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Effects of exposed cross laminated timber on compartment fire dynamics

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ABSTRACT

A series of compartment fire experiments has been undertaken to evaluate the impact of combustible cross laminated timber linings on the compartment fire behaviour. Compartment heat release rates and temperatures are reported for three configuration of exposed timber surfaces. Auto-extinction of the compartment was observed in one case but this was not observed when the experiment was repeated under identical condition. This highlights the strong interaction between the exposed combustible material and the resulting fire dynamics. For large areas of exposed timber linings heat transfer within the compartment dominates and prevents auto-extinction. A framework is presented based on the relative durations of the thermal penetration time of a timber layer and compartment fire duration to account for the observed differences in fire dynamics. This analysis shows that fall-off of the charred timber layers is a key contributor to whether auto-extinction can be achieved.

1. Introduction

There is a global rise in the structural use of engineered timber, along with increasing demand for architectural expression of the timber structure, that is exposing the structural timber internally within buildings. Negative perceptions regarding fire safety in such buildings are one of the key barriers to realising current architectural aspirations. In most jurisdictions the use of combustible enclosures is restricted, and in some the use of a combustible material as an element of building structures is expressly prohibited for buildings of certain types and heights. These obstacles provide an opportunity to revisit compartment fire behaviour and to quantify the impact of these new construction technologies on the compartment fire dynamics.

Cross-laminated timber (CLT) is an engineered mass timber product formed from multiple layers (lamella) of timber, with adjacent lamellae bonded together with an adhesive such that the orientation of the grain is perpendicular. Cross-laminated timber has the advantage of reduced uncertainty in its bulk mechanical properties and can be produced to any desired size. In addition CLT offers significant construction advantages; it is both light and quick to construct, thus reducing the overall cost and duration of the construction programme.

Existing fire safety engineering design methods and correlations are principally based on the dynamics of fires within non-combustible enclosures. An understanding of the fundamental fire dynamics within an enclosure of combustible construction is essential to enable the safe fire design of compartments with exposed structural timber elements. This must be sufficient to enable the designer to predict key fire phenomena for building fire safety design, including the time to flashover, fire growth rate, and size and duration of the fire both within and external to the enclosure.

To understand the relevant challenges that exposed, combustible compartment linings present to fire engineering in multi-storey buildings, and the likely impact on the compartment fire dynamics, a series of large-scale compartment fire experiments have been undertaken. This series of experiments systematically varies the combustible surface configurations within the compartments to evaluate the compartment fire dynamics and material response of exposed CLT linings, and the performance of encapsulation methods for the unexposed CLT surfaces.

In a compartment with exposed structural CLT elements, the combustible timber linings have the potential to ignite and increase the heat release rate (HRR) of a compartment fire. The heat generated by this additional burning also has the potential to increase the burning rate of the compartment contents and other combustible surfaces, and thus the presence of exposed timber is likely to have clear effects on the compartment fire dynamics, and vice versa. Design of such compartments therefore must incorporate a strategy to achieve auto-extinction of the timber after the compartment contents have burnt out [1,2].

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1.1. Ignition and burning wood

Combustion of wood has been studied extensively. The processes of pyrolysis and char formation which control the burning of wood have been studied under a wide range of conditions [3–6]. The pyrolysis process produces a rigid, carbon-rich char in the solid phase and flammable, gas-phase pyrolysis products. The gas phase pyrolysis products can undergo flaming ignition if they are produced at a rate sufficient to form a mixture that reaches the lower flammability limit with surrounding air, and provided that there is an appropriate ignition source. In ambient oxygen environments, data from bench-scale experimentation consistently shows that the critical heat flux for piloted ignition of wood is 12 kW/m^2 and 28 kW/m^2 for unpiloted ignition [7]. The solid phase product of pyrolysis is a low density, porous char with a low effective thermal conductivity. The low thermal inertia and thermal diffusivity of the char layer results in high surface temperature and consequently high heat losses form the surface. This reduces the net heat flux into the virgin material, and consequently leads to a reduction in pyrolysis rate as the thickness of the char layer increases. Therefore, in order to support flaming combustion of timber, an external heat flux is required to overcome the heat losses from the surface. This has been shown to be on the order of 30 kW/m^2 [1,8], corresponding to a critical mass flux of between 3.5 g/m^2s [1] and 4.0 g/m^2s [8]; if the production of volatiles drops below this rate the flame will not be sustained. In the absence of a flame, oxidation of the surface char may occur leading to smouldering combustion.

1.2. Fire behaviour of cross laminated timber

This knowledge can be applied to cross laminated timber however there are two key differences. Firstly the laminated nature of these products introduces complexity as the properties of the adhesive will determine the mechanical properties of the timber. Commonly this has been associated with ‘delamination’ (fall-off of pieces of char and timber) as the timber burns. Although this phenomenon has been previously reported there is little information available to understand the governing physical mechanisms.

The second difference is that cross laminated timber products typically have a large dimensional thickness. Often this can be > 200 mm and as a result the temperature distribution within the timber will affect the burning behaviour and the mechanical properties.

2. Compartment fire behaviour

Compartmentation is a cornerstone of fire safety engineering design. However, the failure modes of common compartment construction systems and materials are relatively poorly documented from a scientific (rather than compliance testing) perspective. Failures can arise due to loss of material properties at high temperature and/or a system failure, as a result of the interaction or failure of one or multiple materials or components. In general failure of the compartment is defined by spread of the fire to an adjoining compartment (breach of compartmentation), or by excessive heating on the unexposed face of a fire-separating partition (inadequate insulation). In the context of compartments with exposed combustible linings, failure can be defined as the inability to reach auto-extinction, since this means that burnout has not been achieved. In both cases, failure modes are intrinsically linked to the characteristic timescales of the compartment fire.

Compartment fires have been the subject of extensive studies, with some key aspects summarised below. There are three phases commonly referred to during a fire in a compartment. First, a fuel-controlled growth phase until flashover is reached. Flashover has been studied extensively and numerous correlations exist to predict the necessary/sufficient conditions for it to occur, see e.g. Drysdale [7]. The subsequent post-flashover stage corresponds to a situation when all combustible surfaces are burning, and this fully-developed fire is typically referred to as a Regime 1, ventilation-controlled fire [7]. In this phase the burning rate and temperature in the compartment depend on the ventilation conditions rather than the fuel load, and can be approximated by Eq. (1), where A_V is the ventilation area, and H_V is the height of the ventilation opening. As the burning rate of the fuel decreases and extinction is approached, the fire will enter a decay phase, during which it will transition back to a fuel-controlled fire.

