Description of small and large-scale cross laminated timber fire tests

Citation for published version:
Emberley, R, Gorska Putynska, C, Bolanos, A, Lucherini, A, Solarte, A, Soriguer, D, Gutierrez Gonzalez, M, Humphreys, K, Hidalgo, JP, Maluk, C, Law, A & Torero-Cullen, J 2017, 'Description of small and large-scale cross laminated timber fire tests', *Fire Safety Journal*, vol. 91, pp. 327-335. https://doi.org/10.1016/j.firesaf.2017.03.024

Digital Object Identifier (DOI):
10.1016/j.firesaf.2017.03.024

Published In:
Fire Safety Journal

Fire Safety Journal; http://dx.doi.org/10.1016/j.firesaf.2017.03.024; Received 10 February 2017; Accepted 15 March 2017.

Description of Small and Large-Scale Cross Laminated Timber Fire Tests

RICHARD EMBERLEY[1, 2], CARMEN GORSKA PUTYNSKA[1], AARON BOLANOS[1], ANDREA LUCHERINI[1], ANGELA SOLARTE[1], DIANA SORIGUER[1], MATEO GUTIERREZ GONZALEZ[1], KATHRYN HUMPHREYS[1], JUAN P. HIDALGO[1], CRISTIAN MALUK[1], ANGUS LAW[1, 3], and JOSE L. TORERO[1]

[1] School of Civil Engineering, The University of Queensland, Australia
[2] Mechanical Engineering Department, California Polytechnic State University, California, USA
[3] BRE Centre for Fire Safety Engineering, The University of Edinburgh, UK

ABSTRACT

A large-scale fire test was conducted on a compartment constructed from cross laminated timber (CLT). The internal faces of the compartment were lined with non-combustible board, with the exception of one wall and the ceiling where the CLT was exposed directly to the fire inside the compartment. Extinction of the fire occurred without intervention. During the fire test, measurements were made of incident radiant heat flux, gas phase temperature, and in-depth temperature in the CLT. In addition, gas flow velocities and gas phase temperatures at the opening were measured, as well as incident heat fluxes at the facade due to flames and the plume leaving the opening. The fuel load was chosen to be sufficient to attain flashover, to achieve steady-state burning conditions of the exposed CLT, but to minimize the probability of uncertain behaviors induced by the specific characteristics of the CLT. Ventilation conditions were chosen to approximate maximum temperatures within a compartment. Wood cribs were used as fuel and, following decay of the cribs, self-extinction of the exposed CLT rapidly occurred. In parallel with the large-scale test, a small scale study focusing on CLT self-extinction was conducted. This study was used: to establish the range of incident heat fluxes for which self-extinction of the CLT can occur; the duration of exposure after which steady-state burning occurred; and the duration of exposure at which debonding of the CLT could occur. The large-scale test is described, and the results from both the small and large-scale tests are compared. It is found that self-extinction occurred in the large-scale compartment within the range of critical heat fluxes obtained from the small scale tests.

KEYWORDS: compartment fires; heat transfer; CLT; self-extinction.

INTRODUCTION

The demand for cross laminated timber (CLT) construction has significantly increased in the last few years with substantial media interest around “tall timber”, and a large body of research effort around the performance of timber in fire. The aim for many architects and engineers is to deliver high-rise CLT buildings where the timber linings are partially or completely exposed. Regulators around the world are currently attempting to adapt regulations to the demands of industry by incorporating clauses to permit large-scale timber construction.

Any attempt to create high-rise CLT buildings must address two fundamental issues:

1. The existing regulatory framework for fire resistance is based on the intention to survive burnout of the fuel load inside the compartment – since exposed structural CLT is combustible, the definition of burnout is no longer relevant unless it can be demonstrated that, following the consumption of the fuel load in the compartment, the CLT eventually self-extinguishes.
2. Existing fire safety provisions to prevent vertical fire spread assume that the area of combustible material is limited to the floor – since the exposed CLT is on the walls and ceiling, this will substantially increase the area of fuel involved in the fire, create an excess of pyrolysis gases [1], and hence also increase the size/intensity of the external plume. It must therefore be demonstrated that any proposed safety measures are sufficient to prevent external floor-to-floor fire spread.

This paper focuses on the first of these issues, and presents a description of the background behind a large-scale CLT test. A description and preliminary analysis of the test results is presented.

Project Context

The large-scale fire test that is reported in this paper was part of a wider project investigating the feasibility of modular systems, and the construction methodologies for CLT. The project was based on a real case study of a proposed apartment building in Brisbane, Australia. Consequently at every stage of the test design, the constraints of a real project were considered. This included developing design arrangements intended to deliver compliance with the Building Code of Australia [2] (whether using deemed to satisfy provisions or alternative solutions) – including structural design, acoustic performance, termite resistance, and fire safety.

The outcome of this design process was that the team proposed a medium rise CLT apartment building that had architecturally expressed (i.e. exposed) CLT on one wall and the ceiling. It was identified that for this project (and any future projects) it would be necessary to demonstrate as part of the approvals process that exposed timber linings are capable of self-extinction in this arrangement.

SELF-EXTINCTION

Principles of Self-Extinction

The burning of timber is enabled by the imposition of an external source of heat. When this heat flux is completely removed, self-extinction of flaming combustion of timber occurs [3]. This is due to the fact that the heat flux provided by the flames of the burning timber is not sufficient to sustain the mass loss rate needed to sustain flaming combustion at the surface of the timber [4]. A critical mass loss rate and associated external heat flux value exists for specific species and air velocities [5].

