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SIMPLIFIED ENGINEERING METHOD TO ESTABLISH STRUCTAL ADEQUACY OF MASS TIMBER COLUMNS FOR FULL FIRE DURATION

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ABSTRACT: Data from mass timber experimental research has shown that thermal penetration continues into a load-bearing member after the peak temperatures from fire exposure are reached. Based on an analysis approach developed for high-rise mass timber projects, and after an extensive literature review, results from the CodeRed series of experiments have been used to further refine and verify an engineering methodology to assess the impact of thermal penetration on structural adequacy of an exposed mass timber column, during fire growth and decay. The methodology specifically addresses the thermal degradation of strength and stiffness that occurs at depth behind the char layer and introduces the concept of the thermal degradation depth. Columns are particularly vulnerable given their potentially four-sided fire exposure, their compressive strength parallel to the grain reducing substantially and irreversibly at temperatures over 120ºC, and their susceptibility to small changes in slenderness ratio. The results show that when the thermally degraded timber is included in the assessment of structural adequacy, the load-bearing resistance of a column is reduced, compared with the calculated resistance of a column using just char depth and a fixed zero-strength layer. Of concern is the lack of guidance regarding the design for exposed mass timber columns, as thermal degradation depth may not be checked, and structural adequacy may be based on the char depth at the time of cessation of flaming. This is particularly worrying as a column may be most vulnerable after the fire was extinguished, when firefighting activities are still occurring.

KEYWORDS: Mass timber, fire engineering, tall timber buildings, columns, structural engineering.

1 – INTRODUCTION AND BACKGROUND

Buildings constructed with mass timber continue to increase in popularity globally, with owners and architects wanting to express the timber structure, rather than protect it behind non-combustible boards. The process of fire engineering is highly complex for buildings with exposed mass timber, given the timber location, amount of exposed area and the type of timber can change the post-flashover fire conditions significantly, when compared with non-combustible structures. To protect building occupants and firefighters and prevent structural failure, building regulations and codes require high-rise buildings to have a greater resilience against fire, with increased fire resistance ratings and fire protection measures [1].

The assessment of fire resistance for a high-rise structure needs to consider a range of design fires including both standard and natural fires, generally on the basis of sprinkler protection failure and no firefighting intervention [2, 3]. This extreme fire scenario to assess structural performance is either required by fire safety codes (explicitly or implicitly) or is expected as part of a performance-based design approach, with precedence set by similar analysis for buildings constructed with structural steel or concrete. All structural materials are vulnerable to fire and need to be designed accordingly and understanding how both the growth and decay phases of a fire impact the stability of the structure, an important part of any high-rise building solution [4]. For a high-rise building with exposed mass timber, the structural adequacy must be assessed until the member strength is no longer impacted by the heat of the fire. This simple concept, of determining the member strength until it is no longer thermo-mechanically degraded (thermal degradation) due to heat, appears to be rarely carried out by engineers. This is due to the complexity of the problem, the effort (time) involved and because codes do not require this type of analysis. As mass timber is often being used beyond what prescriptive codes have accounted for, the level of analysis and critical review is required to increase. Many fire engineers do not have the requisite structural engineering knowledge and experience, and most structural engineers do not have the necessary fire knowledge or experience. Thus, it requires a close working relationship between the two disciplines.

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An assessment of the thermal degradation to a structure (i.e. of its mechanical properties) that occurs after the fire has reached its peak temperature shows that columns are the most vulnerable building element, which is particularly concerning given the importance of columns to a structure's resistance to progressive collapse (robustness). For columns, structural adequacy is highly sensitive to buckling length (slenderness ratio). Once the column is exposed to fire, charring reduces the cross-sectional area on all four sides and the increasing slenderness ratio can change the failure mode from strength-based to buckling-based, resulting in significantly reduced load-bearing capacity.

In carrying out engineering designs for high-rise buildings with exposed mass timber, it was clear to the authors that current international guidance for the assessment of structural adequacy for mass timber structures exposed to fire is not comprehensive, does not acknowledge the issues to be addressed in the fire decay period and may result in non-conservative outcomes. This paper provides a description of the key issues impacting the vulnerability of mass timber columns in high-rise buildings exposed to fire. It proposes an engineering method for assessing structural adequacy, accounting for the loss of strength due to both charring and the thermally degraded timber behind the char layer.

