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Citation for published version:
Wiesner, F, Thomson, D & Bisby, L 2021, 'The effect of adhesive type and ply number on the compressive strength retention of CLT at elevated temperatures', *Construction and Building Materials*, vol. 266, no. Part B, 121156. https://doi.org/10.1016/j.conbuildmat.2020.121156

Digital Object Identifier (DOI):
10.1016/j.conbuildmat.2020.121156

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Construction and Building Materials

The effect of adhesive type and ply number on the compressive strength retention of CLT at elevated temperatures

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Abstract

This paper describes novel experiments to identify the reduction in compressive strength of cross-laminated timber (CLT) at elevated temperatures. The adhesive type and number of timber plies was varied between CLT samples to allow an assessment of the CLT 'system', rather than timber only. Samples were subjected to steady state and transient heating conditions and their ultimate load bearing capacities were measured. At ambient reference temperatures, a statistically significant difference in ultimate compressive strength was observed between ply numbers but not between adhesive types. For transiently heated samples, capacity was reduced at 100 °C for CLT bonded with polyurethane adhesive type as compared to samples bonded with melamine formaldehyde. The presented results indicate that the composition of CLT can influence the whole system structural response, both at ambient temperature and under fire conditions.

1 Introduction

Mass timber is increasingly being used as a construction material for larger and more complex structures [1]. Cross-laminated timber (CLT), in particular, has been at the forefront of this development as it enables prefabrication of slabs and panels for wall and floor elements. Due to fire safety considerations mass timber elements are typically either encapsulated with a combination of plasterboard and/or non-combustible insulation or are dimensioned to include a sacrificial thickness of timber that, in case of fire, is transformed into char by pyrolysis reactions, thereby forming a protective layer for the uncharred timber below [2]. In either case the timber below the encapsulation or the char layer will be heated to elevated temperatures, thus causing reductions in its mechanical properties. These reductions must be quantified in order to assess the load bearing capacity of compressive timber structures both during and after a fire.

Multiple studies investigating the effects of elevated temperatures on the strength of sawn timber are available within the technical literature. Gerhards [3] published a comprehensive review on the effects of heat and moisture on the mechanical properties of timber. This research showed that determination of the reductions in mechanical properties of timber depends strongly on the experimental conditions due to the complex interactions between load, temperature, and moisture movements in timber. This explains considerable observed variation arising in reported outcomes of heated compression elements for timber. Young and Clancy [4], as well as Manriquez Figueroa and Dias de Moraes [5], reported increases in compressive strength at temperatures above 100 °C, after an initial linear reduction. In both cases, the experiments heated the timber prior to applying load, which is likely to have caused the specimens to dehydrate before stress was applied, and may thereby have reduced or negated the effects of moisture. Tiemann [6], however, based on findings from extensive experimental testing, states that moisture has a more severe effect on mechanical properties of timber than elevated temperatures. On the issue of moisture and creep in timber, Schniewind [7] has, in a review of wood rheology research from the 1960s, highlighted that changes in moisture content and interaction effects of moisture and temperature effects are two separate issues, thereby confirming the complex interactions that were earlier illuminated by Thiemann [6]. This effect of combined loading and transient heating was also illuminated in experimental results by Chang [8], which showed that combined heating and loading of small timber bends led to more severe losses in capacity compared to a separate application load and heat.

Knudson and Schniewind [9], as well as Schaffer [10], determined linear and quasi linear reductions in strength with temperature, respectively. More recent research by Van Zeeland et al. [11] and Konig and Walleij [12] have suggested a bilinear strength loss model with a ‘breakpoint’ at 100 °C, at temperatures above which the rate of strength loss reduces considerably. Both of these models [11, 12] were determined using a combined empirical and analytical approach. For the latter, the strength reduction was back-calculated based on the behaviour of timber studs in furnace tests imposing a cellulosic standardised temperature-time curve. The resulting strength reduction curve is subsequently proposed in the current Eurocode 5 [13] to be used when applying advanced calculations models to determine the fire resistance of timber structural elements.

Cross-laminated timber (and other laminated timber products) rely on adhesive bond strength to ensure composite action between different timber boards. For CLT the two most commonly utilised adhesive types are polyurethane (PU) and melamine urea formaldehyde (MF). It has been established that the mechanical performance of different wood adhesives will be affected differently by elevated temperatures or moisture contents, even within adhesive types. Shear tests on PU glued timber pieces by Frangi et al. [14] have shown that, even within a relatively narrowly defined adhesive type like one-component PU, the reduction in cohesive strength at elevated temperatures of the glue will vary significantly between different specific adhesive products and manufacturers. Similarly, Serrano and Källander [15] observed variations between different PU adhesive formulations, and also found a difference in failure time for different samples using the same PU formulation. Richter and Steiger [16] observed a dependence of the observed reductions in shear modulus on adhesive thickness for in PU bonded beech specimens tested at elevated temperatures. In the same study, differences in elevated temperature performance were also noted between different adhesive types. Stoeckel et al. [17] reviewed multiple studies and identified that PU adhesives typically suffer large losses in stiffness at elevated temperatures, while MF is comparatively less sensitive in this regard, most likely due to its highly cross-linked molecular structure. Recent research by Zelinka et al. [18] tested MF, phenol-resorcinol-formaldehyde (PRF) and two types of PU in lap shear tests at elevated temperatures, and compared to the performance to solid wood lap shear samples. According to the authors, the adhesives in this study were those that are commonly used in laminated timber, especially in CLT. The study showed that PRF performed best, with MF showing intermediate performance and both PU types having the worst performance; when reduced shear strength and modulus were considered relative to solid wood. It is clear that complex interactions occur between adhesives and timber at elevated temperatures. Chorlton and Gales [19] measured the structural capacity of LVL and Glulam beams *after* fire exposure compared to control specimens with a reduced cross-section equivalent to the char depth. They determined that fire exposure resulted in higher capacity losses in bending compared to the control and partially attributed this to deterioration of the adhesive bond below the char timber interface although, in the absence of controls, they were not able to explicitly confirm this claim from their experimental results.

To the knowledge of the authors, virtually all available targeted research into temperature induced compressive strength loss of timber has been carried out on sawn lumber, and it can therefore not be guaranteed that the observed relationships will apply equally to engineered timber such as CLT. Experimental data on the compressive yield behaviour is required to accommodate the further development and validation of increasingly complex material constitutive models for engineered timber products [20]. As an engineered wood product, the properties of CLT products may be varied via multiple parameters, most notably its layup configuration (i.e. the number and thickness of the timber boards) and the adhesive type used. Oh et al. [21] have previously postulated, using Monte Carlo simulations, that a lamination effect will decrease the variability (measured by coefficient of variation) of strength in CLT as compared with individual boards of sawn lumber. They attributed this to the fact that defects in individual boards were compensated when more boards were present to share applied loads. The current paper is based on research reported in Wiesner's PhD thesis [22] and investigates the influence of ply number and adhesive type on the compressive load bearing capacity of CLT at both ambient and elevated temperatures. It is the first study to investigate heated CLT on a material scale, where the interactions between timber and adhesives may play a role.

2 EXPERIMENTAL SET-UP

2.1 SPECIMENS

The cross-laminated timber samples used in this study were all from a single manufacturer [23] and were standard, commercially available products (i.e. not produced specifically for the experiments herein). Four different configurations were used, arising from variation of two production parameters: (1) the adhesive type, and (2) the number of timber plies. The samples were fabricated from spruce (picea albies), and at least 90 % of the boards conformed to a C24 grading, with an admissible share of 10 % boards with grade C16/L17 [24]. The specimens had a width of 100 mm, a height of 200 mm, and a depth of 150 mm. The depth of the specimens was reduced to 100 mm during the experimental series as it became clear that the higher than anticipated failure loads were potentially damaging the experimental set-up. Since the measured variable was the failure load (and hence stress), the change in specimen size was deemed not to have an important influence on the results; this was confirmed by the data. The adhesives used to bond the samples were: (1) a one-component polyurethane (PU), and (2) a melamine urea formaldehyde (MF) formulation – which was applied in combination with a hardener. The applied pressure for the CLT bonding process was 0.6 to 1 MPa for both adhesive types. For the two adhesive types used in this study the manufacturer recommended press duration for the MF adhesive was up to 5.4 times the recommended time for the PU adhesive. However, this is strongly dependent on the ratio of hardener and MF adhesive, as well as the moisture content of the timber and ambient relative humidity. The PU and MF adhesives conformed to the requirements of EN 14080 [25] and EN 14425 [26], and EN 301 [27], respectively.

