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Citation for published version:
Wiesner, F, Deeny, S & Bisby, L 2020, 'Influence of ply configuration and adhesive type on cross-laminated timber in flexure at elevated temperatures', *Fire Safety Journal*. https://doi.org/10.1016/j.firesaf.2020.103073

Digital Object Identifier (DOI):
10.1016/j.firesaf.2020.103073

Document Version:
Peer reviewed version

Published In:
Fire Safety Journal

Influence of ply configuration and adhesive type on cross-laminated timber in flexure at elevated temperatures.

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Highlights:

- CLT beams were subjected to heating under sustained loading.
- Significant effect of adhesive type on heat induced deflections was measured.
- Sizeable heat induced deflections were found to be irrecoverable.

Abstract:

This paper describes experiments on cross-laminated timber (CLT) beams exposed to uniform non-charring temperatures under sustained loading. Two different ply configurations and two different adhesive types were examined under sustained loads of both 30 and 50 % of the ultimate ambient temperature flexural capacity. It was found that the adhesive type has a significant influence on the magnitude of the deterioration in structural stiffness during heating. From image correlation analysis this influence was attributed to increased shear strains along the adhesive lines between timber plies for specimens bonded with a polyurethane (PU) adhesive, when compared to those that used a melamine urea formaldehyde (MF) adhesive. It was also found that considerable deflections that were measured during heating were irrecoverable during cooling of the CLT, suggesting that these deformations were driven by creep of the timber – and possibly also the adhesives.

Keywords: timber; adhesives; structural response; creep; protection of wood; cross-laminated timber

1. Introduction

Cross-laminated timber (CLT) is an increasingly popular engineered timber product which consists of layers (plies) of timber boards that are stacked in alternating directions and bonded together with an adhesive. Due to its combustibility fire safety remains a major concern for its use in the construction of multi-story timber buildings [1]. The structural fire safety of cross-laminated timber (and elements of construction in general) is predominately defined in terms of fire resistance, which is a relative measure of how long elements of construction can maintain their structural capacity, insulation, and integrity when exposed to a standardised temperature time curve in a furnace test.

As an engineered material the manufacture of CLT can be varied in multiple ways, most importantly the adhesive used to bond the plies together and their configuration (i.e. their thickness, quantity, and orientation). Currently the selection of adhesives is dominated by economic (i.e. manufacturing time and costs) and indoor climate considerations (i.e. emissions of hazardous gases), and its influence on the fire safety of a timber building is only recently being recognised from a fire dynamics perspective to minimise the occurrence of char fall off in a fire [2, 3]. While it is recognised that different adhesive types display varying performance when heated or subjected to changing moisture levels [4-6], the influence of adhesives on the *structural* capacity of CLT in fire is not currently considered in design and is not well understood.

When timber is heated it will start to pyrolise which will culminate in its conversion to char, which has only negligible remaining mechanical strength or stiffness but is, through its insulating properties and as a barrier for pyrolysis gases, considered to act as a sacrificial protective layer for the uncharred timber below. A region of timber at elevated temperatures lies below the char layer and this timber has reduced mechanical properties [7]. To accurately assess the remaining structural capacity of timber elements in fire it is necessary to understand the magnitude and extend of these reductions in mechanical properties within the timber element. Currently, within the fire resistance framework, the reduction of strength in heated uncharred timber is mostly addressed through a theoretical zero strength layer (ZSL), which is perceived as a finite depth below the char with zero strength and stiffness and all timber below the ZSL is assumed at ambient properties [8]. The effect of the thermal stability of adhesives on the structural capacity of engineered timber is not currently considered in design guidance documents.

The reduced mechanical properties of heated uncharred timber is especially important in the fire decay phase, when the progression of char in timber stops but elevated temperatures continue to be redistributed within a cross-section [9, 10]. In fire resistance furnace testing the structural response is dominated by the formation of the char layer and this limits the insights that can be gained into the effects of the elevated temperatures below the char layer.

This paper describes a series of experiments on CLT beams, bonded with two different adhesive types and two different ply configurations, under sustained load that are subjected to slow quasi uniform heating below charring temperatures. The aim of these experiments is to gain a better understanding of the influence of the adhesive and ply numbers on the structural behaviour in flexure to enable CLT manufacturers and designers to account for fire safety when optimising CLT products against a range of design considerations. It should be noted that the work presented in this paper is different to the assessment of char fall off, which is an important fire dynamics consideration but has no direct influence on the structural behaviour.

2. Material and Methods

The CLT beams for this study consisted of C24 graded timber [11], and were face but not edge bonded with either a one component polyurethane (PU) adhesive [12] or with a melamine urea formaldehyde (MF) adhesive [13], which was applied in combination with a hardener. In each case the same adhesive was used for the finger joints. The ply number was varied so that three ply CLT beams with a 40-20-40 mm configuration, and five ply CLT beams with a 20-20-20-20-20 mm configuration were tested; both configurations had a total thickness of 100 mm. The beams had a length and width of 3000 and 300 mm, respectively. The beams had a mean density of 458 ± 4 kg/m^3 and an estimated mean moisture content of 9 ± 0.1 %, which was determined from separate timber pieces that were stored in the same conditions as the tested beams. A total of 24 beams were tested, eight at ambient temperatures, and eight each at a 'high' and 'low' load level at elevated temperatures.

2.1 Ambient temperature reference tests

To understand the influence of elevated temperatures the structural capacity at ambient temperature must be quantified; this was also used to define appropriate load levels for the heated experiments.

Two repeats for each configuration were subjected to four point crosshead stroke controlled bending at ambient reference temperatures, resulting in eight beams tested. The free span of the beams was 2700 mm and the constant moment section at the longitudinal centre of the beam was chosen as 500 mm (see Fig. 1). This constituted a relatively small section of constant moment in the mid span region relative to the free span. This was chosen to favour a bending failure mode by tensile rupture rather than rolling shear failure in the shear region at ambient temperature.

