Mass timber fire safety

2021 Experimental series

There is a continued demand for mass timber buildings using cross laminated timber (CLT) and glulam because of the low-carbon benefits they offer, the speed in construction and resulting efficiency in design, and associated cost savings. One of the typical concerns in the use of mass timber as a structural material, in particular for high-rise and other high-risk buildings, is to do with its safety in the event of a fire. In particular the need for evidence of its structural stability during and after the fire, supporting safe evacuation, property protection and fire-fighting.

To address this challenge, more than 60 fire experiments have been conducted globally, since 2000, to understand the effect of exposed timber on fire dynamics. These experiments have been limited to compartments well under 90m^2 (970ft^2) in floor area and representative of residential units or an office for about 8 people. These experiments to date have been very informative and influenced building standards, codes and engineering guidance globally. The main findings were that exposed timber alters the fire dynamics within a compartment, resulting in more intense temperatures, longer durations, and a slower decay phase of the fire when compared to rooms without timber.

To date, how fires grow and develop in larger spaces, such as those more typical to office buildings and schools, formed with exposed mass timber has not yet been studied. As part of Arup's commitment to safety and sustainability we have conducted a series of full-scale fire experiments in a very large purpose-built compartment of 352m^2 (3,800ft^2), about the size of an office for 40 people. This is a new facility uniquely available at CERIB, France (as shown in figure 1). The fire science group, Hazelab, of Imperial College London led by Prof Guillermo Rein participated in the experimental programme and were part of the steering group. The first experiment was successfully undertaken on 9th March 2021, and the last in December 2021.

Experiment goals

The goals for the fire experiments were to investigate the impact of large areas of exposed mass timber on the fire dynamics that occur in an open-plan compartment, to understand how exposed timber structures including high rise withstand complete fire decay and smouldering, and to develop robust fire scenario calculations as the basis for future designs. These design fire scenarios will enable future evacuation, structural design and fire-fighting planning, all of which are critical components of the robust use of mass timber in buildings around the world.

The experimental series comprised four experiments:

- Experiment one
  Fully exposed CLT slab in compartment comparable to previous non-combustible experiment
- Experiment two
  Fully exposed CLT slab in compartment with half of the window openings closed
- Experiment three
  Fully exposed CLT slab with automatic water suppression system
- Experiment four
  Partially exposed CLT with window openings as in experiment one

Getting ready to commence the fire experiment

The set up

The purpose-built structure, designed by Arup based on previous experiments led by Imperial College, and built by CERIB, consisted of block walls and a CLT ceiling.

The CLT panels forming the ceiling were exposed and designed to replicate the aesthetic desired in modern timber office buildings. The CLT ceiling comprised five ply CLT with MUF adhesive and in the first experiment was left without any other additional protection, throughout the compartment. Glulam columns were also included to allow research on the interaction between CLT ceiling panels and exposed glulam columns. The CLT and glulam was purchased direct from a European supplier. The main fuel source for the experiment, and the first fuel to be ignited, was a continuous wood crib, as it allowed for a highly controllable fuel load.

Extensive instrumentation was provided to measure temperatures and heat flux inside the building. Temperatures were also recoded within the CLT and glulam columns and non-combustible screens were placed above window opening to measure the external flaming to study the impact on the building envelope and vertical fire spread. Cameras within and outside the compartment captured flame spread across the crib and the CLT, fire size and external flaming. The building design enabled variation in both fuel load and ventilation, parameters which were varied through the experimental campaign (see figure 1). No fire-fighting intervention was undertaken, giving insight into the long-term fire decay and smouldering behaviour of the CLT.

First experiment

For the first experiment 20.5% of the wall surface area was openings with an opening factor of 0.071 $m^{1/2}$. The continuous wood crib covered a floor area of 174 m^2 with an approximate fuel density of 374 MJ/m^2. This fuel load was chosen to limit the risk of damage to the structure but to still be within the range of typical fuel load densities in office buildings. Image analysis showed that the fire spread across the exposed CLT faster than along the wood crib, and more quickly than expected. The speed of fire spread at the wood crib was enhanced by the radiative heating from the burning CLT. Any increase in speed of fire spread impacts occupant evacuation options, and fire-fighting response scenarios.