The process of timber combustion involves both a transient and steady-state phase. The transient regime of burning is marked by an initial peak in mass loss rate when the char layer begins to form. As the char layer increases in thickness, the heat flux entering the pyrolysis front of the timber is regulated by the insulating thermal properties (and volume) of the char. As the thickness increases, the heat flux reaching the pyrolysis front decreases until an approximate constant value (proportional to the incident heat flux) is reached.

This process can be explored by analyzing the energy balance for the char layer as described by Emberley et al. [6]. The mass loss rate can be defined in accordance with Equation (1):

$$\dot{m}''_f = \frac{1}{\Delta H_p}\left[\dot{q}''_{ext} + \dot{q}''_{ch} - \dot{q}''_{loss} - \left(-k\left.\frac{dT}{dx}\right|_{x=x_{ch}}\right) - \frac{\partial(\delta q''')}{\partial t}\right] \qquad (1)$$

Where $\dot{m}''_f$ is the mass loss rate per unit area, ΔH_p is the heat of pyrolysis, $\dot{q}''_{ext}$ is the external heat flux per unit area (corresponding to the summation of the contributions of any heat source independent of the fuel being produced and the heat feedback from the combustion of the fuel being produced), $\dot{q}''_{ch}$ is the energy generated due to reaction of the char per unit area, $\dot{q}''_{loss}$ is the heat losses from the surface per unit area, k is the thermal conductivity of the timber, $\left.\frac{dT}{dx}\right|_{x=x_{ch}}$ is the thermal gradient of the heat losses into the virgin timber, δ is the thickness of the char layer and $(\delta q''')$ is the energy stored in the char layer per unit area.

When the timber starts to burn, the exposed surface tends towards the oxidation temperature of the char and the surface losses, therefore, tend towards a steady state. As the timber continues to burn, the char layer becomes thicker but the exposed surface begins to regress. In the absence of debonding, the thickness of the char layer (δ) and the energy stored in the char eventually tend to a constant and subsequently the right hand term of Equation (1) approaches zero. During this period, the in-depth temperature gradients ($\left.\frac{dT}{dx}\right|_{x=x_{ch}}$) will reach a steady-state minimum, and therefore the external heat flux required to maintain the burning rate reaches also a steady-state minimum. This condition requires the minimum supply of external energy to maintain a constant burning rate [6].

Extinction of a diffusion flame occurs when the supply of reactants is insufficient to maintain the flame temperature above a critical value [5]. If the flow conditions remain constant, then the mass loss rate is the only variable that affects whether extinction occurs. In the context of Equation (1), and under steady state conditions, the only variable that can cause a drop in the mass loss rate is the external heat flux.

To identify conditions for self-extinction, it is necessary to identify the critical mass loss rate for extinction and the corresponding heat flux. The mass loss rate for extinction will be the same during the transient and steady state conditions of burning. However, during the transient period, the magnitude of the different terms in Equation (1) evolves which means that the heat flux at which extinction occurs will vary as a function of time. During the transient phase, self-extinction could occur at a relatively high heat flux; however, during the steady state, self-extinction will not occur until the external heat flux decreases below the minimum value described above. Consequently, the worst case condition for self-extinction in a compartment fire is once the timber has attained the steady state burning condition.

If separation of lamellae occurs as the thermal wave penetrates the CLT, then fresh timber is exposed and there is a rapid increase in mass loss rate (and associated flaming combustion).

Consequently, to investigate the viability of self-extinction of timber in a compartment fire, it is necessary to ensure that any CLT linings are not in the transient phase of burning. Any debonding may cause re-ignition of the linings and prevent self-extinction – hence it is also necessary to minimize the likelihood of debonding.

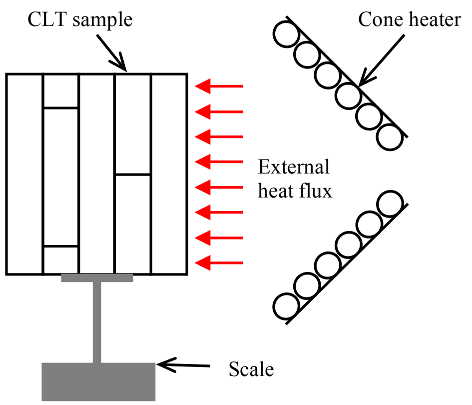
For the purposes of this paper, separation of the lamella and associated fall off of timber/char shall be referred to using the term *debonding*. To investigate the critical mass loss rate, associated incident heat flux value, and potential for debonding – a series of small scale tests were performed.

Small Scale Testing Methodology

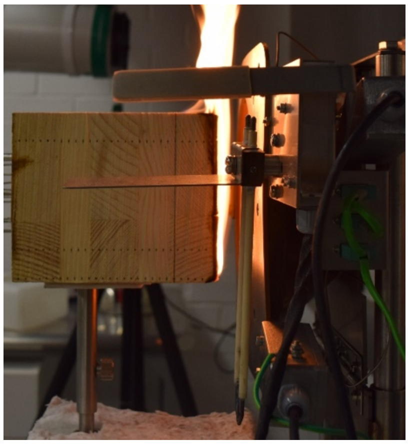
To investigate the self-extinction criteria for CLT, timber blocks (150 mm thickness) with surface area of 120×120 mm were exposed to a range of external heat fluxes by a cone heater [6]. The samples were comprised of five layers of thicknesses 45 mm, 20 mm, 20 mm, 20 mm, and 45 mm, respectively – the CLT samples were sourced from XLam and were Radiata Pine.

