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BENDING CHARACTERISTICS OF CLT FROM RECOVERED SPRUCE

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ABSTRACT: The circular use of construction materials is an essential step in the drive to reduce the environmental impact of the construction sector. Structural materials, such as timber, recovered from demolition of buildings is a valuable resource. Reuse or recycling these materials in new buildings products reduces waste and the overall carbon footprint of the build environment. This paper investigates the use of spruce recovered from demolition of a roof structure in the manufacture of CLT panels. Bending tests are performed on 3-layer panels made from this recovered material and also on panels made from new timber and hybrid panels with mixed new and recovered timber. Results show that the performance of CLT panels using recovered timber is equivalent to that of panels from new timber in terms of bending strength and stiffness.

KEYWORDS: recovered timber, circular construction, mass timber, spruce, Douglas fir, secondary timber, salvaged, reclaimed

1 INTRODUCTION

The construction sector is the largest consumer of raw materials and accounts for about 50% of all extracted materials [1,2] and the built environment is responsible for 25-40% of global carbon emissions [1]. At the same time, the OECD has predicted that the world's consumption of raw materials will more than double over the period 2017-2060 [3] and the construction sector will account for much of this increase.

To address this, policy initiatives aimed at enhancing the sustainability of the construction sector have been introduced as a key priority for Europe. As part of the European Green Deal, the European Commission in 2020 adopted a new Circular Economy Plan [2], which promotes circularity principles throughout the lifecycle of buildings. It is addressing the sustainability performance of construction products through revision of the Construction Product Regulation, including the possible introduction of recycled content requirements for certain construction products and revising material recovery targets set in EU legislation for construction and demolition waste.

As construction and demolition is currently responsible for more than a third of all waste within the EU [4], reuse and recycling of building materials has the potential to significantly reduce this waste and also reduce the carbon footprint of the built environment through extending the life span of building components.

Timber recovered from buildings at the end of life, often referred to as recovered or secondary timber, is a valuable natural resource with significant potential for reuse and recycling. To optimise the environmental benefits of reuse and recycling and support the circular economy, recovered timber should be used in long-life products, such as structural products for buildings. However, in most European countries timber construction and demolition waste is, for the most part, converted into chips for use in energy production with smaller amounts used for particle board or pallet block manufacture and for composting [5-7]. Key factors inhibiting reuse of recovered timber in the manufacture of structural products are the fact that it is currently prohibited by regulations and that grading standards are not available. To support the development of standards on the reuse of timber, further research is necessary concerning the properties of recovered timber and identification and characterisation

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of new engineered timber structural products suitable for use of this material.

This work has already begun with a number of European projects focussing on circular use of building materials. The Buildings as Material Banks project (BAMB2020) [8] investigated ways to increase the value of building materials through flexible, circular building design. The CaReWood project [9] introduced an upgrading concept for recovered solid timber as a source of clean and reliable secondary wooden products. In the InFutUReWood project, [10] key problem areas were identified and technical and methodological solutions were proposed to maximise reuse of timber from current buildings especially as a structural material.

The recent growth in interest in timber construction across the globe can be credited not only to the necessity to reuse the embodied carbon of construction materials but also to the development of cross-laminated timber (CLT), which is a high-performance panel product that can displace reinforced concrete and steel in demanding structural applications [11]. CLT was first commercialised in Austria in the 1990s [12] and production in Europe has grown exponentially in the intervening years. While most European CLT is manufactured from Norway spruce, many studies have been carried out to investigate the potential use of locally-grown timber, including lower grade species, for CLT production [13-15]. In the future, it will be challenging to meet the growing demand for timber to produce CLT and other products from the finite supply of new timber from our forests. Supplementing the new timber with suitable material recovered from buildings at the end of life offers a potential solution.

Some recent studies have started to investigate the potential use of recovered timber for CLT production. Llana *et al.* [16] investigated the flexural performance of three-layer CLT panels manufactured using 200-year-old recovered oak. Four different designs were investigated: all new oak, all recovered oak, outer lamina recovered oak with new oak core and outer lamina new oak with recovered oak core. Based on results from tests on three replicates of each design, they found no significant different in the flexural stiffness of the four designs. However, the bending strength of the panels with new oak on the outer layers was about double that of the panels with recovered oak on the outer layers. Rose *et al.* [17] compared the properties of three-layer CLT panels manufactured from recovered mixed-species softwoods with those made from new Scandinavian pine timber. Comparing results from bending tests of three specimens of each type, the modulus of elasticity of the panels made from recovered timber were found to be double that of the panels from new timber. However, the bending strength of the recovered timber panels was only 60% of those from new timber. The fact that 70% of specimens failed at finger joints may have contributed to the difference in strength values.