2.1. Burning rate and compartment heat release rate

The burning rate in a post-flashover compartment fire is commonly calculated using Eq. (1). The mass burning rate, $\dot{m}$ is dependent on the product $A_V\sqrt{H_V}$ and a coefficient based on the fuel (typically 0.09 for wood [7]). The origins of this correlation are based on the buoyancy driven flow and the stoichiometric burning of air inside the compartment and it is generally assumed to hold over a limited range of $A_V\sqrt{H_V}$ and fuel configurations [7]. If the opening is sufficiently increased relative to the fuel surface area, the burning rate will become independent of $A_V\sqrt{H_V}$, leading to a fuel-controlled burning regime [7].

$$\dot{m} = 0.09 A_v \sqrt{H_v} \tag{1}$$

2.2. Compartment temperatures

The maximum temperatures achieved in post-flashover compartments have been extensively studied. Thomas [9] presents an analysis based on the opening factor, $A_T/A_V\sqrt{H}$. For low opening factors (< 15) the compartment temperatures increase as a function of opening factor. Beyond this limit, compartment temperatures decrease with increasing opening factor. The resulting curve is captured by the following expression [10]:

$$T_{max} = \frac{6000(1 - e^{-0.1\Omega})}{\sqrt{\Omega}} \tag{2}$$

where

$$\Omega = \frac{A_T - A_V}{A_V\sqrt{H_V}} \tag{3}$$

and A_T is the total area of the compartment linings.

2.3. Effects of combustible linings

In general compartment fire testing has been carried out with inert compartment linings. Relatively few studies have investigated the effects of combustible linings on the resulting compartment fire dynamics. Butcher et al. [11] studied compartments with combustible fibre insulation board (FIB) linings on the walls and ceilings, and compared these to data gathered from cribs of equivalent fuel loading with inert compartment linings. The compartment with FIB linings reached higher temperatures faster than the compartment with wood cribs, and resulted in a fully-developed fire with flames filling the whole compartment and significant external flaming. No direct explanation for this behaviour was given; however it is logical to assume that the large surface area of fuel and the fixed ventilation conditions resulted in production of pyrolysis gases at a rate greater than they could be oxidised by the air inflow to the compartment. This suggests that the correlations provided above may not hold for compartments with significant areas of exposed combustible material.

Li et al. [12] carried out a series of 10 fire tests using compartments representative of common cross laminated timber constructions. Three of those tests had exposed CLT surfaces; one with one wall exposed, one with two opposite walls exposed (4.5 m×2.5 m), and one with two perpendicular walls exposed (4.5 m×2.5 m and 3.5 m×2.5 m). Both of the tests in which two walls were exposed experienced a secondary flashover, attributed to delamination of the charred CLT, whereas the compartment with only one exposed surface appeared to demonstrate auto-extinction after burnout of the compartment fuel load. These experiments provide a useful comparison point however the primary focus is the contribution of exposed timber to the heat release rate. This leaves the changes in fire dynamics and potential for auto-extinction as the configurations of exposed timber are changed unaddressed.

2.4. Effects of cross laminated timber construction systems on compartment fire dynamics

When compared to experimental fires undertaken in compartments with non-combustible linings, the construction of cross laminated timber systems introduces several complexities that are likely to influence the compartment fire dynamics. The components of the system and their potential impacts on the fire behaviour are summarised below.

2.4.1. Exposed timber

It is likely that exposed timber surfaces will be ignited by burning of the compartment fuel load. The risk of sustained burning of the exposed timber arises from the contribution of pyrolysis gases from the timber to the compartment. The rate of pyrolysis of exposed timber is a function of the compartment fuel load and the radiation from the hot gas layer and the compartment linings. If the critical pyrolysis rate for sustained flaming is exceeded (as identified above), then sustained, on-going combustion of the exposed timber will occur. This will have implications for the integrity of the compartment and structural system.

2.4.2. Fall-off (or 'delamination') of the char layer

The laminated nature of CLT has been shown to result in fall-off (sometimes referred to as 'delamination') of individual timber layers as the CLT burns and char depth increases. As the char front advances within the CLT, the conditions at the glue line may be such that the char layer can no longer remain adhered to the underlying timber and, under the action of gravity, differential thermal expansion, cracking, warping, etc., will fall. This may be due to charring of the adhesive layer or increase in temperature beyond the glass transition temperature resulting in loss of bond. Falling off of the charred timber material allows an increase of the heat transfer to the virgin material, resulting in higher pyrolysis rates. The addition of pyrolysis gases from the newly exposed timber surfaces will prolong the compartment fire and potentially increase the heat release rate both inside and outside the compartment, if the conditions are appropriate. Kippel et al. [13] report that the fall-off is less pronounced on vertical surfaces compared to horizontal surfaces. If the rate of fall off is sufficiently high, the contribution of pyrolysis gases to the compartment will be sufficient to sustain flaming combustion and auto-extinction will not occur after the fire load has burnt out.

2.4.3. Encapsulation

To prevent the exposed (structural) timber from becoming involved in the fire it is common to use non-combustible encapsulation systems. The specifics of these systems vary, but in general they consist of fixing a thermal barrier (inert layer) onto the timber. Encapsulation systems are typically designed to meet requirements of structural fire design, and thus tend to focus predominantly on limiting the thermal penetration into, or "charring rate" of, the timber. It may be considered acceptable using such a design approach for the encapsulation to fail and for the exposed timber to ignite, provided that structural integrity and compartmentation are maintained for the desired duration of standard fire exposure (as demonstrated using full scale standard furnace tests of the particular encapsulation system being used). It is important to note, however, that if encapsulation systems fail to remain in place during the fire, then exposed timber is likely to contribute to the fire dynamics. If a sufficient area of timber becomes exposed, then the energy balance in the compartment may permit sustained combustion of any exposed timber and making it unlikely or impossible to achieve burnout.