The samples were placed on a scale to measure the rate of mass loss over time – as illustrated in Fig. 1. The external heat flux was instantaneously applied to the samples and caused the surface of each sample to increase in temperature and then auto-ignite. The samples were allowed to burn until flaming combustion ceased or until the sample was completely burned. As the surface regressed away from the cone heater, the external heat flux on the exposed surface decreased due to the increased distance from the heat source. The time to self-extinction and the corresponding distance away from the heater were measured. A Schmidt-Boelter heat flux gauge was used to measure the external heat flux at the location of the exposed surface when self-extinction occurred. This value corresponded to the critical heat flux for self-extinction. A total of 27 samples were tested across various heat fluxes. The minimum number of repetitions was two, and the maximum number of repetitions was eight. The methodology was rigorously tested and the data was consistent both between samples and with values from literature [7].

The critical mass loss rate for self-extinction could be identified as the mass data was collected over time; the transient and steady-state phases of burning could also be distinguished.



a)



b)

Fig. 1. a) Schematic of the experimental setup; b) Image of test.

Fire Safety Journal; http://dx.doi.org/10.1016/j.firesaf.2017.03.024; Received 10 February 2017; Accepted 15 March 2017.

Small Scale Test Results

Figure 2a shows the 2 minute averaged mass loss data for each of the heat fluxes applied (with the maximum and minimum for all data shown in grey); the two phases of burning are clearly evident. These results show that ignition is faster with higher external heat fluxes and that after ignition, a peak mass loss rate occurred in the early stages of heating. The peak value increases with the external heat flux. As the burning continued, the mass loss rate began to decrease. This behavior is consistent with the process described above. The transition to steady state burning was not instantaneous; however, it can be observed that it occurred faster for high heat fluxes than for low heat fluxes; this was due to the time taken to form the char layer. For the lower heat fluxes it was estimated that steady state occurred after approximately 13 minutes, and for higher heat fluxes steady state occurred after approximately 8 minutes. Given the range of heat fluxes common in a compartment fire, it was assumed that 10 minutes is a representative time for transition to steady state. Figure 2(a) shows that beyond this representative steady-state time the mass loss rate continues to decay. Nevertheless, for the purposes of this study this further decay will be neglected and the terminal mass loss rate is assumed to be reached at 10 minutes from the onset of exposure. The average and terminal mass loss rates depend on the external heat flux with higher heat fluxes resulting in higher mass loss rates.

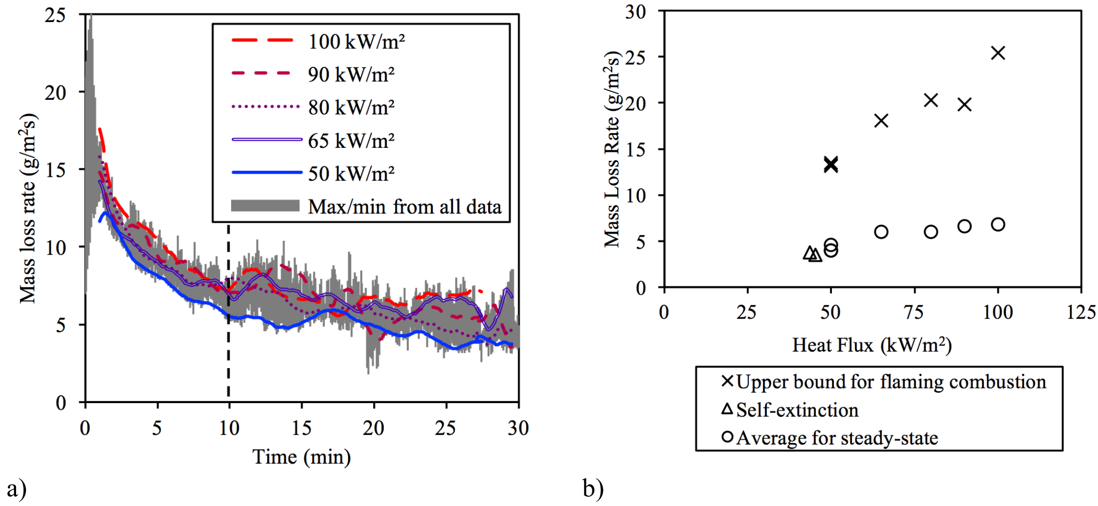


Fig. 2. Mass loss rate of timber exposed to external heat fluxes.

Figure 2b shows the mass loss rate and the associated heat flux values for each test. For each heat flux value, the peak (upper bound) and average steady-state (terminal) mass loss rate is included to show the upper and lower bounds for the test. Values above or below the range are not physically possible for the test configuration and parameters. The peak values occurred just after ignition while the average steady-state values were recorded just after 10 min of burning. The critical mass loss rate for flame extinction was measured as 3.7±0.2 g/m^{2}s while the critical heat flux was 45±1 kW/m^2.

