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Structural response of fire-exposed cross-laminated timber beams under sustained loads

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ABSTRACT

Cross-laminated timber (CLT) is a popular construction material for low and medium-rise construction. However an architectural aspiration exists for tall mass timber buildings, and this is currently hindered by knowledge gaps and perceptions regarding the fire behaviour of mass timber buildings. To begin to address some of the important questions regarding the structural response of fire-exposed CLT structures in real fires, this paper presents a series of novel fire tests on CLT beams subjected to sustained flexural loading, coincident with non-standard heating using an incident heat flux sufficient to cause continuous flaming combustion. The load bearing capacities and measured time histories of deflection during heating are compared against predicted responses wherein the experimentally measured char depths are used, along with the Eurocode recommended reduced cross section method and zero-strength layer thickness. The results confirm that the current zero-strength layer value (indeed the zero-strength concept) fails to capture the necessary physics for robust prediction of structural response under non-standard heating. It is recommended that more detailed thermo-mechanical cross-sectional analyses, which allow the structural implications of real fire exposures to be properly considered, should be developed and that the zero-strength layer concept should be discarded in these situations. Such a novel approach, once developed and suitably validated, could offer more realistic and robust structural fire safety design.

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1. Introduction and background

Cross-laminated timber (CLT) is an engineered mass timber product that is increasingly being used as a primary structural material in multi-storey construction. It is typically made from lamellae of softwood lumber, which are bonded one on top of another in a crosswise fashion using a polymer adhesive. The resulting alternating grain directions give CLT strength and stiffness in two directions, making it suitable for two-way spanning slabs, walls, and diaphragms. Cross-laminated timber falls within the "mass timber" family of engineered wood products, alongside glued-laminated timber, which has been widely used in buildings for decades. Construction using mass timber building systems is, however, becoming ever more popular due to various sustainability advantages, both real and perceived, alongside considerable benefits in terms of the speed and ease with which CLT buildings can be constructed in congested urban centres, the use of advanced offsite and modularised construction methods, and reductions in foundation size due to the reduced overall building mass. However, the use of mass timber as a primary structural material in multi-storey buildings is often limited due to the fact that timber is a combustible material, unlike traditional multi-storey building materials such as masonry, concrete, and steel. Before taller mass timber buildings can be designed with full confidence, particularly in cases where there is a desire to express (i.e. expose) the timber elements in the completed structure, the structural response of CLT elements during real fires must be better understood.

1.1. Current approach for fire resistance design

Structural fire design guidance for mass timber elements is available in design codes internationally, and takes many forms. The most advanced and rational guidance is likely that set out in Eurocode 5 [1], which can be used to determine the standard fire resistance of timber elements based on a simplified, notional charring rate and a reduced cross section calculation methodology

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Nomenclature

b_0	original breadth of structural element [m]
b_T	transformed breadth of structural element [m]
β_0	one-dimensional charring rate under a standard cellulosic fire exposure [mm/min]
$E_{\parallel}$	Young's Modulus parallel to the grain direction [N/m^2]
$E_{\perp}$	Young's Modulus perpendicular to the grain direction [N/m^2]
L	span length [m]
M	applied bending moment [Nm]
$M_{A,c}$	ambient temperature bending moment capacity established from control tests [Nm]
P	applied vertical load [N]
θ_n	free rotation at node n [rads]
v_n	free vertical translation at node n [m]
V	applied shear force [N]
Xa-b-c	specimen naming scheme (X=ambient temperature (A) or in fire (F), a=number of layers; b=load level; c=test number)

(described later). While CLT is not explicitly treated in the Eurocode, current practice in industry is to design CLT essentially as would be done for solid softwood timber; incorporating suitable modifications to account for CLT's crosswise lay-up. This approach takes advantage of so-called self-protection of the timber by surface charring and loss of an acceptable sacrificial depth of the surface timber, which protects and insulates the underlying (cool) timber.

Two specific, simplified methods are suggested in Eurocode 5 to determine the load bearing capacity of a mass timber (and, by extension, CLT) element during exposure to the ISO 834 [2] standard cellulosic compartment fire; (1) the reduced cross section method, and (2) the reduced properties method. The reduced properties method only applies to elements subject to fire from three or four sides, which is not typically applicable for CLT elements and is therefore not discussed herein (indeed, it is rarely used in practice even when applicable, and is slated for deletion from the upcoming revision to Eurocode 5).

The reduced cross section method assumes that timber will char at a notional charring rate during exposure to a standard fire, and then uses this notional charring rate to predict the depth of charred timber. The char is assumed not to contribute to the element's load bearing capacity and, to account for the presence of a zone of heated timber beneath the char, an additional 7 mm layer of 'zero-strength' timber is also assumed to make no contribution to strength or stiffness. The capacity of the timber structural element is then determined based on its ambient temperature mechanical properties, accounting only for the reduced cross section with the charred timber and zero-strength layer ignored.

The reduced cross section approach was originally derived in the 1980s based on numerical simulations of the fire behaviour of glued-laminated timber beams exposed to fire on three-sides by Schaffer [3]. Fig. 1 shows that this approach is fundamentally based on an assumed variation of mechanical properties of the timber below the char, which in turn is based on a small number of tests and on Monte Carlo analysis of the predicted responses. This is also for a specific North American timber species under specific, standard testing conditions (both heating and loading), rather than based on a rigorous assessment of mechanical properties from mechanical tests of the constituent timber materials and adhesives used. Based on his analysis and assumed mechanical inputs for heated timber below the char, Schaffer concludes that timber at depths below 0.3 in. (≈ 7 mm) from the base of the char layer can be assumed to be at full strength, with all other charred and heated timber ignored (as shown in Fig. 1(b)).

It is noteworthy that the 7 mm zero-strength layer approach has not been carefully experimentally assessed for application to CLT elements in bending, and that previous authors have criticised it as being inaccurate and physically unrealistic for solid timber or

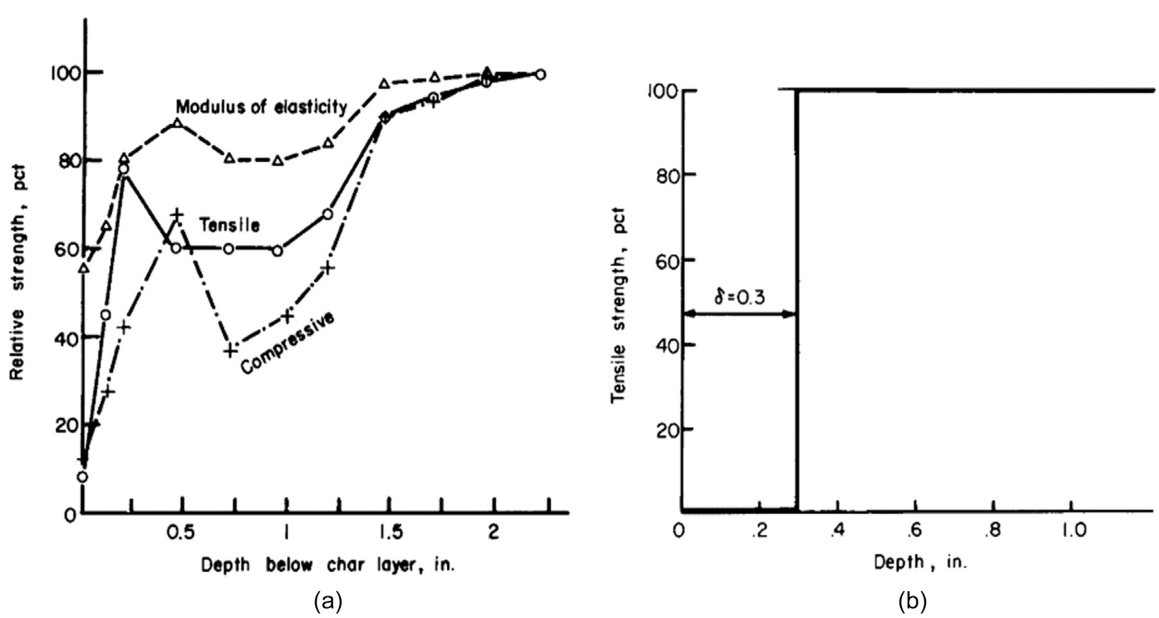

Fig. 1. The origins of the zero-strength layer in the work of Schaffer (after [3]) based on (a) variation of mechanical properties of timber beneath the char layer and (b) an assumed ambient temperature reduced cross section.