2.4.4. Onset of pyrolysis by thermal penetration

If the encapsulation system remains in place, then penetration of the thermal wave may be sufficient to induce pyrolysis in the underlying timber. This may result in the sustained smouldering of the timber beneath the encapsulation system, and pyrolysis gases may enter the fire or adjacent compartments, again with potential (however likely less severe) consequences for the compartment fire dynamics.

3. Experimental configuration

Five large-scale compartment fires were undertaken varying the configurations and number of exposed CLT internal surfaces to investigate the above issues. These are described during the remainder of this paper.

3.1. Compartment geometry

An approximately cubic compartment of internal dimensions $2.72 \times 2.72 \times 2.77\ m^3$ (width×length×height) was used to study three

Table 1
Compartment geometries and exposed areas of timber for configurations Alpha, Beta and Gamma.

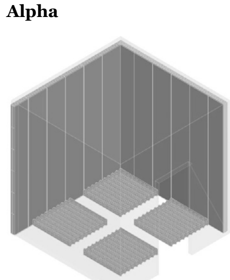
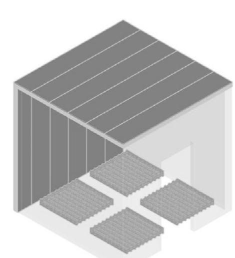
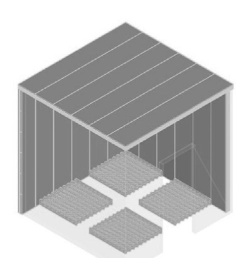
	Alpha	Beta	Gamma
			
Exposed surfaces	Back wall and side wall	Back wall and ceiling	Back wall, ceiling, and side wall
Number of experiments	2	2	1
Exposed timber area, m^2	15	14	22
Area averaged thermal inertia, $Jm^{-2}\ K^{-1}\ s^{-1/2}$	314	315	319

Table 2
Ambient temperature properties of materials immediately facing the interior of the compartment.

Property	Timber	Plasterboard	Stone wool insulation [18]	Char [19]
Thermal conductivity, W/mK	0.13 [15]	0.24 [16]	0.039 [0.034–0.044]	0.071[b]
Density, kg/m^3	548 [470–625][a]	784 [16][a]	164 [167–180]	200
Heat capacity, J/kgK	1600 [15]	950 [17]	700 [600–800]	1000 [670–1350]
Thermal inertia, J m^{-2} K^{-1} s$^{-1/2}$	338	423	67	119
Thermal diffusivity, m^2/s	1.48×10^{-7}	3.22×10^{-7}	3.40×10^{-7}	3.55×10^{-7}

[a] Indicates measured quantity.
[b] Measured at 90 °C.

configurations, denoted Alpha, Beta, and Gamma, of exposed timber surfaces. The compartment geometries, exposed surface areas, and area averaged compartment thermal inertias are presented in Table 1. The thermal properties presented in Table 2 are used to calculate the averaged thermal inertia. An opening in the form of a door with dimensions 1.84×0.76 m^2 (width×height) was used resulting in an opening factor, $A_T/A_V\sqrt{H}$=19 m$^{-1/2}$ and $A_V\sqrt{H_V}$=1.9 m$^{5/2}$. The difference in exposed timber area between Alpha and Beta configurations is a result of the overlap between the ceiling and the walls necessary for construction. Using the formulae presented by Drysdale [7] the heat release required for flashover is in the range 800–1400 kW. The calculation of the averaged thermal inertia assumes that unexposed timber surfaces are plasterboard.

Using Eq. (1) above, the post-flashover burning rate expected in the compartment is 0.17 kg/s equivalent to a heat release rate of 2900 kW (assuming a heat of combustion of wood of 17.5 MJ/kg [7]). The maximum expected temperature calculated using Eq. (2) is 1174 °C.

3.2. Material properties

It is well known that the thermal properties of the compartment walls and ceiling influence the resulting compartment fire dynamics, particularly as regards the time to flashover and peak compartment temperatures [7,14]. The timber used in these experiments was a 5-layer, commercially available cross laminated timber panel composed predominantly of Spruce wood bonded with a polyurethane adhesive. The total panel thickness was 100 mm, and each layer (lamella) had a uniform thickness of 20 mm. The grain orientation on the inner surface ran vertically from floor to ceiling. The moisture content was nominally 12% at the time of testing.

All non-exposed surfaces were protected using a system with two layers of 12.5 mm Type F plasterboard immediately facing the interior of the compartment. In all experiments other than Alpha-1, a layer of stone wool and additional layer of plasterboard were inserted between the external plasterboard and the timber. The compartment floor was lined with 50 mm of high density stone wool insulation. Typical thermal properties of the timber, plasterboard, and stone wool at ambient temperature are given in Table 2.

3.3. Compartment construction

The five compartments were constructed under the 15 MW calorimeter in the Burn Hall at BRE Global, Watford, UK. The compartments were freestanding and constructed from five CLT panels to form the four walls and the ceiling. Timber panel connections were butted and screwed every 300 mm. Double layer plasterboard insulation was installed with overlapping seams and fixed with screws centred approximately every 300 mm with 20 mm spacing from the edge of boards. Screws of length not less than 100 mm were used to attach the outer plasterboard layers directly to the timber walls A false floor was installed to allow placement of load cells to measure the mass loss of the compartment fuel load (i.e. the timber cribs). Visible joints in the CLT and non-combustible encapsulation were sealed with fire cement prior to testing.

3.4. Fuel load

Wooden cribs were used as the fuel load in the compartment. The fuel load was chosen based on the heat release required for flashover, and using a burning rate calculated using a method proposed by Babrauskas [20] to ensure burnout of the wooden cribs within a short period of time after flashover (the strict applicability of these correlations is not discussed here). This was to allow specific investigation of the contribution from the exposed timber linings and the likelihood for auto-extinction. Four cribs were used, with each crib consisting of 5 layers of sticks of cross section 0.025×0.025 m^2 and 1 m in length, and a clear spacing 0.075 m. The total mass of timber was approximately 56 kg in each experiment. Assuming a heat of combustion of 17.5 MJ/kg, the fuel load was 132 MJ/m^2 and assuming an inert compartment and neglecting any mass loss before flashover, this would result in a fire duration of approximately 5.5 min. Cribs were ignited by fibre strips soaked in paraffin. The initial ignition point was at the compartment opening. Fig. 1 shows a view inside a typical compartment prior to ignition.

