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FLAME SPREAD CHARACTERISTICS IN LARGE COMPARTMENTS WITH AN EXPOSED TIMBER CEILING

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ABSTRACT: In the pursuit of the net-zero agenda set by the global community to fight climate change, more architects and engineers have turned their attention to heavy/mass timber as an alternative structural material to concrete and steel which are the materials predominantly used in building construction. Current evidence from fire experiments is primarily limited to small compartments with an area of 84m^2 or less. To address the lack of knowledge in this area, Arup, CERIB and Imperial College London completed the CodeRed experiments in a 352m^2 open-plan compartment with an exposed CLT ceiling and glulam columns. Four experiments were undertaken in total in 2021, with three of them focusing on fire dynamics. The facility was a replica of the previous largest experiment with a non-combustible ceiling undertaken to date, such that a direct comparison on the impact of the timber ceiling can be made. This paper presents an overview of these experiments, and specifically presents the experimental outcomes relating to flame spread rates observed on the fuel bed, and the influence of the timber ceiling on fire dynamics when compared to experiments completed similar non-combustible compartments. These experiments show that a timber ceiling significantly accelerates the fuel-bed flame spread rates compared to a comparable non-combustible compartment. This has implications for means of escape of occupants, fire-fighting interventions as well as structural response.

KEYWORDS: timber ceiling, large-scale compartment fire experiment, flame spread rates, fire safety

1 INTRODUCTION

In the pursuit of the net-zero agenda set by the global community to fight climate change, more architects and engineers have turned their attention to mass timber as an alternative structural material to concrete and steel which are the materials predominantly used in building construction. Understanding he response of mass timber to fire is critical to delivering safe and sustainable building designs. Two key parameters that must be considered with respect to structural fire protection in mass timber buildings are: a) the size of the fire compartment and b) the materials of construction exposed to the fire compartment.

Our experience indicates that architects are increasingly considering mass timber as the primary structural material for buildings designed for office, retail, and assembly occupancies. These buildings often have large open-plan floor areas (e.g. >1000m^2) with aspirations of maintaining as much timber exposed as possible to meet sustainability goals (reducing use of applied cladding materials) and improve aesthetic appeal for occupants and stakeholders. The exposed timber surfaces in open-plan office buildings are often desired to be in the form of a CLT or glulam ceiling (soffit) supported by a glulam frame.

Traditional fire safety design for structural fire resistance (termed "loadbearing capacity" in UK guidance) is based on small compartments. The 'travelling fire' design concept (see Figure 1) has been developed over the past 10 years, and is increasingly applied to large open-plan compartments. However, existing experimental evidence for travelling fires is based on compartments constructed from largely non-combustible materials. Travelling fires are assumed to cover a limited area of a compartment ("near field") and spread across the floorplate. The burning area is defined by the leading edge (front of the fire) and the trailing edge of the fire, where the fuel has been consumed leading to burn-out of the fire. Both the leading and trailing edges spread until the total available fuel is consumed [1].

A review by Rackauskaite et al. [2] has highlighted previously that compartment fire experiments with exposed timber surfaces published at the time of the authors' review were limited to a compartment area of 84m^2. This limits the understanding of fire regimes that can occur in larger compartments, such as characteristics of flame spread, which are less significant in small compartments. Furthermore, temperatures in large compartments can vary significantly both spatially and temporally. This is important because there is a potential that traditional structural fire protection design may lead to under- or over-provision of protection materials to large compartments. The former is potentially unsafe, while the latter is unwelcome in terms of sustainable development.

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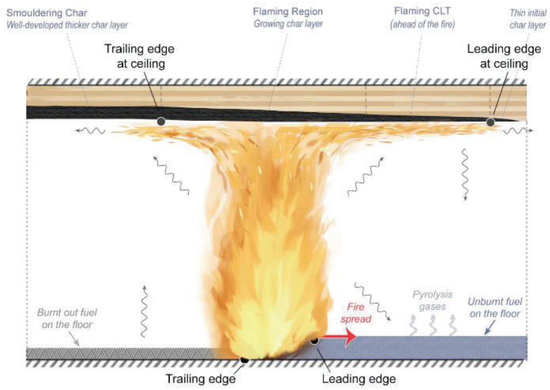

Figure 1*: The travelling fire dynamics phenomena expected in a large scale open-plan compartment with exposed mass timber ceiling. Arrows indicate radiation from fire and heated surfaces preheating fuel and timber ahead of the flames, and continuing heating of charred timber behind the flames in addition to the heating from smoke (not indicated in this figure for clarity).*[2]

Therefore, there exists an important gap in knowledge around understanding fire dynamics in large timber compartments. This gap must be filled to establish credible design fire scenarios and to inform fire safety design methods for timber buildings that adequately mitigate risks introduced by the timber construction.

To address this knowledge gap, a consortium comprising Arup, Imperial College London and CERIB completed the CodeRed experimental series[3].

This paper presents an overview of the outcomes from the CodeRed experiments. It focusses on the impact of the timber ceiling on fire dynamics, and specifically how this influences flame spread rates within the compartment. Detailed results from each experiments are published separately for each experiment in [4]–[6] &[9].

2 THE EXPERIMENTS

A series of full-scale fire experiments in a purpose-built, compartment of 352m^2 was conducted in 2021. These experiments aimed to capture fire dynamics in large compartments with exposed timber. The experiments examined different parameters such as ventilation, encapsulation and the provision of a water mist system.

