MEASURING THE CHAR RATE OF CROSS LAMINATED TIMBER IN AN INTERMEDIATE-SCALE FURNACE

T.R Moser, M.T Aitken and M.J Spearpoint

Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch

Email: michael.spearpoint@canterbury.ac.nz

ABSTRACT

An important parameter in determining the fire performance of CLT is its charring rate. The aim of this research is to measure the charring rate of CLT by conducting a series of experiments in an intermediate-scale fire resistance furnace under ISO 834 conditions. The char rate was measured using implanted thermocouples to track the progression of the char layer through the sample, giving a char rate of 0.83 ± 0.20 mm/min. A second measure of the char rate was obtained by removing the char layer after the experiment and manually measuring the decrease in cross-sectional depth. This technique measured the char rate of CLT to be 0.83 ± 0.11 mm/min. Care should be taken in applying these results in a design context and it is recommended that full-scale furnace testing under standard fire conditions be undertaken to assess whether the char behaviour observed during this research is applicable to larger panels of CLT.

1 INTRODUCTION

Cross laminated timber (CLT) consists of boards glued together in perpendicular layers to form panels. CLT is used in the construction of residential and commercial structures. CLT can be used as load bearing walls or floors in a structural system and offers a range of environmental, architectural and structural advantages over alternate construction materials. The primary factor that influences the structural fire performance of a timber product is its charring behaviour. As a timber element chars the cross section decreases leading to a reduction in the capacity of the element. As well as carrying loads, in a fire event CLT panels are also required to maintain their integrity and provide insulation within a structure.

A typical specification for the char rate is to use 0.65 mm/min for the first layer of CLT, based on the value for solid Radiata pine in NZS 3603 [1], and for subsequent layers the char rate is doubled to 1.3 mm/min to allow for the effect of delamination as observed by Frangi et al. [2]. In the calculation of structural capacity a 10 mm zero strength layer is assumed adjacent to the char front.

The purpose of this research is to assess the charring rate of CLT using an intermediate-scale furnace. The charring rate was measured perpendicular to the panel surface as this is the likely direction of exposure in a fire event. The potential for delamination as a result of fire exposure was also investigated. Improved understanding of the charring behaviour will allow designers to model the fire performance of CLT more accurately allowing more efficient fire design of CLT structures in the future.

2 FIRE PERFORMANCE OF TIMBER

2.1 Performance Requirements

The New Zealand Building Code specifies fire requirements with the intention of safeguarding people from an unacceptable risk of injury or illness caused by a fire; protecting other property from damage caused by fire and to facilitate firefighting and rescue operations. To achieve these performance requirements building elements need to provide a specific fire resistance rating (FRR). The FRR is a measure of the time it takes a building element to resist exposure to the standard fire curve. As load bearing walls and floors, CLT panels are required to provide a specified fire resistance rating for stability, integrity and insulation. The charring behaviour has a large influence on the ability of the panel to provide the necessary FRR.

2.2 Charring Behaviour

Collier [3] conducted research into the charring behaviour of glued laminated timber (Glulam) made from New Zealand Radiata pine. He concluded that the factors that have the greatest influence on the charring rate of timber are moisture content and density. Collier obtained a mean charring rate for Glulam of 0.77 mm/min from samples with a 12 % moisture content and density of 452 kg/m3.

Lane et al. [4] conducted experiments to measure the char rate of laminated veneer lumber (LVL) made from New Zealand grown Radiata pine with a density of 604 kg/m3 at 12 % moisture content. Their experiments included pilot furnace testing under ISO 834 conditions. From this it was concluded that the char rate of LVL was 0.72 mm/min and that charring behaviour under ISO 834 conditions equates closely to an irradiance exposure of 35 kW/m2.

