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# OBSERVATIONS OF SMOULDERING FIRE IN A LARGE TIMBER COMPARTMENT

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**ABSTRACT:** Understanding the end of the decay phase in a compartment fire is important for safety design, as it can indicate when structural hazards in a compartment have ceased. However, smouldering, a slow, persistent, and flameless form of combustion, can continue for days and hours following flames. Smouldering of mass timber has rarely been reported in timber experiments due to many experiments being stopped shortly after flames. This work presents for the first-time observations following the end of flames in three large compartment experiments with cross-laminated mass timber ceiling and glulam columns, known as CodeRed. The analysis focuses on initiation and growth of smouldering over 48 hours. 0.012–0.58 hotspots per m of timber edge developed in 19 locations, and nine spread through the CLT, forming holes in the ceiling, compartment integrity failure, and collapse of an unloaded column. Visual and infrared imaging was used to track smouldering, extinction, suppression, transition to flaming, and formation of holes. This paper shows that smouldering poses a hazard to mass timber buildings because it is hard to detect and can weaken the structure over days following flames, and transition to flaming, starting new flaming fires. These findings are important for building post-fire recovery.

**KEYWORDS:** Mass timber, Wood, Fire safety, Smouldering, Tall building

## INTRODUCTION

Fire safety is a hazard that continues to be a hot topic in safe mass timber design. As well-acknowledged in previous research [1] and current design standards such as Eurocode 5, timber elements including ceiling slabs and columns will char and degrade during a building fire, reducing their overall structural capacity and posing hazards that need to be addressed in design. However, comparatively less research and recommendations have been made to address the hazards posed to a timber building after flames have become extinct. One key hazard present after a building fire is smouldering.

Smouldering is a phenomenon involving the slow, persistent, flameless combustion of porous media such as timber [8,9]. Timber smouldering has been studied in the context of wildfires, however little research is available on the smouldering in real mass timber compartments. Thick timber elements such as logs and roots can continue to smoulder in the hours and days after a wildfire has passed through a region, known as residual burning [13]. There has been very few observations of smouldering in timber compartment fire experiments (currently <5 cases of smouldering in the 65< experiments in the literature). This can firstly be attributed to firstly to previous experiments not including a large volume of mass timber compared to current building demands – the largest compartment timber experiments prior to 2021 were 84 m$^2$, resulting in less usage of mass timber, and less complex design requirements (e.g. minimal slab-to-slab timber connections). Secondly, many experiments conclude observations either during or shortly after the end of flames by means of suppression or cessation of data collection, meaning observation bias may impact the perception of the likelihood of smouldering following a timber building fire.

A previous mass timber compartment fire experiment [11] observed structural failure of a mass timber ceiling 29 hours following the onset of heating, which was attributed to unseen smouldering. As only the collapse of the ceiling was observed, smouldering was only highlighted as a possible driving factor. Smouldering of mass timber has been investigated at the small scale [3], which determined that, for CLT in the arrangement specified, smouldering did not self-sustain unless subjected to a threshold heat flux and airflow.

However, very little work has been done to analyse the formation and spread of smouldering in structural mass timber elements following a compartment fire. Despite this concern, smouldering has been highlighted as a hazard in timber design by insurance bodies [10], researchers [1] and fire-safety design [14].

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As a result, this paper outlines for the first time experimental observations and analysis of smouldering following the end of flames in three large open-plan mass timber compartment fire experiments. This paper will overview the Infrared (IR), visual and thermocouple analysis carried out on a smouldering hotspot observed in the CLT over 38 hours following the end of flames in the compartment.

## 1 METHODOLOGY

The CodeRed experiment series comprised of a 352m$^2$ compartment with a CLT ceiling and two glulam columns [12], as shown in figure 1. In the three experiments discussed (CodeRed #01 [5], #02 [6], and #04 [7]), the ventilation (50% reduction in CodeRed #02) and level of encapsulation (50% CLT encapsulated in CodeRed #04) were varied to investigate their impact on fire dynamics and charring during and after the end of flames.

