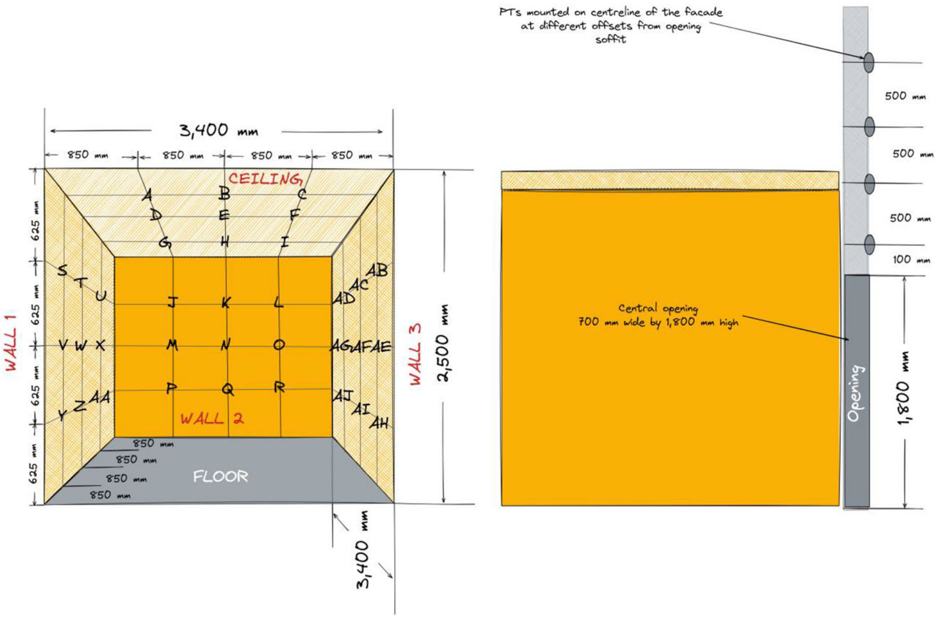


Figure 5. Instrumentation locations and surface references (left) view inside the enclosure; and (right) side elevation.

tions on a surface. Thus, an average charring rate versus time was adopted when computing $\dot{Q}_s$.

5. Results

In all cases, experiments were run until such time that either (a) initial self-extinction of flaming combustion was observed, or (b) steady continuous flaming over a prolonged period resulted in a need to intervene to prevent potential damage to the laboratory facilities. This typically resulted in an experimental duration and, thus, data logging period of ca. 2.5 h (150 min). Experiments were run without any external fire-fighting intervention, except where required to terminate the experiment. The only exception to this was Experiment 1a, where water was applied to the floor of the compartment to cool propane supply lines, at ca. 15 and 40 min from ignition. As a result, Experiment 1a was excluded from the further analysis and the need to cool the supply lines was resolved for Experiment 1b onwards.

Section 5.1 provides a summary of observations from all experiments. In Sect. 5.2, the datasets of two specific experiments are presented as examples, while Sect. 6 provides a comparative analysis of all experiments.

5.1. Observations

A precis of observations for each experiment is given in Table 2. Cases where self-extinction of flaming combustion was initially observed are shown with a green background. Those where self-extinction of flaming combustion was not achieved are shown with an orange background. For the purpose of interpreting the summary, it is considered that the CLT did not become involved if post-experimental inspection of the samples did not indicate significant pyrolysis, i.e., significant discolouration.

5.2. Sample Results

The following figures depict a representative dataset obtained from two experiments, specifically Experiment 3a and Experiment 7a. The plots show mean values as a dashed line and the standard error of the mean as a shaded region. A more exhaustive representation of the data is given in Sect. 6, where all the experiments are analysed and compared. In Sect. 6, most of the analysis is conducted by averaging the experimental data between the minute 50 and 60 of each experiment, as illustrated in Figures 6 and 7.

Figure 6 shows the time evolution of the gas-phase temperatures inside the compartment (dashed line, left y-axis), the incident radiant heat fluxes to the internal walls (solid line, right y-axis) and the incident radiant heat fluxes to the façade for sensors located at different heights, as per Sect. 4.4 (solid line with different grey shades, right y-axis).

Since the gas burners were configured in the same manner across all the experiments, the fire development had similar timescales and burning characteristics.

Table 1
Terms and Constants Adopted to Estimate Radiative Heat Flux to Ceiling and Floor, Adopted From [38].

Parameter	Description	Value	Unit
ε_{pt}	Emissivity of the PT	0.9	–
σ	Boltzmann constant	$5.67\,10^{-8}$	$W/m^2/K^4$
h	PT convection coefficient	10	$W/m^2/K$
K_{cond}	Conduction correction factor	8	$W/m^2/K$
T_{pt}	PT temperature	Varies	K
T_{∞}	Ambient temperature	293	K
ρ_{st}	Density of steel plate	8100	Kg/m^3
c_{st}	Specific heat of steel plate	460	J/kg/K
δ	Thickness of steel plate	0.00123	m

Typically, flashover occurred within approximately 10 min, initiating a fully developed fire stage that lasted for approximately 60 min. During this stage the highest temperatures and heat fluxes were recorded. Subsequently, the gas burners were progressively shut down causing the fire to enter a decay stage. For enclosure configurations that achieved initial self-extinguishment of flaming, the decay stage would continue until recording ambient conditions. This is apparent in Experiment 3a presented in Figure 7. However, in the case illustrated in Figure 6 and other configurations that did not self-extinguish, the fire either developed into a second fully developed fire or it sustained continuous burning with lower temperatures and heat fluxes than during the fully developed phase, but with no indications that the fire would eventually self-extinguish.

Another variable of interest is the charred depth of the exposed CLT. Based on the readings from the in-depth thermocouples, the charred depth over time can be calculated as discussed in Sect. 4.4. The results of this calculation are presented in Figures 8 and 9 for Experiment 7a and Experiment 3a, respectively. From these data, the charring rates and the heat release rate contribution from initially exposed surfaces are estimated. This is discussed further in Sect. 6, where a more detailed analysis and comparison between experiments is presented.

6. Analysis and Discussion

6.1. Gas-Phase Temperatures Inside the Compartment

In the 1970s, Thomas and Heselden [41, 42] developed the enclosure fire framework to determine the fire load on the structure and fire regimes based on an opening factor. The latter represents the relationship between the heat losses through the boundaries of the enclosure and the heat generation inside represented by the air inlet, as indicated in Eq. (4).

