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ACCOUNTING FOR POST-PEAK COMPARTMENT TEMPERATURE THERMAL DEGRADATION OF MASS TIMBER

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ABSTRACT:

Mass timber load-bearing members need to be assessed for structural adequacy in fire. For high-rise buildings their strength has to be determined once the fire has completely decayed and the timber member is no longer impacted by the heat of the fire. For a decaying fire, the thermal penetration into a timber member continues well after the peak compartment temperature, resulting in timber strength degradation, which is not typically assessed and accounted for. From a review of experimental data sets for exposed mass timber members and using the glulam column data from the CodeRed large scale compartment experiments, an assessment of the issues for thermal penetration and heat diffusion has been carried out. Initial studies have shown that peak temperatures in a timber column will occur well after the end of flaming and that thermal loss from the member in the decay phase of the fire is slowed by the char layer built up. Assessment of structural adequacy of columns has shown that the reduced cross-section needs to account for the compartment post-peak temperature thermal penetration, or the engineering design may be non-conservative.

KEYWORDS: Mass timber, structural fire engineering, heat transfer, fire resistance, columns

1 INTRODUCTION

Buildings constructed with mass timber continue to increase in popularity globally. Low and medium rise buildings with exposed mass timber can generally be designed to meet fire safety goals of local regulations, codes or standards. Where mass timber is exposed within a high-rise building, the structure needs to be able to withstand a range of design fires, that includes both the standard fire and natural (physically based) fires. The structural adequacy of mass timber elements that resist loads in a fire is based on determining an effective cross-section, after exposure to a design fire. Where large areas of mass timber are exposed, design fires are influenced by that exposed timber and changing ventilation, a highly complex assessment. The effective cross-section is determined from a reduced initial cross-section, based on a char layer and the reduced strength of the wood ahead of the char, due to thermal impact. Simple design rules are based on the effective cross section supporting the applied loads for the period of fire exposure, such as EN 1363-1 [1] or ASTM E119 [2].

For a timber member exposed to a natural fire, the heat flux received varies with time and as the external heat flux reduces from a peak, the resultant thermal penetration (thermal wave) will continue to cause timber degradation after the compartment peak temperature has been reached. The resultant strength reduction in-depth after the peak exposure temperature has had limited research, is not normally assessed by engineers and is highly relevant for high-rise mass timber structures exposed to longer duration and decaying fires, and in particular, vertical load-bearing elements such as columns.

This paper presents the initial work carried out in literature reviews, background theory and summary of results from the CodeRed series of large-scale experiments. Work is on-going and further updates are to be published later in 2023 that includes finite element modelling and developing an engineering method to predict the impact of thermal degradation on timber strength for the decay phase of natural fires.

2 BACKGROUND

Timber exposed to a heat flux has three distinct zones, as was first described by Schaffer [3], being a charred layer where the temperature is in excess of 300°C, a transitional zone (pyrolysis zone) between 300°C and ambient temperature, typically called the thermal penetration depth, and ambient temperature timber (assumed to be 20°C). The position of the char front is set by the 300°C isotherm and under standard fire exposure (such as to EN 1363-1 or ATM E119), is predicted using a nominal char rate (β_o) of 0.65mm/min. The structural adequacy (capacity) of an exposed timber member reduces when exposed to fire based on the time of exposure, with the constant char rate (β) and a fixed zone of timber behind the char with no strength (zero strength layer, ZSL), to determine where the cross-section has full strength (effective cross-section). This is based historical fire

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testing to the standard fire. The fixed char rate and ZSL are only valid for standard fire exposure.

2.1 Relevance of Timber Strength Proportional to Temperature

The strength of timber reduces at relatively low temperatures. The mechanical properties of timber are reversible if temperatures are lower than 100ºC. For timber of temperatures higher than 100ºC, the properties are permanently degraded [4]. Research indicates that wood between 100ºC and 200ºC is considered to be in transition, with thermal breakdown occurring at temperatures past 200ºC. Once fully charred at 300ºC, timber is considered to have lost all strength. The transitional zone between the fully charred and ambient temperature timber therefore has three parts - the timber at a temperature between ambient and 100ºC which has a reversible strength reduction; temperatures of 100ºC and 200ºC where temperature effects are not reversible, though temperatures are not elevated enough to start pyrolysis; and the timber between 200ºC and 300ºC, where pyrolysis occurs and the mechanical properties degrade to zero [4, 5, 6].

From an engineering point of view, the question to be addressed in the design of a timber member is at what point of the thermal penetration of timber between 100ºC and 300ºC does temperature matter? Eurocode 5 (EN 1995-1-2) [7] provides data for the reduction in mechanical properties for timber proportional to temperature. This data is only applicable for standard fire exposure. Schmid et al [8] shows this data for strength and stiffness, with f_c representing compression, f_t for tension and f_v for shear (see Figure 1).