***Figure 1:*** *Photo of CodeRed compartment before ignition.*

Following the end of flames, both IR and visual cameras were used to track localised regions of smouldering, known as hotspots, in both the CLT ceiling and Glulam columns. Hotspots were identifiable visually by glowing and the emission of smoke, although not in all cases, particularly for concealed or in-depth smouldering. IR imaging was significantly more effective at identifying hotspots, as they were indicated by regions of high IR intensity, indicating regions of elevated temperature, as depicted in figure 1.

All mass timber elements were studied for the development, progression, and extinction of hotspots over the 48 hours following the end of flames for each experiment. Sixteen smouldering hotspots in total were observed across the three experiments, with nine resulting in holes through the thickness of the CLT ceiling, and one resulting in the collapse of a glulam column. The lateral spread rate of several hotspots were also tracked to further understand the behaviour of smouldering timber hotspots. Using IR, the lateral spread of smouldering hotspots was tracked as shown in figure 2.

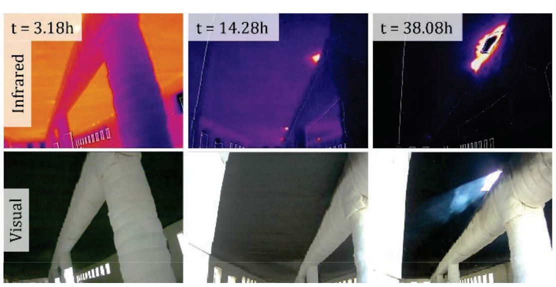


***Figure 2:*** *Initiation and spread of an observed hotspot in CodeRed #01, underneath the concrete beam above the crib ignition line. At 3.18h after flames, the hotspot is only visible in infrared, and not visual observation. The hotspot spreads in-depth until a hole is formed through the ceiling, at which point the smouldering is visible due to the hole and smoke emitted.*

## 2 RESULTS AND DISCUSSION

### 2.1 FORMATION OF HOTSPOTS AND HOLES

***Table 1:*** *Summary of observed smouldering behaviour*

| CodeRed # | 01 [5] | 02 [6] | 04 [7] |
|---|---|---|---|
| Hotspots | 3 | 7 | 9 |
| Holes | 2 | 6 | 2 |

Immediately after the flames along the timber ceiling and wood crib reached extinction, the entire charred ceiling surface continued to glow, until internal compartment temperatures steadily decayed to ambient conditions within 4 hours, as shown in figure 3. However, over this period of decay and cooling several localised regions in all three experiments continued to glow, both in the ceiling and glulam columns; these regions are known as smouldering hotspots, an example of which is shown in figure 2. A summary of the number of smouldering hotspots in each experiment is given in table 1, which shows that over three experiments 19 hotspots were observed, nine of which resulted in holes through the thickness of the mass timber ceiling, and one resulting in the collapse of a glulam column.

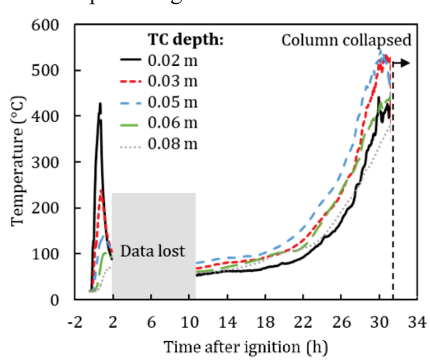


***Figure 3:*** *Column base temperature in CodeRed #02 after ignition. Flames lasted for 27 min before temperatures decayed to ambient levels. In the 32 hours following this, the base column temperatures increased steadily, indicating smouldering.*

Smouldering hotspots in the ceiling initiated exclusively along the edges of each slab, including connection lines between two CLT slabs, connections between the wall and CLT slabs, and the interface between CLT slabs and the insulated concrete column along the compartment length. A summary of the smouldering observed over the three experiments is outlined in table 1.

In CodeRed #01, over the 38 h after flames, a hotspot developed and spread at the ignition end of the compartment (figures 2 and 5), at the midpoint of the CLT

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surface near the mineral wool insulated concrete mid-span beam. Infrared imaging was applied to identify the location of the hotspot which immediately after the end of flames were not otherwise identifiable from direct observation. Figures 2 and 5 show that smouldering occurred in the CLT in a small, localised region, which grew in area over the span of 38 h after the end of flames. At 38 h after flames, a 23 min period of rainfall occurred, causing the smouldering to extinguish. Although suppression is an important tool in fire response, without thermal tools such as thermocouples or IR cameras these hotspots can be hard to identify before they begin to alter the structural capacity of the mass timber element.