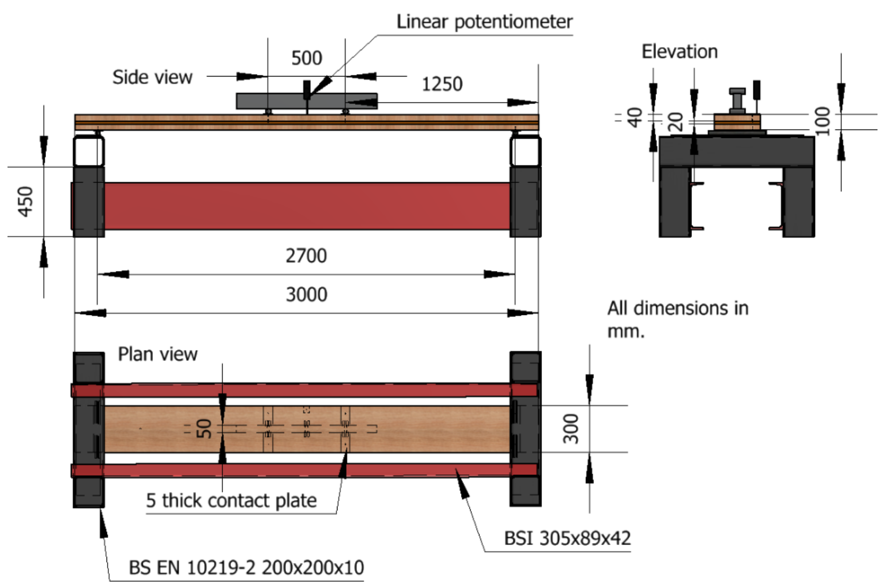

Fig. 1. Elevation and plan view of the experimental set-up for CLT beams in four point bending at ambient reference temperatures. All dimensions in mm.

A linear potentiometer (LP) was placed at midspan to record vertical deflections. At midspan and near the support a speckle pattern was added to the side of the beams to enable digital image correlation (DIC) [14] to be performed based on images recorded by two cameras at five second picture intervals of both the midspan section and the vicinity near the support; this allowed for complementary deflection measurements and was also used to monitor the strain on the side surface of the timber.

2.2 Elevated temperature experiments

The main piece of equipment used for the experiments described in this paper was a bespoke heating chamber that was built around a large reaction beam to expose construction elements with lengths of up to 3000 mm to elevated gas phase temperatures [15]. It was fitted with two heaters at each end which were placed in line with a closed circulation system that was driven by an external fan. The heaters were controlled by a PID temperature control system connected to a resistance thermometer (RTD), which provided temperature readings at mid height above the specimens in the centre of the chamber, thereby controlling the gas phase temperature within the chamber. Within the chamber the loading setup was replicated to the same characteristics as the ambient temperature reference experiments in Fig. 1, i.e. a clear span of 2700 mm and a constant moment region of 500 mm at the centre of the beam. Drawings of the experimental set-up for beams in the heating chamber are shown in Fig. 2. The temperatures in the chamber were limited to 150 °C in the gas phase. The rate of heating was not specifically set and was therefore as fast as possible.

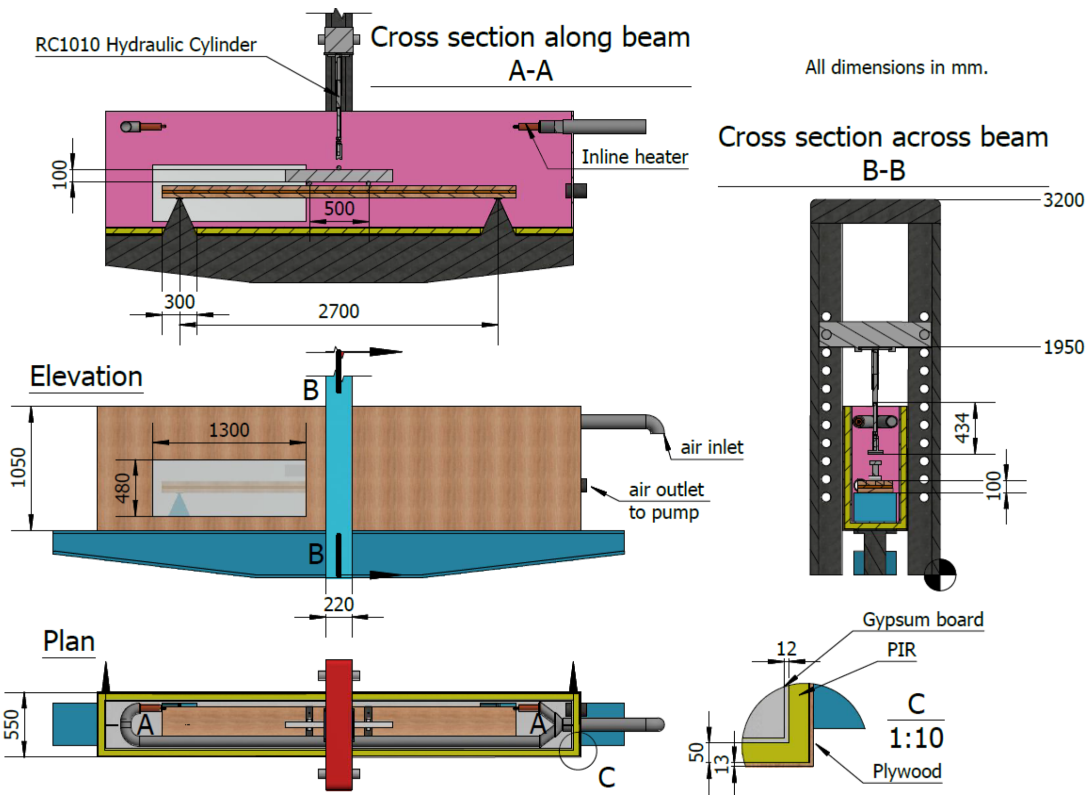

Fig. 2. Plan, section, elevation and detailed views of the experimental set-up for heating of CLT beams under sustained loads. All dimensions in mm.

The midspan displacements of the heated beams were measured using a string pot gauge that was extended into the heating chamber using Invar wire, an alloy with a very low thermal expansion coefficient of approximately 1.2 x 10^{-6} K^{-1}, thereby minimising the influence of thermal expansion of the wire on the deflection measurements. In addition, two cameras were used at the viewports to monitor either side of the beam at the supports; this was done to measure the strains near the support of the beams.

