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PROTECTION AND THERMAL EXPOSURE OF CLT CEILING AND FLOOR SURFACES

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ABSTRACT: Timber is increasingly used in buildings because of its favourable embodied carbon credentials compared to traditional materials such as steel and concrete. However, due to it combustible nature, encapsulation products are frequently used to prevent or limit the timbers contribution to a fire. These encapsulation products introduce additional weight, cost and carbon to project, which limit the benefit of timber construction. The performance of these products in natural fires and the relative fire severity experienced by products placed near the ceiling and the floor has received little attention. Here we present data on the performance of encapsulation applied to the timber ceiling and floor elements within the *CodeRed* experiments – a series of large-scale timber compartment experiments with varying ventilation and extent of exposed timber. Compartment temperatures were measured at the ceiling and near the floor, indicating a lower temperatures at floor level; the time temperature curve 'seen' by the floor encapsulation is dependent on whether or not there is residual glowing embers on the floor. Both the 25 mm calcium silicate encapsulation to the floor, when located below the wood crib and when adjacent to it, and the three layers of 12.5 mm gypsum fibreboard board applied to the ceiling were shown to be adequate in preventing the ignition of the underlying timber. However, smouldering was observed to sustain remote to encapsulation, but eventually spread beneath the encapsulation which facilitated continued smouldering. This highlights that smoulder can progress behind encapsulation. A 1D Finite Difference Model (FDM) was used to explore the temperature development of timber surfaces beneath simulated encapsulation details using the gas temperatures measured near the ceiling and floor. Converting the modelled peak temperatures to time equivalent times revealed an 23% average reduction in time equivalent fire severity near the floor level for natural fires with a severity equivalent to a 30 min standard fire. When considering greater fire severities, this reduction remained similar, indicating that applying the same fire protecting rating to the floor as to the ceiling is likely overly conservative. The study represents the first step in quantifying a more refined protection required at the floor and to the ceiling; with further research it may be possible to justify a reduction in the required fire protection performance of floor level encapsulation for long duration fires compared to that on the ceiling, taking into account the observed distribution of compartment gas temperatures in large compartments. Ultimately this offers an opportunity to reduce the embodied carbon, costs, and weight of the structural design.

KEYWORDS: encapsulation, timber, *CodeRed*

1 INTRODUCTION

The construction industry is quickly turning to timber as construction material as a solution to achieving the net-zero carbon agenda. However, as the influence of exposed timber on fire dynamics creates new hazards, is complex and subject to extensive research still, timbers surfaces are encapsulated to limit or eliminate the involvement of timber in a fire [1]. This in turn, reintroduces additional embodied carbon, cost, construction time to the project. BS EN 13501-2:2016 defines the performance of an encapsulation system to protect a substrate, with the designation of a K2 classification [2]. The standard requires the encapsulation system to limit the temperature increase at the surface of the substrate to below 250 °C on average or 270 °C in any location while preventing the pyrolysis of the protected material when exposed to a "standard fire". In addition, there can be no collapse of the covering during the test. However, this standard makes no distinction between the requirements of a floor or ceiling element. The temperature distribution within real fires is such that the thermal severity of a floor may be expected to be less than that of a ceiling in a timber compartment. Studies found that, in a ventilation controlled fire, gas temperature near the floor are on average 100 – 200 °C lower than near the ceiling [3–7], as shown in Figure 1. As such applying the same fire protection for encapsulation on both the ceiling and floor may result in excessive conservative encapsulation, inflating the mass, embodied carbon, and cost of a building. It is valuable to understand not only the performance of encapsulation system in real fire scenarios but also understanding the

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extent of protection required for the protection of CLT floor slabs.

This paper presents data from *CodeRed #01*, *#02* and *#04*, experiments from a series of large-scale timber compartment experiments which varied ventilation, and extent of exposed mass timber/encapsulation. We analyse the performance of the encapsulation of the CLT and floorboards to improve the understanding of such measures.

Additionally, this paper presents a first proposal in quantifying relative fire severity experience near the ceiling and floor. This is done in the following way:

- An idealised calcium silicate board protection over CLT is modelled to establish the timber surface temperatures, for both ceiling and floor arrangements, for the respective time- temperature profiles near the floor ceiling observed from the *CodeRed* experiments; this is done using a 1D Finite Difference Model (FDM).
- Using those peak temperatures at the surface of the encapsulated timber, the time equivalent 'fire protection' rating is derived that would deliver the same surface temperature in a standard fire test; this is done to convert the results into a commonly used fire safety performance metric.
- A ratio of those time equivalent values between the ceiling and floor is calculated to quantify the relative fire severity between the ceiling and the floor.
- A simplified design fire is created, informed by the *CodeRed* temperature measurements, to extend the analysis to fires of greater severity.