Table 2
Summary Observations for Each Experiment Alongside Percentage of Initially Exposed CLT Surface Area

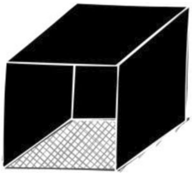
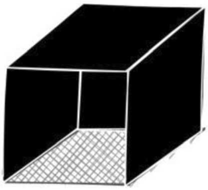
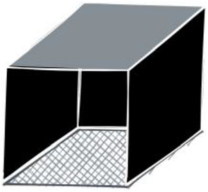
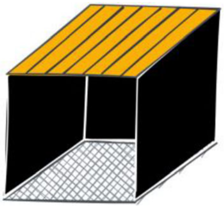
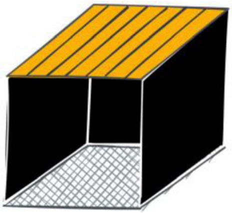
Experiment	Configuration	% of initially exposed CLT surface area	Initial self-extinction of flaming combustion	Observations
1a		0	Not applicable	CLT did not become involved. Water was applied to the floor at ca. 15 and 40 min from ignition to cool propane supply lines into the enclosure
1b		0	Not applicable	CLT did not become involved
2a		0	Yes	CLT became involved after ceiling was exposed c. 75 min from ignition of burners
3a		26	Yes	Ceiling was exposed from the outset. Self-extinction of flaming combustion was observed after the turning off propane burners, i.e., c. 90 min from ignition
3b		26	Yes	Ceiling was exposed from the outset. Self-extinction of flaming combustion was observed after the turning off propane burners, i.e., c. 90 min from ignition. Smouldering persisted behind the wall linings after self-extinction of flaming combustion

Table 2 continued

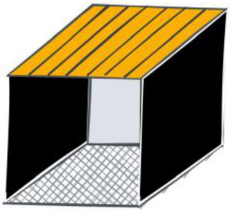
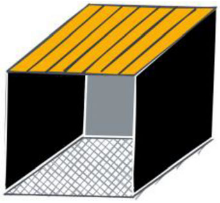
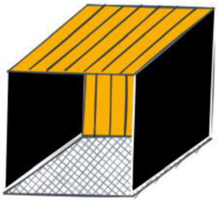
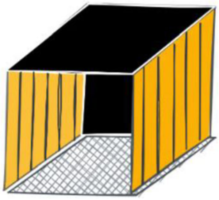
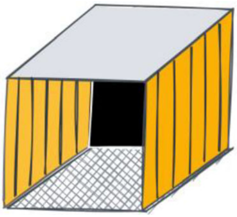
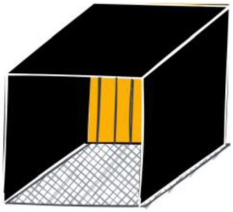
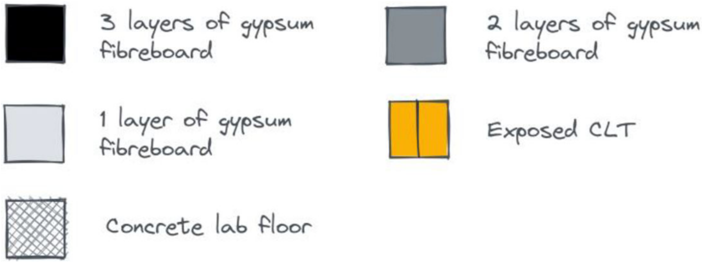
Experiment	Configuration	% of initially exposed CLT surface area	Initial self-extinction of flaming combustion	Observations
4a		26	No	Ceiling exposed from outset. Wall 2 involved from c. 30 min. Continued flaming of Wall 2 observed, with intervention required to halt flaming behind the lining
5a		26	No	Ceiling exposed from outset. Wall 2 involved from c. 90 min. Combustible gases observed to burn through cracks in board to Wall 2. Intervention required to stop flaming behind boards to Wall 2
6a		46	Yes	Ceiling and Wall 2 exposed from the outset and involved. Flaming observed to stop without intervention after c. 120 min from ignition
7a		38	No	Walls 1 and 3 exposed from the outset. Detachment of ceiling lining after c. 120 min leading to secondary ignition. Burn-through of wall connections observed leading to experiment termination
8a		38	No	Walls 1 and 3 exposed from the outset. Detachment of the ceiling lining after c. 30 min. Continued flaming of ceiling and Walls 1 and 3. Burn-through of wall splice connections observed leading to experiment termination

Table 2 continued

Experiment	Configuration	% of initially exposed CLT surface area	Initial self-extinction of flaming combustion	Observations
9a		19	No	Ceiling lining failure after c. 75 min, leading to flaming of ceiling and Wall 2, and a need to intervene
Key				

$$O_F = \frac{A_T}{A_W\sqrt{H}} \approx \frac{\text{heatlosses}}{\text{heat generation}} \quad (4)$$

where O_F is the opening factor, A_T is the area of the walls and ceiling, A_W is the area of the opening and H is the height of the opening.

The Thomas and Heselden correlation, presented in Figure 10 with the black line, establishes the link between the gas-phase temperatures of a fully developed fire and the opening factor. The plot also indicates two distinct regimes in which the fire can burn, ventilation-controlled and fuel-controlled. Each regime presents different fire dynamics governed by different physical phenomena [41, 42].

Following on from the Thomas and Heselden correlation, this study applies the same analysis as in Gorska et al. who also studied the compartment fire framework with the presence of exposed timber surfaces [43]. In her study it is discussed that the opening factor should be modified ($O_{F,modified}$) and reduced by the area of exposed CLT surfaces (A_{CLT}). This way, the heat losses term is corrected, and it does not consider the CLT surfaces to behave as a heat sink, as given in Eq. (5)