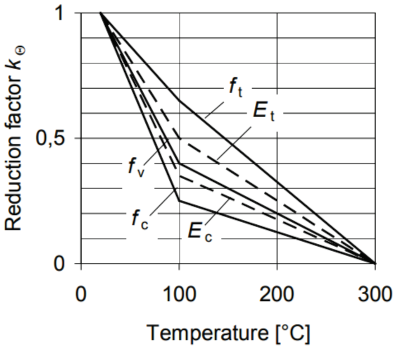

Figure 1: *Reduction factors for strength and stiffness properties from adapted from Eurocode 5, for standard fire exposure [8]*

Of most relevance is how sensitive compressive strength is to temperature. Timber at 140ºC has lost 80% of its compressive strength. At the same temperature timber has lost only 40% of its tensile strength. For columns that are under load and have timber that has reached 140ºC, whether the impact of thermal strength degradation is reversible or not, losing 80% of compressive strength is very significant. The 140ºC isotherm may not need to penetrate too far into a column before the member would lose structural adequacy, typically through buckling. Once structural adequacy has been lost, the reversibility of the timber strength loss is moot.

2.2 Relevance of Zero Strength Layer and Thermal Penetration Depth

The ZSL is an engineering approximation for the thermal penetration depth and is used to account for the area of reduced strength behind the char layer, given the temperature range is between 300ºC (charred wood) and ambient, for standard fire exposure. The thermal penetration depth has been researched for over 40 years with data from fire testing on solid timber and glulam being analysed [9]. Janssens and White [10] summarised test data and provided a method to determine the temperature at any point and showed that temperatures reached ambient at 40mm behind the char layer, for various softwood timber species. Frangi and Fontana [11] estimated 25mm to 50mm (see Figure 2).

These temperature correlations were used to determine the ZSL as 7mm behind the char zone, as an approximation for engineering design, to account for thermal penetration depth. The use of 7mm has been reviewed for many years as not reflecting known mechanical properties of timber and is revised in the current Eurocode 5 update [12], with higher values for the ZSL, depending on the forces being resisted in the timber for compression, tension or shear, reflecting actual timber mechanical properties.

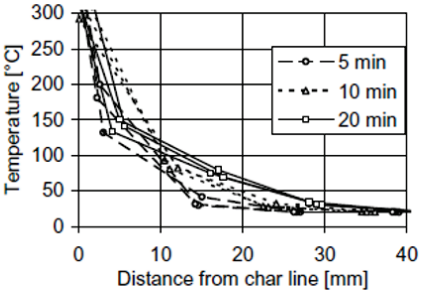

Figure 2: *Temperature profiles in a timber beam, behind the char, for 60min standard fire exposure [11]*

The experimental results above for thermal penetration depth are only accurate for standard fire exposure and not applicable for a natural fire, or the decay phase of a fire. To determine the thermal penetration depth for a natural fire, the temperature through the timber cross-section needs to be assessed, which requires the heat transfer into the timber to be analysed. This can be completed by experimental work or finite element modelling.

2.3 Determination of Thermal Penetration Depth for Natural Fire Exposure

There have been over 40 different compartment experiments with exposed mass timber and a natural fire. Temperature growth and decay curves are shown in Figure 3 from a Canadian experimental series [13], showing the relatively slow decay phase due to the extent of exposed mass timber, with limited ventilation.

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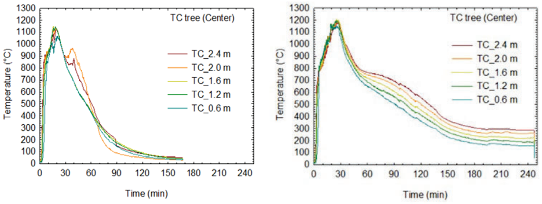

Figure 3: *Temperature profiles from an exposed mass timber compartment fire, with no timber exposed (left) and CLT exposed on one wall (Test 2) (right). The difference in temperatures at 120 mins can be seen. The change in rate of cooling near 700ºC can also been seen. The CLT had proven glue line integrity in fire [13]*

A natural fire will decay (ignoring fires that do not decay due to CLT glue line failure or encapsulation failure) and the fire heat release will trend to zero and room temperatures trend to ambient. The lack of fire and thermal exposure will result in the charring of any exposed mass timber to stop. While the charring may stop, the thermal wave from the compartment fire and the glowing and smouldering residual fuel on the floor, will continue to penetrate the mass timber element. A review of experimental data shows that the thermal penetration continues to occur well after the peak compartment temperature has been reached and through the full decay phase of the fire. Determining where the thermal penetration is between 300ºC and 100ºC behind the char layer in a timber member, during the fire decay phase, becomes essential to determine structural adequacy.

3 REVIEW OF RELEVANT EXPERIMENTAL WORK

To determine the extent of experimental data that shows how thermal waves penetrate timber members in the decay phase of fires, over 60 experimental works were reviewed. The following is brief summary of the most relevant work.

The experimental series "Fire Testing of Rooms with Exposed Wood Surfaces in Encapsulated Mass Timber Construction" [13] was based on natural fire tests with exposed CLT, with in-depth thermocouples in the CLT, recording temperatures during the decay period through to four hours after ignition. Using Test 2 as an example (see Figure 4), the peak compartment temperature occurred at 28 to 31 mins after ignition and did not drop below 200ºC. The peak temperatures in the CLT at depths of 35mm and 52.5mm are at initially near 120mins after ignition, then continue to rise through to the test being extinguished at four hours. Char depths of the CLT wall measured after the fire was extinguished ranged from 50mm to 95mm, with high values located near the floor. Ignoring the values at the base of the panel where charring was deeper due to the burning of the residual fuel on the floor, the average char depth was 62mm.