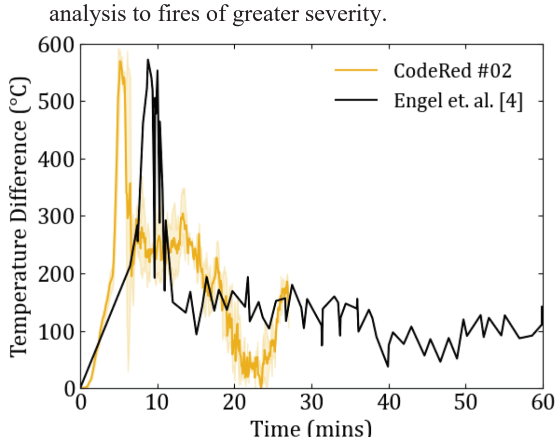

Figure 1: *Gas temperature difference measured near the ceiling and the floor, averaging at around 200 °C while the fire is ventilation controlled. At minute 18, the fire becomes more akin to fuel controlled in CodeRed #02.*

2 *CODERED* EXPERIMENTS

The *CodeRed* experiments were conducted in a purpose-built structure at CERIB's site in Epernon, France. The compartment measured 10.27 m wide, 34.27 m long and 3.1 m tall. The experimental set up is shown in Figure 2. A detailed description of the experimental set up is available in [6–8]. The compartment included a CLT ceiling and continuous wood crib (6 × 29 m) with a fuel load of around 380 MJ/m^2. The crib was ignited along its full width at one end, and the fire then allowed to naturally spread.

Thermocouples were distributed within the compartment at 100 mm, 700 mm, 2100 mm and in limited locations 2800 mm (T12, T14, T16) below the ceiling level to study the fire dynamics. The thermocouple measurements were corrected using the β-method [9] to account for radiative heat flux from the fire. In *CodeRed #02* and *#04*, eight, 18 mm plywood floorboards (P1-P8) where placed within the compartment as indicated in Figure 2, which were then protected with a single layer of 25 mm thick calcium silicate board encapsulation. These were instrumented with thermocouples on the surface of the board and at the interface between the plywood and the encapsulation.

In *CodeRed #04*, just under 50% of the CLT ceiling was encapsulated using a proprietary K_260 protection product comprising 3 layers of each 12.5 mm thick gypsum fibreboard.

Thermocouples were placed between each layer of boarding and at the interface with the CLT. Data from *CodeRed #02* and *#04* are used to study the performance of the encapsulation of the CLT and floorboard.

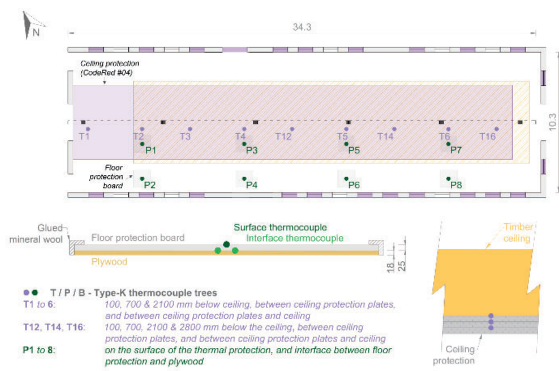

Figure 2: *Floor plan of the CodeRed experiments, sections of the encapsulation build ups, and instrumentation. Ceiling protection was only provided in CodeRed #04. Units in metres.*

The key differences between the *CodeRed* series are summarised in Table 1.

Table 1 *Summary of the differences in the key parameters between the CodeRed series*

Parameter	*CodeRed #01*	*CodeRed #02*	*CodeRed #04*
Ceiling	Fully exposed	Fully exposed	48% encapsulated
Ventilation	20.5%	10%	20.5%

3 NUMERICAL METHODS

A simple 1D heat transfer model was implemented using FDM which used two layers: an encapsulation layer and a timber layer. This model does not consider the contact resistance between the layers. Figure 3 shows a cross section of the floor encapsulation system as an example. The first layer represents encapsulation with a thickness is modified between analysis, while the second layer represents the 140 mm thick timber. The timber thickness was taken as 140 mm (the thickness of the CLT) instead

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of 18 mm (the thickness of the plywood floorboards) to avoid modelling additional layers, and to reduce error at the internal boundary.

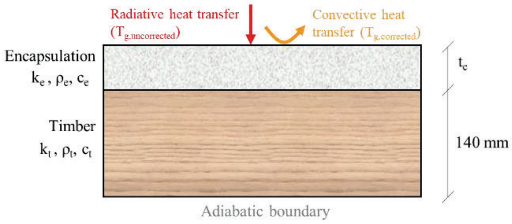

Figure 3 *Cross section of the model build up.*

The thermal model uses a simple finite difference scheme that calculates temperature at each internal nodes using the following equation:

$$T_n^{s+1} = Fo(T_{n-1}^s + T_{n+1}^s) + (1 - 2Fo)T_n^s \quad (1)$$

Where T is the temperature of a given node, n is the space step level, *s* is the time step level and *Fo* is the Fourier number.

For the temperature at the interface between the encapsulation and the timber, the calculation is given by:

$$T_n^{s+1} = Fo_1(T_{n-1}^s - T_n^s) - Fo_2(T_n^s - T_{n+1}^s) + T_n^s \quad (2)$$

Where Fo_1 and Fo_2 is the Fourier number of the encapsulation and CLT respectively. The distribution of grid nodes needs to be arranged accordingly such that Fourier number for both layers are similar. This is to reduce errors, especially at the internal boundaries for multilayer thermal modelling as noted by Waters et al [10].

