

Advancing Timber for the Future Built Environment

EVALUATION OF PARAMETRIC FIRE MODELS FOR UNDER-VENTILATED MASS TIMBER COMPARTMENTS

Amanda Quan¹,

ABSTRACT: Timber is combustible yet is efficient for building structures with unusual yet beneficial thermal properties. Research suggest that the timber structural elements can contribute to a fire event and add to the compartment's fuel load. This results in a more hazardous and intense fire event. Despite these challenges, the search for analytical method(s) for fire safe design using timber can create pathways for mass timber structures. This paper critically investigates the assumptions and analytical methods in developing parametric fire curves for timber fire compartments. This involves reproducing parametric time-temperature curves, comparing to historical experimental results, and observe the fire dynamics within exposed timber compartments. By highlighting key governing factors during fire, this paper will bring society a step closer to a universally acceptable method for structural timber design and enable progress towards fire safe complex timber building structures

KEYWORDS: timber structures, fire safety, parametric

1. INTRODUCTION

Building designs are required to consider the impact of catastrophic events, such as fires, which result in significant consequences. Unfortunately, timber burns; therefore, today's society tends to steer away from selecting timber for complex structures. Currently, in the built environment industry, timber can be used as lightweight frames in domestic homes and structurally for buildings up to 25m in effective height. It can also support non-loadbearing structures in complex buildings and serve as surface linings for walls, floors, and ceilings. Building codes and global regulations prescribe limitations for timber use due to its combustible nature. This does not align with the rapidly growing demand for sustainable materials, prompting designers to adopt a performance-based design approach.

Several studies suggest timber structural elements, when exposed to fire, contributes to the Heat Release Rate (HRR) and adds to the compartment fuel load, resulting in more hazardous and intense fire event^{1,2,3}. This poses challenges to minimising fire risks, with designers encouraged to apply onerous fire engineering requirements. These requirements often restrict the architectural vision for biophilic design and/or counteract the building's sustainable rating.

The search for a verified analytical method or guideline for structural timber design in fire safety has been the subject of ongoing investigation, as engineers and academics seek to apply its material properties in mass timber structures. The analytical method or guideline will be fundamental to support the holistic fire safety strategy, which is required to demonstrate protection of life safety and property during and after a fire event. Universally acceptable method(s) for structural timber design enable society to progress towards complex timber building structures.

2. LITERATURE REVIEW

2.1 COMPARTMENT FIRES

The term "compartment fire" has been described in several ways. In layman's terms, a compartment fire is simply a fire that is confined within a room or enclosure in a building⁴. The room or enclosure typically has vertical openings, such as windows, which can potentially allow the fire or smoke to spread beyond the room. The development of a fire in a compartment does not differ between combustible and non-combustible structures. The time to reach flashover conditions can vary depending on the contents of the compartment (fuel load) and the size of ventilation openings⁴. A non-combustible compartment with fire-resistant fuel loads and minimal ventilation openings will result in a prolonged time for a fully developed fire, (if any). However, in this era, building design is becoming more innovative and creative, requiring clever engineering to ensure life safety during and after a fire event. Currently, mass timber structures are uncommon due to their combustible nature.

2.1.1 FIRE DYNAMICS

¹ Amanda Quan, Fire Safety Engineer, Aurecon, Perth, Australia, <u>Amanda.Quan@aurecongroup.com</u>

The nature of fire dynamics in compartments is based on the fundamental work of Kawagoe (1958) and Thomas et $al.(1962-1972)^5$.

Flaming combustion requires oxygen for continued development^{4 to6}. For compartments of small openings or minimal leakage, fires typically become oxygen-starved or progress with a very slow burning rate. Kawagoe found that the burning rate within a fire compartment is proportionally dependent on the ventilation factor. The ventilation factor can be used to determine if a fire will develop into a ventilation-controlled or fuel-controlled fire.