2.3 Fire Testing on CLT Panels

Frangi et al. [2] conducted experimental testing on European produced CLT under ISO 834 [5] conditions exposed to the underside of horizontal panels. Their samples consisted of 28 mm layers of spruce timber with a moisture content of 12 % and a mean density of 420 kg/m3, bonded by a polyurethane adhesive. They observed a faster char rate for CLT than homogeneous timber and this was attributed to delamination under gravity caused by failure of the adhesive layer which removed any insulating char material protecting the inner core. They therefore proposed that the performance of the adhesive at elevated temperatures was an important factor in the fire performance of CLT. Figure 1 shows the effect of delamination on the char rate with a clear increase in gradient at charring depths of 28 and 56 mm.

Klippel et al. [6] report an average charring rate of 0.79 ± 0.03 mm/min from four tests on loaded CLT floors exposed to the ISO 834 standard fire curve for one hour. They partially attributed the charring rate to a tendency of charred layers to fall off the horizontal elements.

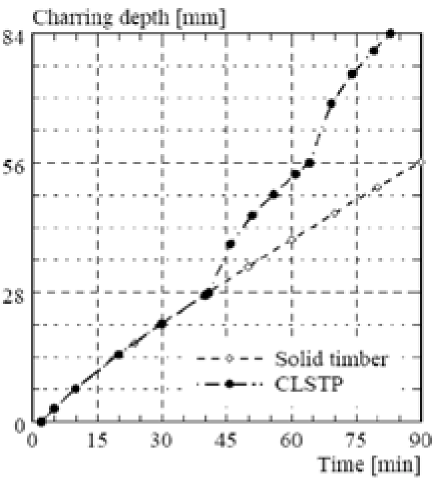


Figure 1: *Charring depth with time of a CLT panel (CLSTP) consisting of 28 mm thick layers compared with solid timber, Frangi et al. [2].*

Previous research undertaken on the performance of CLT in fire conditions were conducted by McTavish and Palmer [7]. They conducted small-scale testing using the ISO 5657 [8] ignition apparatus and although their results were inconsistent due to nonlinear charring at the edges of the samples, shown in Figure 2, they found that the char rate of CLT panels subjected to a radiant heat flux of 35 kW/m2 was 0.88 ± 0.12 mm/min using results from embedded thermocouples.

Figure 2: *The edge effect on small samples of charred CLT, McTavish and Palmer [7].*

3 MATERIALS AND METHODOLOGY

3.1 Fire Resistance Furnace

The experimental apparatus used was an intermediate-scale fire resistance furnace located at the University of Canterbury. The furnace had an internal compartment measuring 350 × 350 × 500 mm and six electrical elements that could be used to control the temperature.

3.2 Sample Preparation

The experiments used CLT panels of Radiata pine with a density of 437 ± 8 kg/m3, made of 35 mm laminations glued with a one-component polyurethane (PUR) adhesive. The panels were first cut to the size of 210 × 210 × 440 mm and individually weighed then 3 mm diameter holes for thermocouples were drilled at depths of 10, 18, 30, 40, 60 and 75 mm from the exposed surface. Two thermocouples were implanted at each depth (Figure 3). Each hole extended 65 mm into the sample as this was the longest drill bit of this diameter available. The cross shape was chosen to avoid significant loss of material in the same vertical plane. The depths of 30 and 40 mm were chosen to measure the char rate across the 35 mm lamination. The 10 mm and 18 mm depths also correspond to depths used in the research of Frangi et al. [2] and McTavish and Palmer [7]. The panels were stored in the laboratory at 18 – 20 °C and immediately prior to the experiment the moisture content of each sample was measured as 12 ± 1 % using a hand-held digital probe.

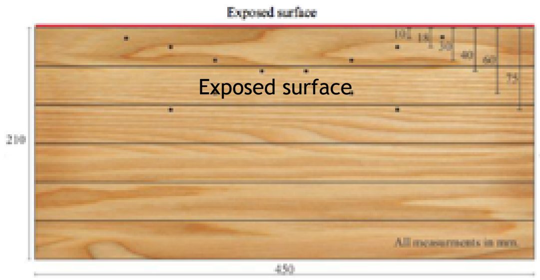


Figure 3: *Schematic of thermocouple placement throughout sample.*

3.3 Experimental Procedure

At the start of each experiment the 12 thermocouples were connected to a data logging system and then inserted into the sample. The sample was then placed within a box constructed of 50 mm thick non-combustible insulating boards on five sides to permit one sided exposure. The insulating box containing the sample was then placed into the furnace and the furnace sealed with insulating material. During later experiments, following inconsistencies in thermocouple results, any exposed thermocouples within the furnace were further insulated to minimise the effect of conduction up the wire.