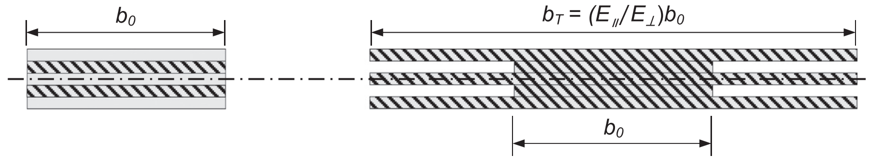

Fig. 2. Schematic showing the transformed section analysis approach commonly used to predict the flexural properties of CLT structural elements.

glued-laminated elements [4]. The current paper presents non-standard fire tests on loaded CLT beams, undertaken to carefully study the applicability of the zero-strength layer concept specifically, and the overall reduced cross section method more generally. It is important to note that the Eurocode 5 [1] reduced cross section method is strictly applicable only to standard fire exposures, however the physical realism of the reduced cross section approach can be interrogated using non-standard heating.

The one-dimensional charring rate (β_0), which is applicable for structural fire design of CLT planar elements subjected to an ISO 834 standard fire, and given in Table 3.1 in Eurocode 5 [1], is 0.65 mm/min. This value is quoted for 'softwood and beech, and for solid timber with a characteristic density greater than 290 kg/m^3', and strictly speaking would apply for the CLT elements tested in the current study only if they were exposed to a standard fire [2] in a fire testing furnace.

The mechanical properties of timber, as well as their variation with temperature, depend greatly on the grain orientation with respect to loading. The orthogonal crosswise lay-up of timber lamellae in CLT panels means that, when subjected to one-way bending, the crosswise layers contribute comparatively little to the strength and stiffness of the element. To account for this issue during analysis, an effective cross section can be defined by using a simple transformed section analysis, based on an assumed ratio of elastic moduli for the strong (i.e. longitudinal) and weak (i.e. cross-ply) layer orientations. This modular ratio, which is denoted as $E_{\|}/E_{\perp}$, is commonly assumed as about 30 for softwood timber [5]. This approach has been experimentally verified at ambient temperatures by Okabe [6], and is shown schematically in Fig. 2. It is assumed herein that this transformed section approach applies equally during fire.

1.2. Response of Timber to Heating

When timber is heated to temperatures exceeding 200 °C, pyrolysis occurs and a layer of carbonaceous char is formed at the fire-exposed surfaces [7]. This char layer is of low effective thermal conductivity and acts as natural insulation for the underlying timber, reducing the rate of charring and insulating the core of the timber element. Beneath the char layer exists an uncharred but heated drying and pyrolysis zone, which shows visible discolouration and has reduced mechanical properties (see Fig. 1 for example).

A number of controlling processes affect the heat transfer beneath the char layer; these include: species, rate of heating, surface oxidation, crack formation, reaction kinetics, pressure gradients, and moisture content. Evaporation of moisture at temperatures close to 100 °C significantly influences the internal thermal gradients [8]. The available research shows that the resulting temperature distribution through heated timber elements can be predicted with reasonable accuracy [8]. This is recognised by Eurocode 5 [1], and enables thermo-mechanical sectional analysis approaches in lieu of the simplified reduced cross section method, which is currently more commonly used in practice. Sectional analysis approaches, however, require that the mechanical property reductions for heated timber beneath the char layer can be accurately accounted for. While this is not the focus of the current paper, the tests (and novel test method) discussed herein will be used to support the development of such approaches in the future.

1.3. CLT Flexural elements in fire

A number of furnace tests assessing the structural performance of isolated CLT elements under exposure to standard fires [2] and concurrent sustained mechanical loading are available in the literature [9–13]. The validity of the reduced cross section and zero-strength layer concepts for CLT elements in bending has also previously seen initial investigation [11]. Based on these tests, proposals have been made for revised zero-strength layer thicknesses, which depend on the specific lay-up of the CLT, the presence of cross layers, section depth, and whether the fire-exposed timber is in the tension or compression zone of an element [9]. All of the proposed revised zero-strength layer depths from available research are greater than the Eurocode's currently suggested 7 mm. It has been concluded from prior research that specific revisions to the reduced cross section method (or entirely new methods of analysis) are needed to properly account for potentially different loading modes, non-standard fire exposures, protected versus unprotected elements (i.e. heating and charring rates), and full-frame assemblies. This large number of revisions raises the question of whether the fundamental basis of the reduced cross section analysis method is adequate to properly account for the necessary physics, and whether an alternative analysis/design method, using available (and future) scientific knowledge on the thermal and mechanical response of heated timber and based on a thermo-mechanical sectional analysis method, rather than one based on a reduced cross section, may be necessary.

The available literature on the fire performance of CLT appears to have been primarily interested in improving the reduced cross section method, typically by proposing revised zero-strength layer depths for different situations, whereas the impetus of the current paper is to better understand the mechanics of heated/charring CLT in bending under sustained loading.

2. Experimental programme

The experimental programme in the current study consisted of tests on 12 one-way spanning CLT beams tested under four point bending. Two different CLT lay-ups with the same overall thickness of 100 mm were studied; one with three lamellae and one with five. The overall dimensions of all specimens were identical. Four control specimens were tested to failure under displacement control at ambient temperature (two of each lay-up) and the remaining eight specimens were subjected concurrently to sustained mechanical loading and severe radiant heating. Heating was from below, within the beams' constant moment regions until flexural failure. Details of the testing matrix are given in Table 1.

Table 1
Testing matrix used in the current study.

Beam designation	Testing condition	Number of lamellae	Loading
A5-00-1	20 °C	5	2 mm/min to failure
A5-00-2	20 °C	5	2 mm/min to failure
A3-00-1	20 °C	3	2 mm/min to failure
A3-00-2	20 °C	3	2 mm/min to failure
F5-20-1	Constant incident heat flux from below	5	20% of ambient capacity
F5-20-2	Constant incident heat flux from below	5	20% of ambient capacity
F5-10-1	Constant incident heat flux from below	5	10% of ambient capacity
F5-10-2	Constant incident heat flux from below	5	10% of ambient capacity
F3-20-1	Constant incident heat flux from below	3	20% of ambient capacity
F3-20-2	Constant incident heat flux from below	3	20% of ambient capacity
F3-10-1	Constant incident heat flux from below	3	10% of ambient capacity
F3-10-2	Constant incident heat flux from below	3	10% of ambient capacity

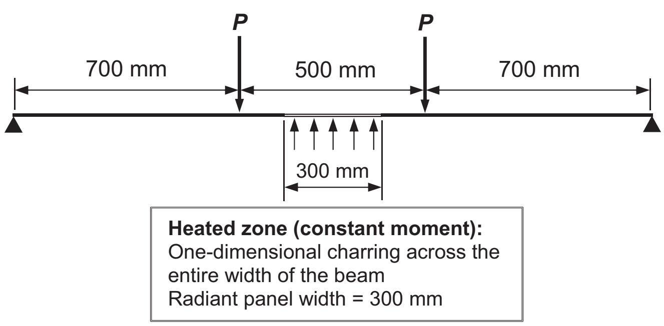

Fig. 3. Loading (and heating) arrangement used for the ambient flexural (and fire) tests.