Two sets of experiments were run. One with a high loading ratio of 50 % of the mean ambient ultimate load capacity and one with a lower load ratio of 30 %. For the 50 % loaded samples the experiments were run until structural failure was observed or until the hydraulic jack exceeded its maximum travel distance due to excessive deflections. For the 30 % load ratio, the samples were heated for three hours and then subsequently cooled for three hours in order to gain insights into the recovery of deflections in the CLT beams as they were cooling. The sustained loads during heating were applied prior to heating via a hydraulic jack that was fitted within a slot in the 1000 kN Avery load frame; it was powered by hydraulic power pack and connected to a pressure transducer to control the applied loads. The reach of the hydraulic jack was elongated using a bespoke extension rod that was threaded into the cylinder of the jack. This loading arrangement ensured that loads could be applied to the beams whilst the cylinder of the jack remained outside the heating chamber and not exposed to direct heating.

Inconel sheathed 1.5 mm K-type thermocouples were placed at the longitudinal centre at a depth of 50 mm and spaced at 75 mm along the width of the sample to measure the timber temperatures throughout the durations of the experiments. At the end of the beam close to the view port thermocouples were placed at varying depths from the surface (16.7, 33.3 and 50 mm) 200 mm from the longitudinal beam edge, spaced 15 mm longitudinally along the centre line. The positioning of the drilled holes for the TC placements both at midspan and near the support are shown in Fig. 3.

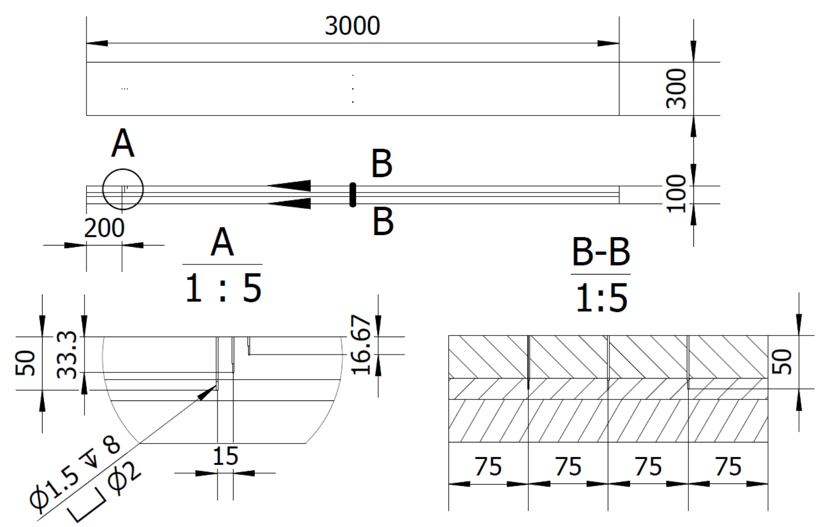

Fig. 3. Thermocouples placements within the CLT beams. All dimensions in mm.

3. Results

3.1 Ambient temperature reference experiments

The load applied to the eight tested CLT beams is plotted against the midspan deflection obtained from DIC data in Fig. 4 a) for 3-ply and b) for 5-ply CLT with different adhesives distinguished by line type and repeats (i.e. 01 or 02) by colour shadings. For all beams a similar behaviour was observed: an initial linear elastic loading response was followed by slight non-linearity, likely caused by plasticity of the compression zone, and a sudden drop in load due to brittle failure.

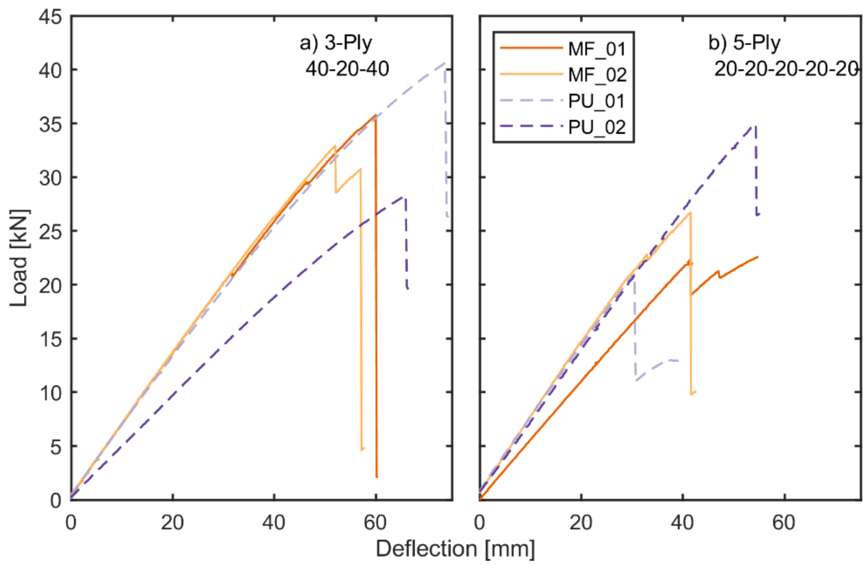

Fig. 4. Load response of CLT beams with increasing midspan deflections for a) three ply and b) five ply configurations.

The mean ultimate loads supported by the beams were measured as 26.3 and 34.3 kN for five and three ply beams, respectively. Since, for the three ply samples more timber was placed with fibre direction orientated parallel to the main stress direction these samples were able to sustain higher loads before failure. One interesting point of note can be observed for Specimen 1 for the five ply melamine formaldehyde configuration (5MF_01). The load drops at a deflection of around 40 mm before resuming to increase and reaching its ultimate load. This can be attributed to the fact that the strength and stiffness of the individual boards, even though they are attributed to the same strength class, are random variables. If an individual board fails the overall load carrying capacity reduces but load can be redistributed across different boards and different layers.

The mechanical properties of the material can be computed in the form of the elastic modulus, E, and the modulus of rupture (MoR), which are computed from Eq. 1 and Eq. 2 , respectively, where M is the ultimate sustained bending moment, y is the distance from the neutral axis to outer fibres, I is the second moment of area, m is the slope of the load deflection path, a is the distance between the supports and the load points, and l is the overall length of the beams. The second moment of area is based on an effective cross-section for which crosswise orientated layers are scaled by the ratio of the elastic moduli between parallel and cross-wise orientated timber, which is assumed as 30 [16]. This method therefore accounts for different ply configurations for linear elastic considerations.

$$\sigma_b = \frac{My}{I} \tag{1}$$

$$E = m\frac{a}{48I}(3l^2 - 4a^2) \tag{2}$$

The modulus of rupture and the elastic moduli for the ambient beam samples are shown in Fig. 5, grouped by adhesive and ply number. For the MoR values it can be seen that the medians between different adhesives and different ply configurations do not differ by much and that the difference observed is likely due to natural variability of the timber. This can be confirmed numerically by performing an analysis of variance (ANOVA) on the varied parameters, the results of which are shown in Table 1. It can be seen that, for the MoR, the null theory of equal sample means, is not rejected for either adhesives or layers, meaning that no difference in the underlying populations should be expected between these parameters.