The furnace was operated as close as possible to standard fire conditions as defined by ISO 834 [5] with temperature-time data from the furnace logged in real time. Using the ISO 834 fire curve allows the data to be used when considering fire resistance ratings and allows comparisons to other previous charring research. Samples were predominantly charred for 60 min with several shorter and longer experiments undertaken to consider the charring behaviour with time. Times were generally chosen to correspond to fire resistance ratings, but some experiments had to be terminated prematurely due to equipment malfunction.

Upon completion of an experiment water was applied to the sample to lower the temperature below 300 °C which prevented further charring [2]. Once the sample had cooled sufficiently the sample was removed from the insulating box and the char layer removed with a wire brush. Manual char depth measurements were taken using Vernier callipers. To ensure consistency of measurements, each sample was placed in a box of known size and the Vernier calliper was dropped from fifteen uniformly spaced reference points on a 3 × 5 grid. Maintaining constant char measurement points while varying samples ensured no bias in points chosen for measurements. The outside 50 mm boundary of the sample contained no reference measurement points due to corner rounding that occurred during the experiments.

4 RESULTS AND DISCUSSION

4.1 Furnace Temperature Performance

Figure 4 shows the time temperature curves for each of the ten experiments conducted. The ISO 834 curve with the upper and lower tolerances has been overlaid. The plot has been terminated at 40 min as large fluctuations in thermocouple readings occurred after this point due to electrical interference from the furnace elements.

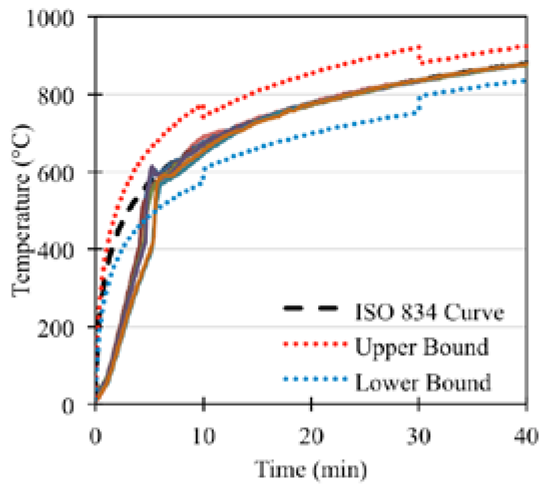


Figure 4: *Furnace time temperature curves with ISO 834 curve and tolerances overlaid.*

From Figure 4 it can be seen that the furnace was unable to provide the steep initial temperature climb specified by the standard fire curve. This meant that most experiments were outside the ISO 834 tolerance for approximately the first five minutes. From approximately ten minutes onwards each experiment closely follows the standard fire curve, well within the allowable tolerance. Figure 4 also shows a large increase in temperature at approximately 400 °C which is due to the ignition of the sample that occurred around this temperature.

4.2 Manual Measurements

The manually measured results are summarised in Table 1. Over the ten samples the average char rates ranged between 0.81 and 0.86 mm/min. From the 150 Vernier measurements the average char rate was found to be 0.83 mm/min with a standard deviation of 0.074 mm/min. In this, and subsequent tables the error displayed is half of the measured range, consistent with McTavish and Palmer [7].

Table 1: Summary of manual char measurements.

