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Advancing Timber for the Future Built Environment

STRENGTH AND STIFFNESS OF (RELAMINATED) CLT EDGE-TRIMMED OFF-CUTS

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ABSTRACT: Although timber construction offers the potential to decarbonise building construction drastically, mass timber production is associated with waste material that is not biodegradable. This paper reports on an experimental campaign that studied the potential use of trimmed off-cut material as standard boards and as material for relaminated cross-laminated timber. A comparison of strength and stiffness from four-point bending tests and shear strength shows a remarkably good comparison with reference timber and cross-laminated material, albeit with a more significant variation in results. Considering the added benefit of reduced embodied carbon, such reuse shows substantial benefits in moving towards a more circular value chain in the built environment.

KEYWORDS: Cross-laminated timber, embodied carbon, timber engineering, mass timber production.

1 – INTRODUCTION

This paper reports on results from an experimental campaign that investigated the potential recycling and structural reuse of cross-laminated timber (CLT) off-cut material with the aim of reducing and redirecting waste associated with the CLT manufacturing process. The experimental campaign consisted of two parts. In one part, the on-edge bending capacity of off-cut (trimming) material is compared to that of sawn timber used to manufacture the reference CLT panels. The second part investigated the out-of-plane bending and shear capacity of relaminated CLT panels produced by glueing such off-cut material in different configurations. Values are compared with the reference CLT from which off-cut material was produced. It is shown that mean values for strength and stiffness compare well. Finally, informed by the strength and stiffness comparisons, the study reports on the estimated embodied carbon reduction obtained with such relaminated mass timber panels.

2 – BACKGROUND

With the building sector accounting for approximately 37% of global carbon emissions and 34% of global energy consumption [11], timber-based building materials can provide significant environmental advantages over more traditional construction materials such as concrete and steel [13]. Although timber is biodegradable by nature, CLT is produced with glues that are not. Moreover, individual cross-laminated timber building components are produced with a substantial volume of off-cut material (5% to 25% [1, 4, 12]). Some studies have investigated the reuse of larger pieces of waste material that results from cutting openings in CLT panels (e.g., [5, 6]), whilst others have investigated the use of timber waste at the end-of-life stage of building structures for the production of CLT (e.g., [2]). However, a need remains to consider the reuse potential of smaller trimming off-cut material from CLT production.

3 – PROJECT DESCRIPTION

To address this issue, the study described here investigated the capacity of such off-cut material as (i) *an alternative to similar-sized sawn timber boards* and (ii) *relaminated CLT panels*. The embodied carbon reduction associated with such material is also estimated. Off-cut material from 3-lamella CLT (3 × 22 mm = 66 mm thick) that is commercially produced with South African Pine (softwood) is compared with S5 Pine [7] from which the reference material is produced. All timber in this study was obtained from the same sawmill. Moreover, using the same industry standard glue throughout, the same commercial CLT manufacturer pressed the reference and relaminated CLT panels in a hydraulic press.

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(a) (b)

Figure 1. On-edge flexural tests of (a) a sawn timber board and (b) an off-cut board.

4 – EXPERIMENTAL SETUP

This section outlines the experimental setup for the various tests conducted to compare off-cut material with sawn timber and as relaminated material with reference CLT. It should be noted that the number of experimental tests conducted depended on off-cut material availability at the time of testing. As such, sample sizes were smaller than stipulated in SANS 6122 [8] for testing timber boards in bending and in SANS 8892 [9] for CLT performance tests.

4.1 TESTING OF BOARDS

On-edge four-point bending tests were performed on planed off-cut material, and the reference sawn timber boards that were reduced to the same dimensions. A total of 18 specimens of both the off-cut and reference boards were tested. Due to variations of off-cut material, two widths were tested for both the off-cut material and resized reference sawn timber: (i) *12 specimens 22 mm wide and (ii) six specimens 15 mm wide*. All specimens had a span length of 1200 mm, following SANS 6122 [8], as shown in Fig. 1 and Fig. 2.

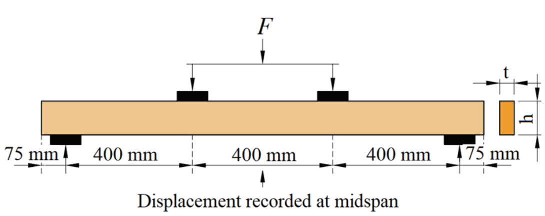

Figure 2. On-edge bending test configuration of boards.

