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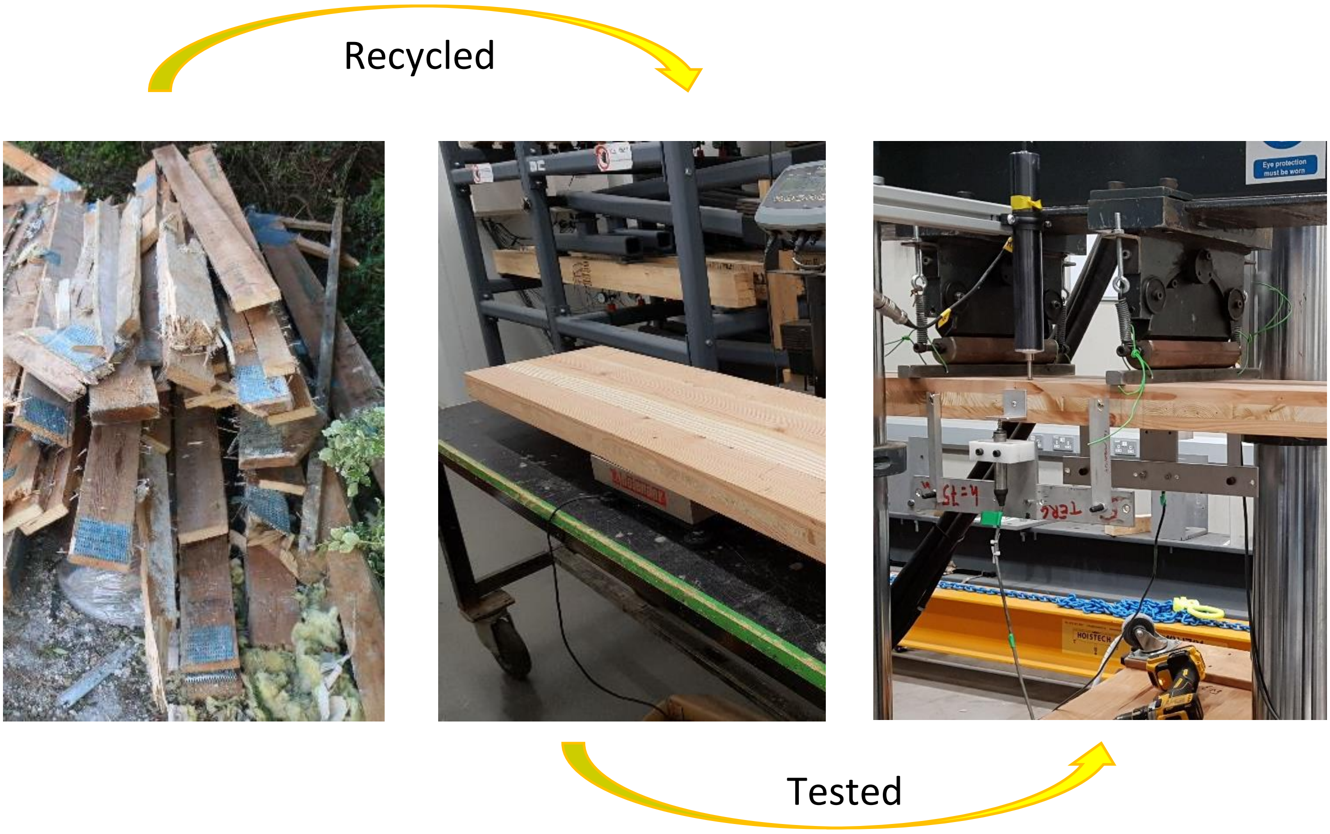

Innovative Design for the **Fut**ure – **U**se and **Re**use of **Wood** (**InFutUReWood**)

Deliverable Report *D3.2* of WP3

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Recycling timber in new mass timber products

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Innovative Design for the **Fut**ure – **U**se and **Re**use of **W**ood (**InFutUReWood**)

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Foreword

This report is published under the InFutUReWood project - Innovative Design for the Future – Use and Reuse of Wood (Building) Components. Work Package 3.

The InfutUReWood project has seven work packages:

- WP 1 Coordination and management led by Karin Sandberg, RISE, Sweden
- WP 2 Design of timber structures for the future, led by Ylva Sandin, RISE, Sweden
- WP 3 Product design using recovered timber, led by Annette M. Harte, NUI Galway, Ireland
- WP 4 Inventory, deconstruction and quality of recovered wood, led by Mark Hughes, Aalto University, Finland
- WP 5 Properties of recovered wood, led by Daniel Ridley-Ellis, Edinburgh Napier University, UK
- WP 6 Environmental and economic assessment of design for recycling in building construction, led by Michael Risse, TUM, Germany
- WP 7 Dissemination and engagement, led by Carmen Cristescu, RISE, Sweden

ForestValue

Project InFutUReWood is supported under the umbrella of ERA-NET Cofund ForestValue by Vinnova – Sweden´s Innovation Agency, Formas, Swedish Energy Agencythe Forestry Commissioners for the UK, the Department of Agriculture, Food and the Marine for Ireland, the Ministry of the Environment for Finland, the Federal Ministry of Food and Agriculture through the Agency for Renewable Resources for Germany, the Ministry of Science, Innovation and Universities for Spain, the Ministry of Education, Science and Sport for Slovenia. ForestValue has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773324.

The research and academia project partners are RISE (Sweden), Edinburgh Napier University (UK), National University of Ireland Galway (Ireland), University College Dublin (Ireland), Universidad Politécnica de Madrid, (Spain), University of Ljubljana (Slovenia), Aalto University Helsinki (Finland), and Technical University Munich (Germany).

The industry partners are Kiruna Municipality Technical Service, Swedish Wood, Derome, IsoTimber, Offsite Solutions Scotland, Hegarty Demolition, SIP Energy, Connaught Timber, The Federation of the Finnish Woodworking Industries, Jelovica, The Swedish Federation of Wood and Furniture Industry, Balcas Timber, Stora Enso, Klimark + Nova domus Hábitat, and Brenner Planungsgesellschaft.

Summary

The Innovative Design for the Future Use and Reuse of Wooden building components (InFutUReWood) project aims to examine if recovered timber is suited for contemporary timber architecture. To address this aim, series of structural testing programmes were carried out on products manufactured using recovered softwood and hardwood timber from a number of partner countries. These products include cross-laminated timber (CLT) panels, glued-laminated timber (GLT) beams and IsoTimber wall panels. In addition, series of tests were performed on similar products manufactured from new timber and on hybrid panels with mixed recovered and new timber to enable the evaluation of the relative performance characteristics of the different products. Tests were also carried out to evaluate the bonding characteristics and the embedment behaviour of recovered wood. Finally, a comparison between the environmental impacts of CLT manufactured from recovered and from primary wood was performed using life cycle assessment (LCA) methodology

The report shows that the use of recovered timber in high-value material applications like CLT or GLT is to current knowledge an environmentally and technically feasible option and can contribute to the implementation of wood cascading as part of a bio-based economy.

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1. Introduction

1.1. Background

This report was produced as part of the *InFutUReWood - Innovative Design for the Future – Use and Reuse of Wood (Building) Components* project, which aims to answer two main questions:

- How easy is it to reuse wood from the current building stock, especially as a structural material?
- How can past experience help in future timber reuse?

To address these questions the project identifies key opportunities and challenges, proposing technical solutions that aim to exploit the opportunities and reduce the challenges identified that may lessen the cascading use potential of building timber.

Work Package (WP) 3 *Product design using recovered timber* is divided into four tasks. The first task (T3.1) focuses on the specification requirements for timber products and identifies the current range of timber material that is potentially available from demolition. The second task (T3.2) examines the recycling potential of wood in engineered-timber manufacture generally. The third task (T3.3) examines how to improve the design of new products to optimise their reuse potential of timber. The fourth task (T3.4) investigates traceability protocols for wood products.

This deliverable is the result of the work carried out within task T3.2 *Recycling timber in new mass timber products with laboratory scale testing.*

1.2. Aims and Objectives

The aim of this report is to provide scientific data to support the potential reuse of recovered timber in the production of structural mass timber products. To achieve this, several objectives are set out:

(i) Investigate the processing of recovered softwood and hardwood timber into cross-laminated timber (CLT) panels and glued laminated timber (GLT) beams and compare their structural performance with equivalent products from new timber.
(ii) Characterise the performance of adhesive bonds in CLT and GLT manufactured from recovered timber.
(iii) Undertake a study of the embedment behaviour of recovered timber for use in connection design of recycled products.
(iv) Quantify the environmental impact of CLT produced from recovered timber.

It is intended that the results will inform designers, standardisation authorities and industry on the performance characteristics of recycled timber products for construction applications.

1.3. Methods

To achieve the objectives outlined above a number of multi-national research studies were undertaken and these are presented in Chapters 2-5 of this report.

Chapter 2 describes experimental programmes carried out to investigate the development of mass timber structural products from recovered softwood timber in Ireland and recovered hardwood timber in Spain. Details of material preparation for mass timber production, mechanical characterisation of the recovered timber and experimental testing and analysis of the final CLT and GLT products are provided. In parallel with this, similar products using new timber and using mixed recovered and new timber are produced and assessed. Recovered spruce timber was used in the manufacture of an IsoTimber wall panel and its capacity in compression was compared to that of panels made from new timber.

Chapter 3 describes experimental test programmes carried out in Ireland, Spain and the UK to characterise the adhesive bonding performance of glue lines in mass timber products manufactured from recovered timber.

Chapter 4 provides details of a study carried out in Ireland, which characterises the embedment behaviour of recovered spruce from a demolition site in Ireland and recovered oak and spruce from two demolition sites in Slovenia. The applicability of current Eurocode 5 design rules for dowel type timber connections to recovered wood structures is discussed.

Chapter 5 summarises the life cycle analysis (LCA) carried out in Germany to quantify the environmental performance of CLT manufactured from recycled timber and CLT manufactured from new timber.

1.4. Limitations

The results presented in this report are based on recovered timber from a limited number of sources so the results presented must be interpreted with that in mind. The academic literature on the properties of recovered timber is very limited and studies on the performance of engineered wood products from this material even more so. This provides limited opportunities to evaluate the findings relative to other studies. There have been no studies that we are aware of that have looked at the embedment behaviour of recovered timber. While this is a drawback, it also highlights the importance of this work in contributing to the development of circular construction in timber.

1.5. Target group

Primarily, this report is targeted towards the research team of the InFutUReWood project. The findings are aimed at architects, engineers, manufacturers, and national code and regulation authorities, to highlight building procedures that may improve the cascading potential of timber from construction and demolition.

1.6. Short glossary of terms

Some key terms used in this report are defined as follows:

Mass timber is used here to refer to structurally large section engineered timber-based building products, including cross-laminated timber (CLT) panels and glued laminated timber beams (GLT).

New timber is used here to refer to graded timber before its first use.

Recovered timber is used here to refer to timber recovered from building or demolition for reuse. Where the term timber is replaced by the wood species (e.g., *recovered spruce*) here refers to a particular timber species that is recovered from building or demolition for reuse.

Recycling is any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. (EC (2008)).

Reuse is any operation by which products or components that are not waste are used again for the same purpose for which they were conceived, with minimal pre-processing, i.e., checking, cleaning, and repairing. (Adapted from EC (2008)).

Timber is used here to refer to any wood-based building material, whether structural or non-structural. Depending on the context, the word is used to refer to sawn wood in a prepared state for use in building (or wood intended for that purpose), but it can also be used in a general sense to include laminated elements and other engineered wood products. Light wood-based panel products are not, themselves, referred to as timber, but they do fall under the general heading of timber construction. In some countries, timber refers to specific end-uses and/or cross-section sizes, but that distinction is not made here (Adapted from ISO 6707-1 (2020).

2. Mass-Timber Products from Recovered Timber

2.1. Introduction

To investigate the potential reuse of timber recovered from demolition sites in the manufacture of mass timber construction products, studies were carried out in Ireland, Spain and Sweden. Both softwood and hardwood timber resources were included in the study. In Ireland, spruce recovered from the demolition of a roof structure was used in the manufacture of cross-laminated timber (CLT) panels. In Spain, oak recovered from the demolition of a post-and-beam structure was used to manufacture CLT panels and glued-laminated timber (GLT) beams. Reference CLT and GLT products were manufactured from new timber for comparison purposes. In addition, hybrid products combining recovered and new timber were manufactured. Flexural testing was carried out to evaluate the relative performance of new, recovered and hybrid products in these two studies. In Sweden, spruce timber recovered from three buildings was used in the manufacture of an IsoTimber wall panel, which was tested in compression. This chapter describes the preparation and characterisation of the timber samples, the manufacturing of the mass timber products, testing in accordance with EN standards and analysis of results.

2.2. Investigation of CLT Production from Recovered Spruce - Ireland

Caitríona Uí Chúláin, Daniel F. Llana, Annette M. Harte

2.2.1. Recovered timber description, preparation and characterisation.

The following outlines the collection, transport, cleaning, and the measurement and testing methods used to select appropriate material for mass timber manufacture.

Spruce timber boards were recovered from the roof trusses of an office block in Stillorgan, Co. Dublin (Figure 2-1). The building was constructed in the 1970s and was vacant for over two years before its deconstruction. The building was demolished mechanically and all materials were sorted post demolition at ground level on-site. Most timber from the site was due for exportation for wood-chip production, but from the general wood pile, a suitable sample of timber boards was chosen by researchers for use in this task.

The boards were trimmed for transport on-site using a handheld cordless reciprocating saw (Hilti WSR 22A) and significant metal content was removed. Figure 2-2 shows the recovered timber trimmed and stacked for transport.

Significant metal content was manually removed on-site before removal to the Timber Engineering Laboratory at NUI Galway where the timber was cleaned of building debris, adhesives and detectable metal. Residual metal content was removed at the CLT manufacturing facility during the panel manufacture. Figure 2-3 shows a typical example of the metal content in the recovered timber and Figure 2-4 shows the prepared wood stacked for conditioning before testing and subsequent transport to the joinery for manufacture of the CLT panels.

The moisture content (MC) in the wood at the time of recovery was high (between 18% and 23%) as estimated by a handheld moisture meter based on the electrical resistance method. This was attributed to pre-demolition of water ingress onto the structural timber through damaged slates and sarking felt in the roof envelope. The trusses were assembled with punched metal plates. The timber contained grade stamps indicating that they were M75. As it was clear from the ring width that the timber was imported spruce and not Irish-grown, this marking indicates that the timber grade is approximately TR26. This is typical of the material that is found in timber roof structures in Ireland and is representative of the material that would available from demolition. Figure 2-1 shows the trussed roof in Dublin before the demolition of the building. The damage to the roof felt is clearly visible.

Figure 2-1: Roof trusses manufactured from spruce timber

Figure 2-2: Recovered Irish spruce trimmed and stacked for collection

Figure 2-3: Metal content for removal

Figure 2-4: After removal of metal in lab

The full sample of 78 recovered spruce boards was evaluated non-destructively to determine the dynamic modulus of elasticity. The mass, length, and mean cross-section dimensions of each board were measured and a handheld acoustic grader (Mobile Timber Grader (MTG), Brookhuis, Enschede, Netherlands) was used to record the longitudinal vibration. From this, the dynamic modulus of elasticity (MOE) (E_{dyn}) parallel to grain of the boards was determined. The MC of the timber was estimated using the electrical resistance method. At the time of testing, the MC values of the recovered boards ranged from 15.7% to 20.1%, with an average value of 17.6%. Direct adjustment of E_{dyn} to $E_{dyn,12,adj}$ (MOE at 12% MC) was made relative to the actual MC in accordance with MTG guidelines and EN 384+A1 (2018). Figure 2-5 shows the distribution of adjusted dynamic MOE values for the sample. The nominal cross-section of most of the boards was about 142 x 35 mm^2.

To reduce variability, boards with $E_{dyn,12,adj}$ in the range of 11,000 to 14,000 N/mm^2 were selected for manufacture of the CLT panels. The boards used had $E_{dyn,12,adj}$ values between 11,008 N/mm^2 and 13,880 N/mm^2, with an average value of 12,364 N/mm^2.