Experiment	Exposure time (min)	Average char depth (mm)	Average char rate (mm/min)
1	30	25.6 ± 7.4	0.85 ± 0.025
2	50	43.9 ± 3.2	0.86 ± 0.062
3	60	49.1 ± 3.5	0.82 ± 0.058
4	60	48.4 ± 4.3	0.81 ± 0.072
5	60	50.9 ± 4.5	0.85 ± 0.074
6	60	49.3 ± 3.5	0.82 ± 0.058
7	60	48.8 ± 5.2	0.81 ± 0.087
8	60	49.8 ± 5.0	0.83 ± 0.083
9	90	75.3 ± 4.7	0.83 ± 0.052
10	80	66.8 ± 9.1	0.84 ± 0.110

4.3 Thermocouple Measurements

Reliable thermocouple data was only obtained from the last five experiments. During the first five experiments data was unreliable as a lack of protective insulation resulted in damage to thermocouples. A typical temperature profile from within a sample as measured by the pairs of thermocouples at each depth is shown in Figure 5. The temperature progression measured was as expected with the shallower thermocouples heating faster than deeper layers. A plateau can be seen at around 100 °C where energy is being used to overcome the latent heat of vaporisation of moisture within the sample. Data from after 40 min is not shown due to large fluctuations in readings.

Frangi et al. [2] and Lane et al. [4] both considered 300 °C to be the temperature at which timber chars and so the char depth was taken to be when the thermocouple measurements achieved this criterion. From the char depth results the char rate was then calculated where Table 2 summarises the char measurements obtained from the thermocouple data.

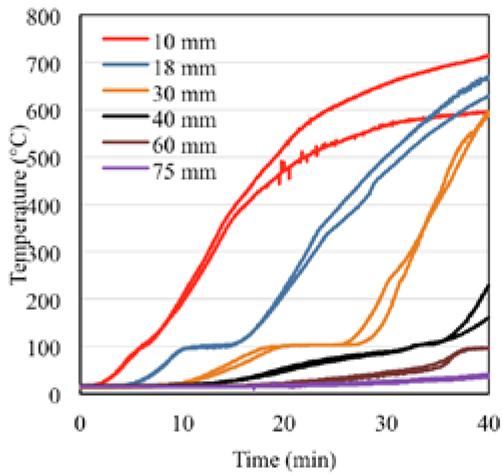


Figure 5: *Temperature profile within sample during Experiment 8.*

Table 2: Summary of thermocouple measurements.

Thermocouple depth (mm)	Average time to reach 300°C (min)	Average char rate (mm/min)
10	13.4 ± 2.1	0.74 ± 0.10
18	22.0 ± 2.8	0.82 ± 0.09
30	34.4 ± 5.1	0.87 ± 0.11
40	45.8 ± 7.0	0.87 ± 0.12

A measured average char rate of 0.83 ± 0.20 mm/min is obtained from the results given in Table 2. A slower char rate over the first 10 mm was observed from the thermocouple data and this was an expected result as it typically took the furnace approximately four minutes to ignite the CLT sample. Thereafter the char rate measured by the deeper thermocouples was relatively consistent. Due to the fluctuations in thermocouple readings after 40 min it was not possible to use data from thermocouples deeper than 40 mm to calculate the char rate.

4.4 Char Behaviour across Laminations

By placing two thermocouples at depths of 30 and 40 mm in each sample the char behaviour across the 35 mm lamination could be observed. Table 3 summarises the measured char behaviour across the lamination. Only the results from the five experiments that provided reliable thermocouple measurements have been considered. From the measurements the average char rate across the lamination was calculated to be 0.92 ± 0.30 mm/min which is 11 % faster than the overall measured char rate.

Table 3: Char behaviour across the 35 mm lamination as measured between the 30 and 40 mm deep thermocouples.

Experiment	Average time to char across lamination (min)	Average char rate across lamination (mm/min)
6	9.0 ± 1.7	1.11 ± 0.17
7	8.1 ± 0.6	1.24 ± 0.06
8	15.7 ± 2.2	0.64 ± 0.22
9	12.8 ± 4.4	0.78 ± 0.44
10	11.8 ± 1.6	0.85 ± 0.16

It is important to note that since the thermocouples were inserted into 3 mm diameter holes this created variances from the prescribed depth. When the char rate is measured across the 10 mm distance this variance results in an uncertainty of 0.30 mm/min.