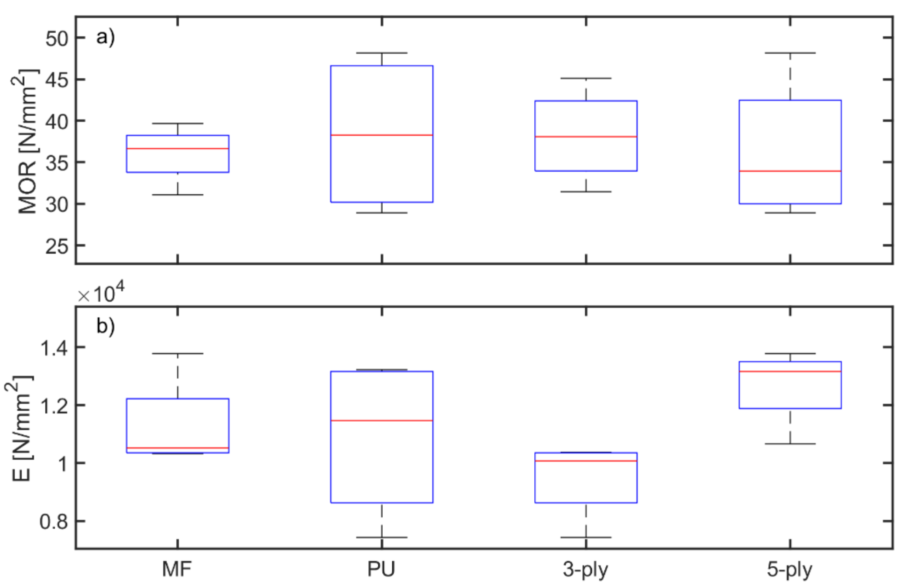

Fig. 5. Box plot comparison of a) modulus of rupture (MoR) and b) elastic modulus (E) for different sample configurations of CLT beams.

For the elastic modulus in Fig. 5 b) no significant difference can be discerned between median values for the adhesive types and this is confirmed by the p-values in Table 1. However, a statistically significant difference (at the 5 percentile significance level) in elastic modulus can be observed between three and five ply sample groups; this does not necessarily reflect the material properties of the timber but rather the experimental conditions. For the three ply sample the effective length to depth ratio is smaller and the cross-layer in the centre is subjected to higher shear stresses, hence it is reasonable to expect that the shear deflections and therefore the overall deflections are larger for these beams.

Table 1. ANOVA *p*-value summary for beams at ambient temperature

	Adhesive	Ply configuration
Modulus of rupture	0.68	0.73
Elastic modulus	0.74	0.03

From the DIC measurements shear strains were calculated via linear strain triangles that were fitted between pixel clusters in each image. The absolute shear strains before structural failure for a three and five ply beam are plotted in Fig. 6 a) and b), respectively. It can be observed that the shear strains were concentrated in the plies that are orientated perpendicular to the main loading direction, as would expected considering that these plies have a lower mechanical resistance than those orientated parallel to the main loading direction.

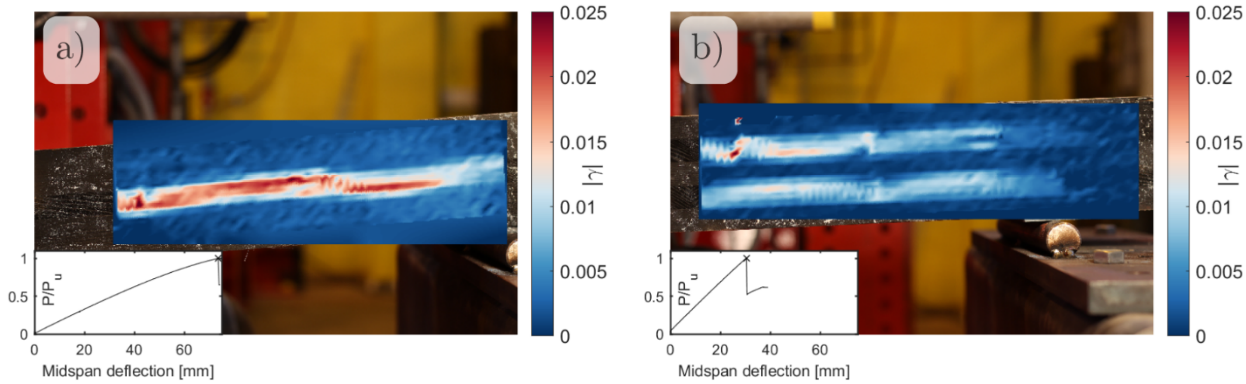

Fig. 6. Shear strains from DIC near the support for a) 3 ply and b) 5 ply CLT beam, bonded with PU adhesive.

3.2 Elevated temperature experiments

Temperature measurements

The gas temperatures for both an experiment at 50 and at 30 % load level are shown exemplary in a) and b) respectively. It can be observed that gas temperatures near the air inlet and the box centre did not vary significantly. The temperatures near the viewport were consistently lower than those near the centre, which was most likely due to imperfect mixing conditions in this region.

The mean temperatures in the beams during elevated temperature experiments with a 50 and 30 % load ratio are displayed in Fig. 8 and Fig. 9, respectively. The standard deviation of measured temperatures between different specimens is shown as a shaded area. As would be expected it can be observed that the temperature varies throughout the depth near the support, while only moderate variation between different thermocouples was measured at midspan, where the thermocouples were spaced along the width, rather than depth, of the beams. It can also be observed that the temperature increases at 50 mm were less near the support compared to those measured at midspan, as would be expected considering Fig. 7. This effect appears to be consistent between experiments and it can therefore be assumed that all experiments were subjected to similar temperature conditions, allowing a comparative analysis of the structural behaviour.