2 - COMPARTMENT FIRE WITH EXPOSED TIMBER

A natural (physically based) design fire will include growth, development and decay phases (in contrast to an ever-growing furnace test fire). The decay stage of a fire has a role in structural adequacy for all materials [5], though the decay phase of fires has not received significant research and is not normally addressed in engineering design. With increasing focus on performance-based fire design of structures, researchers and engineers are starting to ask more questions. Recent research on structural steel behaviour exposed to a decaying fire has shown less than ideal structural resilience [6], indicating more research is needed on fire decay on all structural materials.

A natural fire will be influenced by the type of mass timber, the area of exposed timber, the location and orientation of the exposed timber, the type of encapsulation and the architecture of the building [7, 8]. As exposed mass timber influences and changes the heat release rate and decay of the fire, when compared to a non-combustible structure, a range of design fires need to be assessed and account for the mass timber fuel being consumed by the fire. Design fires are therefore a complex problem and require an iterative approach to the solution [9]. To reliably predict the design fire, the fire engineer needs to ensure a decay phase occurs. The area of exposed timber will need to be limited and unpredictable fires prevented by having mass timber, especially cross laminated timber (CLT) that exhibits bond line integrity in fire, and non-combustible encapsulation proven to prevent timber charring.

2.3 - WHAT IS THE DESIGN CHAR DEPTH?

For most high-rise mass timber projects where the fire engineer is carrying out analysis, the primary aim is to determine a maximum char depth so that structural adequacy can be assessed by the structural engineer. The simplistic "effective cross-section" approach is usually adopted for mass timber, which involves determining a depth of char and accounting for a thermally degraded layer behind the char (the zero strength layer), based on exposure to the standard fire (e.g. ISO 834, or ASTM E119). The position of the char front is set by the 300°C isotherm and under standard fire exposure the nominal (average) char rate (β_o) is 0.65mm/min for periods of exposure of 60 mins or more [10]. This approach, originally intended for low- and medium-rise buildings is applied to high-rise buildings and performance-based approaches, often without consideration of the limitations.

The above effective cross-section method is a sound approach for assessing structural adequacy, provided the inputs are adjusted for a natural fire, for three impacting issues: (1) the char rate will not be fixed and will vary based on the received heat flux (not addressed further in this brief paper); (2) as the fire decays, the thermal penetration into the timber continues at temperatures that will reduce strength and can continue for hours after the fire has peaked; (3) the thermally degraded timber behind the char layer is not a fixed depth and varies with fire exposure, fire decay and efficiency of heat dissipation. Each of these three factors impacts structural adequacy for an exposed mass timber member when exposed to a fire. Items (2) and (3) are discussed further, given they are the key engineering inputs for the accurate analysis of exposed mass timber columns.

2.4 - THERMALLY IMPACTED LAYER

Current methods to determine structural adequacy consider a fully charred zone (>300°C) with a 7mm deep heat impacted layer directly behind the line of char (zero strength layer) [10]. The depth of the zero strength layer

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has been subject of review and re-evaluation [11]. The thermal penetration depth, the depth of the layer between the char and ambient wood, has been researched for over 40 years with data from fire testing on solid timber and glulam being analysed [12, 13]. Janssens and White [14] summarised test data and based on White's research showed that temperatures reached ambient at 40mm behind the char layer, for various softwood timber species. Frangi and Fontana [15], estimated 25mm to 50mm (see Fig 1). The 7mm zero strength layer is a simplification that is adequate for basic structural assessment but is too simplistic for detailed analysis of structural performance for longer duration fires (in excess of 60 mins) and for natural fires. It is especially relevant with the slower decaying fires that are representative of exposed mass timber compartments. Of concern is that using a fixed 7mm zero strength layer can lead to non-conservative results.

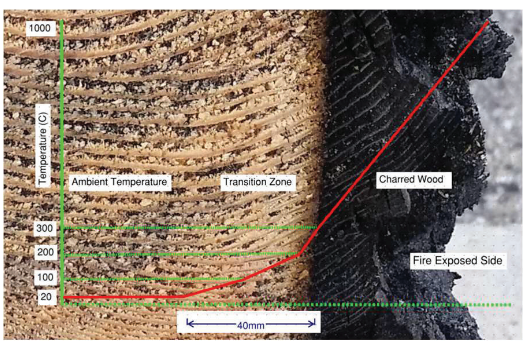

Figure 1: Temperature changes through the char layer in a typical mass timber member

A more accurate method to asses thermal impact, reflecting actual timber properties, is to identify three distinct temperature zones between ambient and the 300°C isotherm: (1) timber between ambient and 100ºC with reduced strength properties that are reversible on cooling; (2) timber between 100ºC and ~120ºC where moisture is being driven out (published values range from 100ºC to 140ºC) and strength reduction is irreversible on cooling; (3) timber between ~120ºC and 300ºC where drying and transition to char occurs, mechanical properties degrade to zero, with strength reduction not reversible on cooling [16, 17, 18]. A key input for engineering is that timber with a temperature above ~120ºC does not regain strength on cooling, a physical property of timber that is not well researched.

