Experimental study on the impact of adhesive type on the fire performance of hybrid commercial CLT structures

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March 2023

Introduction

Mass timber systems are being considered more frequently as a framing solution for new office buildings due to their embodied carbon, aesthetics, and constructability. Hybrid construction solutions, using timber (in the form of cross-laminated timber or CLT) alongside other materials such as steel and concrete have become more popular in the UK, facilitating longer column free spans with reduced embodied carbon. Recent guidance published by the Structural Timber Association (STA) [1] has clarified the design evidence that should be provided by engineers to demonstrate adequate structural fire performance in buildings using combustible structural framing solutions. However, as noted in a review of CLT enclosure experiments [2] that was undertaken as part of the STA project, the research that has been conducted to date has tended to focus on smaller residential enclosures which are substantially different to the configuration and scale of commercial buildings. Given this, the STA project team sought to generate experimental data that can support designers in the evidence-based realisation of timber-hybrid commercial buildings. This focussed on the impact of adhesive type used to bond CLT lamella on premature char fall-off, the likelihood of the auto-extinction of flaming combustion and the associated implications for the structure's ability to withstand a fire.

As discussed in this study, the work has found that for the specific configuration examined with an exposed CLT ceiling and no other combustible boundaries or structure, the type of adhesive does not influence whether flaming extinction occurred, with both ultimately leading to the stopping of flaming combustion. The compromise is that one adhesive results in the greater loss of section over the other.

Objectives

A series of experiments described in detail by Hopkin et al. [3] have been conducted at ITB in Warsaw to support designers in the realisation of mass timber commercial buildings. The objectives of this work were to investigate:

- When faced with only a combustible ceiling, i.e., without combustible walls or adjacent combustible structural elements, whether CLT adhesive type and the associated phenomena of premature char fall-off has a significant bearing on the ability of the structure to stop burning (i.e., the auto-extinction of flaming combustion) and survive the fire,
- Even if the adhesive choice did not have a significant impact on the structure's ability to stop burning, whether there are other benefits for adopting more robust adhesives and / or what compromises must be accepted if they are not used, and
- The expected fire development in a larger enclosure with exposed combustible ceiling given the flame extension characteristics, and what this might mean for the rate and extent of internal fire spread.

The experiments were extensively instrumented with the aims of determining the CLT contribution to the heat release rate, the radiant heat fluxes to various surfaces forming the enclosure, temperature profiles and charring depths within the timber and CLT slab deflection.

Enclosure configuration

The fire enclosure had internal dimensions of 3.75m (depth) by 7.6m (width) by 2.4m (height). Given commercial construction is typically characterised by a large amount of perimeter glazing, one elevation of the enclosure featured an opening, measuring 7.6m wide and 2.0m high (Figure 1). The enclosure was constructed from exposed lightweight concrete blockwork that was 240mm thick.

Figure 1: View of the fire enclosure towards the opening with the propane burner shown on the raised plinth

CLT slabs

The project team completed three large-scale fire experiments conducted on protected and exposed CLT ceilings. In all cases, the CLT was 160mm thick, with the lay-up of the lamellas being 40-20-40-20-40mm, with an estimated moisture in the range of 12-14% of the dry mass. To form the ceiling of the enclosures, four CLT panels were adopted in each experiment. The panels spanned 3.75m from front to back of the enclosure to broadly aligned to that commonly adopted in hybrid commercial (office) construction. Each pair of slabs was designed to permit independent vertical movement for the purposes of measuring their mass.

The CLT used in the experiments adopted different edge-bonding procedures and inter-lamella adhesives, with two using non-edge-bonded CLT with a widely used polyurethane (PUR) adhesive with European certification (standard PUR adhesive) and the other using edge-bonded lamellas and a PUR adhesive with improved fire properties (modified PUR adhesive). The first experiment used CLT slabs with the standard PUR adhesive that was lined with 2x 15mm thick layers of fire-rated plasterboard.

The second experiment also used the CLT slabs with a standard PUR adhesive and the third used the modified PUR adhesive intended to reduce the likelihood of premature char fall-off. The CLT panels in experiments two and three were unlined.

Fire source and compartment heat release rate (HRR)

The ceilings were exposed from below to a propane burner fire source for a duration of 110 minutes which reached a maximum HRR of 1,250 kW (Figure 2). The configuration was designed to induce flame extension across half of the ceiling length when the CLT was lined. The experiments featuring exposed CLT delivered a peak HRR that was up to three times larger than that of the lined case in which the HRR followed the burner output. Thereafter, during the steady burning phase, the contribution of the CLT increased the fire's HRR by a factor of around 1.4 times.