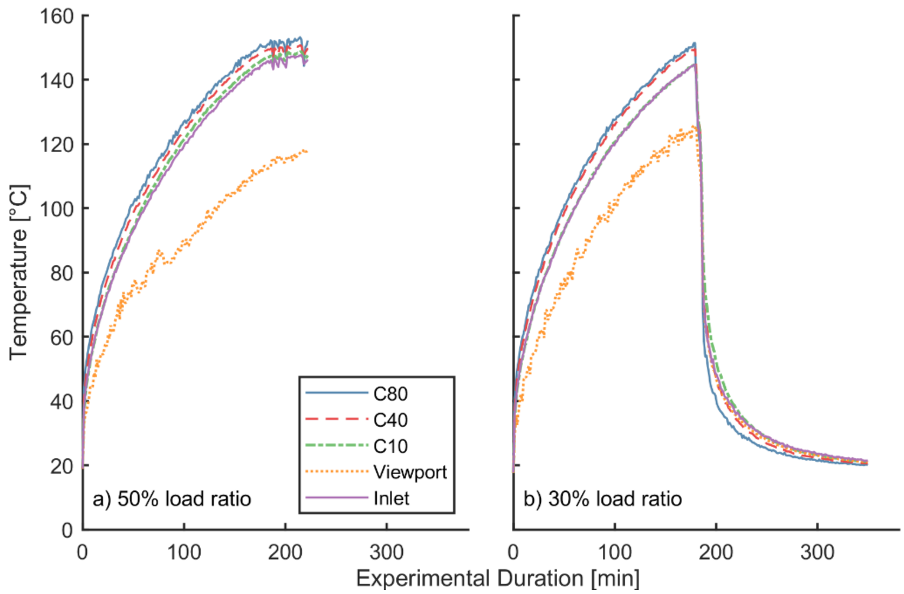

Fig. 7 Exemplary gas phase temperature development for a) 50 % load ratio until failure and b) 30 % load ratio and cooling phase. ‘CX’ denotes thermocouples at the longitudinal centre of the box and their height from the bottom

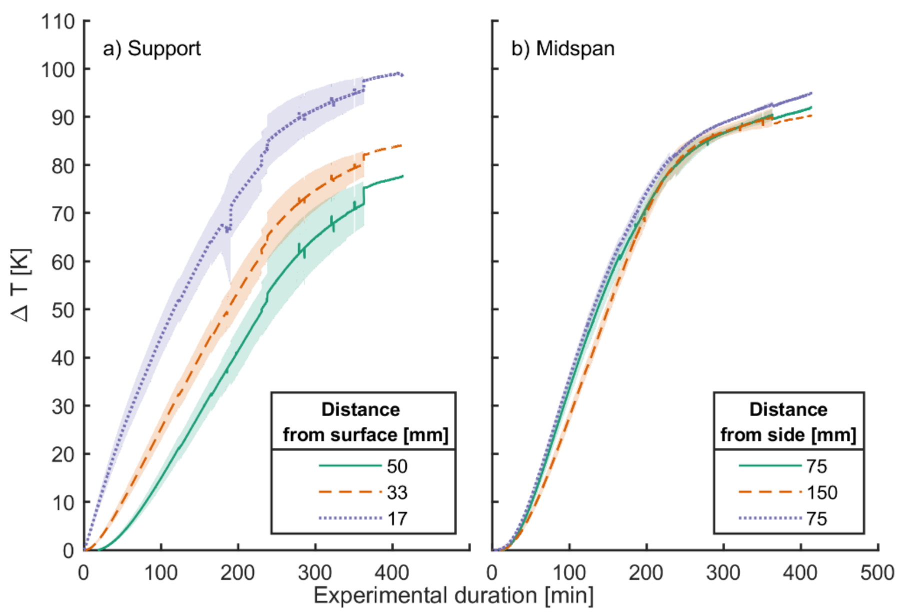

Fig. 8. Mean and one standard deviation of solid phase temperature increase for samples loaded to 50 % of ambient capacity for a) temperatures above the support and b) temperatures at midspan at 50 mm depth.

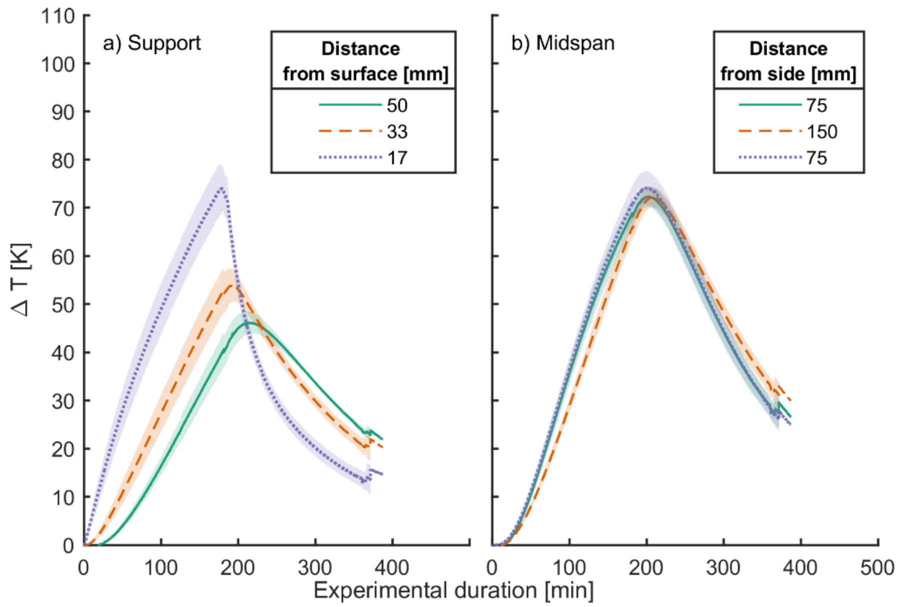

Fig. 9. Mean and one standard deviation of solid phase temperature increase for samples loaded to 30 % of ambient capacity for a) temperatures above the support and b) temperatures at midspan at 50 mm depth.

Structural response

The heating induced deflections of the beams are graphed against the experimental duration in Fig. 10 and Fig. 11 for the high and low sustained load ratios, respectively. For all specimens it can be observed that the applied heating caused the beams to deflect.