The boundary condition for the exposed surface is given by:

$$T_0^{n+1} = \frac{2dt}{\rho_1 c_{p_1} dx_1}\left(h_c\left(T_g^s - T_0^s\right) + q_{rad}\right) + 2Fo_1(T_1^s - T_0^s) + T_0^s \quad (3)$$

Where *dt* is the time step, ρ_1, c_{p_1} and dx_1 is the density, heat capacity and node size of the encapsulation respectively, T_g is the gas temperature at the exposed side corrected with the *β*-method [9] , T_0 is the temperature at the exposed surface, h_c is the convective heat transfer coefficient set at 25 and 35 W m^{-2} K^{-1} , for furnace conditions and natural fires respectively in line with EC1, and q_{rad} is the radiative heat transfer.

The radiative heat transfer is estimated using *eq* 4, and uses the uncorrected thermocouple (T_u) measurement as this captures the influence of radiation so provides a more accurate measure of the radiative temperature.

$$q_{rad} = e\sigma\left({T_u^s}^4 - {T_0^s}^4\right) \quad (4)$$

Where e is the surface emissivity set at 0.8 as recommended by EC1 and σ is the Stefan-Boltzmann constant.

For the back boundary of the CLT is assumed to be adiabatic and the temperature at the boundary is formulated as:

$$T_n^{s+1} = 2Fo_2(T_{n-1}^s - T_n^s) + T_n^s \quad (5)$$

To ensure numerical stability, *Fo* and *Fo*(1+*Bi*) is limited to 0.5 by limiting time step, *dt* to 0.1 s.

3.1 MATERIAL PROPERTIES

The material properties are that are used for the simulations are described in Table 2. These properties are provided by the manufacturer or material handbook and are assumed to be constant with varying temperature. As the thermal property is expected to change with temperature, which is not accounted in this work, some modelling errors are expected to be introduced.

Table 2 *Material thermal properties obtained from the product literature.*

Materials	Thermal conductivity, κ (W m^{-1} K^{-1})	Density, ρ (kg m^{-3})	Specific heat capacity, c_p (J kg^{-1} K^{-1})
Plywood/CLT [11]	0.126	380	2300
Gypsum fibreboard [12]	0.32	1150	1100
Calcium silicate board [13]	0.20	900	960
Light weight concrete [14]	1.00	1600	840
Normal weight concrete [14]	1.60	2300	1000

4 RESULTS

4.1 CLT CEILING ENCAPSULATION

In the *CodeRed* experimental series the encapsulation was generally found to be effective in preventing the ignition of timber both at the ceiling and the floor. The temperature development measured between the layers of encapsulation is presented in Figure 4. The average peak temperature measured at the ceiling encapsulation (across all locations apart from T1) was 106°C, 104°C, and 94°C for thermocouples between layer three and two, two and one, and at the interface of the CLT respectively. The similarity of the peak temperatures at all depths below the exposed surface may be due the formation of gaps between the encapsulation panels preventing heat transfer through the encapsulation, reducing the temperature within the encapsulation system as well as the evaporation of moisture content. However, no rigorous investigation on why such observation was made as it is outside the scope of the *CodeRed* experiments.

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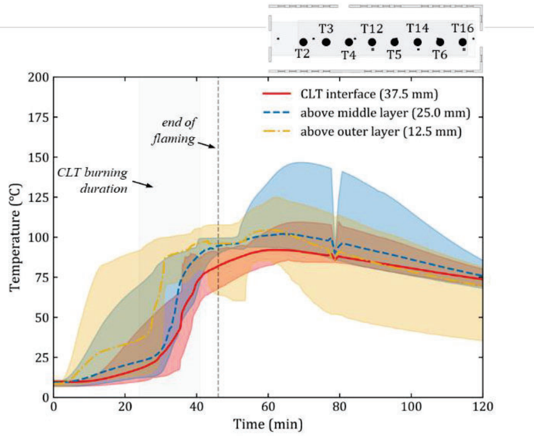

Figure 4: *Temperature development within between the layers of encapsulation. Solid line represents the mean temperature development, while the cloud should the range of measurements.*

The ceiling encapsulation was observed to remain in place until near the end of the fire at which point cracks started to form and portions of the outer layer of the encapsulation began to fall off. However as this occurred during the cooling period, after the cessation of flaming, it never exposed any of the underlying CLT. However, this highlights the benefits of a multilayer encapsulation system whereby the failure of a single layer does not result in the exposure of the underlying timber.

At the perimeter of the ceiling encapsulation some charring was observed beneath the encapsulation, but smouldering did not appear to sustain or spread. The damage was limited to within 40 mm of the end of the encapsulation.

Some smouldering occurred at the junction between one perimeter wall and the ceiling, over the course of several days without any firefighting intervention, which spread approximately 1.3 m beneath the encapsulation. The encapsulation provided a seemingly hospitable environment for the smouldering despite the test being completed in the winter, as it spread and consumed a larger extent than was seen in previous experiments (see Figure 5). This can, in part, be explained by the longer period of time to deconstruct CLT ceiling during without any firefighting intervention.

Hence, encapsulation can potentially hide smouldering; which means that it may be necessary for firefighters to remove encapsulation to identify any residual pockets of smouldering so they can be supressed.