The facility used for the CodeRed series was built at CERIB's site in Epernon, France. The CodeRed experiment configuration was constructed to match as closely as possible that of an existing non-combustible building used in a series of experiments, known as *x-ONE* [7] and *x-TWO.1* [8]. These prior experiments studied travelling fire dynamics in open-plan compartments of non-combustible construction. The CodeRed experiments were design to enable, so far as was practicable, direct comparison of the impact of exposed timber on fire dynamics.

2.1 THE NON-COMBUSTIBLE COMPARTMENT EXPERIMENTS (x-ONE and x-TWO.1)

Compartment configuration

x-ONE and xTWO.1 were carried out in an existing building near Warsaw, Poland. The building had one floor that was mostly open plan with thick external masonry walls. The beam and block concrete slab ceiling was supported by reinforced concrete columns, beams, and external masonry walls. The experiments were carried out in the open-plan section of the building which had a floor plan of approximately 384 m^2. The compartment was 10.8m wide, 35.5m in length, and height ranging from 2.93m to 3.19m.

Ventilation was provided via fixed open holes in the concrete perimeter walls of the experimental building. See Table 1 for the % perimeter area of ventilation provided.

Fuel load design

The fuel load used in x-ONE and x-TWO.1 constituted of a continuous wood crib to encourage a natural spatial and temporal fire growth. The fuel load density of was approximately 370 MJ/m^2 (19.4 kg/m^2) and covered a floor area of 174 m^2 (6 m x 29 m).

The fuel bed was not covering the whole length of the compartment, and started approximately 6m from one end. This was the part of the fuel bed that was ignited.

The fuel setup consisted of 11.5 layers of a continuous wood crib (4 sticks each layer). In x-ONE two layers of 4 mm fibreboard were included within the crib build-up and across the whole fuel area to facilitate a faster flame spread. In x-TWO.1 the additional fibreboard was provided only to the first metre of the fuel load.

The previous experimental series had one further case, *x-TWO.2* [8] that had a reduced fuel load density. In this case the flames did not touch the ceiling, and therefore this experiment is not included in the comparisons set out in this paper.

2.2 THE COMBUSTIBLE COMPARTMENT EXPERIMENTS (CODERED)

Compartment configuration

The details of the CodeRed compartments are set out below and in Figure 2 to demonstrate their equivalence to the previous experiments described above.

- 10.27 m wide,
- 34.27 m long and
- 3.1 m high,

The building was constructed from aerated concrete blocks (365 mm thick, 350 kg/m^3). The ceiling was composed of 14 CLT panels supported by hinge connections on the perimeter walls and a central concrete beam. The CLT consisted of 5 ply (40-20-20-20-40 mm) spruce wood with MUF adhesive; the CLT was not treated with any fire retardant. The CLT ceiling been tested by

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the manufacturer not to experience char fall-off (no glue line integrity failure in fire) in a long duration fire exposure (120 minutes to the ISO 834 standard fire). As the primary focus of the experiments was to observe the fire dynamics, the structure was supporting self-weight only and was not substantially connected mechanically. Figure 1 describes the building layout and Figure 3 describes typical instrumentation provided.

Ventilation was provided via fixed open holes in the concrete perimeter walls of the experimental building. See Table 1 for the % perimeter area of ventilation provided.

Fuel load design

All three CodeRed experiments reported in this paper matched the x-TWO.1 fuel load design. See the yellow area in Figure 2 for the extent of the fuel bed. This was designed to match the fuel bed of x-TWO.1.

Instrumentation

The fire development in the *CodeRed* experiments, inside and outside the compartment, were captured via thermocouples, plate thermometers, as well as fixed and drone mounted cameras, as seen in Figure 3.

Parameters varied in each experiment

The four experiments comprised:

- *CodeRed #01* – arrangements similar to that of non-combustible experiments, but with an exposed CLT ceiling and glulam columns [4]
- *CodeRed #02* – same as *CodeRed #01* but with 50% of the ventilation [5]
- *CodeRed #03* – looking at the effectiveness of a water mist system with timber ceilings (outside the scope of this paper) [9]
- *CodeRed #04* – same as *CodeRed #01* but with ~50% of the timber encapsulated in fire resisting cladding. The extent of encapsulation is shown in the blue box in Figure 3. [6]

Overview of fire response

CodeRed #01, *#02* and *#04* had no suppression or firefighting intervention, allowing the fires to grow, spread and decay naturally and enabling smouldering to be observed. Combustion of the wood cribs was observed as follows:

- #01 – Flaming ended: 22 min 30 s after ignition. Smouldering observed for 48 hours;
- #02 – Flaming ended 26 min 30 s after ignition, smouldering observed for 60 hours; and
- #04 – Flaming ended 45 mins after ignition, smouldering was observed for 24 days.

As indicated above, after the flames had ceased in the crib, smouldering and intermittent flaming was observed in the CLT of all experiments in multiple locations. In many instances the smouldering spread through the thickness of the CLT panel leading to the formation of holes in the CLT slab.

Figure 2: Floor plan and sections of the compartment used for the CodeRed experiments. Units in metres.