The ply configurations were 20-20-20-20-20 and 40-20-40 mm of timber boards in the typical orthogonal CLT configuration, with boards on the outer faces arranged so that the grain directions ran parallel to the main longitudinal loading direction. The ply configuration for the three-ply samples represented an extreme case scenario, where a majority (80 %) of the load bearing timber was placed in the outer plies. This orientation was chosen deliberately to investigate the effects of thicker outer plies, based on prior research by Wiesner et al. [28] that had shown that this approach can be detrimental for the load bearing capacity of CLT compression elements in fire (since early loss of timber oriented in the primary loading direction shortens the time to structural failure). A total of 44 specimens were tested at ambient temperatures, and 99 experiments were performed at elevated solid phase temperatures up to 200 °C.

The samples had estimated mean moisture contents of 9 % with associated standard error of 0.1 %; this was determined from mass loss dehydration of sacrificial separate timber samples that were stored in the same location and conditions as the samples used in this study. The mean bulk density of all the specimens in this study was measured as 465.2 kg/m^3 with a standard deviation of 23.2 kg/m^3.

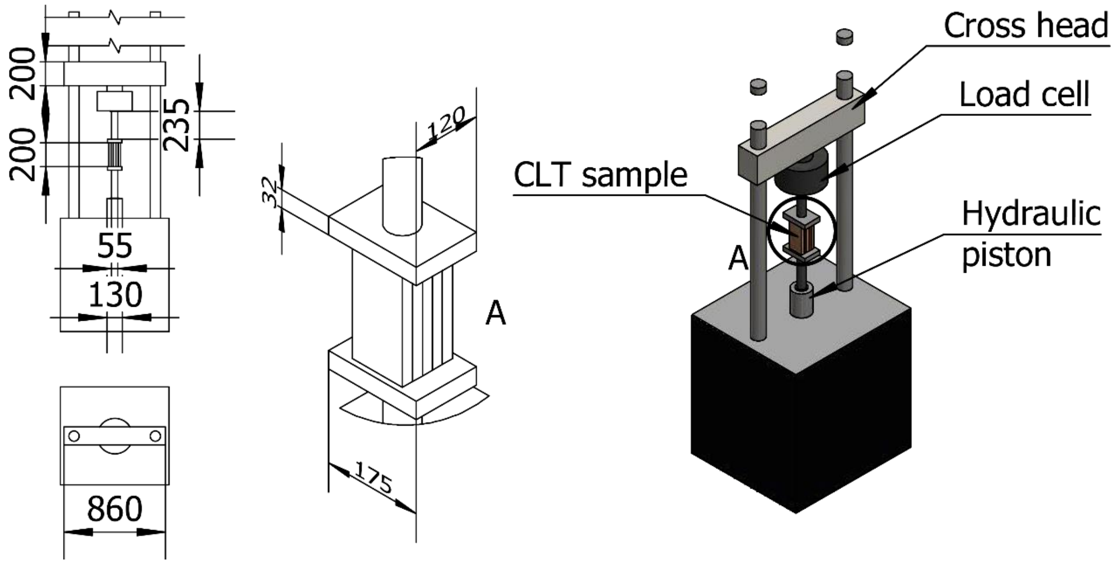

Fig. 1. Experimental loading set-up in a universal test machine with rectangular compressions load platens.

2.2 AMBIENT TEMPERATURE EXPERIMENTS

A universal test machine was fitted with custom made steel rectangular load platens that were able to impose a uniform displacement onto the specimens' top and bottom surfaces. The specimens were placed concentrically between the platens and then subjected to crosshead displacement-controlled loading to failure (and beyond). Testing was initially continued until a cross head displacement (i.e. movement of the hydraulic piston) of 15 mm (for three ply specimens), this was subsequently reduced to 5 mm, since it was determined that the final 10 mm of crosshead displacement yielded no additional insights, however the resulting lateral displacements posed a risk of damage to the testing machine.

2.3 INSTRUMENTATION

The crosshead displacement of the universal test machine and the corresponding loads were recorded throughout each experiment. In addition, a digital camera was used to record images at an interval of 5 seconds (i.e. at a crosshead displacement interval of 42 microns) of the front faces of the samples (i.e. showing a side view of the gluelines).

2.4 ELEVATED TEMPERATURE EXPERIMENTS

Two types of elevated temperature experiments were performed: (1) steady state thermal, and (2) transient state thermal. For the former, the specimens were heated until they were deemed to have reached a steady state temperature, and were then subjected to displacement controlled compressive loading until failure. For transient state thermal experiments, the specimens were placed under sustained compressive loading of either 25 or 50 % of their ambient temperature failure load and were then subjected to heating at a gas phase increase rate of either 5 °C/min ('fast' heating) or 0.5 °C/min ('slow' heating). The higher loading value of 50 % was chosen as an upper limit wherein loading could be applied without the risk of causing structural failure before heating was applied, and the lower value of 25 % was semi-arbitrarily chosen as half of this value.

Heating of the samples was achieved in an environmental chamber that was situated within the universal test machine testing machine and incorporated the support platens and rods internally. The heating chamber enclosed the ambient temperature set-up (refer to Fig. 1) to enable heating and loading to occur simultaneously, as detailed in Fig. 2. The environmental chamber had electrical heating elements at front and centre, an interlock, and a fan which was separated from the heating chamber via a mesh and a steel sheet with a circular cut-out to circulate hot air uniformly through the chamber (i.e. a highly convective environment). Four target steady state timber temperatures were chosen at which to assess the effects of elevated temperatures on the compressive loading response of CLT: 50, 100, 150, and 200 °C. This range of temperatures was chosen so as to obtain regular temperature interval increases and to bracket 100 °C, the boiling point of water. The upper limit of 200 °C was chosen since higher temperatures had previously [29] been observed to lead to charring and ignition of timber samples tested under similar conditions. Heating was imposed through an increase of the environmental chamber's gas phase temperature, which was controlled by a thermocouple located within the oven. Due to the comparatively low thermal conductivity of timber, the temperature was set as 110 % of the target solid phase timber temperature, i.e. 55, 110, 165, and 220 °C.

CLT specimens subjected to steady state heating were instrumented with three thermocouples at evenly spaced distances from their outer surfaces. Inconel sheathed K-type thermocouples, with an outer diameter of 1.5 mm, were inserted into predrilled holes which had an initial diameter of 2 mm and a diameter of 1.5 mm for the last 8 mm of their depth. This procedure ensured a tight fit near the temperature measurement location near the tip, however still allowing insertion of the thermocouples with relative ease. In addition, one thermocouple was placed to measure the gas phase temperature in front of the timber surface at mid height, and one thermocouple was placed to measure the surface temperature of the timber at mid height. The internal thermocouple arrangement is shown in Fig. 3.

Due to the need to assess whole cross-sections of CLT, the specimen dimensions in this study were relatively large (when considered on a material scale). This issue, coupled with the relatively low thermal inertia of timber, resulted in significant temperature gradients within the specimens during heating. In order to assess the material response at elevated steady state temperatures, a quasi-uniform temperature gradient was required. This was achieved via monitoring of the internal temperature gradients during heating; uniform steady state heating was assumed to have been satisfactorily achieved once the linear slope of the temperature in the sample was 0.3 % or less. The time to achieve this steady state condition varied significantly between the different target temperatures. Specimens heated to, or above, 100 °C displayed a heating plateau due to moisture evaporation which considerably extended the required heating times to achieve the target steady state condition.