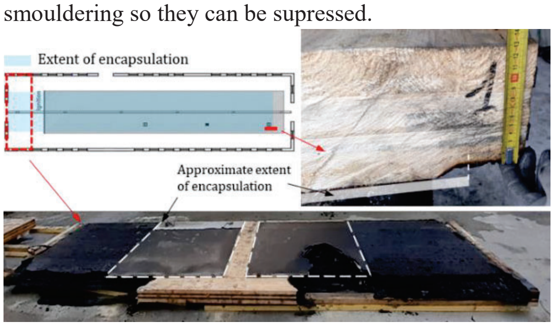

Figure 5: *Char and smouldering beneath encapsulation. figure in the top right shows a cut through the CLT slab, and the extend of charring. bottom image shows the underside of the first CLT panel in the compartment.*

4.2 FLOORBOARD ENCAPSULATION

Floorboards comprising a layer of 18 mm ply protected by 25 mm calcium silicate board were placed below and alongside the wood crib to represent the potential encapsulation of a CLT floor from a fire from above. The average peak temperatures measured at the surface of the encapsulation and the interface with the timber are presented in Table 3 for both *CodeRed #02* and *#04*. No floorboards were used in *CodeRed #01*.

Temperatures at the surface of the plywood below the protective board did not exceed 200°C, and there was no evidence of ignition of charring. Notably, this is greater than the temperature measured beneath the outer layer (12.5 mm) ceiling encapsulation, despite the locally lower measured temperatures. It is unclear why the performance of the ceiling encapsulation appeared to perform better than that on the floor. It may be due to the characteristics of the specific encapsulation product, moisture content within the encapsulation and inclusion of multiple layers which may introduce insulating air gaps.

Table 3: *Peak temperatures measured at the floor protection at the surface and the interface with the timber below.*

Experiment	Position	Peak temperature (°C)	Time to peak (min)
Temperature at surface of protective boards			
CodeRed #02	Below crib	497	28
	Next to crib	576	20
CodeRed #04	Below crib	330	37
	Next to crib	431	44
Temperature at surface of plywood (below protective board)			
CodeRed #02	Below crib	193	59
	Next to crib	187	47
CodeRed #04	Below crib	155	68
	Next to crib	147	60

The experiment showed that 25 mm calcium silicate board provided adequate protection for a fire with similar severity as the *CodeRed* experiments. However, with a more severe fire, it is expected that the same board thickness may not be sufficient.

In all cases the peak temperature occurs after the cessation of flaming, due to the effect of thermal lag, as the thermal wave continues to propagate through the encapsulation. The temperature development of the floorboard in *CodeRed #02* and *#04* is illustrated in Figure 6.

While the peak temperatures measured at the interface with the timber surface are similar for floorboards located below and along the crib, the time at which the peak occurs happens later where the boards are below the wood crib.

The peak temperatures measured at the surface of the encapsulation was, on average, 90°C hotter beside the crib compared to those under the crib. However, for the floorboards under the crib, the surface of the encapsulation remained around 300-500°C for longer,

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well after the end of flaming, while beside the crib the temperatures decreased towards the end of flaming. This difference is likely due to the burning wood crib initially shielding the floorboards beneath from some of the radiation within the compartment but, before the remnants of the glowing embers of what is left of the wood crib continued smouldering after the end of flaming, and conducting heat towards the floor.

The similarity in the average peak temperature of the timber floorboard is noted, despite the differences in the temperature profiles measured at the surface of the encapsulation; it may be coincidental. It highlights the importance of considering the impact of smouldering of fuel remnants on the floor in the consideration and design of floor build up and section thickness, as this will contribute to the continued conductive heating through the encapsulation to the timber below.

Further research is needed to understand the heat transfer into floor elements from above, and the significance of a smouldering fuel bed heating the floor slab after the end of flaming.

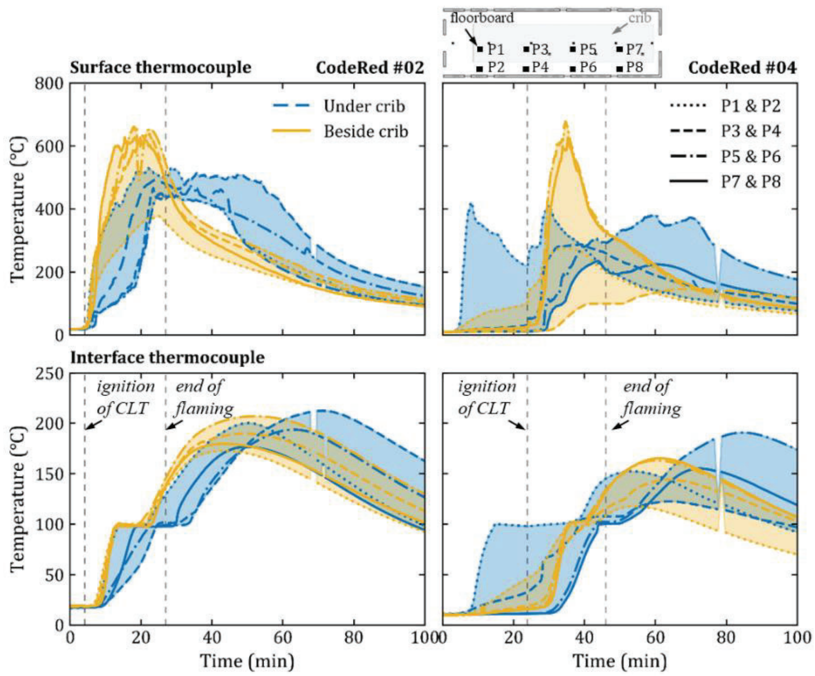

__Figure 6:__ Temperature development of eight plywood floorboard samples P1 to P8 each protected by a 25mm thick layer of calcium ciliate in CodeRed #04. Gas temperature given for reference.