3.5. Diagnostics

In all experiments, 60 gas phase temperature measurements were obtained with five individual thermocouple trees inside the compartment – one in the centre, and one near each of the four corners. Temperature evolution in the timber was measured using 168–269

Fig. 1. View inside a typical compartment prior to ignition for configuration Alpha showing the four wooden cribs and gas phase thermocouple trees.

thermocouples (dependent on the specific compartment configuration). Inconel sheathed, K-type thermocouples (1.5 mm diameter) were used to measure temperatures in the walls and ceiling, and these were positioned at nominal depths of 5–80 mm from the exposed surface of the CLT. The precise position of the thermocouple positions, as installed, was recorded prior to testing. The total heat release rate was calculated by oxygen consumption calorimetry [21]. The mass loss rate of the cribs was measured directly using load cells installed beneath the false floor of the compartment. Pre- and post-fire photographs and video recording were used to record visual observations.

4. Results and discussion

4.1. Experimental observations

4.1.1. Test alpha-1

Flashover occurred 4.6 min after ignition of the wood cribs. Approximately 20 s prior to flashover, flame spread across the exposed rear wall of exposed CLT was observed. Shortly after flashover the peak heat release rate increased rapidly to 5300 kW, 6.27 min after ignition. After a brief period of quasi-steady heat release, the heat release decreased until approximately 2200 kW at 31.7 min. A gradual increase then followed until 43.5 min whereupon a transition to a ventilation-controlled fire with external flaming occurred as indicated by a rapid increase in the HRR over a short period of time. The fire then maintained a steady state of approximately 4000 kW until it was manually extinguished after 61.3 min. During the test there was significant fall-off of the plasterboard encapsulation system. This had the effect of directly exposing the timber surfaces to fire. The first recorded fall-off of the plasterboard was at 22.6 min. Twenty-six instances of plasterboard fall-off were recorded by the load cell system, with an average mass of 3.8 kg resulting in a total of 99 kg of plasterboard. Post experiment visual observations indicated that the entire area of encapsulated timber was eventually exposed.

4.1.2. Test alpha-2

In Alpha-2 and all subsequent experiments, the plasterboard encapsulation was augmented with a 25 mm high density stone wool layer behind the double layer plasterboard. This encapsulation system effectively protected the remaining surfaces, and no involvement of non-exposed surfaces was observed. Peak temperatures in the timber behind the encapsulation system were measured as being no more than 70 °C. Flashover occurred after approximately 5.1 min and, as before, was preceded by approximately 20 s of burning on the rear wall (Fig. 2(a)). The peak heat release rate was 4700 kW and occurred 5.5 min after ignition. As in the case of Alpha-1, a period of decay followed until approximately 32.4 min (Fig. 2(b)) when the heat release rate reached a minimum of approximately 2000 kW. This was followed by a period of increase up to approximately 3500 kW prior to manual extinction after 60 min (Fig. 2(c)). As before, approximately 105 kg of plasterboard was recorded to have fallen off the encapsulated surfaces, starting from 25.0 min and continuing until the end of the test.

4.1.3. Test beta-1

Flashover occurred after 8.6 min and the heat release rate increased up to 6200 kW after 8.8 min (Fig. 3(a)). A period of decay (Fig. 3(b)) followed until 15.3 min after which external flaming ceased and the compartment HRR decreased. In this case auto-extinction was observed with a small location of persistent flaming between partially delaminated layers. No plasterboard fall-off was observed in the encapsulation system. Post-test images show that charring was predominantly limited to the first layer with only localised areas of fall-off of the char (Fig. 3(c)).

4.1.4. Test beta-2

Flashover occurred after 4.2 min and a peak heat release of 5200 kW was recorded after 7.8 min (Fig. 4(a)). The heat release rate then rapidly decreased to a minimum of 1800 kW after 19.6 min (Fig. 4(b)). This was followed by a sharp increase in HRR reaching a peak of 3900 kW after 26.0 min before decaying again to a minimum of 1500 kW after 40.5 min. Again, the heat release rate then increased to a maximum of 3600 kW after 49.3 min (Fig. 4(c)). The heat release decreased to 2200 kW prior to manual extinguishment after 62.5 min. Loss of approximately 8 kg of plasterboard was recorded during the full duration of this test, starting from 23 min.

4.1.5. Test gamma-1

Flashover occurred at 5.4 min and a peak heat release rate of 6700 kW was achieved after 5.6 min. The heat release rate decreased sharply until reaching 3700 kW after 21.3 min. Thereafter the HRR

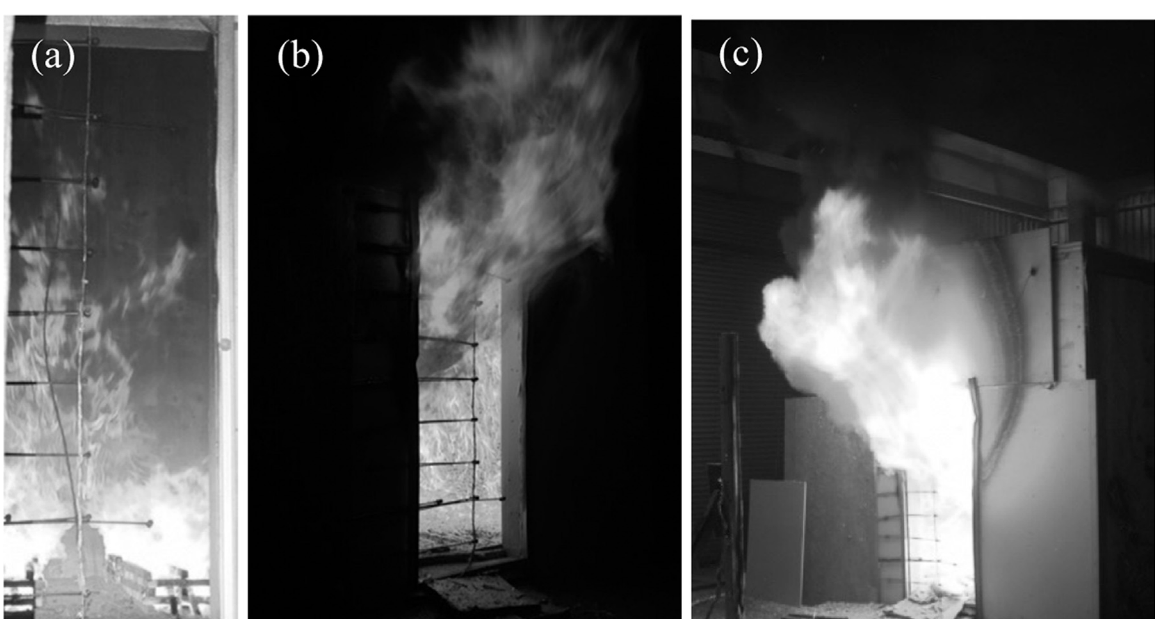


Fig. 2. Fire behaviour observed during test Alpha 2. (a) Ignition of the exposed timber on the back wall; (b) burning of the exposed timber surfaces and (c) increase in HRR prior to manual extinction.