Thomas et al. expanded on Kawagoe's theorem by expressing the burning rate as a direct function of gas phase temperatures. Furthermore, they found that a Regime I fire (ventilation-controlled) was more severe than a Regime II fire (fuel-controlled)⁵. This finding encourages designers to consider incorporating large window areas where possible to reduce the need for fireproofing compartment boundaries. Studies by Harmathy recognized that the difference between the Regime fires lies in the relationship between gas phase temperature and the duration of the fire⁷. It was observed that fuel-controlled fires burn at lower temperatures and have shorter burn durations, while oxygen-controlled fires burn at higher temperatures and have longer burn durations.

It is worth noting that these studies are based on quasicubic small room enclosures, and research on abstract open plan compartments is still in its early stages⁸. However, these concepts serve as tools for fire engineers to analytically describe compartment temperatures and burning rates as functions of ventilation factors.

Additionally, the theorems and concepts derived by Kawagoe and Thomas et al. are based on non-combustible compartments and are intended to understand fire dynamics within enclosures with different fuel loads⁶. They do not account for combustible compartments that contribute to the fuel load and impact the fire dynamics of the compartments. Therefore, integrating these theorems and concepts to formalise an engineering expression for combustible materials, such as timber, is an intuitive step.

2.2 FIRE CURVES

The most common method of determining the fire performance of a structure is by conducting a full-scale fire test. The fire test corresponds to a standard fire curve (ISO834), which establishes uniform fire test conditions for structural members. The standard fire curve describes a fully developed fire but neglects the decay phases of the fire. Various methods are used globally to conduct fire tests and establish standardised values for structural elements exposed to fire, known as Fire Resistance Levels (FRLs). Ideally, conducting physical fire tests for building design purposes can help determine the effectiveness and safety of the proposed strategy. However, these tests are costly and require time and labour to produce a test certificate that describes the structural element's fire performance. As a result, analytical methods are preferred and commonly used in design. It is critical to ensure that these analytical methods are continuously verified and validated by multiple qualified and competent engineers or researchers.

2.2.1 PARAMETRIC FIRE CURVES

Parametric fire equations are typically expressed in terms of temperature as a function of time. Currently, the Eurocode 1 (European Committee for Standardisation 2002) provides guidelines for developing parametric fire curves. The Eurocode 1 method (EN 1991-1-2:2002) provides a good approximation of the burning period of the Swedish curve, thereby offering a realistic timetemperature relationship for key parameters such as fuel load, ventilation openings, and wall lining materials⁶. These parameters are critical in understanding the fire dynamics of the compartment.

The Eurocode method is based on the work done by Wickstrom, who developed a suitable method for design purposes9. This method allows post-flashover compartment fires to be expressed in a single timetemperature curve. It is an improvement over the standard fire curve (ISO 834) and involves modifying the heating rate from the standard curve specified in the Swedish building code (SBN 1975) to reflect the ventilation conditions and thermal inertia of the compartment boundary. The key parameters of the Eurocode timetemperature curve method include the fire load within the compartment, the presence of openings in the walls and/or roof, and the type and characteristics of the compartment's walls. However, it is worth noting that the study by Franssen suggests that the method has limitations in its applicability because it assumes a uniform temperature throughout the compartment¹⁰.

The Eurocode 1 method is also based on a comparison with the time-temperature curves presented by Magnusson and Thelandersson⁶. Magnusson and Thelandersson developed a systematic representation of a parametric time-temperature curve, commonly referred to as the "Swedish curves" This method provides a gas temperature profile as a function of the compartment's fire load density, opening factor, and the type of compartment (boundary material type).

Unfortunately, the methods described above for parametric fire curves do not consider the impact on the gas temperature within the enclosure if the fire compartment is combustible and contributes to the fuel load. Like Wickstrom's approach, one possible response could be to modify or adjust the heating curve to accommodate combustible compartments. However, a validated method to accurately represent a combustible parametric fire curve has not yet been achieved.