Maximum temperatures occurred over a range of heights throughout the compartment, not just near the CLT ceiling, confirming previously published research on CLT fire behaviour (see figure 2).

Following the end of flaming some hotspots in the CLT were observed, although the majority of the CLT had stopped burning. The following day, three hotspots were detected via thermal imaging and visual detection. Temperatures within the timber columns showed a "thermal lag" where peak temperatures occurred after the fire had decayed. One hotspot near the central beam continued to smoulder and burn through the thickness of the CLT, eventually being extinguished through rainfall (see figure 3).

A peer reviewed journal has been published in Fire and Materials and is available here, or by contacting fire@arup.com. A short video of the experiment can be viewed here.

Figure 1. The purpose-built facility 11m wide, 35m long and 3m in height, shown set up for Experiment one. The team are stacking the fuel crib within the compartment to exact specifications.

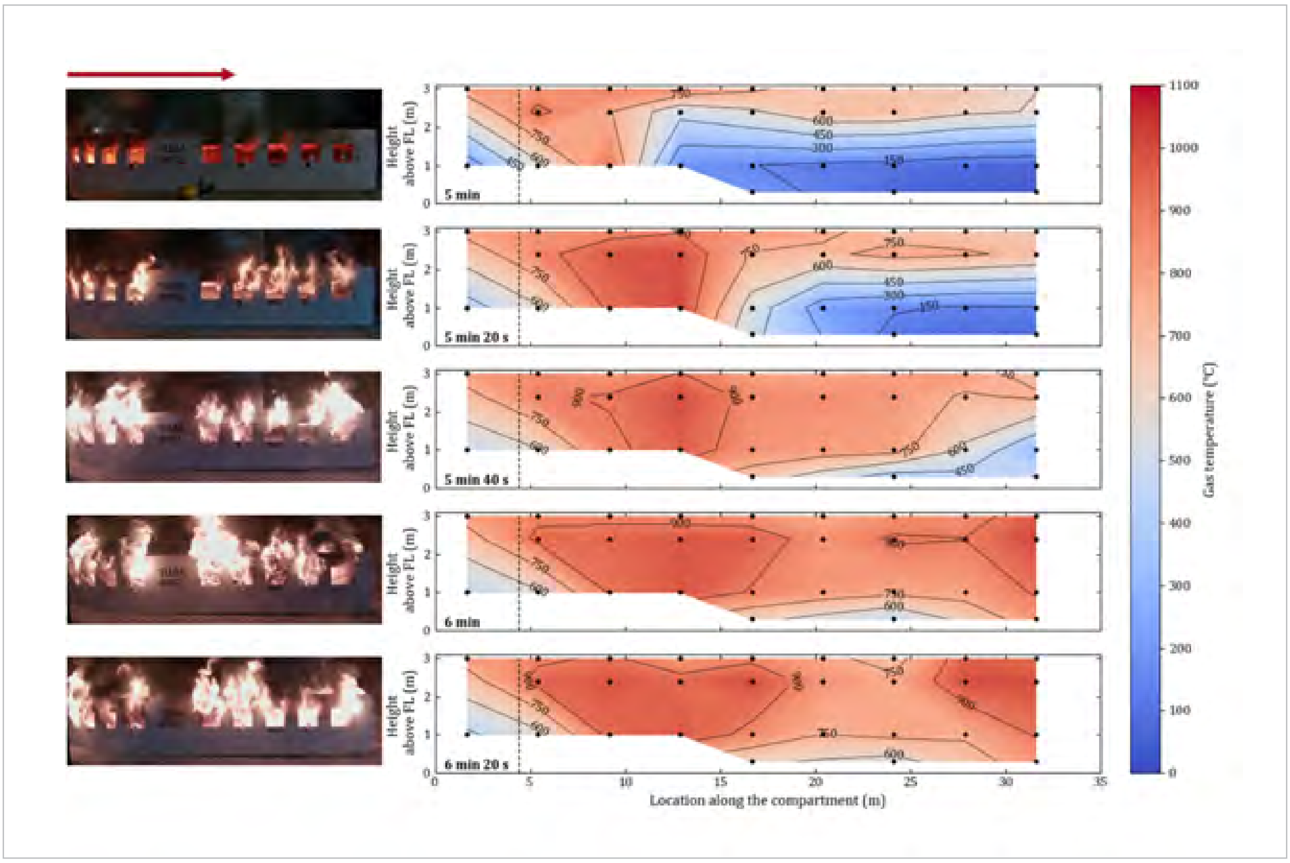

Figure 2. Vertical temperature distribution down the centreline of the compartment presented at various times from 5 min (top) to 6 min 20 seconds (bottom) after ignition. Black dots indicate location of thermocouples, while the black dashed line gives the ignition location (near the 4m mark). The photographs provide a visual of the compartment fire at the time of the adjacent contour plot.

Figure 3. Smouldering continued and burnt though the thickness of the CLT, as seen during experiment one.

Second experiment