Tests were conducted using a hydraulic press that applied a displacement-controlled load at a rate of 5 mm/min. A linear variable differential transformer (LVDT) was placed at mid-span on either side of the boards. Vertical displacement was taken as the average of the two displacement values.

Force-displacement results were used to determine the elastic stiffness (Modulus of Elasticity, MoE) and the bending strength (Modulus of Rupture, MoR). The 95% confidence interval (CI) of MoE and MoR for each board size (20 × 66 and 15 × 66) included the mean of the other board size for the reference sawn timber and off-cut boards. As such, results from both board dimensions were considered as a combined set of results.

4.2 TESTING OF CLT

Flatwise bending

Six reference CLT specimens (hereafter referred to as "*Reference*" panels) were tested in out-of-plane bending in the major direction. Two forms of relamination were considered: (i) panels with all lamellae consisting of off-cut material (hereafter referred to as "*Relam*", 14 specimens), and (ii) panels with the middle lamella consisting of off-cut material, whilst the outer lamellae consist of standard S5 sawn timber boards (hereafter referred to as "*Hybrid*", six panels). Fig. 3 shows the surface finish of the *Relam* panels. All specimens had a span of 1800 mm and a width of 308 mm and were tested following SANS 8892 [9]. The test configuration was, therefore, similar to that shown in Fig. 2 but with a greater span length.

Tests were conducted using a hydraulic press that applied a displacement-controlled load at a rate of 10 mm/min. An LVDT was placed at mid-span below CLT panels.

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Figure 3. Surface finish of the Relam panels.

Flatwise shear

Off-cut material availability limited the number of shear tests that could be performed. Two of each panel type were tested in three-point bending in the major direction following SANS 8892 [9]. All specimens were 305 mm wide and had a span length of 400 mm. A hydraulic actuator applied a displacement-controlled force at the centre of the span at a rate of 2 mm/min. An LVDT below the centre of the specimens recorded vertical deflection. Fig. 4 shows the test configuration.

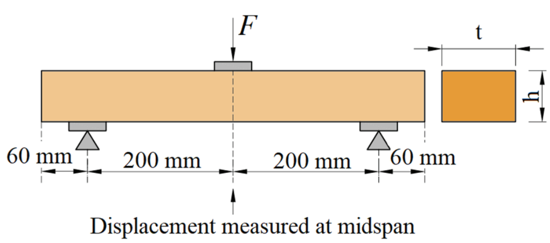

Figure 4. Flatwise shear test configuration of CLT panels.

5 – RESULTS

This section reports the statistical comparison of experimental results.

5.1 FLEXURAL CAPACITY OF BOARDS

Fig. 5 compares the force-displacement results for the 18 sawn timber boards (grey lines) and the 18 off-cut boards (black lines). The spread of results for most boards compares well. Nevertheless, some off-cut boards showed lower stiffness and strength compared to most results.

Recorded force-displacement results were used to calculate the Modulus of Elasticity and Modulus of Rupture according to SANS 6122 [8], as shown in Equation (1) and Equation (2), respectively.

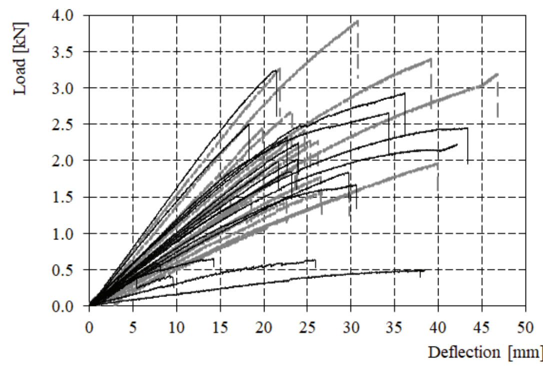

Figure 5. Force-displacement results for the sawn timber boards (grey) and the off-cut boards (black).

$$MoE = \frac{23 \cdot F_i \cdot L^3}{108 \cdot t \cdot h^3 \cdot \Delta_i} \quad (1)$$

$$MoR = \frac{F_{max} \cdot L}{t \cdot h^2} \quad (2)$$

Where:

F_i is the load increment [N]

F_{max} is the ultimate load [N]

L is the span [mm]

t is the width [mm]

h is the vertical depth [mm]

Δ_i is the central displacement increment [mm]

To ensure that statistical outliers were identified, quartile values for MoE and MoR were calculated for both sawn timber and off-cut boards. Using lower and upper limits set at 1.5 times the interquartile range beyond the first and third quartiles, no outliers were identified in the results. Therefore, all results were considered for subsequent analysis.