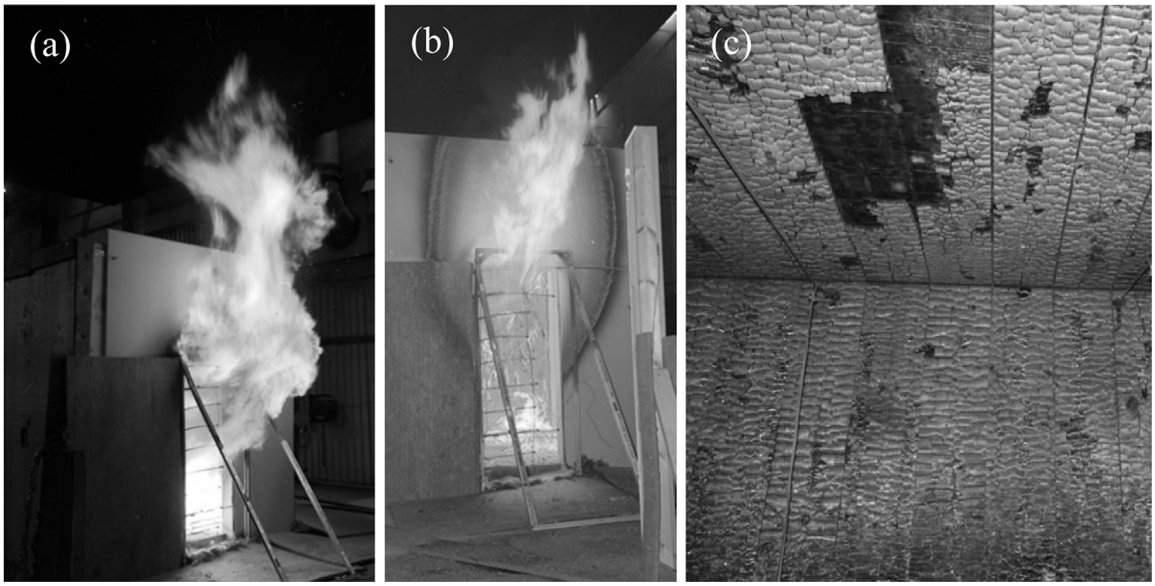


Fig. 3. Fire behaviour observed during test Beta 1. (a) Ventilation controlled burning soon after flashover; (b) decrease in observed external flaming prior to auto-extinction of the timber; (c) charred timber on the ceiling and back wall after auto-extinction (note localised areas of fall-off of the first lamella on the ceiling).

was quasi steady state between 3100 kW and 4000 kW for the remaining duration of the experiment until manual extinction after 78.0 min. The mass of plasterboard falling off could not be estimated due to failure of the load cells.

4.2. Time to flashover and peak heat release rate

A summary of the experimental results is given in Table 3. The time to flashover was typically on the order of 5 min; however Beta-1 experienced a longer time to flashover, close to 8.5 min. The total heat release rate at flashover varied between 1170 and 1709 kW, with a weak dependence on the exposed area of timber. This is expected given the similarity in material properties between the timber and other compartment linings, and similar area averaged thermal inertia of the compartment linings. The visual observations of the onset of flashover

Table 3
Summary of the experimental results.

Experiment	Time to flashover [min]	Total HRR at flashover [kW]	Time to peak HRR [min]	Peak total HRR [kW]	Maximum char depth in exposed timber after 60 min [mm]
Alpha-1	4.56	1709	6.27	5267	53
Alpha-2	5.13	1448	5.50	4677	53
Beta-1	8.55	1551	8.75	6213	11
Beta-2	4.23	1463	7.78	5248	44
Gamma-1	5.35	1171	5.55	6679	58

