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Cross Laminated Timber (CLT) manufactured with European oak recovered from demolition: Structural properties and non-destructive evaluation

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ABSTRACT

The demolition sector generates a large amount of timber waste that could be directly reused or recycled in other products for structural purposes. Timber should be graded before it is used for structural purposes, and visual strength grading standards designed for new timber do not properly grade recovered timber. Cross Laminated Timber (CLT) is now one of the most common wood products used in construction. CLT would therefore be a good option for recycling timber due to the high quantity of material used in CLT manufacturing. This paper investigates the possibilities of using recovered timber from demolition to manufacture CLT. Twelve CLT panels from recovered and new timber were manufactured and tested. The static modulus of elasticity was found to be the same between recovered and new timber, while the bending strength of CLT from recovered timber was lower than it was for CLT from new timber. Non-destructive testing for the estimation of mechanical properties of boards and CLT panels was successfully developed.

1. Introduction

Although most of the references found cover Cross Laminated Timber (CLT) in Austria and Germany from the beginning of the 1990s [1,2], older records exist. A research project denominated “Laminated Lumber” was conducted by the Tennessee Valley Authority [3] from 1940 to 1947 in a pilot plant in Knoxville (TN, USA). High-grade cross-laminated lumber manufactured from low-quality hardwood timber was studied for flooring applications. Nájera [4] described the possibilities of CLT manufactured from Spanish poplar for furniture applications. Other authors as Krzosek and Kłosińska [5] dated the first idea of CLT in Cziesieski [6]. Large scale CLT production for structural application was developed in the 1990s due to the interest of the sawmill industry in obtaining a higher value product from low quality or small size timber [7]. Research on CLT for structural purposes was specially developed in the TU Graz (Austria) following the Doctoral thesis of Prof. Schickhofer on rigid and flexible laminated composite structures, focusing on CLT [8]. CLT is now one of the most common structural timber products due to its advantages, such as bidirectional load-bearing, a high degree of prefabrication, quick on-site assembly or easier execution of repair and

alteration work on facades, insulation and installation [9]. Most of the CLT commercialized nowadays is manufactured using softwoods and polyurethane adhesives. According to Espinoza and Buehlmann [10], specific adhesives for hardwoods should be developed which are different from those for softwoods, and a higher capacity press is needed for processing hardwoods. Yusof et al. [11] and Brunetti et al. [12] found poorer performance when polyurethane glues were used than was the case with other adhesives (phenol resorcinol and melamine) in hardwoods. However, according to Brunetti et al. [12] none of the three adhesives studied passed the standard softwood delamination test. Musah et al. [13] also investigated phenol resorcinol- and melamine-based adhesives, with very promising results in CLT from mixed hardwoods.

The demolition sector generates a large amount of timber waste that is suitable for structural reuse [14–17]. Furthermore, the increasing demand for timber and the exponential rise in new timber prices over the last two years [18] should encourage demolition timber reuse. Wood waste from demolition is currently reduced to chips and used for either energy production or wood panel manufacturing, or it may end in landfill [19–21]. Proposed potential structural end-uses mainly focus on

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recycling in Engineered Wood Products (EWP) such as glue-laminated timber and CLT [22]. Two recent European projects worked in this field. The CaReWood project [23] studied the possibilities of recycling recovered timber in laminated products used as a solid wood replacement for furniture, window frames, mouldings and fittings. However, it cannot be used for load-bearing construction because timber waste may come from different species, which it would be difficult to identify [24]. Furthermore, the manufacturing yield stands at around 30%. Smith [25] also reported that strength grading parameters are species-dependent, and that the species of recovered timber species is usually unknown. The InFuTReWood project [26] is currently working on design for deconstruction and recycling recovered timber in EWP. The potential of recycling recovered timber in CLT was recently experimentally tested for the first time [27] using mixed recovered softwoods and new Scots pine. Rose et al. [27] tested 3 CLT 3-layer specimens ($820 \times 105 \times 51 \text{ mm}^3$) in bending and nine small specimens in compression from recovered and new timber, showing that CLT from recovered timber had higher stiffness and lower strength than CLT from new sawn timber. It should be taken into account that 70% of specimens failed in finger joints. Arbelaez et al. [28] tested 18 CLT 3-layer panels ($2300 \times 300 \times 94 \text{ mm}^3$) in four-point bending from recovered and new Douglas-fir, and from MDF. They found poorer properties of CLT with MDF in the cross layer. Moreover, CLT from recovered and new timber was found to have similar stiffness. Stenstad et al. [29] tested 28 CLT 3-layer specimens ($2400 \times 150 \times 100 \text{ mm}^3$) manufactured using recovered Norway spruce only in the cross layer. Bending test results showed that the cross layer had minimum influence on results. To summarize, the aforementioned studies tested different configurations of CLT manufactured with recovered softwood timber, and there is no agreement on whether stiffness differs in CLT from recovered or new timber.