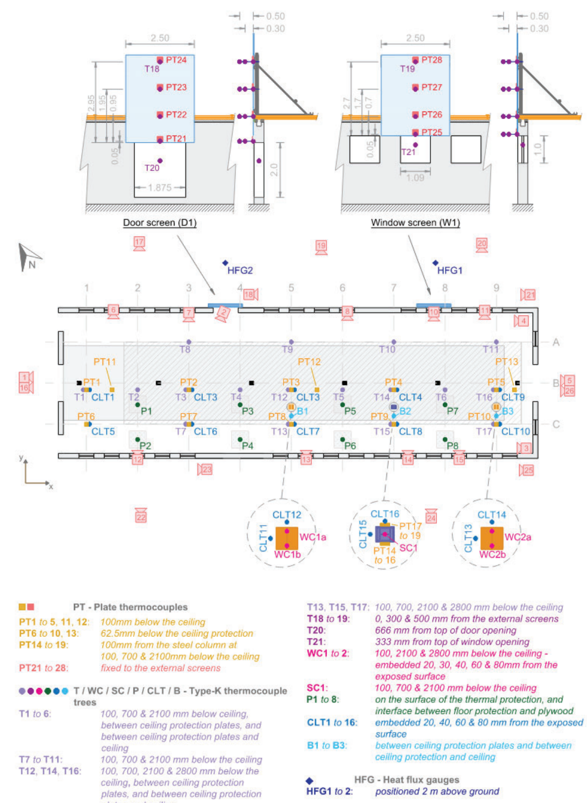

Figure 3: Typical instrumentation in the CodeRed experiments.

2.3 COMPARISON OF FEATURES

With regards to the specific objectives of this paper, footage from all recovered cameras were used to measure the locations of the leading (i.e. flame front) and trailing (i.e. burn-out) edges of the fire as in *x-ONE* [7] and x-*TWO.1* [8]. Cameras located inside the compartment and at compartment openings were placed in heat and radiation-resistant containers to protect the instrumentation and data collected.

See Table 1 for a comparison of the relevant experiments.

Table 1. Summary of the differences in the key parameters of interest between the previous non-combustible travelling fire experiment and the CodeRed experiments. CodeRed #03 is not included in the table as its aim is not related to this study.

Parameter	x-ONE [7], x-TWO.1[8]	*CR#01* [4]	*CR#02* [5]	*CR #04* [6]
Ceiling	Non-combustible	*Fully exposed ceiling (CLT)*	*As CR #01*	*52% exposed*
Ventilation	20%	*21%*	*10%*	*As CR #01*
Width x length	10.8 m x 35.52 m	10.27 m x 34.27 m	*As CR #01*	*As CR #01*
Height	2.93 m to 3.19 m	3.1 m	*As CR #01*	*As CR #01*
Area	384m^2	*352m^2*	*352m^2*	*352m^2*
Type of fuel – wood sticks	Wood sticks 0.03m x 0.03m x 1m	Same as x-ONE and x.TWO.1	Same as x-ONE and x.TWO.1	Same as x-ONE and x.TWO.1
Fibreboard	Wood fibreboard throughout (x-ONE) and only in first meter (x-TWO.1)	Same as x.TWO.1	As x.TWO.1	As x.TWO.1
Size of fuel bed	6 m x 29 m	As x-ONE and x-TWO.1	As x-ONE and x-TWO.1	As x-ONE and x-TWO.1
Fire duration (cessation of flaming of wood cribs)	25 min (x-ONE) 32 min (x-TWO.1)	22.5 min	27 min	46 min

3 IMPACT OF EXPOSED TIMBER ON FLAME SPREAD

The CodeRed experimental set-up mimicked previous “travelling fire dynamics” experiments undertaken in a non-combustible compartment to allow for direct comparison between each experiment series. For reference purposes the extracted locations of the flame and spread rates of the flames for x-TWO.1 are shown in Figure 4 [8].

3.1 FLAME SPREAD IN NON-COMBUSTIBLE COMPARTMENTS

In x-TWO.1 the flame spread rate showed two main conditions. For the first 5m of the fuel bed, flame spread 4.16 mm /s (0.25 m/min). this took approximately 14 minutes. As the flames passed the large ventilation opening that was present in this location, the flame spread rate then increased to an average value of almost 58.3 mm/s (3.5 m/min) until reaching the end of wood crib. After 5 min from the ignition, a clear trailing edge of fire started to move along the compartment, with the spread rate of ~ 4.2 mm /s (0.25 m/min) almost the same as the leading edge. After 13 minutes from ignition of the fuel bed, the spread rate of the trailing edge of the flames accelerated to a maximum value of 41.7 mm/s (2.5 m/min). The spread of the trailing edge stopped at around 25 minutes. In the locations where the trailing edge has passed the fuel had experienced burn out. See [8] for more information on the experimental results.

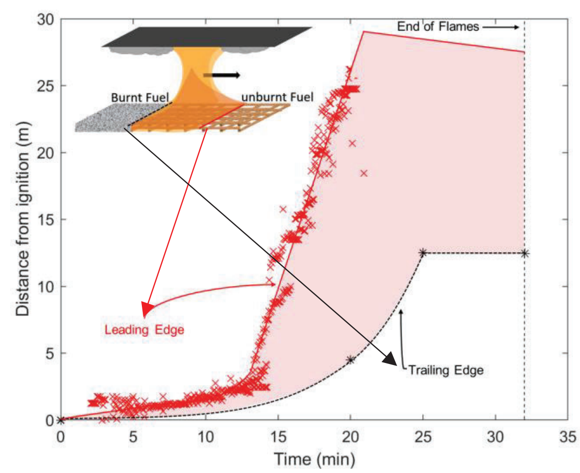

Figure 4: Locations of the leading and trailing edges of flame spread across the compartment for x-TWO.1.[8]

3.2 FLAME SPREAD IN CODERED #01

As shown in **Error! Reference source not found.** in *CodeRed #01*, the flame spread along the crib was observed to follow two main burning regimes. For the first 2.5 minutes of spread, the leading edge spread rate was approximately steady at 11 mm/s, 2.5 times the rate of the x-TWO.1 experiment. The spread rate accelerated substantially at the point the CLT ceiling surface ignited, spreading across the full fuel bed within 5 minutes of ignition. Noting that it took the x.TWO.1 experiment 20 minutes for the leading edge to reach the far end of the fuel bed.