2.3 TIMBER STRUCTURES

Common building materials possess different structural and thermal properties that make them favourable for design purposes. Steel and concrete exhibit advantageous thermal properties, enabling them to withstand fire exposure and maintain their strength under long-duration loads². Despite timber's susceptibility to burning when exposed to fire, it also offers beneficial strengths for structural design, such as significant insulating properties¹.

Contemporary building design places emphasis on materials that are more sustainable, aesthetically pleasing, and efficient for construction. In response to these demands, engineered timber products have been developed to address the existing issues associated with traditional timber. Nonetheless, concerns regarding the fire performance of timber persist, resulting in some reservations about its use.

2.3.1 TIMBER EXPOSED TO FIRE

Timber primarily consists of cellulose, hemicellulose, and lignin¹. When timber is exposed to external heat, its outer layer begins to decompose, resulting in the formation of a char layer. The occurrence of flaming combustion or smouldering combustion depends on the availability of sufficient oxygen and external heat flux.

Previous research has established that the thermal degradation of wood can be categorized into different temperature zones, including the drying zone, pyrolysis zone, and char oxidation zone¹. It has been observed that when timber burns, a char layer is formed, which undergoes pyrolysis (typically between temperatures of 220°C and 400°C) and subsequent oxidation (between 400°C and 550°C)¹¹.

The formation of a char layer in timber structural elements can lead to several issues¹. The char layer typically contains cracks and fissures, allowing heat and mass transfer between the uncharred wood and the flame. Toxic gaseous pyrolysis products from the char layer are burned and released into the fire compartment, increasing the heat release rate and raising the compartment temperature. The charred layer does not provide any structural performance, and the remaining dry section of the wood sustains the applied loads.

Over time, the char layer can experience char fall-off or degradation of the adhesive between lamellae in CLT (cross-laminated timber) structures, adding to the fuel load within the compartment¹². Predicting char fall-off can be challenging and depends on the loading conditions of the structure. Adhesives such as polyurethane-based or melamine formaldehyde may experience degradation in adhesion or reduced cohesion performance at temperatures below the char formation, before the char zone reaches the glue line. While using a thermally stable adhesive can help delay char fall-off, it should not be the sole focus in design considerations.

Fire encapsulation, such as using fire-rated plasterboard or intumescent coating, is an alternative solution to enhance the fire resistance of timber structures¹². Encapsulation can delay charring and slow down the char rate on the unprotected timber for a tested duration. Encapsulation can still fail, and the aesthetic appearance of the timber structure is hidden beneath the encapsulation layer. There is a risk of thermal feedback and continuous burning once the unprotected timber is exposed to fire, which can potentially lead to catastrophic failure of the timber structure.

To ensure the effectiveness of encapsulation, designers are encouraged to prevent mechanical failure of the encapsulation and avoid the presence of oxygen when encapsulation fails. Successful encapsulation relies on various factors, including proper application and maintenance throughout the building's lifecycle.

One advantage of timber structures is their insulation capability, which can be maintained if the integrity and stability criteria of the timber structure are preserved¹.

2.3.2 STRUCTURAL TIMBER COMPARTMENT FIRES

Research into timber compartment fires is still in the early stage-. The study conducted by Kotlovinas et al. (2022) in an open plan compartment with CLT ceiling and columns highlighted the significant impact of combustible elements on fire dynamics¹³. The results showed that fire spread was three to eight times faster when CLT was used in the ceiling compared to a non-combustible compartment. This

emphasises the importance of considering the presence of combustible materials in fire safety design.