The three temperature zones are relevant to the engineering design of mass timber as load-resisting properties reduce at relatively low temperatures, compared to concrete and steel. Of importance is the reduction in strength and stiffness for timber compressive strength parallel to the grain. Fig 2 shows the relative strength and stiffness values as documented within EN 1995-1-2, showing compressive (f_c) and tensile strength (f_t), modulus of elasticity in compression (E_c) and in tension (E_t). At 140ºC, timber has lost 80% of its compressive strength (f_c), which is not reversible on cooling. The behaviour of timber at relatively low temperatures has been published on since the 1980's [16, 19], and yet some engineers are still surprised by these values. Using the in-depth temperature correlation from [14], a column exposed to a standard fire will have a 120°C isotherm to a depth of 14.5mm of timber (behind the char layer) and a 77% reduction in f_c parallel to the grain, that is permanently reduced. For larger columns exposed to standard fires, the 14.5mm depth of reduced strength behind the char layer may not be significant and will only need to be checked for slender columns. For natural fires, the assessment of the 120°C isotherm becomes more critical given the thermally degraded depth increases during the fire decay phase.

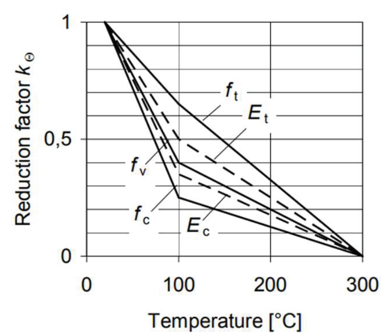

Figure 2: Reduction factors for strength and stiffness properties (adapted from EN 1995-1-2 [20])

3.0 – THERMAL PENETRATION IN THE POST-PEAK COMPARTMENT FIRE

3.1 – MASS TIMBER IN A COOLING FIRE

Compartments with large areas of exposed mass timber will have natural fires with a relatively long fully developed and decay phase, as the mass timber as fuel impacts the fire [for example 21, 22, 23]. As moveable fuel is consumed and the post-flashover fire decays (ignoring those fires that do not decay due to CLT bond line or encapsulation failure that progressively feed more timber to the fire as fuel), the heat release trends to zero and compartment temperatures trend to ambient. As the received heat flux at the exposed timber reduces to zero, the progression of charring of the exposed

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timber will slow and stop. While charring may stop, heat from the compartment fire continues to penetrate mass timber elements, with the heating and slow cooling of the timber behind the char, due to: (1) thermal inertia due to the incident heat flux of the compartment fire; (2) received radiative heat flux from the cooling compartment boundaries; (3) the char being a heat source as it slowly cools (including glowing and smouldering), and; (4) the insulative properties of the char preventing heat dissipating from the timber member back to the cooler compartment [24]. The influence of these four factors results in thermal penetration behind the char that can be on-going for hours and cooling at a very slow rate.

The relative impact of each of the four influences will change relative to the member and the compartment. The slow cooling and insulative properties of the char can be the most influential as a barrier to dissipative cooling, especially for a column. The same insulative properties of char that are welcomed as they prevent the timber from being damaged by the fire in the growth stage, become problematic in the cooling phase of the fire, as the char slows the timber member from dissipating heat back to the much cooler compartment. There is a point where the char stops protecting the timber member from the compartment heating, and due to the residual heat in the char and the insulative properties of the char, becomes a source of slowly decaying heating. The thermal penetration behind the char layer can continue for hours after the fire has peaked, and continues to reduce the strength of the member. Research into decay phase char acting as a heat source and slows a mass timber member cooling has not been prevalent and more data is needed.

Given the above factors, columns are most vulnerable given there are few paths for heat dissipation with most columns having charring to four sides. Beams and floors have at least one side exposed to a non-fire compartment for heat dissipation. The slow heat dissipation that will occur in columns, and the significant reduction in compressive strength with elevated temperatures above 120°C, results in columns being highly vulnerable to thermal penetration in the fire decay phase.

