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FIRE-PROTECTED TIMBER ELEMENTS OF CONSTRUCTION – RESPONSE DURING FIRE DECAY AND COOLING PHASE

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ABSTRACT: The Building Code of Australia now permits the use of Fire-protected Timber in all classes of buildings up to an effective height of 25 metres (typically 8-storeys). Fire-protected Timber elements of construction consist of lightweight structural timber-frame or massive timber elements protected by fire-protective grade linings to reduce the risk of ignition of timber members and achieve the required fire-resistance level in addition to other criteria such as the acoustic and thermal performance appropriate to the class of building.

In support of this Code change, research was undertaken to investigate the post-fire decay and cooling phase behaviour of lightweight structural timber-frame or massive Fire-protected Timber elements for which there is currently limited research and publicly available data. As with all structural building materials, this post-fire behaviour can lead to failure of structural building elements if not adequately addressed. The research demonstrated that on-going combustion of Fire-protected Timber elements could be prevented using encapsulation provided by an appropriate layer of fire-protective grade coverings.

KEYWORDS: Lightweight timber-frame, CLT, fire, decay phase, cooling phase

1 INTRODUCTION

Changes to the Building Code of Australia Volume One (BCA) in 2016[1] and 2019[2] introduced Deemed-to-Satisfy (DTS) provisions as a means of demonstrating compliance for mid-rise timber buildings based on the concept of Fire-protected Timber.

These changes now permit lightweight structural timber-frame or massive timber elements protected by fire-protective grade linings, installed in conjunction with automatic sprinkler systems, to be used in all classes of building up to 25 metres in effective height (vertical distance from the ground floor storey to the floor of the topmost storey - typically up to 8-storeys); where previously non-combustible building elements were required.

In support of this Code change, a risk-based approach was adopted, incorporating multi-scenario analyses requiring evaluation of scenarios where the ignition criteria of protected timber were exceeded. Conservative assumptions were made including the assumption that if fire brigade intervention was unsuccessful, and the protected timber element was ignited, the element would fail (i.e., self-extinguishment would not occur).

Subsequently, additional research has been undertaken to investigate the potential for exposed and Fire-protected Timber to self-extinguish or, if sustained combustion continues, to evaluate the rate of deterioration of the timber elements during the post-fire decay and cooling phase to further extend applications for timber construction. The post-fire behaviour of both lightweight structural timber-frame and massive Fire-protected Timber construction elements are being investigated.

Detailed analyses undertaken in support of the Australian Code change were made with several conservative assumptions; including that if the surface temperature of timber exceeded 250°C for lightweight timber framing, or 300°C for massive timber elements, combustion would continue until failure occurred; unless fire brigade intervention occurred prior to the temperatures being exceeded.

This paper describes subsequent research undertaken investigating the post-fire behaviour of these timber building elements when exposed to the standard heating regime in accordance AS 1530.4[3] and more severe fire scenarios. This post fire behaviour can lead to failure of structural building elements if not adequately addressed which is not unique to timber.

Further details of the research and analysis is provided in the WoodSolutions Technical Design Guides #18[4] and #38[5].

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2 DECAY AND COOLING PHASE RESPONSE

Building enclosure fires are typically categorised into four stages – (1) incipient/initiation, (2) growth, (3) fully developed and (4) decay. In some applications, it may be necessary to extend the analysis and consider a cooling phase if the behaviour of elements of construction after extinction of the contents (i.e., the moveable fire load) and combustible elements is to be considered – refer Figure 1. Typically, this may be necessary where degradation of elements of construction occurs after extinction of the contents due to thermal inertia, degradation on cooling (Dimia *et al*[6]) and/or localised smouldering combustion of elements of construction (McGregor[7]).

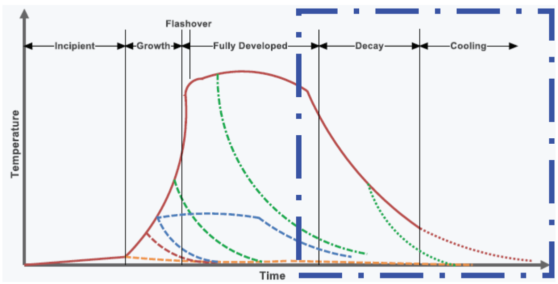

Figure 1: *Building enclosure fire stages*

The response of elements of construction during the decay and cooling phase can be an important consideration; particularly in applications such as high-rise buildings where fire brigade intervention and evacuation of occupants may be difficult during some fire scenarios.