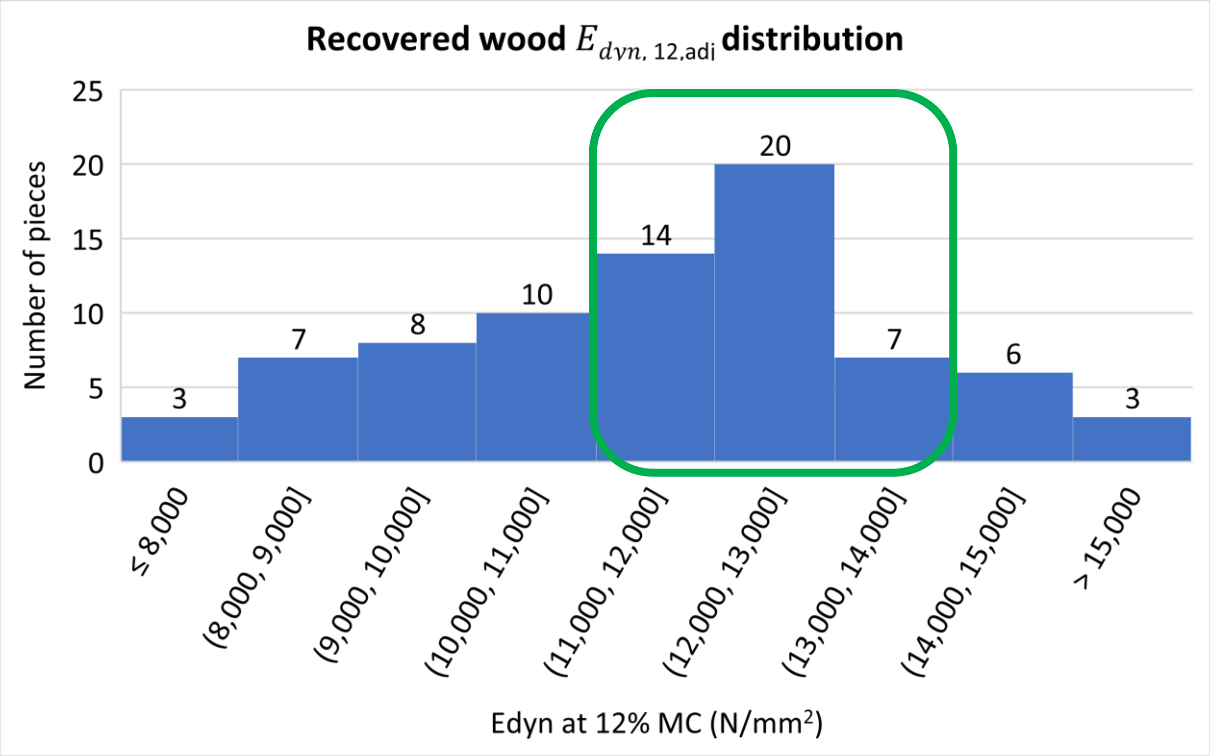


Figure 2-5: E_{dyn} at 12% MC distribution for recovered spruce timber

2.2.2. New timber selection and characteristics

A matching sample of new timber was selected for manufacture of reference CLT panels and also for the hybrid panels. The sample was matched on the basis of dynamic MOE measurements. The most suitable sample available was Irish grown Douglas fir (*Pseudotsuga menziesii*). A sample of 101 boards was assessed. The MC of the new timber boards ranged from 10.8% to 14.5%, with an average value of 13.0%. The distribution of dynamic MOE values adjusted to a reference MC of 12% is shown in Figure 2-6. The selected new-timber batch had adjusted dynamic MOE values ranging between 10,557 N/mm^2 and 14,553 N/mm^2, with an average value of 12,602 N/mm^2. The nominal cross-section of the new timber boards was 110 x 45 mm^2.

The mean $E_{dyn,12,adj}$ of both new and recovered timber boards was greater than 11,000 N/mm^2, which is the mean value for grade C24 in accordance with EN 338 (2016).

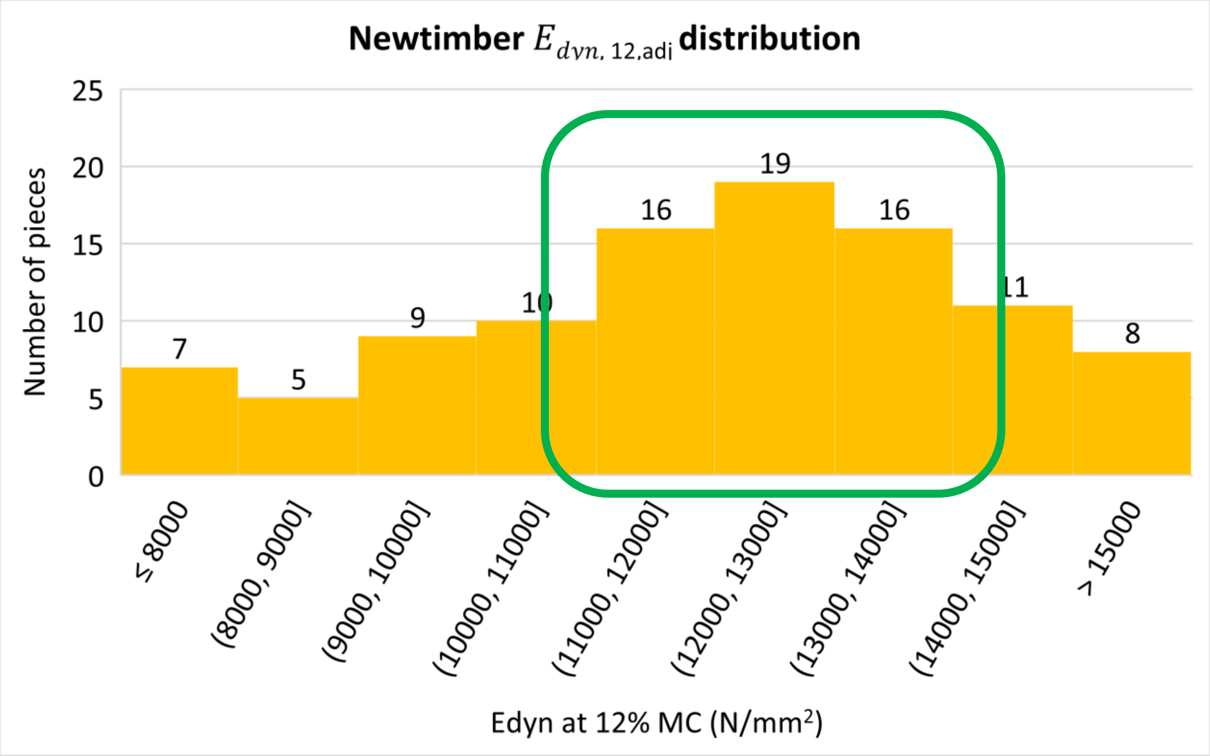


Figure 2-6: E_{dyn} at 12% MC distribution for new Douglas fir timber

2.2.3. CLT panel design and manufacture

Based on the available recovered timber dimensions, it was decided to manufacture and test three-layer CLT panels. Each panel was 60 mm deep, 360 mm wide and 1620 mm long comprising 8 no. 20 mm x 90 mm x 1620 mm planed boards in the longitudinal layers at the top and bottom with the core layer comprising 18 no. 20 mm x 90 mm x 360 mm boards in the transverse direction. Figure 2-7 shows the layup of the panels.

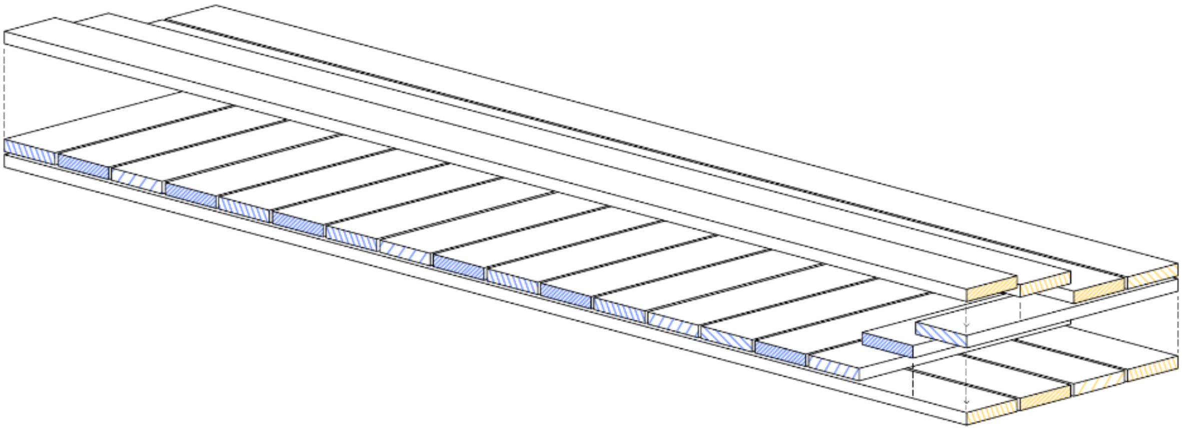


Figure 2-7: 60 mm x 360 mm x 1620 mm three-layer CLT panel

In all, 12 three-layer CLT panels were manufactured for testing. Initially, three CLT panels were made with recovered spruce boards (R-3-20-1, R-3-20-2, R3-20-3), three with new Douglas Fir boards (N-3-20-1, N-3-20-2, N-3-20-3) and three with new timber in the longitudinal direction and recovered wood in the cross-layers (H-3-20-1, H-3-20-2, H-3-20-3). After these nine panels were tested, three further hybrid panels (H-3-20-4, H-3-20-5, H-3-20-6) were manufactured from the remaining boards and tested. The average dynamic modulus of elasticity of the boards for these additional panels was lower than that from which the initial specimens were manufactured.

The timber boards were planed to the required cross-sectional dimensions prior to application of Loctite HB 309 Purbond adhesive. The panels were clamped using a pressure of 0.6 MPa for a minimum of two hours. The adhesive selection and pressing parameters were selected based on previous studies carried out at NUI Galway using new spruce timber (Raftery *et al*. 2008, Sikora *et al*., 2016). The panels were manufactured in an external joinery and then stored at NUI Galway in a conditioning chamber with a relative humidity of 65 ± 5% and temperature 20° ± 2° C for three weeks before testing.

The MC values were determined by electrical resistance method. The average MC of panels was 14.6% for the recovered timber, 13.5% for the new timber and 14.5% for the hybrid panels.

2.2.4. Out-of-plane Bending Tests on CLT panels

The CLT panels were tested in four-point in accordance with EN 408 (2012) and EN 16351 (2015) to determine the modulus of elasticity in bending (E_m) and the bending strength (f_m). The panels were simply supported over a span of 1560 mm (26 x panel thickness). Loads were applied at two points 360 mm apart and arranged symmetrically about the central axis. The load was applied at a constant rate of 0.01 mm/s and was measured to an accuracy of 0.1 % of the maximum applied load.

Two 6 mm linear variable differential transformers (LVDTs), with a measurement accuracy of ± 0.01 mm, were used to measure the local deflection ($w_{l,0.4}$) of the neutral axis over a central gauge length of 300 mm in the shear-free zone between the load heads, one at each edge of the panel. Two 100 mm LVDTs were used to measure global deflection ($w_{g,max}$) at midspan relative to the supports. They were supported independently of the test panel. The test set-up is shown in Figure 2-8.

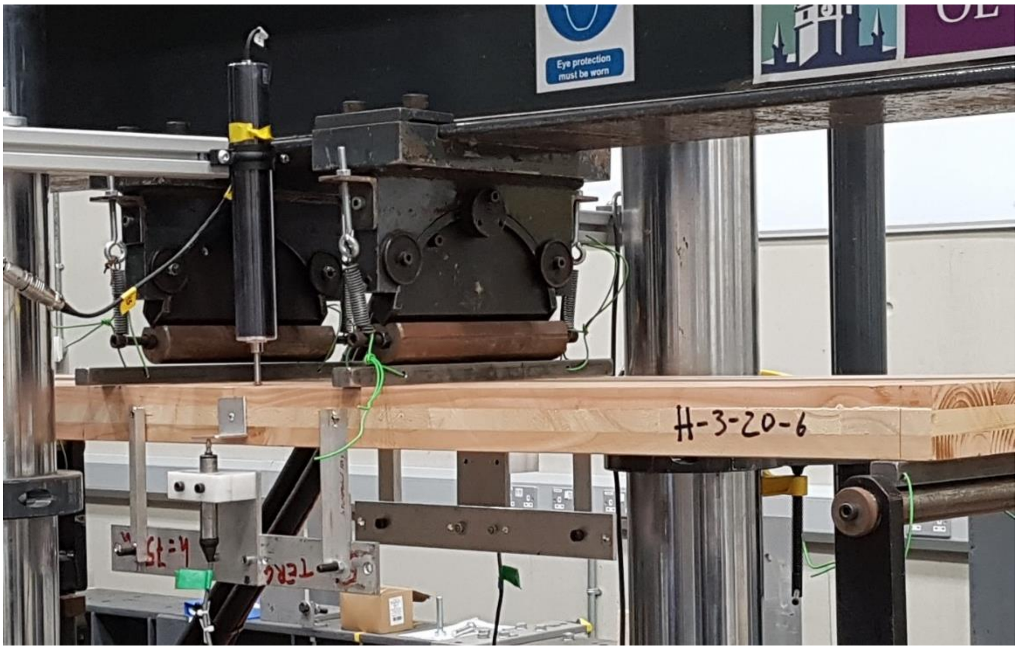


Figure 2-8: CLT four-point bending test set-up (NUI Galway)

The local modulus of elasticity was calculated using Equation (2.1) [adapted from EN 408/9.3 Equation (1)].

$$\boldsymbol{E_{m,l}\,I = \frac{a l_1 \,(F_2 - F_1)}{16\,(w_2 - w_1)}} \qquad (2.1)$$

where $F_2 - F_1$, in kN represents an increment of load in N on the regression line, and $w_2 - w_1$, in mm, represents the corresponding increment in deformation. The terms a, l_1, I represent distance between load and the nearest support (600 mm), central gauge length (300 mm), and second moment of area of the panel, in mm^4, respectively.

The global modulus of elasticity was calculated from Equation (2.2) [adapted from EN 408/10.3 Equation (2)].

$$\boldsymbol{E_{m,g}\,I = \frac{3al^2 - 4a^3}{24\left(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh}\right)}} \qquad (2.2)$$

where l, b, h, in mm, represent the span, panel width, and depth, respectively. The mean shear modulus G is taken as 650 in N/mm^2 in accordance with EN 408 (2012) and EN 16351 (2015).

The bending strength was calculated using Equation (2.3)

$$\boldsymbol{f_m = \frac{F_{max} a h}{4\,Itr}} \qquad (2.3)$$

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

2.2.5. Irish CLT panel bending test results

The load-displacement response for the each of the recovered timber panels is given in Figure 2-9. The behaviour is seen to be consistent for all three panels tested.

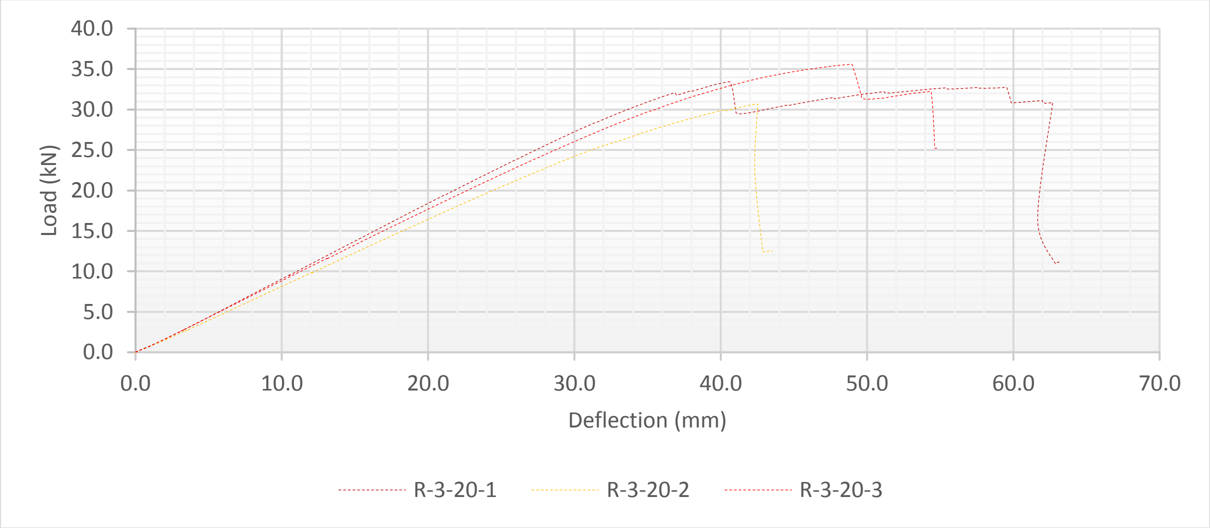


Figure 2-9: Load-deformation response – recovered timber panels

Similar load-deflection responses were found for the CLT panels from new timber (Figure 2-10) and the hybrid panels (Figure 2-11, Figure 2-12). The average deformation at failure was greater for the recovered timber panels but it should be noted that this observation is based on results from a limited number of panels and further testing would be required to confirm this behaviour.