4.5 Comparisons

Figure 6 shows a comparison between the manual and thermocouple measurements for the experiments that gave reliable thermocouple data. There are no clear trends in the differences between the two types of measurements. Therefore it is expected that the differences in measurements are due to random experimental error rather than a systematic error such as the incorrect definition of the char temperature.

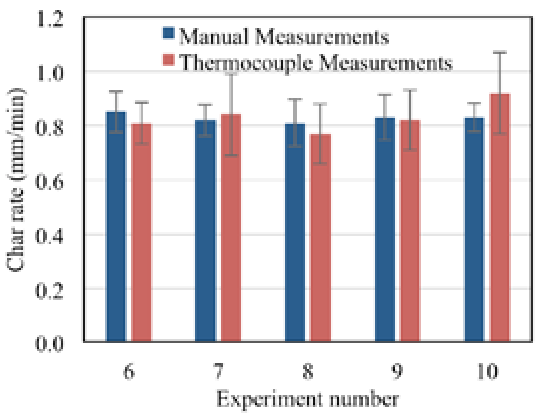
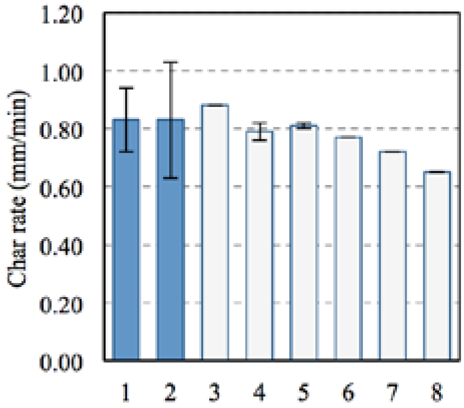


Figure 6: *Comparison between manual and thermocouple char rate measurements.*

As both measurement methods produce similar results within the bounds of experimental error it can be concluded that they are both suitable methods to measure the char rate. Generally there is less variability associated with the manual measurements with the error associated with the thermocouples on average around 70 % greater than the error amounting from the manual measurements.



Key:
1: Manual measurements
2: Thermocouple measurements
3: McTavish and Palmer [7], CLT at 35 kW/m2
4: Klippel et al. [6], CLT to ISO 834
5: AS 1720.4 [9]
6: Collier [3], Glulam
7: Lane et al. [4], LVL
8: NZS 3603 [1], Radiata pine

Figure 7: *Comparison of measured results against other published char rate values.*

Figure 7 shows a comparison of the measured char rates in this work against several published values. For exposure to a radiant heat flux of 35 kW/m2 McTavish and Palmer [7] manually measured the average char rate to be 0.75 mm/min compared to 0.83 ± 0.11 mm/min in this work. Furthermore McTavish and Palmer obtained a char rate of 0.88 mm/min measured using thermocouples under a radiant heat exposure of 35 kW/m2 compared to the average char rate of 0.83 ± 0.20 mm/min measured by the thermocouples in this work. Equation 2.1 of AS 1720.4 [9] gives

$$c = 0.4 + \left(\frac{280}{\delta}\right)^2 \qquad (1)$$

where c = notional charring char rate (mm/min); δ = timber density (kg/m3) at a moisture content of 12 %. Using the measured density of the CLT panels gives 0.81 ± 0.01 mm/min for the char rate. A recent summary of work carried out by SP in Norway [10] on CLT exposed to a natural fire obtained char rates from 0.70 mm/min to 1.4 mm/min with an average of 1.1 mm/min.

5 OBSERVATIONS

5.1 Char Profile

The nonlinear charring around the edges of the sample experienced by McTavish and Palmer [7] was still observed in these experiments however the use of larger samples meant that a large area of relatively uniform char was obtained that allowed a grid of Vernier calliper measurements to be taken. A typical char profile is shown in Figure 8(a) and Figure 8(b) shows a surface plot of the sample from Experiment 8. The plot includes measurements taken from beyond the boundary of the Vernier calliper reference point grid with the edge effect clearly illustrated. As a large area of CLT is typically used as part of floor and wall systems it is expected that such edge effects will have minimal influence on the structural behaviour of the panel.