For transient heating regimes three additional thermocouples (labelled ETC in Fig. 3) were placed at 10 mm from the bottom of the specimen at the same depths as the three mid-height thermocouples. These additional TCs were included since multiple failures near the bottom loading platen were observed during the first set of transient heated experiments. The gas phase temperature in the heating chamber was increased at a rate of 5 °C /min for all steady state heating experiments. For the transient heating the heating rate was either 5 or 0.5 °C /min; these are subsequently referred to as the 'fast' or 'slow' heating rates, respectively.

The measured mean timber temperatures from multiple specimens during the normalised (i.e. until heating was deemed steady state) heating period are shown for a 200 °C target temperature in Fig. 4. A pronounced temperature plateau exists at 100 °C which is most prominent for the thermocouple located at the specimens' centre (i.e. at 50 mm from the surface). This plateau is less pronounced for 5-plies as compared against three ply CLT; this is likely due to the smaller overall volume of the 5-ply specimens.

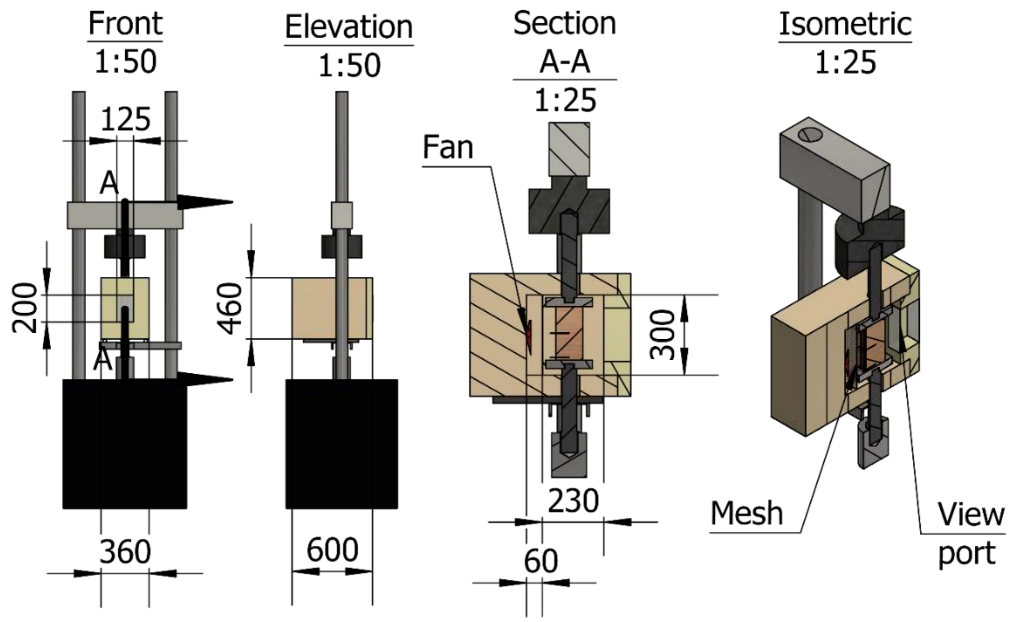

Fig. 2. Schematics showing the experimental heating chamber enclosing the loading platens.

The sample numbers for the various experimental configurations, which are differentiated as a mix of number of plies (either three or five), type of adhesive (PU or MF), and imposed heating conditions (transient or steady state) are outlined in Table 1. Since each specimen is denoted by two experimental parameters (i.e. ply number and adhesive type), specimens are repeated across the two main parameters, for example a 3MF050 specimen is listed in the '3' column under number of plies and the 'melamine urea formaldehyde (MF)' column for 50 °C steady state heating.

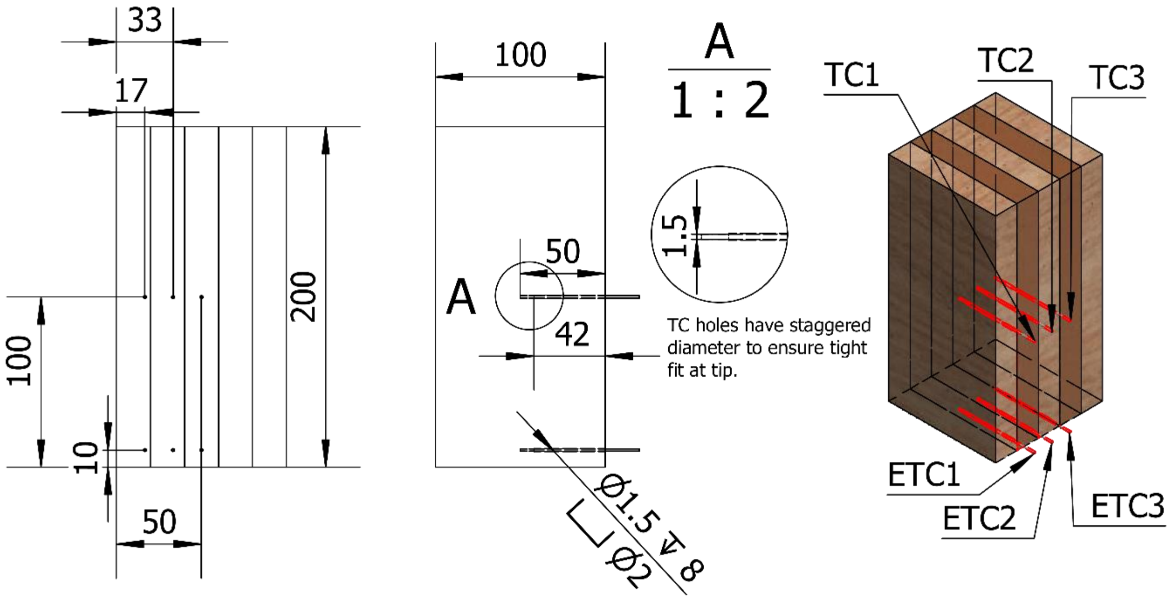

Fig. 3. Placement of solid phase thermocouples at mid height and near the base of the CLT specimens.

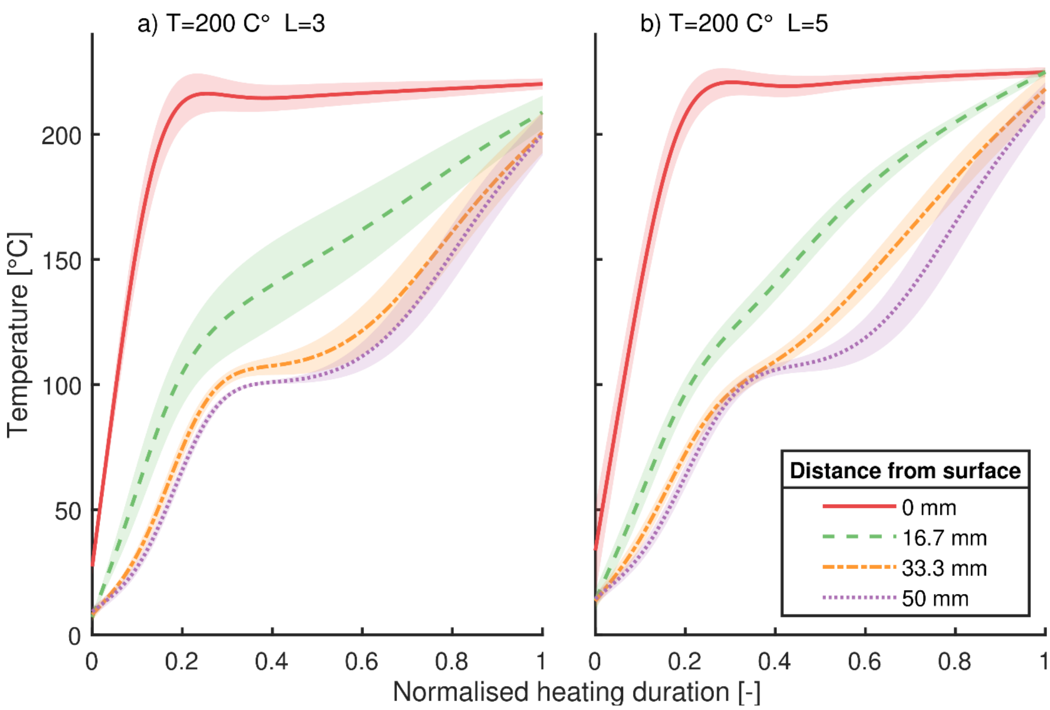

Fig. 4: Mean and ± one standard deviation summary for thermocouple readings of different specimens at fixed distances from the timber surface in experiments with a target temperature of 200 °C for a) three ply CLT and b) five ply CLT.