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Modulus of Elasticity

Table 1 summarises and compares stiffness results from sawn timber boards and off-cut boards, whilst Fig. 6 compares box and whisker plots of this property. Covariance results for the sawn timber boards are within a range that can be considered typical for material properties (between 0.03 and 0.30, according to [3]). In contrast, stiffness results from off-cut boards show a greater covariance.

Table 1: Modulus of Elasticity (MoE) comparison.

Board:	**Sawn timber**	**Off-cut**
Average	6691.5 MPa	6463.4 MPa
St.dev.	1532.8 MPa	2726.6 MPa
Cov.	0.229	0.422

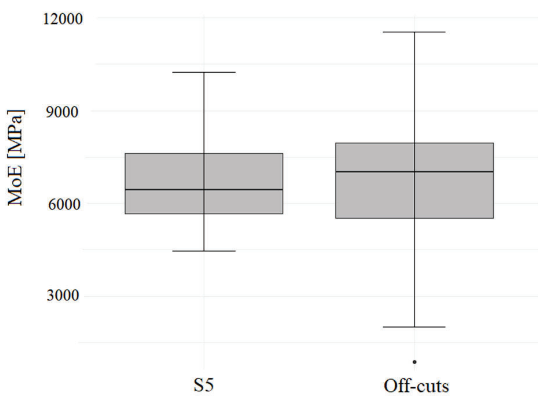

Figure 6. Box and whisker plots of bending stiffness (MoE) of sawn timber boards (left) and off-cut boards (right).

A two-sample t-test of MoE results for the two board types resulted in a p-value of 0.759 and a 95%CI for difference in mean results of (-1285.2 MPa; 1741.4 MPa). Although a greater distribution of stiffness results is observed for the off-cut boards than for the sawn timber boards, there appears to be no statistically significant difference in the mean bending stiffness.

Modulus of Rupture

Table 2 summarises and compares bending strength results from sawn timber boards and off-cut boards, whilst Fig. 7 compares box and whisker plots of this property. Similar to bending stiffness results, the covariance of bending strength results for sawn boards are within the range typically associated with material properties [3], whilst that from off-cut boards was greater.

Table 2: Modulus of Rupture (MoR) comparison.

Board:	**Sawn timber**	**Off-cut**
Average	34.08 MPa	27.68 MPa
5^{th} percentile	21.09 MPa	7.61 MPa
St.dev.	9.27 MPa	13.08 MPa
Cov.	0.272	0.473

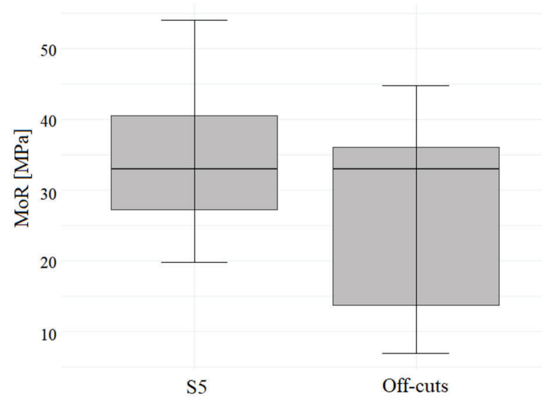

Figure 7. Box and whisker plots of bending strength (MoR) of sawn timber boards (left) and off-cut boards (right).

A two-sample t-test of MoR results for the two board types resulted in a p-value of 1.000 and a 95% CI for difference in mean results of (-6.28 MPa; 6.28 MPa). Similar to bending stiffness, there appears to be no statistically significant difference in the mean bending strength for the two board types.

However, the greater distribution of bending strength results obtained for the off-cut boards results in a 5^{th} percentile characteristic bending strength that is 64% lower than that of the sawn timber boards.