For the highly loaded beams most beams experienced structural failure, which is marked out by runaway deflections. Two specimens (one 3MF and one 5MF) did not exhibit any failure in the observed experimental duration and had to be terminated as the experiments could only be run during lab opening times and were therefore subject to a time limit. It can be observed that specimens consisting of three plies that were bonded with the PU adhesive deflect at a faster rate and fail earlier than those bonded with the MF adhesive. No clear distinction can be observed for the five ply specimens.

For the beams subjected to a 30 % load ratio only one of the 3PU specimens experienced structural failure before the heat was stopped and the cooling phase was initiated. For the remaining beams it can be seen that after a short period of continuous deflections the sustained deflections remained almost constant throughout the cooling phase of the timber. A slight dip in deflection can be observed upon instigation of the cooling phase. This is likely linked to an inflow of cool air and contraction of the compressive surface fibres. It can also be observed that a high repeatability exists for the beams subjected to lower loads: the deviation between repeats of the same configuration is less than that between configurations.

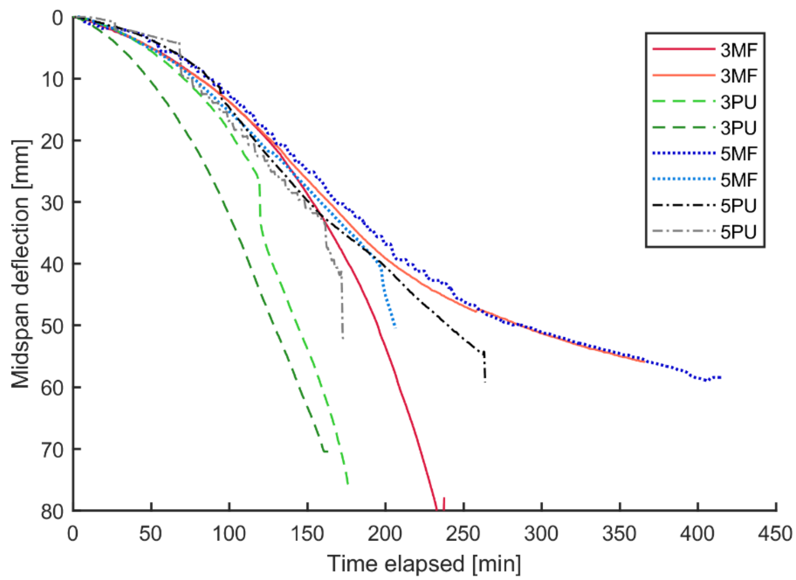

Fig. 10. Heat induced deflections in CLT beams under a sustained 50 % load ratio.

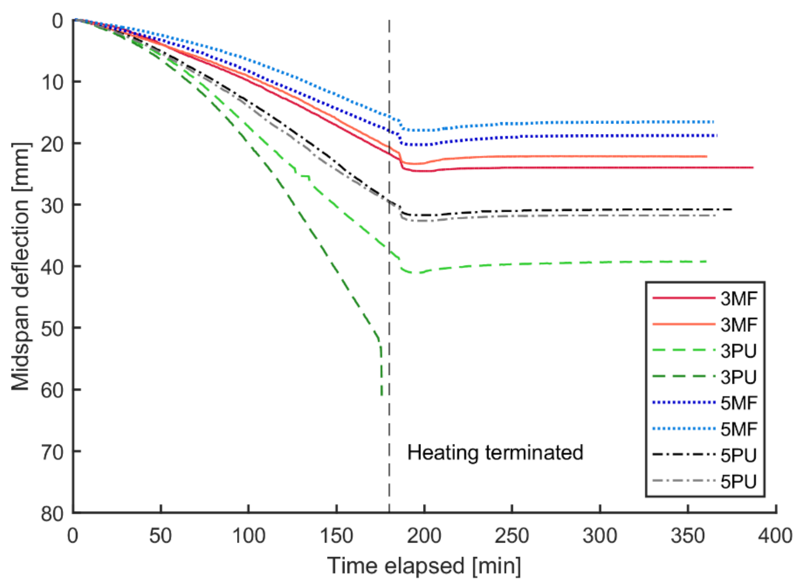

Fig. 11. Heat induced deflections in CLT beams under a sustained 30 % load ratio.

Shear strains near the support were obtained from linear strain triangles of DIC deflection points as for the ambient temperature reference specimens; these are shown in Fig. 12 and Fig. 13 for five and three ply CLT beams, respectively, for both adhesive types. The quality of the shear measurements is not as clear as for the ambient temperature samples, which can be attributed to the fact that the images had to be taken through the view port glazing and that the timber surface was subjected to heating induced noise, e.g. moisture flow. The individual layers can still be identified clearly. It can also be seen that shear strains are higher for PU bonded CLT and that these shear strains are concentrated in clusters along the adhesive bond lines.

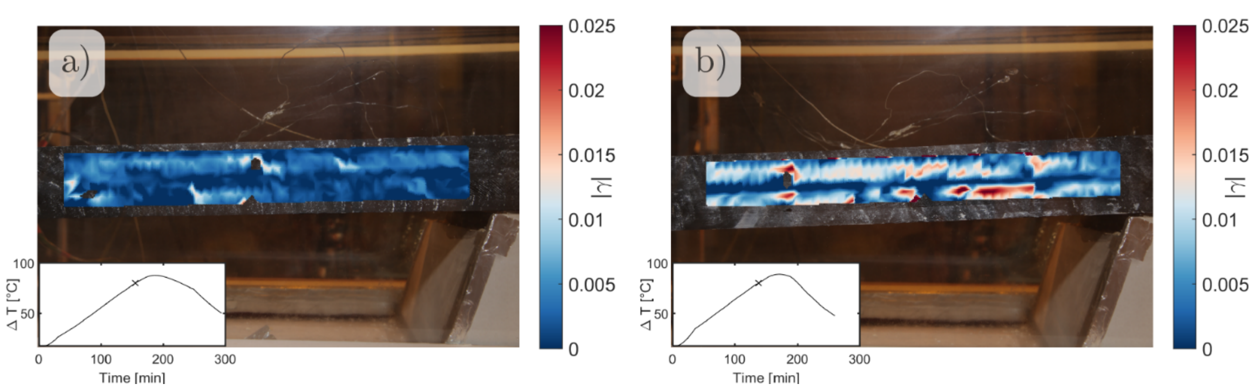

Fig. 12. Absolute shear strains at 80 °C beam centre temperature in 5 ply CLT beam subjected to 30 % load ratio and bonded with a) MF adhesive and b) PU adhesive.