In a Norwegian study, Stenstad *et al*. [18] used recovered timber with a variety of defects, such as holes, in the cross-layer of three-layer CLT panels. All the boards had their original grade stamps indicate that they were C24. New timber of grade T22 was used in the outer layers. The bending stiffnesses of these panels were found to be the same as those manufactured using new timber in all layers. Arbelaez *et al.* [19] also found similar bending stiffness in 3-layer panels manufactured from new and recovered Douglas fir.

Within the InFutUReWood project [20], the recycling potential of recovered timber in new mass timber products has been investigated. This paper presents results of a study carried out as part of this project to investigate the processing of recovered spruce onto cross-laminated timber panels and to compare their structural performance with equivalent products from new timber.

2 MATERIALS AND METHODS

Norway spruce (*Picea abies* (L.) Karst.) timber boards were recovered from the roof trusses of an office building in Dublin, Ireland. The building was constructed in the 1970s and had been unoccupied for over two years before its demolition. The building was demolished mechanically and materials were sorted at ground level (Figure 1). A sample of 78 boards was recovered, most of which had cross-sectional dimensions of 142 mm x 35 mm. Grade stamps visible on some of the boards indicated that the timber was imported grade TR26 spruce. This timber grade is commonly used in Ireland and the UK for roof trusses. TR26 grade timber has a mean modulus of elasticity in bending of 11000 MPa and a characterisitic bending strength of 28.3 MPa [21].

Using a hand-held moisture meter, the moisture content of the timber boards at the site was estimated to be between 18% and 23%. This high moisture content is attributed to rain penetration of the roof through damaged slates and felt over an extended period of time prior to demolition. Punched metal plates and other metal content were removed on site where possible.

Figure 1: *Recovered timber on site awaiting collection.*

The material was moved to the Timber Engineering Laboratory at the University of Galway where all remaining detectable metal content was removed and it was stored in a conditioning room at 65% relative humidity and 20°C until it reached the equilibrium moisture content.

2.1 NON-DESTRUCTIVE TESTING

Non-destructive testing based on acoustic measurements is widely used for the evaluation of timber mechanical

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properties [22]. In this study, non-destructive evaluation of the recovered timber boards was carried out using a handheld acoustic grader (MTG, Brookhuis, Netherlands) to record the longitudinal vibration frequency *f*. The dynamic modulus of elasticity E_{dyn} was then determined using Equation (1), where the density ρ for each board was determined based on measurements of mass and dimensions and L is the board length. Values were then adjusted to a reference moisture content of 12% in accordance with EN 14081-2 [23].

$$E_{dyn} = 4\,\rho\, f^2 L^2 \tag{1}$$

For the boards, the adjusted values, $E_{dyn,12,adj}$, ranged between 8000 N/mm^2 and 15000 N/mm^2. To reduce variability between specimens, from the full sample boards with $E_{dyn,12,adj}$ values between 11000 N/mm^2 and 13900 N/mm^2 were selected for the manufacture of CLT panels.

A matching sample of new timber was sourced for manufacturing reference CLT panels and hybrid panels. As Irish-grown spruce is normally graded to C16, its properties are not equivalent to TR26 material and so it deemed unsuitable as reference new timber. The most suitable available material was Irish grown Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco). Based on acoustic measurements of 101 new boards, a batch of timber boards with $E_{dyn,12,adj}$ values between 10600 N/mm^2 and 14600 N/mm^2 was chosen for processing into CLT panels. The nominal cross-section of these boards was 110 mm x 45 mm.

2.2 CLT MANUFACTURE AND TESTING

Three-layer 60 mm thick CLT panels were manufactured using recovered and new timber, as shown in Figure 2. Three different material combinations were used: recovered timber in all layers, new timber in all layers, and hybrid with new timber in top and bottom layers and recovered timber in the core. Three panels of each material combination were manufactured for testing. All boards were planed to a final cross-section of 90 mm x 20 mm. Additional nails that had not previously been detected in the recovered timber were removed at this stage. Panels were bonded using a one-component polyurethane adhesive using a pressure of 0.6 MPa for a minimum of 2 hours. The adhesive selection and processing parameters were based on previous studies carried out in the University of Galway using new spruce timber [24, 25]. The final panel dimensions were 1620 mm x 360 mm.