5.2 STIFFNESS AND STRENGTH OF CLT

FLATWISE BENDING

Considering lower and upper limits set at 1.5 times the interquartile range beyond the first and third quartiles, no MoE outliers were identified for any of the laminated panel types considered. One MoR value from the set of *Relam* panels tested was identified as a statistical outlier beyond the upper bending strength limit. To err towards conservative analysis, results from this panel were subsequently omitted from the database.

Fig. 8 shows the force-displacement results for the conventional (*Reference*) CLT panels and those for the *Hybrid* panels. Fig. 9 shows a similar plot comparing *Reference* panels with *Relam* panels. The spread of elastic stiffness and bending strength compare well in both cases. The high bending strength of one of the *Relam*

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panels, which is considered a statistical outlier, is clearly visible in Fig. 9.

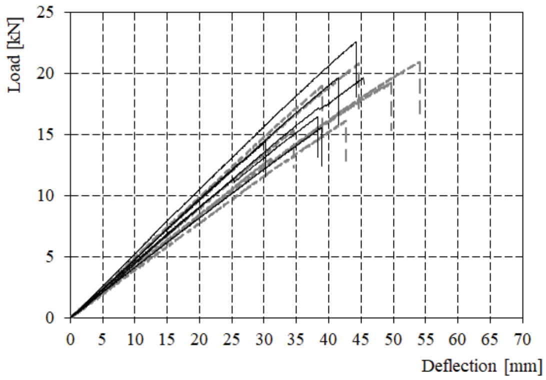

Figure 8: Force-displacement results of the conventional (Reference) CLT panels (grey) and Hybrid panels (black).

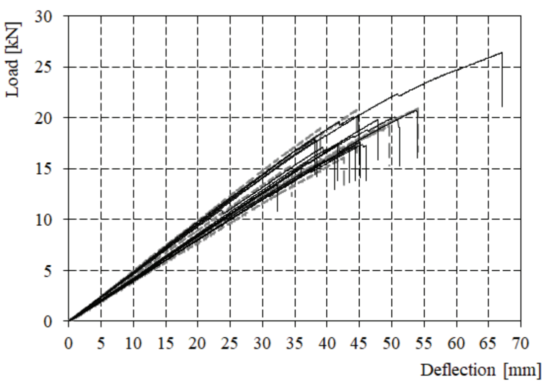

Figure 9: Force-displacement results of the conventional (Reference) CLT panels (grey) and Relam panels (black).

Modulus of Elasticity

Table 3 summarises and compares stiffness results for the *Reference*, *Hybrid*, and *Relam* panels, whilst Fig. 10 compares box and whisker plots of this property. All covariance results are within a typical range for material properties [3], with only a marginal difference between the three panel types.

Table 3: Modulus of Elasticity (MoE) comparison.

Panel:	**Reference**	**Hybrid**	**Relam**
Average	5705.5 MPa	6101.8 MPa	5136.0 MPa
St.dev.	568.2 MPa	558.2 MPa	370.0 MPa
Cov.	0.100	0.091	0.072

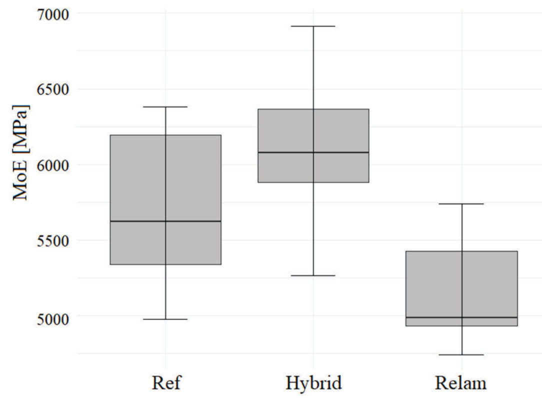

Figure 10. Box and whisker plots of bending stiffness (MoE) of the Reference panels (left), Hybrid panels (centre) and Relam panels (right).

An analysis of variance (ANOVA) was conducted to compare the mean MoE across the three panel types. There was a statistically significant difference in MoE between the groups, with a p-value of 0.001.

Two-sample t-tests revealed no statistically significant difference in the mean bending stiffness between the *Reference* and *Hybrid* panels ($p = 0.251$). A near-significant difference was observed between the bending stiffness of the *Reference* and *Relam* panels, with a p-value of 0.059. The most significant difference in mean bending stiffness was between the *Hybrid* and *Relam* panels ($p = 0.006$).