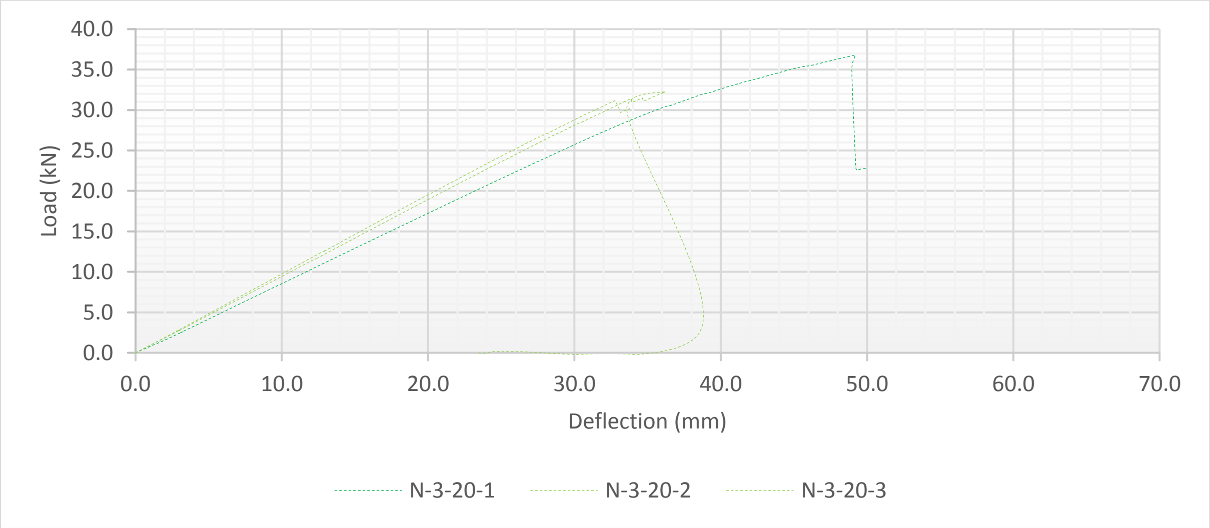


Figure 2-10: Load-deformation response – new timber panels

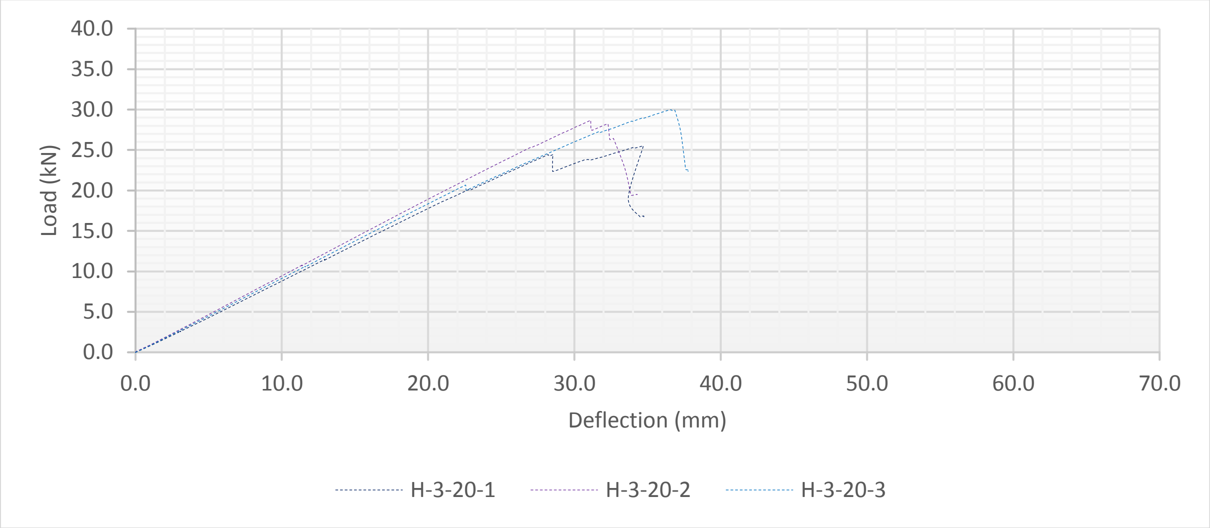


Figure 2-11: Load-deformation response – hybrid timber panels (1-3)

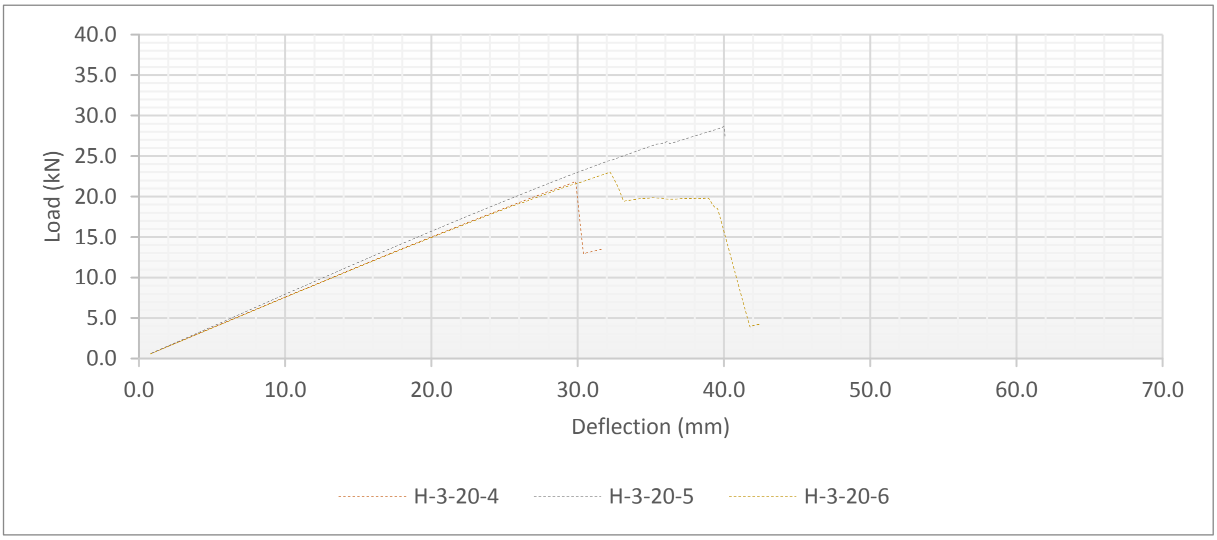


Figure 2-12: Load-deformation response – hybrid timber panels (4-6)

For all panels tested, the failure mode was similar. Failure initiated at the bottom of the panel at the location of a knot or large slope of grain and failure then propagated though the thickness of the panel as seen in Figure 2-13.

Figure 2-13: Bending failure in panel H-3-20-6

Table 2-1 gives a summary of the bending test results for all panels including the local and global modulus of elasticity and the bending strength, which were calculated using the gamma method as outlined in Bogensperger *et al.* (2012). For the first 9 panels, which were manufactured using matched boards, the mean global modulus of elasticity was found to be effectively the same for the recovered, new and hybrid designs. The mean bending strength of the CLT panels from the recovered timber is almost identical to the mean value for those from new timber. For hybrid panels 1-3, the mean strength is 41.7 N/mm^2, which is lower than that of the recovered and new specimens of 49.4 N/mm^2 and 49.7 N/mm^2, respectively. It is unclear what the reason for this difference is other than greater effect of localised strength reducing characteristics in those panels. The shear strength study described in Section 3.2 shows that the shear strength of the bonds in these panels is excellent as borne out by the matched stiffness values. The additional three hybrid panels had a lower mean global modulus of elasticity than the first nine panels. This was expected as the mean dynamic modulus of elasticity of the boards was lower than that used to make the earlier specimens. The mean bending strength was also lower at 36.2 N/mm^2.

Table 2-1: Bending test results summary

Timber type	CLT panel no.	$E_{m,l}$ (N/mm^2)	$E_{m,g}$ (N/mm^2)	f_m (N/mm^2)
Recovered spruce	R-3-20-1	11750	10910	49.7
	R-3-20-2	9720	9700	45.5
	R-3-20-3	9980	10420	52.9
	Mean	**10480**	**10340**	**49.4**
	COV	**10.5%**	**5.9%**	**7.5%**
New Douglas fir	N-3-20-1	11750	10120	54.6
	N-3-20-2	11730	11070	48.0
	N-3-20-3	13300	11400	46.4
	Mean	**12260**	**10870**	**49.7**
	COV	**7.3%**	**6.1%**	**8.7%**
Hybrid Douglas fir – Spruce - Douglas fir	H-3-20-1	10940	10480	37.9
	H-3-20-2	11760	11090	42.7
	H-3-20-3	13400	10760	44.6
	Mean	**12030**	**10780**	**41.7**
	COV	**10.4%**	**2.8%**	**8.2%**
	H-3-20-4	8500	8730	32.3
	H-3-20-5	10440	9160	42.3
	H-3-20-6	8890	8740	34.0
	Mean	**9280**	**8870**	**36.2**
	COV	**11.0%**	**2.8%**	**14.8%**

Symbols: $E_{m,l}$ - Local elastic modulus; $E_{m,g}$ - global elastic modulus; f_m – bending strength.

2.3. Investigation of CLT Production from Recovered Oak - Spain

Daniel F. Llana, Violeta González-Alegre, Guillermo Íñiguez-González

2.3.1. Recovered wood description, preparation and characterisation.

The Spanish oak was recovered from a 150 to 200-year-old house in Álava. The exact location of the house is unknown as timber was provided by a recovered timber supplier. A total of 40 large cross-section pieces of European oak (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.) with average dimensions 146 x 164 x 2488 mm^3 were used (Figure 2-14). The information of timber origin is scarce, but large cross-section timber 150-200 years ago in non-coastal areas of Spain were usually from the surrounding forests. Holes, mortise and tenon were found in the pieces due to carpentry joints. The MC estimated by electrical resistance method according to EN13183-2 (2002) was on average 19%.

Figure 2-14: Recovered Spanish oak

As most of the pieces contained lots of rusty broken nails in at least one face, due to floor planks fixing on the beams, nails were removed before sawing the timber into boards. Between three and five boards were obtained from each piece (Figure 2-15). The total number of boards was 169 of average dimensions 25 x 109 x 2500 mm^3.

Figure 2-15: Five boards and wood waste sawn from a piece

The MC of the boards was estimated by electrical resistance method. The MC value ranged from 14.5% to 23.6% and average of 17.6%.

The mass, length, and mean cross-section of each board was measured and the first mode of natural frequency in longitudinal vibration was recorded using Mobile Timber Grader MTG (Brookhuis, Enschede, Netherlands) (Figure 2-16). Velocity and dynamic modulus of elasticity (Edyn) were determined according to Equations (2.4) and (2.5), respectively.

$$V=2*f*L \tag{2.4}$$

$$Edyn=\rho*V^2*10^{-6} \tag{2.5}$$

where V is velocity in m/s; f is frequency in Hz; L is length in m; Edyn is dynamic modulus of elasticity in N/mm^2; ρ is density in kg/m^3

The velocity was adjusted to a reference MC of 12% using adjustment factors proposed by Kollmann and Krech (1960) and density was adjusted according to EN 384 (2018).

Figure 2-16: Longitudinal vibration testing by MTG

Furthermore, the most significant visual parameters (cracks, knots, slope of grain and wanes) were recorded.

Recovered boards for CLT and GLT were selected based on the more significant visual parameters. A total of 105 recovered timber boards were selected. Edyn values from MTG (Figure 2-17) were used to have a similar average Edyn in each specimen.

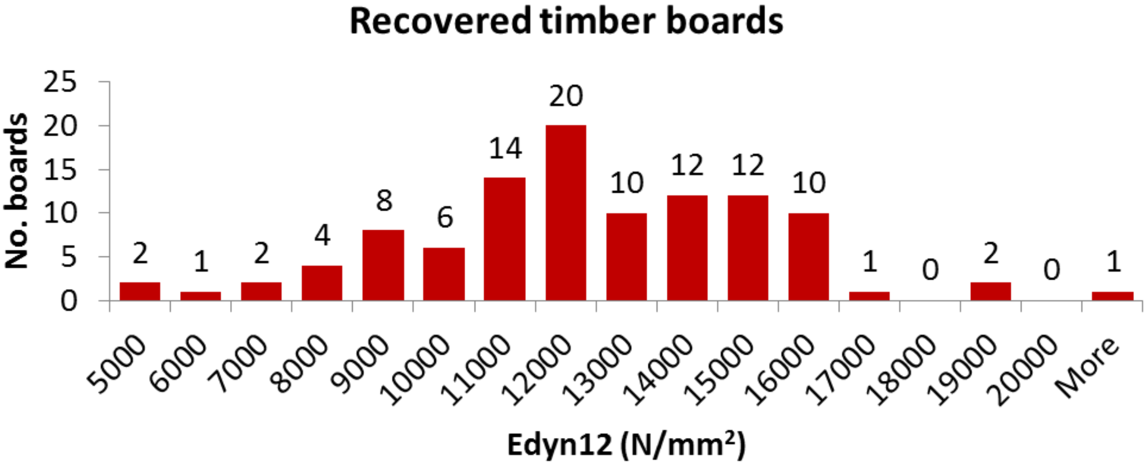


Figure 2-17: Distribution of Edyn12 for recovered timber boards

2.3.2. New wood selection and characteristics

A batch of new timber of European oak was bought. A total of 72 boards of average dimensions 27 x 114 x 2338 mm^3 were used for CLT and GLT manufacturing. The MC value ranged from 12.7% to 16.3% with an average of 14.5%. Edyn values were obtained from MTG measurements (Figure 2-18).

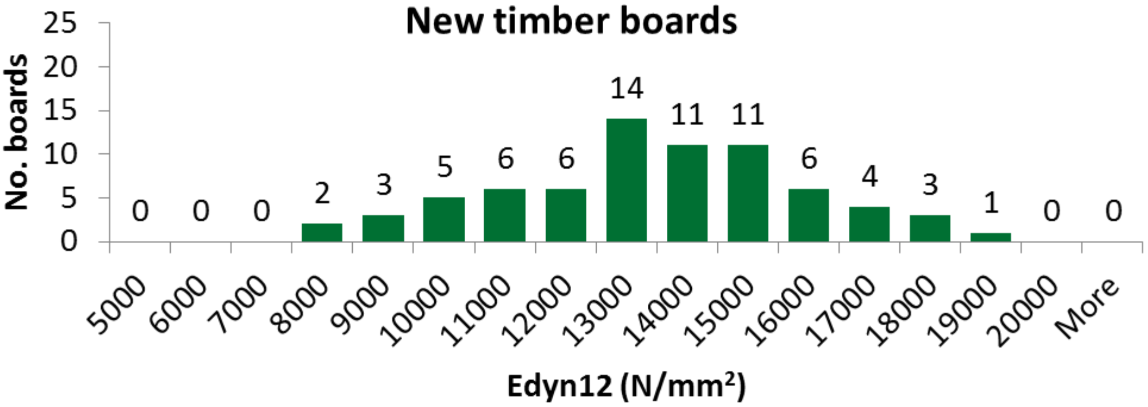


Figure 2-18: Distribution of Edyn12 for new timber boards

Table 2-2 shows the MC, density and Edyn of boards used for CLT panels and GLT beams manufacturing. Edyn values from new timber were slightly higher than those from recovered timber, while density was the opposite.

Table 2-2: Boards MC, density and Edyn

No.	Kind of boards	MC		Density12		Edyn12	
		Mean (%)	CV (%)	Mean (kg/m³)	CV (%)	Mean (N/mm²)	CV (%)
105	Recovered	17.6	11.20	763	7.91	11906	24.33
72	New	14.5	6.66	726	7.04	12812	19.36

As MC of recovered timber (17.6%) was higher than new timber (14.5%), recovered boards were conditioned to a MC similar to that of new timber before CLT and GLT manufacturing.

2.3.3. CLT panel design and manufacture

Based on the facilities for manufacturing and testing available and that according to EN 16351 (2015) the width of the specimens shall be at least 300 mm, it was decided to manufacture and test twelve 3-layer CLT panels. Each panel was 60 x 300 x 1800 mm^3 (Figure 2-19). From this calculation it was determined that a minimum of 36 longitudinal boards of 1800 mm in length and 108 transversal boards of 300 mm in length with a nominal cross section of at least 25 x 105 mm^2 were required.