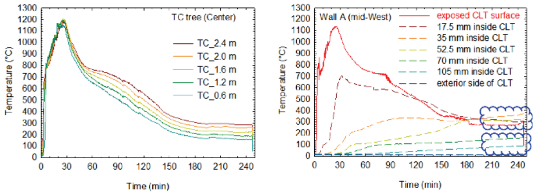

Figure 4: *Temperature profiles from Test 2 with an exposed mass timber wall (left). Temperature profiles within the CLT wall with increasing temperatures in-depth clouded [13]*

When compared with the temperatures recorded in-depth of the CLT wall, at 70mm from the exposed surface the temperature reaches 140ºC at approximately 210 mins after ignition. At 105mm depth from the exposed surface the temperature is just over 100ºC at 240 mins after ignition and was still increasing. These thermocouple readings indicate that thermal penetration occurred through to 70mm and up to 105mm deep into the CLT, compared to the char depth recorded that was between 50mm and 85mm, with an average of 62mm, with thermal penetration still increasing at 240 mins when the experiment was stopped. The char depth would indicate structural adequacy could be assessed using a reduced cross section in the order of 62mm, whereas the in-depth thermocouples would indicate that thermal degradation impacting timber strength occurs past 70mm and likely 105mm into the CLT.

In the "Compartment Fire Testing of a Two-Story Mass Timber Building" by the US Forest Service [14], natural fire tests with exposed CLT were completed, with temperatures recorded at depth within the CLT. The recorded post-experiment char depth in the panels was measured at approx. 30 to 35mm. For the experiment with CLT walls exposed, the delay in peak temperatures in-depth in the CLT are significant when compared to the time of the temperature peak for the natural fire. Figure 5 shows the peak temperatures in the living room and bedroom were at approx. 15 to 25 mins after ignition.

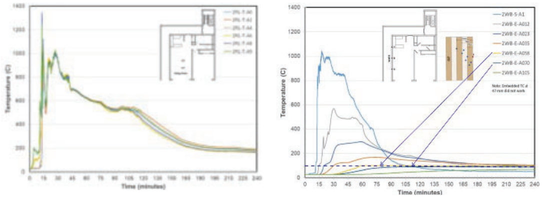

Figure 5: *Temperatures from the USFS Test 3 compartment fire with CLT walls part exposed. Living room temperature profile (left). Temperature profiles within the living room CLT wall, with 100ºC line annotated (blue line) (right) [14]*

Within the living room the temperature at 35mm from the exposed surface is between 140ºC and 160ºC at 75 mins after ignition; and at 58mm depth between 100ºC and 120ºC between 60 mins and approx. 180 mins. Within the bedroom the temperature at 47mm from the exposed surface is between 120ºC and 140ºC at 105 mins after ignition; and at 58mm depth between 100ºC and 120ºC between 105 mins and approx. 180 mins. Hence, the in-depth thermocouples show that thermal penetration in the timber occurs through to a depth of 47mm and up to

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58mm in the fire decay phase but measured char depths only record about 35mm. The additional depth of thermally degraded timber (approx. 12 to 23mm) that would have reduced strength, is not accounted for.

Harada's tests on a 100mm thick glulam timber wall [15] were exposed to a 60 min ISO834 fire and allowed to cool within the furnace, while in-depth thermocouple data was recorded. The glulam wall was 800mm by 800mm of exposed area, with thermocouples located at 20mm, 40mm, 60mm, and 80mm from the exposed surface. The exposed surface temperatures decay steadily but slowly due to the furnace enclosure and at 240 mins range from 120°C to 350°C (see Figure 6).

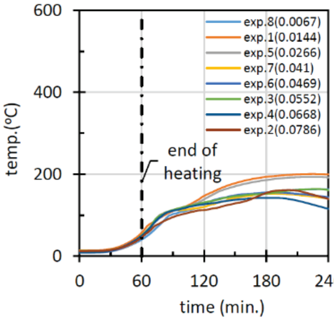

Figure 6: *In-depth temperatures measured at 60mm from the exposed surface [15]*

Based on the 60mm in-depth thermocouples, thermal degradation occurs through to 4 hrs of exposure, with thermocouples measuring between 120°C to 200°C. The data indicates the timber strength would be permanently impacted past 70mm depth. Charring post-test was recorded at approx. 52mm, showing the thermal degradation in-depth was deeper than the post-test char measurements.

Zeng et al [16] completed experiments on 3 and 5 ply CLT floors, exposing them to both standard and a simulated natural fire. In-depth CLT temperatures were recorded through the decay period for some of the experiments. The researchers recorded char depths of 37mm to 41mm after the test. Test (F5-20-N) shows thermocouples TC7 at a depth of 49mm and TC8 at a depth of 56mm from the exposed face recorded temperatures greater than 250°C and 140°C respectively through the fire decay period, and the temperatures were still increasing at the end of the test (see Figure 7). Thus, the timber at a depth of at least 56mm was thermally degraded, but char depths recorded were only up to 41mm, noting temperatures were still increasing when the experiment was stopped.