After the leading edge reached the end of the fuel bed, it was also observed to regress into the compartment as the crib was consumed from both ends. This was not observed in the x.TWO.1 experiment.

The trailing edge, was identifiable and began to substantially traverse the compartment at approximately

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12 min (comparable to x.TWO.1) and steadily spread across the compartment with an average spread rate of 37 mm/s (2.2 m/min). This is at the higher end of the trailing edge spread rates observed in x.TWO.1.

The distinct and identifiable movements of both the leading and trailing edge are characteristic of a travelling fire. This demonstrates that it is valid to consider travelling fire conditions in compartments of this size.

The average spread rate of flames across the CLT, based on the time between the ignition of the CLT and the flames reaching the far end of the compartment, was 200 mm/s (12 m/min) spreading 30 m in 2 min 29 s. This is approximately 3.5 times faster than the x-TWO.1 test results.

The fire was at its maximum size between 6 and 12 min when the full extent of the crib and CLT were burning simultaneously. This was not observed in the x.TWO.1 experiment, as the trailing edge had spread before the leading edge reached the far end of the fuel bed. This meant that the fuel at the start of the compartment had already burnt out as the fire was travelling.

3.3 FLAME SPREAD IN CODERED #02

As shown in **Error! Reference source not found.**, in *CodeRed #02* as in *CodeRed #01* flame spread across the ceiling was rapid once the CLT ignited. At 7 min 25 s the leading edge of both the crib and the ceiling arrived simultaneously to the far end of the compartment as seen in **Error! Reference source not found.** The crib at the far end of the compartment was observed to quickly burn out, resulting in the leading edge receding back through the compartment at approximately 13 min 30 s after ignition. The trailing edge appeared to progress much slower than the receding leading edge.

Based on the timing of the ignition of the CLT and the arrival of the flames at the end of the compartment the average flame spread rate across the CLT in CodeRed#2 was 153mm/s (9m/s) compared to 200mm/s (12m/s) for *CodeRed #01.* The spread rate across the crib was less impacted than the CLT, with an average spread (after CLT ignition) of ~147 mm/s (0.15 m/s), compared to 161 mm/s (0.16 m/s) in *CodeRed #01*. As such the reduction in ventilation appeared to have a greater overall impact on the spread rate of flame across the CLT (-23%) than the crib (-8%). Similarly to CodeRed #01, in CodeRed #02 the crib was burning simultaneously for the majority of the fire duration unlike x-TWO.1

3.4 FLAME SPREAD IN CODERED #04

Overview of difference with other tests

In *CodeRed #04* ~50% of the ceiling was encapsulated, mostly above the fuel bed. In this experiment there was an initial delay of 20 minutes until the exposed CLT ceiling ignited (see Figure 7. This delay was because of the encapsulation preventing flames and hot gasses impinging on the CLT directly above the fuel bed, where CodeRed #01 and #02 ignited first. Instead of direct flame impingement from the wood crib fire onto the CLT ceiling, the fire in the wood cribs instead heated up the encapsulation instead, driving out the moisture in the board protection. Additionally, the moisture of the wood cribs was higher than the earlier experiments due to environmental conditions during *CodeRed #04* which took place in December. This effect is discussed in detail below.

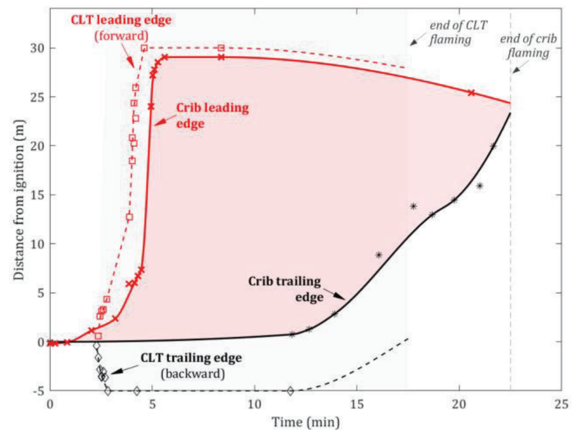

Figure 5*: Locations of the leading and trailing edges of flame spread across the CLT (dashed lines) and the wood crib (solid lines) for CodeRed #01. The time of end of observed flaming combustion of the CLT (17.5 min) and crib (22.5 min) are marked with vertical shaded area and dotted line, respectively.*[4]

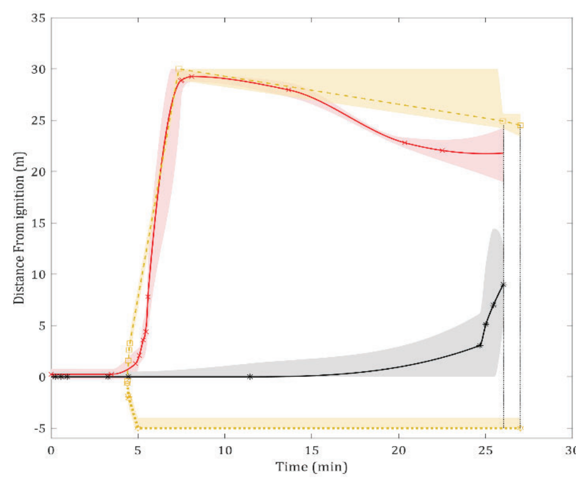

Figure 6: *Leading and trailing edges of flame spread along the wood crib, and leading flame edges both forwards and backwards under the CLT ceiling for CodeRed #02. Error cloud indicates deviations in edge location along the width of the crib, as edges are not constantly parallel to compartment width.* [5]