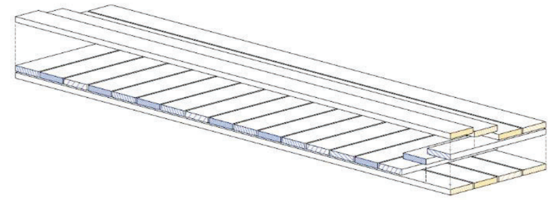

Figure 2: *60 mm x 360 mm x 1620 mm three-layer CLT panel*

All panels were conditioned at 65% relative humidity and 20°C prior to testing in out-of-plane bending in accordance with EN408 [26] and EN 16351 [27]. The four-point bending tests were carried out over a span of 1560 mm (equivalent to 26 times the depth h) with the load heads spaced at $6h$. Global deflection of the panels was measured at each edge at midspan using two 100 mm linear variable differential transformers (LVDTs).

The global modulus of elasticity was calculated from Equation (2) [adapted from EN 408 [26] 10.3 Equation (2)].

$$E_{m,g}\, I = \frac{3al^2 - 4a^3}{24\left(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh}\right)} \tag{2}$$

where l, b, h , in mm, represent the span, panel width, and depth, respectively. The mean shear modulus G is taken as 650 N/mm^2 in accordance with EN 408 [26] and EN 16351 [27].

The bending strength was calculated using Equation (3)

$$f_m = \frac{F_{max}ah}{4\, I_{tr}} \tag{3}$$

where F_{max} is the failure load, I_{tr} is the transformed second moment of area and other terms are as defined above and in EN 408 [26].

3 RESULTS AND DISCUSSION

3.1 LOAD-DISPLACEMENT RESPONSE

The load-displacement response of the recovered, new and hybrid CLT panels are presented in Figures 3, 4, and 5, respectively. The displacement in each case is the average of the displacement measurements from the two LVDTs mounted at the panel edges.

Similar linear responses until close to failure are seen in each panel type.

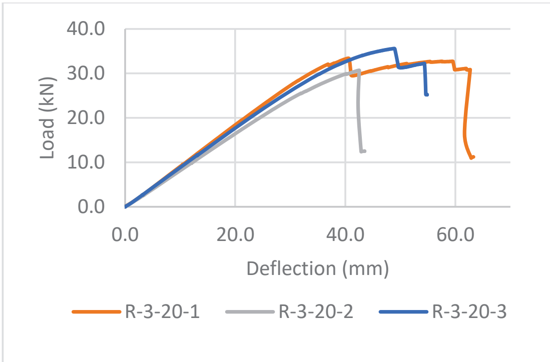

Figure 3: *Load-deflection response – recovered timber panels*

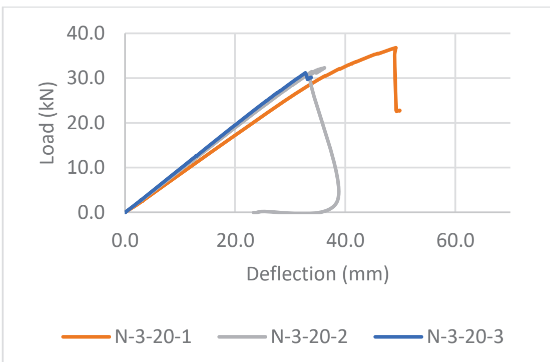

Figure 4: *Load-deflection response – new timber panels*

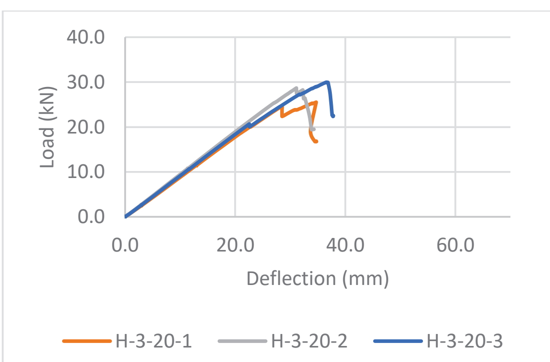

Figure 5: *Load-deflection response – hybrid timber panels*

All panels failed in bending, which initiated at the location of a knot or large slope of grain on the underside of the panel and then propagated through the thickness of the panel as seen in Figure 6.

Figure 6: *Bending failure of hybrid CLT panel*

3.2 MODULUS OF ELASTICITY

The mean global modulus of elasticity and bending strength for each test series together with the coefficients of variation are given in Table 1. The mean modulus of elasticity was 10300 N/mm^2, 10900 N/mm^2 and 10800 N/mm^2 for the recovered, new and hybrid panels, respectively. There is no significant difference between the means of each group as can be observed visually in Figure 7. This is to be expected as the panels were manufactured with timber boards with similar dynamic modulus of elasticity values. This finding is consistent with other studies [16, 18, 19].

As the modulus of elasticity values of the CLT panels are consistent with the modulus of elasticity of the boards used in their manufacture, it indicates that the bonding of the layers was successful for both recovered and new timber.