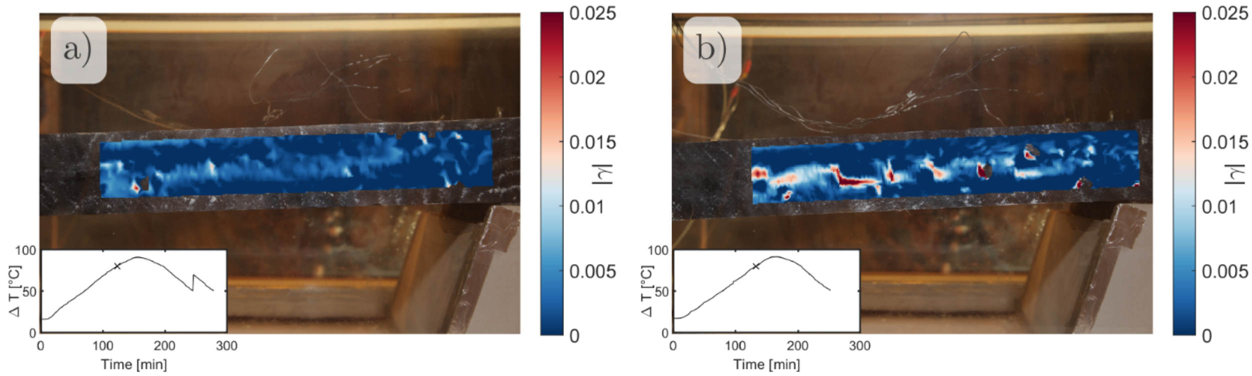

Fig. 13. Absolute shear strains at 80 °C beam centre temperature in 3 ply CLT beam subjected to 30 % load ratio and bonded with a) MF adhesive and b) PU adhesive.

4. Discussion

From the results in Fig. 10 and Fig. 11 it is evident that a difference in deflection rates with increasing temperatures exists between the assessed configurations. Specimens bonded with the PU adhesive perform worse when heated than their respective MF counterparts. Since this effect was not evident for the ambient temperature reference samples, it is likely that the effect of heat on the adhesion between plies contributed to the deflections, potentially due to a reduction in composite action between plies.

For the beams with applied 50 % load ratio the distinction between the different groups is less clear than for those subjected to a 30 % load ratio. This suggests that at a higher load, individual defects and weaknesses in the timber dominate the behaviour and can mask the influence of the adhesive since the deterioration of timber fibres at this load level appears to dominate the structural performance, indicating that the applied load level is an influencing factor when the rate of loss of strength and stiffness of timber at elevated temperatures is considered.

A clear hierarchy of performance (with the assumption that less deflection indicates a better performance) upon heating can be identified in Fig. 11 for the configuration groups. This is summarised in Fig. 14, which shows the heat induced deflections in beams subjected to the lower load level after 180 minutes of heating. The 3PU specimen that failed structurally is not included in this comparison, as it failed before 180 minutes of experimental duration. The clear difference in flexural behaviour between the adhesive types can be observed with a 34.8 % reduction in median deflections for MF bonded specimens compared to those bonded with PU. For the layers the difference between median deflections was 7.9 %; this suggests that these heat induced deflections were mainly driven by the adhesive type. ANOVA *p*-values in Table 2 show that these effects can be considered statistically significant.

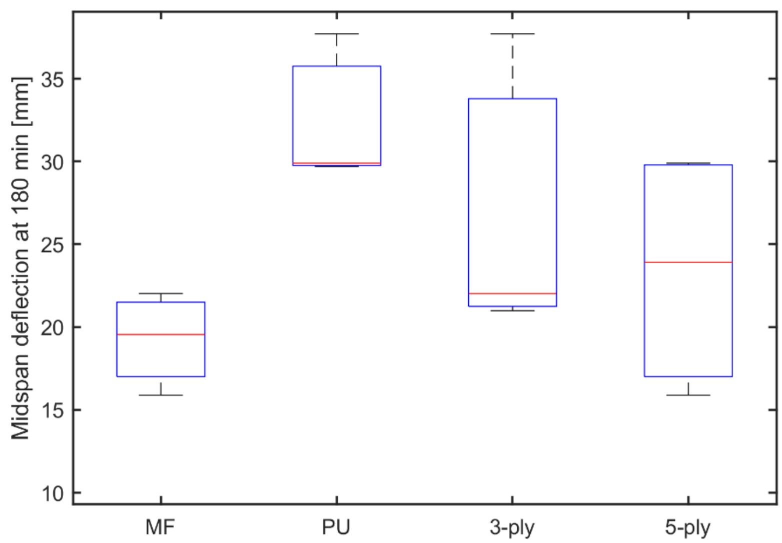

Fig. 14. Boxplot comparison of midspan deflections after 180 minutes for beams subjected to 30 % of their expected ambient load bearing capacity.

The measured shear strains near the supports at elevated temperatures in Fig. 12 and Fig. 13 show that shear strains for CLT beams bonded with PU adhesive are larger than those bonded with MF. This could simply be caused by the larger deflections that arise in the PU bonded specimens, however, it can also be seen that the highest shear strains for those specimens bonded with the PU adhesive are concentrated near the glue lines; this suggests that debonding and a loss of composite action occurs at these glue lines and therefore that the increased deflections that are measured for PU bonded CLT are caused by a loss in adhesion of the PU adhesive at the assessed temperatures. Adhesive performance under heating can be very variable between different chemical formulations, even within the same group of adhesives (e.g. 1-component PU adhesives) [17]; only two types of adhesives were assessed herein and no general conclusions regarding MF and PU adhesives should be drawn. In practice the performance of the adhesive in CLT should be part of a multi parameter optimisation process. For example, MF adhesives can have detrimental effects on indoor climate, and this effect, amongst others (e.g. costs) should be considered against potential increases in structural safety.