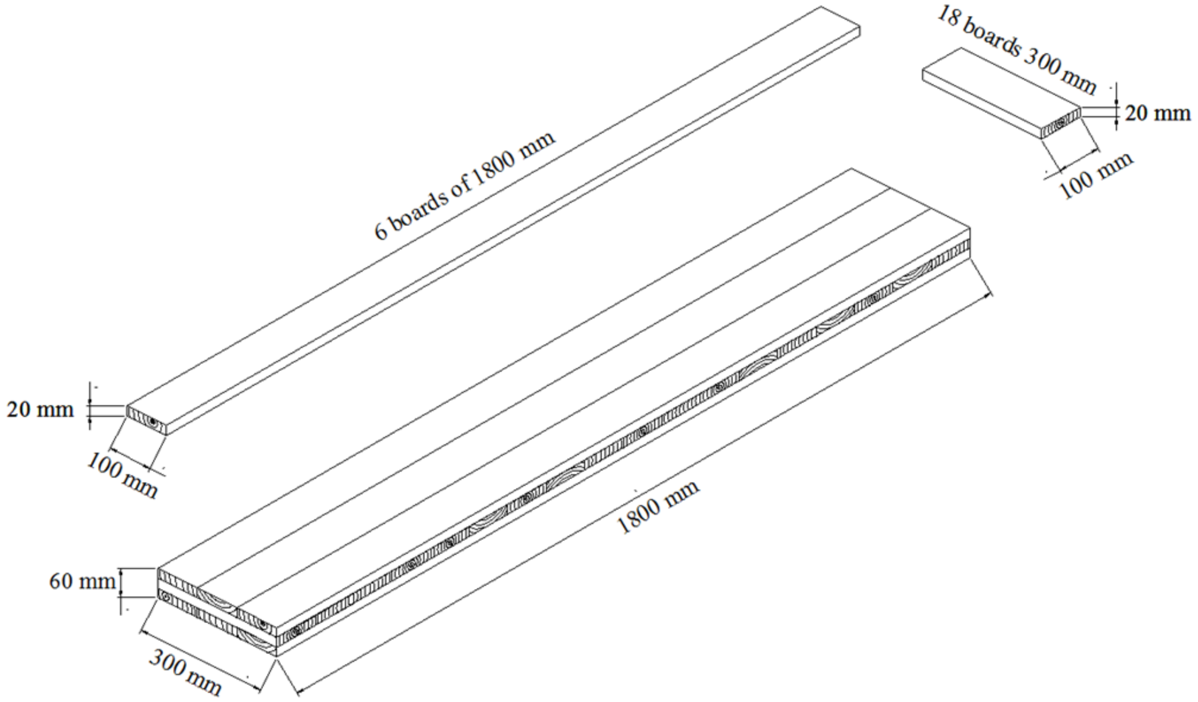


Figure 2-19: CLT panel design

Boards were planed to the final cross-section of 20 x 100 mm^2 less than 24 hours before CLT manufacturing. The adhesive used was Loctite HB S309 Purbond (Henkel, Düsseldorf, Germany) and a pressure of 0.4 N/mm^2 was applied for a period of five hours.

Twelve 3-layer CLT panels with dimensions 60 x 300 x 1800 mm^3 were manufactured (Figure 2-19). Four different CLT panel configurations were manufactured:

- Three panels from recovered timber (RRR)
- Three from recovered timber in the longitudinal layers and new timber in the cross layer (RNR)
- Three from new timber in the longitudinal layers and recovered timber in the cross layer (NRN)
- Three from new timber (NNN).

The timber yield was low, as large cross-section pieces were used for mass timber products manufactured. The initial piece cross-section was on average 146 x 164 mm^2 and the final board cross-section was 20x100 mm^2. While pieces are sawn in boards, around 50% of timber is wood waste (Figure 2-15). Furthermore, after selection of boards and planing, the final yield was around 15%. As large cross-section is the most commonly recovered timber in the south of Europe a direct reuse for rehabilitation works will be a more efficient use of the material (Llana et al. 2020).

2.3.4. Out-of-plane Bending Tests on CLT panels

Four-point bending tests with a span 24 times the panel thickness according to EN 16351 (2015) were made.

Apparatus:

- Universal testing machine: Load cell 200 kN (readability 0.01 kN) (Microtest S.A., Madrid, Spain)
- 2no. 10 mm LVDT's (Schreiber Meßtechnik GmbH, Oberhaching, Germany) with readability 0.001mm to measure local deflection (w_(l,0.4)) at the neutral axis. The frame mounting the local LVDT's were suspended from the CLT panels or glulam beam on hangers, each 150 mm from the central axis in the case of CLT and 250 mm from the central axis in the case of glulam. The local measurement assembly was de-mounted after the initial non-destructive loading (F_0.4)
- 1no. 60 mm LVDT (Schreiber Meßtechnik GmbH, Oberhaching, Germany) with readability 0.01mm to measure global deflection (w_(g,max)). It was supported independently of the test panel or beam and measured the deflection directly in the central point of the downface.
- Forced air drying oven DAF-635 (Raypa, Terrassa, Spain), for determination of MC and density from a slice free of knots and resin pockets obtained after mechanical testing.

2.3.5. CLT panel bending test results

Four-point bending tests were performed until panel failure (Figure 2-20) and results are shown in Table 2-3.

Table 2-3: Bending test of CLT panels

CLT panels		**MOEglo12**		**MOEloc12**		**Bending strength**		**DEN12**	
No.	**Kind**	**Mean (N/mm^2)**	**CV (%)**	**Mean (N/mm^2)**	**CV (%)**	**Mean (N/mm^2)**	**CV (%)**	**Mean (kg/m^3)**	**CV (%)**
UPM1	RRR	12650	-	12436	-	35.81	-	792	-
UPM2		12206	-	11177	-	53.72	-	745	-
UPM3		11464	-	11193	-	44.70	-	771	-
UPM 1 to 3	*RRR*	*12106*	*4.95*	*11602*	*6.23*	*44.74*	*20.02*	*769*	*3.06*
UPM4	RNR	12028	-	11952	-	42.62	-	776	-
UPM5		11788	-	13216	-	48.15	-	785	-
UPM6		12152	-	12097	-	48.69	-	755	-
UPM 4 to 6	*RNR*	*11989*	*1.54*	*12422*	*5.57*	*46.49*	*7.23*	*768*	*2.09*
UPM 1 to 6	**R_R**	**12048**	**3.33**	**12012**	**6.46**	**45.62**	**13.43**	**769**	**2.35**
UPM7	NRN	10711	-	10923	-	72.45	-	761	-
UPM8		12047	-	11818	-	71.10	-	746	-
UPM9		10784	-	11733	-	74.84	-	781	-
UPM 7 to 9	*NRN*	*11180*	*6.72*	*11491*	*4.30*	*72.80*	*2.60*	*761*	*2.48*
UPM10	NNN	11494	-	11892	-	76.66	-	709	-
UPM11		11491	-	12409	-	72.79	-	744	-
UPM12		12137	-	12432	-	72.59	-	741	-
UPM 10 to 12	*NNN*	*11707*	*3.18*	*12245*	*2.49*	*74.01*	*3.11*	*730*	*2.58*
UPM 7 to 12	**N_N**	**11444**	**5.28**	**11868**	**4.65**	**73.40**	**2.72**	**745**	**3.15**

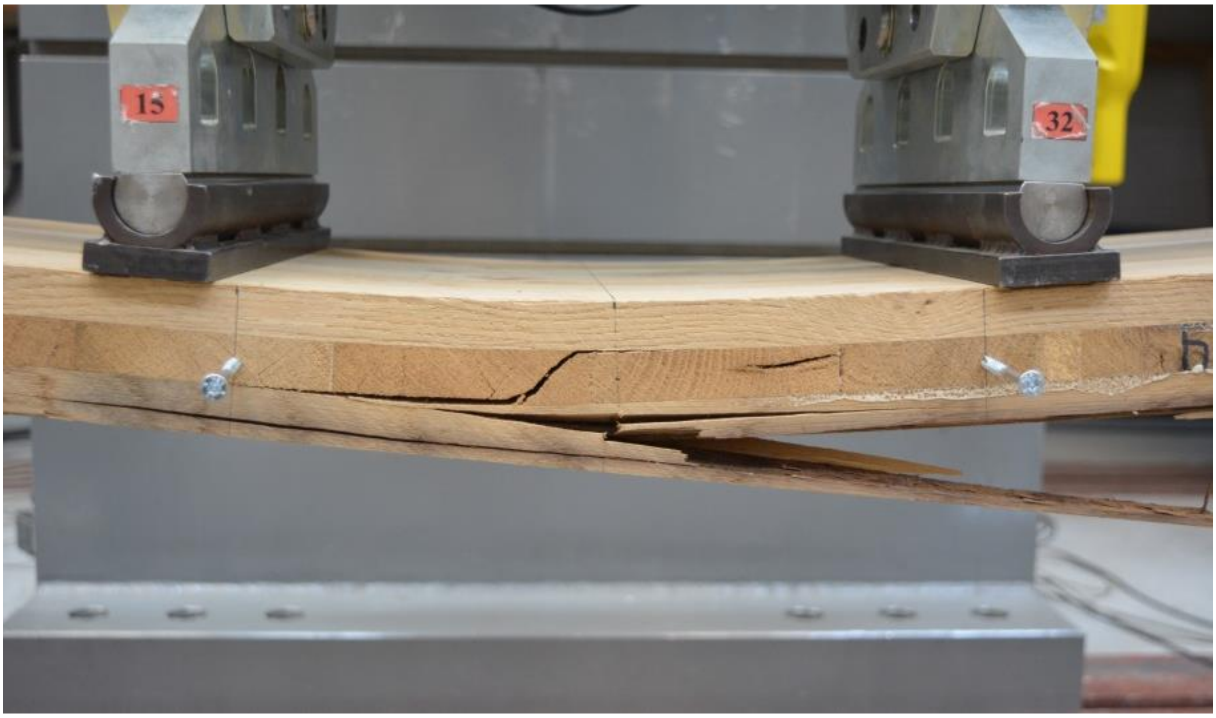


Figure 2-20: RRR CLT panel at failure under four-point bending at 52.20 kN

Results in Table 2-3 suggest that the mechanical properties are mainly affected by longitudinal layers as was also reported by Stenstad et al. (2021). Analyses of Variance were carried out for global modulus of elasticity (MOEglo12) and bending strength (MOR) (Figure 2-21 and Figure 2-22).

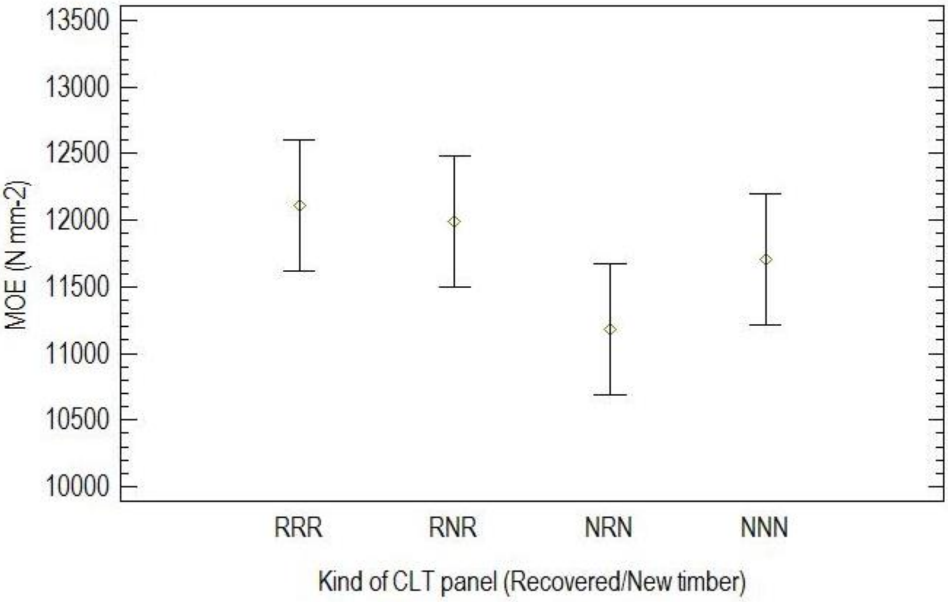


Figure 2-21: ANOVA mean test for CLT MOEglo12 (95% confidence level)

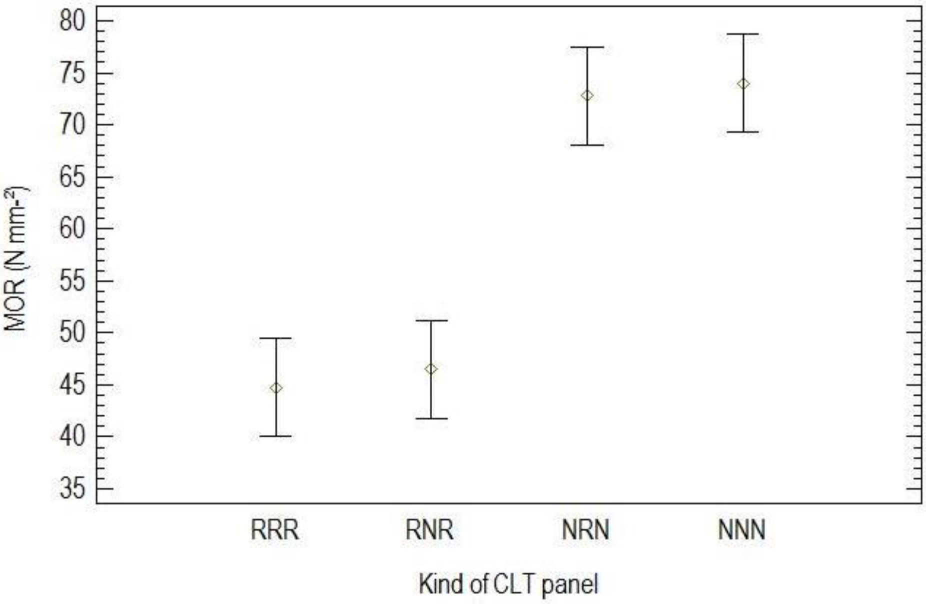


Figure 2-22: ANOVA mean test for CLT MOR (95% confidence level)

In the case of the MOE (Figure 2-21), no significant differences were found for the 95% confident level between the different kind of panels. In the case of MOR (Figure 2-22), significant differences were found between CLT panels manufactured with recovered and new timber in the longitudinal layers. Unchanged MOE and lower MOR in case of recovered vs new timber was also reported by Arbelaez et al. (2020) testing recovered Douglas-fir timber CLT panels. Although lower MORs were found in the case of panels using recovered timber in the longitudinal layers than in those using new timber, these lower values of MOR are more than enough (lowest individual value was 35.81 N/mm^2) for structural applications of these CLT panels (Llana *et al.,* 2022).

Note: the results, based on twelve CLT panels from recovered and new timber, require validation with a larger sample.

2.4. Investigation of GLT Production from Recovered Oak - Spain

Daniel F. Llana, Violeta González-Alegre, Guillermo Íñiguez-González

2.4.1. Recovered wood description, preparation and characterisation.

The recovered and new timber used for the manufacture of GLT beams is the same as that used for the CLT manufacture, described in Sections 2.3.1 and 2.3.2.

2.4.2. GLT beam design and manufacture

Based on the facilities for manufacturing and testing available, it was decided to manufacture and test twelve 5-lamellae GLT beams. Each GLT beam was 100 x 100 x 1900 mm^3 (Figure 2-23). From this calculation it was determined that a minimum of 30 boards of 1900 mm in length with a nominal cross section of at least 25 x 105 mm^2 were required.