Once the majority of the fire load is consumed, the burning rate will reduce significantly leading to reduced enclosure temperatures. However, there may still be potential for a thermal wave to spread through an element due to its thermal inertia and/or for smouldering combustion of timber structural elements to continue.

Under some circumstances, a thermal wave can subsequently lead to structural collapse of common building structural materials used such as timber, concrete and steel. The risks of smouldering combustion or of incipient fire spread is specific to combustible materials and can also eventually lead to structural collapse or reignition of flaming combustion.

In most instances, both natural and furnace fire-resistance tests are terminated at the end of a nominated exposure time so there is relatively limited data on their behaviour during the decay and cooling phases; which can last for extended periods varying from several hours to 24 or more hours in extreme cases. Recent studies, such as the Epernon Series[8] and Fire Safe Implementation of Visible Mass Timber[9], have monitored conditions at the end of tests to evaluate performance during the decay phase.

2.1 PREMATURE STRUCTURAL FAILURE

Premature structural failure of building elements may occur as a result of failure of automatic sprinkler systems, fire-protective coverings, and detection and alarm systems as well as a relatively slow fire brigade response. However, structural failures can also occur sometime after fire exposure due to several causes, including:

- temperatures of structural elements continue to increase during the decay period of a fire due to the thermal inertia of the enclosure fabric and fire protection systems
- stresses may be induced on cooling
- material properties may change on cooling, and
- smouldering combustion and incipient spread of fire may continue.

Some fire-resistance tests performed for FWPA have included monitoring of simulated decay phases in conditions with normal atmospheric concentrations of oxygen by removing specimens from the furnace and continuing exposure of the specimen to heat as described below.

3 TESTED SYSTEMS

3.1 ENCAPSULATED LIGHTWEIGHT ENGINEERED FLOOR-CEILING SYSTEM

A full-scale, loadbearing fire-resistance test was undertaken on a lightweight engineered timber floor-ceiling system to determine the fire resistance of various types of lightweight engineered beams (e.g., timber and metal webbed parallel chord floor trusses, timber and metal webbed I-joists) protected by a plasterboard ceiling system. The specimen was subjected to the AS 1530.4 standard heating regime for 122 minutes.

The ceiling system comprised three layers of fire-protective grade plasterboard, each 16 mm thick, fixed to metal furring channels that were supported from the floor joists by direct fixing metal brackets using typical industry installation practices. The test was terminated after two hours without failure under the criteria of structural adequacy, integrity and insulation and achieved a 2-hour fire-resistance (FRL 120/120/120).

In addition, a 120-minute Resistance to the Incipient Spread of Fire (RISF) level was also achieved. RISF is a criterion within AS 1530.4 which was originally introduced for ceiling membranes to ensure that the space between a ceiling and roof, or ceiling and floor above, is insulated so as to limit the temperature rise of materials in this cavity space to a level that will not permit the rapid and general spread of fire throughout the space to adjoining compartments. Failure under the criterion of RISF is deemed to have occurred when the maximum temperatures at the nominated positions on the ceiling system exceed 250°C. Application of the RISF criteria was extended to other light-weight Fire-protected Timber elements such as partition wall systems by the BCA in 2016.

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After 120 minutes, the heating was terminated and the specimen was raised 600 mm above the furnace allowing free access to the laboratory atmosphere while being exposed to heat from the furnace floor and walls to simulate the decay and cooling phases under natural convection. The floor-ceiling specimen was then monitored for a further 17 hours without intervention – refer Figure 2.

Figure 2: *Exposed face of specimen at the end of the monitoring period.*

The temperatures measured below the ceiling during the fire test exposure and for the first two hours of the cooling phase are shown in Figure 3. The specimen then continued to support the full test load while cooling to ambient temperatures over the remaining 15 hours of the monitoring period.

There was no evidence of combustion of the timber elements during the test and throughout the monitoring period. The temperatures on the upper surface of the plasterboard sheeting peaked after approximately 150 minutes (30 minutes after termination of heating) but temperatures did not exceed 250°C as shown in Figure 4.

