An Investigation into the Effect of Exposed Timber on Thermal Load

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ABSTRACT: Recent buildings and research projects have demonstrated the benefits of using engineered timber as a structural material; in addition, changes to codes around the world (including the BCA) are facilitating the use of Cross-Laminated Timber (CLT) as a construction material for medium and high rise buildings. As the material becomes more widespread, the benefits associated with careful engineering of every component of the structure become greater. The loads that a structure experiences during a fire are one such aspect of the design, and this paper presents an assessment of the thermal load that may result from using exposed CLT panels within a building. The thermal load associated with "conventional" compartment fires is already known; however, there is little data on compartments where elements of the timber structure are exposed. This paper therefore presents the results and analyses of a series of small scale tests on Cross-Laminated Timber compartment fires and seeks to give an indication of the likely thermal load that a structure by experience. Comparison will be made against "conventional" compartments to analyze how a timber structure contributes to the fire by adding more fuel load, and resulting in a different thermal load that the structure has to resist

1 INTRODUCTION

There is an increasing demand within Australia and around the world to use timber within medium and high rise buildings. Recent changes to the Building Code of Australia have allowed timber construction up to an effective height of 25m. However, severe limitations are placed on the architectural expression of timber (i.e. it must be protected by additional layers of fire protection material), this has a negative impact on the aesthetics of the building, the economics of any project, and the time required on site to provide the necessary protection.

Consequently, there is a demand to facilitate exposed timber elements within buildings. However, as wood is a combustible material this presents a number of challenges in relation to the delivery of an effective fire safety strategy for the building.

1.1 *Challenges for Fire*

Current design methodologies embedded within existing building codes typically assume:

1. That the structure (and compartmentation) is able to endure the effects of the fire until all the fuel in the compartment is consumed; and
2. The fire is contained to one floor of the building i.e. it cannot vertically grow.

For steel and concrete structures time to burnout is defined by the amount of furniture (i.e. fuel) within the compartment and therefore the fire resistance of the structure is related to the expected quantity of fuel.

In the case of exposed timber structures, the timber linings contribute to the total amount of fuel in the compartment; it is not therefore possible to use the previous approach to define burnout, because the linings (i.e. the structure) may continue to burn after all the furniture has been consumed. This presents a fundamental challenge to the assumption that it is appropriate to use existing fire resistance solutions for exposed CLT construction.

In relation to vertical fire growth, conventional construction (and existing building codes) define fire safety measures intended to prevent spread. These measures are based on knowledge regarding the size and shape of the plume. This knowledge has been based on the assumption that the linings of the compartment do not substantially contribute to the fuel load and fire development. Consequently, if combustible linings are provided, it may be necessary to revisit the fire safety measures required to prevent vertical fire spread.

Based on the above, there is a clear need to investigate fire behavior within timber lined compartments in order to adequately define burnout, and therefore determine the required arrangements to ensure that the structure can resist a fire. Additionally, there is a need to check that the plume behavior associated to a timber lined compartment is not substantially different from an inert compartment.

Therefore, this paper provides a preliminary investigation in order define which parameters of the fire may be affected by the provision exposed timber linings.

1.2 *Self extinguishment (or auto extinction)*

In the context of a conventional compartment, the definition of time to burnout is the point at which mass loss rate is equal to zero. In the context of a CLT compartment a similar definition should be adopted. Hence it is proposed that the definition of auto extinction should be the transition from flaming to smoldering combustion. Once this transition occurs, the relative mass loss rate drops almost to zero.

2 FIRE DYNAMICS IN COMPARTMENTS

2.1 *Temperatures inside compartments*

Fire engineers conventionally use temperature as the basis for the severity of thermal attack on a structure (e.g. parametric fire curves, and standard temperature time curves). Current knowledge of the maximum temperatures in compartment fires is derived from experiments in rectilinear compartments (Drysdale, 2011). Thomas et al (P.H. Thomas, 1972) compiled over 400 experiments with different compartment shapes and openings and found the maximum temperature that could be expected within a compartment. Thomas et al found the temperature to be dependent on the opening factor and independent of total mass of fuel. This was expressed as per

and shows the maximum temperatures during a fully developed fire for different opening configurations.