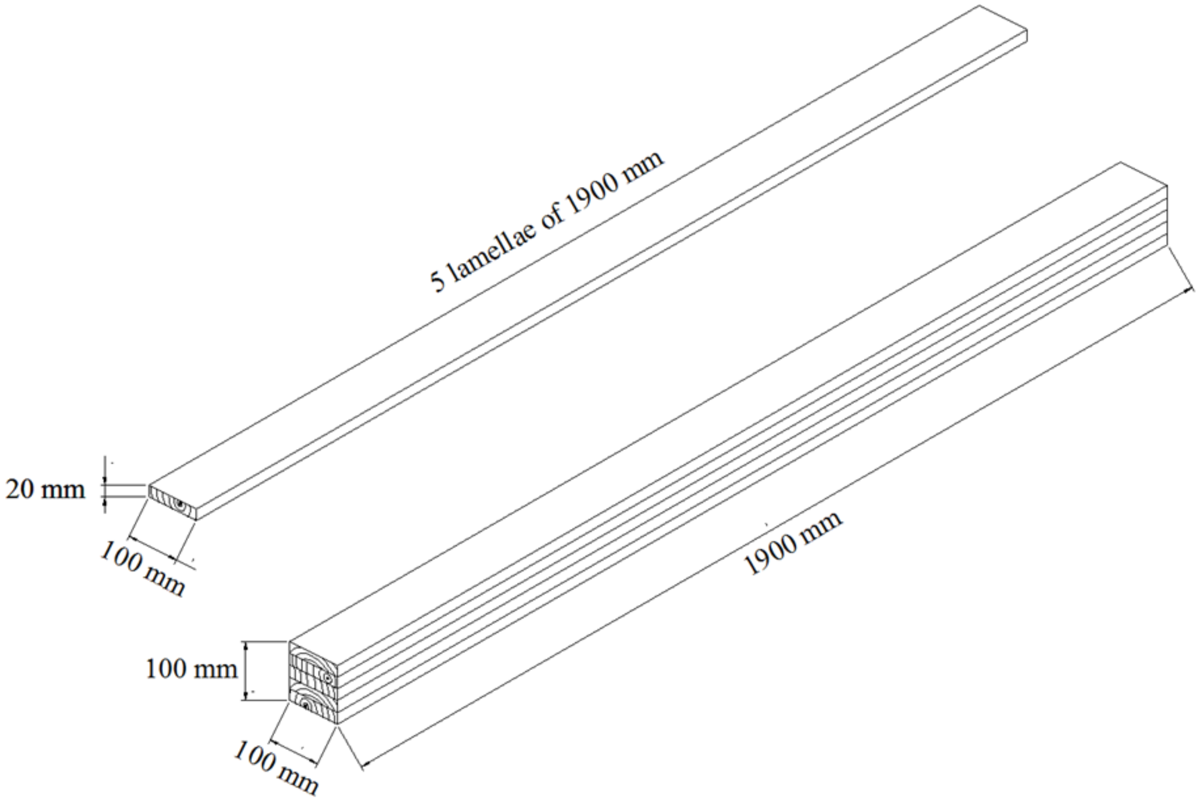


Figure 2-23: ***GLT beam design***

Boards were planed to the final cross-section of 20 x 100 mm^2 less than 24 hours before GLT manufacturing. The adhesive used was Loctite HB S309 Purbond (Henkel, Düsseldorf, Germany) and a pressure of 0.4 N/mm^2 was applied for five hours.

Twelve 5-lamellae glulam beams with dimensions 100 x 100 x 1900 mm^3 were manufactured (Figure 2-23). Two different GLT beam configurations were manufactured:

- Six from recovered timber (R)
- Six from new timber (N)

2.4.3. Out-of-plane Bending Tests on GLT beams

Four-point bending tests with a span of 18 times the GLT beam thickness according EN 408 (2012) were made. The apparatus used is described in Section 2.3.4.

2.4.4. GLT beams bending test results

Four-point bending test was performed until panel failure and results are shown in Table 2-4. The GLT beam VG6 testing failed and was not possible to obtain testing values.

Table 2-4**: **Bending test of GLT beams

Glulam beams		**MOEglo12**		**MOEloc12**		**Bending strength**		**DEN12**	
No.	**Kind**	**Mean (N/mm^2)**	**CV (%)**	**Mean (N/mm^2)**	**CV (%)**	**Mean (N/mm^2)**	**CV (%)**	**Mean (kg/m^3)**	**CV (%)**
VG1	R	10489	-	11516	-	37.54	-	738	-
VG2		11522	-	12947	-	36.85	-	745	-
VG3		11800	-	12185	-	36.19	-	815	-
VG4		10187	-	10303	-	48.10	-	750	-
VG5		11875	-	13707	-	31.87	-	800	-
VG6		failed	-	-	-	-	-	-	-
1 to 5	**R**	**11175**	**7.00**	**12132**	**10.81**	**38.11**	**15.76**	**770**	**4.59**
VG7	N	11189	-	11918	-	78.73	-	743	-
VG8		11276	-	11711	-	63.69	-	734	-
VG9		10650	-	10593	-	51.85	-	677	-
VG10		13457	-	14653	-	82.55	-	717	-
VG11		11960	-	12539	-	84.82	-	696	-
VG12		12129	-	12716	-	79.43	-	711	-
7 to 12	**N**	**11777**	**8.36**	**12355**	**10.95**	**73.51**	**17.61**	**713**	**3.40**

Analyses of Variance were carried out for global modulus of elasticity (MOEglo12) and bending strength (MOR) (Figure 2-24 and Figure 2-25).

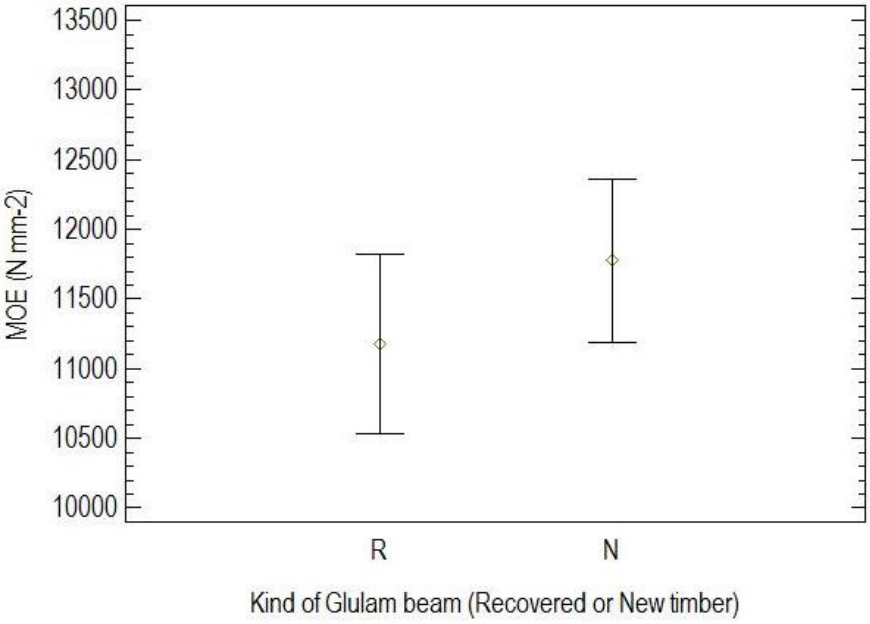


Figure 2-24: ANOVA mean test for GLT MOEglo12 (95% confidence level)

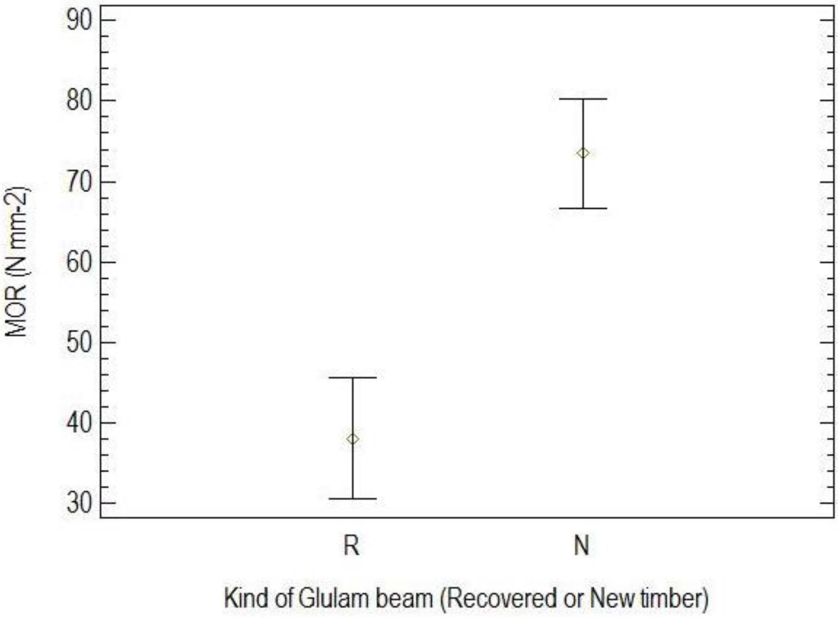


Figure 2-25: ANOVA mean test for GLT MOR (95% confidence level)

Similar to the CLT panel results for MOE (Figure 2-24), no significant differences were found for the 95% confident level between the different kind of GLT beams. In the case of MOR (Figure 2-25), significant differences were found between GLT beams manufactured with recovered and new timber. Although lower MORs were found in the case of GLT beams manufactured from recovered timber than in those manufactured from new timber, these lower values of MOR are high enough (lowest individual value was 31.87 N/mm^2) for structural applications of these GLT beams.

Note: the results, based on 11 GLT beams from recovered and new timber, require validation with a larger sample.

2.5. Investigation of IsoTimber panel production from recovered pine – Sweden

Carmen Cristescu, Karin Sandberg, Mitja Plos

2.5.1. Recovered wood description, preparation and characterisation

According to Henriksson (2021), the recovered spruce timber (*Picea Abies L.)* was collected from three buildings situated around Östersund, Sweden that were in the process of demolition during May 2021. The challenge was not only to find healthy used timber but also that the length should be at least 2400 mm.

The first source was a building dated as "over 100 years" in an estate register from 1939. The pieces of timber were taken from the floor of the house. A note written in pencil was found on one piece of timber, which contains the location, the name of the owner and the number '1881' that is assumed to be the year when the beam was marked, proving to be a good method of traceability (Figure 2-26).

Figure 2-26: To the left: Hand-note written on a piece of the floor: "Östbacken, Jonas Nilsson, 1881". To the right: recovered timber taken from the floor of the house to be prepared for reuse (photo by Mikael Östling, IsoTimber)

The second source of wood was sawmill that was built in 1898. The building was disassembled, moved and reassembled in 1927. It served as a sawmill until the 1970s. In 1995, parts of the building, such as roof trusses were again reused, for a carpentry workshop. According to Henriksson (2021) the timber from this source, which had been in use for 120 years, was easy to "clean off" (take away other materials) because it had large dimensions, and it had not been in direct contact with other materials. Only the ends (edges) of the beams had nails.

The third source of wood came from a timber storehouse (outdoor shelter) built in the 1960s. The wood came mostly from nailed pillars that supported the roof so it was in a covered outdoor environment. The timber dimensions ranged between 45-70 mm thickness, 120-200 mm width and 3000-5000 mm length. Unfortunately, it is difficult to date the unsorted timber parts, but it is estimated that they are 30–50 years old. (Henriksson 2021).

2.5.2. Selection and preparation of the boards

A first visual inspection was made to choose wooden boards that did not seem to be affected by moisture nor biological attack. All other materials and products were removed from the boards, such as nails and screws. A metal detector was used on all four sides of each of the timber pieces selected to ensure that the timber did not contain metal that would impede the sawing-to-size process. In the selection process, it was decided to eliminate parts of the boards where they presented the following defects: deep saw cuts from the deconstruction process, warp, and concrete stuck to the beam. After cleaning, the recovered timber was cut to the size needed to manufacture uprights for IsoTimber panels i.e. 2345 mm long and 88 mm wide.

2.5.3. Appearance grading of the boards

The selected boards were cut to size and were visually graded according to SS 230120 (2010) into four sorting classes (T0 to T3). The SS 230120 standard (Nordic grading rules – INSTA 142:2009) defines visual sorting classes for softwood construction timber from the North and Northeastern Europe, i.e. "NNE Europe" according to EN 1912 (2012). Only three features were chosen as criteria because of the time limit of the project. The features considered as the most relevant for mechanical properties according to the literature (Fröbel, 2019) were the number of single knots per edge and surface, corner knots and slope of grain. The four sorting classes T0, T1, T2, T3 of SS 230120 (2010) correspond to strength classes C14, C16, C24 to C30 of the EN 338 (2016).

2.5.4. Moisture content measurements

The moisture content was estimated using a moisture meter at 300 mm from the ends of the boards for all pieces according to EN 13183-2. The results ranged from 5.8 -14.9 %. None of the boards exceeded the MC limit timber to be used in construction timber, which is 18 % according to Bergkvist & Fröbel (2013).

2.5.5. Dynamic MOE measurement

The dynamic MOE (E_{dyn}) was measured using the software from the STIG machine developed by the University of Ljubljana and the Slovenian company ILKON. The STIG software records the vibration input (in this case sound from a microphone) and calculates the natural longitudinal vibration frequency using the fast Fourier transformation (FFT). From the first eigenfrequency (v) the dynamic MOE (E_{dyn}) is calculated using the equation (2.6):

$$E_{dyn} = (2Lv)^2\rho(1-0.005*(w-12))/(1-0.01*(w-12)) \qquad (2.6)$$

where ρ is the estimated density of the wood, L is the length of the piece measured and w is the moisture content. The density of wood was adjusted to 12 % MC.

The input data comprised the length, height, width, density and moisture content. The frequency was obtained by using a generic microphone connected to the computer where the STIG software was running. A generic hammer was used to strike the end of a beam. The microphone was placed 500 mm from the wood end at the same height as the piece of wood. The mean value of the dynamic MOE before sawing the air ducts was 9819 MPa and after sawing the air ducts it was 9719 MPa, as seen in Table 2-5.

Table 2-5 Results of strength grading, moisture content and MOE before and after sawing air ducts on 19 recovered timber specimens.

Nr	**Visual sorting class**	**Strength class**	**Moisture content (%)**	**MOE before sawing air ducts (N/mm²)**	**MOE after sawing air ducts (N/mm²)**	**Thickness (mm)**
1	T1	C18	13.0	10230	9760	62
2	T1	C18	5.8	10320	9720	45
3	T3	C30	6.4	10710	10810	52
4	T1	C18	10.2	9060	8620	52
5	T2	C24	11.5	10240	10040	52
6	T1	C18	6.7	9840	9660	52
7	T0	C14	8.7	9530	9030	52
8	T2	C24	9.5	9840	9430	52
9	T1	C18	12.6	7230	7040	52
10	T1	C18	11.7	11060	9990	45
11	T2	C24	11.1	7650	10710	45
12	T2	C24	14.9	10200	10570	45
13	T2	C24	12.3	9760	9450	52
14	T3	C30	6.0	6900	6000	52
15	T1	C18	10.0	8790	8580	52
16	T2	C24	8.4	10350	10610	52
17	T2	C24	10.2	11350	11190	50
18	T2	C24	6.0	10950	11020	50
19	T3	C30	12.0	12570	12440	50
Average			**9.4**	**9820**	**9720**	

Using intermediate posts with air ducts as components of a wooden panel is characteristic for the IsoTimber system and the manufacturer was interested to find out how the stiffness of the recovered wood posts was affected by the removal of the wooden material. Therefore, an analysis to compare the dynamic MOE results of boards before sawing and after sawing air ducts was performed. In Figure 2-27, the relation between the dynamic MOE measured before and after the sawing of the air ducts is plotted. If the orange marked outlier piece is excluded from the analysis, the coefficient of determination is $R^2 = 0.95$ and the linear regression formula is close to $E_{\mathrm{dyn,with}} = E_{\mathrm{dyn,without}} \times 1.1 - 1000$. (where $E_{\mathrm{dyn\ with}}$ represents boards with sawn air ducts and $E_{\mathrm{dyn\ with}}$ represents boards without air ducts, before these had been sawn).

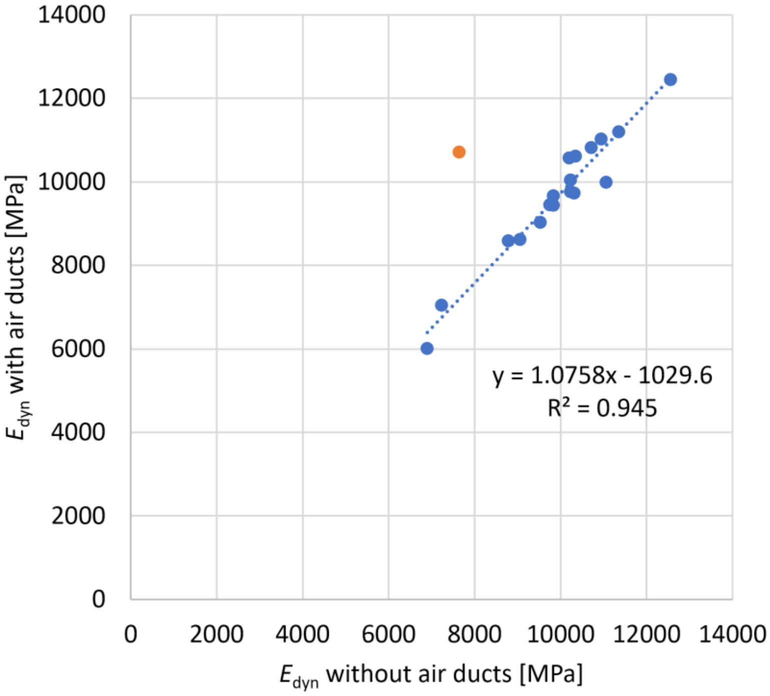


Figure 2-27: Comparison of Edyn with and without the sawn air ducts

2.5.6. Manufacturing new (standard) panel

The IsoTimber panel is made of a wooden frame and uprights (intermediate posts). Air ducts are sawn on both sides of the uprights (Figure 2-28), which are placed next to each other, and covered by plywood sheets glued on both sides. The species used is pine *Pinus Sylvestris L*. in the frame and the core while the plywood is made of spruce. The species used is pine *Pinus Sylvestris L*. in the frame and the core while the plywood is made of spruce. The plywood is glued to the frame using urea-formaldehyde resin. Fresh timber was used to industrially manufacture six standard panels (type S), according to IsoTimber (2021). The uprights had timber of strength class C14 (EN 338, 2016) with cross-section 45 mm x 88 mm. The size of the assembled panel was 2430 mm long, 1200 mm wide and 100mm thick.