4.3 NUMERICAL ANALYSIS

The different encapsulation systems used at the floor and the ceiling makes direct comparison of their thermal response difficult. Therefore, to study the relative fire severity experienced by an encapsulation product fixed the ceiling and floor based on the different temperature distribution observed in *CodeRed*, a 1D FDM model was used to represent the thermal response of a hypothetical single layer encapsulation system fixed to the floor and ceiling. The model output was then compared to the measured results found from the *CodeRed* experiments to assess its performance.

4.3.1 Modelling floor protection vs experimental observations

The floorboard arrangements in *CodeRed #02* and *#04* were modelled, using the temperatures measured by the T12 thermocouple tree as the input for the boundary conditions on the basis that gas temperature were measured both near the ceiling (Ceiling level (CL) -100 mm) and near the floor level (floor level (FL)+300 mm). These locations also represent the worst-case temperature profile as indicated by the deepest char depth measured in *CodeRed #02* and *#04*. The modelled results are then compared against the temperatures measurements at the interface at floorboards P3 and P5 as they are the closest floorboards to T12, located approximately 3.7 m away.

An example model prediction of the floorboard temperature development is presented in Figure 7. The temperature at the interface between the encapsulation and plywood is overestimated in both *CodeRed #02* and *CodeRed #04* by an average of 39.9 % and 19.4 %, respectively.

The interface temperature prediction for *CodeRed #02* shows a larger discrepancy than *CodeRed #04* despite similar average and peak temperatures being recorded in both experiments. The likely explanation for this discrepancy is moisture content in the encapsulation and/or timber. The moisture content the temperatures at the interface between the encapsulation and the plywood stagnates at 100 °C for approximately 10 and 5 min for *CodeRed #02* and *#04*, respectively, which is not captured by the model. Other potential errors include: not considering varying thermal properties with temperature, contact resistance, and modelling the ply layer as 140mm thick CLT rather than ply on a concrete screed.

Despite these errors, the model is suitable to provide a comparative analysis of the relative fire severity near the ceiling and floor level using the local temperature measurements and considering an idealised and simplified single layer encapsulation product.

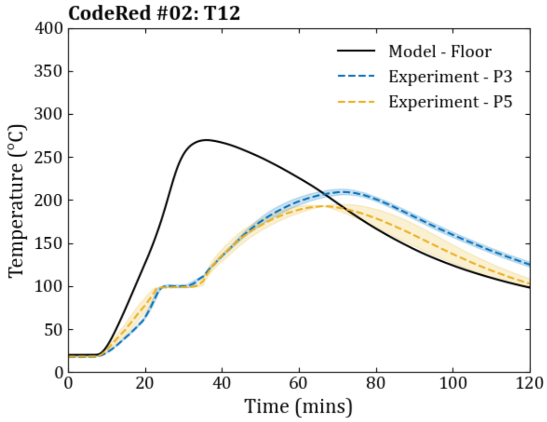

Figure 7: Comparison between the model of the interface temperature and the measured value in the experiment. Temperature over prediction is likely due to not modelling moisture content

5 INVESTIGATING RELATIVE FIRE SEVERITY AT THE CEILING VS AT FLOOR LEVEL

5.1 MODEL CONFIGURATIONS INVESTIGATED

The different encapsulation systems used at the floor and the ceiling makes direct comparison of their thermal response difficult.

Therefore, to study the relative fire severity experienced by an encapsulation product fixed to the ceiling and floor, the thermal response of the following hypothetical scenarios were further studied, comprising:

- a single layer of 25 mm thick encapsulation system fixed to 140 mm thick CLT, exposed to
- the temperature-time curves measured at T12 near the ceiling and floor in the *CodeRed #01*, *#02* and *#04* experiments (to simulate the exposure of encapsulation at the floor and ceiling), and
- The standard fire curve.

The analysis was undertaken using the FDM model and associated input parameters described in section 4.3 above, using calcium silicate boarding as encapsulation product.

The resulting modelled peak timber temperatures using the *CodeRed* time temperature curves were then converted using the time equivalence method. For the purposes of this study it is defined as the modelled exposure duration to a standard fire (in line with Eurocode 1 (EC1)) required to achieve the equivalent peak timber surface temperature found using the *CodeRed* fire curves.

5.2 RESULTS FROM *CODERED* FIRE CURVES

The model predicted timber surface temperatures beneath the ceiling encapsulation to be 75 °C (34 %), 66 °C (24%) and 52 °C (28%) greater compared to the timber surface temperatures below the floor encapsulation, using fire curves of *CodeRed #01*, *#02* and *#04*, respectively.

The simulation results suggest that in terms of fire exposure to the encapsulation system, *CodeRed #02* is experienced the most severe condition (i.e. least reduction out of all three), followed by *CodeRed #01* and *CodeRed #04*, as shown in Figure 8Figure 8.