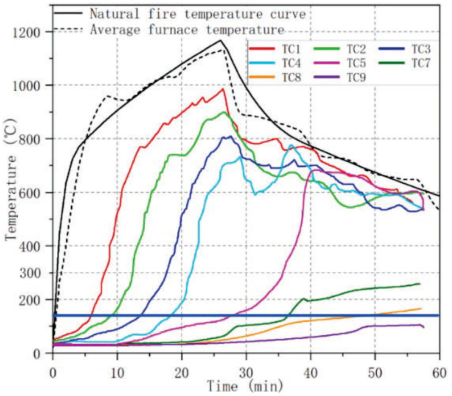

Figure 7: *Temperature profiles in a 5 ply CLT floor exposed to a natural fire (F5-20-N). Blue line indicating 140°C [16]*

3.1 Summary of Review

A review of experimental work indicates there are only a limited number of useful data sets that provide information on in-depth temperatures during fire decay within timber. There are few experiments that have a decaying fire, where data is recorded for multiple hours without firefighting intervention. Of those experiments, many do not have thermocouples located deep enough to record useful data.

What the above useful data shows is that in the fire decay period, whether that be natural fire or a form of decaying fire within a furnace, that temperatures do not decay quickly in-depth and that temperatures can still be increasing when the experiment stops. The in-depth temperatures are also elevated enough to degrade strength. Where char depths at the end of an experiment are recorded, the in-depth thermocouples indicate that strength degradation occurs to a much greater depth than the recorded char layer.

4 IMPACT OF THERMAL PENTRATION DURING NATURAL FIRE DECAY – APPLICATION

For high-rise buildings with exposed mass timber (timber not encapsulated so exposed to the full heat of a fire), engineers need to determine the strength of a load-bearing timber member for the full duration of a fire. The strength of the timber member has to include the period through fire decay, such that the timber member is no longer impacted by the heat of the fire. In the growing phase of a fire the timber member chars, with the char providing insulative protection, with the char layer typically at temperatures between 300°C and 600°C. Once the fire reaches its peak temperature and starts to decay the timber member is exposed to a reducing heat flux. In a compartment with large areas of exposed mass timber, the fire decays more slowly, compared to a non-combustible compartment (see for example experiments from [13], [14]).

The reviewed data has shown that for a decaying fire, the thermal penetration into a timber member behind the depth of char continues well after the peak compartment temperature and during the fire decay phase. As the compartment cools, the timber member starts to dissipate heat back to the compartment, as the char will be at a higher temperature than the surrounding compartment. This heat dissipation from the member occurs slowly given there are four possible impediments to rapid cooling: (1) thermal waves still penetrating the timber member from the peak heat flux; (2) the received radiative heat flux from the cooling compartment boundaries; (3) the char being a heat source, and (4) the insulative properties of the char preventing heat dissipating from the timber member back to the cooler compartment. The same insulative properties of char that prevent the timber from being damaged by the fire in the growth stage of a fire then become problematic as the char slows the timber member from cooling, as the compartment cools.

Thus, designing timber structures assuming the thermal impact in the timber member ceases when the fire peak temperature is reached, such as for a standard fire; or when the flaming ceases, such as for a natural fire, can be non-conservative. These approaches do not account for the ongoing heat transfer into the timber member and the associated thermo-mechanical degradation to the timber. This is relevant for high-rise timber structures and disproportionally impacts compressive members such as columns and load-bearing walls.

4.1 Implications

Columns are most vulnerable for the assessment of thermal penetration post-peak compartment temperatures, given there are few paths for heat dissipation given the four-sided charring. Their base can also be surrounded by smouldering residual fuel, continuing to conduct heat into the lower part of the column. Beams are normally exposed on three sides with the fourth side fixed to a floor system allowing for heat dissipation to a colder non-fire compartment. Hence, the slow heat dissipation that will occur in columns, and the significant reduction in compressive strength with elevated temperatures above 100ºC (see Figure 1), results in columns being highly vulnerable to thermal penetration in the fire decay phase. Given the lack of sufficient data sets, it was determined by the project team in the formation of the CodeRed experimental series that glulam columns were to be included within all experiments to provide a novel data set [17, 18].

5 DATA AND FINDINGS FROM THE CODERED EXPERIMENTAL SERIES

The CodeRed large scale compartment experiments were set up to provide a detailed data set on thermal degradation in-depth of the timber, and data was recorded for a period in excess of 24hrs after fire ignition. The compartment had an internal floor area of 352 m^2. The fuel bed was identical in all experiments and consisted of continuous wood cribs with a fuel load density of ~380 MJ/m^2 over a floor area of 174 m^2. Two glulam columns were included within the CodeRed series of experiments and instrumented with thermocouples to collect in-depth data. The CLT panels located at the ceiling were also instrumented with in-depth thermocouples. The columns were 400mm x 400mm and the CLT panels were 5 ply (40-20-20-20-40 mm) spruce wood with MUF adhesive. Information presented below is from the first two experiments CodeRed #01 and #02 [17, 18]. A full description of the experimental setup, fuel load, ventilation, instrumentation, fire dynamics and charring behaviour in the timber members is within the referenced papers.