Figure 2-28: Structure of an IsoTimber panel: frame, uprights, plywood

2.5.7. Manufacturing the panel from recovered wood

In the panel containing recovered timber, the frame was made from fresh pine timber strength class C14 while the uprights were all made from recovered wood. The air ducts were manually sawn. They were placed next to each other as in a standard industrially produced IsoTimber panel (Figure 2-29).

Figure 2-29 Manufacturing of an IsoTimber panel using recovered wood for the uprights (Henriksson 2021).

2.5.8. Testing standard panels and the panel made from recovered wood

The compression tests were performed at RISE Skellefteå. Panels were place horizontally, on the test beam, Figure 2-30. A uniform load was applied longitudinally, using a hydraulic cylinder and steel loading beams, with movable fastening on the pressure side and rigid fastening on the support side. The loading rate was 4 mm/min.

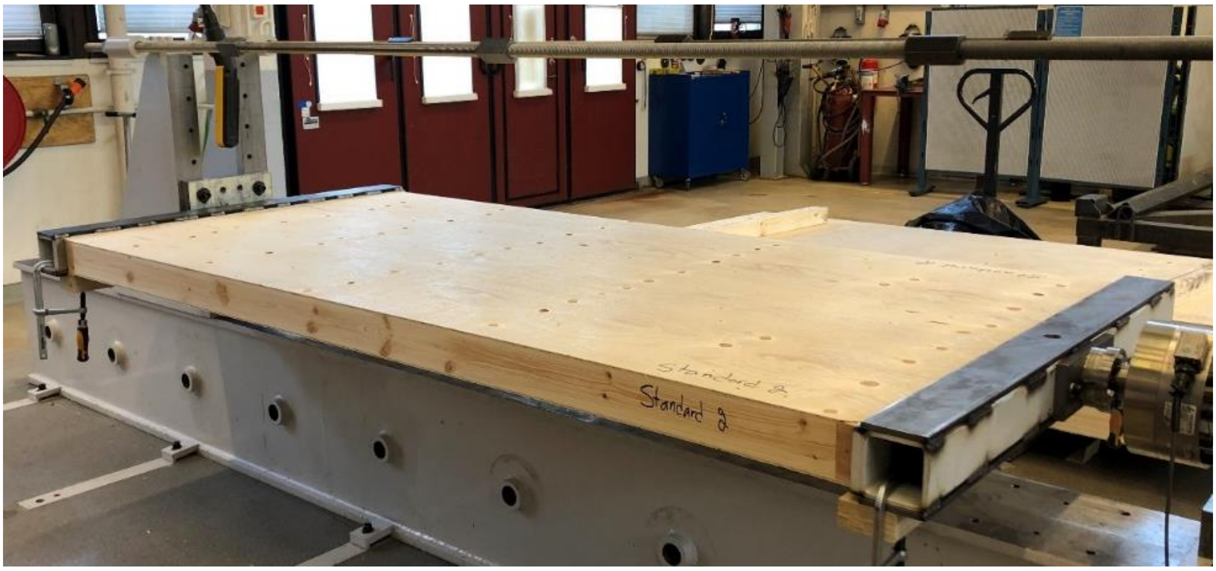


***Figure 2-30. Test setup: an IsoTimber board under longitudinal compression (photo by Urban Häggström, RISE*)**

As it was the first time that commercial IsoTimber panels were tested with a longitudinal compression force, the breaking force value was not known. It was estimated by the manufacturer IsoTimber as being under 400 kN. For all boards in the experiment, the test stopped when the applied load reached 400 kN because of a limitation in test setup (Figure 2-31). For the six standard panels (S1-S6), the plywood sheets cracked at the ends at the support at a compression force ranging from 150 – 220 kN. No other evidence of failure was noticed in the panels.

The R-panel that contained reclaimed timber as uprights was tested twice. The first time, testing was interrupted at 200 kN and no visible damage was present. The second time, when the R-panel was tested up to 400 kN, the plywood boards were cracked at the ends at a compression force of 220 kN. No damage was visible in the rest of the panel. Above about 270 kN, there is a noticeable reduction in the stiffness of this panel as seen in Figure 2-31.

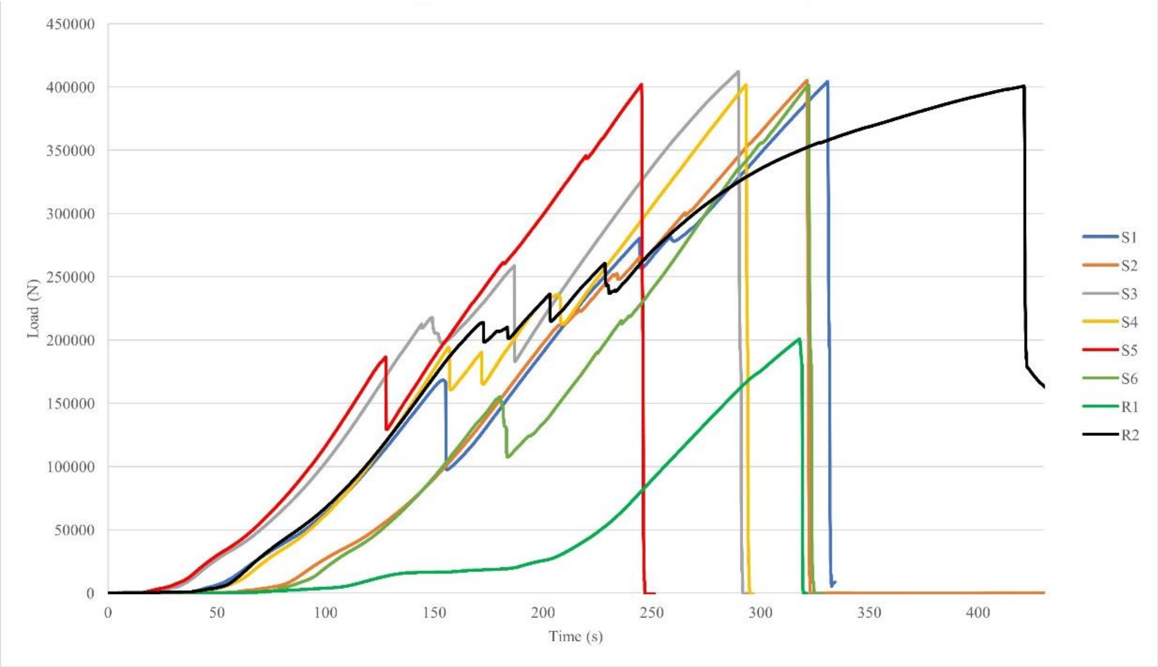


Figure 2-31 Compression test results. S - standard panels (6 specimens), R - reclaimed timber in the core (1 specimen). R1 is pretest of the reclaimed panel up to 200 kN; R2 is retest of same panel up to 400 kN.

2.6. Conclusions of Mass Timber Study

Mass timber products from recovered and new timber were manufactured, tested and the relative performance assessed.

In the Irish study, spruce boards were recovered from a roof structure that had been under load for about 45 years and subject to high relative humidity in its later years. Three-layer CLT panels from this material were manufactured in a local joinery together with similar panels made with new Douglas fir boards having the same range of dynamic MOE values. As it is often difficult to recover long lengths of timber, hybrid panels were also manufactured using new timber for the longitudinal layers and recovered timber for the shorter cross layers. Three replicates of each design were tested in bending. The study found no difference in the mean bending MOE between the three designs, which ranged between 10340 and 10870 N/mm^2. The bending strength of the recovered and new panels was also the same with the hybrid panels slightly lower. The mean bending strength values ranged between 42 and 50 N/mm^2. An additional sample of hybrid panels was manufactured from boards with a lower mean dynamic MOE and this resulted in panels with correspondingly lower mechanical properties. Overall, the study has shown no difference in the performance of CLT manufactured from recovered and new softwood timber.

In the Spanish study, CLT panels and GLT beams were manufactured from recovered and new oak specimens. The recovered material was quite different to the Irish study. In this case, the specimens were about 150-200 years old and were of large cross-section, which were cut into several smaller pieces to manufacture the mass timber products. Three-layer CLT panels were manufactured with recovered timber, new timber, hybrid with new outer layers and recovered timber core and hybrid with recovered timber outer layers and new timber core. Results show that the MOE remains unchanged when testing CLT panels manufactured from new or recovered timber. However, in the case of bending strength, while lower values were obtained in recovered timber longitudinal-layer panels, these values are high enough for structural applications. Similar findings were obtained in the GLT study. For five-layer GLT beams made from recovered oak and from new oak, the MOE remains the same, while the bending strength was lower for beams manufactured from recovered oak. The values were high enough for structural applications.

It can be concluded from these two studies that the mechanical performance of mass timber products from recovered softwood and hardwoods is comparable to those of similar products made with new timber and both are suitable for structural applications. It should be borne in mind that the number of specimens tested in both cases was small and validation of these findings on a larger sample size is recommended.

Regarding the yield from the recovered timber, in the case of the Irish mass timber products 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. The commercial availability of a wider range of recovered wood sizes will be necessary to make this possible. In the case of Spanish mass timber products, the yield was really low (around 15%) as the recovered timber was of large cross-section (146 x 64 mm^2) and pieces were sawn to final boards and lamellae (20 x 100 mm^2) generating much wood waste.

In terms of yield, mass timber products are a good option for recycling medium cross-section recovered timber (e.g. joist and roof rafters). However, for large cross-sections, direct reuse for rehabilitation works will be a more efficient use of the material.

In the Swedish study, the IsoTimber panel with reclaimed timber as material for uprights showed a similar capacity to resist compression loads up to 400 kN as the panels manufactured using new timber. However, there was a significant stiffness reduction above 270 kN compared with panels with new timber.

As only one panel was manufactured from recovered wood, it is not possible for draw firm conclusions but the following lessons were learnt that will be useful for the company IsoTimber, which intends to use recovered wood in its manufacturing process and to undertake further comparative studies of new and reclaimed wood used as component of a structural elements:

- It is important to perform measurements of density, MC, non-destructive MOE measurements not only on the recovered timber but also on the fresh timber as well. Selecting samples of similar characteristics in both groups could also contribute to better understanding the differences in behaviour when the panels of recovered and fresh timber are subjected to an identical load.
- When IsoTimber panels are assembled in wall elements of a building they are subjected not only to vertical loads but also to lateral loads and therefore lateral load tests would also need to be carried out.

3. Adhesive Bonding Integrity in Engineered Wood Products Manufactured using Recovered Timber

Caitríona Uí Chúláin, Daniel F. Llana, Violeta González-Alegre, Guillermo Íñiguez-González, Marlene Cramer, Daniel-Ridley Ellis, Annette M. Harte

3.1. Introduction

The structural performance of engineered wood products depends on the integrity of the bonding between the elements. To investigate the performance of adhesive bonding between recovered timber substrates in engineered wood products, studies were carried out in Ireland, Spain and the UK. These studies investigated bonding in CLT and GLT elements manufactured from recovered timber in addition to equivalent elements manufactured with new timber and hybrid elements using a combination of new and recovered timber.

The studies examined the following:

- Irish study: Adhesives bonding in 3-layer CLT panels manufactured from recovered softwood, new softwood and hybrid panels with mixed new and recovered softwood
- Spanish study: Adhesive bonding in 3-layer CLT panels and 5-layer GLT beams manufactured from recovered hardwood, new hardwood and hybrid elements with mixed new and recovered hardwood
- UK study: Adhesive bonding in 5-layer and 6-layer GLT beams from recovered softwood.

3.2. Adhesive bond testing of CLT specimens from recovered softwoods: Irish study

Caitríona Uí Chúláin, Daniel F. Llana, Annette M. Harte

This experimental study aims to assess the bond strength of the glue lines between the crosswise layers of 3-ply CLT panels manufactured using recovered timber and new timber as detailed in Section 2.2 of this report. The panels used were those manufactured using (i) recovered timber in all layers, (ii) new timber in all layers, and (iii) new timber in the outer layers and recovered timber in the core layer, which were tested in bending as described in Chapter 2. The test programme involved the determination of the bond strength of the glue lines between the crosswise layers of specimens extracted from each panel using the delamination test and shear test in accordance with EN 16351 (2015). Two samples were taken from each of the 12 panels for each type of test.

3.2.1. Materials and methods

Materials:

The raw materials and manufacturing of the CLT panels from which the specimens were extracted for this study are detailed in Section 2.1 of this report.

Test procedures:

This test programme comprised the determination of the bond strength of the glue lines between the crosswise layers of the three-ply CLT panels using the delamination test and the shear test outlined in EN 16351 (2015) Annex C and D, respectively. Two samples were cut from each of the 12 panels for each type of test. In all, 48 specimens were tested, and both glue lines in each specimen were assessed. This report will present 95 bond strength test results. The panels had been tested to failure in bending prior to the glue line bond strength tests (see Section 2.2). The specimen locations did not coincide with the support and loading positions, or any broken timber.

Delamination tests:

For the delamination tests, two specimens of nominal size 100 x 100 x 60 mm^3 were cut from each of the 12 panels. The specimens were taken from different positions in each panel to ensure a random sample set. The specimens were stored in a conditioning chamber with a relative humidity of 65 ± 5 % and temperature 20 ° ± 2 °C for at least two weeks prior to testing. The samples were sanded to provide an adequate end grain surface quality to measure accurately the delamination length after the wetting and drying of the specimens. The initial mass of each specimen was recorded.

To examine any potential glue line delamination, the specimens were immersed in water between 10 °C and 20 °C and a 70 kPa vacuum was applied for 30 minutes. Then followed the application of 550 kPa pressure on the immersed samples for 2 hours. The specimens were then dried at 75 °C until their mass was between 100% and 110 % of their initial values. The maximum and total delamination lengths were measured within an hour of drying. Both the total delamination (D_{tot}) and maximum delamination (D_{max}) in the glue lines were recorded as percentages. Their values were calculated using Equations (3.1) and (3.2), respectively.

$$D_{tot} = 100 \times \left(l_{tot,delam} / l_{tot,glue\ line} \right) \tag{3.1}$$

where $l_{tot,delam}$ is the total delamination length and $l_{tot,glue\ line}$ is the sum of the perimeters of all the glue lines in the specimen.

$$D_{max} = 100 \times \left(l_{max,delam} / l_{glue\ line} \right) \tag{3.2}$$

where $l_{max,delam}$ is the maximum delamination length in one glue line perimeter, $l_{glue\ line}$.

Shear tests:

For the shear tests, two 50 x 50 x 60 mm^3 specimens were cut from each of the 12 panels at different positions in the panel to ensure a random sample set. The specimens were stored in a conditioning chamber with a relative humidity of 65 ± 5 % and temperature 20 ° ± 2 °C for at least two weeks prior to testing. They were then placed in the shearing tool so that a vertical load was applied in the direction of the wood grain on one side of the glue line and perpendicular to the grain on the other side of the glue line. The load was applied at a constant rate of 2.8 mm/min. with data recorded at a rate of 32 Hz. The load rate was calculated such that failure occurred after no less than 20 seconds. Both glue lines in each specimen were tested in shear. The shear strength (f_v in N/mm^2) was calculated using Equation (3.3).

$$f_v = k\, F_u / A \tag{3.3}$$

where F_u (in N) is the ultimate load, A (in mm^2) is the sheared area and the factor $k = 0.78 + 0.004\, t$ modifies the shear strength for test pieces where the length in the grain direction of the sheared area is less than 50 mm. t is the thickness of the specimen in mm. The characteristic shear strength value $f_{v,k}$ (N/mm^2) for each type of panel was calculated in accordance with EN 14358 (2016). Figure 3-1 shows the delamination and shear tests in progress. (While both the local and global displacement was measured for each shear test, these values are not reported here.)