Regarding the manufacturing yield of recycled recovered timber in EWP, Llana et al. [30] reported that it depends on the kind of recovered timber in question. This varies between countries due to the building systems that were used in the past. In Central and Northern Europe recovered timber is from mid cross-sections and buildings less than 100 years old. Even so, timber was originally graded in some demolitions from the 1970 s and 1980 s. In Southern and Eastern Europe, recovered timber is mainly large cross-section from buildings more than 100 years old. When manufacturing EWP, the manufactured yield obtained from mid cross-sections is higher than it is from large cross-sections, where more waste wood is generated. It should also be pointed out that the European CLT standard EN 16351 [31] does not cover CLT produced from re-used timber. Another barrier is that timber should be graded before use for structural purposes, and current Visual Strength Grading (VSG) standards designed for new timber downgrade most recovered timber [32–35]. Furthermore, Azambuja et al. [36] commented that most of the VSG standards focus on the edgewise use of solid timber, while in the case of CLT, timber is mostly tested flatwise, and this especially affects the evaluation of knots.

The mechanical properties of CLT are determined by the mechanical properties of the raw material used to manufacture it [37]. VSG and Non-Destructive Testing (NDT) are commonly used to grade timber boards for CLT manufacturing [38,39]. However, the mechanical properties of the raw material used do not always accurately reflect the properties of CLT. Azambuja et al. [36] used below-grade (under-graded) timber to manufacture CLT, and found better than expected CLT properties. Crovella et al. [40] also found better than expected CLT properties when it was manufactured from two low-grade hardwood boards. Studies which evaluate new timber CLT panels using NDT have also been published. Some of these studies focus on serviceability behavior [41,42], while others center on the estimation of mechanical properties [43]. Gsell et al. [44] used vibration frequencies and modal plate analysis to estimate the stiffness properties of CLT panels. Zhang et al. [45] evaluated CLT panels manufactured with timber of different ages, finding that the dynamic modulus of elasticity (E_{dyn}) obtained from transverse vibration decreases with increasing deterioration.

Opazo-Vega et al. [46] studied the variability of the properties of CLT panels manufactured from low-grade radiate pine timber, using transverse vibration.

The main aim of this work is to demonstrate that CLT manufactured using recovered hardwood timber is suitable for structural applications. Its specific aims are therefore to compare the mechanical properties of CLT manufactured from recovered and new timber hardwood, and to compare CLT manufactured from mixed (recovered and new timber) and CLT made only from new timber. It also develops a novel mixed CLT manufactured using recovered timber in the external layers and new timber in the cross layer. It will also analyze the possibility of estimating the mechanical properties of CLT on the basis of NDT measurements.

2. Materials and methods

2.1. Materials

A total of 28 recovered pieces with an average cross-section of $146 \times 164 \text{ mm}^2$ and an average length of 2488 mm of European oak (*Quercus robur* L.) were sawn into boards for CLT manufacturing (Fig. 1). The pieces were recovered from the demolition of a 200-year old house in the Basque Country, Spain. 72 new European oak timber boards with average dimensions of $27 \times 114 \text{ mm}^2$ and a length of 2336 mm were purchased.

2.2. CLT manufacturing

Broken or damaged ends were cut off and nails were removed from the recovered pieces before sawing them into $25 \times 105 \text{ mm}^2$ boards with an average length of 2400 mm. A total of 77 boards from the 28 recovered pieces were obtained in the sawing process. Recovered and new boards were conditioned until they had a Moisture Content (MC) of approximately 15%. All of the boards were then planed to the final dimensions of $20 \times 100 \text{ mm}^2$ according to EN 16351 [31]. 12 CLT 3-layer panels were manufactured, 3 from recovered timber (RRR), 3 from recovered timber in the longitudinal layers and new timber in the cross layer (RNR), 3 from new timber in the longitudinal layers and recovered timber in the cross layer (NRN) and 3 from new timber (NNN) (Fig. 2). Finger-joints were not used in any layer of the boards. Loctite HB S309 Purbond (Henkel, Düsseldorf, Germany) was used as adhesive. CLT panel dimensions were $60 \times 300 \times 1800 \text{ mm}^3$, fulfilling the requirements of European standard EN 16351 [31].

2.3. Moisture Content (MC) estimation

An electrical resistance moisture meter Hydromette HT 85 T (Gann Mess-u. Regeltechnik GmbH, Gerlingen, Germany) was used to estimate MC according to standard EN 13183-2 [47].

2.4. Non-Destructive testing (NDT) experiments

VSG according to the French standard NF B52001-1 [48] was carried out on timber boards before CLT manufacturing.

Longitudinal vibration was measured in the timber boards and CLT panels using the Portable Lumber Grader (PLG, Fakopp Enterprise Bt., Sopron, Hungary). Boards and CLT panels were simply supported at the ends, and the center of one end was struck by a hammer. The sensor was a microphone placed on one end of the specimen (Fig. 3). The first mode natural frequency was obtained from the signal recorded through Fast Fourier Transform (FFT) software. Velocity (V) and E_{dyn} were calculated according to Eqs. (1) and (2) respectively. The dimensions and mass of boards were recorded to determine their density.

$$V = 2fL \quad (1)$$

$$E_{dyn} = \rho V^2 \quad (2)$$



Fig. 1. Recovered European oak pieces for CLT manufacturing.