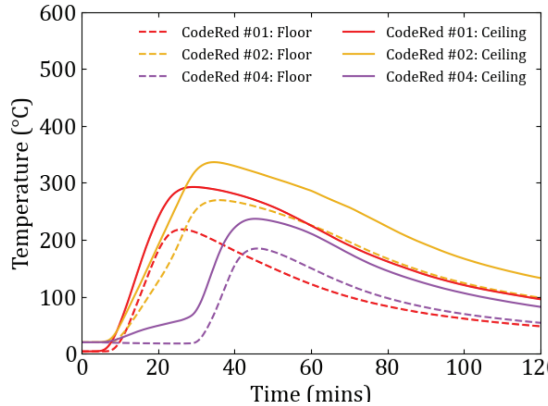

Figure 8: *Comparison of the modelled timber surface temperatures of the hypothetical encapsulation build ups position of the floor and ceiling when exposed to the CodeRed temperature curves. Model comprised of 25 mm calcium silicate encapsulation fixed to 140mm CLT .*

This is likely due to the increased burning duration in the ventilated-controlled fire of *CodeRed #02* which resulted in a more severe fire. As such the simulation results are consistent with previous observation where the average char depth is higher in *CodeRed #02* than *CodeRed #01* [6], suggesting a more severe fire in *CodeRed #02*. The slow temperature increase in *CodeRed #04* is due the gypsum fibreboard encapsulation preventing the CLT ignition until 23 min 53 s after the ignition of the crib compared to 2 min 47 s and 4 min 11 s in *CodeRed #01* and *#02* respectively.

5.3 TRANSLATION TO TIME EQUIVALENT VALUES

These results were then translated to a “time equivalent” value (TE), which is a standard metric used by fire engineers to compare fire severity. Here it is considered to be the time required for the timber surface temperature beneath the encapsulation to reach the peak temperature (modelled using the *CodeRed* fire curves) when exposed to a standard fire test. This is practice is often used for protected steel members.

Table 4 summarises the peak temperature at the timber surface following the *CodeRed* fire curves at each position, the time equivalent value, and the ratio between the time equivalence of the ceiling and floor, calculated as TE_{floor} / $TE_{ceiling}$.

Table 4: *Peak timber surface temperature and associated time equivalence calculated for the three CodeRed fire curves, at the floor and ceiling respectively, and the ratio found between them.*

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CodeRed fire curve	Location	Peak timber surface temperature - *CodeRed* (°C)	TE (min)	TE ratio (-)
#01	Floor	218	26	0.74
	Ceiling	293	35	
#02	Floor	270	30	0.79
	Ceiling	336	38	
#04	Floor	185	21	0.78
	Ceiling	237	27	

The predictions shows that the time equivalence is, 26%, 21% , 22% lower at the floor than at the ceiling when using fire curves derived from *CodeRed #01, CodeRed #02* and *CodeRed #04* respectively.

This indicates that a lesser fire protection rating may be sufficient for the floor encapsulation to achieve an equivalent performance to that on the ceiling.

These results are based on a short fire, achieving time equivalences severity of around 30 min. Further analysis was completed to examine how the time equivalence ratio might change in fires with greater durations.

5.4 EXTRAPOLATING TO INVESTIGATE LONGER DURATION FIRES

To understand how more severe fires could affect the time equivalence ratio, a simplified time temperature profile was derived from the *CodeRed* data in the absence of available data for long duration large compartment fires.

To derive the time-temperature profile for longer duration fires at the floor and ceiling, the maximum temperature during the peak flaming period (as defined in [6–8]) in the most severe fire (*CodeRed #02*) was used, namely 912 °C measured near the ceiling and 617 °C near the floor. These temperatures are rounded to 900 °C and 600°C respectively and are applied as fixed boundary conditions to the encapsulation build up.

The time equivalent ratios between encapsulation on the ceiling and floor exposed to fires of greater severity were calculated as follows:

Step 1 - Calculate the minimum thickness of encapsulation necessary to keep the timber surface temperature at or below 270°C (one of the acceptance criteria for the K_2 protection in BS EN 13501-2:2016) for 30, 60, 90 and 120 min of standard fire exposure.

Step 2 - Calculate the equivalent '*CodeRed* fire duration' using the *ceiling temperature* curve (i.e 900°C) to achieve the 270°C at the timber surface temperature (see Figure 9) using the minimum thicknesses calculated in step 1.

Step 3 - Calculate the timber surface temperature of the same encapsulation build up established in Step 1, for the '*CodeRed* fire duration' established in Step 2, using the *floor temperature* curve (i.e 600°C) (see Figure 9).

Step 4 - Calculate the time equivalence for the timber surface temperature established in Step 3 by modelling the same encapsulation thickness found in step 1 exposed to the standard fire.