It should be noted that this plot is based on results from compartments with non-combustible linings and represents the temperature achieved in the steady state condition. If a compartment were provided with combustible linings, Thomas's conclusions imply that for a ventilation controlled fire, the temperatures would not change.

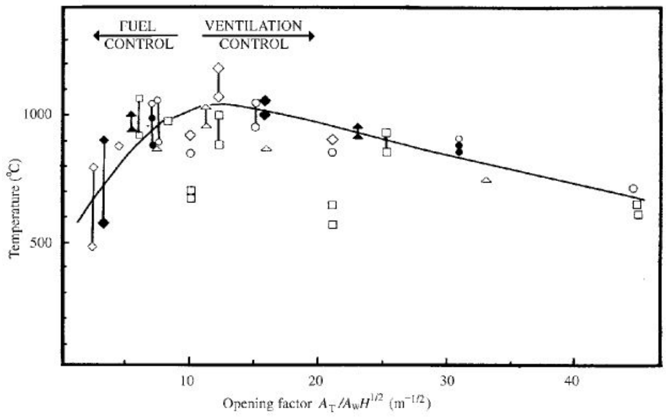

Figure 1 Average compartment temperatures for the steady burning period for fires in enclosures as function of the "opening factor" (P.H. Thomas, 1972)

2.2 *Burning rate*

Kawagoe (Kawagoe, 1958) studied how the size of an opening would influence the burning rate of wood cribs in a compartment that is ventilation controlled (Drysdale, 2011). After performing several tests, he suggested the following formula for the burning rate:

$$\dot{m} = 0.09 A_w \sqrt{H}$$

Where $\dot{m}$=burning rate [kg/s], A_w= area of the opening [m^2], H= height of the opening [m], and 0.09 was the constant to represent the other compartment conditions. This formula can be used to estimate the time to burnout if the total fuel load is known.

Kawagoe's correlation is valid for ventilation controlled fires, but it has not been reviewed in the context of combustible linings.

2.3 *Flame behavior spilled from an opening*

Law (Law, 1989) performed an extensive study on the shape and the size of the external flames, in order to estimate the heat transfer to the external structure.

Law considered that radiation is the main form of heat transfer for this type of problem. Therefore, Law based her calculations on the fact that intensity of radiation is proportional to the fourth power of the absolute temperature. Law to developed correlations to predict parameters such as: flame height, flame width, temperature distribution along the flame axis, etc. All these correlations are dependent on the burning rate ($\dot{m}$) and, similarly to Kawagoe, Law assumed that the burning rate is dependent on the opening factor. The heat flux associated with Law's assumed burning rate can therefore be reviewed in the context of timber linings.

2.4 *Summary*

All these features described above are essential to define the thermal load that a structure will need to withstand. The objective of this investigation is to characterize the impact that combustible (CLT) linings may have on each parameter.

3 METHODOLOGY

To allow the above to be studied an experimental program was executed whereby:

1. A series of case tests were conducted with inert compartment linings; and
2. A series of tests were conducted with CLT compartment linings.

The first set of experiments was conducted to allow the performance of the equipment to be verified and to allow a baseline set of data for a "conventional" compartment to be created.

The subsequent tests with CLT lining allowed any differences associated to combustible linings to be observed and quantified.

3.1 *Experimental setup*

For this work, a medium scale test setup was designed, as shown in Figure 2.

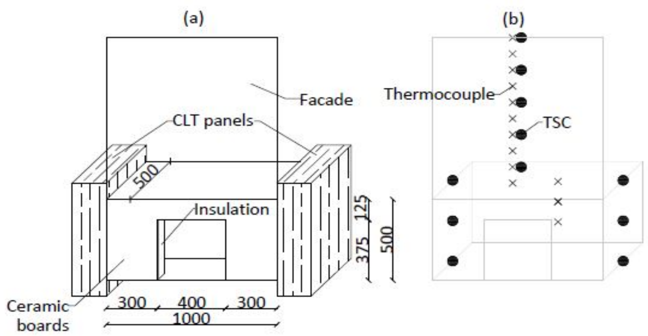

Figure 2 Experimental setup and instrumentation.