12 three-layer CLT panels

- 3 recovered timber (RRR)
- 3 recovered + new + recovered (RNR)
- 3 new + recovered + new (NRN)
- 3 new timber (NNN)

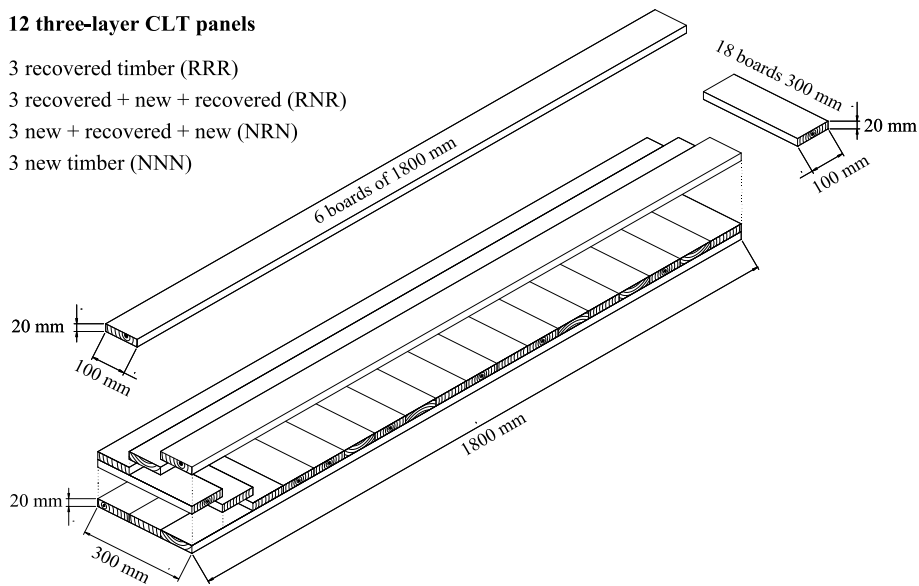


Fig. 2. Composition and dimensions of CLT panels.

where V is the velocity; f is the first mode natural longitudinal frequency; L is specimen length and ρ is density.

Velocity was adjusted to a reference MC of 12% using the adjustment factors proposed by Kollmann and Krech [49] using Eq. (3), while density was adjusted according to EN 384 [50] using Eq. (4).

$$V_{12} = \frac{V_u}{[1 - 0.008(u - 12)]} \tag{3}$$

$$\rho_{12} = \rho_u [1 - 0.005(u - 12)] \tag{4}$$

where V_{12} is velocity at 12% MC; V_u is velocity at testing MC; u is the MC at testing; ρ_{12} is the density at 12% MC; ρ_u is the density at testing MC.

The first mode natural frequency from transverse vibration was recorded in the CLT panels. Transverse vibration testing was carried out with supports at 0.224 L, and the central span of the panel was struck by a hammer. The signal was recorded by a microphone placed in the center of the span and the frequency obtained was processed by FFT software. E_{dyn} was calculated according to Eq. (5), as published by Zhang et al. [45] and derived from the equations published by Leissa [51].

$$E_{dynT} = \frac{48 a^4 \rho f^2 (1 - \nu^2)}{\pi^2 h^3 (m - 1)^4 + 6 h^3 \left(\frac{a}{b}\right)^2 (1 - \nu) (m - 1)^2} \tag{-5}$$

where ρ is the density; f is the first mode natural transverse frequency; ν is Poisson's ratio; a is the panel length; b is the width; h is the thickness; m is a coefficient that depends on boundary conditions.

The Poisson coefficients applied in Eq. (5) were reported for *Quercus petraea* [52]. An average between ν_{LT} and ν_{LR} was applied. The value was 0.475.

E_{dyn} from transverse vibration was adjusted to a reference MC of 12% using adjustment factors developed by Llana et al. [53] from data published by Sellevold et al. [54] using Eq. (6).