Table 1: Experimental matrix of assessed parameters at different heating conditions.

Heating condition	Temp. [°C]	Number of plies		Adhesive	
		3	5	Polyurethane (PU)	Melamine urea formaldehyde (MF)
		No of samples			
Ambient	**20**	20	24	22	22
Steady State	**50**	8	7	8	7
	100	6	6	6	6
	150	6	6	6	6
	200	6	6	6	6
Transient	**'slow'**	12	12	12	12
	'fast'	12	12	12	12

3 RESULTS

The available area of timber with fibres orientated parallel to main direction of loading is different for the two types of ply configurations investigated in this paper. Hence, to obtain a comparable normalised parameter of the average compressive stress in the material, the effective compressive stress has been calculated according to Equation (1), where P is the measured load, th is the thickness, d is the depth of the specimen and subscripts all, pa and cs denote overall, parallel and crosswise layers, respectively. Any reference to stress in this paper refers to the mean effective stress, as defined in Equation (1). Applying this transformation accounts for the difference in stiffness between the layers based on an assumption that the elastic modular ratio is 30 [30, 31] parallel to the grain with respect to perpendicular to the grain.

$$\sigma_{eff} = \frac{P}{\frac{th_{all}}{100} \cdot d \cdot (th_{pa} + \frac{th_{cs}}{30})} \tag{1}$$

3.1 AMBIENT TEMPERATURE EXPERIMENTS

The measured stresses with increasing stroke displacements are shown in Fig. 5 for ambient temperature reference experiments. The three-ply samples experienced larger compressive deflections, as it was decided to reduce the ultimate imposed crosshead stroke for the five ply samples. This was motivated by the fact that no valuable additional information was gained at extreme crosshead stroke values for the three-ply samples, and excessive lateral movement at large stroke displacements were identified to potentially damage the thread on the loading platens. The stress response can be identified as essentially linear elastic with an onset of plastification (manifested as fibre buckling of the timber in compression) before the ultimate strength was reached; this was followed by strain softening. This plastic failure mechanism, due to fibre buckling in the parallel layers, can also be identified visually in the typical failure mode shown in Fig. 6. The mean peak stresses (i.e. ultimate strength), their standard deviations, the resulting coefficients of variation (CoVs), and the Pearson correlation coefficients between ultimate strength and density of the specimens at ambient temperature are shown in Table 2. The experimentally determined ultimate strengths measured for the five ply samples were higher than for those for CLT with three plies. It can also be seen that the CoV was lower for five plies compared to three. Overall, no significant correlation can be identified between the density of the specimens and their resulting strengths in compression. The only statistically significant correlation between density and ultimate compressive strength is found for the sample set of three plies bonded with polyurethane (3PU).

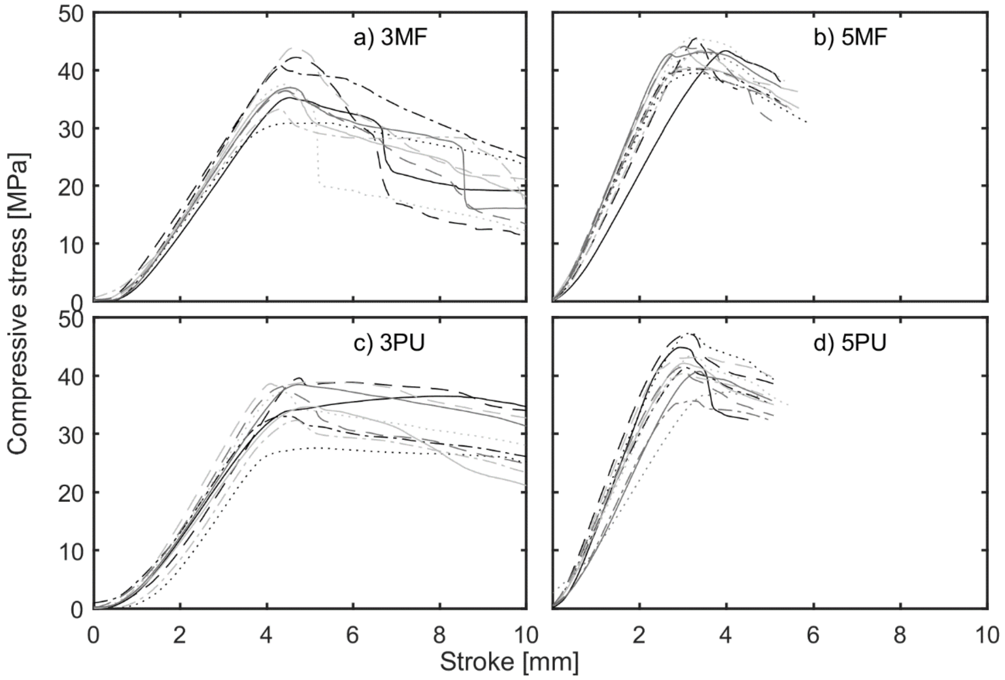

Fig. 5: Stress response of four CLT configurations against cross-head stroke displacement at ambient temperatures.

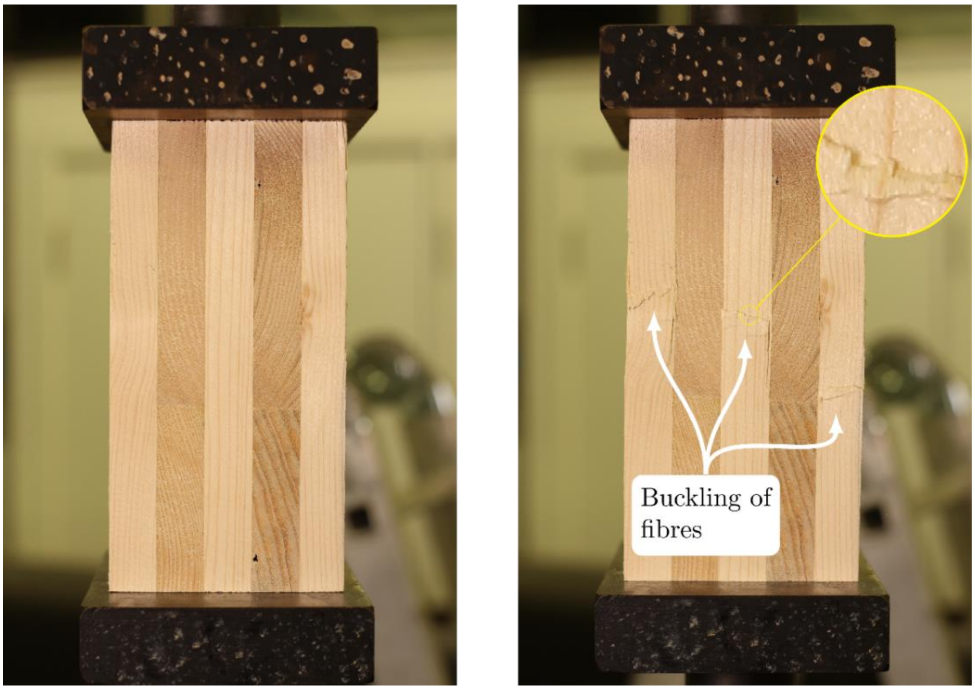

Fig. 6. Five ply specimen (5PU04) between loading platens, both before loading and immediately after failure when tested at ambient temperature.