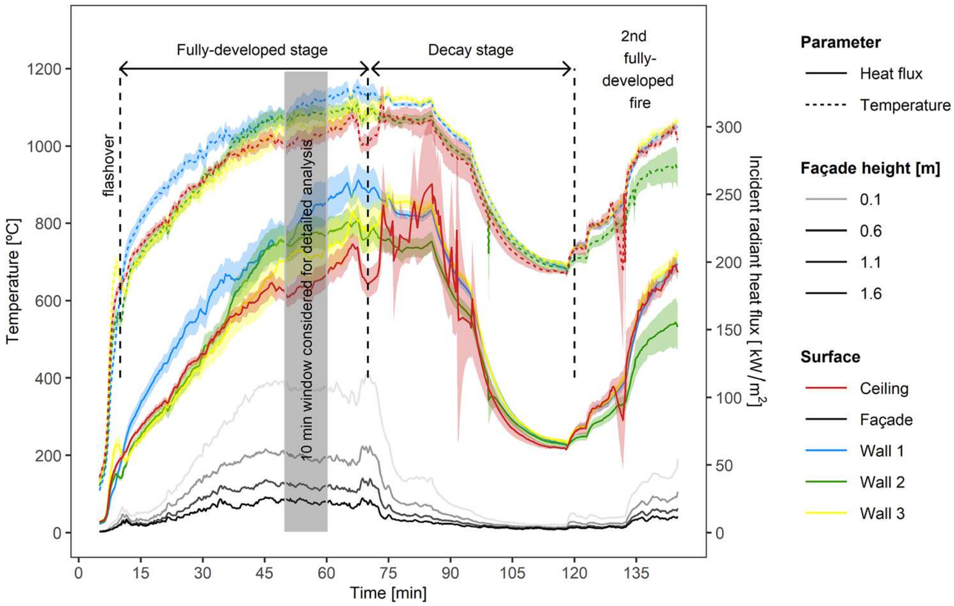


Figure 6. Sample data for Experiment 7a, showing plate thermometer temperatures and estimated radiative heat fluxes with time for internal surfaces and façade extension.

$$O_{F,modified} = \frac{A_T - A_{CLT}}{A_W \sqrt{H}} \quad (5)$$

Figure 10 presents the average gas-phase temperatures and standard error of the mean (SEM) during the last ten minutes of the fully developed stage of the experiments, plotted as coloured points and error bars. These data were measured with type K thermocouples, for which the error by radiation is not estimated, as it is assumed to be similar across all the configurations. The effect of radiation on the gas temperature measurements does not appear significant as the enclosures with the highest exposed surface area (and, thus, flame radiation) do not exhibit the highest gas phase temperatures. The experimental data are plotted using Eq. (5) to calculate their respective modified opening factor and considering the area of exposed timber during the last ten minutes of the fully developed phase. For the experiments where plasterboard fall-off occurred, the initial percentage of exposed CLT is indicated in brackets. Therefore, Figure 10 provides a means to compare the CLT experimental results with the Thomas and Heselden correlation.

Experiment 1b and 2a represent baseline cases in which all the CLT is still encapsulated and not contributing to the fire. It is noteworthy that these two baseline experiments exhibit nearly identical temperatures, indicating good repeatability. However, the experiments present a significant discrepancy with the Thomas and Heselden correlation of approximately 220℃ (during the last 10 min

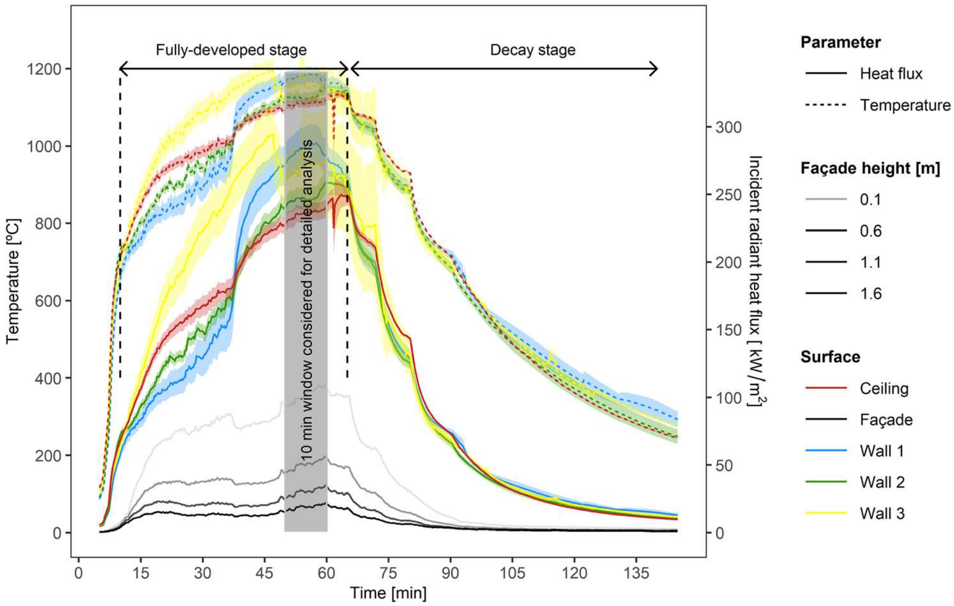


Figure 7. Sample data for Experiment 3a, showing plate thermometer temperatures and estimated radiative heat fluxes with time for internal surfaces and façade extension.

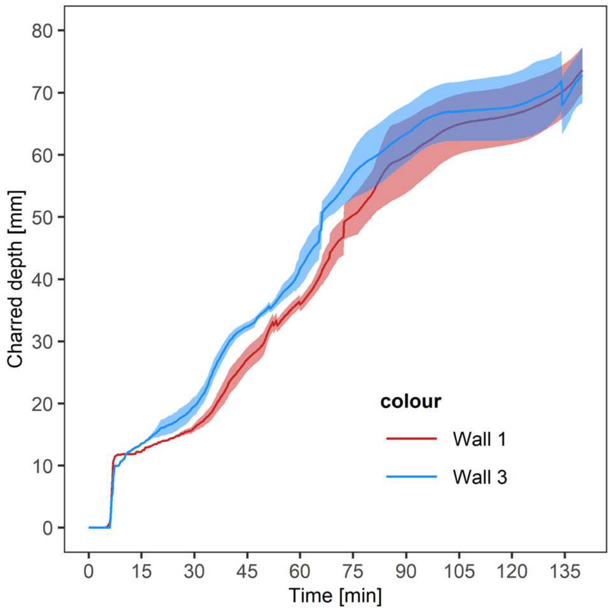


Figure 8. Sample data for Experiment 7a, showing charring depth with time for left and right walls.

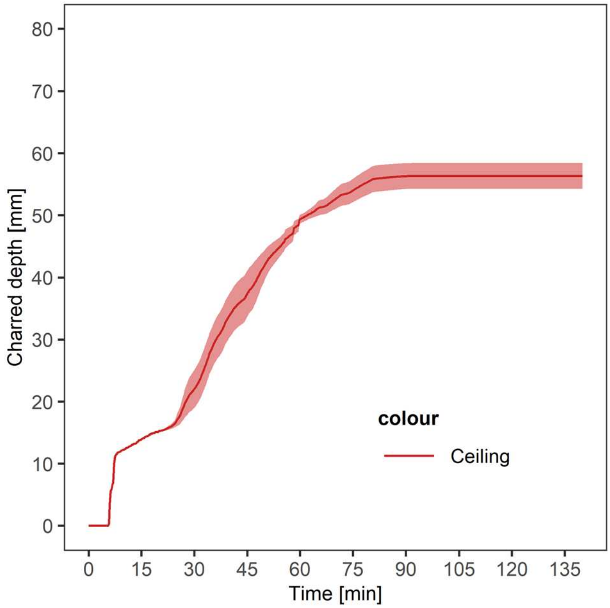


Figure 9. Sample data for Experiment 3a, showing charring depth with time for the ceiling.