Fire spread observations

Figure 7 presents the positional data of the leading and trailing edge gathered from image analysis for *CodeRed*

#04. Before the first ignition of the CLT, the leading edge spread linearly with an average spread rate of 3 mm/s (0.18 m/min). By comparison, in *CodeRed #01* this spread was 11 mm/s (0.66 m/min), over a shorter duration, and while the fire was spreading through the section of the crib with fibreboard. When the CLT ignited, the leading and trailing edges had already travelled 4.4 m and 3.0 m respectively. As a result, a smaller extent of the crib was involved during the peak fire period in *CodeRed #04* compared to *CodeRed #01*and *#02*.

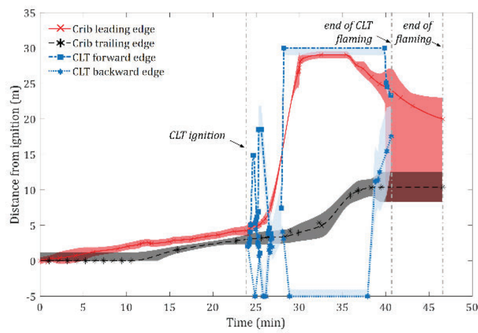

***Figure** 7: Locations of leading and trailing edges of flame spread across the cross-laminated timber (CLT) (dashed lines) and the wood crib (solid lines) for CodeRed #04. The time of end of observed flaming of the CLT (40 min 59 s) and crib (46 min) are marked with vertical dotted lines.* [6]

Following the sustained ignition of the CLT, the spread rate of crib fire grew to an average of ~107 mm/s (6.4 m/min), taken between the time of sustained CLT ignition and when the flame spread was observed to spread the length of the crib. The average spread across the CLT was ~222 mm/s (13.3m/min), measured from the point of sustained ignition of the CLT. In *CodeRed #01,* the spread rates were 161 and 200 mm/s (9.6 and 12m/min) for the crib and CLT, respectively.

Impact of encapsulation

The encapsulating boards were observed to largely remain in place over the whole flaming period, preventing flaming from the surface of the protected CLT ceiling. The last layer failed in some instances during decay but the encapsulation met its objectives in preventing flaming.

The decrease in flame spread rate in *CodeRed #04* across the crib is likely due to the effects of the calcium silicate board protection and different moisture content in the *CodeRed #04* crib. The encapsulation of the CLT delayed ignition of the CLT and instead resulted energy being absorbed in driving out moisture from the board protection [10]. The encapsulation also reduced radiative feedback from the ceiling to the fuel bed. The flame spread across the CLT was broadly within the same range, as in *CodeRed #01* once the CLT ignited.

Impact of moisture content

The greater moisture content within the wood crib of *CodeRed #04* (17.7%) compared to that in *CodeRed #01* (13.5%), and the presence of the board protection is expected to have reduced the spread rate of the leading edge, as greater energy and time are required to dry the wood. This difference in moisture content in the crib equates to an approximately 34% increase in energy required to dry the wood, and an approximately 32% increase in the overall energy required to combust the timber which also includes heating (to 350 ℃, specific heat capacity = 2.3MJ/kgK [11]) and pyrolyzing the timber (1.82 MJ/kg [12]).

Therefore, when comparing the results of *CodeRed #04* with those of *CodeRed #01*, the increased moisture and resulting increase in energy required to heat the timber, needs to be taken into consideration as it a significant influence on the results, particularly in the initial stage of the fire. The energy required to dry the moisture from the encapsulation system may have also played a role.

The results from CodeRed #04 suggest that in partly encapsulated compartments the flame spread over the fuel bed will be slower than fully exposed ceilings but faster than non-combustible compartments. However, when ignited, the exposed CLT ceiling spread flame at the same rate as a fully unprotected CLT ceiling.

3.5 FIRE SIZE OF WOOD CRIBS

The amount of fuel load burning at one time is important to the understanding of how quickly a severe compartment fire may grow and spread. Therefore, the amount of the fuel bed burning simultaneously was compared between all the tests.

As discussed earlier the same wood crib configuration was used in the x-ONE, x-TWO.1 and CodeRed experiments. All experiments had the same number and arrangement of wood sticks. A wood fibreboard throughout the fuel load was also included in x-ONE and but only in first meter for x-TWO.1 and CodeRed.

Figure 8 plots the length of the wood cribs on fire simultaneously as a comparison across all the compared experiments. Comparing the fire length on the fuel bed allows to establish the extent of flaming within the compartment at any given time and be able therefore to compare the relative impact of the timber ceiling in affecting the extent of flaming of the cribs. The crib fire size results are presented for the duration of each test after CLT ignition occurred (CodeRed) or flames touched the ceiling (x-ONE & x-TWO.1) for a more representative comparison over time.

Based on the results it can be seen that the CodeRed #01 and #02 experiments resulted in a larger extent of the cribs burning simultaneously compared to x-TWO.1, even though the fuel load configuration was identical. The fully exposed timber ceilings of CodeRed #01 and #02 also resulted in a larger extent of the wood cribs flaming

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simultaneously compared to the presence of the fibreboard in the x-ONE experiment. Comparing CodeRed #04 with x_ONE and x-TWO.1, a similar peak size of flaming was reached between the three experiments but in the case of CodeRed #04 that was reached more quickly than the non-combustible experiments.