Table 2: Summary statistics for compressive strength of four different CLT configurations tested at ambient temperature.

Exp. series	n -	σ [MPa]	sd(σ) [MPa]	CoV(σ) -	Corr(σ,ρ) -
3MF	10	37.7	4.1	10.9	-0.05
3PU	10	35.6	3.8	10.7	0.82
5MF	12	43.5	2.2	5.1	0.05
5PU	12	42.6	3.4	8.0	0.26
All	44	39.7	4.5	11.3	0.17

3.2 Steady state elevated temperature experiments

The stress response to imposed stroke displacements for all specimens heated to elevated steady state conditions is shown in Fig. 7 for the four sample sets and tested at different temperatures, where each line represents one specimen. As was observed for the ambient temperature reference experiments (refer to Fig. 5) higher ultimate strengths were measured for five ply compared to three ply specimens. It is also clear that specimens at elevated temperatures exhibited significantly reduced strengths; this effect, and the influence of the controlling variables, is further explored in Section 4.

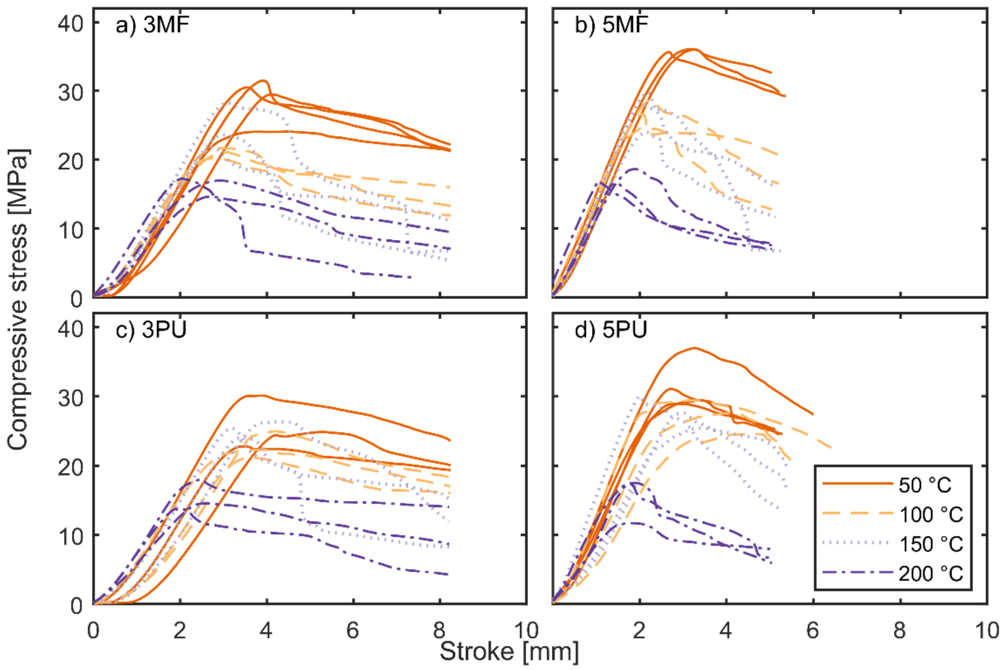

Fig. 7. Stress-stroke response of CLT specimens of different configurations at elevated steady state target temperatures.

3.3 Transient state elevated temperature experiments

The measured stroke deflections with mean temperature in the failure zone, for all transient thermal regime experiments, are shown in Fig. 8. The failure zone refers to either the row of thermocouples at mid-height of the specimens, or to the additional thermocouples that were placed near the bottoms of some samples (refer to Fig. 3) The display of these results is organised by heating rate and loading applied. As expected, it was observed that, for the higher loading ratio (i.e. 50 % of the mean ambient temperature capacity), runaway deflections and failure occurred at lower temperatures than for the lower loading ratio (i.e. 25 % of the mean ambient temperature capacity). The median difference in failure temperatures for the two assessed heating rates is 10 % and therefore significantly less pronounced than the median difference of 95 % between the failure temperatures between the two load levels. For the higher loading ratio, the stroke rate increased until failure occurred, while the samples tested at the lower loading level experienced a reduction in the rate of stroke after an initial increase. For the faster heating rates, it was observed that the samples bonded with PU adhesive tended to fail at lower temperatures than the samples bonded with MF adhesive. Whilst this observation also applies to some of the individual samples subjected to slow heating, the effect cannot be confirmed without a more thorough investigation of the failure loads and temperatures; this is provided in Section 4.

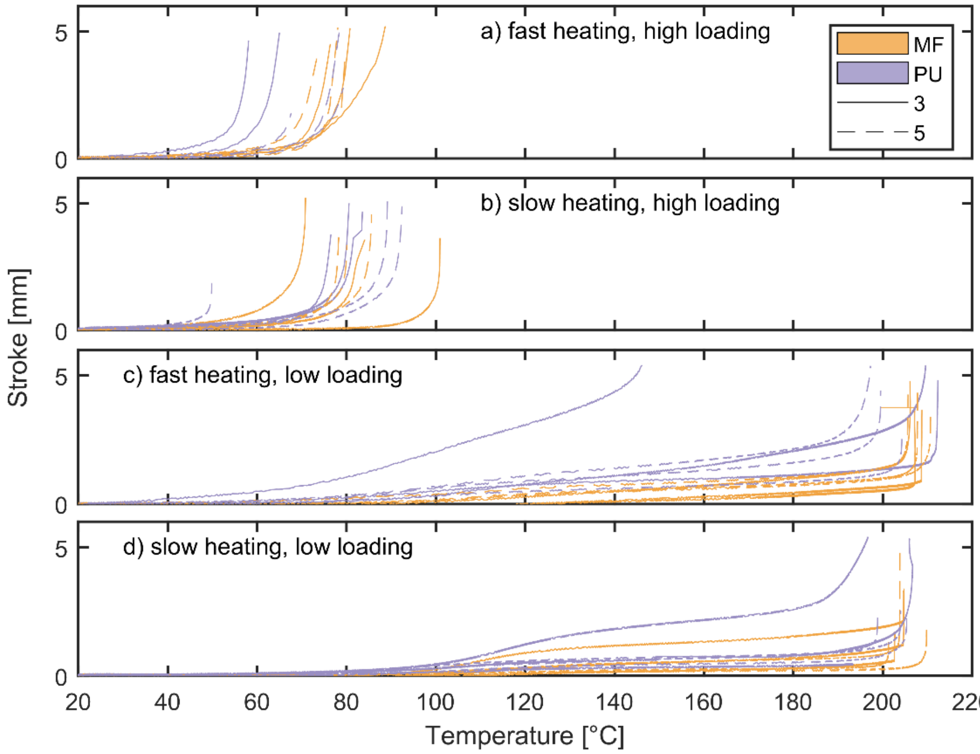

Fig. 8. Cross-head stroke against mean solid phase temperature for transiently heated CLT in sustained compression.

4 ANALYSIS AND DISCUSSION

The ultimate compressive stresses observed at ambient temperature for the four parameters investigated are shown as trimmed violin plots, which are similar to box plots, but also show the probability density distribution of the data [32] in Fig. 9; it can be observed that the median compressive stress is higher for five ply and MF bonded specimens compared to three ply and PU bonded specimens, respectively. Approximately Normal distributions can be identified for all parameters, and the CoV is lower for five ply samples as compared with three ply ones, as was shown in Table 2.