The second experiment was conducted on the 1st of June, 2021, and was identical to the first experiment, with regards to the structure, the fuel load, and exposed timber elements. However the window openings were reduced by half compared to the first experiment, resulting in an opening factor of 0.039 $m^{1/2}$. Adjustments were made to the instrumentation and non-combustible protective boards were installed at locations on the floor to observe their ability to protect timber flooring against fire exposure from above.

Devices to measure radiant heat were also installed directly outside windows in the second experiment. As in experiment one, no fire-fighting intervention was undertaken during the flaming. Initial observations from the experiment indicate the fire spreading across the CLT ceiling and through the building at a similar rate to the first experiment, followed by a longer phase of intense burning compared to the first experiment.

During this prolonged burning phase, flame extension from the windows and doors was significant (see figure 4). As occurred in the first experiment, after a period of time the fire in the wood- crib reduced and flaming ceased at the CLT.

Flaming was still visible at the columns for some time when there were only glowing embers remaining on the floor (see figure 5). Without firefighting intervention, small pockets of CLT again continued to smoulder for hours, eventually breaching the CLT thickness (see figure 6), with some pockets also transitioning back to flaming combustion. Smouldering also continued for several hours in one column, resulting in the loss of most of the cross section at the base of the column.

A peer reviewed journal has been published in Fire and Materials and is available here, or by contacting fire@arup.com. A short video of the experiment can be viewed here.

Figure 4. Photo from experiment two showing extensive external flaming from openings, as the fire reaches the end of the compartment. Wooden crib at the end of the compartment has not yet fully ignited.