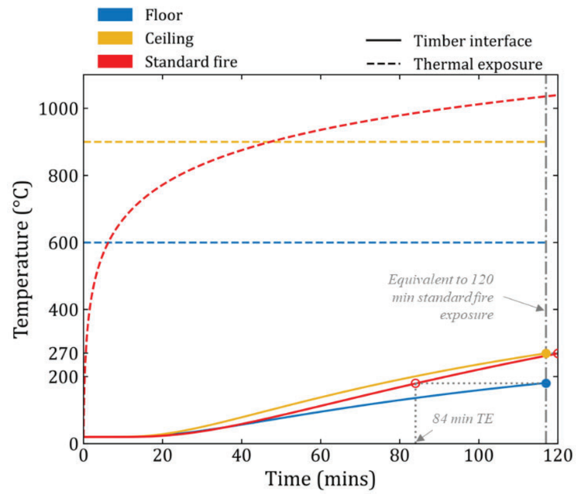

Figure 9: *Simplified time temperature development within modelled ceiling and floor encapsulation to 120 min equivalent exposure based on averaged temperature data from the CodeRed #02 fire curve, and resulting temperatures at the timber interface below the encapsulation.*

5.4.1 Example calculation

For instance, to find the ratio time equivalence ratio for a fire of 120 min fire severity the steps outline above are illustrated in Figure 9 and performed as follows:

Step 1: The minimum thickness of encapsulation necessary to keep the peak temperature of the timber surface protected after 120 min standard fire exposure to 270°C is 60.5 mm of calcium silicate board (noting again that this analysis is simplified with limitations that have been discussed earlier in this paper, and that actual thicknesses must be demonstrated by testing to the relevant standard as the likely failure mechanism will be fixings which cannot be modelled).

Step 2: The duration of exposure to the *ceiling temperature* curve to achieve the same timber surface temperature (270°C) as 120 min standard fire exposure is 117 min.

Step 3: Modelling the temperature development within the build-up using the near floor temperature condition of 600°C for 117 min, yields a predicted peak temperature of 180°C.

Step 4: This, in turn, equates to an 84 min time equivalence value. The time equivalence ratio is 0.7. As such the relative fire severity near the floor is 30% less than near the ceiling for a 120 min fire.

5.4.2 Time equivalent ratios for longer fire durations

The relative fire severity near the floor and ceiling and was similar for 90, 60 and 30 min equivalent exposure, as shown in Table 5. As expected, the ratio calculated for an equivalent 30 min exposure is similar to that calculated using the *CodeRed* temperature profiles which had time equivalent severity between 21-38 min. This may suggest the use of the 900 and 600°C temperature conditions is a reasonable approximation.

To explore this further, the critical thickness calculated for 90 min standard fire exposure is modelled with the floor level thermal condition (600°C) for 117 mins (equivalent to 120 min fire exposure using the near ceiling condition, 900°C). The peak interface temperature was predicted to be 228°C. Similarly, the predicted interface temperature for a 60 min and 30 min rated floor encapsulation in a 90 and 60 min equivalent standard fire exposure was 248 °C and 298 °C, respectively. This indicates that reducing the floor encapsulating fire rating by one step may be possible for 120 and 90 min fire exposure but not for 60 min fire exposure and as this results in a temperature rise greater than the 270°C required for K_2 protection. On this basis there may be an opportunity to reduce the prescribed protection required to the floor while maintaining the intended performance. However, due to simplification taken in these models, more research must be undertaken before any conclusive guidance can be given.

Table 5: *Summary of extended fire duration exposure of encapsulation on floor and ceiling. Results are modelled using ceiling (900℃) and floor (600℃) temperatures to model peak timber surface temperature, associated time equivalence values and time equivalence ratios.*

Standard fire duration (min) [encapsulation thickness (mm)]	Location	Peak timber surface temperature (°C)	TE (min)	TE ratio (-)
120 [60.5]	Ceiling	892	120	0.70
	Floor	589	84	
90 [51.0]	Ceiling	891	90	0.70
	Floor	587	63	
60 [39.5]	Ceiling	888	60	0.68
	Floor	583	41	
30 [25.0]	Ceiling	882	30	0.70
	Floor	574	21	

5.4.3 Limitations

It is important to emphasise that there are significant uncertainties regarding the temperature development and heat transfer for long duration fires.

Also, the results are modelled based on a primarily ventilation-controlled fire which in CodeRed were observed to have more variation across the vertical temperature profile. Vertical temperatures in a fuel-controlled fire have been found to be more uniform. However, it is expected that a fuel-controlled fire will typically have a shorter duration and is less likely to require significant fire ratings.

The preliminary results presented here indicate that the concept of setting different fire protection levels for the ceiling compared to the floor may be viable, subject to further study.

While the assumptions used here are deliberately simplified to test the viability of the idea of prescribing different fire protection performance for the ceiling compared to the floor, they provide a model which produces reasonable results when applied to both the natural fire as well as the standard fire as an initial study into the relative fire severity near the floor and ceiling.

The idea is promising, however the time equivalence ratios determined here should not be used to justify a reduction in encapsulation specification. However, it does suggest that such reduction may be possible provided further experimentation or more advanced models.

6 DISCUSSION

The current analysis suggests that due to the post flashover temperature gas differences near the ceiling compared to near the floor level it may be possible to reduce the fire protection requirements of the encapsulation provided to the top surface of timber floors to protect them from fire from above, while still achieving a similar performance to the ceiling encapsulation of the mass timber ceiling in case of fire from below. The analysis presented also indicate that this reduction may be more likely and reasonable where greater fire resistance / fire protection is required.