Regarding the representation of actual conditions, some studies have used wood cribs to simulate mass timber construction, but it is recognized that incorporating realistic fuel loads such as furniture provides a better representation¹⁴. Furthermore, open plan well-ventilated compartments and the impact of traveling fires are areas that are still under ongoing research and development, indicating the need for further investigation in these aspects

Study undertaken by Brandon et al. compared experimental and numerical analysis to determine onedimensional charring rate, notional charring rates and zero strength layers corresponding to a range of parametric curves¹⁵. The study reviewed different parametric fire tests in accordance with Eurocode 1 (EN1991-1-2 2002) with ventilated controlled compartment fire tests. Time to failure and charring rates were measured. While the numerical prediction for charring rate correlated well with the experimental results, there was a significant deviation in the charr depth, with the experimental results showing a more significant charr depth compared to the numerical prediction. This finding suggests that the current method proposed in Eurocode 5 (EN1995-1-2) may not be conservative enough and may require further refinement.

The study conducted by Lange et al. focused on the investigation of the 7mm zero strength layer for timber exposed to fire as prescribed in EN1995-1-2¹⁶. The hypothesis that this value may be unconservative for members in bending was found to be true, with the actual zero strength layer being greater than 7mm depending on the type of fire exposure. This finding emphasises the importance of considering reasonable safety factors to account for potential variations in the zero-strength layer

In the case of heavy timber structures exposed to fire, it is possible that only a thin layer of char forms, and the charring rate may be slow¹⁶. This implies that the fuel load added to the fire compartment from the charred layer could be negligible. Additionally, there is a possibility that the fire may self-extinguish or starve before the charred wood fuel load becomes significant enough to impact the fire dynamics of the compartment. However, this outcome is dependent on the availability of oxygen within the compartment.

Experimental research is generally limited to small compartments with limited ventilation. Review by Hangyu et al. suggested these studies are more suitable and comparable to residential buildings¹⁴. These studies are

valuable in understanding thermal feedback between surfaces and can shed light on challenges such as increased burning rate, char fall-off, or failure of encapsulation that may occur in small compartments.

The investigation of timber compartments is still an active area of research, particularly in response to the growing demand for mass timber structures. Fire models and methods are being developed to better understand and predict the behaviour of timber compartments. However, there is still ongoing research to identify the parameters that govern the fire development in timber compartments. It is important to critically evaluate these fire models and methods and test their assumptions to ensure their applicability for design purposes.

The ultimate goal is to develop reliable engineering expressions and design guidelines that consider the unique characteristics and behaviour of timber structures in fire. This requires a comprehensive understanding of the fire dynamics of timber compartments and the validation of fire models and methods through experimental data and real-world applications.

2.4 EUROCODE 5 METHOD

Parametric fires are only applicable to encapsulated timber surfaces i.e., only non-combustible surfaces. Although parametric curves are typically used when the compartment boundaries are non-combustible and do not contribute to the fuel load, further studies by Brandon proposed that parametric curves can be modified to account for combustible mass timber¹⁶. This can be achieved through an iterative procedure, where the char depth is estimated by adjusting the fuel density.

It is important to understand the assumptions in developing the proposed iterative procedure. These assumptions include:

- Glue line integrity of engineered timber lamella is maintained. This means designers are encouraged to propose adhesives that are thermal resistant
- No char fall off or failure of encapsulation can occur. This is an unrealistic assumption because char fall off is unpredictable and dependent on the severity of the fire dynamics in the enclosure.
- Maximum floor area is limited to 500m² and maximum enclosure limited to 4m in height. New builds are pushing the limits of building geometry, and these geometry limits may not be applicable to complex buildings
- Opening factor limits also apply $(0.02 \le 0 \le 0.20)$

The proposed iterative method has been incorporated into the Eurocode 5 standard for industry use. However, it is essential to verify and validate the applicability of this method and ensure that designers have a clear understanding of its implementation. In the Eurocode 5 standard, there is no specific critical temperature prescribed for the exposed timber structure. The failure mode considered in Eurocode 5 is the time at which the exposed timber experiences structural deformation or collapse. This is determined by comparing the residual strength of the timber with the fire limit loads after a certain duration of fire exposure. This method provides opportunity to use parametric fires beyond encapsulated timber surfaces

A new version of the Eurocode 5 standard is in draft form and will soon be published. Currently used version is the 2004 edition. Academics and fellow industry experts in timber are being called upon to review this standard, given the growing demands for timber use in buildings.