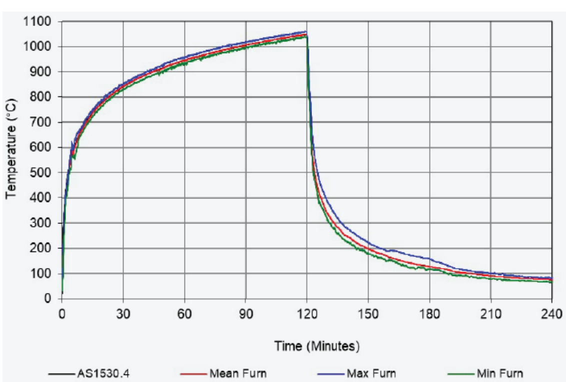

Figure 3: *Complete heating and first two hours of cooling exposure measured by exposed thermocouples*

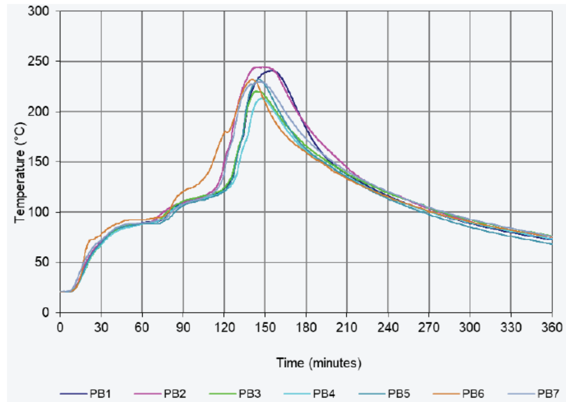

Figure 4: *Temperatures of upper surface of the plasterboard*

3.2 PROTECTED CROSS-LAMINATED TIMBER PANEL

3.2.1 Section within encapsulated lightweight engineered floor system test

A section of cross-laminated timber (CLT) was included within the encapsulated lightweight engineered floor system cavity (described in Section 3.1) and temperatures were measured at various positions within and adjacent to the CLT element. These temperatures are summarised in Table 1 which illustrates that a thermal wave passed through the CLT with temperatures at depths of 20 mm and 55 mm peaking at 94°C and 84°C respectively more than 120 minutes after the end of the heating period.

Table 1: *Peak CLT specimen temperatures and temperatures after 120 minutes*

Ref	Description	Temp. °C @ 120 minutes	Max. Temp. °C
CL-1	Plasterboard-CLT interface temperature	120	226
CL-2	19 mm below CLT soffit (air temp)	109	161
CL-3	CLT soffit	96	151
CL-4	10 mm depth	77	105
CL-5	20 mm depth *(lower glue line)*	52	94
CL-6	55 mm depth *(upper glue line)*	58	84

3.2.2 One layer of 16 mm fire-protective grade plasterboard – Shorter test duration

Two standard fire-resistance tests, in accordance with AS 1530.4, were performed on 105 mm thick CLT panels protected by one layer of 16 mm fire-protective grade plasterboard. The first test was of 45 min duration and the second of 60 min duration. Prior to the tests, the time for the CLT plasterboard interface to reach 300°C was estimated to be approx. 30 minutes and this was confirmed in both tests. Also in both tests, volatiles from the CLT panels ignited at joint positions in the plasterboard but self-extinguished during the monitoring period.

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The following is a more detailed review of the 60-minute test.

The specified and measured furnace temperatures for the 60-minute test are shown in Figure 5 for the heating period. At the end of the 60-minute heating period, the area under the mean furnace temperature/time plot exceeded the prescribed standard heating regime by approximately 1.5%.

At the end of the heating period the interface temperatures between the plasterboard and CLT were approximately 500°C and as the specimen was raised above the furnace to allow natural airflow across the surface of the specimen, flaming at the joint between the plasterboard sheets was observed as shown in Figure 6.

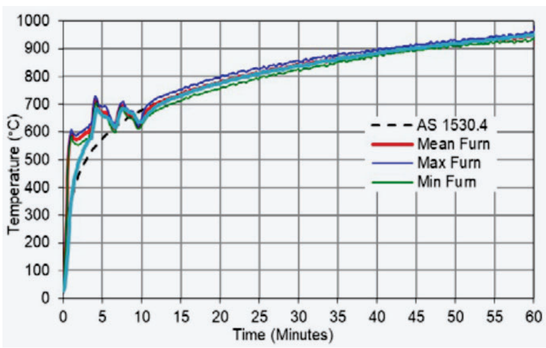

Figure 5: *Furnace temperatures during the 60-minute heating period*

Figure 6: *Flaming from joint between plasterboard 30 seconds after the end of the heating period.*

The flaming gradually reduced and ceased after approximately 11 minutes.