To examine the value such a reduction in fire resistance may bring, the estimated mass and embodied carbon of toppers is summarised in Table 6. The FDM was utilised to approximate the critical thicknesses of typical materials available as floor topping to prevent the surface of the timber igniting, as done previously. The critical thickness was calculated for 30, 60, 90 and 120 min of standard fire exposure (see Table 6). These are conservative thicknesses as the model does not account for such things as moisture, thermal contact resistance, or temperature dependent thermal properties. This was similarly modelled by [15], and has good agreement.

Table 6 emphasises the potential significant contribution of the encapsulation system to the total mass and embodied carbon of the structural system. For instance, the reduction from 120 min to 90 min protection to the topside of the floor slab, with normal weight concrete, would results in a 17.6% decrease in required material. This translates to a reduction of 2074 kg of embodied carbon and a 20.1 tonnes in total mass, for a 500 m^2 compartment. This reduction in mass may also return additional reductions in the section of the structural members.

In the interest of reducing carbon in the construction industry further research is needed to evaluate the relative thermal severity experienced near the floor level compared to near the ceiling in more detail.

Table 6: *Critical thickness of CLT floor toppers to limit the temperature of the timber below 270℃, in line with a K2 classification according to BS EN 13501-6:2016 and using a standard fire. Boundary conditions used are in line with Eurocode 1*

Topper material	Critical thickness (mm) [embodied carbon (kg CO_2e/m^2)]				Embodied Carbon (kg CO_2e/m^3) [Reference]
	120 min exposure	90 min exposure	60 min exposure	30 min exposure	
Calcium Silicate board	60.5 [7.1]	51.0 [6.0]	39.5 [4.6]	25.0 [2.9]	117 [16]

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Light weight concrete	105.5 [32.1]	88.0 [26.8]	67.0 [20.4]	40.5 [12.3]	304 [17]
Normal weight concrete	99.5 [23.6]	82.0 [19.4]	62.0 [14.7]	35.5 [8.4]	237 [16]

7 CONCLUSIONS

This paper investigated the performance of encapsulation in protecting the timber floor and ceiling in the *CodeRed* experimental series, a series of large-scale timber compartment fires. Both the 25 mm calcium silicate floorboard encapsulation and the three layers of 12.5 mm gypsum fibre boarding applied to the ceiling was shown to be adequate in preventing the ignition of the underlying timber. However, while smouldering beneath the encapsulation was not sustained immediately after the cessation of flames, smouldering was observed to sustain remote from the encapsulation and beneath the ceiling protection, where it burned an area of timber approximately 3 × 1.3 m in extent in one location. This suggests that while encapsulation may be effective in preventing the ignition of CLT, it is not 100% effective in preventing smouldering which can occur and spread behind the encapsulation.

Gas temperature measurements from the *CodeRed* experiments have showed that the temperatures near the floor are significantly lower (~300 °C) than near the ceiling in ventilation-controlled conditions. The significance of the difference in gas temperature near the ceiling and floor on the fire protection performance of encapsulation products in these positions was studied using a 1D FDM model. A single layer of 25mm calcium silicate encapsulation protecting a 140 mm CLT was modelled, using the measured gas phase temperatures near the ceiling and floor from the *CodeRed* experiments as the boundary condition of this model.

The predicted peak temperature at the surface of the timber was converted to time equivalent values. The ratio between the time equivalent value modelled for the encapsulation positioned on the floor and ceiling revealed, on average, a 23% reduction in the fire severity on to the encapsulation on the floor compared to the ceiling. This suggests that a reduced fire protection performance may be sufficient to protect a CLT floor, compared to the fire protection required for a CLT ceiling.

While the CodeRed experiments are estimated to have the approximate time equivalent fire severity of a 30 min standard fire, fires of greater severity and duration were also modelled to study the influence its influence on the time equivalence ratio.

This was done by developing simplified design fires for near ceiling and floor level exposure based on measurements taken from *CodeRed #02* and applying them to encapsulation thicknesses which were optimised to achieve the K_2 encapsulation standard (270°C at the surface of the encapsulated timber) after 120, 90, 60, and 30 min standard fire exposure. Comparing the standard fire time equivalent values of the encapsulation exposed to the ceiling and floor level design fires revealed a 30% reduction in fire severity to the encapsulation on the floor compared to the ceiling for severities up to 120 min.

Modelling an optimised encapsulation thickness exposed to a fire duration of 120 and 90 minutes standard equivalent fire for the ceiling respectively revealed that 90 and 60 min encapsulation performed adequately when positioned on the floor and exposed to the floor level design fires. However, applying a 30 min optimised encapsulation thickness to a 60 min standard fire equivalent floor level design fire yielded temperatures greater than the 270°C required for K_2 protection.

There may be an opportunity to develop a protection regime for mass timber compartments where the prescribed protection required to the floor is lower than that applied to the ceiling while maintaining the intended performance. This reduction offers an opportunity to reduce, the mass, embodied carbon and cost associated with encapsulation products. It should be noted that the results found here should not be directly applied to justify a reduction in prescribed fire resistance requirements. This study is the first step in quantifying the relative standard fire resistance requirements required at the floor and to the ceiling to help guide practitioners on designing and constructing safe and sustainable buildings and highlight the need for further research to enable better characterisation of fire severities at ground level of large compartments with a timber ceiling.

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