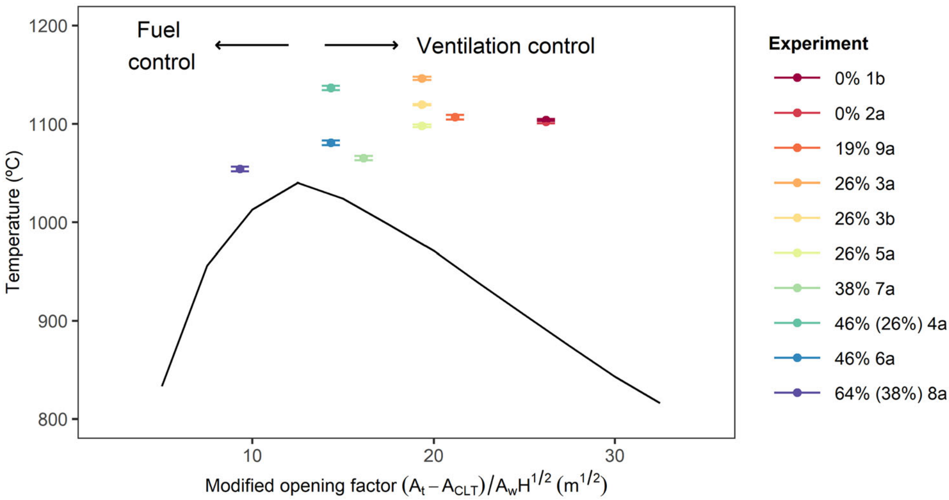


Figure 10. Comparison of the averaged gas-phase temperatures inside the compartment, of the last ten minutes of the fully developed fire of all the experiments, with Thomas and Heselden correlation.

of the fully developed phase of all experiments). Most likely this is because the materials used for these experiments (CLT and plasterboard) are highly insulative compared to the masonry used by Thomas and Heselden. Consequently, the baseline threshold values for this experimental campaign are higher than the ones predicted by the traditional correlation.

The experimental data also reveal that as more CLT is exposed (19–26%), there is an increase in temperatures inside the enclosure of up to 40°C. However, by exposing even more CLT surfaces (36–64%) the average temperatures start to decrease. For these cases, the temperatures are even lower than for the baseline experiments by 50°C. The exception to that is Experiment 4a, which suffered plasterboard fall-off during the fully developed fire and that might have created changes in the energy balance inside the enclosure and the subsequent gas-phase temperature.

This phenomenon aligns with the findings in [43], where it is theorized that gradually exposing more CLT surfaces (increasing fuel) should lead to increasing average temperatures during the fully-developed phase until reaching the adiabatic flame temperature, after which the temperatures should plateau. However, the observed temperature reduction indicates the influence of other physical phenomena on the fire once a certain percentage of timber surfaces is exposed. Gorska et al. [43] demonstrate that with greater CLT exposure, the excess of pyrolysis gases creates a highly fuel-rich environment inside the enclosure, resulting in less efficient combustion, lower temperatures, and a change in the fire regime. The authors of this paper also consider that heat losses through exposed CLT may be larger than those through CLT protected with plasterboard, further contributing to the decrease in average enclosure temperatures when more CLT surfaces are left unprotected. These arguments could explain why the plasterboard on the ceiling of experiment 9a with 19% of exposed timber area fell earlier than in experiment 7a with 38% of exposed timber. This would be because the severity of the internal fire and subsequent thermal boundary condition to the plasterboard was more onerous in experiment 9a versus 7a, as per Figure 10.

Nevertheless, the experimental data indicate an increase in gas-phase temperatures during the fully developed stage for configurations with 26% or less exposed timber. The configurations that had a higher percentage of exposed timber surfaces presented a decrease in temperatures, which are lower than the baseline experiments without exposed CLT.

6.2. Charring Rate and Heat Release Rate

The data on charring rates of different exposed timber surfaces from the different experiments and the estimated total heat release rates are presented in Figure 11. The datapoints are the estimated averaged values of the last ten minutes of the fully developed fire and the corresponding SEM values plotted as error bars reflecting the experimental deviation from the mean. The left y-axis shows the charring rates, with each surface represented by a different colour, while the right y-axis gives the estimated heat release rates from exposed surfaces.

The data of the rear wall of Experiment 4a are marked with '*' in Figure 11. This wall was exposed during the fully developed fire after the lining protection fell off. However, in this case the rear wall was not instrumented with in-depth thermocouples. Therefore, it was not possible to estimate its charring rate based on the temperature gradient. The presented values of the HRR represent three different scenarios:

- Lowest value: The HRR from the rear wall is not accounted for.
- Middle value: The HRR from the rear wall is calculated assuming the charring rate of the exposed ceiling in Experiment 4a.
- Highest value: The HRR from the rear wall is calculated assuming the charring rate of the exposed rear wall in Experiment 6a.

During the steady-state burning, the averaged charring rate was approximately 0.59 mm/min, with the exception of the ceiling in Experiment 8a where the plasterboard fell off, after c. 30 min from ignition, resulting in a higher charring rate of approximately 1.50 mm/min.

There is no clear trend indicating changes in the charring rates with variations in enclosure configurations. However, different averages suggest a relatively slower charring rate for the ceiling surfaces at approximately 0.51 mm/min compared to the walls at approximately 0.65 mm/min. This phenomenon has also been observed by Gorska et al. [43], where it is argued that the presence of a smoke layer restricts the oxygen and heat reaching the ceiling, resulting in a slower reaction rate. Due to this phenomenon, the total HRR can be correlated to the charring rate of the different exposed surfaces of CLT, but it is not proportional to the total area of exposed CLT surfaces.

On the other hand, there is a clear increase in the heat release rate of the combined contribution from the propane burners and CLT surfaces that are both initially exposed and exposed after any lining falls-off. As more CLT surfaces are exposed, the higher the heat release rate becomes. Starting with the reference value of 1800 kW, the heat release rate is estimated to increase up to 4100 kW for the Experiment 8a.