Figure 8 shows temperatures in-depth within Column 1, with thermocouples at depths of 20, 30, 40, 60 and 80mm. The variance of temperatures over column height is also shown through three different heights of thermocouple locations. Similar data was obtained for column 2 and also from experiment CodeRed #02, which had 50% less ventilation to the compartment. The data shows a delay to reaching the peak temperatures within Column 1 (centrally located) with peak of just over 300ºC at 60 mins after ignition at 30mm depth; and a peak of just over 200ºC at ~70 mins at 40mm depth. At 60mm depth, the peak temperature of just over 100ºC is not reached until close to 90 mins after ignition (see Figure 9). Column 2 had similar results, though slightly lower temperatures as this column was closer to the building end. The measured char depth at the end of the experiment was 23mm for column 1 and 18mm for column 2 (weighted average).

Based on the temperatures recorded within the columns, thermal degradation occurs at a greater depth than the post-test char recordings show. At a 40mm depth the timber is thermally degraded with temperatures ranging from 139ºC to 207ºC and average close to 180ºC. The peak temperatures occur 43 mins after the end of wood crib flaming. At a depth of 60mm, temperatures are very closely aligned with a range of 92ºC to 106ºC, with a peak occurring approx. 60 mins after the end of wood crib flaming. Based on the thermocouple data and using a temperature limit of 140ºC (as discussed in Section 2.1 above), there is thermal degradation through to 52mm of column depth. This differs significantly from the post test charring with an average of 23mm deep. The data is also shown in Figure 10, represented by plotting at different column heights, the delay to reach peak temperature and the temperature reached. Further data is shown in Table 1. This data shows that the temperatures in the columns continue to increase well after the peak fire temperature (20 mins after ignition) and after the flaming has stopped (27mins after ignition). The additional timber that is thermally impacted behind the char layer needs to be accounted for in engineering design.

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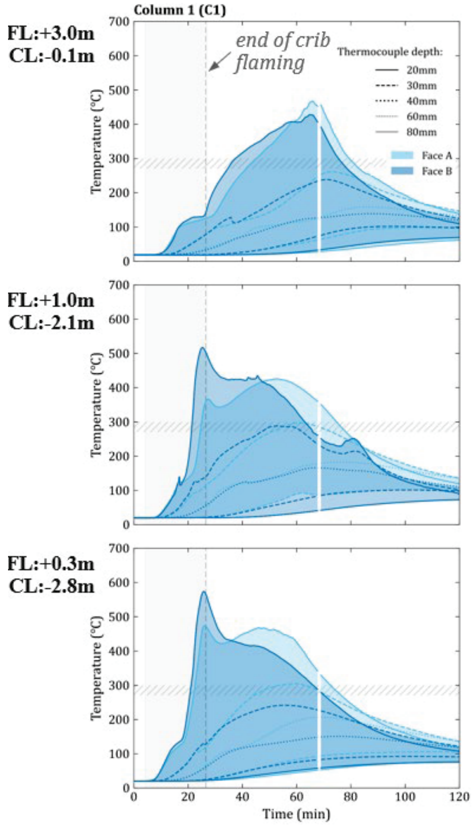

Figure 8: *Column C1 temperatures at various depths from CodeRed #01, at three different heights from ceiling (FL +3.0m) to floor (FL: +0.3m). End of crib flaming is shown. Peak compartment temperature was at 20 mins*

TC depth	Column 1	Column 2	Delay to Peak
20 mm	426 - 574°C	460 - 632°C	25 - 66 mins
30 mm	238 - 304°C	164 - 467°C	42 - 73 mins
40 mm	139 - 207°C	110 - 215°C	61 – 88 mins
60 mm	92 - 106°C	75 - 96°C	76 – 251 mins
80 mm	65 - 80°C	58 - 82°C	124 – 297 mins

Table 1: *Summary of Column 1 and 2 in-depth peak temperatures, based on thermocouple depth. Range shows the difference in peak temperatures depending on thermocouple location. Third column shows range of time to reach peak*

5.1 Relevance of the Delay of In-depth Peak Temperatures

The data from CodeRed illustrates an important factor in the engineering design and assessment of mass timber elements exposed to fires, being the delay in reaching peak temperature in-depth within the timber member. The thermal penetration into a timber member takes significant time to occur, relative to the growing and decaying fire, which has not received discussion in the literature reviewed. The CodeRed data for columns 1 and 2 show delays in peak temperatures that are relevant for thermal degradation of up to 88 mins after ignition (40mm depth), with the end of flaming of all flaming occurring at 27 mins. A graph of the delay to peak temperature is shown in Figure 11, indicating the trend.

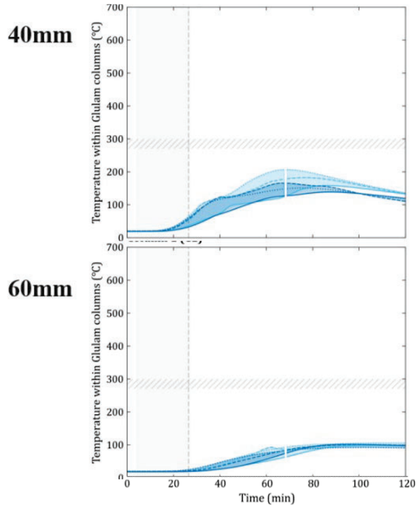

Figure 9: *Column C1 temperatures at 40mm and 60mm deep from CodeRed #01, with vertical dotted line showing the end of crib flaming. Peak compartment temperature was at 20 mins*