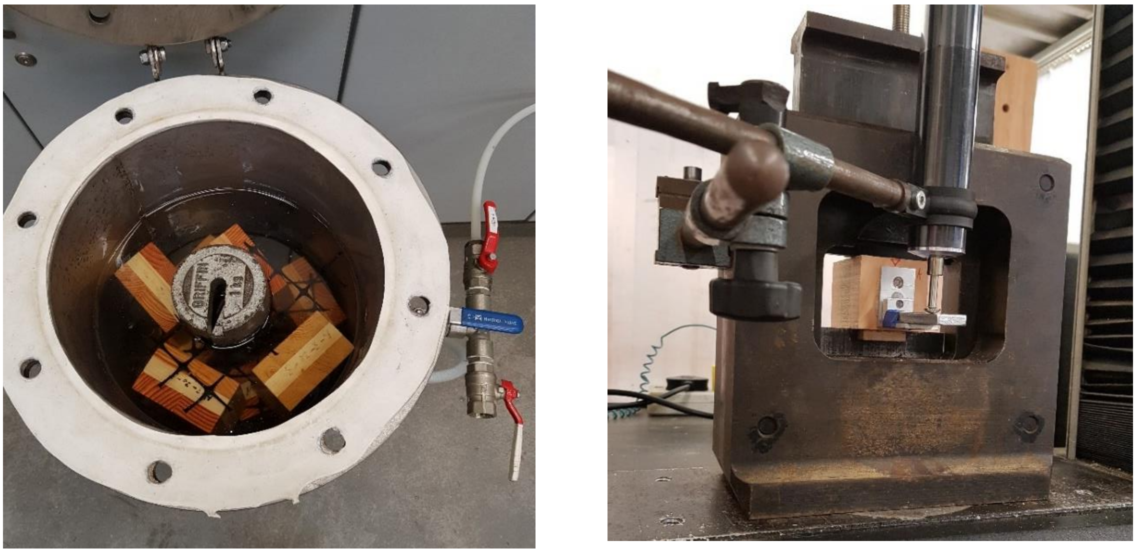


Figure 3-1: ***Delamination testing (left) and shear testing (right) at NUI Galway***

Data analysis:

A pass/fail evaluation was conducted on the delamination test results. According to the requirements of EN 16351 (2015), D_{max} should not exceed 40 % of the perimeter of a single glue line and D_{tot} should not exceed 10 % of the sum of all the glue lines. Where the delamination limits were not met, the glue lines were split, and the wood failure percentage (WFP) was assessed. To pass, the minimum WFP for a single glue area should not be less than 50 % and the minimum WFP of the sum of all the split areas of the specimen should not be less than 70 %. A pass/fail evaluation was conducted also for the shear test results according to the requirements of EN 16351 (2015) where the bond strength is deemed to be sufficient when the shear strength f_v of each glue line is at least 1 N/mm^2 and the characteristic shear strength $f_{v,k}$ of the sample tested is greater than 1.25 N/mm^2.

3.2.2. Results and discussion

<u>Delamination tests</u>:

The bond strength of the glue lines between the cross layers of the three-ply CLT panels were determined by delamination test in accordance with EN 16351 (2015) Annex C.

Table 3-1 presents the test results for specimens extracted from 3-layer CLT panels made with recovered spruce.

Table 3-1: Delamination test results of glue lines of CLT panels made with recovered timber

Panel	Specimen #	Glue line	$l_{glueline}$	$l_{max,delam}$		D_{max}	$l_{tot,glueline}$	$l_{tot,delam}$		D_{tot}
			(mm)	(mm)	(%)	≤ 40 %	(mm)	(mm)	%	≤ 10 %
R-3-20-1	1	A	398	62	15	Pass	796	161	20	Fail
		B	398	99	25	Pass				
	2	A	390	0	0	Pass	797	0	0	Pass
		B	398	0	0	Pass				
R-3-20-2	1	A	401	0	0	Pass	802	31	4	Pass
		B	401	31	8	Pass				
	2	A	399	0	0	Pass	799	0	0	Pass
		B	399	0	0	Pass				
R-3-20-3	1	A	400	0	0	Pass	799	13	2	Pass
		B	399	13	3	Pass				
	2	A	400	0	0	Pass	797	186	23	Fail
		B	397	99	25	Pass				

All specimens passed the individual glue line check. Four of the six specimen passed the total delamination tests. As the total delamination exceeded 10 % of the total glue line perimeter in two specimens (R-3-20-1_1 and R-3-20-3_2), these specimens were then subjected to a second stage testing to determine the wood failure percentage measured in accordance with EN 16351 (2015), Clause C.4.2.4. The glue lines in these specimens were split using a metal wedge and hammer and the minimum wood-failure percentage of each split glued area was measured. The wood failure results for these two specimens are presented in Table 3-2.

Table 3-2.: Wood failure percentage of glue lines of CLT panels made with recovered spruce (R-3-20-1 and R-3-20-3)

Panel	**Specimen #**	**Glue line**	**Surface area**	**Wood failure area**		**Min. wood failure %**	**Min. wood failure sum %**
			(mm^2)	**(mm^2)**	**(%)**	**≥ 50 %**	**≥ 70 %**
R-3-20-1	1	A	9920	6420	65	Pass	Pass
		B	9918	9918	100	Pass	
R-3-20-3	2	A	9990	9990	100	Pass	Pass
		B	9909	5410	55	Pass	

All glue lines passed the second stage testing as the wood failure percentages were in all cases above the minimum thresholds. From the results presented in

Table 3-1 and Table 3-2, it can be concluded that all CLT specimens manufactured with recovered spruce met the quality requirements for CLT with respect to delamination set out in EN 16351 (2015).

The CLT panels from new timber boards were manufactured using the same adhesive and pressing protocol as those from recovered timber. The bond strength delamination test results of the panels made with new timber are shown in Table 3-3.

Table 3-3: Delamination test results of glue lines of CLT panels made with new timber

Panel	Specimen #	Glue line	$l_{glueline}$	$l_{max,delam}$		D_{max}	$l_{tot,glueline}$	$l_{tot,delam}$		D_{tot}
			(mm)	(mm)	(%)	≤ 40 %	(mm)	(mm)	%	≤ 10 %
N-3-20-1	1	A	401	21	5	Pass	803	99	12	Fail
		B	401	61	15	Pass				
	2	A	401	0	0	Pass	801	98	12	Fail
		B	400	77	19	Pass				
N-3-20-2	1	A	401	0	23	Pass	801	142	18	Fail
		B	401	94	0	Pass				
	2	A	400	0	0	Pass	799	0	0	Pass
		B	400	0	0	Pass				
N-3-20-3	1	A	399	0	0	Pass	797	0	0	Pass
		B	398	0	0	Pass				
	2	A	398	0	0	Pass	796	0	0	Pass
		B	398	0	0	Pass				

All specimens manufactured with new timber passed the individual glue line check. However, only three of the six specimens passed the delamination tests. As the total delamination exceeded 10 % of the total glue line perimeter in specimens N-3-20-1_1, N-3-20_2 and N-3-20-2_1, the glue lines of these specimens were split using a metal wedge and hammer and the minimum wood-failure percentage of each split glued area was measured in accordance with C.4.2.4 of EN 16351 (2015). The wood failure results are given in Table 3-4.

Table 3-4: Wood failure percentage of glue lines CLT panels made with new timber)

Panel	Specimen #	Glue line	Surface area	Wood failure area		Min. wood failure %	Min. wood failure sum %
			(mm^2)	(mm^2)	(%)	≥ 50 %	≥ 70 %
N-3-20-1	1	A	10100	3750	37	Fail	Pass
		B	10130	10130	100	Pass	
	2	A	10070	10070	100	Pass	Pass
		B	10060	2985	30	Fail	
N-3-20-2	1	A	10060	2610	26	Fail	Pass
		B	10500	10500	100	Pass	

As seen in Table 3-4, each of the three split specimens had one passing glue line with 100% wood failure and one failing glue line, with wood failure less than 50%. However, all specimens exceeded the minimum wood failure sum of 70%.

The bond strength delamination tests on specimens from the hybrid CLT panels made with outer layers of new timber and a recovered timber core are shown in Table 3-5.

Table 3-5: Delamination test results of glue lines of hybrid CLT panels

Panel	**Specimen #**	**Glue line**	$l_{glueline}$	$l_{max,delam}$	D_{max}		$l_{tot,glueline}$	$l_{tot,delam}$	D_{tot}	
			(mm)	**(mm)**	**(%)**	**≤ 40 %**	**(mm)**	**(mm)**	**%**	**≤ 10 %**
H-3-20-1	1	A	402	59	15	Pass	804	76	9	Pass
		B	402	0	0	Pass				
	2	A	402	62	15	Pass	803	119	15	Fail
		B	401	58	14	Pass				
H-3-20-2	1	A	400	65	16	Pass	800	72	9	Pass
		B	400	0	0	Pass				
	2	A	400	31	8	Pass	799	31	4	Pass
		B	399	0	0	Pass				
H-3-20-3	1	A	399	0	0	Pass	798	0	0	Pass
		B	399	0	0	Pass				
	2	A	398	0	0	Pass	797	0	0	Pass
		B	399	0	0	Pass				
H-3-20-4	1	A	400	8	2	Pass	801	61	8	Pass
		B	400	53	13	Pass				
	2	A	401	0	0	Pass	801	45	6	Pass
		B	400	45	11	Pass				
H-3-20-5	1	A	402	73	18	Pass	802	73	9	Pass
		B	400	0	0	Pass				
	2	A	401	0	0	Pass	801	0	0	Pass
		B	401	0	0	Pass				
H-3-20-6	1	A	400	0	0	Pass	799	8	1	Pass
		B	400	8	2	Pass				
	2	A	399	25	6	Pass	798	45	6	Pass

		B	399	0	0	Pass

For the hybrid panels, 11 of the 12 specimens passed the initial delamination test. As the total delamination exceeded 10% of the total glue line perimeter for H-3-20-1 Specimen 2, the wood-failure percentage was measured for this specimen. The hybrid wood failure results are shown in Table 3-6. The glue lines in the specimen pass all the requirements of the standard.

Table 3-6: Wood failure percentage of split glued area of the hybrid CLT panel (H-3-20-1)

Panel	Specimen #	Glue line	Surface area	Wood failure area		Min. wood failure %	Min. wood failure sum %
			(mm^2)	(mm^2)	(%)	≥ 50 %	≥ 70 %
H-3-20-1	2	A	10090	8340	83	Pass	Pass
		B	10070	7495	74	Pass	

<u>Shear strength tests:</u>

Two specimens were extracted from each of the 12 CLT panels for shear testing. The bond strength of each of the glue lines between the cross layers of each specimen was determined by shear testing in accordance with EN 16351 (2015) Annex D and the characteristic value for each sample was determined in accordance with EN 14358 (2016). Table 3-7, Table 3-8 and Table 3-9 present the results of the shear tests on glue lines from CLT panels made with recovered timber, new timber, and mixed new and recovered timber, respectively. Glue line B of the test specimen R-3-20-1_2 was damaged during testing so no result is presented.

Table 3-7: Shear test results of glue lines specimens with recovered timber

Panel	Specimen #	Specimen dimensions			MC	Density ρ	Glue line	Shear strength f_v	Check
		h (mm)	d (mm)	t (mm)	(%)	(kg/m^3)		(N/mm^2)	($f_v \geq 1$ N/mm^2)
R-3-20-1	1	51	50	60	11	423	A	5.92	Pass
							B	4.13	Pass
	2	51	51	60	11	416	A	5.40	Pass
							B	-	-
R-3-20-2	1	50	50	60	11	394	A	3.57	Pass
							B	3.28	Pass
	2	50	50	60	11	382	A	4.02	Pass
							B	5.15	Pass
R-3-20-3	1	50	49	60	11	381	A	4.42	Pass
							B	3.45	Pass
	2	51	50	60	11	397	A	5.80	Pass
							B	5.87	Pass
Characteristic strength value $f_{v,k}$ (≥ 1.25 N/mm^2)								**2.43**	**PASS**

Table 3-8: Shear test results of glue lines of specimens with new timber

Panel type	**Specimen #**	**Specimen dimensions**			**MC**	**Density ρ**	**Glue line**	**Shear strength f_v**	**Check**
		h (mm)	**d (mm)**	**t (mm)**	**(%)**	**(kg/m^3)**		**(N/mm^2)**	**(f_v ≥ 1 N/mm^2)**
N-3-20-1	1		50	61	11	460	A	5.65	Pass
							B	4.60	Pass
	2	50	50	61	11	453	A	5.32	Pass
							B	4.65	Pass
N-3-20-2	1	50	50	61	11	528	A	6.99	Pass
							B	6.18	Pass
	2	50	50	61	11	460	A	7.77	Pass
							B	6.21	Pass
N-3-20-3	1	50	50	61	11	488	A	5.03	Pass
							B	6.66	Pass
	2	50	50	61	11	479	A	6.98	Pass
							B	7.62	Pass
Characteristic strength value $f_{v,k}$ (≥ 1.25 N/mm^2)								**3.82**	**PASS**

Table 3-9: Shear test results of glue lines of hybrid specimens

Panel type	Specimen #	Specimen dimensions			MC	Density ρ	Glue line	Shear strength f_v	Check
		h (mm)	d (mm)	t (mm)	(%)	(kg/m^3)		(N/mm^2)	(f_v ≥ 1 N/mm^2)
H-3-20-1	1	50	50	61	11	450	A	6.64	Pass
							B	6.01	Pass
	2	50	49	61	11	448	A	6.43	Pass
							B	5.78	Pass
H-3-20-2	1	50	49	61	11	462	A	5.13	Pass
							B	3.99	Pass
	2	50	50	60	11	472	A	5.90	Pass
							B	5.34	Pass
H-3-20-3	1	50	50	60	11	415	A	5.58	Pass
							B	6.50	Pass
	2	50	49	60	11	400	A	3.79	Pass
							B	4.30	Pass
H-3-20-4	1	50	50	58	11	428	A	3.03	Pass
							B	3.38	Pass
	2	50	50	59	11	428	A	4.28	Pass
							B	3.11	Pass
H-3-20-5	1	50	50	59	11	448	A	4.78	Pass
							B	5.73	Pass
	2	50	50	59	11	462	A	7.97	Pass
							B	4.47	Pass
H-3-20-6	1	49	50	59	11	525	A	5.48	Pass
							B	6.22	Pass
	2	50	50	59	11	451	A	3.81	Pass

	B	3.82	Pass
Characteristic strength value $f_{v,k}$ (≥ 1.25 N/mm^2)		**2.38**	**PASS**

For the specimens from recovered timber, the shear strength of the individual glue lines varied between 3.28 N/mm^2 and 5.92 N/mm^2, which are well in excess of the minimum requirement of 1 N/mm^2. The characteristic shear strength of this sample was 2.43 N/mm^2 , which is almost double the minimum requirement of 1.25 N/mm^2 specified in EN 16351 (2015).

For the specimens from new timber, the shear strength of the individual glue lines varied between 4.60 N/mm^2 and 7.77 N/mm^2, which are well in excess of the minimum requirement of 1 N/mm^2. Of particular note is the fact that the shear strength of specimens taken from the panels, which failed to meet the required minimum wood failure percentage, are more than satisfactory. This would seem to indicate that the poor performance was localised and may be due to uneven application of the adhesive during manufacturing. The characteristic shear strength of this sample was 3.82 N/mm^2, which is more than three times the minimum requirement of 1.25 N/mm^2 specified in EN 16351 (2015).

Finally, for the specimens from the hybrid panel manufactured from new and recovered timber, the shear strength of the individual glue lines varied between 3.03 N/mm^2 and 7.97 N/mm^2, which are well in excess of the minimum requirement of 1 N/mm^2. The characteristic shear strength of this sample was 2.38 N/mm^2, which is almost two times the minimum requirement of 1.25 N/mm^2 specified in EN 16351 (2015).

The shear strength values for the three series are show in the box plots in Figure 3-2. This figure shows that the shear strength of the new timber specimens is likely to be different from the recovered or hybrid specimens with higher median strength. Nevertheless, all are well in excess of the code requirements for CLT.

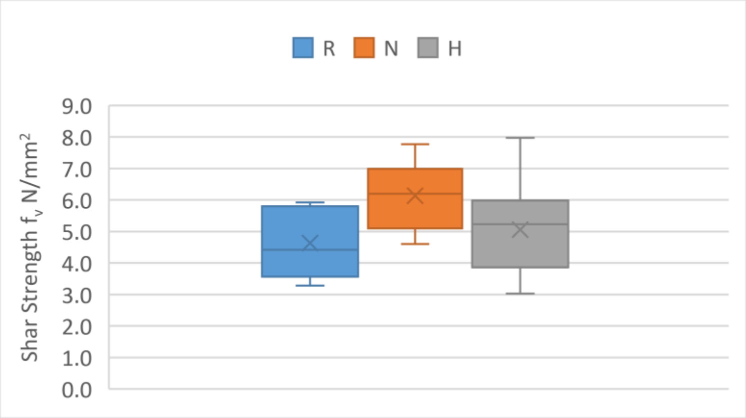


Figure 3-2: Box plot of shear strength values for recovered timber (R), new timber (N) and hybrid timber (H) specimens

3.2.3. Conclusions of Irish study

Based on the test series that measured delamination and shear strength, the following conclusions are drawn:

- The specimens from the CLT panels manufactured with recovered timber and the hybrid CLT panels made with new timber outer layers and recovered timber in the cross layer satisfied all the requirements of the CLT product standard EN 16351 (2015) with respect to delamination and shear strength.
- Of the specimens manufactured with new timber, three failed to satisfy the delamination test requirements. However, all displayed high values of shear strength well in excess of the minimum requirements.
- The shear strength values of the specimens from new timber are higher than those from the recovered or hybrid specimens.
- The results of the test series show that designers can be as confident in the use of recovered timber as with new timber with respect to the bond strength of CLT panels.