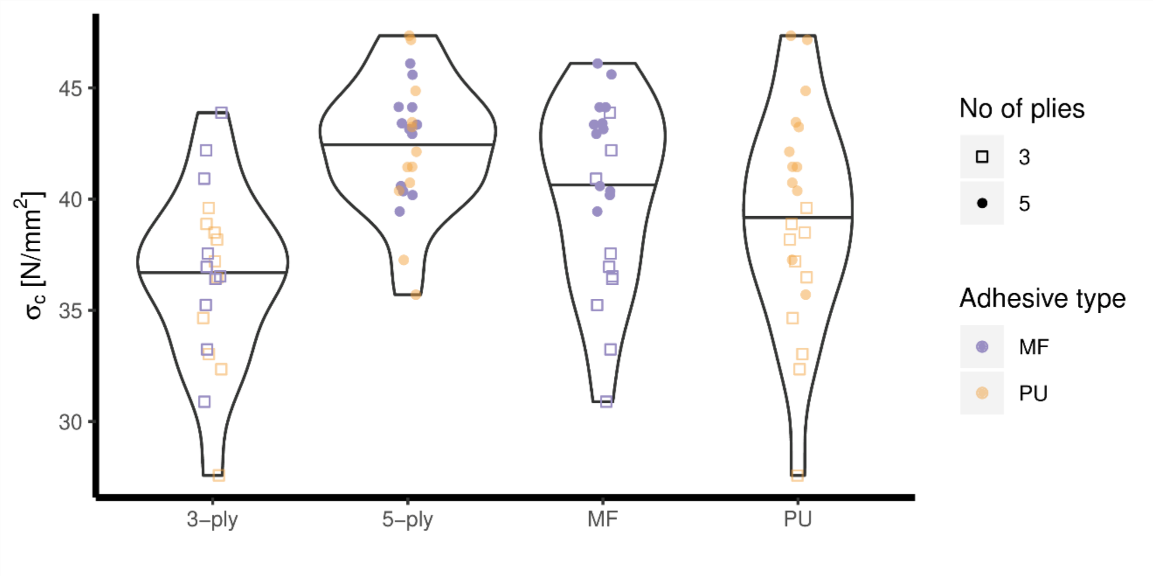

Fig. 9. Compressive strength by ply number and adhesive type for cross-laminated timber specimens at ambient temperature. Individual data points are jittered horizontally for clarity and horizontal line shows the sample median.

The *p*-values from analysis of variance (ANOVA) for the compressive strength are summarised in Table 3. A statistically significant difference between the three and the five ply samples is confirmed by a *p*-value of $7.2x10^{-7}$ between these sample groups. As observed in Fig. 9, the PU bonded CLT specimens have a lower median ultimate compressive strength than those bonded with MF. However, this difference is not judged as being statistically significant, with a *p*-value of 0.26. From the results of the ambient temperature capacities it can be seen that, if a 5 % significance threshold is applied, the null hypothesis of equal means in ultimate compressive strength between the populations of the configurations is upheld when comparing between adhesives, but is rejected between the number of plies for strength. It should be noted here that *p*-values cannot be treated as a panacea, and their use (and abuse) has – in recent years – revived discussion about the meaning of statistical significance [33]. In this instance, what is prominent is the difference in *p*-values when comparing the effect of layers and adhesives on the strength. This indicates that variation in the compression strength of the underlying population is likely to occur for a change in the numbers of lamellae, but likely caused by random chance for a change in adhesive type (at ambient temperature).

Table 3: Compressive strength ANOVA p-values summary for investigated variables at ambient temperature.

	Ply number	Adhesive
Pr(>F)	2.6E-01	7.2E-07

It can therefore be concluded that, at ambient temperatures, there is no significant difference in ultimate compressive strength between samples using different adhesives, i.e. it can be assumed with reasonable confidence that any samples used for heated experiments in this chapter are drawn from a population with the same mean strength, provided that the only variation between samples is the adhesive type. For a change in ply number a different mean strength can be anticipated. This can be explained by a lamination effect, where deficiencies in individual timber boards are compensated for by the presence of other boards; this has previously been postulated from Monte Carlo simulations at ambient temperature [21]. The 5^{th} percentile compressive strength parallel to the grain for C24 timber boards is estimated as 21 MPa in EN 338 [24]. For the results presented herein the 5^{th} percentiles are 31.9 MP, 29.2, and 36.8 for overall, three ply, and five ply samples, respectively. The higher than anticipated compressive strength measured in this study is likely due to a combination of the lamination effect discussed above and the fact that strength grading and rating is never a precise reflection of the actual strength. This is particularly true for compressive strength, which is inferred from measurements of the modulus of rupture which itself is derived from grading conversions from the dynamic modulus or other grade indicators (see e.g. Ridley-Ellis et al. [34] for an in-depth explanation and discussion of timber grading principles).

The coefficients of variation (CoV) in Table 2 can be compared against those given by the JCSS Probabilistic Model Code [35]. For ultimate strength the CoV values are significantly less than the 20 % threshold recommended by JCSS, especially for the samples with five ply CLT. Again, this can be traced to the lamination effect, which evens out the effect of outliers in strength and thereby reduces variability between specimens, as already discussed.

4.1 ELEVATED TEMPERATURES

The effective ultimate compressive strength of samples is plotted against the solid phase temperature for each adhesive type and number of plies in Fig. 10. It is noteworthy that the temperature values for ambient experiments are jittered (i.e. shifted randomly) by up to ± 5 K for visual clarity in this figure, but the nominal assumed temperature for these experiments was 20 °C for all ambient temperature experiments. The temperature at failure is taken as the mean temperature measured at the time of failure (i.e. peak strength) in the region where failure was observed to initiate. The error bars denote the minimum and maximum measured temperature in the timber solid phase. As the temperatures are plotted in absolute terms, it is not surprising to see increasing temperature variations for increasing steady state temperatures and the largest temperature variations for transient heating. Overall, the error bars are sufficiently small to justify the use and distinction of mean temperatures from the thermocouples where failure was identified.

The compressive strengths are normalised against the mean ambient strength of their respective configuration and plotted in Fig. 11 versus the mean solid phase temperature at failure. It can be observed that the steady state results were reasonably consistent between the different ply and adhesive configurations.

A clear difference can be observed in the compressive strength between steady state thermal and transiently heated results. This can probably be attributed mainly to the effect of moisture movements within the specimen and the resulting differences in observed failure modes. Transient specimens at a low load level can be observed to mostly fail at elevated temperatures, where their ‘reduction path’ appears to align with the steady state specimens. This is to be expected since all moisture had been removed (i.e. evaporated) from the specimens at these temperatures.

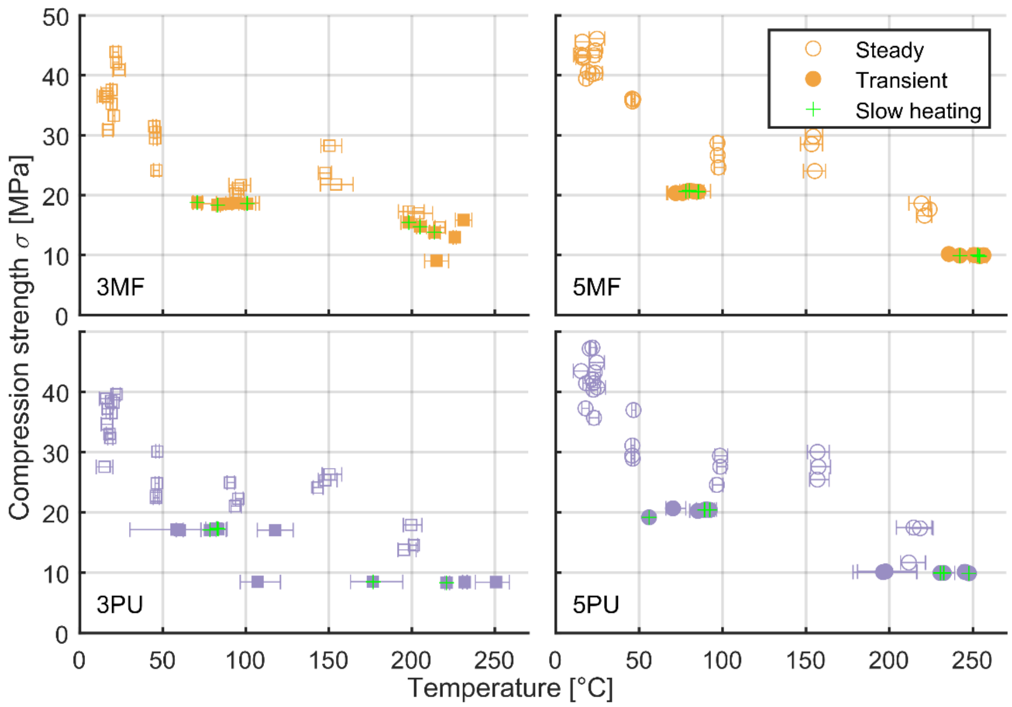

Fig. 10. Measured ultimate effective compressive strengths for increasing temperatures, arranged by adhesive type and number of plies.