Therefore, the CodeRed experiments support a conclusion that exposed CLT ceilings are likely to lead to more severe fire conditions earlier in a fire.

The CLT ceilings also had an influence on external flaming as discussed further by [13].

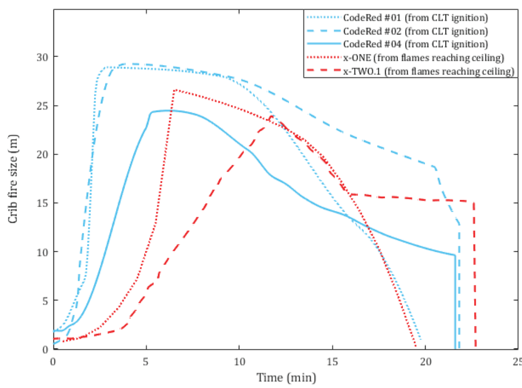

Figure 8: *Fire size of the wood cribs – comparison of all the experiments.*

4 DISCUSSION

This section discusses the impact of introducing the CLT ceiling on flame spread rates, fire duration and Design fires.

4.1 IMPACT ON FLAME SPREAD RATES

In all CodeRed experiments the leading and trailing edges were observed to initially spread across the compartment, characteristic of travelling fires. However, once the timber ceiling was ignited, the flames spread at a rate much faster compared to the equivalent non-combustible compartments x-ONE & x-TWO.1.

Flame spread rates for the experiments across the wood cribs in the non-combustible compartments, and across the wood cribs and the CLT in the combustible compartments are summarised in *Table 2*.

Table 2. Flame spread rates in [mm/s] for the x-ONE and x-TWO.1 and CodeRed experiments. CodeRed #03 is not relevant to this study.

Parameter	*x-ONE*	*x-TWO.1*	*CodeRed #01*	*CodeRed #02*	*CodeRed #04*
Crib spread rate before flames touch the ceiling (x-ONE and x-TWO) or before CLT ignites (CodeRed)	3.3	1.9	11	2.1	3.3
Crib spread rate after flames touch ceiling / after CLT ignites	67	34	161	147	68 (first ignition) 107.5 (sustained ignition)
CLT spread rate	N/A	N/A	200	153	95 (first ignition) 222.1 (sustained ignition)

For the first two CodeRed experiments the presence of the timber ceiling resulted in a much more rapid flame spread in the wood cribs compared to the equivalent non-combustible structure, and consequently also a relatively shorter fire duration.

This increase in flame spread rate of the wood crib with the presence of the timber ceiling is most likely due to radiative heat transfer from the flaming of the CLT preheating the crib, resulting in a faster fire growth than in previous experiments with the same configuration in a non-combustible enclosure.

As expected, the overall fire dynamics experienced in *CodeRed #04*, fall between the characteristics observed in *CodeRed #01* and the reference non-combustible experiments, *x-TWO.1* that had identical fuel load arrangement. x-ONE that has a different fuel load arrangement with the addition of fibreboard led to similar spread rate with *CodeRed #04* when taking the time for first ignition (but slower when taking the taking the time from second ignition). Despite the initial delay for the protected CLT ceiling to ignite, once the CLT had ignited, flames spread rapidly over the timber ceiling albeit not at the same rate as in the cases with a fully exposed ceiling. The slower spread rate across the CLT ceiling in *CodeRed #04* is substantially influenced by 1) the CLT directly above the wood crib being protected with the encapsulation; and 2) some energy was absorbed in driving out the moisture content of the wood crib and board protection covering half of the CLT.

The observed CLT flaming spread rates in the CodeRed experiments are rapid. It should be considered however that the

4.2 IMPACT ON FIRE DURATION

The impact of the timber ceiling on flame spread and overall fire duration is an important consideration as it informs the fire severity that the structure is expected to withstand.

The experimental results suggest that the presence of substantial CLT linings do not substantially reduce the wood crib flaming period due to the more rapid flame spread across the ceiling. This is unlike experience from small compartments where increased fuel load would be expected to result in an increased flaming duration.

Table 3 presents the comparative results on flaming duration. The fire in *CodeRed #01* was growing more rapidly during its initial stage before flames touched the ceiling (11 mm/s) than x-ONE and X-TWO (3.3 mm/s and 1.9 mm/s respectively). In addition, in *CodeRed #04* there was a delay in sustained CLT ignition. Therefore, time differences in the overall wood crib flaming duration are not solely due to the presence of the timber ceiling. Instead considering the duration after flames have ignited the combustible ceiling or when the flames touched the non-combustible ceiling allows for more direct comparisons of the relevant metrics.

Table 3. Fire durations for each experiment

Parameter	*x-ONE*	*x-TWO.1*	*CodeRed #01*	*CodeRed #02*	*CodeRed #04*
Total fire duration from ignition of the wood cribs	25 min	32 min	22.5 min	27 min	46 min
Fire duration after flames touching the ceiling (x-ONE & x-TWO.1) or CLT ignition (CodeRed)	19 min 30 s	23 min	19 min 43 s	22 min 49 s	22 min 07 s (first ignition) 19 min 30 s (sustained ignition)

4.3 IMPACT ON DESIGN FIRES

The CodeRed experiments showed that an exposed timber ceiling leads to a rapid spread of the fire that exhibits both – rapid - travelling behaviour and simultaneous burning across the entire a compartment. It was shown that the increase of fuel load (and therefore heat release rate) in the compartment through the addition of the timber ceiling did not result in a subsequent increase in overall fire duration.