Therefore, Figure 11 clearly demonstrates that the CLT panels make a significant contribution to the total heat release rate. It can be foreseen that the excess pyrolysis gases from the CLT panels will also increase the external flame, as discussed in Sect. 6.3.

6.3. Heat Fluxes to the Façade

Figure 12 illustrates the heat fluxes to the façade induced by the external flame at various distances from the opening, considering different enclosure configurations. In this plot, the data also correspond to the averaged and SEM values of the last 10 min of the fully developed fire. As anticipated, the heat fluxes increase as the measurement location gets closer to the opening in all experiments.

Building upon the discussion in Sect. 6.2, it is further observed that there is a significant rise in heat fluxes to the façade as more timber surfaces are exposed

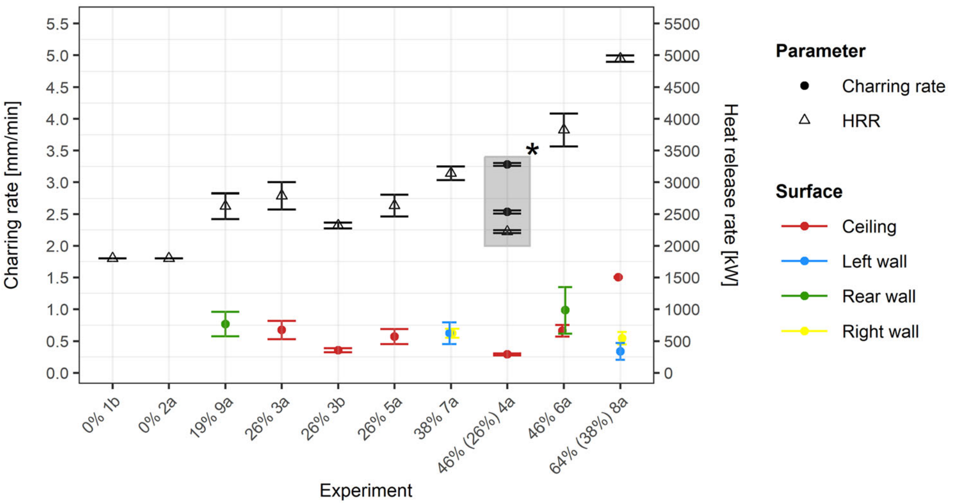


Figure 11. Averaged charring rates of the different exposed CLT surfaces during the last ten minutes of the fully developed fire for all the experiments and the estimated total heat release rate of the enclosure fire.

within the enclosure, aligning with the trend seen in the combined heat release contribution from exposed surfaces and the propane burner. The data suggest that the incident radiant heat fluxes for experiments with larger areas of exposed timber can be more than three times greater than those of the baseline experiments (without exposed CLT). This increase can be attributed to the presence of unburnt pyrolysis gases within the enclosure, which flow out and react with the surrounding air, generating a considerably larger external flame and overall heat release rate.

This phenomenon has also been noted by Gorska et al. [43], Frangi et al. [44], Hakkarainen et al. [45] and others, emphasizing the importance of considering it during the design of buildings with enclosures containing exposed timber surfaces. The higher thermal load on the façade and/or external elements resulting from increased heat fluxes and correspondingly taller flames facilitates vertical fire spread and should be carefully addressed in a fire safety strategy for a mass timber building.

6.4. Decay Stage and Self-Extinguishment

Self-extinguishment of mass timber structures is fundamental to allow compartmentation and CLT structures to perform adequately after the consumption of the moveable fuel load, therefore assuring that the fire duration does not extend beyond the time at which structural elements reach their ultimate strength. For this analysis, self-extinguishment refers to the initial cessation of visible flaming combustion, which can be followed by smouldering or by a complete stop of the combustion. Self-extinguishment of flaming combustion of timber can occur

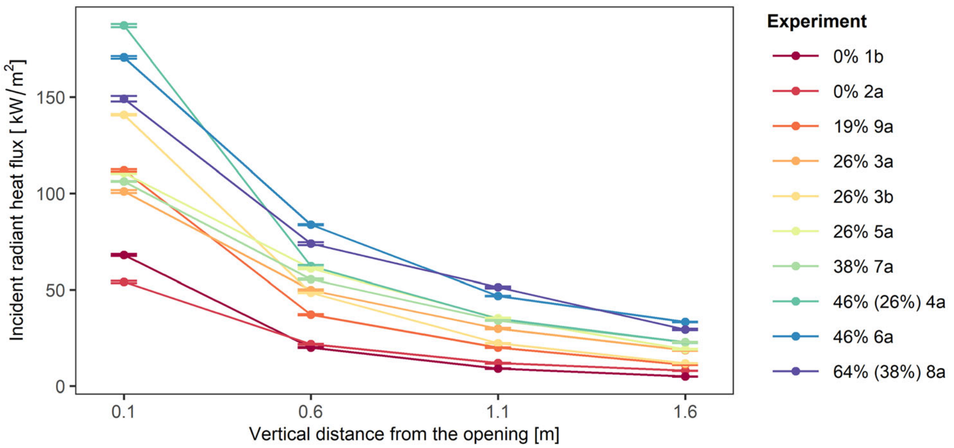


Figure 12. Averaged incident radiant heat fluxes to the façade during the last ten minutes of the fully developed fire at different heights from the opening.

because the flame produced by the burning of solid timber does not provide sufficient energy to sustain a continuous flaming combustion reaction. Hence, continuous burning will only occur in the presence of an additional external heat source [19], such as another exposed timber surface or energy from burning contents.

Previous small-scale experiments conducted by Emberley et al. [46] and Bartlett et al. [47] investigated the conditions for self-extinguishment of 0.12 m^2 Radiata Pine samples exposed to constant external heat fluxes. These experiments showed that self-extinguishment would occur if the mass loss rate drops below 3.65 ± 0.21 g/s/m and the external heat flux is less than 44.5 ± 1.2 kW/m^2 for Emberley et al. experiments and a mass loss rate below of 3.48 ± 0.3 $g/s^1/m^2$ and external heat flux of 31 kW/m^2 for Barlett et al. experiments. The two mass loss rates are within their experimental errors. It is believed that the inconsistency in the heat fluxes may be related to different experimental setups and boundary conditions imposed on the sample [48, 49].

The next step is to establish the conditions for self-extinguishment of timber when the samples are exposed to compartment fire conditions, which include a much higher level of complexity due to the presence of a larger amount of variables (i.e. ventilation conditions, heat exchange between surfaces, plasterboard fall off, delamination) [50].