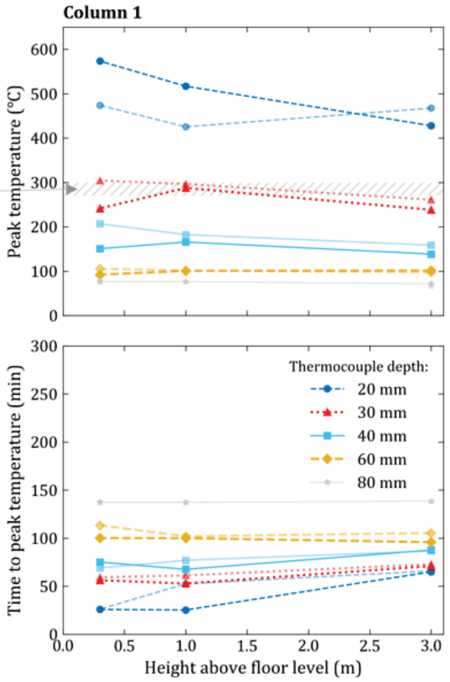

Figure 10: *Column C1 peak temperatures and time to reach that peak temperature at each depth, based on height above floor, for two differing sets of thermocouples at each in-depth location.*

A collated graph of the delay to peak temperature for both the exposed CLT and columns is shown in Figure 12. Whilst there is a range of scatter, the data shows a definite trend that the peak temperatures at the same depth in CLT are lower than in the columns. The time to reach the peak temperature is also slower in the columns.

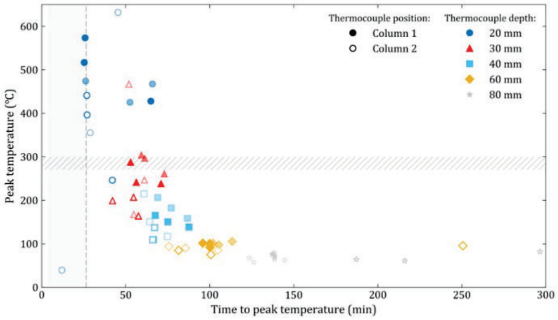

Figure 11: *Columns 1 and 2 from CodeRed #01 showing the peak temperature and time after ignition of that peak temperature, for differing thermocouple depths. Timber with temperatures above 100°C will have reduced strength that is not reversible*

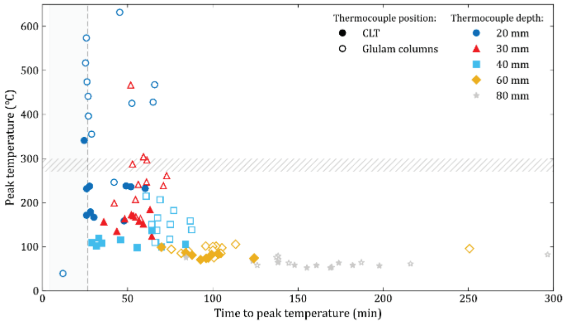

Figure 12: *Column and CLT temperature data from CodeRed #01 showing the peak temperature and time after ignition of that peak temperature, for differing thermocouple depths.*

This data indicates how a CLT floor benefits from having a cool surface on the non-fire surface (topside). This ambient temperature surface assists in reducing the overall temperatures in the CLT and allowing for faster heat dissipation, when compared to columns that are heated on four sides and also have insulative char build-up on all four sides. This difference in time to peak temperature at depth and relative hotter or cooler temperatures between CLT and the columns is undergoing further study, with finite element analysis. It should be also noted that the thermal impact is different to that caused by smouldering, which occurs in a localised area. The thermal penetration occurs throughout the whole column and as the CodeRed data shows, across the whole height of the column.

6 Using Code Red Results - How Is Structural Adequacy Impacted?

A code based approach for the assessment of structural adequacy for a column exposed to a 60 or 120 minute standard fire would be based on a char rate and zero strength layer (as described above in Sections 2.1 and 2.2). Using the EC 5 approach would result in 84mm of charring plus a 7mm zero strength layer, for 120 minutes of standard fire exposure. The cross section would be reduced by this char depth on all four sides to determine structural adequacy.

For engineering design, the CodeRed data (and the other data sets reviewed) shows that the end of flaming for a timber member cannot be taken as the end of the fire. The end of flaming or cessation of flaming is often referred to as “self-extinguishment” of a timber element [see 19, 20 as an example]. Of concern is that engineers and designers are using the end of flaming of a timber member as an indicator that the impact of heating and thermal penetration from the fire has stopped. The data sets reviewed within this paper clearly show that the cessation of flaming or self-extinguishment of timber cannot be used as an indicator for the end of thermal impact on strength for timber members, especially columns. If the cessation of flaming is used as the basis for engineering design of timber members, this will lead to non-conservative results.

Under exposure from a natural fire, the char depth can be calculated by assessing the radiative heat flux from a time-temperature curve and resultant char depth determined, for the growing and decaying fire. From the temperature data presented above, the reduced cross-section where the strength would be adequate for the full duration of the fire exposure is at 60mm depth (for CodeRed #01), given the temperatures are at or just above 100°C and thus thermally impacted strength reduction is reversible. If a limiting temperature of 140°C is used, where 80% of compressive strength parallel to the grain is lost, and this is used to determine effective cross-section, i.e. timber inside this isotherm still has load-carrying capacity, timber outside this does not, this would be at depth of approx. 52mm (based on interpolating average temperatures). If the design was based on the column section having full compressive strength timber, then the depth would be 60mm. As noted above, the CodeRed #01 char depths were 23mm for Column 1 and 18mm for Column 2 (weighted average). Figure 13 shows the percentage reduction in compressive strength for the timber located up to 40mm deep (88% reduction) and 60mm deep (76% reduction) in Column 1 from CodeRed #01.