The flame spread across the cribs was 4.3 to 4.7 times faster in the compartment with a fully exposed timber ceiling compared to the equivalent non-combustible experiment (x-TWO.1), measured from the point of CLT ignition / flame impingement on the ceiling. With 50% encapsulation the flame spread rate across the wood cribs was 2 times faster when taking time from first ignition and 3.2 times faster when taking time from sustained ignition.

While travelling fire characteristics were observed in all experiments, the rapid flame spread rates suggest that uniform flashover conditions may be a good approximate for large compartments with exposed timber ceilings for the characterisation of the internal thermal environment.

Applying such uniform flashover conditions to large compartments for some types of structures that are sensitive to non-uniform compartment temperatures such as steel frames may yield unconservative structural responses [14]. This means it will be necessary to further develop travelling fire analysis models [1] that are suitable to represent fire dynamics in large compartment with exposed timber, and provide adequate design fires for structures under uneven heating conditions.

Barber et al. [15] indicate the importance of assessing thermal penetration in loadbearing timber elements as peak temperatures in mass timber elements occur long after flaming combustion in the compartment has ceased, often several hours later. Columns are particularly vulnerable.

Further analysis is necessary for timber framed structures to investigate the impact of non-uniform burning seen across large compartments with exposed timber surfaces.

It is noted that taking an approach of uniform temperatures across the entire compartment may be overly conservative where heat transfer is evaluated to the floor (i.e. fire exposure from above); this is discussed in more detail in [19]

The presence of the CLT on the ceiling produced more rapid flame spread rates compared to those assumed in the travelling fire methodologies in the literature [16] that assume non-unform burning which have been developed for non-combustible ceilings.

The existing methods do not incorporate the contribution of additional combustible surfaces to the overall energy release inside the compartment, or the role of combustible surfaces in increasing spread rates.

Further research and development is required to incorporate these fire dynamics phenomena into travelling fire design fire methods to make them appropriate for application in large CLT compartments.

Nevertheless, the travelling behaviour occurs so rapidly that further review is also needed to determine under

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which scenarios design fires based on simpler flashover assumptions would yield sufficiently conservative results from a fire safety engineering perspective for mass timber structures.

The timber ceiling also affects external flaming outside the compartment that is not captured by current design methodologies [13]. Further research is needed to understand heat release rates in compartments with an exposed timber ceiling and how this additional combustion is influencing fire severities outside and inside the compartment (% of combustion inside vs outside).

4.4 IMPACT ON MEANS OF ESCAPE AND FIRE-FIGHTING ACTIVITIES

The CodeRed research has shown that once a timber ceiling is ignited flame spread can be rapid.

The recorded flame spread rates over the untreated CLT ceiling are high, with up to 200 mm/s (0.2m/s) where there is a fully exposed ceiling, from the point that the ceiling becomes involved in a fire.

It is acknowledged that in practice, untreated timber surface, which would commonly be assigned a reaction to fire classification of Euroclass D, would not be permitted in large open spaces; common fire safety standards used in e.g. the UK, BS9999 [17], and Approved Document B [18], would expect a Class B reaction to fire finish, unless the rooms are very small.

It is important however to consider how close these observed flame spread rates are to evacuation speeds adopted in fire engineering practice (0.5-1.2 m/s), particularly when considering that people may initially move towards the fire to investigate the cause, and attempt to extinguish it.

The ability of surface treatments to improve the reaction to fire performance of timber to slow fire growth and flame spread in more severe fire conditions would benefit from further study.

The observed increase in flame spread rates and subsequent earlier and larger maximum heat release rate reduced the time available for fire-fighting activities in mass-timber buildings to commence while a fire is still growing. Fire fighting tactics also need to take account of risk of ongoing smouldering e.g. in junctions that can continue for multiple days under the right conditions.

Designers need to take these into consideration when determining fire safety strategies for large compartments with exposed timber ceilings.

5 CONCLUSIONS

The CodeRed series of experiments conducted in 2021 had as one of its fundamental objectives to study the impact of timber on fire dynamics in large open-plan compartments.

This paper specifically focuses on flame spread rates within compartments, comparing CodeRed to previous non-combustible compartment experiments that were used as prototype for CodeRed.

Rapid flame spread was observed across the CLT ceiling once the ceiling ignited (~153 to 220 mm/s). Compared to the reference non-combustible enclosure experiments the flame spread across the wood cribs was also significantly faster (3.1 to 4.7 times faster considering the time from sustained ignition of the CLT ceiling).

In all CodeRed experiments, leading and trailing edges observed, characteristic of a travelling fire, transitioning to full flashover fire where the fire was burning across the entire wood crib and CLT ceiling simultaneously.

The rapid flame spread rates suggest that uniform flashover conditions may be a good approximate for larger compartments with exposed timber ceilings.

However for structural systems sensitive to non-uniform compartment temperatures such as steel frames, and very large compartments, such simplified design fires may yield unconservative structural responses.
There may be a range of different design fires that a combustible structure needs to be evaluated against.

Travelling fire analysis models that are suitable to represent fire dynamics in large compartment with exposed timber are therefore necessary to provide adequate design fires for structures sensitive to uneven heating conditions, and for large compartments where uniform flashover conditions may be unconservative.