In Figure 13 the time evolution of the incident heat flux to the rear wall of the enclosure is presented for all configurations. The figure clearly distinguishes between the fully developed fire and the decay phase, with experiments that achieved initial self-extinguishment (of flaming combustion) shown by blue lines and those that continued burning shown by red lines.

Figure 13 indicates that the internal fire dynamics during the fully-developed fire stage do not play a significant role in the self-extinguishment phenomenon. This is evident as the red curves (no self-extinction) sometimes exhibit lower heat fluxes than the blue curves from experiments that did achieve self-extinguishment. However, during the decay phase, the red curves display a slower rate of decay (gradient) compared to the experiments that self-extinguished. As a result, some experiments that did not self-extinguish showed higher heat flux values during the decay-phase compared to the self-extinguished experiments, despite having lower heat fluxes during the fully developed fire. This suggests that the fire curve during the decay phase is crucial in predicting whether self-extinguishment will occur or not. The experiments that continued burning did not fall below the critical threshold for self-extinguishment defined by Emberley et al. of 44.5 ± 1.2 kW/m^2 at any time.

Based on the analysis of Figure 13 it could tentatively be concluded that the previously defined critical value for self-extinction in bench-scale experiments is also applicable to large-scale enclosure fires. Experiments that crossed this critical value achieved self-extinguishment, while those that produced sufficient thermal feedback during the decay phase to prevent the incident heat flux from falling below the threshold never self-extinguished.

The results from this analysis aligns with the results and conclusions from the previous research conducted by Gorska [50] in which very similar trends were observed as presented in Figure 13 in 36 medium-scale and one large-scale compartment fire experiments with exposed timber.

As in Sect. 2, partial protection has gained traction as a design solution for residential applications owing optimisations that are achieved in the amount of dry-lining material that can be applied to an isolated element whilst achieving a target level of fire resistance in a standard test. From the enclosure experiments conducted herein, it is observed that only one experiment (Experiment 2a) achieved a self-extinction outcome when adopting a form of partial protection solution. In this case, the ceiling was provided with two layers of plasterboard which were insufficient to prevent pyrolysis of the ceiling CLT for the full duration of the fire. Despite this, the protective lining delayed the involvement of the CLT until the propane burners were entering the decay phase, with fall-off observed from c. 75 min from ignition. In all other cases adopting a partial protection solution, self-extinction was not achieved. Of note is the contrast between Experiments 4a, 5a and 6a. The former two adopted partial protection to the rear wall, comprising either one or two layers of plasterboard. The latter exposed the CLT to the rear wall. In all three, the ceiling was exposed from the outset. Experiment 6a self-extinguished, whilst Experiments 4a and 5a did not. This suggests that partial protection can, in some configurations and despite greater protection quantities, reduce the likelihood of achieving self-extinction and, thus, the ability of the structure to remain stable through the full duration of a fire event.

Closer observation of experiments that featured partial protection highlights that linings can permit the pyrolysis of the substrate yet remain attached to the CLT. This was particularly the case for partially protected walls, where cracks were observed to develop in the attached linings, leading to the migration of pyrolysis gases and flaming at the fissure locations. It is postulated that partial protection solutions that permit pyrolysis but remain attached to the substrate prevent self-extinction as the heat flux from the lining is sufficient to keep the

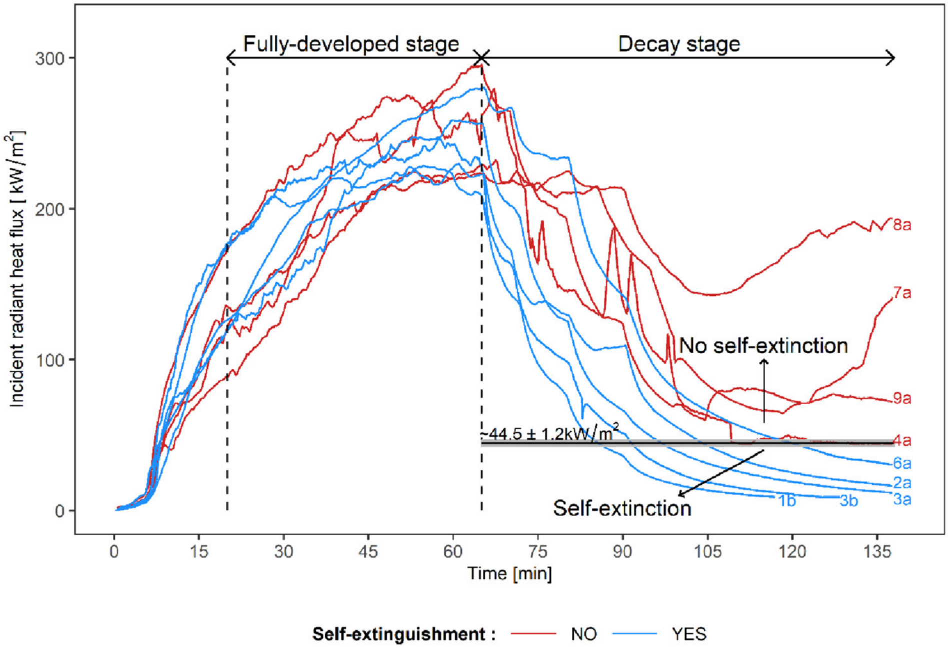


Figure 13. Incident radiant heat flux to rear wall with time for all experiments, indicating whether or not self-extinction of flaming combustion was achieved.

CLT above the self-extinction threshold (Figure 14). Ensuring that a structure can remain stable where partial protection is adopted is likely to place great emphasis on the fire and rescue service to remove lining materials to tackle combustion occurring behind the lining.

6.5. Lining Versus Char Fall-off

Experiments 7a and 8a could be said to have suffered secondary flashover events after appearing to enter a decay phase. In both cases, this followed the extensive fall-off of dry-lining protection materials to the ceiling.

Owing to the CLT adhesive adopted, alongside the duration of thermal exposure, CLT elements were observed to suffer bond-line failures leading to premature char fall-off in all experiments where CLT was initially exposed. This was generally more pronounced to ceiling versus wall elements and comprised pieces of burned CLT that were c. 100 100 mm in size at most. Despite this, initial self-extinction occurred in several cases and, thus, averting premature char fall-off was not a prerequisite, as was observed in other studies by the authors [32].

Based on the experiments presented here and as discussed in [51], it is posited that the fall-off of lining materials has a substantially larger influence on the uncertainty of how a fire might develop within a CLT enclosure compared to premature char fall-off. This is important in terms of potential hazards to occupants and the fire and rescue service, as the course of a fire's development was consistently more 'predictable' in cases where CLT surfaces were exposed from the outset. That is not to say that this predictability infers a positive outcome in all cases. Instead, that the hazard is identifiable and does not substantially alter with time due to a sudden increase in exposed combustible surface area that typically coincides with the failure of dry-lining materials.