2.1. Test beams

The CLT beams were cut from 2 m × 2 m CLT plates supplied by Hasslacher Norica Timber.[1] All of the 12 beams had overall dimensions of 2000 mm (length), 300 mm (breadth), and 100 mm (depth). The specific layer configurations used were:

- Five-layer configuration: 20(s)+20(w)+20(s)+20(w)+20(s) mm
- Three-layer configuration: 33(s)+34(w)+33(s) mm

where s and w signify strong (longitudinal) and weak (perpendicular) grain orientations, respectively. The manufacturer's specifications gave a characteristic bending strength of 24 MPa and a shear strength of 0.8 MPa. The average density of the CLT was measured by the authors as 457 kg/m^3, and the average moisture content was also measured by the authors – based on mass loss dehydration – as 10% at the time of testing. The specific CLT product used in was fabricated from common spruce/pine timber and bonded using melamine formaldehyde adhesive.

2.2. Test setup and loading conditions

The four point loading configuration used in both the ambient and elevated temperature tests is shown in Fig. 3. To establish the capacities and corresponding failure modes of the two specimen lay-ups, two specimens of each were loaded to failure at ambient temperature to determine their failure modes and actual, as opposed to manufacturer specified, material properties.

The control beams failed either in tension at their soffits (i.e. bending failure), or by a ‘rolling shear’ failure in the weak lamella at loads very close to the theoretical tensile (i.e. bending) strength. Both 5-layer specimens failed by tensile rupture of the bottom lamella (bending), whereas both three-layer specimens failed in rolling shear. Rolling shear is a mode of failure specific to cross-laminated timber products, wherein the weak lamella “rolls” as the adjacent strong layers slide past each other due to shear flow developed via composite action.

All specimens tested at ambient temperature displayed essentially linear load versus deflection responses, as expected, and failed at loads that reasonably agreed with predictions assuming nominal mechanical properties for the timber. The average bending strength of the timber resulting from these tests was 35 MPa, with a standard deviation of $\pm$2 MPa, as compared with the manufacturer specified characteristic value of 24 MPa. The average flexural elastic modulus of the timber was determined to be 10,500 MPa $\pm$ 1200 MPa.

For the fire tests it was desired to apply sustained loads to the specimens during heating that could be considered as representative of the sustained loading levels that would be expected in a typical service condition. Based on prior work by others [10], and on the loading and resistance factors suggested in relevant design codes, the applied (sustained) loads during the fire tests were selected as either 10% or 20% of the beams' experimentally determined ambient temperature capacity.

Despite the rolling shear failure mode that was observed for the three-lamella configuration during ambient temperature tests, a decision was taken to only assess flexural failure modes during heating (see Fig. 3) during the initial studies presented herein, and the beams were heated only within their constant moment region. The potential for rolling shear failures under fire conditions is significant and will be assessed in future tests in which the shear span will be preferentially heated to assess the rolling shear strength of CLT beams at elevated temperature.

2.3. Fire test setup

The fire test setup is shown in Fig. 4. This custom designed fire testing setup enabled the CLT beams to be simultaneously subjected to sustained loading and heating (from below), and importantly to be carefully assessed for their structural performance under severe (non-standard) heating. This novel testing approach avoids many of the pitfalls of standard furnace testing, in which careful measurements and visual observations of response are more difficult to make.

[1] The specific CLT manufacturer is named simply for the purposes of factual accuracy. This should not be construed as commercially-motivated.

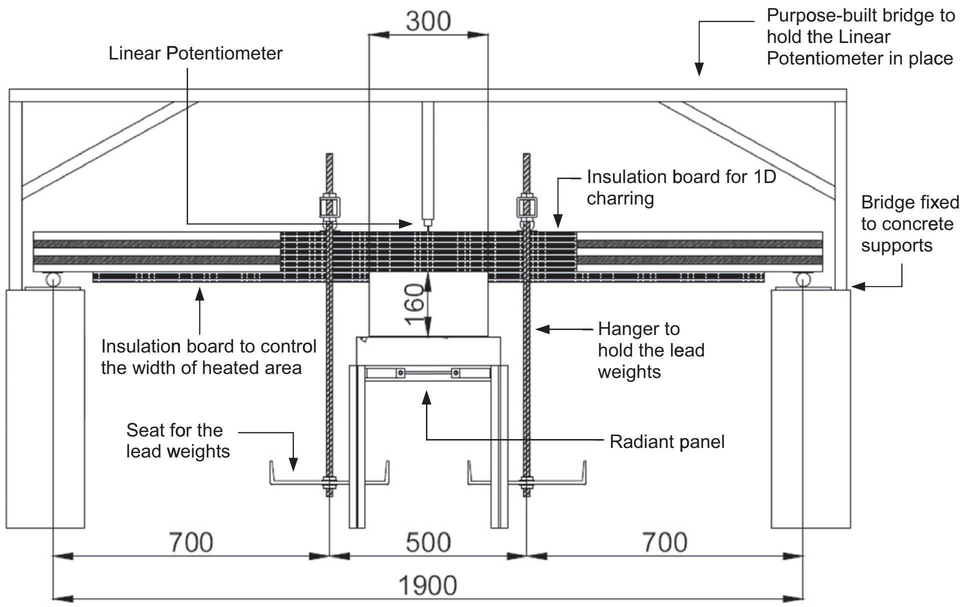

Fig. 4. Details of the experimental set-up for the fire tests (all dimensions in mm).

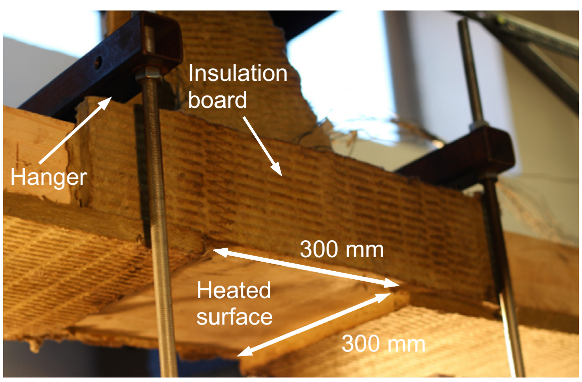

Fig. 5. Detail photo of a typical beam's heated surface, mineral wool insulation, and hanger rods for load application (photo taken prior to heating).

The heating imposed was a constant incident heat flux from a propane-fired radiant panel; this was situated beneath the specimens' constant moment region (i.e. fire exposure on the tension face). The incident heat flux from the radiant panel, measured at the surface of the timber using a Gardon gauge, was 27.7 ± 2.5 kW/m^2. It is noteworthy that the imposed heat flux in the current testing programme is somewhat less than expected during a standard ISO 834 [2] furnace test; the analysis and discussions presented below should be considered with this fact borne in mind. Charring rates for timber under a range of different heat fluxes have previously been presented and discussed for example by Bartlett et al. [14], among others.

Mineral wool was used to create a heated area of dimensions 300×300 mm in which the heat flux was in the in the desired range. This was applied on the sides of the specimen in the area above the radiant panel and along the soffits (Fig. 5). This also assisted in promoting one-dimensional heat transfer. Mineral wool was selected as the insulation material because it would not contribute significantly to the specimens' flexural strength.

Both the incident heat flux used and the length of the heated portion of the beam were essentially arbitrarily selected, but were dictated by the radiant heating panels available and the overall geometry of the testing setup. Given these constraints, it was desired to achieve the highest practicable incident heat flux within a beam's constant moment region.