3. PROJECT DESCRIPTION

The aim of this thesis was to critically investigate the assumptions and analytical methods in developing parametric fire curves for timber fire compartment. This involved the following:

- 1) Reproduce parametric time-temperature fire curves for compartment fires
- Identify design parameters which govern or influence the fire dynamics in large scale timber compartment from past research fire tests. This will be presented as a curated data base of this study.
- Review parametric fire methods to real-fire compartment from past studies results and will observe Eurocode 5 method validity
- Evaluate the relative performance of parametric fire models for application to timber buildings and review the apparent limits of their applicability

By achieving this, the study hopes to contribute to the mature development of appropriate analytical methods for designers to use as part of the performance-based design approach for mass timber structures. If this goal is achieved, it will support the development of robust fire safety strategies for timber structures, with validated parametric fire models.

4. DESIGN PROCESS

4.1 STAGE 1: PARAMETRIC TIME-TEMPERATURE FIRE CURVE

This stage focuses on developing analytical tools to describe the combustible parametric time-temperature fire curve using the Eurocode 5 method. The analytical tools were used to compare and analyse previous parametric fire test results.

4.2 STAGE 2: CURATE DATABASE OF LARGE-SCALE TIMBER COMPARTMENT FIRE TESTS

During Stage 2 of the project, the focus was on curating a comprehensive database of large-scale compartment fire tests on combustible structures. The purpose of curating this database was to identify trends, anomalies, and gaps in knowledge that required further investigation.

4.3 STAGE 3: APPLICABILITY OF PARAMETRIC FIRE MODELS FOR REAL TIMBER BUILDING DESIGN

The analytical results were combined and compared to correlate these findings, aiming to assess the applicability of analytical methods for real timber building designs.

5. INTERNAL FIRE DYNAMICS THEORY

The fundamental principle used to calculate the temperature in a compartment fire stems from the conservation of energy. This expresses that the energy generated from the heated upper layer of the fire compartment equals the combined energy within that layer and the rate at which energy changes over time in the upper layer. This is also applicable to the lower layer.

Historically, multiple researchers have studied the temperature of compartment fires to predict real fire events based on the conservation of energy principle. This is driven by the fact that the energy balance in a compartment fire is frequently determined by the characteristics of the temperature-time pattern.

Eurocode Parametric fire and Thomas formulation are analytical methods to approximate a compartment fire. It is implied that Eurocode method is more onerous compared to Thomas formulation. Eurocode method considers a design fire fuel load, whilst Thomas formulation considers the fuel load density. By considering the design fire fuel load, Eurocode considers firefighting activities, occupancy type and floor area. In addition to this, the curve for each method is different as the Eurocode method approximates an exponential curve for heating with a slow decay for cooling. Comparatively, the Thomas formulation shows a horizontal gradient for heating phase (no fire growth from time=0) and a rapid cooling phase.

Both models predict the compartment fire temperature as a function of the compartment's opening factor, O_F , expressed below:

$$O_F = \frac{A_T}{A_W H^{1/2}} \dots \quad (1)$$

- A_T is the total surface area excluding floor and opening (m²)
- A_W is the area of ventilation opening (m²)
- *H* is the weighted average of opening heights on all walls (m)

The subsequent section will describe the theoretical approach to compare to the experimental results.

5.1 THOMAS PLOT METHOD THEORY

The maximum temperature and burning duration within a compartment using Thomas Plot Method theory is described below. Thomas et al. correlated the research from Kawagoe to identify the maximum temperature in a compartment fire while considering varying opening factors.

The opening factor is determined by equation (1) for noncombustible structures in ventilation-controlled fire scenarios. The maximum gas temperature in the compartment can be determined directly from the Thomas et al. plot. For the timber compartments, the opening factor will be modified and defined as Equation (2).