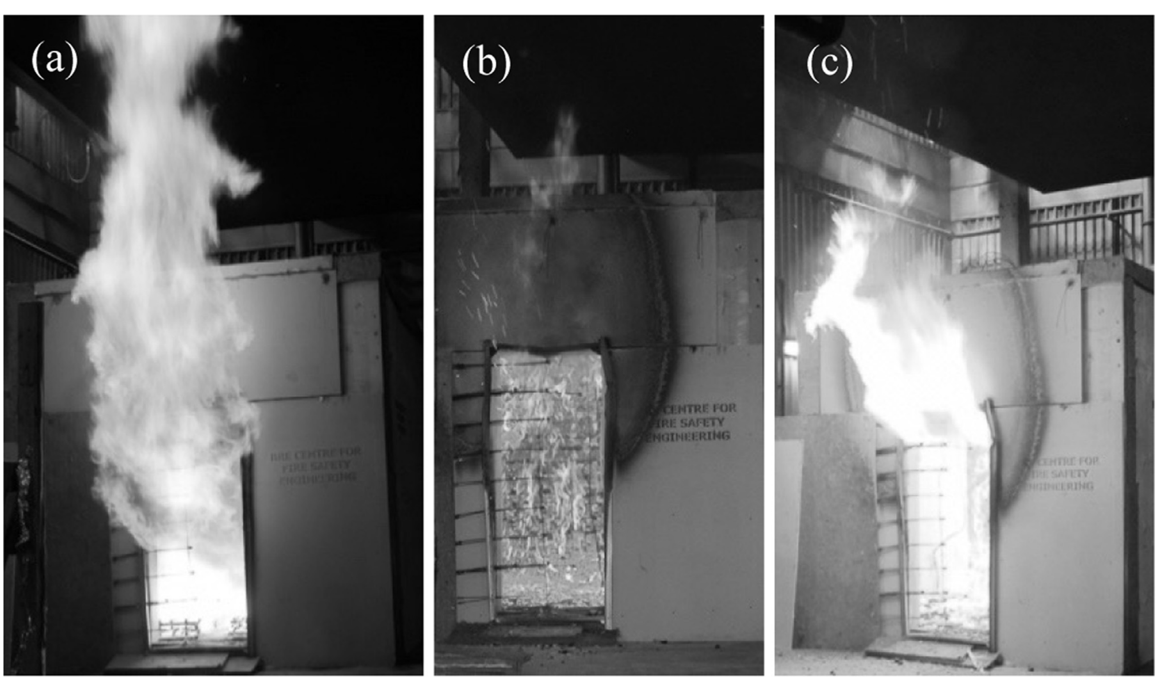


Fig. 4. Fire behaviour observed during test Beta 2. (a) Ventilation controlled burning soon after flashover; (b) decrease in observed external flaming and burning of the exposed timber surfaces; (c) increase in heat release rate associated to fall-off of char on the ceiling and back wall.

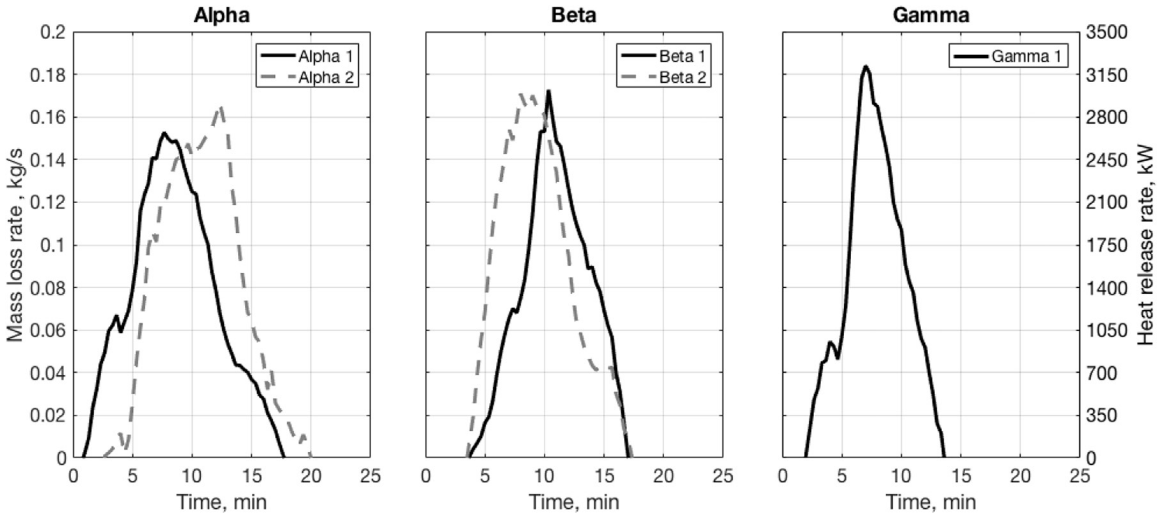


Fig. 5. Mass loss rate of the wooden cribs for each experimental configuration.

indicate that the process is governed by the ignition of the exposed timber area, resulting in rapid increases in heat release due to the large surface area available. In all cases the peak heat release rate occurred between 0.2 and 3.65 min after flashover. This short duration is expected due to the charring nature of timber.

4.3 Crib heat release

The mass loss rate of the cribs is shown in Fig. 5. After ignition the mass loss rate increased over a period of approximately 10 min with maximum mass loss rate in the range 0.14–0.18 kg/s. The one exception is test Beta-1, wherein the ignition and fire growth of the crib were delayed. This reduced burning rate early in the experiment is the cause of the long time to flashover noted in the previous section. Crib combustion was dependent on the configuration of the exposed timber surfaces. Changing the position of the exposed surfaces but keeping the exposed area constant reduces the burning duration of the fuel load to 17 min from a maximum of 20 min (configuration Beta and Gamma, respectively). Increasing the number of exposed surfaces, reduces the burning duration further to 13 min. These differences are attributed to increased heat feedback due to improved radiative view factors to the cribs due to ignition of the ceiling (configuration Beta) and increased area of burning surface (configuration Gamma). Assuming a heat of combustion of timber of 17.5 MJ/kg [7] the peak heat release rate from the cribs was between 2600 and 3200 kW; this exceeds the theoretical heat release rate required for flashover in the compartment. At flashover, the heat release rate from the cribs was in the range 600–1500 kW. However, the visual data indicate that additional energy was supplied from the exposed timber surfaces. Using the data in Table 3 this additional contribution from the exposed timber surfaces was approximately 500–800 kW (for Test Beta-1 the additional contribution using this method is 0 kW). This confirms the earlier observations that flashover occurs after the ignition of the exposed timber walls.

4.4. Compartment heat release

Time series of heat release rate data are given in Fig. 6. Initial inspection reveals that the three compartment configurations display markedly different behaviour. In all cases the compartment fire behaviour is characterised by a growth to 1–1.5 MW whereupon flashover occurs followed by a further increase in heat release rate. For configuration Alpha, peak heat release rates are in the region of 5 MW. This increases to approximately 6 MW for configurations Beta and Gamma. Since the area of exposed timber is approximately equal in the Alpha and Beta configurations and ~50% different between Beta and Gamma, this suggests that the exposed ceiling may contribute to increase in the peak HRR. It is interesting to note that the loss of encapsulation in Alpha-1 is manifested only by a slightly higher peak heat release rate after 44 min, and an increase in HRR after 60 min of only 800 kW compared to Alpha-2, despite almost all surfaces becoming exposed. After 55 min, the HRR in compartment Alpha-2 appears to be decreasing.

To further analyse the periodic growth-peak-decay heat release data, we introduce the concept of characteristic time of the compartment fire. This is defined as the time between minima in the heat release data. Configuration Alpha demonstrates a characteristic time on the order of 30 min and Beta a characteristic time of 20 min (as can be observed in Fig. 6). A characteristic time for Gamma cannot be defined as the heat release rate tends to a constant value. Since the burning duration of the compartment fuel load is shorter than these times this indicates that the characteristic times are dominated by fall-off of the timber layers. The shorter timescales for configuration Beta (with exposed horizontal surface) is in agreement with the observations in Kippel et al. [13]. Further analysis of these timescales and relation to the thermal penetration depth of the timber is discussed below.