Sustained loading was applied to the beams during testing by hanging lead weights on steel hangers at a distance of 700 mm from each end, as depicted in Fig. 4. The beams were loaded gradually under ambient temperature conditions, prior to ignition of the radiant panel. Deflection readings were taken throughout this process and the load-deflection response was compared against

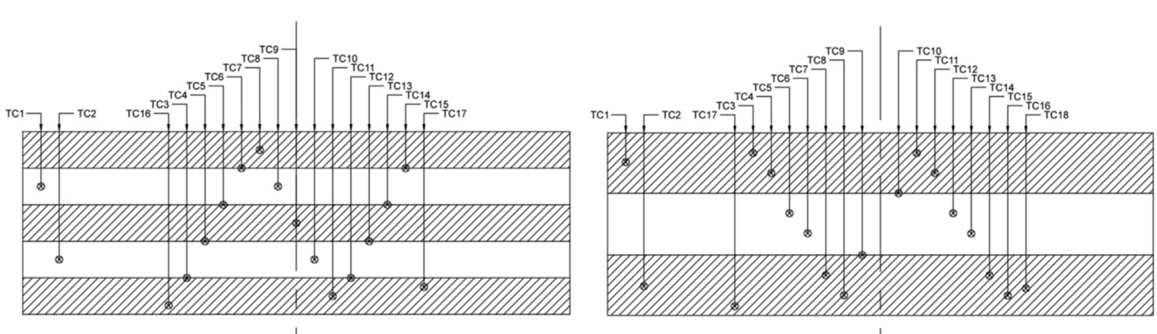

Fig. 6. Thermocouple arrangement for the five-layer (left) and three-layer (right) beams.

the ambient temperature tests; deflections under the sustained loads agreed with ambient temperature tests with a maximum deviation of 1.5%.

A linear potentiometer (LP) was situated at mid-span to measure vertical deflection during heating. The temperatures through the beam's cross section were measured using 1.5 mm diameter Type-K Inconel sheathed thermocouples (TCs). A total of 17 or 18 thermocouples were used for the five-layer and three-layer tests, respectively. The thermocouples were installed from the back of the sample in accordance with published best practice for precise thermocouple placement in timber test specimens [8]; their specific placement is shown in Fig. 6. These thermocouples account for less than 0.02% of the beams' cross-sectional area within the heated zone, and it is therefore unlikely that the presence of the thermocouples had any effect of the structural integrity or response (this assumption was partially verified during the fire tests by comparing the flexural stiffness of the thermocouple-instrumented beams during loading prior to heating with that obtained for beams without thermocouples tested at ambient temperature; no observable differences were noted for beams with or without thermocouples).

3. Structural fire response predictions

3.1. Flexural capacity with heating

The reduced cross section method, along with the assumed transformed section (see Fig. 2), was used to predict the structural fire response of the specimens under the loading and heating conditions shown in Figs. 3 and 4. Predictions were made using Eurocode 5 [1]; wherein the reduced cross section method was used to establish the reduced cross section and properties during each analysis time step at one-minute intervals. Initially these predictions were made assuming that either no delamination of lamellae (i.e. separation of the heat-exposed outer layers of the CLT during heating) would occur, or that delamination would occur when the effective char depth for a particular lamella exceeded the depth of its glue line. It should be noted that the causes of delamination remain unknown, as are the factors that exacerbate its occurrence, although some authors [11,13] have suggested that it depends primarily on the type of adhesive used in the CLT manufacture.

The resulting predicted reductions in flexural capacity with heating for both three- and five-layer CLT configurations are shown in Fig. 7, and suggest that the potential consequences of delamination are more significant for the five-layer configuration due to the fact that this configuration relies quite heavily on its central lamella to maintain structural capacity. It is important to remember that the predictions in Fig. 7 assume a standard fire exposure, and hence standard fire charring rates, and that this is not what was actually achieved during the tests presented herein.

3.2. Time-history of deflection with heating

To better understand the mechanics of the CLT beams under heating, it was also desired to make theoretical predictions of their time history of deflection. This was accomplished again using the reduced cross section method, the effective cross section shown in Fig. 2, the assumed Eurocode 5 [1] charring rates, and a simple direct stiffness beam model. A direct stiffness approach was necessary since only the central 300 mm of the beam was directly exposed to heating, and thus the reduced cross section method was only applied in this area. A time step of one minute was again used, and the following analysis procedure was implemented (Refer to Fig. 8):

1) The beam was divided in half, using symmetry, and then divided again into heated and unheated elements.

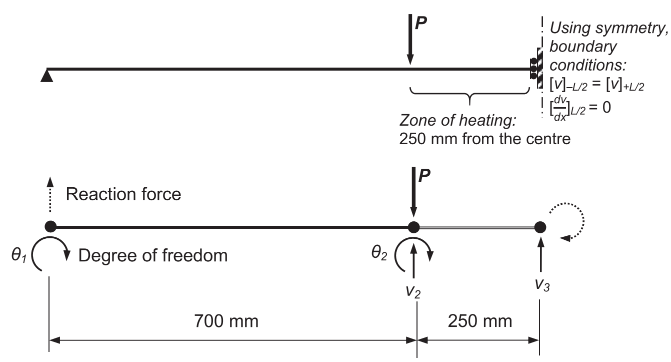

Fig. 8. Schematic showing the physical basis of the deflection prediction model.

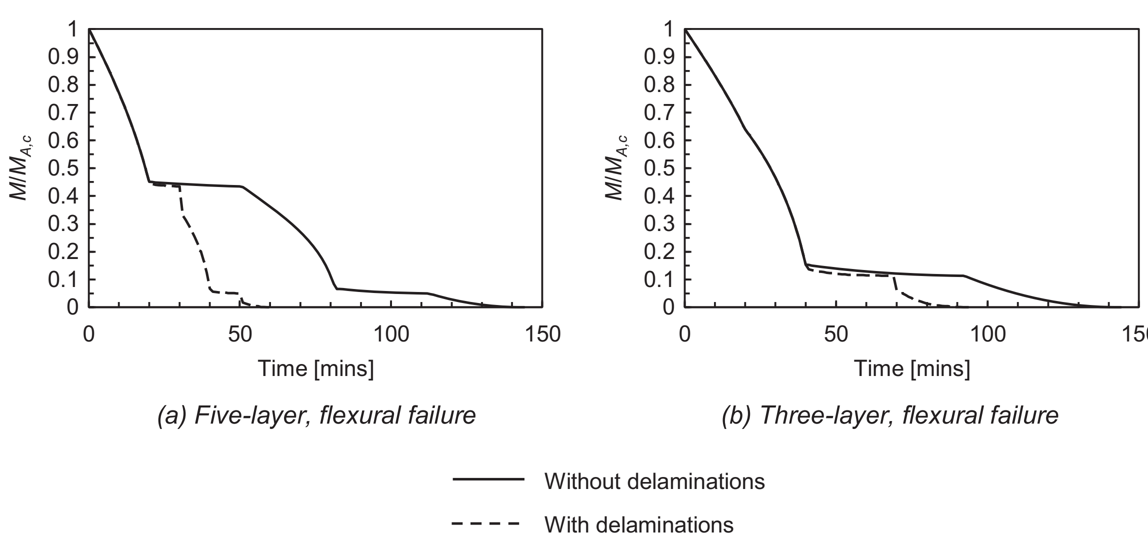

Fig. 7. Predicted reductions in flexural capacity for both three-layer and five-layer CLT specimens, with charring rates and material properties assumed in accordance with Eurocode 5 [1], for exposure to the ISO 834 [2] standard fire, and providing solutions both with and without delamination of fully charred lamellae.