The heating phase is defined by the time to burn out or burning duration, t_{bo} (minutes). This is expressed below:

Heating phase =
$$t_{bo} = \frac{M_{fuel}}{\dot{m}_{fuel}} = \frac{Q^{"} \times A}{\Delta H_C \times R}$$
 (2)

- M_{fuel} is the total mass of fuel (kg)
- \dot{m}_{fuel} is the burning rate of fuel (kg/s)
- Q'' is the Fuel load density (MJ/m²)
- ΔH_c is the heat of combustion of fuel (MJ/kg)
- *A* is the Floor area (m^2)
- *R* is the rate of burning (kg/s)

The rate of burning is expressed in the equation below:

$$R = 0.1 A_W H^{1/2}(3)$$

It is conservatively assumed that the cooling period is twice as long as the heating phase.

Cooling Phase =
$$2.t_{bo}(4)$$

Once the heating phase and cooling phase time periods or durations are determined, the Thomas correlation timetemperature curves can be plotted.

The theory assumes the heat losses used in the energy balance are defined by the areas of the walls and ceiling (A_T) . Thereby the maximum temperature of a compartment fire is governed by the thermal properties of compartment walls and HRR. This is generally true for non-combustible compartment boundaries. This assumption is no longer applicable for when timber panels are introduced as compartment boundaries. It is expected the burnt timber will contribute to internal fire dynamics and therefore, expected to increase in temperature and turbulent flow of fire gases in the compartment.

Research by Putynska studies this assumption and found that additional flux of pyrolysis gases is expected when timber structure is burnt¹⁹. This results in increased velocities at the opening and shifts to a momentum-driven profile as opposed to hydrostatic pressure differential profile. Therefore, a ventilation-controlled fire is no longer appropriate, but instead fuel controlled.

The opening factor is therefore modified to account for the shift in regime. Theoretically, the opening factor needs to be reduced to account for the timber boundary. Further studies by Putunska developed an expression below for modified opening factor, whereby A_{timber} is the exposed timber area $(m^2)^{19}$:

$$O_{F,modified} = \frac{A_T - A_{timber}}{A_W H^{1/2}} (5)$$

5.2 EUROCODE TEMPERATURE-TIME METHOD THEORY

The Eurocode 5 Annex A provides a guideline to quantify the theoretical temperature-time curve to include the contribution of timber during fire duration. Unlike the Thomas Plot method, the Eurocode 5 method does not require modifying the opening factor for the exposed timber. Instead, the fuel load density (or fire load) is adjusted to include the structural fuel load in addition to the floor related fuel load (movable fuel load). The following expression defines the total fuel load with accordance to Eurocode 5 Annex A (6)

5.2.1 MODIFIED OPENING FACTOR

Traditional fire models have found ventilation-controlled fire scenarios are more onerous than fuel-controlled fire scenarios. This refers to the temperature within compartments. This is often governed by the compartments opening factor.

$$q_{f,k} = q_{m,k} + q_{s,k}(6)$$

Whereby,

- q_{f,k} is the characteristic fuel load according to EN 1991-1-2 (Eurocode 1)
- q_{m,k} is the movable fuel load according to EN 1991-1-2 (Eurocode 1)
- q_{s,k} is the structural fuel load according to EN 1995-1-2 (Eurocode 5)

The structural fuel load is determined using an iterative procedure as a function of time. It considers the combusting surface area of the structural timber relative to the floor surface area. The determined design charring rate was used to determine the effective heat release rate per square meter of timber.

The total characteristic fuel load from Eurocode 5 is applied to the parametric temperature-time curve given in Eurocode 1. Based on these methods, it is expected the maximum gas temperature and fire duration (heating and cooling) will increase.