4.5. Compartment temperatures

Compartment temperatures are governed by the heat released in the compartment and the heat losses through the compartment boundaries. As a result, compartment fire temperatures follow similar trends as the heat release rates. Additional information can however be extracted from Fig. 7, which shows temperatures in the centre of the compartment, 220 cm above the floor. Measurements are not corrected for radiation. Measured maximum compartment temperatures range from 1114 °C (Beta-2) to 1236 °C (Alpha-1) with an average maximum compartment temperature across all experiments of 1174 °C. Using Eq. (2), a maximum temperature in the compartment of 1174 °C is predicted. Given the empirical nature of the correlation in Eq. (2), and the deviations from the conditions under which it was derived, this precise agreement must be considered partly co-incidental. However, this does demonstrate that the influence of exposed timber linings on compartment temperatures is small.

Configurations Alpha and Gamma lead to the highest temperatures, while configuration Beta resulted in the lowest temperatures (particularly Beta 2). This can be explained by the difference in the compartment linings in each configuration. In configuration Alpha the majority of the plasterboard fell off during the experiment, exposing either timber (charred) surface (Alpha-1) or mineral wool insulation (Alpha-

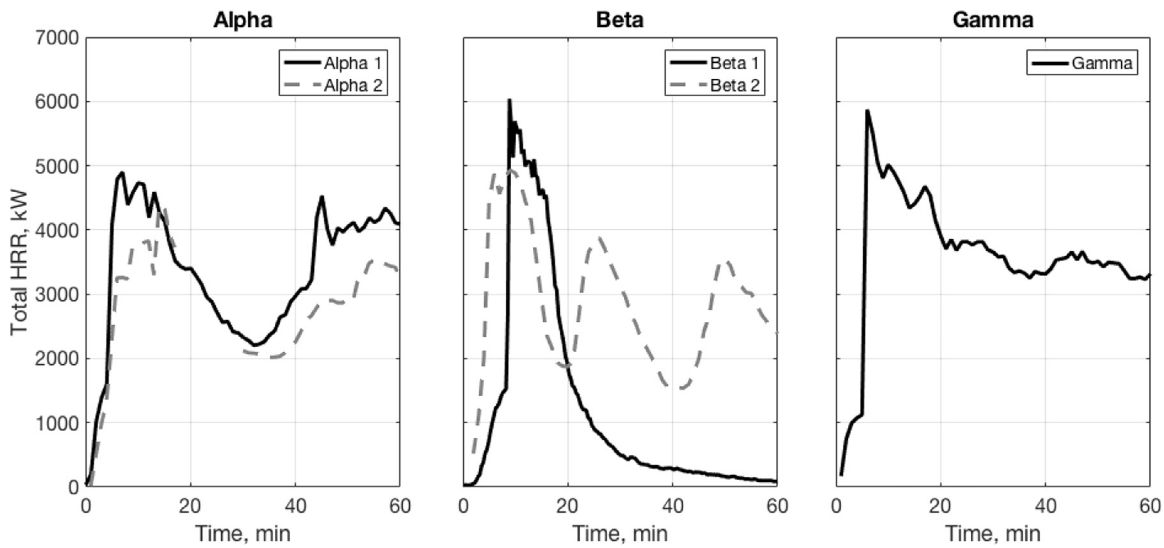


Fig. 6. Total heat release rates for all experiments. Data are incomplete for Alpha-2 between 17 and 28 min after ignition due to a data acquisition problem.

2). This contrasts with the Beta configuration in which little or no plasterboard fell off. The higher thermal inertia of plasterboard compared to char or stone wool results in larger heat losses from the compartment and lower compartment temperatures. This is confirmed by the high temperatures observed in Gamma, where the thermal properties of char and stone wool surfaces at long times results in higher compartment temperatures.

4.6. Thermal penetration

The measured data of char depths at the characteristic times of each compartment configuration (as defined above) are presented in Table 4. These data reveal that for configuration Alpha, the average char depth after the characteristic time was 22–23 mm, slightly more than the thickness of one layer of CLT. In Beta-1 the average char depth was 10–11 mm, with the maximum depth not exceeding the depth of the first timber lamella. In Beta-2 the char depths on the back wall after the first characteristic time period were comparable to Beta-1 (11 and 10 mm, respectively). After the second characteristic time period, the char depth had increased a further 15 and 12 mm, to 26 and 22 mm on the back wall and ceiling, respectively. The observation of lower charring depths on the ceiling compared to the back wall can probably be attributed to lower oxygen concentration near the ceiling and the resulting lower pyrolysis rate [1].

Table 4
Thermal penetration depths measured after the characteristic time for configurations Alpha and Beta. The two values reported for Beta-2 reflect the two characteristic time periods observed during the experiment.

Experiment	Surface	Average char depth after characteristic time [mm]	Maximum char depth after characteristic time [mm]
Alpha-1	Back wall	23	31
	Side wall	22	25
Alpha-2	Back wall	23	34
	Side wall	20	26
Beta-1	Back wall	11	15
	Ceiling	10	13
Beta-2	Back wall	11, 26	14, 38
	Ceiling	10, 22	13, 36