Debonding

Debonding can occur in CLT [8] and is characterized by large peaks in the mass loss rate data. The large peaks occur when a significant portion of either the char layer or the timber plies fall off – reducing the insulation and exposing the virgin timber to higher heat fluxes. The mass loss rate remains higher than steady-state values until the char layer increases to sufficient depth to reduce the heat flux delivered to the pyrolysis front. Debonding occurred in several of the tests described above. The resulting peaks in mass loss rate can be seen in Fig. 3.

Fire Safety Journal; http://dx.doi.org/10.1016/j.firesaf.2017.03.024; Received 10 February 2017; Accepted 15 March 2017.

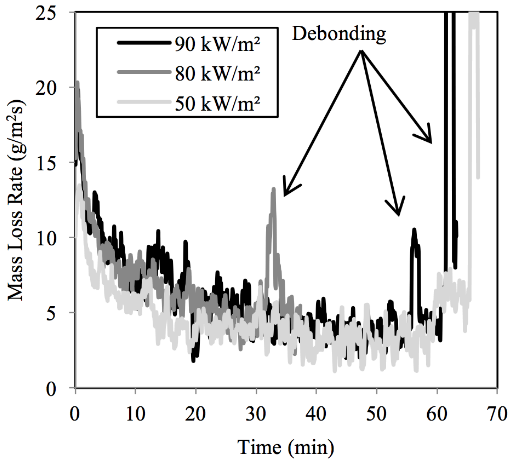


Fig. 3. Mass loss rate over time – debonding events are annotated.

Achieving Self-Extinction in a Compartment Fire

The small scale tests above were used to inform the development of the large-scale fire test. It is clear from the test that if self-extinction occurred before 10 min of burning had occurred – then the timber was still within its transient burning phase. However, it was also clear that if the test lasted beyond 30 min, then debonding would be likely to occur – and therefore significant uncertainties would be introduced into the test.

Steady-state burning occurred after approximately 10 min (as evidenced by the small scale tests shown in Fig. 2a); debonding of CLT started to occur 30 min after ignition (as evidence by Fig. 3). It was therefore concluded the target burning time for the large-scale compartment after the ignition of the CLT (or flashover) should be between 10 and 30 min.

MOTIVATION FOR LARGE-SCALE TEST

The motivation for the large-scale test was to demonstrate that, for the proposed geometry, self-extinction could be achieved under conditions where uncertain behaviors (e.g. debonding of the exposed CLT or failure of the fire protection) could be prevented. Hence, a test configuration was derived that represented a balance between the various constraints on the project. The optimum balance was where the test represented realistic configurations and construction detailing, while minimizing the uncertainties associated to the debonding of CLT.

The following considerations were taken into account:

- The opening factor of the compartment was chosen to induce a temperature that approximately corresponded to the maximum temperature in a Regime I [9] compartment fire;
- The opening factor was also chosen to ensure that the compartment during the fully involved phase could be considered as a Regime I fire (the Thomas opening factor was 18.5 $m^{-1/2}$ [or 10 $m^{-1/2}$ if the CLT walls are omitted from the wall area calculation]);
- The fuel load and configuration were chosen such that they would be sufficient to induce flashover – two wood cribs were provided with a total of 80 kg of fuel and centrally located in the room (indicated on Fig. 4);
- The fuel load was chosen to ensure that the fully developed phase would last beyond the transient period of CLT flaming combustion – it was intended that the fully involved phase of the fire should last a minimum of 10 min from the ignition of the CLT;
- The fuel load was chosen to ensure that debonding of the outermost layer of the CLT did not occur (i.e. the fire should not last longer than 30 min from the ignition of the CLT).

The test design was therefore intended to deliver a worst case scenario in terms of maximum heating exposure of the CLT; ensure that the CLT was in the steady-state of burning; and minimize the likelihood of a debonding event.

It should be noted, therefore, that while some aspects of this test were designed to be worst case (e.g. maximum incident heat flux), many other aspects of the test could have been adjusted to create a more onerous scenario e.g. duration of the fully-developed fire. If the fuel load had been greater (i.e. greater mass of wood cribs), then debonding of the CLT could have been more likely and the other elements of construction (e.g. fire protection and connection details) would have been tested more severely. Similarly, a reduction in the outer lamella thickness would have hastened the onset of debonding. This would have introduced uncertainty in terms of the decay phase of the fire and, therefore, possibly reduce the likelihood that self-extinction could have occurred. The limitations associated with the outcome of this test are discussed further below.

TEST SETUP

Geometry and Construction

The geometry of the compartment (Fig. 4) was based on the dimensions of a living room in the project described above. To introduce a level of standardization with other compartment fire testing, the aspect ratio of the plan was adjusted to a 1:1 ratio. The ceiling height was not adjusted. This resulted in a base build compartment geometry of internal dimensions 3.5×3.5×2.7 m. An opening was provided based on typical door dimension (0.85×2.1 m). To meet the structural requirements for the project, each element of CLT was 150 mm thick, comprised of five lamellae with a buildup of 45×20×20×20×45 mm (this was the same stock of CLT that was used for the small scale testing described above). The compartment was raised 500 mm above ground level to facilitate access beneath the compartment.

An internal floor buildup was developed that met the project's acoustic requirements. This consisted of a layer of acoustic rubber; 50 mm mineral wool insulation; 22 mm fiber cement floor panels. In any finished apartment there would also be a surface finish (e.g. tiles, or carpet). 50×50 mm wooden battens at 500 mm centers were provided in the insulation layer. Where the CLT walls were provided with non-combustible linings, this was comprised of 2×13 mm Knauf FireShield plasterboard liners independently secured at 200 mm spacing. The Knauf FireShield is a commercially available product that is frequently used in Australia for fire protection; product datasheets indicate that the core is comprised of calcium sulphate dehydrate with small quantities of glass fibre and vermiculite. This boarding solution was a standard fixing applied to a non-standard (i.e. CLT) substrate. The internal wall linings reduced the overall compartment dimensions commensurate to their thickness.