For the consideration of fire safety, the steady state thermal experimental results are – in most cases – less relevant than transient state experiments, since a steady state heating condition is unlikely to occur within timber during a compartment fire, given that heating conditions of the timber can virtually always be assumed to be transient – even for the fire decay and timber cooling phases where some areas of timber will continue heating and others will cool down. This will be accompanied by changes in moisture content. In considering the effects of the interactions between moisture and elevated temperature the following analysis therefore focuses on experimental results where transient heating and moisture can be assumed to have been present within the timber at failure. Within this constraint all experiments that involved transient heating and those that heated the timber to a target temperature of 50 °C are considered, under the assumption that the latter still contains moisture. Given the temperature gradients during the heating phase it can be assumed that moisture movement occurred [36], however from the experimental set-up herein it cannot be confirmed if this movement continued (i.e. lagged) after quasi steady state temperatures were achieved. It can also not be determined if moisture movement before the application of load would affect the load bearing capacity, although this would be an interesting application for further research. It is clear from the data, and the consideration of the evaporation temperature of water, that a linear regression analysis would not be an appropriate tool to assess these data. Instead, a bilinear reduction curve with a fixed value of zero remaining strength at 300 °C has been assumed, similarly to the reduction in mechanical properties for timber proposed by Eurocode 5; timber is generally assumed to be converted to char at this temperature, and thus has negligible strength and stiffness.

To assess the uncertainty in the data and the chosen bilinear fit, a bootstrap approach [37, 38] has been adopted int his paper. This involves repeated sampling of the available data *with replacement,* thereby giving a distribution of possible solutions based on the variability of the individual data points.

Since the remaining normalised compressive strength is set to zero at 300 °C, the severity of the heat induced strength reduction can be expressed through the remaining strength at the breakpoint. To obtain comparable values, this breakpoint is fixed at 100 °C which represents a logical choice considering that moisture and its movement have been identified as key factors affecting the strength of timber at elevated temperature. The resulting strength retention at 100 °C presents a discrete value that expresses the extent of deterioration of the tested CLT configurations. From the bootstrap data a distribution of retention factors can be obtained for the parameters considered in this study, i.e. adhesive types and number of plies. These are shown in Fig. 12.

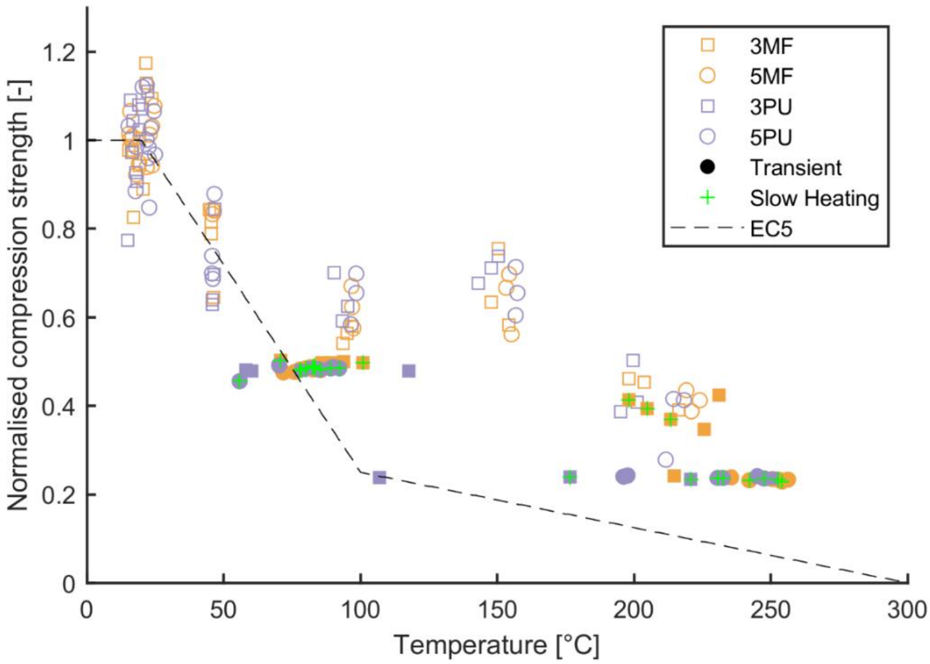

Fig. 11. Normalised ultimate effective compressive strength with increasing temperature for both steady state thermal and transient heating regimes.

The strength retention factors are approximately normally distributed, and it can be seen that a significant difference exists between PU and MF samples. This is confirmed by assessing the difference between the two variables through subtraction of the PU data from the MF data. This returns a range of values with a median of 0.087 and 95 % confidence bounds of 0.003 and 0.186. Since these bounds do not contain zero, it can be stated with 95 % confidence that a difference in strength retention between polyurethane and melamine formaldehyde adhesives exists at 100 °C for the imposed bilinear reduction and under the assumptions stated above. This assessment does not hold for a 99 % confidence interval.

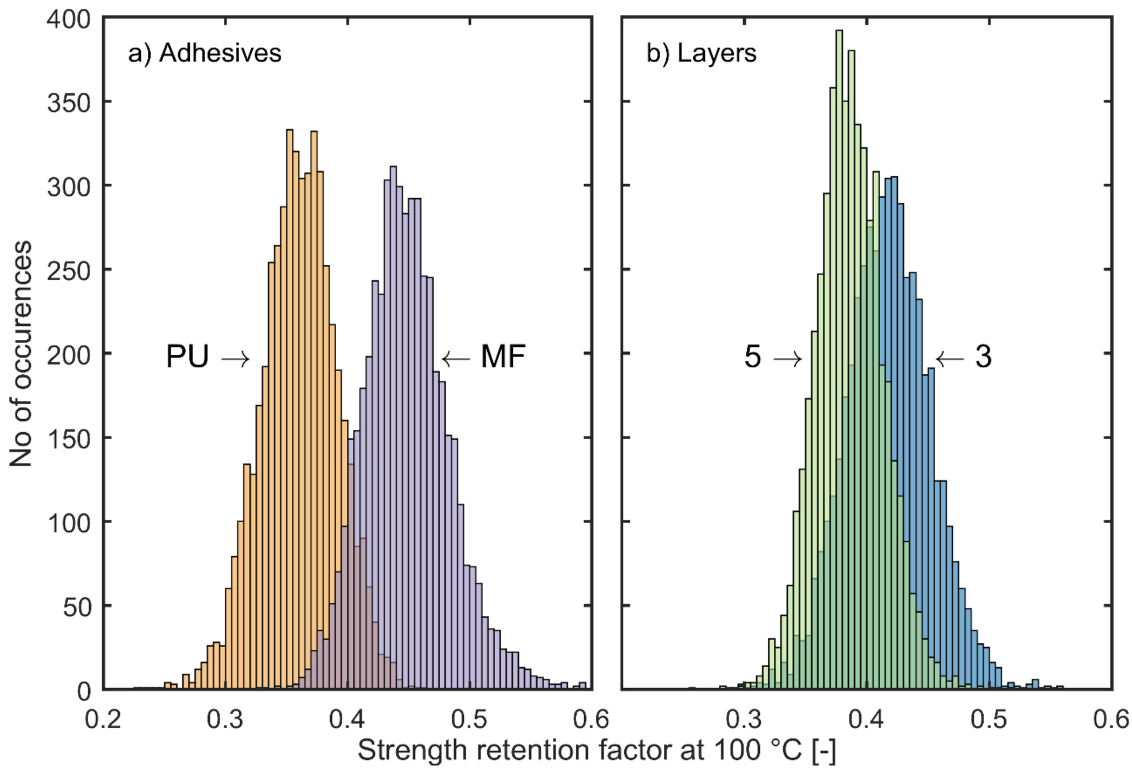

Fig. 12. Histogram of strength retention factors at 100 °C (i.e. breakpoints) determined from a 5000-sample bootstrap by: a) adhesive type, and b) number of plies in CLT samples.