Table 1: *Bending test results*

Panel type	Panel #	$E_{m,g}$ N/mm^2	f_m N/mm^2
Recovered	R-3-20-1	10900	50
	R-3-20-2	9700	46
	R-3-20-3	10420	53
	Mean	*10300*	*49*
	COV %	*5.9*	*7.5*
New	N-3-20-1	10100	55
	N-3-20-2	11100	48
	N-3-20-3	11400	46
	Mean	*10900*	*50*
	COV %	*6.1*	*8.7*
Hybrid	H-3-20-1	10500	38
	H-3-20-2	11100	43
	H-3-20-3	10800	45
	Mean	*10800*	*42*
	COV %	*2.8*	*8.2*

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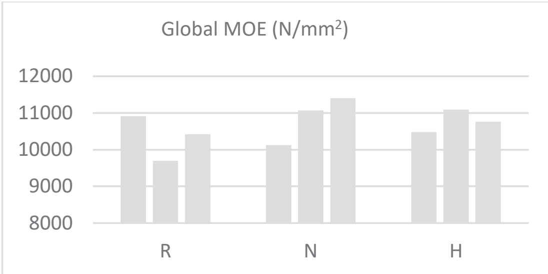

Figure 7: *Global Modulus of elasticity – all panels*

3.3 BENDING STRENGTH

The mean bending strength was 49 N/mm^2, 50 N/mm^2 and 42 N/mm^2 for the recovered, new and hybrid panels, respectively (Table 1), with low coefficients of variation in the range 7.5%-8.7%. The strength values for the hybrid panels were consistently lower than those of the recovered and new panels (Figure 8). There was no obvious reason for this detected during testing. However, as only three panels were tested in each series and significant variability is expected in timber strength due to the influence of features such as knots, these differences in strength values may not be significant.

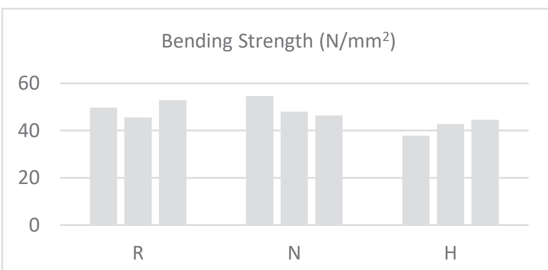

Figure 8: *Bending strength – all panels*

This finding is different to that reported by Rose *et al.* [17] who reported a 60% lower bending strength for recovered softwood panels compared to new panels. These panels had a different failure mode to the current study which may be a factor in the different outcomes. For hardwoods, Llana *et al.* [16] recorded a 50% reduction in bending strength for panels using recovered oak compared to those made from new oak. Kránitz *et al.* [28] in their extensive literature review on the effects of aging on wood, reported a decrease in bending strength for hardwoods. However, this review indicated that for softwoods there was no difference in the bending strength between new and wood up to 400 years old. For the present study, the age of the recovered timber was about 50 years so no deterioration would be expected based on the conclusions of five different studies.

While bending strength and stiffness do not appear to be adversely affected by being under load for 50 years, other properties need to be investigated. Kránitz *et al.* [28] reported an increase in brittleness, which may affect the properties perpendicular to the grain.

4. YIELD OF CLT

Regarding the yield from the recovered timber, the recovered timber cross-section (142 x 35 mm^2) was significantly larger than the board dimensions required for panel manufacture (90 x 20 mm^2) and this resulted in a yield of about 28% when length reductions are included. The yield would be greatly increased if recovered timber dimensions closer to the final board dimension were available. For example, using 130 mm x 30 mm boards to produce a 90 mm thick panel would have increased the yield to 70%. The commercial availability of recovered timber in a range of sizes close to those required for panel manufacture will be necessary to ensure efficient reuse of the material.

5. CONCLUSIONS

Spruce members were recovered from the demolition of a timber roof truss that had been under load for about 50 years and which was exposed high relative humidity during its later years. A sample of new timber with a similar range of dynamic modulus of elasticity values was source. CLT panels of three different designs were successfully manufactured and tested in bending from this material. These included panels made entirely from recovered timber, panels from new timber and hybrid panels with new timber in the outer layer and recovered timber in the cross-layer. Overall, this study has found no difference in the mechanical properties in bending of CLT manufactured from recovered and new softwood timber.

While these results are very positive, it should be borne in mind that the number of specimens tested was small and used recovered timber from a single source. Further testing of panels manufactured from a wide range of sources is recommended to confirm these findings.

In terms of yield, mass timber products are a good option for recycling of recovered timber subject to availability of boards with cross-sections close to the final size required.

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