$$E_{dynT12} = \frac{E_{dynTu}}{[1 - 0.0126(u - 12)]} \tag{6}$$

2.5. Mechanical testing and density determination:

A four-point bending test was conducted to obtain the global and

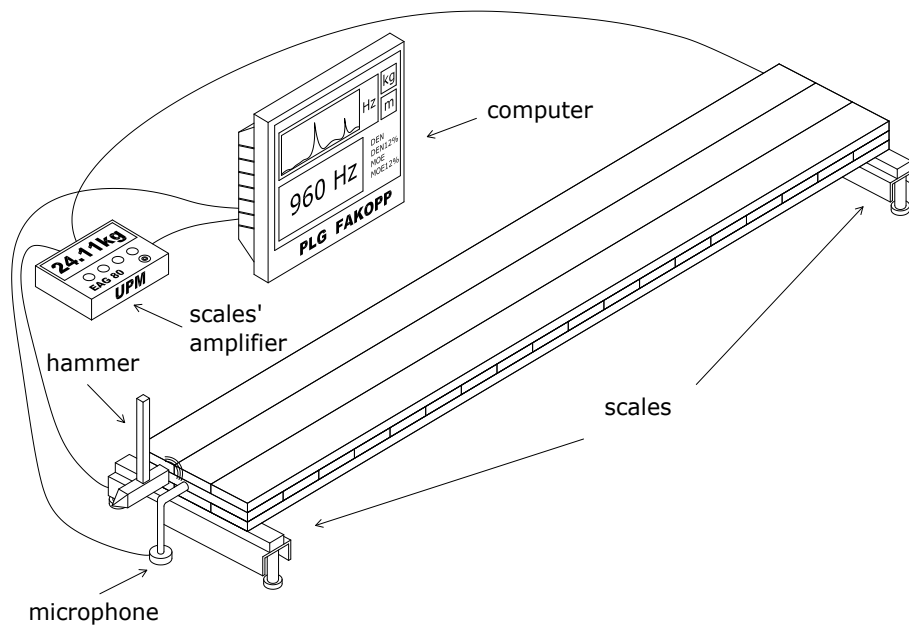


Fig. 3. Longitudinal vibration testing set-up.

local modulus of elasticity (MOE) and bending strength (MOR) according to Annex F of the EN 16351 [31] standard. CLT panels were simply supported over a span of 1440 mm (24 times panel thickness). Loads were applied at two points 360 mm (6 times panel thickness) apart, symmetrically from the central axis. Two Linear Variable Differential Transformers (LVDTs), one at each side of the panel, were used to measure local deflection of the neutral axis over a central gauge length of 300 mm (5 times panel thickness). One LVDT was placed at the central undersurface midspan to measure global deflection. CLT panel density was determined as mass / volume from a small sample (100 × 100 mm²) taken after failure.

3. Results and discussion

3.1. Timber boards for CLT manufacturing

Table 1 shows the results of measurements on timber boards before CLT manufacturing, and Fig. 4 shows Edyn12 according to visual grading and assigned strength class.

No significant differences were found for Edyn between recovered and new timber at 95% confidence level. However, significant differences were found for density.

Comparing VSG in recovered and new timber, more boards were rejected in recovered timber than in new timber. However, in both cases knots were the main reason for rejection, especially edge knots (in 84% of the rejected recovered boards and 89% of the rejected new boards). In the case of recovered boards, the second most common reason was fissures, while in new timber boards it was distortion. The most common singularities affecting recovered timber are holes and damage [29],

together with distortion and fissures [35]. In the present study, the singularities cited by these authors were not the main causes of rejection, as they were eliminated during sawing. Nor is any clear relationship between visual grades and Edyn in recovered or new timber, as is shown in Fig. 4. Most of the rejected boards present similar Edyn values to the graded boards. No relationship between visual grades and Edyn was reported by Stenstad et al. [29].

Knot size is one of the main factors that affect bending strength and therefore the size of the biggest knot or cluster of knots on the face and edge is limited in VSG standards. As is shown in Fig. 5a, relative face knot size is higher in recovered timber than in new timber, and in Fig. 5b it is definitely higher, especially knots which affect the complete board edge (relative knot size = 1).

Recovered and new timber boards were randomly divided into four groups to manufacture the four different kinds of CLT panels.

3.2. Comparison between CLT panels from recovered and new timber

Fig. 6 shows load-deformation curves for the four kinds of panels tested.

As shown in Fig. 6, although the elastic behavior of all kinds of panels is equivalent, the ultimate load clearly differs between panels with external recovered timber layers (RRR and RNR) and external new timber layers (NRN and NNN).

All panels were subjected to qualitative analysis of rupture sections after testing, and it was concluded that they all broke due to wood failure in the tension face in the central section (between the two loads), as shown in Fig. 7. No differences in failure mode were detected between panels made of recovered and new timber. No rolling shear or glue-line

Table 1
Moisture Content (MC), Visual Strength Grading (VSG) and Non Destructive Testing (NDT) results on boards for Cross Laminated Timber (CLT) manufacturing.

Boards	No.	Cross-section	MC		VSG (NF B52001-1-2011)				Edyn12		Boards density 12	
			Mean (mm ²)	CV (%)	1	2	3	Reject	Mean (N mm ⁻²)	CV (%)	Mean (kg m ⁻³)	CV (%)
Rec.	77	25 × 105	17.2	9.74	0	5	18	77	12,078	19.40	765	7.52
New	72	27 × 114	14.5	6.66	28	21	23	28	12,812	19.36	726	7.04

*Strength classes assignments for visual grades 1, 2 and 3 according to EN 1912 [55].