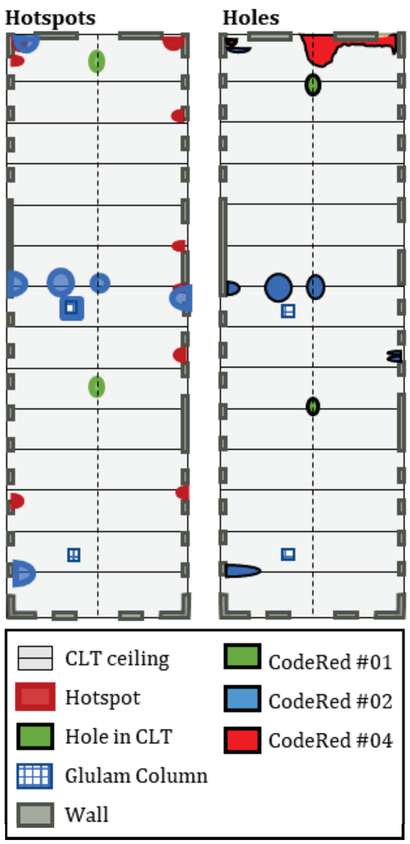


*Figure 4: Sketch of smouldering hotspots in the ceiling and columns from the end of flaming to the end of smouldering (> 48 h) in each experiment. Straight black lines represent edges of timber slabs.*

## 2.2 SMOULDERING IN COLUMNS AND ENCAPSULATION

Columns are typically structurally loaded elements and can therefore be of increased risk of structural failure during, or after, a fire [4]. However, each glulam column was unloaded and had no in-built connection to the ceiling or floor, partially contributing to one column in CodeRed #02 falling to the ground. This column was observed to smoulder at its base from 0 h after the end of flames. The column reached temperatures of ≤ 400°C during the fire, before steadily cooling below 100°C. However, as can be seen in Fig. 7, temperatures at thermocouple locations

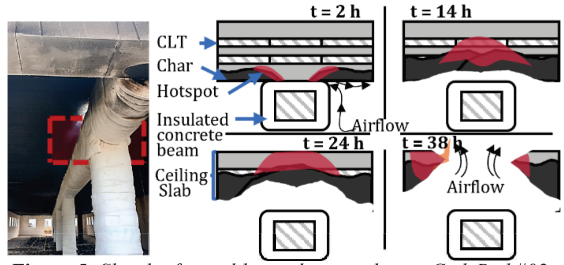


***Figure 5:** Sketch of smouldering hotspot during CodeRed #02 progressing through the ceiling thickness, and forming a hole in the ceiling.*

embedded both inside the timber element and along the glue line began to increase above ambient conditions from around 12 h following the end of flames, indicating the spread of smouldering from the base of the column in-depth and upwards along the column length. Smouldering at the base of the column was also observed with IR imaging. The column base smouldered for 31.82 h through the cross-section of the column base until the top of the column was observed to shift from the ceiling connection point. At 32.02 h, as shown in Fig. 6, the column collapsed fully onto the floor. This was attributed to degradation of the column base cross-section due to continued smouldering.

Embedded thermocouples at the base of the column are depicted in Fig. 7, showing the column base reaching up to 500°C at 28 h after the end of flames, above the temperature at which flaming could reoccur. After the column collapse, the side of the column facing the floor continued smouldering, resulting in near-full decay of the column cross-section across the column length, as shown in figure 6.