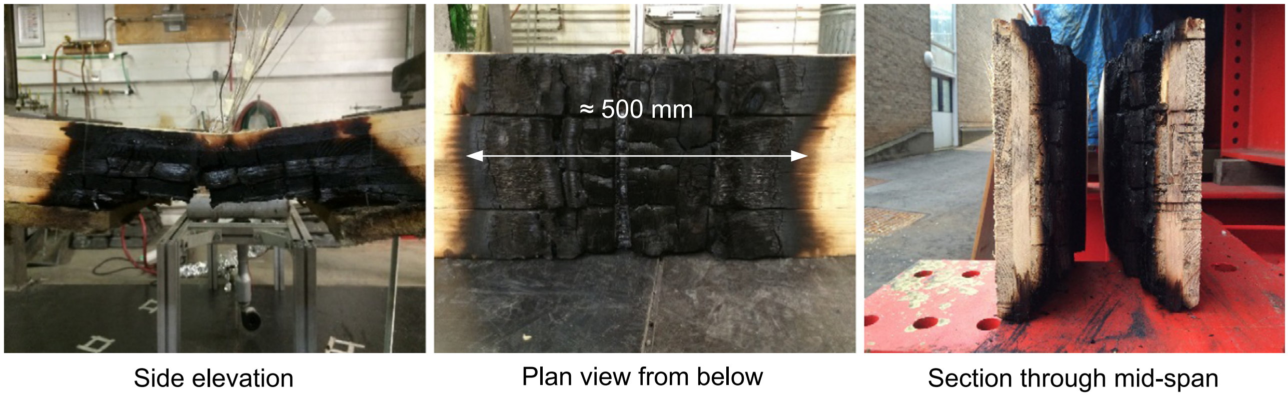

Fig. 9. Photos of a representative CLT sample after fire testing.

2) Flexural stiffness matrices were established for both elements for both unheated (uncharred) and heated (reduced cross section) elements. The unheated element's elastic properties were assumed invariant with time, while the heated element's cross section was reduced based on the assumed charring depth at each one-minute interval.
3) The global stiffness matrices applicable to the free degrees-of-freedom of the system were developed for each time step using a MATLAB script.
4) The system was then solved for the central vertical displacement at each time-step under the constant sustained load.

It is noteworthy in Fig. 8 that the length of the heated element assumed in this analysis was 500 mm, rather than the heated length of 300 mm. This is due to the fact that post-test investigation demonstrated a charring length of approximately 500 mm resulting from three-dimensional heat transfer within the beams. This is shown for a typical specimen in Fig. 9.

4. Results and discussion

4.1. Char depth and charring rates

The critical aspect of all currently used simplified models to predict the structural response of CLT (indeed all timber elements) under exposure to fire is the assumed charring rate. The charring rate observed in the current tests must therefore be examined if the goal is to assess either the physical validity of the Eurocode 5 reduced cross section approach or the 7 mm zero-strength layer thickness. The tests described herein were not performed within a fire testing furnace, and they thus cannot be used to directly criticise the specific charring rates or zero strength layer quoted within Eurocode 5 [1].

Before discussing observed charring rates, it must be noted that no significant delamination was observed during any of the tests presented herein. Very minor, localised delaminations were observed very late in the tests, in most cases coincident with structural failure, although these are not thought to have had any obvious influence on the observed charring rates. It should also be reiterated that the beams tested in the current study were only exposed to heating over a short length, and are therefore unlikely to represent the response of CLT elements within a fully involved compartment fire.

The time-dependent evolution of the char depth was determined based on the in-depth temperature measurements recorded during each test. Temperature was plotted as a function of depth and a least-squares best-fit cubic polynomial was fitted to the data at each time step; this was then used to interpolate for char depths between thermocouple measurement locations. As is typical in the literature [1], the char depth was assumed as the location of the 300 °C isotherm. The interpolated (calculated) char depth response data were numerically differentiated to obtain the instantaneous charring rate.

The resulting and expected char depth and charring rate responses for non-standard fire exposure are shown in Fig. 10. The Eurocode 5 predictions (again, which are strictly valid only for heating in accordance with an ISO 834 furnace test) are also shown for comparison. It is clear that the experimental charring depths were, in all cases, less than those expected on the basis of the Eurocode 5 constant notional charring rate; by 3–8 mm. It is also clear that the observed charring responses were, as expected, considerably more complex than assumed by the simplified reduced cross section method.

For simplicity, Eurocode 5 assumes that the char layer begins to form immediately in a fire; this is physically incorrect (however conservative) for real heating scenarios to be expected in building compartment fires. The onset of charring (if defined by the progression of a 300 °C isotherm into the timber element) occurred approximately 10 min from the onset of heating in the tests presented herein according to in depth temperature measurements. The onset of charring for furnace tests with ISO 834 [2] thermal exposure is typically in the range of two to three minutes.

As expected, in reality the char layer does not develop at a constant rate, as is assumed by Eurocode 5 as a simplification valid only for an ISO 834 [2] fire exposure within a standard fire testing furnace. Instead, the charring rate rapidly reaches a peak value before decreasing to a lower, quasi-steady value [7]. The peak charring rate is known to be sensitive to the heat flux [14]. However, for long exposures, the average quasi-steady charring rate becomes independent of heat flux between approximately 30–100 kW/m^2 [14]. The quasi-steady charring rate is lower than the recommended Eurocode 5 value. This should be expected given that the Eurocode charring rate is likely intended to be an approximately constant but conservative value.

The thermal penetration depth, quoted herein as the depth of heated timber beneath the 300 °C isotherm that is heated above ambient, was estimated as between 35 and 45 mm for all heated tests in the current study (once a char layer had formed). This agrees well with values quoted in the literature [3,15], and upon which the reduced cross section method and 7 mm zero strength layer are based.

4.2. Comparisons against Eurocode 5 Predictions

Based on the experimentally observed char depths at failure, and with precise knowledge of the sustained applied load at