3.2 – DETERMINING IN-DEPTH TEMPERATURES

Determining the temperatures between 300°C and 100°C behind the char layer is required for accurate assessment of structural adequacy. Published correlations for thermal penetration depth are accurate for standard fire exposure only. To determine the thermal penetration depth for natural fires, two approaches were completed: review published experimental data; and modelling of a natural fire.

3.2.1 – RESULTS FROM LITERATURE

A review of experimental data of both natural and furnace-based fires with a decay period has shown that thermal penetration continues to occur well after the peak temperature has been reached and there are useful data sets to assist with an engineering method [25]. The review shows that many datasets are of limited application, as thermocouple spacings and number are not sufficient. Also, most experiments do not collect data long enough after fire decay to capture the complete increase with in-depth temperatures, i.e. temperatures are still increasing hours after the fire decay and peaks are not recorded (see Fig 3 for an example from experiments reported by Brandon [26]).

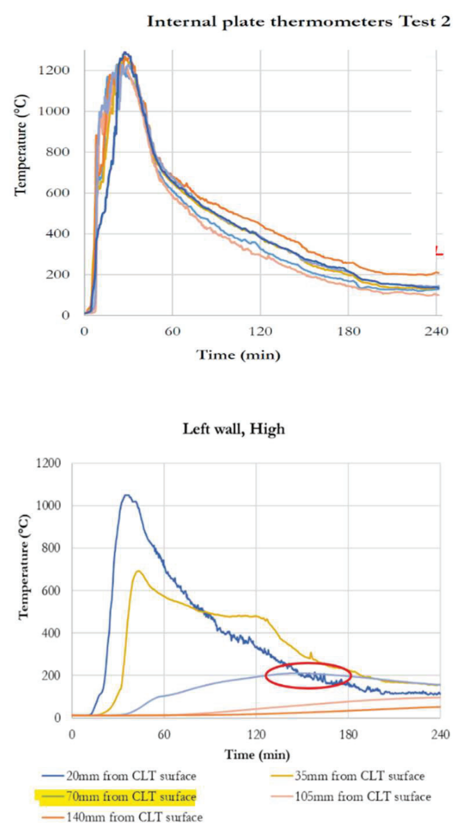

Figure 3: (Upper image) - Compartment temperatures from exposed CLT experiment (Test 2), with fire peaking at 35mins. (Lower image) - Test 2 CLT temperature measurements in-depth, fully exposed CLT showing at 70mm temperature peaked at 202°C at ~160 mins and 105mm depth temperature was still climbing (and above 120°C) [26]

Most authors point out the in-depth temperature increases (see for example [26]), though do not assess the issue further as it is not a focus of their work. The review shows that more experimental series are required, preferably with columns, exposed to a natural fire with thermocouples embedded in-depth and the experiment data is collected for up to six hours after ignition. The accuracy of in-depth temperature measurements also needs to be addressed [27].

3.2.2 – TEMPERATURES USING MODELLING

If experimental data sets are not available, finite element (FE) modelling is the most appropriate method to determine in-depth temperatures. FE modelling can provide estimates of in-depth temperatures for a timber member, based on a natural fire input. It can also be used to provide intermediate data points between experimental measurements, i.e. establish temperatures at closer centers if thermocouples are located sparsely. To model the in-depth isotherms requires experimental data to verify modelling assumptions and thus, experimental data is always initially needed. The FE modelling of charred timber is limited in accuracy regardless of the tool being used and the more data sets that can be incorporated for verification, with a fine mesh, the more accurate as a predictive tool [28]. FE modelling is also relatively time consuming for the assessment of multiple fire scenarios. A limitation with FE modelling is that input physical properties of timber are based on standard fire exposure, and hence of limited accuracy for natural fires [29].

4.0 – ENGINEERING METHODOLOGY

An engineering methodology to assess mass timber column strength has been developed over a number of years. The initial concept method was applied on the exposed glulam columns for the 12 floor Framework building, that achieved building approval though not constructed, in Portland (Oregon) in 2016 [30]. The methodology was further developed and applied to several mid-rise buildings as part of internal Arup research. A more comprehensive method was used for the Ascent Tower, the 25 floor mass timber – concrete residential building constructed in Milwaukee, completed in 2022 [31].