The experiments consisted of a compartment box, built out of ceramic boards, which were protected with a 50mm insulating interior lining. The insulation was necessary to diminish the heat losses through the walls of the compartment. This allowed the temperatures inside to grow faster and ensured that flashover would occur.

The dimensions of the compartment were 1x0.5x0.5m. With these dimensions the test is similar to the tests performed by Thomas.

A vertical panel was located on the top of the compartment simulated a facade; this was necessary to ensure an adhered spill plume and, therefore, capture the behavior of the plume spilled from the opening.

In the tests where combustible linings were used, two 130mm thick panels were situated at the lateral sides (as illustrated). This configuration was chosen because for future tests it would allow the effect of separation distance between the panels to be studied

Five "baseline" tests were run with non-combustible linings, and two tests with the CLT panels.

The instrumentation was as follows:

- *Mass balance.* The entire compartment was placed on a balance that registered the mass every second. This was measured to do a further analysis on the mass loss rate and the heat release rate.
- *Six thin skin calorimeters (TSC) inside the compartment*. These devices measure the incident radiant heat flux, three were placed in front of each timber panel, as shown in Figure 2.b. Their purpose was to measure the radiation into the panel from the fire and the opposite panel.
- *Five thin skins calorimeters (TSC) in the facade*. These TSC measured the radiation from the exterior plume into the facade.
- *Three thermocouples inside the compartment*. These devices measured the temperature of the gas phase at different heights as shown in figure 2.b
- *Five thermocouples in the facade.* These devices provide the temperatures of the flame along the height of the façade, the data is used to make convective correction of the TSCs

3.2 *Fuel*

The objective for these experiments was to study the parameters described above. Therefore, it was decided to create a fire with the three phases: growth phase; flashover (including involvement of the timber linings) followed by a fully developed fire; and a decay phase. The intent was to reach flashover and get a fully developed fire of a duration of approximately 10min to ensure that the timber lining will ignite.

Since the intent of this work was not to study fire resistance, it was derived from (L.H. Hu, 2003) that 5kg of timber cribs stacked in a pallet configuration would provide approximately 10min of fully developed fire followed by a decay phase. Eights cribs were provided over the floor of the compartment, and two of the central cribs had basins beneath, filled with a small volume of heptane and paraffin to facilitate ignition and the growth of the fire.

3.3 *Ventilation and opening factor*

An opening factor of 15 was chosen for this set of tests. This value that still lies inside the regime of ventilation controlled fires, and it allows the compartment to approach its maximum theoretical temperatures. From Equation 1 it is established that the dimensions of the opening need to be 0.37x0.4m.

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

Where O_f = opening factor; A_T = Area of the walls and ceiling discarding the area of the opening; A_W = area of the opening; H = height of the opening.

4 RESULTS

4.1 *Temperatures inside the compartment.*

The highest temperatures (i.e. from the top thermocouple placed inside) are presented in Figure 3. The rapid rate of temperature rise clearly indicates that flashover occurred within the compartment. From this data it is also possible to distinguish that each fire has a "fully developed" period where the temperatures state high and continue to rise (as steady state is approached). The results indicated that the decay phase occurs as temperatures begin to drop.

It is observed that the tests with the CLT panels have a longer "fully developed fire" period.