7. Conclusions

This study has examined the impact of CLT surface exposure on fire behaviour and performance within residential type enclosures. The results revealed that the traditional correlation between gas-phase temperatures and the opening factor developed by Thomas and Heselden did not align well with the baseline experiments likely due to the insulative properties of the CLT and plasterboard materials used. Modified opening factors have been previously introduced to account for the exposed CLT surface area and correct the heat losses term.

The data showed that as the percentage of exposed CLT surfaces increased up to a certain point (36–64%), the temperatures inside the compartment decreased, indicating the influence of other physical phenomena, such as the excess of pyrolysis gases.

Charring rates did not exhibit a clear trend with variations in enclosure configurations, but the total heat release rate increased as more CLT surfaces were exposed. The CLT panels significantly contributed to the total heat release rate, which in turn led to higher heat fluxes to the façade.

Regarding initial self-extinguishment of flaming combustion, the analysis demonstrates that the fire dynamics during the decay phase play a crucial role. Experiments that crossed the critical heat flux threshold obtained from bench-scale testing of 44.5 ± 1.2 kW/m^2 achieved self-extinguishment, while experiments that maintained sufficient thermal feedback did not self-extinguish. Partial protection, i.e., protection that is not designed to withstand the whole duration of the fire, did not increase the possibility of self-extinguishment as also concluded by Su et al. [27]. In all but one instance, partial protection could be said to have hindered a self-extinction outcome by allowing heat to be trapped at the interface between the protective lining and CLT substrate.

Uncertainty in the development of fires in the CLT enclosures was more significant where lining materials detached either during the fully developed or decay phases of a fire. In two instances, this led to secondary flashovers. Premature char fall-off was observed in all experiments that featured initially unprotected CLT surfaces. This was not an impediment to self-extinction where the exposed surface area of the enclosure was sufficiently low, with the interaction of multiple combustible surfaces having a more significant influence over whether self-extinction of flaming combustion occurred. These observations align with the conclusions found in the work of Bøe et al. [25, 26].

Thus, these experiments suggest that for these types of enclosures, the fall-off of partial protection and the amount of exposed timber surfaces during the decay

Figure 14. Flaming behind plasterboard and in cracks in boards for partially protected solution.

phase play a key role in predicting self-extinguishment. Whereas char fall-off is a third variable of a lesser influence on the self-extinguishment phenomenon.

The study contributes to a better understanding of fire behaviour in such scenarios, enabling more informed fire safety measures and design considerations for CLT-based construction. It is noted that 'more protection' does not necessarily equate to more reliable self-extinction outcomes and that partial encapsulation can have an opposing consequence by inhibiting heat losses and thus preventing self-extinction.

Acknowledgements

The authors wish to acknowledge the contributions of the wider STA-SiG project team, including the discussions and technical contributions made by the Structural Timber Association (STA), BK Structures and Eurban.

Author Contributions

DH—conceptualization, methodology, formal analysis, writing, original draft preparation, project administration. WW—conceptualization, methodology, experimental investigation, writing, review and editing. CG—conceptualization, formal analysis, writing, review and editing. MS—conceptualization, methodology, writing, review and editing. HK—conceptualization, supervision, project administration, funding acquisition, writing, review and editing. TS—conceptualization, supervision, project administration, funding acquisition, writing, review and editing. RB—conceptualization, supervision, project administration, funding acquisition, writing, review and editing. GS—supervision, conceptualization, project administration, funding acquisition, writing, review and editing. All authors have read and agreed to the published version of the manuscript.

Funding

The funding made available by Stora Enso, KLH and Binderholz to undertake this work is gratefully acknowledged.

Funding

The funding made available by Stora Enso, KLH and Binderholz to undertake this work is gratefully acknowledged.

Declarations

Consent for Publication AI tools have been used to proof check the text in this article. During the preparation of this work the author(s) used ChatGPT in order to proof check the article and also assist with the abstract and conclusions. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Open Access

References

1. 68% of the world population projected to live in urban areas by 2050 says UN | UN DESA | United Nations Department of Economic and Social Affairs. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html. Accessed 04 Jul 2023

2. Facts about the climate emergency. UNEP–UN Environment Programme. http://www.unep.org/facts-about-climate-emergency. Accessed 04 Jul 2023
3. Kisic M, Ferguson C, Clarke C, Smyth J (2018) Building pressure. CDP, London
4. Smedley T (2023) Building with wood could be the ultimate carbon capture. The New Climate. https://medium.com/the-new-climate/building-with-wood-is-the-ultimate-carbon-capture-technology-f667e04c4d84. Accessed 04 Jul 2023
5. Sustainable building: the hottest new material is, uh, wood - Vox. https://www.vox.com/energy-and-environment/2020/1/15/21058051/climate-change-building-materials-mass-timber-cross-laminated-clt. Accessed 04 Jul 2023
6. The Biophilic Response to Wood: Can it Promote the Wellbeing of Building Occupants?', ArchDaily. Accessed: Jul. 04, 2023. [Online]. Available: https://www.archdaily.com/974790/the-biophilic-response-to-wood-can-it-promote-the-wellbeing-of-building-occupants
7. Waugh Thistleton Archtitects website. https://waughthistleton.com/murray-grove/
8. Are mass-timber buildings a fire safety risk?. Dezeen. https://www.dezeen.com/2023/03/22/mass-timber-fire-safety-timber-revolution/. Accessed 04 Jul 2023
9. Bisby LA (2021) Structural fire safety when responding to the climate emergency. Struct Eng 99:26
10. Law A, Hadden RM (2020) We need to talk about timber: fire safety design in tall buildings. Struct Eng 98(3):10–15
11. Todd C (2018) Report for the Grenfell Tower inquiry; legislation, guidance, and enforcing authorities relevant to fire safety measures at Grenfell Tower. CS Todd & Associates Ltd, Farnham
12. HM Government (2018) The building (Amendment) regulations 2018. Ministry of Housing, Communities and Local Government. http://www.legislation.gov.uk/uksi/2018/1230/made
13. BSI (2018) BS EN 13501-1:2018 Fire classification of construction products and building elements. Classification using data from reaction to fire tests. BSI, London
14. Law A, Butterworth N (2019) Prescription in English fire regulation: treatment, cure or placebo?. Proc Inst Civil Eng For Eng . 10.1680/jfoen.19.00004
15. Approved Document B: Fire safety—frequently asked questions. GOV.UK. https://www.gov.uk/guidance/approved-document-b-fire-safety-frequently-asked-questions. Accessed 05 Jul 2023
16. STA (2020) Structural timber buildings fire safety in use guidance: Volume 6—mass timber structures, compliance with building regulation B3(1). Structural Timber Association, Alloa
17. BS EN 14135:2004 Coverings (2004) Determination of fire protection ability. British Standards Institute, London
18. Pearson A (2016) Dalston Lane: Tall Timber. https://www.building.co.uk/technical-case-studies/dalston-lane-tall-timber/5079749.article
19. Drysdale D (2011) An introduction to fire dynamics, 3rd edn. Wiley, Hoboken. 10.1002/9781119975465.ch1
20. Buchanan A, Ostman B, Frangi A (2014) Fire resistance of timber structures. National Institute of Standards and Technology, Gaithersburg
21. Brandon D, Ostman B (2016) Fire safety challenges of tall wood buildings—phase 2: task 1—literature review. National Fire Protection Association Research Foundation, Quincy
22. Ronquillo G, Hopkin D, Spearpoint M (2021) Review of large-scale fire tests on cross-laminated timber. J Fire Sci . 10.1177/07349041211034460