The engineering methodology developed has focused on determining the thermal degradation depth within the effective cross-section, as the temperatures in-depth increase and decay in response to the natural fire exposure. The term "thermal degradation depth" has been defined as the zone of permanently reducing structural capacity based on the 120°C isotherm. Thermal penetration below 120°C has a reduced impact on timber strength as it is reversible on cooling. Advancing the engineering methodology required more datasets with longer data recording periods, exposed mass timber columns and a natural fire influenced by large areas of exposed mass timber. The CodeRed large scale exposed CLT compartment experiments therefore included two glulam columns.

4.1 - DATA FROM THE CODERED EXPERIMENT SERIES

The CodeRed experiments included an exposed CLT ceiling without encapsulation, for experiment #01 and #02 [32, 33]. Two 400mm x 400mm glulam columns were included in the building. The columns were instrumented to provide a data set of temperatures and data was recorded for over 24 hrs after fire ignition. Both CodeRed #01 and #02 were short duration fires, with all flames ceasing within the compartment within 27 mins of ignition, even with the whole ceiling as exposed CLT. There was no firefighting intervention. Data from CodeRed #02 is reviewed in more detail as this was a slightly longer duration fire and the columns had additional thermocouples embedded. The peak fire temperature was 1058°C at 18 mins after ignition, (based on an average of thermocouple readings) and the mass timber and wood cribs ceased flaming at 27 mins after ignition. During the fully developed fire the recorded in-depth temperatures for Column 2 showed a peak of 303°C at 20mm depth 44 mins, 238°C at 30mm depth at 51 mins and 139°C at 40mm depth at 62 mins (all time after ignition) (see Fig 4).

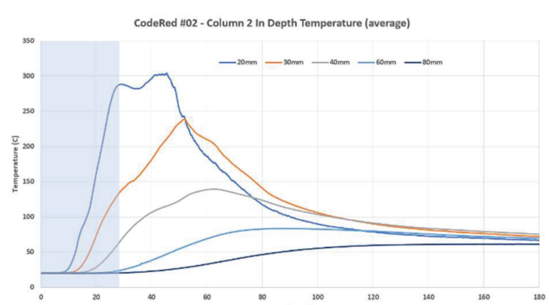

Figure 4: Column C2 in depth temperatures from CodeRed #02, with shaded area showing the end of flaming at 27 mins. Peak compartment temperature was at 18 mins

Column 2 had post test char depth measured of 32mm (average) based on saw cuts. The data indicates that charring occurred in the post flaming stage of the fire,

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given char depth was recorded at 32mm, yet the 300°C isotherm within the column only reached 22mm in depth. Tracking the 120°C isotherm, this peaks at 48mm of column depth and is the thermal degradation depth, occurring at 81 mins after ignition, relatively deep considering how short the fire exposure was at less than 27 mins. The thermal degradation depth occurred at a time three times longer than the duration of flaming, and four and half times longer than when the peak fire temperatures were reached.

The CodeRed experiment series supports the data reviews [25], showing that the cessation of flaming cannot be used as an indicator that thermal degradation has stopped for exposed timber members, especially columns. Post-test measurements indicated a char depth of 32mm, whereas when all flames ceased, the 300°C isotherm was at 17mm depth. If the end of flaming was taken as the time of charring, 15mm of charring would have not been accounted for, hence a non-conservative structural stability outcome. The in-depth temperature data also showed that charring occurred in the post flaming stage of the fire, as the 300°C isotherm only reached 22mm. If the 300°C isotherm was used as the indicator of char depth, 10mm of charring would not have been accounted for. Again, this would result in a non-conservative outcome. Similar results were recorded in CodeRed #01.

4.2 – ASSESSMENT METHODOLOGY INCOPORATING THERMAL DEGRADATION

The assessment methodology developed to assess structural adequacy for a mass timber column, incorporating thermal degradation is explained below, with the CodeRed experiment series used as an example. In short, the aim is to calculate structural adequacy by determining the thermally degraded depth. This is achieved by segmenting the column (5mm or 10mm intervals recommended) so that the timber properties can be determined for each segment, for increasing time steps for the input fire temperature (30 secs or 60 secs recommended. The timber mechanical properties of modulus of elasticity (MoE) and compressive strength (f_c) are calculated for each segment, for each time step, based on the temperature within that segment (midpoint used), based on published correlations [10]. As thermal penetration and temperatures increase, each segment has a reducing MoE and compressive strength, through to zero strength in a segment at 300ºC.