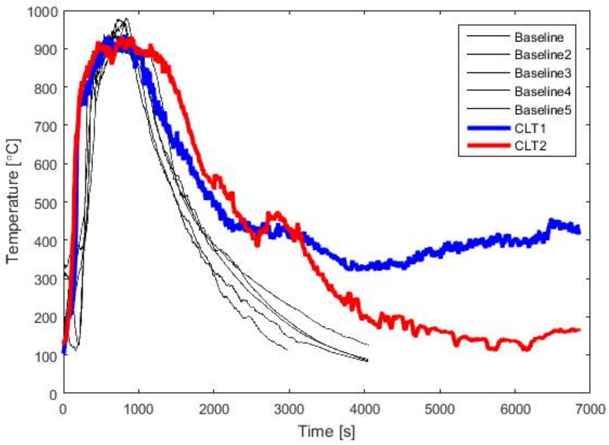

Figure 3 Time-temperature history for the upper layer of gases inside the compartment.

4.2 *Mass loss rate*

The scale logged the total mass of the setup every second during a test, which for further analysis will be used to estimate the mass loss rate ($\dot{m}$) and the heat release rate ($\dot{Q}$).

Since the compartment was submitted to very high temperatures, its structural members suffered thermal decomposition and moisture loss. This meant that the total mass loss was greater than the 5kg of fuel that was provided:

$$\Delta m = m_{final} - m_{initial} > 5kg$$

Consequently, the data was adjusted to account for the known mass loss (Δm). The mass lost from the structure was subtracted linearly for the duration of the fire. i.e. if Δm =A kg then 5/A was the proportion factor to rescale the data.

The same assumption was made for the CLT tests. In this case the mass consumed was determined by weighing the panels before and after the test and adding this to the 5kg of provided fuel. In this case the proportion factor is $(5+\Delta m_{CLT})/A$.

After this correction of the data, the results are presented in Figure 4.

The results show a very good repeatability of the baseline tests, and a clear change of behavior for the CLT experiments.

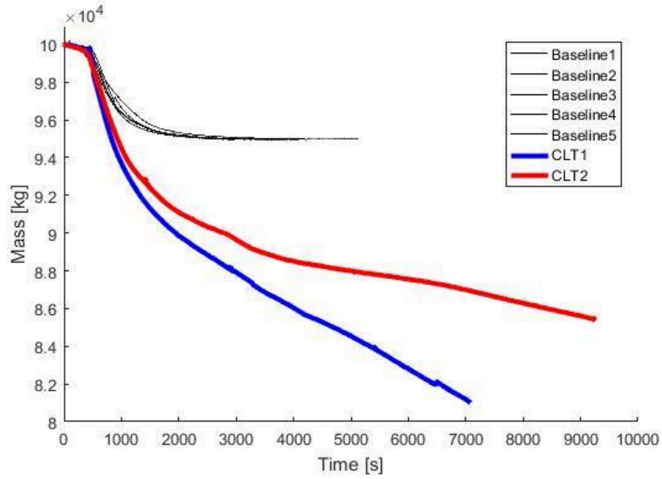

Figure 4 Time-mass history of the experiments, neglecting the degradation compartment.

4.3 *Façade*

Figure 5 shows the highest data of the incident heat flux into the facade during the fully developed phase. These results indicate that the CLT compartments induced higher values than the baseline tests.

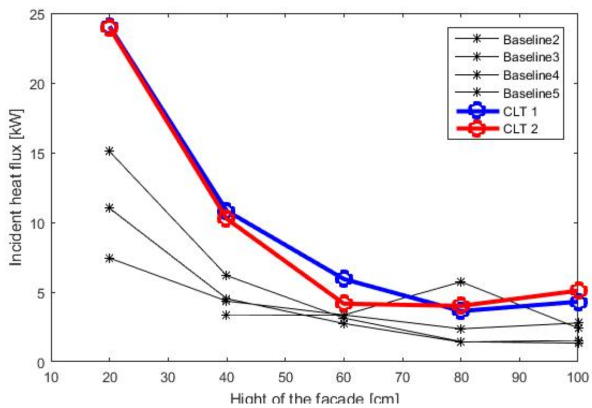

Figure 5 Maximum heat flux into the façade for different heights.