23. Liu J, Fischer EC (2022) Review of large-scale CLT compartment fire tests. Constr Build Mater 318:126099. 10.1016/j.conbuildmat.2021.126099
24. Mitchell H, Kotsovinos P, Richter F, Thomson D, Barber D, Rein G (2023) Review of fire experiments in mass timber compartments: current understanding, limitations, and research gaps. Fire Mater 47(4):415–432. 10.1002/fam.3121
25. Bøe AS, Friquin KL, Brandon D, Steen-Hansen A, Ertesvåg IS (2023) Fire spread in a large compartment with exposed cross-laminated timber and open ventilation conditions: #FRIC-01—exposed ceiling. Fire Saf J 140:103869. 10.1016/j.firesaf.2023.103869
26. Bøe AS, Friquin KL, Brandon D, Steen-Hansen A, Ertesvåg IS (2023) Fire spread in a large compartment with exposed cross-laminated timber and open ventilation conditions: #FRIC-02—exposed wall and ceiling. Fire Saf J 141:103986. 10.1016/j.firesaf.2023.103986
27. Su J et al (2021) Fire testing of rooms with exposed wood surfaces in encapsulated mass timber construction. Natl Res Council Canada Construct . 10.4224/23004642
28. DEFRA (2023) Timber in construction roadmap. DEFRA, London
29. Kotsovinos P et al (2023) Impact of partial encapsulation on the fire dynamics of an open-plan compartment with exposed timber ceiling and columns: *CodeRed #04*. Fire Mater 47(4):597–626. 10.1002/fam.3112
30. Brandon D (2021) Fire safe implementation of visible mass timber in tall buildings—compartment fire testing. RISE Rep 2020:94
31. The New Model Building, Building Net Zero Homes. Waugh Thistleton Architects. https://waughthistleton.com/new-model-building/
32. Hopkin D et al (2022) Large-scale enclosure fire experiments adopting CLT slabs with different types of polyurethane adhesives: genesis and preliminary findings. Fire 5(2):39. 10.3390/fire5020039
33. BSI (2016) BS EN 13501-2:2016 Fire classification of construction products and building elements. Classification using data from fire resistance tests, excluding ventilation services. BSI, London
34. ISO (1999) ISO 834–1:1999 fire-resistance tests—elements of building construction—part 1: general requirements. International Organization for Standardization, Geneva
35. Wade C, Baker G, Frank K, Harrison R, Spearpoint M (2016) B-RISK 2016 user guide and technical manual. Building Research Association of New Zealand, Judgeford
36. HM Government (2022) The building regulations 2010, approved document B (fire safety) volume 1: Dwellings (2019 edition incorporating 2020 and 2022 amendments).
37. Ingason H, Wickström U (2007) Measuring incident radiant heat flux using the plate thermometer. Fire Saf J 42(2):161–166. 10.1016/j.firesaf.2006.08.008
38. Su J, Lafrance PS, Hoehler M, Bundy M (2018) Fire safety challenges of tall wood buildings—phase 2: task 2 & 3—cross laminated timber compartment fire tests. Fire Protection Research Foundation, Quincy, FPRF-2018-01
39. Bartlett AI, Hadden RM, Bisby LA (2019) A review of factors affecting the burning behaviour of wood for application to tall timber construction. Fire Technol 55(1):1–49. 10.1007/s10694-018-0787-y
40. Hopkin D et al (2021) Experimental characterisation of the fire behaviour of CLT ceiling elements from different leading suppliers. Appl Structl Fire Eng 2021:10–11
41. Thomas PH (1973) Behavior of fires in enclosures—some recent progress. Symp (Int) Combust 14(1):1007–1020. 10.1016/S0082-0784(73)80091-8

42. Thomas PH, Heselden AJM (1962) Behaviour of fully developed fire in an enclosure. Combust Flame 6:133–135. 10.1016/0010-2180(62)90081-0
43. Gorska C, Hidalgo JP, Torero JL (2020) Fire dynamics in mass timber compartments. Fire Saf J . 10.1016/j.firesaf.2020.103098
44. Frangi A (2005) Fire performance of timber structures under natural fire conditions. Fire Saf Sci 8:279–290
45. Hakkarainen T, Oksanen T (2002) Fire safety assessment of wooden facades. Fire Mater 26(1):7–27. 10.1002/fam.780
46. Emberley R, Inghelbrecht A, Yu Z, Torero JL (2017) Self-extinction of timber. Proc Combust Inst 36(2):3055–3062. 10.1016/j.proci.2016.07.077
47. Barlett A, Hadden R, Bisby L, Lane B (2016) Auto-extinction of engineered timber as a design methodology. WCTE, Vienna
48. Cuevas J, Hidalgo J, Torero J, Maluk C (2019) Complexities of the thermal boundary conditions when testing timber using the fire propagation apparatus. ISFEH, Naples
49. Gorska C, Hidalgo JP, Torero JL (2017) An experimental study of medium-scale compartment fire tests with exposed cross laminated timber. Doppiavoce, Italy
50. Gorska C (2019) Fire dynamics in multi-scale timber compartments. The University of Queensland, Brisbane
51. Epernon Fire Tests Programme. Epernon Fire tests programme. http://www.epernon-fire-tests.eu/. Accessed 03 Oct 2019