The approach establishes an effective cross-section that has reducing strength properties as the temperature in each segment increases. The strength loss is not reversible in the cooling phase, unless the temperature in a segment remains below 120ºC (taken as the value where full moisture content is driven out). If the segment reaches a temperature above 120ºC, the strength properties are not reclaimed on cooling, diminishing through to zero at 300ºC. The structural adequacy can then be assessed based on the reducing effective cross-section, for each time step in fire growth and decay. Structural adequacy is based on the design rules for columns from Eurocode 5 *Design of Timber Structures Part 1-1 General- Common rules and general rules for buildings* (EN 1995-1-1) [34], for compression parallel to the grain (any recognised national standard can be used).

The following description provides the steps carried out.

Ambient temperature:

1. Assess the ambient temperature structural adequacy, to provide a base value for the column.
2. The method from Eurocode 5 EN 1995-1-1 is used. Section 6.1.4 is applicable for compression parallel to the grain, refer *Section 6.3.2 Columns subjected to either compression or combined compression and bending* to determine stability for a column.

Fire exposure:

1. Determine a compartment time temperature curve, based on exposed mass timber (modelling or from experimental results).
2. Mass timber column is segmented and using experimental data and / or FE modelling, the temperature at the mid-point of each segment is determined for the full duration of the fire, plus 120 mins (at least) of extended duration.
    a. FE modelling may need to be extended for an additional 120 mins (at least) such that the worst case conditions are reached, i.e. no new segment reaches temperatures of 120°C or more, to capture the increase and decay of in-depth temperatures.
3. For each segment, assess timber properties of MoE and f_c based on temperature, for each time step, in temperature increase and decay:
    a. MoE - reduces with temperature, with reduction factor of 1.0 at ambient through to 0.0 at 300°C.

b. f_c - reduces with temperature, reduction factor of 1.0 at ambient though to 0.0 at 300°C.

4. The deepest segment with temperatures >120°C is the thermal degradation depth.
5. Assess structural adequacy of the column with the overall section modulus changing at each time step, given the reducing MoE and f_c properties, for each segment.
6. When a segment reaches 300°C, MoE and f_c remain at zero.
    a. i.e. for CodeRed, the 10mm to 20mm segment (10mm from exposed face) reached 300°C (ave) at 40 mins (after time of ignition) and that segment has zero influence after that time.
7. Where temperatures reach and exceed 120°C, the MoE and f_c remain at their lowest (most reduced) value and do not increase in value on cooling.
    a. i.e. for CodeRed, the 20mm to 30mm segment (20mm from exposed face) reaches a peak temperature of 238C (ave). The reduction factor on MoE is 0.11 and remains at this value once the segment starts to cool and reduce in temperature (see Fig 5).
8. Segments with temperatures that do not reach 120°C can reclaim their MoE and f_c properties on cooling.
9. Each segment contributes to load-bearing capacity, with diminishing influence as the temperature in the segment increases.
    a. i.e. for CodeRed, at 20 mins, compressive strength (f_c) is 17% of its ambient value in the 10mm – 20mm segment, 50% in the 20mm – 30mm segment, 92% in the 30mm – 40mm segment, and 96% in the 40mm – 50mm segment.
    b. And at 40 mins f_c is 0% of its ambient value in the 10mm – 20mm segment, 15% in the 20mm – 30mm segment, 24% in the 30mm – 40mm segment, and 51% in the 40mm – 50mm segment.
10. The total load able to be resisted by the column is the maximum at each time step, given the thermally reduced MoE and f_c properties of each segment, based on the effective section.

4.3 - WORKED EXAMPLE –CODE RED #02, COLUMN 2

The GL30 grade glulam columns were 400mm x 400mm, with a length of 3.1m. Using Eurocode 5: EN 1995-1-1 and a glulam characteristic compressive strength parallel to the grain, $f_{c,0,k}$, of 12 N/mm^2 gives an f_c of 10.56 MPa, with an $E_{mod\ g.o5}$ of 11.3 kN/mm^2. The ambient column structural capacity is 1680kN.

The CodeRed temperature data for the glulam column is based on thermocouples located at 20mm, 30mm, 40mm, 60mm, and 80mm, with a thermocouple tree adjacent to the column to record gas temperatures. The whole cross-section of the column was modelled using Strand 7 Finite Element software, with temperature nodes at every 10mm. The input fire was the CodeRed #02 temperature-time curve. By using temperature data from the thermocouples, the modelling outputs could be verified for all intermediate locations between 10mm depth and 100mm depth. As noted above, the thermally degraded depth for the column was 48mm, occurring 81 mins after ignition (depth of 120°C isotherm), for the very short CodeRed #02 fire of 27 mins.