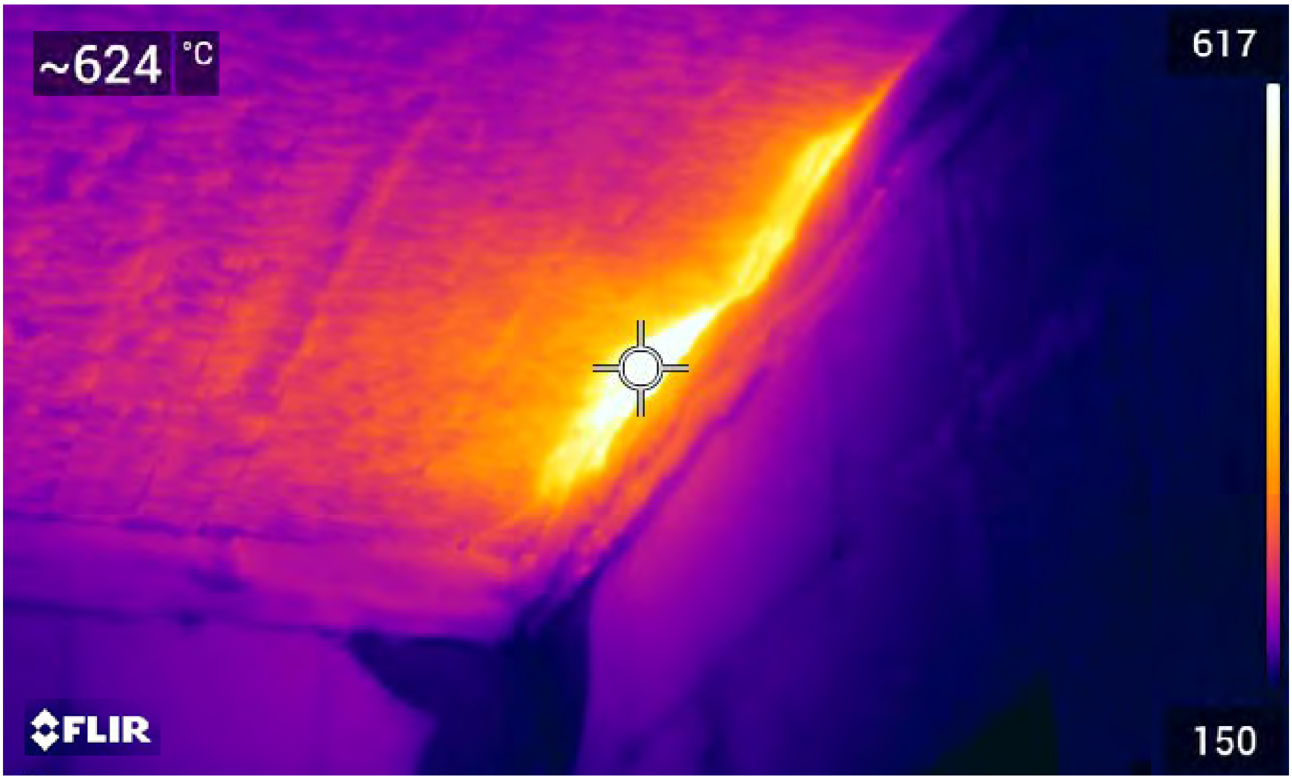

Figure 5. Photo from experiment two showing glowing embers remaining in the wooden crib, with localised flaming continuing at the base of one of the glulam columns.

Figure 6. Photo taken with a thermal imaging camera from experiment two showing ongoing smouldering several hours after flaming combustion ceased.

Third experiment

The third experiment was conducted on the 4th of November, 2021, with the construction being identical to the first experiment, with regards to the structure and exposed timber. For this experiment a commercially available automatic low pressure water mist suppression system was installed to cover the area of the wooden crib. The fuel was amended to reflect the configuration of a water mist corner test and fire load for offices. The continuous wood crib had a fuel load of 570 MJ/m^2. Most of the window and door openings were closed off with some of the openings left open to replicate the condition in a naturally ventilated office building where some of the windows may be open to allow fresh air in. There was a slight breeze during the experiment. The fire was successfully controlled and mostly extinguished by the automatic suppression system, with only a small area of limited flaming extinguished through manual firefighting intervention. There was only limited discoloration visible at the CLT ceiling in the immediate vicinity where the fire was ignited (See figures 7, 8 and 9). This experiment showed the effectiveness of an automatic fire suppression system with large areas of exposed mass timber.

A journal article has been published in SFPE x-tra and is available here, or by contacting fire@arup.com. A short video of the experiment can be viewed here.

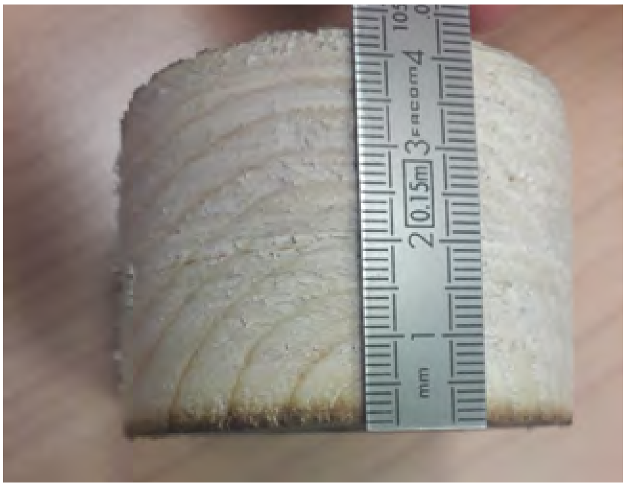

Figure 7. Core sample taken above the fire, showing limited discolouration of the ceiling after the suppression of the fire.