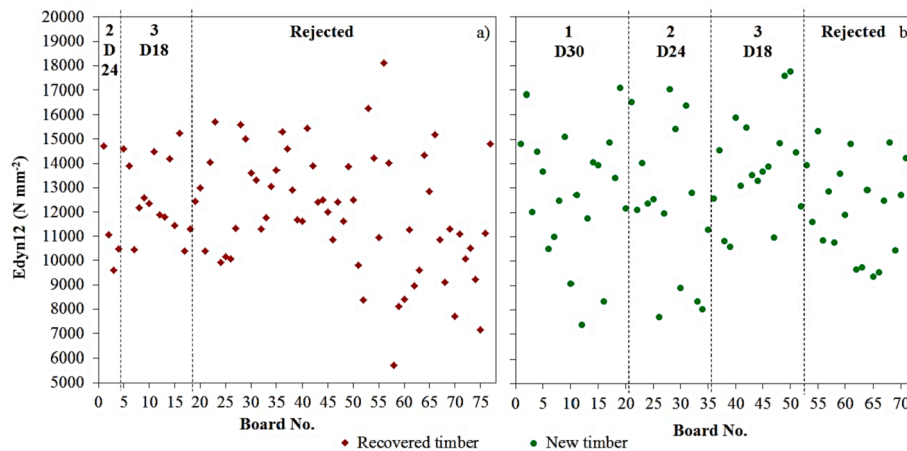


Fig. 4. Dynamic modulus of elasticity (E_{dyn12}) according to visual grading by NF B52001-1 (2011), and strength class assignments according to EN 1912 (2012): a) recovered timber boards, b) new timber boards.

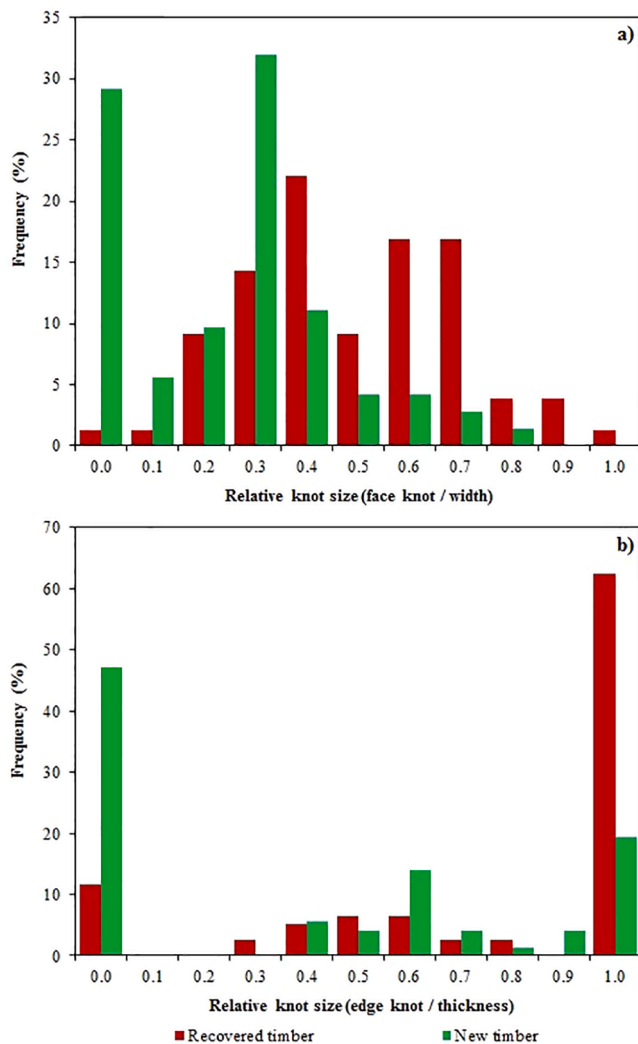


Fig. 5. Histograms of relative knot size distribution in recovered and new timber boards: a) face knots, b) edge knots.

failures were detected.

Table 2 shows the results of MOE, MOR and Density (adjusted to 12% MC according to EN 384 [50]) obtained by mechanical testing of CLT panels.

Based on the MOE_{loc12} results in Table 2, where the lowest average MOE is $11,491 \text{ N mm}^{-2}$, and the fifth percentile of MOR is equal to 35.81 N mm^{-2} and the fifth percentile of density is equal to 709 kg m^{-3} , CLT panel properties may be equivalent to strength class D35 in solid timber, according to EN 338 [56]. However, as is shown in Table 1, most of the recovered timber boards were visually graded as rejected, and none was graded D30, thereby confirming that the VSG procedure downgrades recovered timber. In the case of new timber boards, only 28% were visually graded as D30 (Table 1). These results are in line with those of Azambuja et al. [36], who using visually under-graded yellow-poplar achieved CLT properties equivalent to D35. It should be taken into account that EN 338 [56] strength classes were designed for solid timber, and the present assignment for CLT is only for comparable analysis.

An ANOVA was carried out in order to analyze if there are significant differences in MOE, MOR and density between the different kinds of CLT panels. In the case of MOE and density, as the P values shown in Table 2 are higher than 0.05, no significant differences were found at 95% confidence interval between different kind of panels (Fig. 8a). However, in the case of MOR, as the P value in Table 2 is lower than 0.05, at least one kind of panel is different to the other kinds, and as shown in Fig. 8b significant differences were found between CLT panels manufactured with recovered timber in the longitudinal layers (RRR and RNR) and new timber in the longitudinal layers (NRN and NNN).