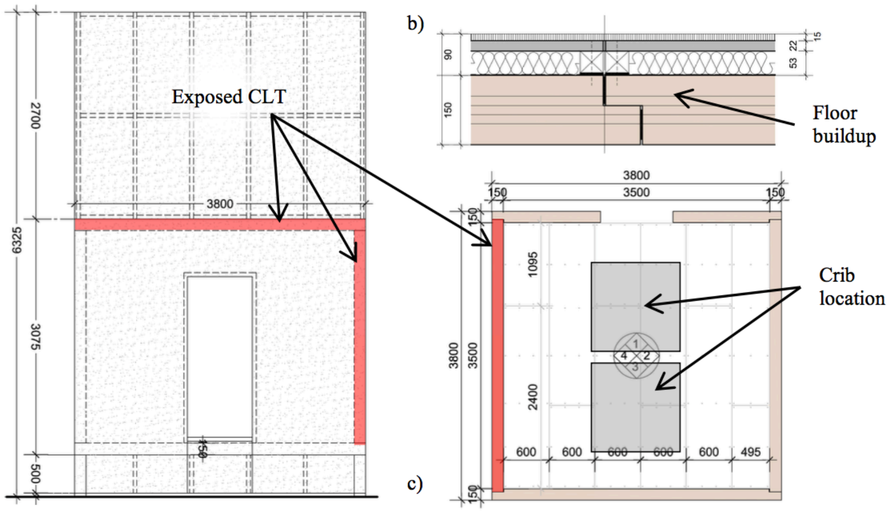


Fig. 4. Drawings of a) the front of the compartment; b) the compartment floor buildup; c) compartment plan view and crib location.

The CLT was secured with Rothoblass fixings including vertically fixed screws for the roof and wall connection; these were fully contained within the CLT. Surface mounted brackets on the floor and wall connections were hidden under the raised floor assembly. Cork strips were utilized at wall, floor and roof junctions for acoustic control as per the proposed apartment design (with caulking).

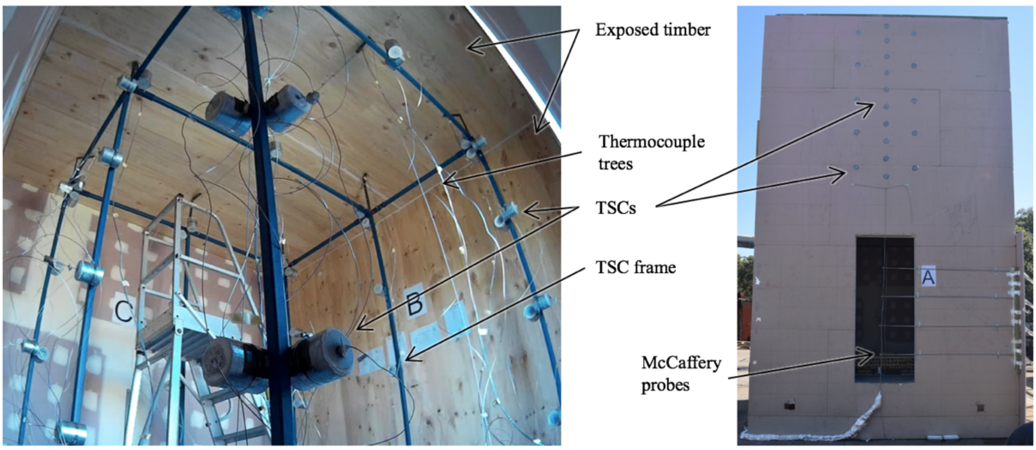
Externally, the front wall of the compartment was extended vertically by an additional 2.7 m (intended to represent one additional story). This vertical facade was constructed using a light timber frame. The entire front of the compartment (i.e. CLT, and upper facade) was covered with 2×13 mm Knauf FireShield board.

Instrumentation

The compartment was instrumented as follows:

- Nine thermocouple trees (i.e. thermocouples positioned at various heights) were provided in a square grid within the compartment. Each thermocouple tree had seven thermocouples distributed over the height of the compartment (min 250 mm, max 2600 mm). The thermocouple trees were comprised of 1.5 mm diameter, type K thermocouples with Inconel sheath. Thermocouple wires passed through holes the floor of the compartment and connected to the data logger.
- Fifty-nine Thin Skin Calorimeters (TSCs) were positioned within the compartment. Each TSC was comprised of a thin (1.2 mm) circular disk of 10 mm diameter with a type K thermocouple welded to the unexposed face. The disk was mounted on the surface of piece of insulation (50 mm thick, and 80 mm in diameter). The devices were calibrated using a cone heater; a full description of theory and calibration process for the TSCs may be found elsewhere [10]. The TSCs were orientated to face into the compartment (refer to Fig. 5a). These were mounted on a frame that was offset from the walls by 575 mm and ceiling by 340 mm. The intent of offsetting the frame was to minimize local radiative interaction/feedback between the instrumentation devices and the exposed CLT inside the compartment.
- Type K thermocouples were placed in-depth within the CLT. In the exposed CLT, measurements were made at seven locations at depths from the exposed surface of 3, 5, 10, 20, 45, 55, 65, and 150 mm. In the unexposed CLT, measurements were made at 1, 20, 45 and 150 mm from the interface CLT-protection.
- The opening of the compartment was provided with a single thermocouple tree (comprised of eight evenly spaced thermocouples) and four evenly spaced bidirectional McCaffrey probes [11] (shown in Fig. 5b).