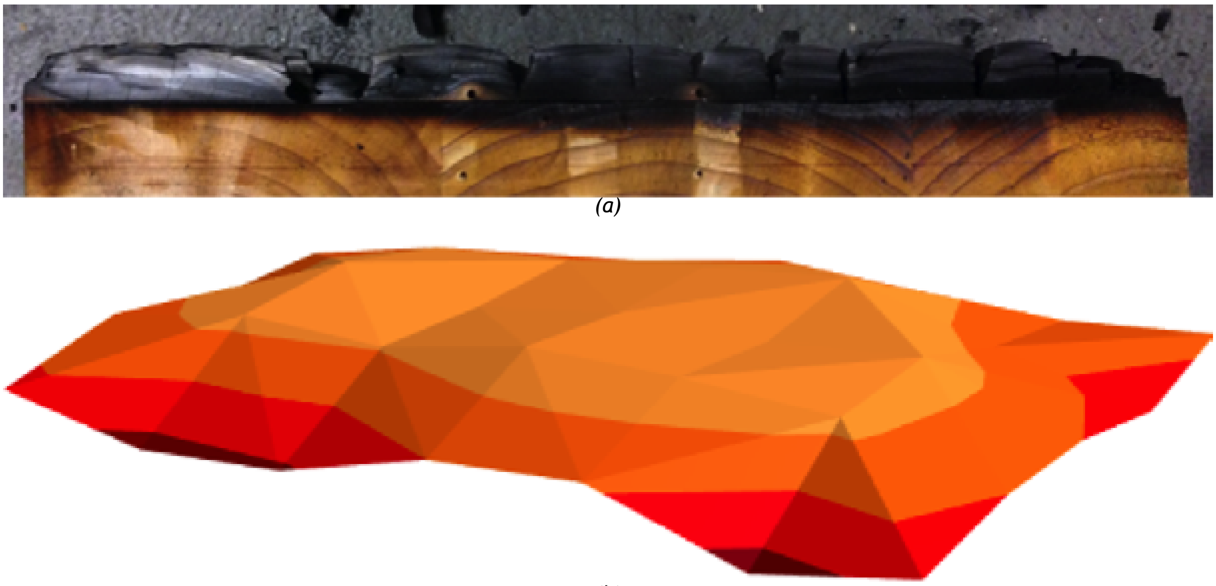


Figure 8: *Typical char profile of sample (a) photograph before removing the char layer, showing the non-linear edge char, (b) surface plot of sample from Experiment 8 showing rounded edges.*

5.2 Performance of Adhesive

To examine the behaviour of the adhesive in fire conditions attempts were made to pry the heated layers apart at the conclusion of experiments. This was done after the water had been applied to extinguish the sample. It was found that with a crowbar it was possible to separate the layers but this occurred due to failure of the wood fibres rather than the adhesive layer. The findings here do not match the results of Frangi et al. [2] who observed delamination of layers due to adhesive failure that led to an increase in char rate. However Lehringer and Gabriel [11] note that despite a loss of shear strength in the glue layer at temperatures above 200 °C in PUR type adhesives, the expected failure mechanism of engineered timber in a fire would be because the bending resistance of wood is exceeded rather than failure of a glue layer.

6 DISCUSSION

A range of measures could be taken to develop better understanding of the charring behaviour of CLT. The experiments undertaken as part of this research were limited to Radiata pine panels. In the future furnace testing on Douglas fir panels is recommended to allow the charring behaviour of this material to be better understood. Also as the sample size is limited to ten thermocouple measurements over five experiments it is recommended that further research is undertaken to get a better understanding of the char behaviour particularly across laminations. It is recommended that full-scale furnace testing under standard fire conditions is undertaken to assess whether the char behaviour observed during this research is applicable to larger panels of CLT.