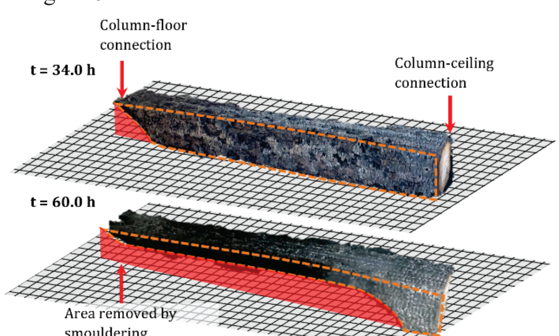


***Figure 6:** Smouldering under collapsed Glulam column from CodeRed #02 after collapsing to the concrete floor.*

Encapsulation is used in mass timber design to protect timber elements from fire, therefore limiting their contribution to the fire load, and limiting the impact of the fire on the element's structural integrity. Smouldering not only can still occur in encapsulated timber elements, but this can often make smouldering more challenging to locate even while using IR [2]. The encapsulation used in CodeRed #04 was a commercial encapsulation that covered 48% of the exposed surface of the CLT ceiling, with the goal of reducing the overall contribution of the CLT to the fire load. During the fire, the majority of protected CLT remained uncharred by the flames. Over


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48 h of observation, no smouldering was observed underneath the encapsulation.

Two hotspots at the interface between the CLT and the crib ignition-end wall formed holes through the CLT thickness. Further to this, both hotspots continued to spread along the width of the compartment, until the smouldering progressed underneath the encapsulation as shown in Fig. 9. 22 days (528h) following the end of flames, an approximately 1.7 m$^2$ region of encapsulation collapsed (Fig., directly below a region of smouldering similar in size that had spread through the thickness of the CLT ceiling. This undetected smouldering indicates that although encapsulation can be effective at mitigating the impact of fire on mass timber elements, it is not completely effective at preventing smouldering, particularly when it spreads from the edges of the encapsulation.

### 2.3 TRANSITION TO FLAMING AND EXTINCTION

Given suitable conditions, smouldering can transition from flameless combustion to flaming combustion. Smouldering to flaming transition is primarily driven by a change in heat flux incident on the smouldering surface, and oxygen supply to the smouldering reaction [20]. Transition to flaming can present a hazard to timber structures following the end of flaming by producing new fires hours after the original fire had ended. This can be particularly hazardous in the case of smouldering that forms penetrations to adjacent compartments or other floors, such as in Fig. 7, as this can lead to unburnt compartments being exposed to a new ignition source.

Smouldering spread and transition to flaming can be more likely to occur with the provision of insulation close to the smouldering surface, while still providing a small gap for air flow. In several smouldering hotspots, transition to flaming was observed following the formation of holes in the ceiling. This is due to an increase in air flow local to the hotspot, providing greater oxygen to the smouldering process, allowing a greater rate of char, leading to flaming.

***Figure 7:*** *CLT ceiling smouldering hotspot 40 hours after flames, forming a hole in the CLT. Transition to flaming is also observed.*

In a design scenario where a compartment of similar design to CodeRed may represent a single floor in a tall timber structure, transition to flaming in a breach of compartmentation between a unburnt compartment and a burnt-out compartment may lead to a new compartment fire being initiated, presenting all new structural hazards. As a result, this paper recommends that future work continues to understand the conditions under which transition to flaming may occur in smouldering mass timber elements following a compartment fire, and methods of avoiding these conditions to prevent multiple fires in the same structure.

Suppression and subsequent extinction of smouldering hotspots was also observed, both by short 20–40-minute periods of rainfall and direct intervention by firefighters using a firehose. Rainfall was only observed to be partially effective at extinguishing hotspots, whereas after significant intervention a firehose was successfully used to extinguish a smouldering hotspot.

## 3 DISCUSSION

The end decay phase of a building fire is typically defined as the time at which the entire compartment has cooled to ambient temperatures [12]. Flaming will cease long before much of the compartment has reached ambient conditions, however smouldering, as evidenced by CodeRed, can continue hours and days after the decay phase is assumed to conclude. Following the end of flames of each CodeRed experiment, the entire of the CLT surface smouldered during the decay phase before extinguishing without suppression, known as self-extinction. The definition of "extinction" is typically used by fire safety experts to define when the hazard posed to a building during a fire has ceased. This is typically defined by either when the flames have ended, or shortly afterwards when most of the compartment has cooled to ambient temperatures. However, as evidenced by this paper, smouldering can not only cause localized regions of high temperature within a compartment, but also extend the period over which structural hazards continue to develop over hours and days after flames have ended.

The 9 holes observed in the CLT ceiling posed not only a structural hazard to the building, but also a failure of compartmentation. Further to this, several hotspots were observed to transition to flaming hours after the end of flames, providing pathways to further larger fires forming and further damaging the structure.