In addition, 3D laser scanning and compartment pressure testing was carried out before and after the test. Three cameras were located to record the behavior of the external plume. The upper facade was instrumented with 20 TSCs and 20 associated thermocouples positioned at different heights above the opening (shown in Fig 5b).



a) b)

Fig. 5. Instrumentation locations (internal and external).

To generate the conditions required for flashover, two wood cribs each comprised of 40 kg of timber were provided. The cribs consisted of 25×25×1000 mm sticks stacked in a 1:1 ratio of air to solid. There were six layers of sticks in each crib. Ignition of the cribs was executed using two 300 ml trays of kerosene placed directly underneath the cribs. These were ignited by kerosene soaked rags. Based on the crib configuration, it would be expected that the maximum heat release rate (for each free burning crib) would be approximately 2 MW [12].

RESULTS

This paper will not present a detailed breakdown of the results because, at time of writing, these are still undergoing analysis. Nevertheless, the key results are described and allow some general conclusions to be drawn.

Test Description

The timeline of the test was as described in Table 1. Many of the events have some level of qualitative judgment in terms of defining the time at which they occurred. Hence to avoid inappropriate precision, times are reported to the nearest 15 s.

Table 1. Timeline of test.

Time	Event
00:00:00	Start of test
00:00:45	Ignition of pans
00:10:00	Cribs fully involved
00:12:15	Involvement of ceiling
00:12:30	Flames reach base of CLT wall
00:23:30	Extinction at base of wall
00:28:00	Extinction of top of wall and ceiling
05:32:00	Test terminated

Visual Observations

Figure 6 shows images from several notable features of the test (and the time after ignition at which the images were captured) specifically:

a) Ignition of the ceiling at approximately 12 min and 14 s;

b) Rapid spread of flame down the exposed CLT wall at 12 min 24 s;

c) Flaming reaching the base of the CLT wall at 12 min 33 s;

d) Fully involved compartment and associated plume at 19 min 58 s (note that this image is illustrative of the conditions throughout the duration of the fully involved fire);

e) Visibly flaming CLT wall at 20 min 13 s;

f) Notable reduction in flame length at the base of the CLT wall at 21 min and 42 s;

g) Very significant reduction in flaming at the base of the CLT wall at 23 min and 22 s;

h) Localization of flames to the top of the CLT wall and ceiling at 27 min 15 s; and

i) Extinct CLT elements at 30 min 36 s.

The visual observations indicate that all fire protection remained in place, and that self-extinction of the compartment occurred, and that this occurred during the decay phase of the wood cribs. The extinction of the CLT panels was notable because, initially, the burning at the base of the CLT wall became less vigorous – with the flames reducing in length until flameout occurred. Over the course of 4.5 min, this process occurred across the full height of the wall. Once the wall ceased flaming, the CLT ceiling ceased flaming immediately. It was also notable from visual observations that during the progression of the self-extinction, extinction at the left side of the ceiling occurred, while flaming continued on the CLT wall i.e. there was uneven distribution of flaming at the ceiling – with more flaming above the CLT wall. It was observed that the maximum char depth (excluding local imperfections) was approximately 20 mm.

Fire Safety Journal; http://dx.doi.org/10.1016/j.firesaf.2017.03.024; Received 10 February 2017; Accepted 15 March 2017.

a) 12 min 14 s after ignition

b) 12 min 24 s after ignition

c) 12 min 33 s after ignition

d) 19 min 58 s after ignition

e) 20 min 13 s after ignition

f) 21 min 42 s after ignition

g) 23 min 22 s after ignition

h) 27 min 15 s after ignition

i) 30 min 36 s after ignition

Fig. 6 Selection of images from test.

Gas Phase Temperature

The gas phase thermocouple data were recorded with relatively high density, and thus it is possible to analyze the temperature data as a function of space and time. For simplicity, Fig. 7 illustrates the overall temperatures in the compartment. The time associated with some of the observations illustrated in Fig. 6 are overlaid onto the plot.

Figure 7 shows the mean temperature in the compartment, the maximum temperature, and the minimum temperature recorded by any thermocouple at each sampling time. It was found that that the highest temperature at any time in the compartment was 1125°C, the maximum average temperature was 1000°C, and the maximum lowest temperature was 706°C. It should be noted that the lowest temperature was consistently recorded at the base of the thermocouple tree adjacent to the opening. Correction of radiation errors [13] has not been completed at this stage.

The data indicated that at the average temperature in the compartment dropped below 100°C after 63 min, and that the maximum temperature dropped below 50°C after 126 min. When the test was terminated at 5 h and 32 min, the average temperature in the compartment was 26°C.