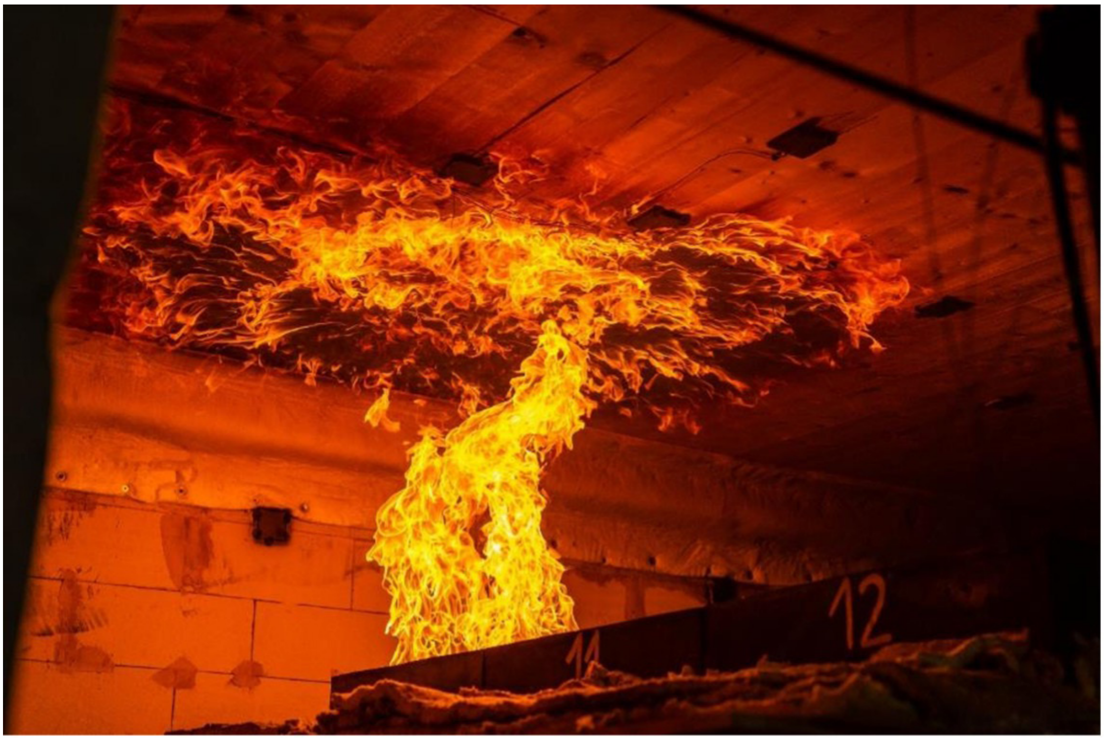

Figure 2: View of the fire enclosure towards the opening with the propane burner shown on the raised plinth

Flame extension

When flames from a fire hit the ceiling of an enclosure they will extend laterally and contribute to the thermal radiation back to the floor. Flame extension was observed over c. 50% of the plasterboard-lined ceiling. For the experiments with exposed CLT, the flaming was observed to extend over the entire enclosure ceiling area at the point the material ignited and burned. The increased flame extension translated to increased radiative heat flux to the floor, when measured relative to the encapsulated case. The heat flux to the floor would have been sufficient to have led to rapid fire spread to combustible items on the floor, had they been present. Therefore, compared to a non-combustible ceiling, the presence of an exposed CLT ceiling increases flame lengths below the ceiling leading to higher heat fluxes both at the ceiling and at the floor, which would likely contribute to a more rapid spread of fire to the enclosure contents.

Char fall-off

Premature char fall-off was observed for the CLT with the standard PUR adhesive and typically coincided with bond-line failure, leading to detachment of larger pieces of lamella in proximity to the fire source (Figure 3). These events were observed to occur several times over the CLT surface, with the detached lamella measuring up to c. 400mm long and 100mm in width. Despite char fall-off, auto-extinction of flaming combustion of the slab was observed once the fire source was switched-off. Char fall-off was also witnessed in the CLT with the modified PUR adhesive, albeit it did not appear to be whole parts of lamella and were instead smaller pieces of char of the scale of c. 50mm square (Figure 4).