It is not entirely clear why the adhesive type should have a significant effect on the strength of heated CLT in a purely compressive experimental set-up: from a structural engineering perspective, even if the adhesion/cohesion of the adhesive were to vanish completely, the individual layers should continue to displace together, thereby maintaining the same strain and stress. The second moment of area, on the other hand, for a specimen with no remaining adhesion between individuals' plies is significantly lower than for a fully bonded sample; thus the occurrence of small bending moments or buckling in the individual plies could explain the failure at lower temperatures for PU samples compared to MF ones. Internal moments could be caused by non-uniform heating, as is the case for the transiently heated samples, however, this does not explain why there is also a difference for the steady state samples heated to approximately 50 °C. The effect of accelerated loss of composite action for PU compared to MF bonded specimen has also been reported for samples in four point bending of the same CLT stock as the samples herein by parallel studies [39]. Another possible explanation, independent of the occurrence of bending or buckling in the specimens, could be the loss or weakening of the lamination effect, which is shown to significantly improve the strength for five plies at ambient temperature. However, this hypothesis is not supported by the steady state results; if a reduction in lamination effect were to occur, the reduction in ultimate strength would be more severe for five ply, compared to three ply, specimens at elevated temperatures. Based on the analysis presented herein, it should also be considered that the reduced strength retention for PU is driven by random differences in the specimens rather than a systematic effect in the underlying populations, considering that only a limited number of data points are available at each temperature and that the difference in adhesives was only valid within the 95 % confidence range.

The increased loss of strength on transient heating, likely attributed to moisture movement and evaporation, is practically significant since mass timber elements in real fires will invariably be heated transiently with temperature gradients facilitating movement of moisture. For the same reasons, the observed effects of temperature and moisture gradients on the differences in capacity between PU and MF adhesive types should be considered further in design, since the results herein showed that CLT with PU adhesives experienced comparatively larger losses in compressive load bearing capacity. The findings herein are also relevant after a fire has reached its peak intensity and begins to decay once the available fuel from the compartment's contents is consumed. These conditions result in shallower in-depth temperature gradients in the timber, with continued heating internally and cooling of timber located closer to the surface. This continued recession and propagation of elevated temperatures will cause further moisture movements. An accurate assessment of the continuously reducing load bearing capacity [40-42] therefore requires detailed knowledge of the reductions in mechanical properties of the system as a whole, rather than the material alone.

The determined bilinear reductions in strength at elevated temperature are shown in Fig. 13, along with their 95 % confidence intervals. The reduction curve proposed in Eurocode 5 [13] provides a conservative estimate, however it can also be seen that the assessed fit does not capture all datapoints correctly which might be due to the constraints that arise from assuming a bilinear fit and the influence of the specimens heated transiently above 150; these were observed to completely evaporate all of their free moisture, and can therefore be expected to behave very differently from specimens that would have been further weakened by the influence of moisture movement. Some of the points that fall below the Eurocode 5 curve could be linked to the general variability of timber rather than a failure to accurately predict reductions, which is the expected when the fits are calculated based on mean or median strength values. In design this is accounted for by the use of characteristic strength values as input parameters.

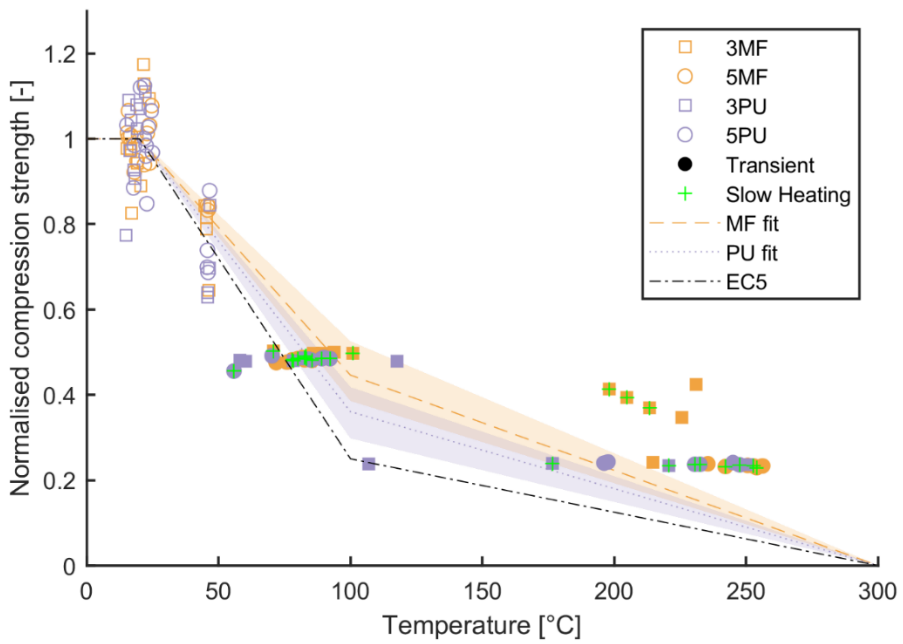

Fig. 13. Reduction in retention factors for CLT with 95 % confidence intervals as shaded areas for different adhesive formulations determined from multi-linear fits with fixed boundary conditions for fully charred timber.

5 Conclusions

One of the aims of this paper has been to assess whether the advanced calculation methods proposed within Annex B of Eurocode 5 [13], originally developed to treat temperature-induced reductions in compressive strength of sawn lumber, are applicable to CLT under predominantly compressive loading. The Eurocode 5 suggested bilinear reduction was shown to provide a conservative lower bound for most of the specimens in the current experimental study, and is therefore likely suitable (or at least conservative) for use in designing laminated timber systems subjected to either transient or steady state heating conditions.

At ambient temperatures a lamination effect was observed with five ply CLT exhibiting higher strengths and a lower variability than CLT comprised of three layers. This is attributed to the fact that timber defects and weaknesses can be compensated for better through a multitude of layers, where stresses in individual layers are reduced.

For samples subjected to heating, either through steady state heating followed by loading to failure or transient heating on samples subjected to constant load, a significant difference was observed in the strength reduction between steady state and transient heated experimental conditions. This highlights the important role of moisture movement within timber, and its effect on the load bearing capacity of mass timber compression elements in particular. Further research on the reduction in structural capacity in laminated timber should consider to what extent different heating rates can influence the movement of moisture within the timber and therefore affect its structural capacity. This research would be aided by the development of techniques to monitor the transient moisture movement in timber exposed to heat and flames.

For transiently heated specimens, a significant difference in strength reduction was found between the two assessed adhesive types. In an assumed bilinear model, specimens bonded with a PU adhesive experienced more severe reductions in load bearing capacity at 100 °C than those bonded with MF adhesive. This highlights the differences in behaviour between these two specific adhesives at elevated temperature, as well as the detrimental behaviours linked to the movement of moisture under transient heating conditions. This point should be highlighted as a potentially important consideration for the whole system response of laminated timber buildings subjected to real – rather than standard – fires, where steep temperature gradients and associated moisture movements could affect the load bearing capacity during and after a fire. This is especially the case for adhesives with a low capacity to maintain adhesion or cohesion at elevated temperatures. Additional research is needed to assess this effect on larger scale building elements that are exposed to transient heating conditions while placed under sustained bending or shear forces.

6 Acknowledgments

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) and the National Centre for Timber Durability and Design Life. Mayr-Melnhof Holz are acknowledged for their generous contribution of materials. The authors thank Mark Partington from the University of Edinburgh for his technical assistance with the reported experiments.

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