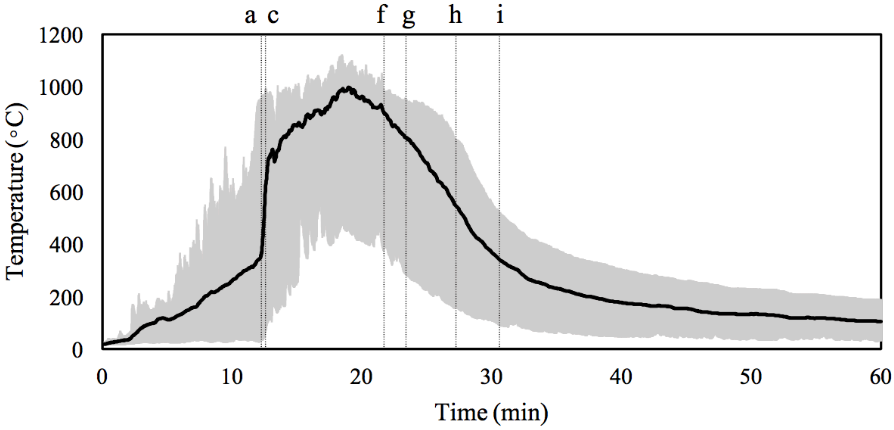


Fig. 7. Gas phase thermocouple data for the first 60 min after ignition. Plot shows mean temperature for all sensors, minimum temperature recorded anywhere in the compartment, and maximum temperature recorded anywhere in the compartment. Letters indicate observations as per Fig. 6.

Incident Radiant Heat Flux

The readings from the TSCs were used to calculate incident radiant heat fluxes using the calibration procedure described in [10]. Of the 59 TSCs in the compartment, 36 failed to provide continuous readings throughout the tests. Nevertheless, key data were recorded for each wall.

It was found that immediately after flashover, the heat flux readings fluctuated significantly. However, as the compartment progressed towards steady-state conditions and during the decay phase the readings were more consistent.

Figure 8 shows the heat flux data from TSCs towards the top and base of the exposed CLT wall throughout the test. In addition, the plot shows the critical heat flux for self-extinction derived from the small scale test. The events illustrated in Fig. 6 are also plotted on the diagram, and the visually observed self-extinction events are annotated on the plot.

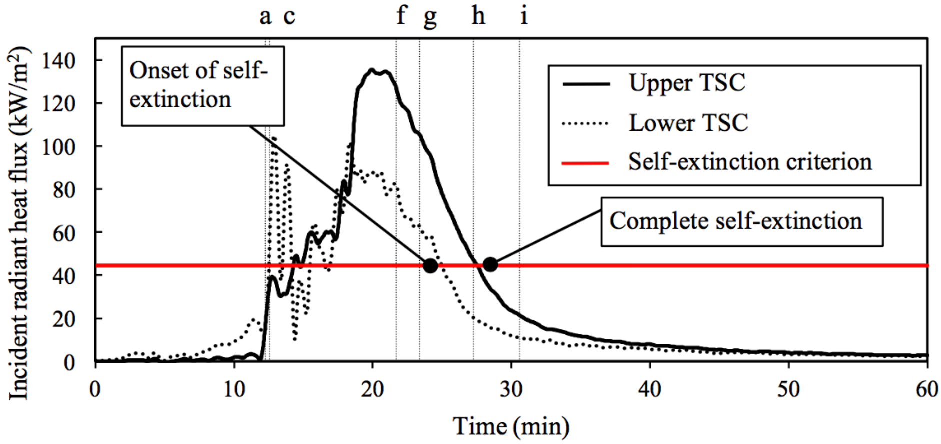


Fig. 8. Heat flux readings during the first 60 min after ignition. Plot shows an upper and lower TSC associated with the CLT wall. Letters indicate observations as per Fig. 6.

DISCUSSION

At time of writing, most of the data generated during the test was still being analyzed in detail. Hence, a detailed discussion of each aspect of the results would be premature. Nevertheless, based on the overall results and most easily analyzed data there are some aspects of the test that are worthy of immediate discussion.

There are several notable observations with regard to the success of the test planning:

1. Time to flashover was longer than had been anticipated. Hence there was less crib fuel available to burn during the fully involved phase. As such, the duration of the fully involved period of the test was approximately 11 min. Hence, the CLT (particularly at the base of the panels where extinction occurred first) was only just within the steady-state burning phase.
2. Debonding of any of the CLT elements did not occur. Consequently, this aspect of the test objective was achieved. Hence, the test configuration appears to have been balanced for achieving a steady-state burning condition in the CLT, but preventing debonding.
3. Self-extinction of the exposed CLT was achieved. Following a reduction in the size of the fire associated with the timber cribs, self-extinction initiated from the base of the CLT wall, and progressed over the course of several minutes to the top of the wall. In the final phase of the fire, the CLT ceiling burned more vigorously in the region above the CLT wall. The ceiling extinguished at approximately the same time as the wall.

Heat Flux and Self-Extinction

Although a number of the TSCs were damaged during the fire, it was possible to extract data for the exposed timber wall. A comparison between data from the large-scale test, and the critical heat flux for self-extinction of Radiata Pine shows that when the maximum heat flux on the wall dropped below 45 kW/m^2, self-extinction occurred within 30 s. This result aligns well with the data from the small scale testing which suggested that self-extinction would occur when the incident heat flux was less than 45 kW/m^2.

However, although the value from the top of the wall aligned well with the critical heat flux for self-extinction, it was found that at the onset of self-extinction (from visual observations), the heat flux readings at the base of the wall were substantially in excess of 45 kW/m^2 (approximately 55 kW/m^2).