Data monitoring continued for 23 hours and during this period, the CLT panel temperatures had effectively reduced to ambient temperatures with no evidence of continuing flaming or smouldering combustion – refer Figure 7 for interface temperatures between the plasterboard and CLT, and Figure 8 for the temperatures of the CLT panel at varying depths.

This data indicates that the charring was restricted to a depth of approximately 6 mm and that self-extinguishment of smouldering combustion had occurred as well as any flaming combustion.

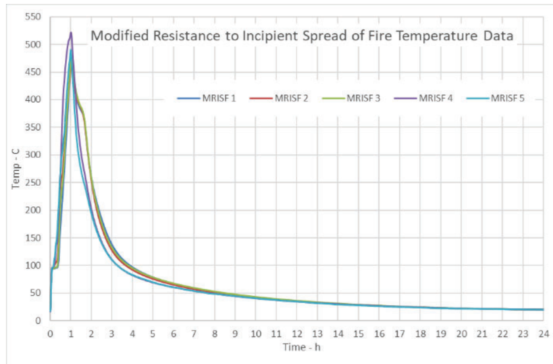

Figure 7: *Thermocouple temperatures at the interface between plasterboard and CLT*

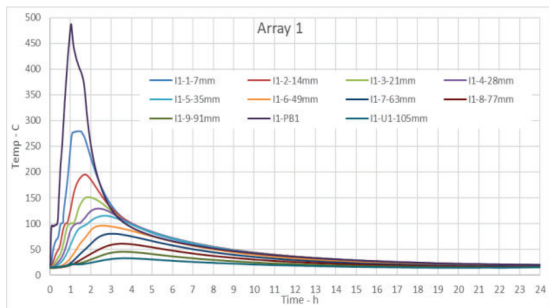

Figure 8: *Thermocouple temperatures across the CLT section*

The incident heat flux to which the underside of the specimen was exposed is shown for the 180 minutes of the monitoring period in Figure 9. Approximately 11 min after completion of heating, the measured heat flux had reduced to approximately 10 kW/m^2; at 42 min after completion of heating, it had reduced to approximately 4 kW/m^2 and 108 min after completion of heating, it had reduced to approximately 2 kW/m^2.

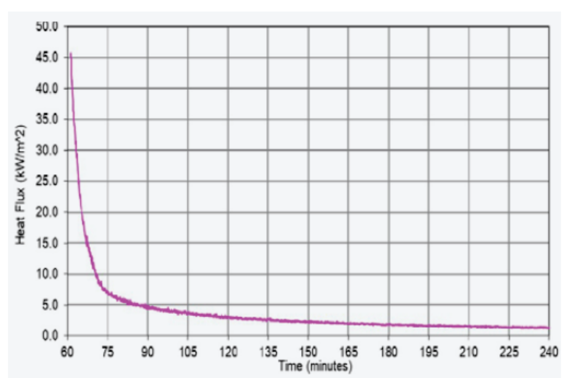

Figure 9: *Heat flux from furnace and specimen for 180 min after heating*

Figure 10 shows the CLT panel with the plasterboard removed clearly highlighting the surface charring to the lower lamella layer. No significant delamination had occurred, but the individual lamella had shrunk in dimension opening the edge joints between the lamella which were not bonded, i.e., no adhesive applied, during the CLT manufacturing process.

Figure 10: *Underside of CLT panel with plasterboard removed after 23-hour monitoring period.*

3.2.3 One layer of 16 mm fire-protective grade plasterboard – Longer test duration

A 225 mm thick CLT panel protected by a single layer of 16 mm plasterboard was subjected to the standard heating regime as a comparative test to the shorter test durations described in 3.2.2.

The CLT panel width was constructed with a central half-lap joint with two joint treatments – half the length of joint sealed with two beads of sealant between the bearing surfaces, and the other half with a plasterboard cover on the non-fire-exposed side.