6. REVIEW OF REAL-FIRE COMPARTMENT TESTS

6.1.1 KOTSOVINOS ET AL. (2022)

The study performed a series of tests in a large-scale compartment with fully exposed cross-laminated timber (CLT). The aim of the study was to improve the understanding of fire dynamics for open-plan, exposed timber compartments. It reviewed the impact on external flaming, smouldering and increased HRR to be considered during building design.

Large-scale compartment had a fully exposed, unloaded, cross-laminated timber (CLT) ceiling and glued laminated timber (glulam) columns, made with adhesives that have been tested to not exhibit char fall-off in fire. The compartment was $352m^2$ in floor area; 10.27m wide, 34.27m long and 3.1m high. The compartment had several vertical openings which resulted in an opening factor of $0.^{071m1/2}$. The fuel load for the test was a continuous wood crib which covered $174m^2$ of the floor area. This approximated to a fuel load of $374MJ/m^2$.

There were several instruments positioned throughout the compartment (internally and externally). These consisted of heat flux plate thermometers and Type K thermocouples.

The fuel load was ignited at one end of the compartment to observe flame spread across the timber ceiling.

Significant flaming was observed at the openings and analysis found that the presence of timber structure approximately doubled the heat release rate compartment to the value expected from the wood crib fuel load alone. It was observed that the CLT ceiling ceased flaming when the fuel bed also ceased flaming. External flaming was observed above the openings which suggests vertical compartmentation and distance between adjacent buildings should be carefully considered for building design. The lower region of glulam columns experiences more charring than the upper region due to the heat transfer from surrounding fuel load embers. Lastly, it was found that smouldering fire was observed throughout the entire decay period which continued to burn the exposed timber structure unless external firefighting intervention is engaged.

6.1.2 BRANDON ET AL. (2021)

The aim of the study was to assess US timber products exposed to fire and seek for methods to improve US code life safety.

The study performed five (5) large scale compartment fire tests. The compartment was constructed of CLT slabs, glulam beam and columns with accordance to US product standards. The exposed surface area was equivalent to at least two times the area of the floor plan. The compartment has internal dimensions of 7m by 6.85m by 2.73m with two (2) different opening factors against different exposure areas of timber. The fuel load was a combination of typical apartment furniture which resulted in a total fuel load of at least 560 MJ/m².

Each test used plate thermometers at the wall and ceiling surfaces to measure temperature. HRR was measured using load cell measurements of the floor and structure. Char depth and flame spread was observed during testing.

Flashover conditions occurred quickly, within 15minute from ignition for all tests. The internal fire maintained

Author	Timber Exposure	Unmodified Opening Factor (m ^{0.5})	Fuel Load (MJ/m ²)	Approximate Maximum Temperature (°C) and time	Eurocode Method Maximum Temperature (°C)
Kotsovinos et al ²⁰	Fully exposed CLT Ceiling with 2 glulam only	14.08	387.64	1000 at 5-10mins	833.94
Brandon et al. ²¹	44% exposure	16.13	586.02	1200 at 30mins	896.60
	80% exposure	16.13	608.84	1200 at 20mins	902.40
Putynska at al. ¹⁹	Fully exposed (0.71 of total surface area)	18.43	121.43	1000 at 18mins	666.31

Table 2 Past compartment tests compared to theoretical results

fully developed fire conditions between 15 to 30 minutes. The decay phase for compartment experiencing flashover fire occurred continuously for 4 hours after ignition at which temperatures were below 300°C. There were visible embers after flashover had already occurred. The tests indicate that two exposed walls in one corner should be avoided to ensure embers and hot-spots during decay phase.

6.1.3 PUTYNSKA ET AL. (2019)

The aim of the study was to analyse the fire dynamics in compartments with different exposed area of timber walls and ceiling. The study reviewed the compartment framework assumptions (Thomas Plot method).

24 medium scale compartment fires of 0.5m by 0.5m by 0.37m internal dimensions with a single opening of 0.3m and 0.28m. The opening factor based on the compartment configuration was $18.43m^{-1/2}$. The 24 tests assessed eight different configurations of exposed timber surfaces. The fuel load consists of a kerosene feeding system to maintain a consistent liquid level.