It should be noted that there are several possible sources or error associated with the measurements obtained from the TSCs. For example, previous work [9] has found that a slight overestimation of the heat flux can be expected during the cooling phase (overestimation was found to be 9 kW/m^2 for the devices in [9]).

Limitations of the Results

Based on the conclusion of these tests, designers may be tempted to draw wide ranging conclusions about how and when self-extinction may occur within compartments with exposed CLT linings. While the conclusions of these tests demonstrate that, under the right conditions, self-extinction can occur – the authors would urge caution in the direct application of this test result to wider design scenarios as there are several limitations associated with this test.

The test was design to minimize the uncertainties that would be introduced by debonding of the CLT or failure of any protection elements – and hence minimize the likelihood that self-extinction would be prevented by unforeseen events.

Several different factors could reduce the likelihood of self-extinction:

- *Debonding*. Any debonding would result in an increase in the mass loss rate for the timber and produce a corresponding increase in the heat release rate of the fire. This would allow the thermal wave to propagate further into the timber and potentially induce secondary delamination. These events could potentially allow all the CLT to be consumed prior to any self-extinction.
- *Failure of the detailing*. If breakout of smoke and flame occurred through the compartment detailing, this might result in a secondary fire that would expose CLT to thermal attack from more than one direction; this might be sufficient to induce a failure prior to self-extinction.

The likelihood of any of these factors could be increased by:

- *Increased fuel load*. Increased fuel load would result in a longer burning duration, and hence a more onerous scenario for many of the considerations above.
- *Reducing lamella thickness*. The CLT used during these tests had a thick outer layer, and hence, there was a substantial time difference between the occurrence of steady-state, and the onset of debonding events. Thinner layers of CLT would result in the more rapid onset of debonding.

CONCLUSION

This paper has demonstrated that self-extinction in CLT can occur in both small and large-scale tests.

Small scale tests have shown that:

- The critical heat flux for self-extinction of Radiata Pine CLT is 45 kW/m^2;
- The time to steady-state burning for Radiata Pine CLT is 10 min;
- The minimum time to debonding for Radiata Pine CLT (with lamella 45×20×20×20×45 mm) is 30 min.

The large-scale test has shown that:

- If debonding is prevented, self-extinction can occur in a compartment with exposed CLT on a wall and ceiling;
- Self-extinction of the CLT wall and ceiling occurred when the maximum incident heat flux reduced below 45 kW/m^2;
- When self-extinction occurred it began at the base of the exposed surface, and progressed to the ceiling.

It is therefore concluded that if uncertainties associated with debonding are minimized then self-extinction can be achieved during the steady-state burning phase of CLT. The limitations of this work are such that it is recommended that the key parameters that may induce uncertainty in the compartment conditions are further investigated.

ACKNOWLEDGEMENTS

The authors would like to thank the Queensland Government, Hutchinson's Builders and Happy Haus for their support of the project under the Accelerated Partnership scheme. In addition, the authors would like to thank: Queensland Fire and Emergency Service for the use of their facilities and engagement with the project;

Bligh Tanner, for their contribution to the structural engineering on the project; Aquatonic for their involvement in the concept design; and Ms Tam Do, for her contribution to the small-scale experiments.

REFERENCES

[1] P. J. Pagni and T. M. Shih, "Excess pyrolyzate," in *16th Proceedings of the Combustion Institute*, 1977, pp. 1329–1343.

[2] *NCC BCA Volume 1*. 2016.

[3] V. Babrauskas, "Ignition of Wood: A Review of the State of the Art," *J. Fire Prot. Eng.*, vol. 12, 2002.

[4] D. Drysdale, *An Introduction to Fire Dynamics*, Third. Chichester: Wiley, 2011.

[5] J. L. Torero, T. Vietoris, G. Legros, and P. Joulain, "Estimation of a total mass transfer number from the standoff distance of a spreading flame," *Combust. Sci. Technol.*, vol. 174, no. 11–12, pp. 187–203, Nov. 2002.

[6] "ISO 13927:2015 Plastics - Simple heat release test using a conical radiant heater and a thermopile detector," 2015.

[7] R. L. Emberley, "Fundamentals for the Fire Design of Cross Laminated Timber Buildings," The University of Queensland, 2017.

[8] R. Emberley, A. Inghelbrecht, Z. Yu, and J. L. Torero, "Self-extinction of timber," *Proc. Combust. Inst.*

[9] P. H. Thomas and A. J. M. Heselden, "Fully Developed Fire In Compartments - CIB report No 20, Fire Research Note 923," Borehamwood, 1972.

[10] J.P. Hidalgo, C. Maluk, A. Cowlard, C. Abecassis-Empis, M. Krajcovic, and J. L. Torero, "A Thin Skin Calorimeter (TSC) for Quantifying Irradiation During Large-scale Fire Testing," *Int. J. Therm. Sci.*

[11] B. J. McCaffrey and G. Heskestad, "A robust bidirectional low-velocity probe for flame and fire application," *Combust. Flame*, vol. 26, pp. 125–127, 1976.

[12] P. J. DiNenno, Ed., *SFPE Handbook of Fire Protection Engineering*. NFPA, 2008.

[13] S. Welch, A. Jowsey, S. Deeny, R. Morgan, and J. L. L. Torero, "BRE large compartment fire tests-Characterising post-flashover fires for model validation," *Fire Saf. J.*, vol. 42, no. 8, pp. 548–567, Nov. 2007.