As a further indication of the impact, column design for a building is highly proportional to the slenderness ratio and cross-sectional area. Using the CodeRed 400mm x 400mm column, with a length of 3.1m, as a design example and following the methodology within Eurocode 5: *Design of Structures. Part 1-1: General – Common Rules and Rules for Building* [21] Section 6.3.2 *Columns subjected to either compression or combined compression and bending*, and choosing typical glulam characteristic compressive strength of the timber parallel to the grain, $f_{c,0,k}$, gives the following comparison (GL30 grade glulam): Using a post-test measured char depth of 23mm + 7mm zero strength layer, could resist an applied load (factored for the fire load combination) of up to 247kN. Using the thermally impacted depth of 52mm, the same column can only resist an applied load (again factored for the fire load combination) of 63kN, i.e. the same column can safely resist only 26% of the load that is estimated from measuring post-test char depth. This indicates that the transient thermal wave has a significant impact on the reduction in column capacity, even with this conservative assessment. Assuming column capacity based on measured char depth alone overestimates the column capacity to adequacy resist loads and is non-conservative.

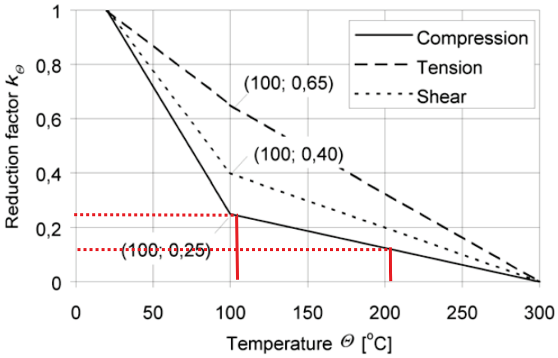

Figure 13: *Reduction factor for strength parallel to grain of softwood from Eurocode 5 [7], with Column 1 peak temperatures at 40mm (207°C) and 60mm (106°C) annotated showing compression strength reduction*

From an engineering viewpoint, the factor of time of thermal exposure is also important. As highlighted earlier in the paper, the in-depth temperatures within the column stay elevated for a relatively long duration, compared with the fire duration. For example, the fire duration in CodeRed #01 to the end of flaming is 27 mins. At 40mm depth, the column is at a temperature of 100°C or more for 90 mins. Experimental data reviewed shows elevated temperatures (above 100°C) can occur in-depth in timber members for three or more hours. This duration of elevated temperature needs to be considered from an engineering design viewpoint, given that fire is seen as an instantaneous load duration condition, and not a short-term loading condition. There is no real guidance available to engineers as to how the duration of exposure to elevated temperatures from a fire should be assessed in the determination of load factors and reduction factors for mechanical properties (impacting k_{mod}). Load duration between short-term and instantaneous is considered the difference between up to a week versus minutes (respectively). As an illustration, the compressive strength parallel to the grain f_c is reduced by 50% at 75°C and in the very short duration CodeRed #01 fire, Column 1 has a temperature at a depth of 40mm higher than 75°C for 2 hours. At 60mm depth the temperature above 75°C occurs for over an hour. Can these elevated temperatures be considered as instantaneous load conditions? Engineers do need to make their own judgements as to whether this thermal degradation duration is important, or not.

6.1 Impact on the assessment of time-equivalence

This information is also important for assessment of time equivalence, an important engineering design analysis needed for building construction. A typical approach would be to equate the 23mm of char depth back to an equivalent fire char depth based on a standard fire exposure, which would be 43 mins (at 0.7mm/min, standard fire exposure plus 7mm). For a heat impacted depth of 52mm, this would equate to 74 mins of standard fire exposure (no zero strength layer would be included). Hence based on the CodeRed data, the column exposure as determined from the post-fire char depth measurement would be adequate to achieve a 60 min fire resistance. But based on the thermocouple data for thermal penetration where (excluding cross-sectional area of timber that has lost 80% of its compressive strength parallel to grain), the column would not achieve 60 mins of fire resistance.

7 DISCUSSION – EXPERIMENTAL DATA

The data reviewed, including the data from the CodeRed series, shows that the peak temperatures in-depth with the timber members are often not recorded within experiments or tests as these occur well after the test has been stopped. In many of the experiments reviewed, the in-depth temperatures are still increasing at the end of the experiment and hence the actual peak temperature at depth are not actually recorded. The data reviewed does not provide suitable sets of data that can be used because thermocouples are not deep enough within the timber, the thermocouples are spaced to far apart and lead to coarse measurements, and the experiments are not being carried out long enough to allow all relevant data to be collected. In hindsight, the CodeRed data also could have benefited from more in-depth thermocouples at locations of 50mm and 70mm.

The review of data shows that more experimental series are required to understand the in-depth temperatures and requires timber members, preferably columns, exposed to a natural fire, with thermocouples embedded in-depth at no more 10mm spacings and the experiment is run to allow temperatures within the timber member to reduce from their peak back to ambient, most likely running the experiment for four to six hours after ignition.