Figure 8. Ignition of the wood crib at the corner of the building, and activation of suppression system.
Figure 9. Limited damage to the wood crib and discolouration of the ceiling after the extinguishment of the fire.

Fourth experiment

The fourth experiment was conducted on the 14th of December, 2021, and was identical to the first experiment, with regards to the structure, the fuel load, and ventilation. The CLT was protected by 3 x 12.5mm boarding achieving a $K_2$60 classification, covering just under 50% of the ceiling, to study the impact of part CLT protection on fire dynamics (See figure 10). The CLT protection was located centrally within the building and along nearly the full length, replicating the architectural intent to have timber exposed at the building perimeter near the windows. Both screws and staples were used to fix the board protection. In addition, eight 1m^2 sample of floor protection and over 60 ceiling mounted service fixings were included, to replicate supports for HVAC services commonly found in office buildings (e.g light, mechanical ductwork, data cabling, fire safety systems etc). Half of the fixings were fixed directly into the CLT and the other half into the protected CLT.

A portion of the fixings were loaded with concrete blocks to resemble their expected design load. Adjustments were made to instrumentation to account for the CLT protection. Again, no fire-fighting intervention was undertaken within the building thereby enabling a detailed study of the long-term fire decay and smouldering behaviour of the CLT and glulam, including behind board protection and around services fixings. Initial observations from the experiment indicate that the position of the encapsulation delayed the ignition of the ceiling, however once flaming of the CLT was sustained, fire spread along the ceiling at a similar rate to the first two experiments. Due to the delayed ignition of the CLT, the fire initially spread slowly along the crib, and resulted in a longer and less severe fire when compared to the first experiment. During this prolonged burning phase, flame extension from the windows and doors was smaller both in extent and height when compared to the first two experiments (see figure 4 vs figure 11).

As occurred in the first two experiments, after a period of time the fire in the wood-crib reduced and flaming ceased at the CLT. Flaming was still visible at the columns for some time when there were only glowing embers remaining on the floor, though no ongoing smouldering at the base was observed in this experiment. Without firefighting intervention, small pockets of CLT again continued to smoulder for hours, again breaching the CLT thickness. Localised failure of the outermost layer of the CLT protection was evident during the cooling phase. Where the residual board protection remained intact, the CLT remained generally protected. Most of the loaded service fixings which were fixed directly to the CLT failed, while those fixed though the encapsulation remained in place. (See figure 12)

A peer reviewed journal has been published in Fire and Materials and is available here, or by contacting fire@arup.com. A short video of the experiment can be viewed here.

Figure 10. Installation of board protection to the CLT ceiling.

Figure 11. Photo from experiment four, showing extensive external flaming from openings at one end of the building, as the fire reaches the end of the compartment 34 minutes after ignition. Wooden crib at the ignition end of the compartment has largely burnt out already.

Figure 12. CLT protection the day after the fire, some localised failure of the outer layer visible, though CLT still protected by residual layers remaining intact; extensive failure of loaded services fixings visible with concrete blocks on the floor where loaded fixings were screwed directly into the CLT.

Conclusions

Analysis of results are already informing innovative low embodied carbon structural designs, and provide data to support three PhD students at Imperial College London, with a focus on fire spread rate at the exposed timber ceiling, fire decay phase, external flaming, charring within columns, transient (residual) heating within the timber and the extent and type of smouldering post-fire. The work will help inform industry guidance and potentially building codes.

Once analysis is complete, all results will be made available so that further research can be continued by anyone interested in the experiments. More detailed results and learnings from this experimental programme will be shared over the coming months with further updates on published papers and updates on the focus areas.

ARUP

Contact:
David Barber
Principal

e: david.barber@arup.com

8 Fitzroy Street, London W1T 4BJ
United Kingdom

arup.com