4.4 *Source of errors*

Possible sources of error include:

- The thin skin calorimeters. These were calibrated using the cone calorimeter, but were handmade and therefore subject to individual variation.
- As mentioned in section 4.2, it is impossible to control degradation of the compartment materials. Consequently, the assumption of a linear degradation simultaneously lowers the error associated to mass loss, but introduces assumptions associated to rate of mass loss.;
- Compartment construction. The compartment, or parts of it had to be replaced after running the tests

due to damage after the severe exposure. The replacements were conduceted using different ceramic boards to check which type of boards would perform better

5 ANALYSIS AND DISCUSSION

To compare against the theoretical data, a series of comparisons were conducted.

5.1 *Maximum temperatures*

Figure 6 presents the maximum temperature data and compares this against the results from Thomas.

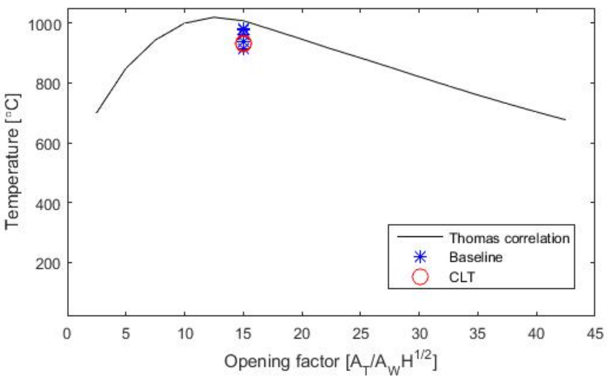

Figure 6 Thomas correlation and maximum temperature data achieved during these tests.

From this data it is observed that the results from these experiments have lower values than the Thomas plot. This may be due to a number of factors including placing of thermocouples, and insulation. However, it should be noted that the values provided by Thomas are indicative of a compartment that has reached steady state. Due to the low fuel load, the test compartments did not have sufficient time to reach steady state. It is therefore unlikely that the maximum temperature (as per Thomas) would be achieved.

What it is important to note, is that disregarding whether the test was with or without CLT, the maximum temperatures achieved inside are very similar. Thus for the parameters tested, the timber linings did not influence the maximum temperature.

5.2 *Mass loss rate ($\dot{m}$) and heat release rate ($\dot{Q}$)*

Based on the data from figure 4, the mass loss rate was been calculated using the following formula:

$$\dot{m} = \frac{\Delta m}{dt} \tag{2}$$

Where $\dot{m}$ =mass loss rate; Δm =mass difference; dt=time period. For this analysis dt=20s (in order to be not unduly affected by minor fluctuations in the data). Figure 7 shows that the baseline tests align with Kawagoe's correlation for wood crib fires described in section 2.2.

However the CLT tests have notably higher values of $\dot{m}$. This was expected because there is a larger combustible surface area is exposed to heat. Thus, the pyrolysis rate is greater and so is $\dot{m}$. This observation indicates that Kawagoe's correlation factor is not necessarily appropriate for compartments with combustible linings

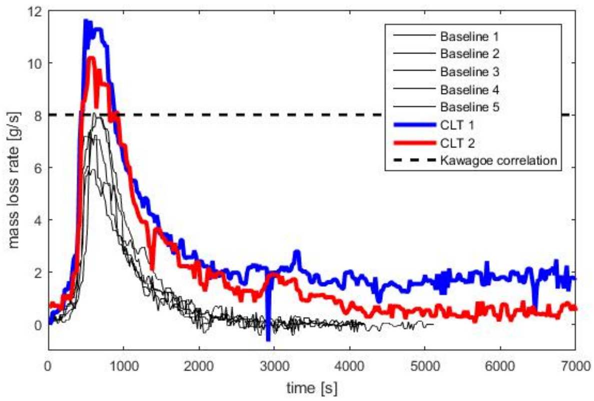

Figure 7 Mass loss rate vs time and Kawagoe's correlation

It can be also observed that the test CLT1 never reaches $\dot{m}$=0. It is because the timber panels did not stop flaming. In that test, the TSC's that were measuring the incident heat flux into the panels were protected with stainless steel columns filled with insulating rockwool. In CLT1, these columns were located adjacent to the panels; this led to significant re-radiation between the columns and the timber panels. This re-radiation was sufficient to sustain flaming until the tests were terminated by the author.