During experiments the samples were simulating a structural floor with heat exposure occurring on the top surface. As CLT panels can act as walls and ceilings fire testing at different orientations would be recommended to see if this influences the charring behaviour. Although adhesive failure is not anticipated, under different orientations it is possible that some of the weaker insulating char layer would fall off under gravity meaning that an increased char rate may be observed.

To gain a better understanding of the adhesive behaviour at high temperatures it is recommended that experiments are conducted with a shear force applied across the glue layer during the heating of the sample. This would allow any deterioration in strength of the glue layer to be measured which could then be applied when designing for CLT in fire conditions.

7 CONCLUSIONS

Ten experiments were conducted in the University of Canterbury intermediate-scale fire resistance furnace in an attempt to measure the charring rate of Radiata pine cross laminated timber. The furnace was controlled to follow the ISO 834 standard fire curve. The furnace was unable to sustain the fast initial climb in temperature but from approximately 10 min onwards closely matched the standard fire curve.

The charring rate was measured using two methods. Thermocouples were implanted between 10 and 75 mm from the exposed surface that measured the time temperature profile within the sample. The char temperature was defined as 300 °C and the time taken to reach this point used to obtain the char rate. Using this method the char rate of the CLT was measured as 0.83 ± 0.20 mm/min. After the experiment the char layer was removed and manual measurements taken to obtain another measure of the char rate. This technique measured the CLT char rate to be 0.83 ± 0.11 mm/min. Results from this work are consistent within experimental error with AS 1720.4 [9] and Klippel et al. [6] although the recent work by SP [10] suggests that charring rates could be higher in natural fires.

An increased char rate applied to subsequent layers represents the effect of delamination observed by Frangi et al. [2]. An attempt to imitate the delamination due to failure of the adhesive layer was carried out and it was found that the timber fibres failed before the adhesive. Because of this observation it is thought that delamination of CLT using a one-component polyurethane adhesive is not likely to be an issue in fire conditions but further experiments are needed to confirm this.

A number of areas of further research have been identified and given this research was conducted in an intermediate-scale furnace then care should be taken applying the results in the design of actual buildings that use CLT panels.

8 ACKNOWLEDGEMENT

The authors wish to thank University of Canterbury fire laboratory technician, Grant Dunlop for his help in configuring the furnace and the sample preparation.

9 REFERENCES

1. NZS 3603, 1993. Timber structures standard. Standards New Zealand, Wellington, New Zealand.
2. Frangi, A., Fontana, M., Knobloch, M., Bochicchio, G., 2008. Fire behaviour of cross-laminated solid timber panels. Fire Safety Science, 9, 1279-1290. doi:10.3801/IAFSS.FSS.9-1279.
3. Collier, P. R., 1992. Charring rates of timber. BRANZ Report No. 42. Wellington, New Zealand.
4. Lane, W., Buchanan, A., Moss, P., 2004. Fire performance of laminated veneer lumber (LVL). Proc. World Conference on Timber Engineering, Lahti, Finland, June 2004, Vol 3, pp 473-478.
5. ISO 834, 2014. Fire resistance tests – elements of building construction. Geneva, Switzerland.
6. Kippel M., Leyder C., Frangi, A., Fontana, M., 2014. Fire tests on loaded cross-laminated timber wall and floor elements. Fire Safety Science, 11: 626-639. doi:10.3801/IAFSS.FSS.11-626
7. McTavish, J., Palmer, C., 2013. Charring behaviour of New Zealand cross-laminated timber. Presented at the Civil and Natural Resources Engineering Research Conference, Christchurch, New Zealand, October 2013.
8. ISO 5657, 1997. Reaction to fire tests – Ignitability of building products using a radiant heat source. Geneva, Switzerland.
9. AS 1720, 2006. Part 4: Fire resistance for structural adequacy of timber members. Standards Australia, Sydney, Australia.
10. Hox, K., 2016. Full-scale fire test of CLT structure used for student housing. Brandposten #53, pp 20-21.
11. Lehringer, C., Gabriel, J., 2013. Review of recent research activities on one-component PUR-adhesives for engineered wood products. Materials and Joints in Timber Structures, Springer Netherlands.