All tests used several items of instrumentation to measure the fire dynamics. Temperature thermocouple trees were placed at the back of the compartment and at the compartment opening that also extended above the opening. Velocity probes were placed at the opening to capture gas velocity profiles. A calorimeter hood above the whole experiment to measure the concentration of O_2 , CO and CO_2 for total HRR calculation.

The test results found that increasing the CLT exposure area does not correlate to a change to internal gas temperature as it would be expected for a ventilated control fire. However, the presence of burning CLT boundaries can produce fuel-controlled flow characteristics as opposed to fire dynamics governed by large openings. The test found that the change in regimes results in a lower burning rate at the ceiling compared to other exposed timber surface. Therefore, the area of exposed timber does not necessarily govern the burning rate, instead the location of timber panels (i.e., ceiling versus wall). The introduction of timber structure contributes significantly to the total heat release rate, which impacts the scale and shape of the external flame.

6.2 OVERVIEW OF RESULTS

These past experiments have suggested that there are key parameters that need to be explored to ensure building design of timber structures maintains life safety (and/or asset protection) during a fire emergency. These being:

- Vertical flaming or plume spill from compartment openings
- Contribution of timber results in significant vertical flame spread to adjacent non-fire affected areas
- Configuration of exposed timber surfaces

This governs gas temperatures and velocity profile at compartment openings, as opposed to the area of exposed timber surfaces

7. VALIDATE WITH PREVIOUSLY CONDUCTED REAL COMPARTMENT TESTS

When implementing the Eurocode 5 method, this study analysis does not align with past experimental results in several ways. Notably, the Eurocode 5 method appears to be more onerous when determining maximum temperatures within a compartment. Furthermore, the findings indicate that the time it takes for a compartment to reach its maximum temperature occurs earlier in experimental scenarios compared to the method's predictions. One significant challenge lies in drawing conclusions about the influence of the opening factor on internal fire dynamics. This complexity arises due to variations in timber exposure levels, making it difficult to establish a clear correlation. The table 2 summarises the findings. Scaling analysis was excluded from this research scope. Comment on Eurocode 5 Applicability

The Eurocode 5 method iteratively determines the exposed timber surface area to quantify the structural fuel load and combines it with the movable fuel load. The theoretical results suggest that when timber panels are introduced, the maximum gas temperature within the compartment is expected to be higher than a non-combustible compartments. Although this is true, the method results in a marginal increase in temperature. Furthermore, the Eurocode method estimates that the time it takes to reach maximum gas temperature (i.e., heating period) is longer than the non combustible compartment. The key findings are:

- The maximum gas temperature is at least 200°C lower
- The heating period is shorter and at a faster fire growth rate
- The cooling period is reasonable however, to be adjusted to occur earlier during the fire

It is recommended to re-evaluate the Eurocode 5 method to adopt a more conservative approach. At the very least, designers are urged to apply safety factors to ensure that the assessment incorporates necessary conservatism. It is crucial to explore the iterative method in determining the structural fuel load, a key parameter that differs from the traditional Eurocode parametric fire curve method for ventilated control compartment fires. Additionally, investigating the heating period calculation in the Eurocode 1 method is recommended to account for the faster fire growth rate observed, attributed to the more vigorous velocity profile at the compartment opening compared to a non-combustible compartment.

8. CONCLUSION

In conclusion, based on this study's findings, the Eurocode 5 method needs re-evaluation for conservatism. Safety factors are recommended to be applied, and the iterative method for structural fuel load determination requires re-evaluation. Eurocode 1 method heating period calculation should adapt to faster fire growth. Timber presence affects external flaming and plume spill, emphasising the need for careful vertical compartmentation and distances between compartments in timber designs. While promising, Eurocode 5 requires further evaluation for accuracy in real fire scenarios.

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