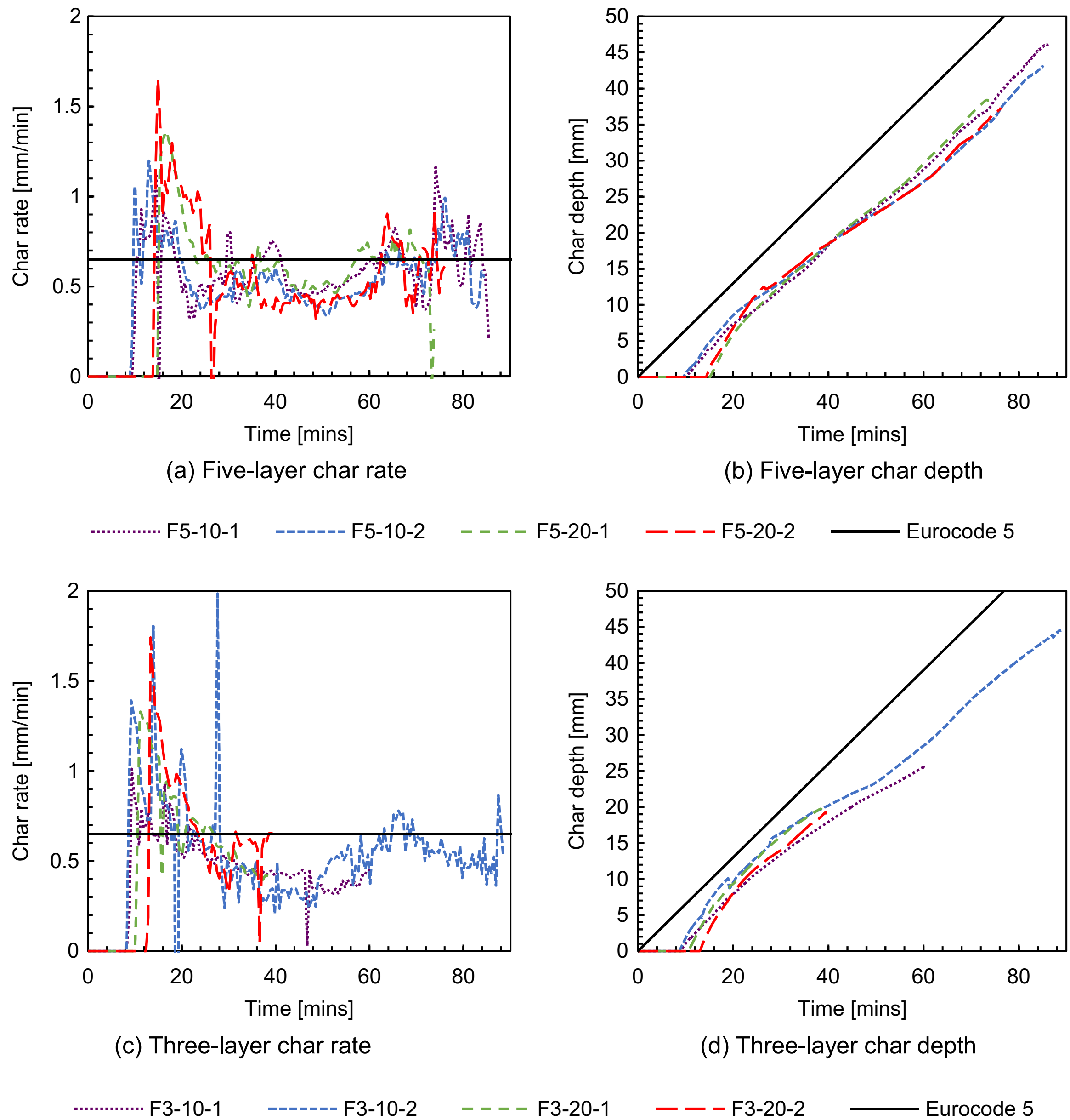

Fig. 10. Experimentally measured and Eurocode 5 [1] predicted charring behaviour for all fire tested specimens.

Table 2
Experimental char responses and calculated zero-strength layer depths; compare to the Eurocode 5 charring rate of 0.65 mm/min and zero-strength layer depth of 7 mm.

Parameter		Five-layer				Three-layer			
		F5-20-1	F5-20-2	F5-10-1	F5-10-2	F3-20-1	F3-20-2	F3-10-1[a]	F3-10-2
Char response	**Depth of char layer at failure (mm)**	38.5	37.2	46.0	43.1	19.6	19.1	25.5[a]	44.5
	Depth of char layer expected based on Eurocode 5 (mm)	48.1	49.4	55.9	55.3	24.7	25.4	39	57.9
	Time to failure (mins)	74	76	86	85	38	39	60[a]	89
	Equivalent Eurocode charring rate (mm/min)	0.52	0.49	0.54	0.51	0.51	0.49	0.43[a]	0.50
Zero-strength layer	**Depth of reduced section at failure (mm)**	61.5	62.8	54.0	57.0	80.5	80.9	74.5[a]	55.5
	Depth required assuming 100% strength (mm)	43.7	43.7	40.0	40.0	67.6	67.6	30.7[a]	30.7
	Depth of zero-strength layer at failure (mm)	17.8	19.1	14.0	16.9	12.8	13.2	43.7[a]	24.8

[a] Test halted prior to true failure.

failure, it is possible to determine the zero-strength layer depth that would be required, based on a transformed section and using the reduced cross section method, to result in bending failure for each specimen. Experimental zero-strength layer values were determined by subtracting the calculated position of the char layer at failure from the depth of full-strength section required to carry the applied sustained load. These comparisons are given in Table 2, along with experimental data for time to failure and zero-strength

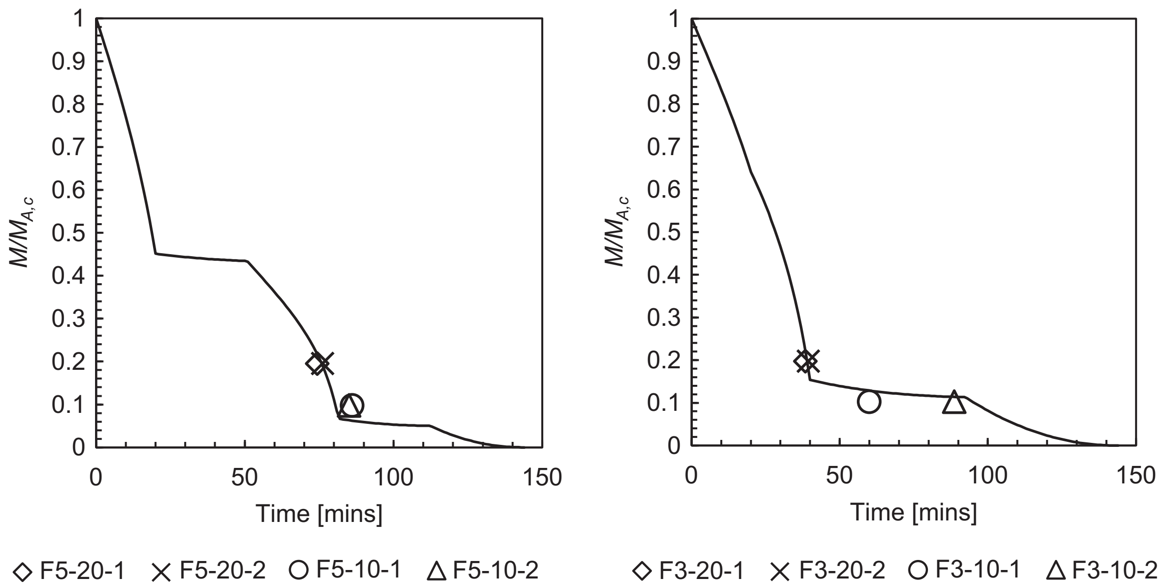

Fig. 11. Experimental results presented along with predicted flexural strength reductions with time for the five-layer (left) and three-layer (right) specimens.

layer thickness. The charring rates denoted as "Equivalent Eurocode" in Table 2 were determined assuming constant charring rates initiating at the onset of heating. It is noteworthy that the difference between onset of heating and onset of charring for ISO 834 [2] furnace tests is in the range of two to three minutes, and is neglected in practice for simplicity. The difference between onset of heating and onset of charring for the tests presented herein was in the range of 10 min.

The average experimental charring rate – excluding Specimen F3-10-1 due to this test being halted prematurely – was 0.51 mm/min; i.e. 22% less than the Eurocode 5 value of 0.65 mm/min. This value would have been higher if the charring rate was calculated using the onset of charring (rather than the onset of heating). However, the purpose of the current paper is to not to assess the validity of the Eurocode 5 charring rates, but rather to interrogate the physical assumptions that are inherent in the reduced cross section method. It is evident from Fig. 10 and Table 2 that the level of applied sustained loading had no significant effect on the charring response.

4.3. Fire resistance predictions

The structural fire resistance times for each of the tested beams (i.e. time to failure under sustained load) can be predicted using the flexural capacity predictions already presented in Fig. 7 as the time when the predicted capacity drops below the applied mid-span moment. Given applied loads of either 10 or 20% of the ambient temperature capacity of the beams, the experimental failure times (and load levels) are shown in Fig. 11 for the case of no delamination, since none was observed during testing.

Fig. 11 shows that the Eurocode 5 flexural capacity prediction model, being based on the Eurocode 5 charring rate along with the a transformed section analysis and the reduced cross section method, actually agrees surprisingly well with the observed failure times for both the three- and five-layer CLT specimens. At first glance, this appears to give credence to the reduced cross section method and 7 mm zero-strength layer, until it is recognised that, as shown in Table 2, the experimentally observed char depths at failure were considerably less (by 5–10 mm, i.e. 18–25%) than would be expected based on a constant charring rate of 0.65 mm/min. The experimentally obtained zero-strength layer exceeded 7 mm in all cases, and on average – again excluding Specimen F3-10-1 – these were 143% larger than suggested by Eurocode 5, at 17 mm.