Modulus of Rupture

Table 4 summarises and compares bending strength results for the *Reference*, *Hybrid*, and *Relam* panels, whilst Fig. 11 compares box and whisker plots of this property. Similar to elastic stiffness results, all covariance results are within a range that can be considered typical for material properties [3], with only a marginal difference between the three panel types.

Table 4: Modulus of Rupture (MoR) comparison.

Panel:	**Reference**	**Hybrid**	**Relam**
Average	23.53 MPa	22.81 MPa	21.28 MPa
5^{th} perc.	19.71 MPa	18.61 MPa	17.96 MPa
St.dev.	2.96 MPa	3.89 MPa	2.32 MPa
Cov.	0.126	0.171	0.109

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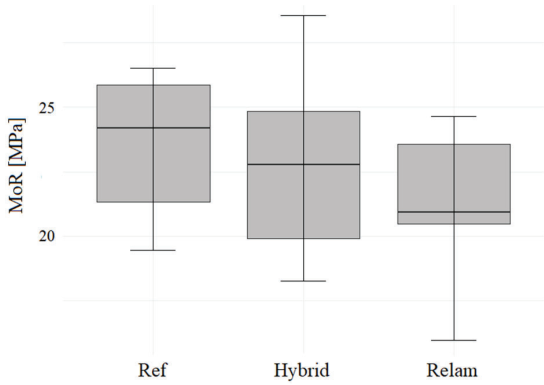

Figure 11. Box and whisker plots of bending strength (MoR) of the Reference panels (left), Hybrid panels (centre) and Relam panels (right).

An ANOVA was conducted to compare the mean MoR across three panel types. The resulting p-value of 0.262 suggests no statistically significant difference in this property between the three groups. Individual two-sample t-tests between each of the panel types confirmed this conclusion.

Both the *Hybrid* and *Relam* panels result in 5th percentile characteristic bending strength values similar to that of the *Reference* panels (6% and 9% lower than the *Reference* panel result, respectively).

FLATWISE SHEAR

Fig. 12 shows the recorded force-displacement results from three-point bending tests. The *Hybrid* panels showed greater stiffness and a maximum load comparable to the *Reference* CLT panels. The stiffness and maximum load recorded for the *Relam* panels were lower than the *Reference* panels.

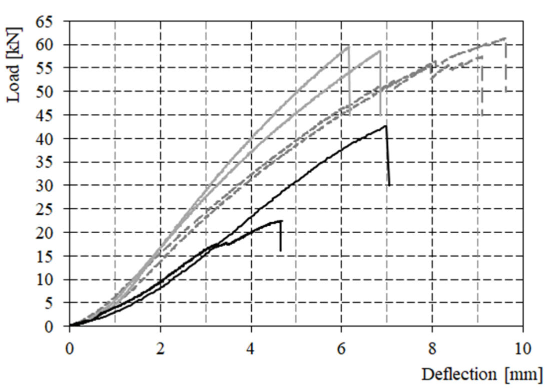

Figure 12. Force-displacement results from three-point bending tests of the Reference CLT panels (grey dotted lines), Hybrid panels (solid grey lines), and Relam panels (black).

The shear strength (V_R) of the CLT panels was calculated following SANS 6122 [8] and SANS 8892 [9], as shown in Equation (3).

$$V_R = \frac{0.75 \cdot P_{max}}{t \cdot h} \tag{3}$$

Results, summarised in Table 5, suggest a similar shear strength for the *Reference* and *Hybrid* panels, whilst that of the *Relam* panels was approximately 45% lower.

Table 5: Shear strength comparison.

Panel:	**Reference**	**Hybrid**	**Relam**
Average	2.21 MPa	2.20 MPa	1.21 MPa

6 – DISCUSSION

Although mean bending stiffness and mean bending strength of sawn timber boards and off-cut boards can be considered statistically similar, the 5th percentile characteristic bending strength of off-cut boards was markedly lower than that of sawn timber boards. However, considering that the off-cut boards are otherwise considered a waste product, the results motivate its usefulness; if not in its original form, then perhaps in engineered timber products, such as CLT or Glulam.

Results from this experimental study highlight the trivial solution that the *Reference* CLT panels obtained better mechanical properties than other forms that contained off-cut material. Differences were, however, in many cases small. Moreover, more off-cut material in CLT panels should reduce the associated embodied carbon.