The smouldering hotspots that progressed under the encapsulation in CodeRed #04 indicate that encapsulation may not be effective at preventing smouldering of CLT in some situations, particularly when smouldering has initiated in a non-encapsulated area and spreads horizontally to encapsulated parts.

The conditions for self-extinction are important to identify when a mass timber element will cease smouldering, therefore reducing further hazards to the structure. The complex design of timber buildings means that heat losses in certain locations can be low, smouldering surfaces can re-radiate onto each other, and sufficient air flows can occur naturally within a compartment. Suppression of hotspots occurred either independently or by the addition of water local to the smouldering region, either from a period of rainfall (occurred in both CodeRed #01 and #02), or with a fire hose.

Due to the complex geometries of timber elements observed in the CodeRed experiments, self-sustaining smouldering hotspots were observed over the 48-h following the end of flames. Smouldering timber favours regions which reduce head losses of smouldering, including voids, underneath encapsulation, and near insulating materials such as mineral wool. Smouldering will also spread at a greater rate when subjected to a higher airflow, providing a greater supply of oxygen to the oxidation reaction. In the context of tall timber buildings, the spread of smouldering may be enhanced by regions where airflow exists, such as small gaps between timber connections. Compared to future and current occupied mass timber buildings the design of the CodeRed compartments is low in complexity, meaning that in practice the presence of smouldering in a modern timber building may be more challenging to predict, detect, and suppress than what is discussed in this paper.

Identifying design components and locations where smouldering is likely to occur is key to not only reducing the likelihood of smouldering, but aiding firefighting services in detecting its presence. To that end, self-sustaining smouldering was only observed along the edge of timber elements. Considering the overall edge length of each experiment (154 – 257 m where edges comprise of ceiling slab to wall connections, ceiling slab to ceiling slab connections, and ceiling slab to insulated concrete beam connections), a hotspot occurrence frequency of 0.012 – 0.58 hotspots per meter of edge was found. Scaling this to modern design demands such as office spaces of 5000 m2, 30 – 150 hotspots may occur, each presenting a hazard to the structure.

The prevention of smouldering in timber buildings can be addressed by avoiding designs which promote its initiation. However, in application timber structures have other design components. Therefore, this paper recommends smouldering is studied further in complex timber design elements to determine the hazard that smouldering may pose. These include voids between compartments with combustible elements (e.g. ceiling and wall slabs, voids behind combustible facades), structural connections (e.g. ceiling slab connections, ceiling to column connections, beam and column connections), penetrations in slabs for electrical/plumbing servicing, and any regions where mass timber is insulated by another design component or an air gap (encapsulation, insulation, and other low-conductivity construction materials).

Detection is vital to help firefighting operations identify if smouldering is present in a timber structure, and therefore if structural hazards are present. This paper has shown that in many cases smouldering may not be visible by direct observation, due to it being flameless and occurring in-depth and in hidden areas of in timber elements. Therefore, it is recommended that when investigating a timber building after a compartment fire, infrared imaging is used [2]. However, it should be noted that concealed timber surfaces such as voids, encapsulation, and cavities can cause smouldering to not be immediately observable with infrared either. This paper and previous work [2] show that water mist hoses can extinguish smouldering hotspots when identified. However, it is recommended that work is conducted to understand the most effective methods to apply water to extinguish smouldering hotspots, and how to extinguish smouldering in regions that may be more challenging for firefighters to access.

# 4 CONCLUSIONS

This paper outlines experimental observations that show that smouldering fire is a structural threat to modern timber buildings. The remaining 19 hotspots observed highlight that structural hazards in a compartment fire continue not only during the decay phase, but in the hours and days afterwards. Smouldering presents a hazard for two reasons: one, the smouldering hotspots after a flaming fire are difficult to detect and suppress, so smouldering can burn through timber elements overnight and lead to partial collapse. Secondly, smouldering can lead to transition to flaming, which creates pathways to further fires hours after both the fire, and decay periods. Also, encapsulation was found to be not completely effective at mitigating smouldering. This is the first study focused on smouldering fires in mass timber, showing that smouldering is proven to be a structural hazard that must be considered and addressed by designers, stakeholders, and firefighters.


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