Fig. 11 and Table 2 therefore actually show that, as expected, the Eurocode reduced cross section method fails to capture the relevant physics, particularly in the case of non-standard thermal exposures. The apparent good agreement between the test data and the model predictions in Fig. 11 is actually due to offsetting errors in this heating scenario – (1) a poor prediction of the charring rate (and hence depth), coupled with (2) a considerable under-prediction of the zero-strength layer depth – and is therefore physically incorrect when applied to the test data presented. The repeatability of testing was excellent using this novel testing approach.

4.4. Predicted deflection-time responses

Additional insights into the response of CLT during fire can be gleaned from investigating the prediction of time-history of deflection of the beams during heating until failure. The deflection prediction model described previously was applied to the tested beams, taking two different approaches to unpick the physics influencing the beams' observed responses:

- *Model 1:* The reduced cross section method was applied exactly as specified by Eurocode 5, including both the notional charring rate of 0.65 mm/min and the presumed 7 mm zero-strength layer.
- *Model 2:* A 7 mm zero-strength layer was used, along with the experimentally measured char depth obtained during each specific test (i.e. the "experimental char depth" lines in Fig. 10).

The results of these two analyses are shown in Fig. 12.

It is clear in Fig. 12 that neither of the models accurately predict the responses of all beams tested in the current study. Model 1 – essentially a direct application of the simplified Eurocode 5 assumptions and methodology – is able to reasonably predict the failure times (i.e. fire resistances) of the beams, however as already noted this is should not be construed as an endorsement of the physics accounted for in this approach. Indeed, the deflection path to failure is poorly predicted, providing additional credence to the idea that a constant zero-strength layer depth of 7 mm is physically incorrect, in particular for fire exposures other than ISO 834

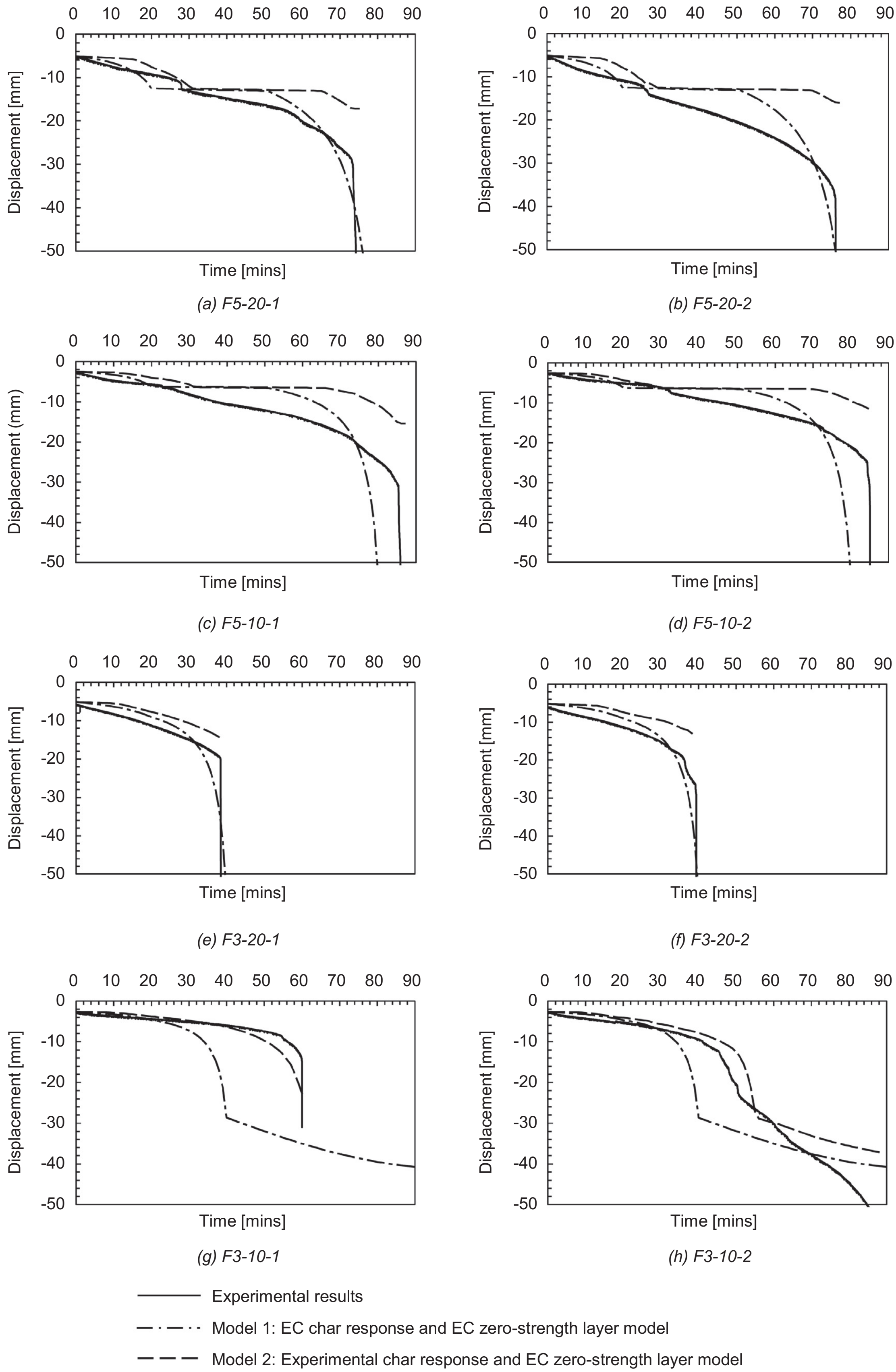

Fig. 12. Deflection responses from experiments and for both models.

applied within a standard fire testing furnace. Model 2 – which uses the true (i.e. experimentally measured) charring depth – makes even less accurate predictions of time-deflection response, and significantly over-estimates flexural capacity during fire. A constant 7 mm zero-strength layer is thus also inadequate even when the correct (i.e. measured) charring depth is used.

It is noteworthy that small "jumps" of increased deflection rate are apparent in the time-deflection responses of most beams during heating, in particular at 28, 26, 24, and 32 min for tests F5-20-1, F5-20-2, F5-10-1, and F5-10-2, respectively. It is suspected that these are a consequence of loss of structural effectiveness of the bottom lamella as the heating front progresses through the bond line with the second lamella, softening the adhesive and resulting in loss of structural composite action. Additional research is needed to better understand the influence of heating on adhesion and composite action between lamellae for the range of adhesives currently used in manufacturing CLT elements in practice.

In reality, even for this simple case of failure within the tension zone of a flexural CLT element, the application of the zero strength layer concept displays notable inaccuracies that are worth considering in practice. For example, the depth of the zero-strength layer must depend on (amongst other factors) the nature and duration of heating, with a 0 mm zero-strength layer at the onset of heating (indeed, for simplicity Eurocode 5 [1] considers the zero strength layer to grow from 0 to 7 mm during the first 20 min of ISO 834 fire exposure) and (apparently based on the tests presented herein) a zero-strength layer considerably more than 7 mm later in the fire exposure. In reality, a complex interplay exists between thermal gradients and mechanical properties in the timber beneath the char layer; this cannot be accounted for with a constant value, particularly for non-standard fire exposures. This renders the reduced cross section method incapable of rationally accounting for the requisite physics, and hence incapable of making good fire resistance predictions for CLT elements under the range of heating and loading conditions that should be expected in real buildings.