6 Further work

The observed CLT flaming spread rates in the CodeRed experiments are rapid. It should be considered however that the experimental configuration may have played a role on the observed flame spread rates in the experiments. In particular the availability and position of ventilation compared to the location of ignition of the fire in both the CoreRed and x-ONE and x-TWO.1 experiments may have influenced the early fire growth period and therefore influenced the outcomes.

Future tests should establish if the observed CLT flame spread rates observed in CodeRed would also apply to other compartment and ventilation arrangements.

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REFERENCES

1. Stern-Gottfried, J. and Rein, G., (2012), "Travelling fires for structural design–Part I: Literature review," *Fire Safety Journal*, Vol. 54, pp. 74–85.
2. Rackauskaite, E.Kotsovinos, P.and Barber, D., (2021), "Letter to the Editor: Design Fires for Open-Plan Buildings with Exposed Mass-Timber Ceiling," *Fire Technology*, Vol. 57, No. 2, pp. 487–495.
3. Arup, "Large compartment fire experiments: expanding knowledge of building safely with timber," 2022. [Online]. Available: https://www.arup.com/perspectives/large-compartment-fire-experiments-expanding-knowledge-of-building-safely-with-timber.
4. Kotsovinos, P.Rackauskaite, E.Christensen, E.Glew, A.O'Loughlin, E.Mitchell, H.Amin, R.Robert, F.Heidari, M.Barber, D.Rein, G.and Schulz, J., (2022), "Fire dynamics inside an open-plan compartment with an exposed CLT ceiling and glulam columns: CodeRed #01," *Fire and Materials*, Vol. 2022, pp. 1–27.
5. Kotsovinos, P.Christensen, E.G.Rackauskaite, E.Glew, A.Loughlin, E.O.Mitchell, H.Amin, R.Robert, F.Schulz, J.Barber, D.and Rein, G., (2022), "Impact of ventilation on the fire dynamics of an open-plan compartment with exposed timber ceiling and columns : CodeRed #02," No. March, pp. 1–28.
6. Kotsovinos, P.Christensen, E.G.Glew, A.O'Loughlin, E.Mitchell, H.Amin, R.Robert, F.Heidari, M.Barber, D.Rein, G.and Schulz, J., (2022), "Impact of partial encapsulation on the fire dynamics of an open-plan compartment with exposed CLT ceiling and glulam columns: CodeRed #04," *Fire and Materials*.
7. Rackauskaite, E.Bonner, M.Restuccia, F.Fernandez Anez, N.Christensen, E.G.Roenner, N.Wegrzynski, W.Turkowski, P.Tofilo, P.Heidari, M.Kotsovinos, P.Vermesi, I.Richter, F.Hu, Y.Jeanneret, C.Wadhwani, R.and Rein, G., (2021), "Fire Experiment Inside a Very Large and Open-Plan Compartment: x-ONE," *Fire Technology*.
8. Heidari, M., "Travelling fires methodology and probabilistic design of structures," Imperial College London, 2021.
9. Kotsovinos, P., Christensen, E.G., Gale, J., Mitchell, H., Amin, R., Robert, F., Heidari, M., Barber, D., and Rein, G., "The Effectiveness of a Water Mist System in an Open-plan Compartment with an Exposed Timber Ceiling : CodeRed # 03," *FPE eXTRA*, Vol. 74, 2022.
10. Frangi, A.Schleifer, V.Fontana, M.and Hugi, E., (2010), "Experimental and Numerical Analysis of Gypsum Plasterboards in Fire," *Fire Technology*, Vol. 46, pp. 149–167.
11. Richter, F.Atreya, A.Kotsovinos, P.and Rein, G., (2019), "The effect of chemical composition on the charring of wood across scales," *Proceedings of the Combustion Institute*, Vol. 37, No. 3, pp. 4053–4061.
12. Tewarson, A. and Pion, R.F., (1976), "Flammability of plastics—I. Burning intensity," *Combustion and Flame*, Vol. 26, pp. 85–103.
13. Glew, A., Turnbull, R., Poulsen, F.M., Christensen, E.G., Kotsovinos, P., O'Loughlin, E., Barber, D., and Schulz, J., "A design approach to external fire spread from buildings with exposed mass timber," in *World Conference on Timber Engineering 2023, WCTE 2023*, 2023.
14. Rackauskaite, E.Kotsovinos, P.and Rein, G., (2017), "Structural response of a steel-frame building to horizontal and vertical travelling fires in multiple floors," *Fire Safety Journal*, Vol. 91, No. February, pp. 542–552.
15. Barber, D., Christensen, E.G., Kotsovinos, P., Heidari, M., Mitchell, H., and Schulz, J., "Accounting for post-peak compartment temperature thermal degradation of mass timber," in *World Conference on Timber Engineering 2023, WCTE 2023*, 2023.
16. Stern-Gottfried, J. and Rein, G., (2012), "Travelling fires for structural design-Part II: Design methodology," *Fire Safety Journal*, Vol. 54, pp. 96–112.
17. British Standard Institution, *BS 9999: Fire safety in the design , management and use of buildings – Code of practice*, 2nd editio. London: BSI, 2017.
18. Regulations, B., *Approved Document B: Fire Safety*, 2020 Editi. HM Government, 2010.
19. Christensen, E.G., Khoo, B., Kotsovinos, Barber, D., and Schulz, J., "Protection and thermal exposure of CLT ceiling and floor surfaces" in *World Conference on Timber Engineering 2023, WCTE 2023*, 2023.

https://doi.org/10.52202/069179-0234