The exact physical explanations of the weakening of the adhesives are not clear. The difference in performance could be linked to a lower glass transition temperature, however, previous research on adhesives by Verdet et al. [18] has suggested that this parameter is not a definite indicator for the performance deterioration of glued connections at elevated temperatures, as the shear strength of adhesives can be reduced before the glass transition temperature is reached.

Table 2. ANOVA p-values summary for influence of adhesives and ply numbers on fraction of deflection after 180 minutes of heating for beams subjected to low load level.

	Adhesive	Ply configuration
Pr(>F)	0.00024	0.00584

Increasing deflections in fire situations might not be considered critical for slabs in bending as long as structural failure can be avoided, however, where CLT is used as a load bearing wall panel, additional deflections will cause increased P-Delta effects and thereby bending moments [19, 20] and ultimately cause earlier failure in a fire and can therefore contribute to a loss of compartmentation and a failure of the fire safety strategy.

From the deflections in Fig. 11 it can be observed that the deflections that were caused during heating were not recovered upon cooling of the CLT beams for all configurations. This suggests that heat induced deformations in timber are non-recoverable upon cooling and that these deflections are caused by creep rather than a loss of elastic modulus. The occurrence of plastic deformation has been considered as a potential alternative explanation for this observation, however, this theory could not be confirmed since no signs of plastic deformation (buckled timber fibres) were found in the specimens after experimentation was completed. The permanence of heat induced deflections is an important finding, since the need to account for failure in the fire decay phase has been recognised by multiple researchers [9, 10] and extend of recovery of the mechanical properties has been identified as a knowledge gap in the numerical assessment of these failures. From these experiments it is not possible to say with confidence whether these creep deflections are mainly caused by the observed influence of the adhesive type or by creep in the timber. Further research at a smaller scale is recommended to identify the driving mechanism for the observed creep deflections.

5. Conclusions

This paper describes elevated temperature experiments performed on one way spanning CLT beams with two types of adhesives used to bond timber plies of varying thickness under sustained flexural loading. From ambient temperature reference experiments, no significant difference in the modulus of rupture was found between either of the ply configurations or the two adhesive types. For the elastic modulus, significantly reduced values were found for three ply CLT elements compared to their five ply counterparts. This is attributed to the increased effect of shear deflections for the three ply samples, which have thicker outer plies and therefore a lower effective length to depth ratio.

Experiments with transient uniform heating of the gas phase surrounding the specimens, to a maximum of 150 °C, were performed on samples that were subjected to sustained four point bending loading of either 30 or 50 % of their respective mean ambient temperature capacities. The measured midspan deflections increased considerably for all samples upon heating.

A qualitative investigation of shear strain distributions over the specimens' sides showed that for CLT bonded by polyurethane adhesive types the shear strains were partially concentrated near the adhesive lines between plies; this was not observed for specimens bonded with the melamine formaldehyde adhesive. Since there were no other experimental parameters varied between these sample groups, this has been interpreted as a weakening of the polyurethane adhesion, causing interlayer slip and partial debonding between adjacent timber plies. Such a phenomenon would partly explain the accelerated midspan deflections for specimens bonded with PU adhesive compared to their MF bonded counterparts. This result suggests that, if only the adhesives assessed in this study are considered, MF adhesive should be significantly preferred over PU for the manufacture of CLT structural elements for which structural response to heating is a relevant consideration.

For specimens subjected to the lower load ratio of 30 % of the ambient temperature capacity, the heating was halted after 180 minutes so as to enable observation of deflections under sustained flexural loading during cooling. No recovery of heat induced deflections were observed, suggesting that these were caused by creep of the timber and/or the adhesives. Further research is recommended to quantify the distinct influence of adhesives and timber on overall creep in CLT, as well as the consequences for structural fire design of CLT structures.

The novel results presented herein, suggest that the choice of the adhesive type is of importance to quantify the structural load bearing capacity of engineered timber products in heat or fire. In addition it is shown that the ply layup also increases the measured deflections through increased shear deformations and that this effect can amplify the reduced composite action from weakening adhesives. The results allow a better understanding of these products and contribute to optimisation approaches where the consideration of structural fire safety is an essential part of the whole building design.

6. Acknowledgements

The authors gratefully acknowledge support from Arup and the University of Edinburgh to undertake the experiments from which this paper draws its primary data. The authors would also like to acknowledge support from the UK Engineering and Physical Sciences Research Council (EPSRC, EP/M508032/1). Mayr-Melnhof Holz are acknowledged for their generous contribution of materials.

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Figure captions

Fig. 1. Elevation and plan view of the experimental set-up for CLT beams in four point bending at ambient reference temperatures. All dimensions in mm.

Fig. 2. Plan, section, elevation and detailed views of the experimental set-up for heating of CLT beams under sustained loads. All dimensions in mm.

Fig. 3. Thermocouples placements within the CLT beams. All dimensions in mm.

Fig. 4. Load response of CLT beams with increasing midspan deflections for a) three ply and b) five ply configurations.

Fig. 5. Box plot comparison of a) modulus of rupture (MoR) and b) elastic modulus (E) for different sample configurations of CLT beams.

Fig. 6. Shear strains from DIC near the support for a) 3 ply and b) 5 ply CLT beam, bonded with PU adhesive.

Fig. 7 Exemplary gas phase temperature development for a) 50 % load ratio until failure and b) 30 % load ratio and cooling phase. 'CX' denotes thermocouples at the longitudinal centre of the box and their height from the bottom

Fig. 8. Mean and one standard deviation of solid phase temperature increase for samples loaded to 50 % of ambient capacity for a) temperatures above the support and b) temperatures at midspan at 50 mm depth.

Fig. 9. Mean and one standard deviation of solid phase temperature increase for samples loaded to 30 % of ambient capacity for a) temperatures above the support and b) temperatures at midspan at 50 mm depth.

Fig. 10. Heat induced deflections in CLT beams under a sustained 50 % load ratio.

Fig. 11. Heat induced deflections in CLT beams under a sustained 30 % load ratio.

Fig. 12. Absolute shear strains at 80 °C beam centre temperature in 5 ply CLT beam subjected to 30 % load ratio and bonded with a) MF adhesive and b) PU adhesive.

Fig. 13. Absolute shear strains at 80 °C beam centre temperature in 3 ply CLT beam subjected to 30 % load ratio and bonded with a) MF adhesive and b) PU adhesive.