In Fig. 8b, the results seem to indicate that the mechanical properties of the cross layer do not affect MOR results, which are determined by the properties of the longitudinal layers, as was reported by Stenstad et al. [29] for MOE and MOR testing CLT from recovered softwoods.

Like the present study, Cavalli et al. [57] reported that most of the research works reviewed which tested recovered solid timber considered that MOE remains unchanged over time. Furthermore, load history has a more significant influence on MOR than it does on MOE in structural solid timber, as is the case in the present study of CLT panels. Rammer [58] reported a MOR reduction of 60% when testing recovered Douglas-fir beams, while the MOE was unchanged. Nakajima and Murakami [59] reported a reduction of 13% in MOR when testing 633 recovered timber beams, and this reduction was associated with the number of nails and holes. Crews and MacKenzie [60] concluded that the load effect is responsible for the lower MOR in recovered timber, and they reported a 50% fall in MOR for structural hardwood timber with a longer load history. Kránitz et al. [61] stated that the increased brittleness of old wood led to poorer strength properties perpendicular to the grain (bending and tension). When Rose et al. [27] compared CLT from mixed softwood recovered timber and from new Scots pine timber, they found a 40% fall in the MOR. However, 70% of CLT failed at finger-joints. They also found a MOE value that was twice as high in recovered timber than

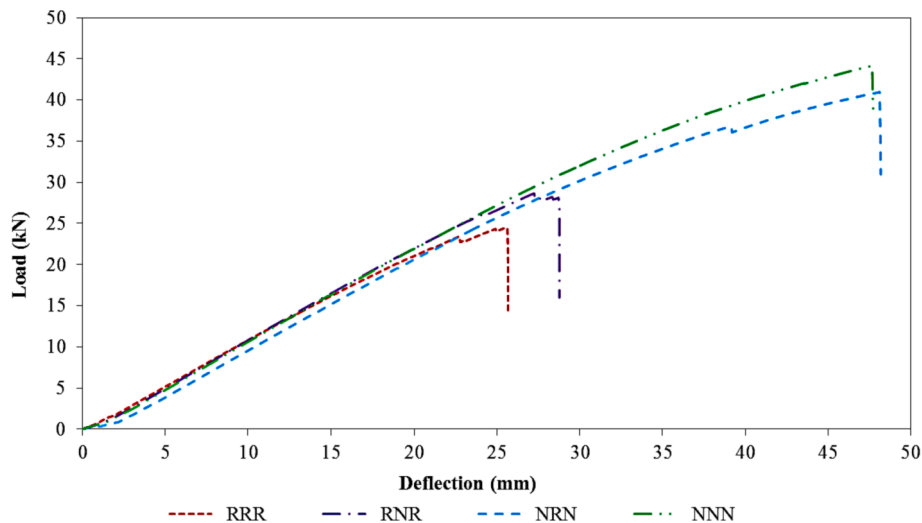


Fig. 6. Load-deformation response in RRR, RNR, NRN and NNN.

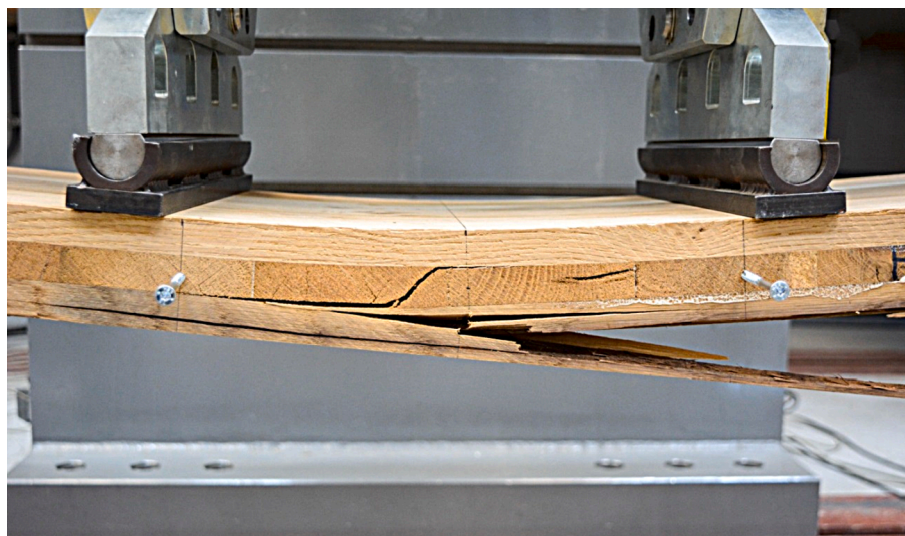


Fig. 7. CLT panel tension failure.

Table 2
Mechanical properties and ANOVA P-values of CLT panels.