Klippel et al. [16] have previously recognised the inadequacy of a constant zero-strength layer for treating the fire resistance of CLT tested using standard heating exposures in furnaces, and have made recommendations for the use of modified zero strength layers to be applied in these cases. However, for non-standard fire exposures the zero-strength layer concept cannot describe the necessary physics and thus cannot, in the opinion of the authors, be resolved by choosing "better" zero-strength layer depths. Beneath the char layer, the temperature profile and the consequent reductions in mechanical properties must be rationally accounted for to properly predict the response of CLT in fire such heating scenarios, such as are now widely applied in performance-based structural fire engineering design.

4.5. Visual observations

To verify some of the key assumptions made during the analytical modelling, all samples were visually examined after testing and cooling. In particular it was desired to verify that the heating/charring was approximately one-dimensional during the testing. Fig. 8 shows that the heated width length was approximately 500 mm centred on the mid-span region.

Fig. 9 also shows that approximately one-dimensional charring was obtained over the mid-span region of the specimens. Mild corner rounding was apparent in some samples, due to a combination of heat penetration behind the mineral fibre insulation and post-failure charring and flaming, which occurred before it could be extinguished once the insulation board was removed from the beam immediately after structural failure. The mineral fibre insulation and charred soffit of a typical beam late in a test are shown in Fig. 13, where the uniformity of the charring can be seen, despite mildly accelerated char penetration at the edges of the beams. Fig. 14 shows a typical beam moments after structural failure; the beam is resting on the radiant panel, resulting in increased charring and flaming and preventing rigorous post-test char depth measurements. In general, the authors are satisfied that the charring response of the tested beams can be approximated as one-dimensional for the purposes of the analyses presented.

Fig. 13. Close-up of the heated zone of a beam during the test.

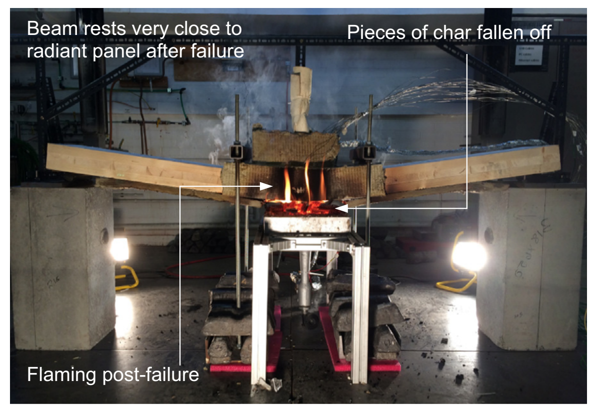

Fig. 14. Representative test just after failure.

5. Conclusions

This paper has presented a series of fire experiments on CLT beams in bending using a novel fire testing method to assess the applicability (and physical realism) of the reduced cross section methodology for predicting the structural response during fire of two specific CLT configurations when subjected to representative levels of sustained load under non-standard fire exposure. The novel test set-up allowed for careful observation of the thermal and mechanical response including measurement of the char front position, the thermal penetration depth, and the time-history of vertical deflection at mid-span.

As expected, the results confirm both that a constant 7 mm zero-strength layer is not applicable to non-standard heating exposures and that, even for this relatively simple loading case, the fundamental concept of a constant zero-strength layer and a reduced cross section analysis is inadequate to accurately predict the structural response or fire resistance of CLT beams for the conditions tested. The discrepancies between predicted and observed responses for the tests described herein are shown to arise both from the assumption of a constant 7 mm zero-strength layer and from an incorrect approximation of the charring depth with heating. Although the inadequacy of the 7 mm zero-strength layer has been identified previously [3], the experiments in the current paper are the first to clearly experimentally demonstrate the failure of the reduced cross section method outlined in Eurocode 5 [1] to properly capture the relevant physical phenomena under non-standard fire exposure, or to clearly highlight the need for the development and validation of a more detailed and rational procedure to model and predict the structural fire response of CLT elements in these scenarios.

Based on the testing and analysis presented in the current paper, it is recommended that a new approach to calculate the thermo-mechanical response of CLT (and timber) be developed, particularly for non-standard fire exposures. This method should account for the progressive loss of strength arising due to the elevated temperatures behind the char layer. Such an approach will require considerable additional research to determine the material properties required to predict the heat transfer beneath the char layer under a range of possible heating conditions, as well as the development of a detailed understanding of the variations in mechanical properties of timber at the expected temperatures and moisture contents.

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References

[1] CEN, Eurocode 5: Design of Timber Structures - Part 1–2: General - Structural Fire Design, British Standards Institute, London, UK, 2009.
[2] ISO, ISO 834-1:1999 - Fire-resistance tests – Elements of building construction – Part 1: General requirements, Int. Organ. Stand. (1999).
[3] E. Schaffer, C. Marx, D. Bender, F. Woeste, Strength Validation and Fire Endurance of Glued-Laminated Timber Beams, Res. Pap. FPL 467, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory,, Madison, WI, 1986.
[4] J. Schmid, A. Just, M. Klippel, M. Fragiacomo, The reduced cross-section method for evaluation of the fire resistance of timber members: discussion and determination of the zero-strength layer, Fire Tech. 51 (6) (2015) 1285–1309.
[5] P. Fellmoser, H. Blass, Influence of Rolling Shear Modulus on Strength and Stiffness of Structural Bonded Timber Elements, International Council for Research and Innovation in Building and Construction, Working Commission W18 – Timber Structures, Meeting 37, Edinburgh, 2004.
[6] M. Okabe, M. Yasumura, K. Kobayashi, K. Fujita, Prediction of Bending Stiffness and Moment Carrying Capacity of Sugi Cross-Laminated Timber, J. Wood Sci. 60 (1) (2014) 49–58.
[7] D. Drysdale, An Introduction to Fire Dynamics, 3rd ed., John Wiley & Sons, Chichester, UK, 2011.
[8] P. Reszka, J.L. Torero, In-depth temperature measurements in wood exposed to intense radiant energy, Exp. Therm. Fluid Sci. 32 (2008) 1405–1411.
[9] J. Schmid, J. König, J. Köhler, Fire-Exposed Cross-Laminated Timber – Modelling and Tests, World Conference on Timber Engineering, Riva del Garda, Italy, 2010.
[10] M. Fragiacomo, A. Menis, I. Clemente, G. Bochicchio, A. Ceccotti, Fire resistance of cross-laminated timber panels loaded out of plane, J. Struct. Eng. 139 (12) (2013).
[11] A. Frangi, M. Fontana, E. Hugi, R. Jöbstl, Experimental analysis of cross-laminated timber panels in fire, Fire Saf. J. 44 (2009) 1078–1087.
[12] J. Schmid, A. Menis, M. Fragiacomo, I. Clemente, G. Bochicchio, Behaviour of loaded cross-laminated timber wall elements in fire conditions, Fire Tech. 51 (2015) 1341–1370.
[13] M. Klippel, C. Leyder, A. Frangi, M. Fontana, Fire Tests on Loaded Cross-laminated Timber Wall and Floor Elements, Fire Safety Science, in: Proceedings of the 11th International Symposium, 2014, pp. 626–639.
[14] A.I. Bartlett, R.M. Hadden, L.A. Bisby, A. Law, Analysis of cross-laminated timber charring rates upon exposure to non-standard heating conditions (San Francisco), Fire Mater. (2015).
[15] A.H. Buchanan, Structural Design for Fire Safety, 1st ed., John Wiley & Sons, Chichester, UK, 2001.
[16] M. Klippel, J. Schmid, A. Frangi, Fire design of CLT, Proceedings of the Joint Conference of COST Actions FP1402 and FP1404, March 10-11, 2016, Stockholm, Sweden.