To assess the impact of incorporating off-cut material in CLT panels, equivalent quantities were calculated to compare the capacity per unit embodied carbon for a standard 6 m × 2 m, 66 mm thick, 3-lamella panel. For this calculation, embodied carbon coefficients were estimated from the *Inventory of Carbon and Energy database* [10] (hereafter referred to as the ICE database). Embodied carbon factors did not consider carbon storage since it was deemed inappropriate for a study considering circular value chains where any sequestered carbon would be released back into the atmosphere. Three main elements were considered in estimating embodied carbon: (i) *softwood sawn timber used to produce CLT* (ii) *Melamine resin,* and (iii) *planing off-cut boards to be pressed into CLT panels*. Volumetric estimates for each quantity were determined in collaboration with a commercial CLT manufacturer from whom the off-cuts and CLT panels were obtained. These estimates were based on the following assumptions:

Timber: 0.263 $kgCO_{2,e}$/kg, with a density of 390 kg/m^3.

Glue: 4.19 $kgCO_{2,e}$/kg, with 200 g/m^2 of contact area.

Planing: 0.434 $kgCO_{2,e}$/kWh electricity on a 10 kW machine.

The resulting comparative embodied carbon per panel, summarised in Table 5, is shown in Fig. 13. The embodied carbon calculated for the *Reference* panel aligns with values typically reported for CLT in the literature [14]. As expected, a clear reduction in embodied carbon is observed with increased off-cut material used.

Table 5: Comparative embodied carbon per production CLT panel size (kgCO2,e per 6 m × 2 m panel).

Panel:	**Reference**	**Hybrid**	**Relam**
Glue	20.1	20.1	20.1
Plane	-	1.5	2.2
Timber	81.2	54.2	-
TOTAL	***101.3***	***75.7***	***22.3***

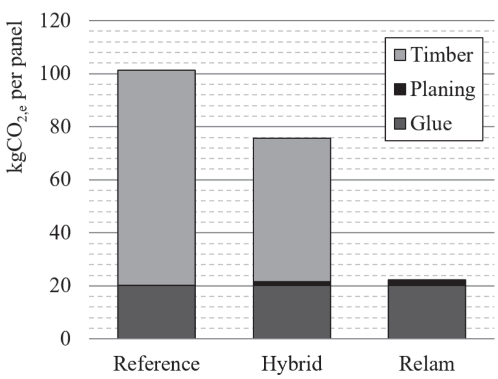

Figure 13. Comparative embodied carbon per panel.

Mechanical properties reported earlier were divided by the total estimated embodied carbon per production panel size to obtain a comparative capacity value per unit of embodied carbon. Although each value, shown in Table 6, is not of direct quantitative value, it does aid in comparing the environmental value of each panel type. Moreover, it speaks to the potential for reduction in embodied carbon through further developing this novel engineered timber waste-to-product process.

Table 6: Mechanical properties divided by embodied carbon estimates (i.e., MPa per $kgCO_{2,e}$ of a production panel).

Panel:	**Reference**	**Hybrid**	**Relam**
MoE_{avg}	56.3	80.6	230.3
MoR_{5th}	0.194	0.246	0.805
Shear	0.022	0.029	0.054

Comparing the values in Table 6, *Relam* panels resulted in the greatest mechanical properties per unit of embodied carbon, whilst the *Reference* panels performed the poorest.

6 – CONCLUSIONS

The results in this study suggest that cross-laminated timber produced from off-cut material could be considered for use in some construction applications. However, given the greater spread in material properties observed when using such off-cut material, full sample size testing is required to confirm mechanical properties definitively.

The encouraging initial results for relaminated CLT suggest that it could be utilised in numerous applications with minimal adjustment to existing production processes. Hybrid relaminated CLT (with off-cut material only in the minor direction) integrates recycled material with the least impact on structural performance and appearance. Thinner, three-lamella panels can reduce raw lumber consumption by a third and embodied carbon by up to 20%. Fully relaminated panels are well suited for applications where fire safety, acoustics or architectural effect are the determining criteria, as opposed to optimised structural utilisation. These are all promising areas for future research.

This study is currently being extended to investigate the benefit of using off-cut material from CLT production in the manufacturing of glued-laminated beams and columns.

7 – ACKNOWLEDGEMENTS

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