CLT panels		MOE _{glo12}			MOE _{loc12}			MOR			CLT density 12		
No.	Kind	Mean (N mm ⁻²)	CV (%)	P value	Mean (N mm ⁻²)	CV (%)	P value	Mean (N mm ⁻²)	CV (%)	P value	Mean (kg m ⁻³)	CV (%)	P value
3	RRR	12,106	4.95	0.2142	11,602	6.23	0.2057	44.74	20.02	0.0001	769	3.06	0.1243
3	RNR	11,989	1.54		12,422	5.57		46.49	7.23		768	2.09	
3	NRN	11,180	6.72		11,491	4.30		72.80	2.60		761	2.48	
3	NNN	11,707	3.18		12,245	2.49		74.01	3.11		730	2.58	

it was in new timber. Arbelaez et al. [28] also found an unchanged MOE and lower MOR in the case of recovered Douglas-fir timber CLT panels.

Another possible explanation would be knottiness. As shown in Fig. 5, relative knot size is higher in recovered timber than it is in new timber. Similarly, Cavalli et al. [57] suggested that the differences in MOR between recovered and new solid timber are not only influenced by aging, as they are also related to the original quality of the timber.

Although lower MORs were obtained in the CLT panels with recovered timber in the longitudinal layers than in those with new timber, these lower values of MOR are still high enough (with a minimum of

35.81 N mm⁻²) for structural applications of these CLT panels (Prof. A. M. Harte, personal communication, October 28, 2021).

3.3. Estimation of mechanical properties

Table 3 shows the results of Edyn obtained by longitudinal vibration (EdynL) calculated with Eq. (2) and by transverse vibration (EdynT) calculated with Eq. (5) on CLT panels. As expected, EdynL12 values are higher than EdynT12, as commonly occurs in sawn timber. Furthermore, comparing Edyn results in longitudinal vibration from boards (Table 1)

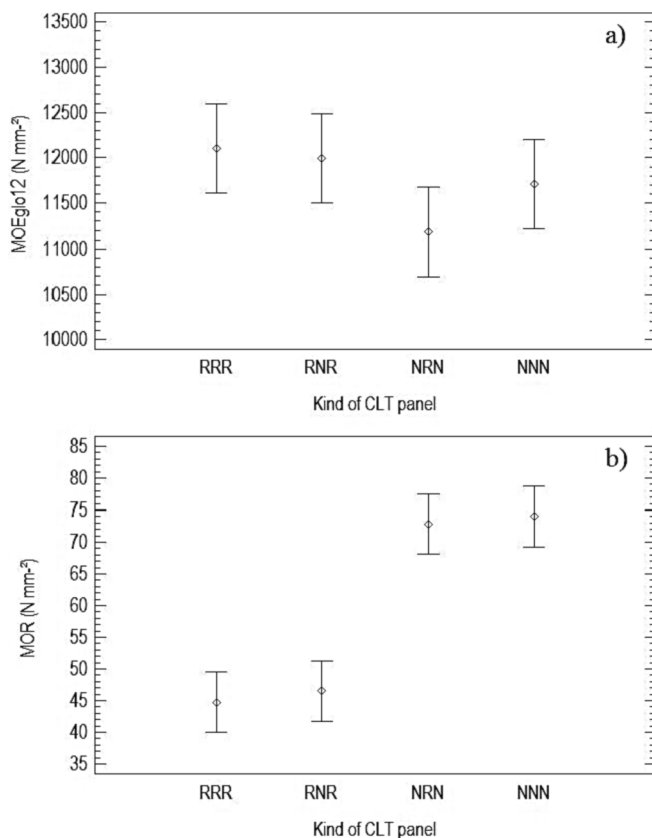


Fig. 8. ANOVA mean test for: a) MOEglo12, b) MOR.

and from CLT panels (Table 3), Edyn from boards is around 30% higher than EdynL from CLT panels. A possible explanation affecting vibration mode would be that the cross-section of panels is larger than that of boards, and it is also composed of boards in two perpendicular directions.

In order to estimate the stiffness of CLT panels based on NDT measurements, linear regression models were developed to estimate MOEglo12 from EdynL12 and EdynT12. As no significant differences between MOEglo12 (P values Table 2), EdynL12 and EdynT12 (P values Table 3) were found respecting the CLT panels, regression models were developed for all of the CLT panels together (Fig. 9).

The linear regression models corresponding to Fig. 9 are:

$$MOEglo12 = 1.9523 EdynL12 - 6445.2 \quad R^2 = 0.61 StE = 383 Nmm^{-2} \quad (7)$$

$$MOEglo12 = 1.6346 EdynT12 - 1235.4 \quad R^2 = 0.85 StE = 234 Nmm^{-2} \quad (8)$$

where MOEglo12 is the global static modulus of elasticity; EdynL12 is the dynamic modulus of elasticity obtained by longitudinal vibration on CLT panels; EdynT12 is the dynamic modulus of elasticity obtained by transverse vibration on CLT panels.