Working through the analysis, 60 mins, 90 mins and finally 120 mins of CodeRed natural fire exposure was assessed for the full cross section of the column so that some strength was starting to be reclaimed. Applying the methodology set out in section 4.2, for each 10mm segment for a time step of 60 secs, the reducing timber strength properties were calculated, for 120 mins of assessment duration The assessment showed that the 400mm x 400mm glulam column 2 has a structural adequacy that reduces to 1058 kN, with the reduced load occurring at 96 mins after fire ignition.

Figure 5 shows the reducing ambient MoE for increasing depth of segment (reduction factor). The structural loadbearing capacity of the column is based on the cross-sectional area, which in turn is informed by the temperature of each segment. As expected, the segment between 0mm and 10mm (at the exposed face) loses all strength quickly, with the 10mm to 20mm segment reaching zero MoE after 41 mins. The 20mm to 30mm segment (20mm to 30mm from exposed face) reaches 25% of ambient MoE at 35 mins and reduces to 11% of ambient for the duration of the fire exposure. The 40mm to 50mm segment reaches a maximum temperature of 107°C at 66 mins, with the MoE decreasing to 34% of the ambient value. Once the segment starts to cool, the MoE losses are reversed, given the segment did not reach 120°C. Compressive

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strength has similar reductions with increasing temperature of each segment.

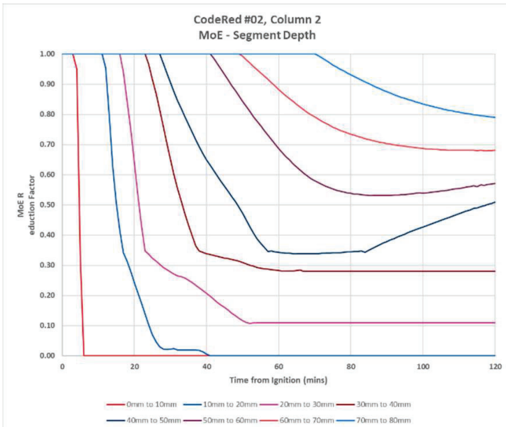

Figure 5: Modulus of Elasticity reduction factor for each 10mm segment ("0-10mm" is the fire exposed edge), showing reducing MoE as the thermal penetration occurs through the column

The 400mm x 400mm column can resist an applied load of 1680kN in normal conditions. When thermal degradation is taken into account, and the 120°C isotherm is used to assess the reducing strength properties within the timber, the same column can only resist 63% of that load (1058kN) (see Fig 7).

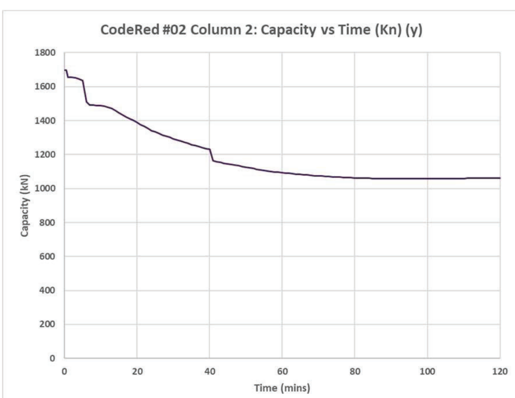

Figure 6: Graph of reducing structural adequacy for CodeRed #02 Column 2 with 120 mins of assessment period, showing reducing capacity as the thermal penetration occurs through the column.

At 98 mins after the fire ignition, the structural adequacy decline starts to reverse with in-depth timber slowly cools and regains lost strength for timber not reaching 120°C. The outcome from the assessment shows that accounting for thermal penetration must be carried out for the accurate assessment of column strength. The CodeRed experiments are a very short duration fire and the impact of thermal penetration on structural adequacy can be seen, with only 63% of ambient temperature capacity retained.

4.4 – OTHER ASSESSMENT METHODS

Engineers can assess the structural capacity of a column exposed to a natural fire with different methods. Three common approaches and their results are briefly described below, for a 400mm x 400mm glulam column.

Assessment method 1: Flames Ceased - Using the char depth when all flames have ceased in the compartment, char depth was 17mm. Applying a nominal 7mm zero strength layer (noting the 7mm is for standard fire exposure, not a natural fire), the column could resist an applied load of up to 1290 kN, based on a residual cross section of 352mm x 352mm.