The test was terminated after approximately 171 min when failure at the joints position was imminent. The conditions were subsequently monitored for a relatively short period of 59 min since the element showed evidence of continuing char oxidation; albeit at a reduced rate. A comparison of the shorter and longer duration CLT tests with one layer of 16mm plasterboard is provided in Table 2.

Table 2: *CLT comparison tests – Single layer of 16 mm fire-grade plasterboard protection*

Test	CLT depth (mm)	Furnace Heating (h:min)	Monitoring period (h:min)	Time CLT-PB interface > 300°C (min)	PB Fall-off (min)
6	105	0:45	15:00	34	No
8	105	1:00	23:00	32	No
2	225	2:51	0.59	32	115

Heat flux measurements from Test 2 during the decay period are presented in Figure 11. It is noteworthy that, despite evidence of some ongoing combustion, the decay of measured heat flux from the specimen (thin line) reduced to approximately 11 kW/m^2 after 60 min and the measured heat flux received by the specimen from the furnace walls and floor (thicker line) is comparable.

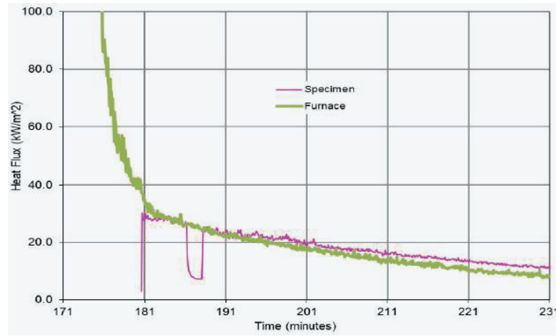

Figure 11: *Heat flux from the furnace and specimen for 60 minutes after heating*

Combustion of the specimen was ongoing at the joint positions and the exposed perimeter of the specimen at the end of the 60-minute monitoring period. Significant delamination occurred such that 90 mm or more of the specimen face had been lost over the heated area, creating a detail at the perimeter where a horizontal face meets a vertical face of timber, facilitating radiative feedback as shown in Figure 12.

Figure 12: *Fire side after the 59-minute monitoring period showing continued edge combustion.*

These observations indicate that as heat penetration into timber elements increases, intersections and joint details will become more critical if self-extinguishment is an objective. It may also be important to maintain fire-protective coverings in place to reduce radiant heat interchanges at intersections of elements.

3.3 TIMBER-FRAME STUD WALL SYSTEM

3.3.1 System construction

A fire-resistance test was undertaken on a loadbearing timber-frame wall system comprising three layers of 16 mm thick fire-protective grade plasterboard applied to each face of 140 mm x 45 mm studs with cavities filled with non-combustible stone wool.

The stone wool insulation was installed, in lamella form, to provide a practical way to reliably install the insulation to be in intimate contact with the timber studs with a controlled level of compression. The high-temperature performance specification and compression was intended to maintain one-directional heating of the timber studs by

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avoiding heat transfer through the cavity. The temperature data from the test indicated this was effectively achieved. Figure 13 shows the internal structure of the timber-frame wall system comprising vertical timber studs, horizontal timber noggings and fitted stone wool insulation.

Figure 13: *Internal structure and non-fire side of the high-performance timber-frame wall system*

Laminating screws were used to secure the outer third layer of plasterboard which facilitated the positioning of screw fixings 38 mm from board edges and a reduction of fixing centres over the board area which was expected to significantly improve the retention time for the outer board layer.

3.3.2 Fire performance

The specimen was subjected to the AS 1530.4 standard heating regime for 227 min, after which the specimen was removed from the furnace and conditions were monitored for a further 30 min. The specimen achieved an FRL in excess of 180/180/180 and the Resistance to the Incipient Spread of Fire (RISF) criteria were satisfied for in excess of 120 min.

A total load of 12.3 kN/stud was applied to the specimen; equivalent to a load ratio of 0.5 (i.e., ultimate fire limit state design load to ultimate (ambient) limit states design load). The full test load was applied until 198 min and then progressively reduced until heating was terminated after 227 minutes due to the potential risk of damage to the loading equipment; with no failures under the criteria for insulation and integrity.

Measurements taken during the test included interface temperatures of each plasterboard layer using thermocouples soldered to copper discs at the centre and centre of each quarter section of the wall. Thermocouples were also fitted at approximately these locations on the inner surface of the base plasterboard layer on the fire-exposed side of the specimen to determine the RISF performance.