Linear regression models have a higher determination coefficient (R^2) and lower Standard Error (StE) when Edyn is used with transverse

vibration than they do with longitudinal vibration (Eqs. (7) and (8)). The R^2 from EdynL12 at 0.61 is lower than the 0.87 obtained with recovered structural Salzmann pine solid timber [62]. However, the standard error of 383 N mm^{-2} is lower than the 579 N mm^{-2} reported by the same authors. Moreover, the R^2 with EdynL12 0.61 is lower than the 0.87 reported for new radiata pine solid timber by Arriaga et al. [63], while the R^2 with EdynT12 at 0.85 is similar to the 0.86 reported by the same authors in transverse vibration.

4. Conclusions

Visual strength grading standards downgraded most of the recovered timber boards (77%). However, this was not due to the typical singularities which affect recovered timber more than new timber (fissures, distortion, holes...) because the recovered timber beams were sawn into boards before grading. The high rejection rate was due to the recovered oak being far knottier than new oak timber. As visual strength grading standards are designed for new timber, highly knotty (thin) boards are hardly penalized by edge knot limitations. As knottiness mainly affects bending strength, no relation between visual grades and Edyn was found.

A novel cross laminated timber panel using recovered timber in the external longitudinal layers and new timber in the internal cross layer was successfully manufactured and tested. Similar results in terms of mechanical properties were found to panels manufactured exclusively from recovered timber. The external longitudinal layers of recovered oak are therefore chiefly responsible for their mechanical properties.

No significant differences in the static modulus of elasticity were found between cross laminated timber panels manufactured from recovered and new timber. This confirms previous findings with solid timber, where the modulus of elasticity remains unchanged. Lower bending strength values were found in recovered timber in comparison with those in new timber. This agrees with previous findings regarding recovered solid timber and cross laminated timber panels manufactured from recovered softwoods. However, the bending strength values of recovered timber panels are still high enough (at least 35.81 N mm^{-2}) for all kinds of structural applications. This bending strength reduction would be explained by a combination of the load history effect and the original quality of the timber, as recovered timber is more knotty than new timber. This knottiness difference arises between recovered European oak and new oak in the market, and it affects the comparison between recovered and new timber.

The static modulus of elasticity of cross laminated timber panels can be accurately estimated by non-destructive testing. Higher determination coefficients were found when estimating the dynamic modulus of elasticity obtained from transverse vibration than was the case when they were obtained from longitudinal vibration. Models were developed to estimate the modulus of elasticity with a high determination coefficient (R^2 0.85) and low standard error.

Given the small number of specimens tested and the heterogeneous raw material, the conclusions should be considered with caution. The results, which are based on twelve panels made from recovered timber hardwoods, require validation with a larger sample in future studies. Nevertheless, cross laminated timber panels manufactured from recovered timber hardwoods (European Oak) were found to be suitable for

Table 3
Moisture Content (MC) and Non Destructive Testing (NDT) results in CLT panels.

CLT panels	MC		EdynL12			EdynT12		
	Mean (%)	CV (%)	Mean (N mm ⁻²)	CV (%)	P value	Mean (N mm ⁻²)	CV (%)	P value
RRR	15.4	3.18	9,423	1.38	0.5026	8,188	4.59	0.1123
RNR	15.6	0.58	9,417	1.95		8,035	1.38	
NRN	14.4	2.97	9,161	4.49		7,579	4.69	
NNN	14.3	2.86	9,270	0.74		7,965	1.43	

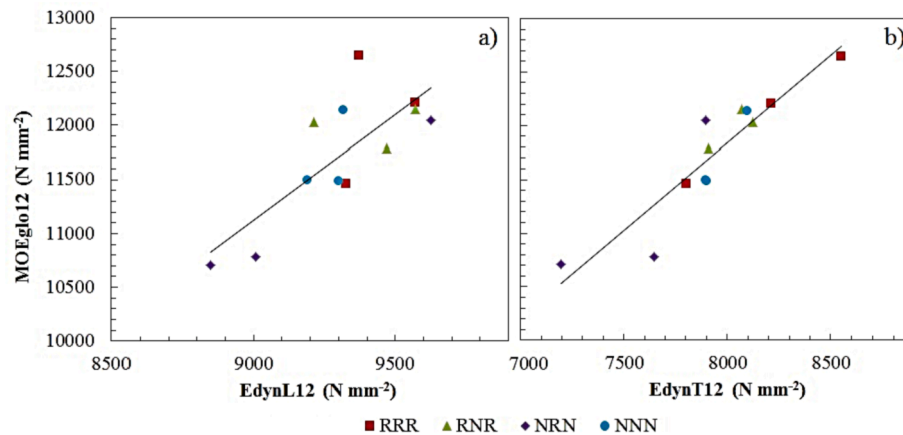


Fig. 9. Linear regression between static MOE and a) EdynL12 from longitudinal vibration, b) EdynT12 from transverse vibration.

structural applications.

CRediT authorship contribution statement

Daniel F. Llana: Conceptualization, Methodology, Validation, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Violeta González-Alegre:** Methodology, Validation, Investigation, Writing – review & editing. **María Portela:** Methodology, Validation, Resources, Investigation, Writing – review & editing. **Guillermo Íñiguez-González:** Funding acquisition, Project administration, Supervision, Conceptualization, Methodology, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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