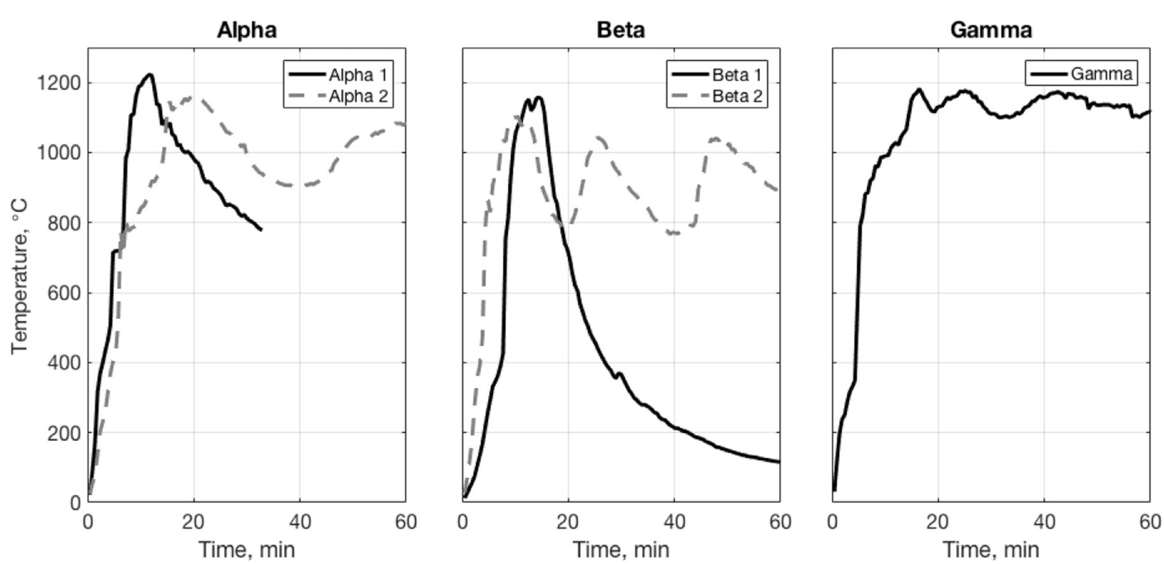


Fig. 7. Compartment fire temperatures measured 220 cm above the floor for all compartments. Data for Alpha-1 are not available after 33 min due to movement of the thermocouple tree. No correction has been made for radiation.

This analysis indicates that, at the local minimum of heat release rate in configurations Alpha and Beta, the char depths were significantly different. This suggests that the mechanisms by which the char layer falls off the timber (resulting in an increase in HRR) is different between these configurations. It is hypothesized that the char on the ceiling falls earlier than char on the walls (under the action of gravity) in agreement with previous observations [13]. This implies that to predict delamination knowledge of the thermal gradient beneath the char line and its effects on the performance of the adhesive are important in predicting this failure mode in this configuration. In configuration Alpha, it is possible that the char became dislodged after the adhesive action was lost due to the char front passing the adhesive layer.

To further assess the role of delamination on the compartment fire dynamics, calculation of the thermal penetration time is used. The thermal penetration depth is a measure of the depth of the heated layer in a solid and is estimated by Eq. (4) [22]:

$$\delta = C\sqrt{\alpha t} \tag{4}$$

where α is the thermal diffusivity (m^2/s) and t time (s) and C is dependent on the dimensionless temperature difference in the solid. In this case C=1.6 (assuming a surface temperature of 1100 °C, a temperature of interest of 300 °C (assumed charring temperature) and an ambient temperature of 20 °C (see [22]). Using the thermal properties presented in Table 2, and a lamella thickness of 20 mm, the time required for the charring front to penetrate the first lamella (the thermal penetration time) is 18 min. This means that after 18 min of fire exposure, it can be assumed that the first layer of the CLT has been completely charred.

This characteristic time can be used in conjunction with the burning duration of the compartment fuel load to further understand the effects of exposed timber on the compartment fire dynamics. In configuration Alpha, the burning duration of the fuel load is longer than the thermal penetration time of the first timber layer. In configuration Beta, the compartment fire duration is slightly lower than the thermal penetration time of the timber layer (due to additional heat feedback as discussed previously). As a result, the outer layer of timber remains intact for the duration of the compartment fire in configuration Beta but not for configuration Alpha. This analysis is confirmed by the observations of char depth made after experiment Beta-1. Using this analysis, the different behaviours observed for the repeated Beta case can be attributed to the uncertainties in the duration of the compartment fire.

The thermal penetration time is much longer than the duration of compartment fuel load burning in configuration Gamma suggesting that the sustained burning in this case is due to radiative exchange between the timber surfaces.

5. Effects of exposed timber on the fire dynamics

To explain the observed fire behaviour in the different compartment configurations, two mechanisms which will prevent auto-extinction are identified. These arise due to the characteristics associated with the burning of the CLT.

Fall-off of the char exposing the fresh timber to the high heat fluxes inside the compartment allows rapid pyrolysis and increase of the HRR. Heat release rate and the auto-extinction will then become a function of the area of fall-off and the thickness of the lamella. This behaviour was observed in Beta-2 and to a lesser extent Alpha-2. This can be evaluated with knowledge of the duration of the fire associated with the compartment fuel load and thermal penetration time of the timber layers.

If the critical heat flux for sustained burning is maintained within the compartment by radiative exchange between the linings, then the pyrolysis rate will be sufficiently high such that sustained flaming will continue. In this case the total HRR will be a function of the air available for combustion inside the compartment and the exposed surface area of timber. This is the mechanism leading to the fire behaviour observed in Gamma-1 and prediction of the fire behaviour requires knowledge of the compartment configuration.

Loss of integrity of the thermal barrier/encapsulation will expose additional timber surfaces and depending on the resulting configuration either mechanism may result. If the area of fall-off is large a heat transfer dominated compartment fire will result as observed in Alpha-1.

6. Concluding remarks

The above analysis highlights several important issues relevant to understanding the compartment fire dynamics of compartments with exposed cross laminated timber linings. The primary conclusion is that auto-extinction has been observed in compartments with two surfaces of exposed timber. This is, however, shown to be dependent on the char layer remaining attached i.e. 'delamination' or fall-off does not occur, during the combustion of the compartment fuel load or during the decay period. For compartment configurations with three exposed timber surfaces, auto-extinction was not observed. This is attributed to the heat transfer between the exposed timber surfaces preventing the critical heat flux for extinction being reached.

The measured peak compartment temperatures were not substantially different from those predicted by existing correlations suggesting that exposed timber surfaces have only a small influence on the compartment temperature. The total heat release rate was, however, found to be higher than predicted using existing methodologies developed for compartments with inert linings and fuel loads located on the floor. This suggests that further work to quantify the effect of fuel position within the compartment is required.

A method based on comparison the burning duration of the compartment fuel load and the characteristic thermal penetration time of the timber layers has been shown to provide explanation of the observed fire dynamics and the onset of auto-extinction. Although this has scope to be developed for engineering applications there are several issues which must first be understood in more detail. These include the effects of the burning surface configurations on the burning of the compartment fuel load and, the loss of integrity of encapsulation systems and the effect this has on the compartment fire dynamics.

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