Assessment method 2: Tracking 300°C Isotherm - The 300°C isotherm reached 22mm deep and can be used to determine the effective cross-section, with again applying a 7mm zero strength layer. The column could resist an applied load of up to 1220 kN, based on a residual cross section of 342mm x 342mm.

Assessment method 3: Char depth - Using a post-test measured char depth of 32mm and applying a nominal 7mm zero strength layer (as above, the 7mm is for standard fire exposure), the column could resist an applied load of up to 1070 kN, based on a residual cross section of 322mm x 322mm.

The methodology based on thermal degradation depth results in a reduced structural adequacy of 1058kN. This can be compared with the other common assessment methods above, with values between 1070 kN and 1290 kN, indicating these methods are not conservative and overestimate the structural adequacy.

5 –DISCUSSION

Mass timber columns are vulnerable when exposed to fire given that thermal degradation depth increases sizeably in the fire decay phase, timber with a temperature above ~120ºC does not regain strength on cooling, and four-sided charring severely limits cooling through heat dissipation. The literature review completed and the data from the CodeRed experiments show that designing mass timber structures assuming thermal degradation to a member ceases when the fire peak temperature is reached, such as for a standard fire; or when the flaming ceases for a natural fire, can be non-conservative. These approaches do not account for the ongoing heat transfer into the timber member and the thermo-mechanical degradation. Of concern is that engineers are using the end of flaming as a marker that heating and charring of the timber has stopped. The data sets reviewed [see 21 -23, 25] clearly show the cessation of flaming is not the end of charring or thermal degradation of timber. This is relevant for high-rise timber structures and disproportionally impacts compressive members such as columns and load-bearing walls, as small changes in cross-sectional area can change the failure mode from strength based to buckling based.

The data from fire experiments also shows that the factor of time of thermal exposure is important. Experiments with in-depth thermocouples show elevated temperatures for multiple hours, compared with the fire duration (less than an hour) (see [28] for example]. There is no guidance available to engineers as to how the duration of exposure to elevated temperatures should be assessed in the determination of reduction factors for the assessment of load and timber properties, given load duration is an important factor for determining structural adequacy for timber (not for concrete or steel). Structural engineers need to decide whether these long thermal exposures need to be factored into their design.

5.1 - LIMITATIONS AND FURTHER WORK

The methodology and analysis has several limitations. For example, FE modelling generally does not determine the insulative properties of char well over the range of temperatures timber is exposed to, and the dissipation of heat from a timber member is difficult to estimate and validate. Experimental in-depth temperatures are also prone to errors due to thermocouple placement and thermal lag [27]. FE modelling needs to be well verified, with multiple datasets of mass timber values, though accuracy should always be considered in relation to the original data set collection. Glowing and smouldering combustion of timber can also influence the thermal penetration and is not considered in this work. Another limitation are the thermomechanical properties of wood based on the standard fire temperature-time curve, which have limited application for non-standard fires. More research is needed to understand the strength properties of wood at the 100°C to 200°C range and how permanent strength reductions are for timber sections above 100°C, when timber cools. There are few published works that are over 40 years old and modern glulam and CLT members need to be evaluated.

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. Thermal gradients and depths in timber are not well studied in the slower decay phase.

6.0 - SUMMARY

Published fire testing and experiments that track mass timber temperatures in-depth have shown that thermal penetration continues well after the peak compartment temperature and after all flames have ceased. Mass timber elements lose strength and stiffness at a temperature of 100 to 120°C as moisture is driven out by the heating, with the strength loss not reclaimed on cooling. Determining the maximum depth reached by this isotherm is critical to establishing the structural adequacy. This is highly relevant for columns where both the modulus of elasticity and compressive strength parallel to the grain reduce significantly at the relatively low temperatures. The thermal degradation that occurs after the peak temperature or after the end of flaming is not addressed in guidance for engineers. Thus, an engineering methodology has been developed to assess exposed mass timber column structural adequacy for the full duration of a fire, with experimental data from the CodeRed series providing a natural fire dataset for verification. The method has a range of limitations, particularly the prediction of temperatures in-depth accurately and use of effective wood properties.

For exposed mass timber columns, engineers need to assess the thermal degradation depth as part of the structural adequacy determination for a growing and decaying natural fire. If this does not occur, they do not adequately identify the weakest state of a column, which can be many hours after flaming combustion has ceased and they can potentially put occupants and fire fighters at risk in high rise timber buildings built with exposed mass timber columns

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