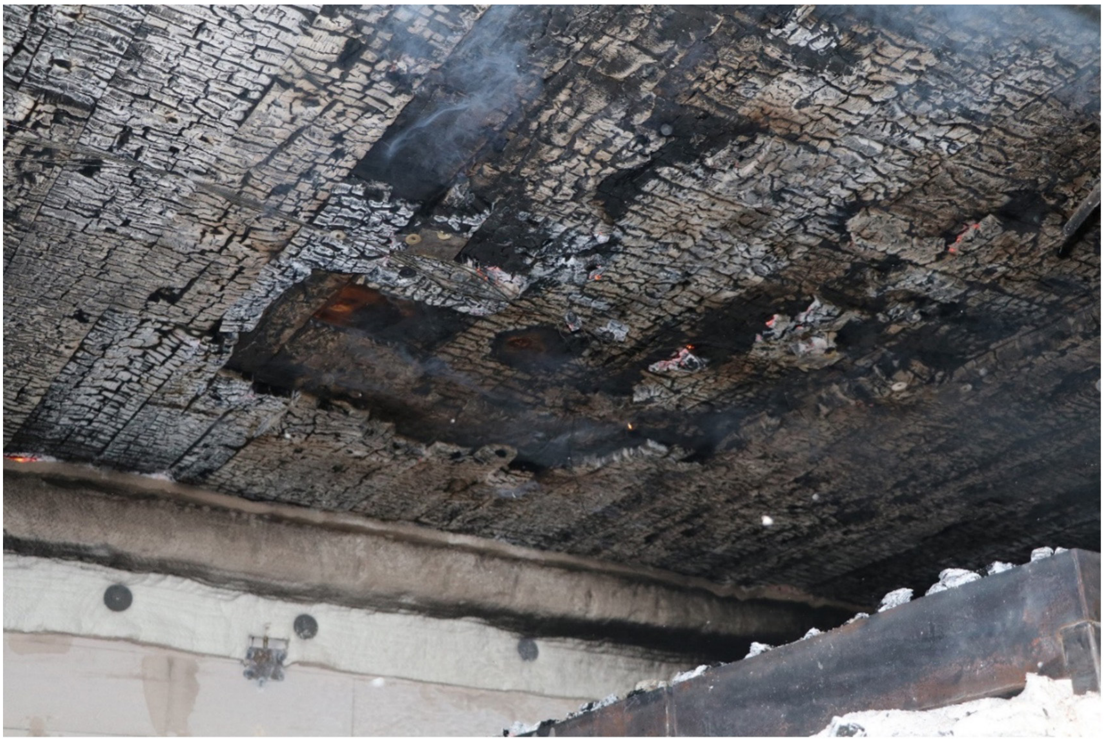

Figure 3: Extensive char fall-off in vicinity of burner from the CLT with the standard PUR adhesive

Figure 4: Limited char fall-off above the burner from the CLT with modified PUR adhesive

The results suggest that for an exposed CLT ceiling in an enclosure with otherwise inert boundaries, flaming combustion of the structure can stop regardless of the occurrence of premature char fall-off. When adopting the standard PUR adhesive, the detached and charred lamella was seen to fall to the floor and flame for a period, before transitioning to smouldering. The heat flux from the fallen flaming or smouldering lamella was not sufficient to support the continued flaming of the CLT ceiling.

Premature char fall-off resulted in locally reduced residual sections to the third lamella from the exposed side for the CLT adopting the standard PUR adhesive. This reduction was not apparent with the CLT with modified PUR adhesive. Therefore, whilst averting significant char fall-off was not a prerequisite for auto-extinction of flaming combustion, it would be expected to come with the compromise of increased section depth to ensure adequate mechanical performance in the event of fire.

Char depth

Despite pronounced char fall-off events in the experiment adopting the standard PUR adhesive, monitored charring depths to the slabs above the burner array were comparable for both adhesive types studied, reaching a mean of c. 45mm in both cases. This suggests the mechanical fixing of instrumentation to the ceiling nearby locally prevented the detachment of the lamella which was observed elsewhere in the experiment adopting the standard PUR adhesive. From post experiment surveys, the charring depths and extent of premature char fall-off were significantly larger in the experiment adopting the standard PUR adhesives over the modified alternative.

Conclusions

The research highlighted that the modified PUR adhesive offers benefits over the standard PUR adhesive. On the one hand, despite extensive premature char fall-off being observed in the standard PUR adhesive experiment, flaming of the CLT structure stopped, with the structure remaining stable under load both during and beyond the period of fire exposure. Flaming of the CLT with the modified PUR adhesive also stopped, indicating that the adhesive type is not a significant factor in the ability of a structure with an exposed ceiling and with otherwise inert boundaries to survive the full duration of a fire. However, this must be balanced against increased section loss and, thus, the efficiency of the structure, should the chosen adhesive result in more extensive premature char fall-off.

Relative to a non-combustible ceiling, the exposed CLT led to increases in the overall heat energy output of the fire, longer flames at ceiling level and correspondingly higher radiant heat fluxes at floor level. This means that fire spread in hybrid CLT commercial buildings are very likely to be more rapid and fires generally much larger than non-combustible counterparts, as has been observed in more recent large-scale fire experiments [4]. The implications of this must be considered by the designer not only in terms of the impact on the structure's stability but also other aspects of a fire safety strategy, such as fire spread and fire and rescue service activities.

Studies reported in Hopkin et al. [5], carried out as part of the larger STA project, noted there to be nominal differences in the fire behaviour characteristics of CLT from three different leading suppliers, subject to the same specification parameters. This suggests that the findings of these exposed ceiling experiments would be applicable to CLT manufactured by different suppliers, subject to consistency in adhesive type, edge-bonding condition, CLT thickness and CLT lay-up.

Acknowledgements

The funding made available by Stora Enso, KLH and Binderholz to undertake this work is gratefully acknowledged.

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