The RISF results are plotted in Figure 14 and the temperature of the RISF thermocouples after 120 min of the test was approximately 130°C before exceeding the 250°C limit after 136 min.

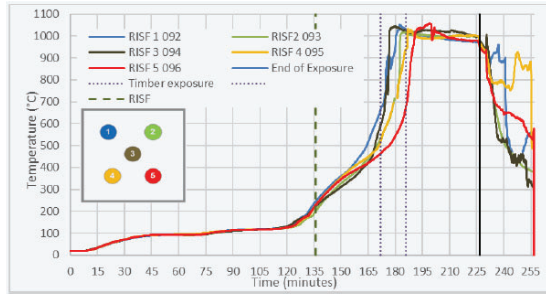

Figure 14: *Resistance to the Incipient Spread of Fire (RISF) temperature data and estimated time of direct exposure of the timber frame to furnace heating*

At the end of the heating period the specimen was removed from the furnace. To enable observation and the fitting of a heat flux meter to measure radiant heat released from the specimen, the specimen was rotated at an angle to the furnace as shown in Figure 15.

(i) Approx. 4 mins post-test *(ii) Approx. 26 mins post-test*

Figure 15: *Exposed face of partition during monitoring period*

Visual observations confirmed continuing combustion and char oxidation with a slight reduction in intensity further away from the furnace, which can be explained by the lower incident radiant heat from the adjacent furnace. Temperatures measured within the char were generally in the range of 500°C to 600°C throughout this period, indicating continued combustion within the char.

Due to the test being of a loadbearing timber-frame, temperature data was obtained from three internal horizontal noggings containing thermocouples and is plotted against time in Figure 16.

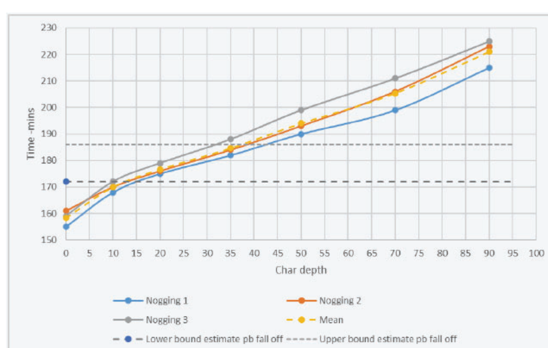

Figure 16: *Char depth versus time along nogging centreline*

Char rates obtained during the test were substantially higher than those recommended in EN 1995-1-2:2004 Eurocode 5[10] and AS/NZS 1720.4:2019[11]. For example, the notional char rate in accordance with AS/NZS 1720.4, assuming a nominal density of 550 kg/m^3, would be 0.66 mm/min and for protected systems is increased by a factor of 1.1 yielding an increased char rate of approximately 0.73 mm/min. Whereas the average calculated char rate from commencement of charring (at approx. 158 minutes) to a char depth of 90 mm (at approx. 221 minutes) was 1.43 mm/min.

This may be explained by the longer pre-heating period and higher heat fluxes due to the longer fire-resistance test period and would highlight the need for an upper bound fire resistance time to be specified for the notional char rates currently specified in design codes or additional char rates specified for long durations and different heating regimes.

4 CONCLUSIONS

The overview of the results of extended fire resistance tests performed on Fire-protected Timber elements has been presented. The specimens were monitored at the end of the heating period to determine if the elements self-extinguish, or sustained combustion continued.

The tests demonstrate that on-going combustion can be prevented using encapsulation provided by appropriate fire-protective grade covering systems that maintain the temperature of the protected timber elements below critical values.

The results so far demonstrate that for timber-framed construction, a temperature limit of 250°C is appropriate but above this limit, ignition and sustained combustion is likely to occur.

The results from tests on fire-protected massive timber construction, such as CLT, indicate that at interface temperatures above 300°C, the CLT member may ignite particularly at the position of joints in plasterboard coverings but self-extinguishment is still possible provided (1) the protective coverings remain in place, (2) the exposure is one-dimensional, (3) solid massive timber elements are used and, (4) detailing of joints between panels and at the perimeter of elements prevents increased heating of the timber.

Further work is being undertaken to evaluate the behaviour of Fire-protected Timber and unprotected timber under different heating conditions.

ACKNOWLEDGEMENT

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