8 NEXT STEPS - ASSESSMENT METHOD

The reviewed and CodeRed data indicates that there are three issues to be considered for the assessment of thermal penetration into a timber column during a natural fire. The first is the depth within a timber member for thermal penetration to occur that results in temperatures that will cause permanently reduced timber strength. The second is the duration of time that the elevated temperature occurs, which can also be measured as the delay until the temperature returns to less than 100°C. The third is whether the reversible strength reduction below 100°C is relevant to the design for the timber column, given that at 75°C, the compressive strength parallel to the grain is reduced by 50% and a column may be exposed to these elevated temperatures in-depth for multiple hours and hence, could actually fail under buckling given this reduction in compressive strength due to the longer-term nature (hours rather than minutes) of the thermal wave. The longer-term nature of this thermal impact is also relevant for fighting actions, which can still be occurring multiple hours after the fire has occurred and been extinguished.

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The next steps with the CodeRed data are to carry out detailed finite element analysis of the columns to attempt to accurately model the recorded data and to then be able to determine methods for engineering design, based on a range of natural fires.

To design a timber column within a high-rise building exposed to a natural fire, the engineer needs to assess the impact of the thermal penetration and heat dissipation within the timber member, what should be a relatively straight-forward assessment of heat transfer. A changing external heat flux for compartment fire growth and decay, means the timber only reaches an equilibrium heat transfer state well after the compartment fire has decayed. Heat transfer analysis of the thermal penetration in the timber can be estimated with the timber element considered as a semi-infinite three part solid, with an outer layer of char and an inner layer of ambient temperature timber and a transition layer. Fourier's law for heat transfer through solids is normally adequate for most heat transfer problems in engineering [22], but the assessment becomes more challenging when the properties of the char are changing with temperature and the dissipation of the heat is not straight forward.

The methodology currently being attempted for a column is to determine the thermally impacted effective cross-section by segmenting the column into thin slices, assessing the temperature and residual strength (reduced mechanical properties, based on temperature of each slice). Modelling the physical properties of char is demanding as timber physical properties are not accurately known for natural fires and modelling the dissipation of heat from a heated timber member is also difficult to verify. As the thermal penetration is assessed through the timber member, the reduction in load-carrying capacity can then be determined, through to the full dissipation of the heat.

The engineering design of columns cannot just be based on designing to withstand a fire until flame cessation (self-extinguishment) or even compartment burnout (fire has decayed to less than 1MW or temperatures have returned to ambient). The method for designing columns must be based on assessing thermal degradation in-depth and determining the strength reduction to that depth to determine structural adequacy (maintaining stability).

8.1 Limitations and further work

There are a number of limitations in the current modelling and design approach. This includes the thermomechanical properties of timber being effective properties based on the standard fire temperature-time curve, which have limited accuracy for other thermal exposures or decaying fires.

More research is needed to understand the strength properties of timber at the 100ºC to 200ºC range and how permanent strength reductions are. This temperature range has received little research or attention as wood pyrolysis has not been reached, which is of interest to fire scientists. The thermomechanical properties of wood above 100ºC, where moisture migration determines the impact requires revisiting given the work by researchers such as Schaffer [9] and Gerhards [23] is 40 years old and is not reflective of modern mass timber members.

The relatively slow decay that occurs in fires with large areas of exposed timber and the resultant duration of thermal penetration in the timber member is also worthy of further research. Determining the importance of the slow thermal dissipation of in-depth heat and the depth of impacted timber is important from an engineering design perspective. In standard fire testing the thermal heating is relatively quick in the first 20 mins and then slowly increases, leading to thermal penetration through the timber that is fairly uniform, given the slowly increasing temperature after 30 minutes of exposure. The thermal gradient between the back of the char layer at 300ºC and ambient temperature therefore occurs over a relatively small thickness of approx. 40mm. For an exposed mass timber compartment, the extended fire decay phase leads to a temperature gradient over a much deeper thickness of timber than 40mm, between 300ºC and ambient.

9 CONCLUSIONS

Experimental data from a range of mass timber studies have shown that thermal penetration continues in a timber member after peak temperatures from fire exposure have been reached. This thermal penetration reduces structural capacity of a timber member in-depth. In the decay phase of a natural fire, the built-up char layer also slows heat dissipation from the timber member. Columns are particularly vulnerable given they have four-sided charring and compressive strength parallel to the grain reduces quickly at elevated temperatures above 50ºC.

Analysis of structural adequacy of timber columns in high-rise buildings where a range of natural fires has to be assessed, needs to account for the loss of structural capacity from the thermal penetration and the slow heat dissipation due to the char layer. Using experimental results from the CodeRed series of experiments, the authors have made progress in the understanding of the engineering issues. Further work is currently being undertaken with finite element modelling to develop engineering methods to predict the impact on structural capacity of timber columns for the full duration of a fire.

To address this issue, possible means of mitigation include (1) increasing the member cross-sectional area to account for the thermal wave, based on a heat transfer analysis; (2) including non-combustible protection to the timber member to prevent heating by fire exposure (3) if columns are to be exposed (not encapsulated), these should be located near windows where the compartment temperatures and thermal impact is reduced.

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