By contrast, it was observed that test CLT2 is much closer to zero at its decay phase. A key different was this tests was the relocation of the TSC columns to the middle of the compartment. Consequently, the columns were much further from the panels and re-radiation was lower and unable to sustain the flaming of the CLT.

During this experiment flaming ceased during the decay phase, and smoldering continued in the panels until the test was terminated. Based on these results, it is considered that (according to the definition provided in section 1.2, auto extinction was achieved)

To calculate the heat release rate ($\dot{Q}$); the heat of combustion (ΔH_C) for wood was chosen from EN 1991-1-2:2002(E): $\Delta H_C = 17.5 MJ/kg$

$$\dot{Q} = \dot{m} \cdot \Delta H_C \tag{3}$$

Where $\dot{Q}$=heat release rate [kJ/s]; $\dot{m}$=mass loss rate[kg/s]; ΔH_C = heat of combustion [kJ/kg]

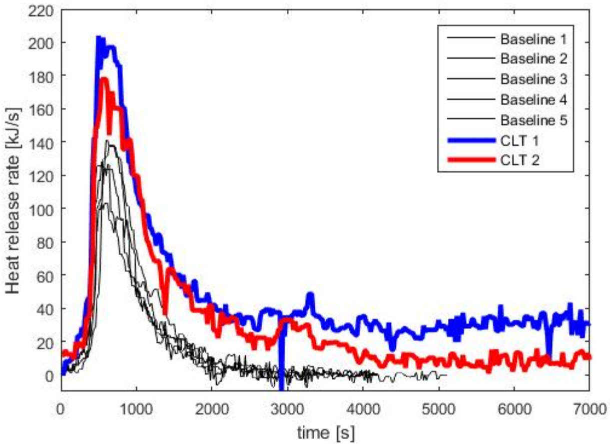

Figure 8 Heat release rate vs time

As observed in Figure 8 the heat release rate for the CLT tests is higher. However, from section 5.1, it is known that the temperatures inside the compartment are similar for both type of tests. This means that a similar amount of heat was released *inside* the compartment in both cases. Consequently, combustion of the excess of the pyrolysis gases in the CLT tests occurred outside the compartment thereby creating a larger external flame. This also has a direct impact on the heat flux imposed on the façade as can be seen from Figure 5.

6 CONCLUSION

A series of tests were conducted on a medium scale compartment. Some tests were conducted with non-combustible linings, and some were conducted with combustible linings; the results were compared against each other, and the fundamental theory associated with compartment fire behaviour.

A small number of test are reported herein, and the results have shown that:

- The temperatures inside the compartment were similar to those predicted by Thomas and were similar for the compartments with and without CLT.
- The mass loss rate for non-combustible linings was similar to that predicted by Kawagoe's correlation. However, when timber linings were used, the mass loss rate increased significantly. This is likely to be due to the increased surface area of fuel.
- The results show that the incident heat flux on the facade is substantially greater when CLT linings are present. Therefore, when using Law's correlations, special attention needs to be given when choosing the value for the mass loss rate since all correlations are related to this parameter.
- The configuration and detailing of the compartment is a significant factor in whether mass loss rate reduced to approximately zero.

It is concluded that auto extinction (or transition to smoldering) is possible for compartments lined with CLT. However, there are a number of complex (and as yet uninvestigated) factors that may affect whether this is achieved.

It is also concluded that the presence of CLT lined compartments may result in a more severe thermal attack on the façade and any structural elements within the compartment. Hence other codified fire safety provision associated to non-combustible construction may need to be re-examined.

However, it should also be noted that the discussion in this paper is based on a very small number of results (five base case tests and two CLT) and therefore while the results are indicative, it is not possible to draw definitive conclusions about the influence of specific parameters, or the precise magnitude of the changes between CLT linings and non-combustible linings.

7 ACKNOWLEDGMENTS

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