3.3. Adhesive bond testing of GLT and CLT specimens from recovered hardwoods: Spanish study

Daniel F. Llana, Violeta González-Alegre, Guillermo Íñiguez-González

This experimental study aims to assess the bond integrity of the glue lines in CLT and GLT specimens manufactured using recovered oak and new oak.

Delamination tests were carried out on specimens extracted from CLT panels and from GLT beams tested as described in Sections 2.3 and 2.4. Shear bond tests were carried out on the GLT specimens.

3.3.1. Materials and Methods

Materials:

Specimens for this study were extracted from CLT panels and from GLT beams tested as described in Sections 2.3 and 2.4.

Methods:

Delamination tests

In the case of CLT panels, delamination tests were carried out according to Annex C and evaluated according to Clause 5.2.5.4.2 in the standard EN 16351 (2015). In the case of GLT beams, delamination tests were carried out according to Annex C, Method B and evaluated according to Table 9 in Clause 5.5.5.2.2 in the standard EN 14080 (2013) (Figure 3-3). Two specimens from each CTL panel with dimensions 100 x 100 mm^2 were tested. Two specimens from each GLT beam with thickness 75 mm were tested except in beam number 8 where it was only possible to obtain one specimen.

Apparatus:

- EasyQ_DLA Compact Embedded XL (Eqce-XL) (Kempf GmbH, Sigmaringen, Germany)
- Balance Adventurer Pro AV2102CM (Ohaus Corporation, Parsippany, NJ, USA) with readability 0.01 g up to 500 g and 0.1 g from 500 g to 2100 g

Figure 3-3: Delamination tests of CLT and GLT

<u>Shear tests</u>:

Shear testing was carried out on specimens extracted from GLT beams. Tests were carried out according to Annex D and evaluated according to Table 10 in Clause 5.5.5.2.3 in the standard EN 14080 (2013) (Figure 3-4). Two specimens from each GLT beam with dimensions 50 x 50 mm^2 were tested.

Apparatus:

- Universal testing machine → Load cell 50 kN (readability 0.001 kN) (Microtest S.A., Madrid, Spain)

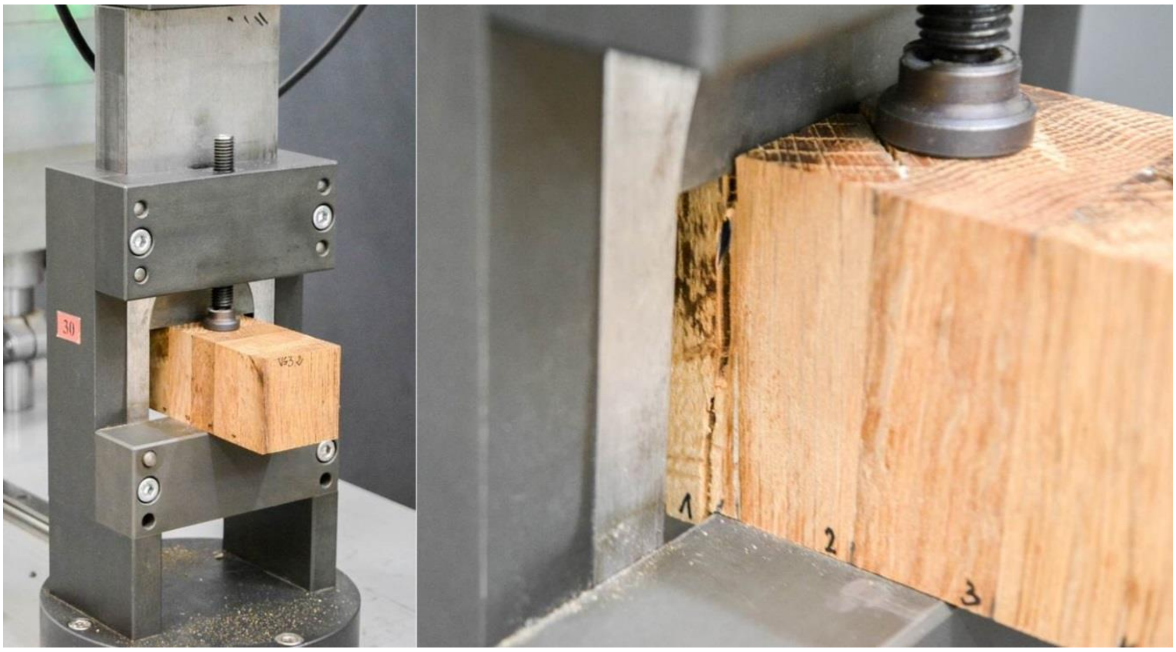


Figure 3-4: Shear test GLT

3.3.2. Results and discussion:

<u>Delamination test results – CLT specimens</u>:
Delamination test results for bond lines in CLT panels manufactured with recovered, hybrid and new oak are presented in

Table 3-10, Table 3-11, Table 3-12 and Table 3-13.

Table 3-10: ***Delamination test on CLT panels RRR***

CLT panel	Specimen	Cross wise	Glue line evaluation				Wood failure evaluation			
			Delam	Max. delam	Delam	Max. delam	Wood failure	Min. wood failure	Total wood failure	Min. Wood failure
			%	≤ 40%	%	≤ 10%	%	≥ 50%	%	≥ 70%
UPM1	1	A	0	Pass	31	Fail	100	Pass	70	Pass
		B	62	Fail			40	Fail		
	2	A	18	Pass	20	Fail	100	Pass	70	Pass
		B	23	Pass			40	Fail		
UPM2	1	A	0	Pass	3	Pass	100	Pass	100	Pass
		B	6	Pass			100	Pass		
	2	A	0	Pass	18	Fail	100	Pass	68	Fail
		B	36	Pass			35	Fail		
UPM3	1	A	0	Pass	15	Fail	100	Pass	95	Pass
		B	29	Pass			90	Pass		
	2	A	25	Pass	13	Fail	70	Pass	85	Pass
		B	0	Pass			100	Pass		

Table 3-11: ***Delamination test on CLT panels RNR***

CLT panel	Specimen	Cross wise	Glue line evaluation				Wood failure evaluation			
			Delam	Max. delam	Delam	Max. delam	Wood failure	Min. wood failure	Total wood failure	Min. Wood failure
			%	≤ 40%	%	≤ 10%	%	≥ 50%	%	≥ 70%
UPM4	1	A	33	Pass	16	Fail	20	Fail	60	Fail
		B	0	Pass			100	Pass		
	2	A	22	Pass	19	Fail	100	Pass	100	Pass
		B	17	Pass			100	Pass		
UPM5	1	A	48	Fail	39	Fail	80	Pass	53	Fail
		B	0	Pass			25	Fail		
	2	A	69	Fail	35	Fail	15	Fail	58	Fail
		B	0	Pass			100	Pass		
UPM6	1	A	7	Pass	25	Fail	100	Pass	80	Pass
		B	44	Fail			60	Pass		
	2	A	19	Pass	30	Fail	20	Fail	15	Fail
		B	40	Pass			10	Fail		

Table 3-12: ***Delamination test on CLT panels NRN***

CLT panel	Specimen	Cross wise	Glue line evaluation				Wood failure evaluation			
			Delam	Max. delam	Delam	Max. delam	Wood failure	Min. wood failure	Total wood failure	Min. Wood failure
			%	≤ 40%	%	≤ 10%	%	≥ 50%	%	≥ 70%
UPM7	1	A	0	Pass	11	Fail	100	Pass	70	Pass
		B	21	Pass			40	Fail		
	2	A	80	Fail	40	Fail	5	Fail	53	Fail
		B	0	Pass			100	Pass		
UPM8	1	A	23	Pass	32	Fail	100	Pass	60	Fail
		B	41	Fail			20	Fail		
	2	A	3	Pass	2	Pass	100	Pass	100	Pass
		B	0	Pass			100	Pass		
UPM9	1	A	23	Pass	14	Fail	60	Pass	80	Pass
		B	5	Pass			100	Pass		
	2	A	22	Pass	26	Fail	70	Pass	85	Pass
		B	30	Pass			100	Pass		

Table 3-13: Delamination test on CLT panels NNN

CLT panel	Specimen	Cross wise	Glue line evaluation				Wood failure evaluation			
			Delam	Max. delam	Delam	Max. delam	Wood failure	Min. wood failure	Total wood failure	Min. Wood failure
			%	≤ 40%	%	≤ 10%	%	≥ 50%	%	≥ 70%
UPM10	1	A	40	Pass	20	Fail	90	Pass	95	Pass
		B	0	Pass			100	Pass		
	2	A	0	Pass	4	Pass	100	Pass	58	Fail
		B	7	Pass			15	Fail		
UPM11	1	A	0	Pass	42	Fail	100	Pass	50	Fail
		B	85	Fail			0	Fail		
	2	A	75	Fail	38	Fail	10	Fail	55	Fail
		B	0	Pass			100	Pass		
UPM12	1	A	0	Pass	23	Fail	100	Pass	55	Fail
		B	46	Fail			10	Fail		
	2	A	48	Fail	24	Fail	20	Fail	60	Fail
		B	0	Pass			100	Pass		

Analysing the results of the previous tables, in the case of glue lines between recovered and recovered timber (Table 3-10), 75% of them passed the delamination test, by wood failure evaluation. In the case of glue lines between recovered and new timber (Table 3-11 and Table 3-12) at least 50% passed the wood failure evaluation. And in the case of glue lines between new and new timber (Table 3-13) only 16% pass the delamination test. The results suggest that recovered timber is gluing better than new timber. Although all timber was planed before gluing using the same equipment and the same procedure, the recovered timber surface was rougher (Cía, 2021), which may explain the better performance.

Delamination test results – GLT specimens:

Delamination test results for GLT beams manufactured using recovered oak and new oak are presented in Table 3-14 and Table 3-15, respectively.

Table 3-14*: *Delamination test on GLT beams R (recovered timber)

Glulam beam	**Specimen**	**Cross wise**	**Glue line evaluation**			
			Delam	**Max. delam**	**Delam**	**Max. delam**
			%	**≤ 30%**	**%**	**≤ 4%**
VG1	1	A	68	Fail	65	Fail
		B	60	Fail		
		C	106	Fail		
		D	24	Pass		
	2	A	95	Fail	76	Fail
		B	62	Fail		
		C	64	Fail		
		D	81	Fail		
VG2	1	A	23	Pass	52	Fail
		B	6	Pass		
		C	103	Fail		
		D	75	Fail		
	2	A	43	Fail	62	Fail
		B	26	Pass		
		C	107	Fail		
		D	74	Fail		
VG3	1	A	42	Fail	69	Fail
		B	83	Fail		
		C	64	Fail		
		D	87	Fail		
	2	A	101	Fail	69	Fail

		B	87	Fail		
		C	61	Fail		
		D	26	Pass		
VG4	1	A	40	Fail	55	Fail
		B	72	Fail		
		C	85	Fail		
		D	23	Pass		
	2	A	41	Fail	48	Fail
		B	90	Fail		
		C	57	Fail		
		D	4	Pass		
VG5	1	A	62	Fail	74	Fail
		B	100	Fail		
		C	90	Fail		
		D	43	Fail		
	2	A	46	Fail	64	Fail
		B	94	Fail		
		C	102	Fail		
		D	13	Pass		

Table 3-15: ***Delamination test on GLT beams N (new timber)***

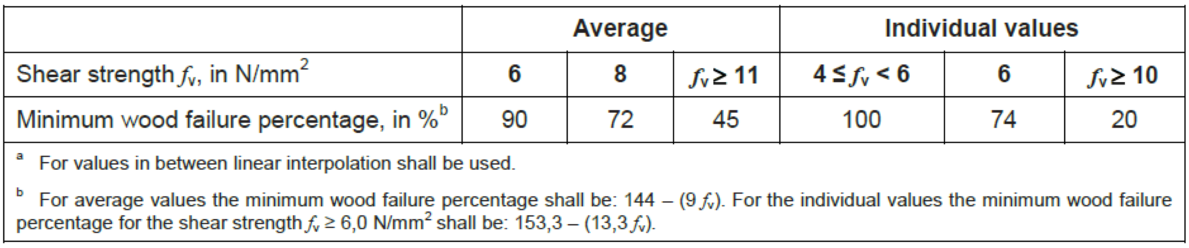
Glulam beam	**Specimen**	**Cross wise**	**Glue line evaluation**			
			Delam	**Max. delam**	**Delam**	**Max. delam**
			%	**≤ 30%**	**%**	**≤ 4%**
VG7	1	A	58	Fail	37	Fail
		B	15	Pass		
		C	34	Fail		
		D	41	Fail		
	2	A	89	Fail	61	Fail
		B	86	Fail		
		C	46	Fail		
		D	23	Pass		
VG8	1	A	4	Pass	18	Fail
		B	5	Pass		
		C	48	Fail		
		D	16	Pass		
VG9	1	A	0	Pass	32	Fail

		B	25	Pass		
		C	46	Fail		
		D	58	Fail		
	2	A	19	Pass	15	Fail
		B	7	Pass		
		C	31	Fail		
		D	3	Pass		
VG10	1	A	43	Fail	61	Fail
		B	59	Fail		
		C	39	Fail		
		D	100	Fail		
	2	A	100	Fail	58	Fail
		B	44	Fail		
		C	74	Fail		
		D	11	Pass		
VG11	1	A	7	Pass	60	Fail
		B	97	Fail		
		C	80	Fail		
		D	55	Fail		
	2	A	9	Pass	51	Fail
		B	71	Fail		
		C	64	Fail		
		D	60	Fail		
VG12	1	A	38	Fail	59	Fail
		B	100	Fail		
		C	53	Fail		
		D	42	Fail		
	2	A	42	Fail	70	Fail
		B	100	Fail		
		C	89	Fail		
		D	45	Fail		

In the case of delamination tests of GLT (Table 3-14 and Table 3-15), all of them failed. One of the explanations for the high failure would be that the most aggressive Method B from EN 14080 (2013) was used instead of the commonly industry Method A.

Shear tests – GLT specimens:

According to EN 14080 (2013), Table 10, the shear strength of glue lines in GLT must meet the requirements shown in Figure 3-5.



	Average			Individual values		
Shear strength f_v, in N/mm^2	**6**	**8**	$f_v \geq$ **11**	**4** $\leq f_v <$ **6**	**6**	$f_v \geq$ **10**
Minimum wood failure percentage, in %[b]	90	72	45	100	74	20

[a] For values in between linear interpolation shall be used.

[b] For average values the minimum wood failure percentage shall be: 144 – (9 f_v). For the individual values the minimum wood failure percentage for the shear strength $f_v \geq 6{,}0$ N/mm^2 shall be: 153,3 – (13,3 f_v).

Figure 3-5: Table 10 of EN 14080 - Minimum wood failure percentages relating to the shear strength f_v

The individual shear strength requirements have to be met by each glue line and average requirements by each cross-sectional specimen.
Results of the shear tests on glue lines in GLT beams manufactured from recovered oak and new oak are presented in Table 3-16 and

Table 3-17, respectively.

***Table 3-16**: Shear test on glulam beams R (recovered timber)*

Glulam beam	Specimen	Cross wise	Shear strength					
			Shear strength N/mm^2	Wood failure %	Req. 14080	Shear strength N/mm^2	Wood failure %	Req. 14080
VG1	1	A	13.51	100	Pass	14.42	96	Pass
		B	15.06	90	Pass			
		C	15.08	95	Pass			
		D	14.01	100	Pass			
	2	A	13.91	80	Pass	12.31	59	Pass
		B	9.13	0	Fail			
		C	13.38	75	Pass			
		D	12.80	80	Pass			
VG2	1	A	13.30	60	Pass	12.95	53	Pass
		B	13.18	45	Pass			
		C	11.81	10	Fail			
		D	13.52	95	Pass			
	2	A	11.59	85	Pass	12.85	80	Pass
		B	11.48	95	Pass			
		C	13.63	90	Pass			
		D	14.70	50	Pass			
VG3	1	A	13.73	95	Pass	11.83	55	Pass
		B	6.80	10	Fail			
		C	12.94	60	Pass			
		D	13.84	55	Pass			
	2	A	9.46	70	Pass	9.99	60	Pass
		B	4.06	95	Fail			
		C	11.75	60	Pass			
		D	14.67	15	Fail			
VG4	1	A	7.15	60	Pass	9.92	61	Pass
		B	8.09	95	Pass			
		C	12.22	20	Pass			
		D	12.21	70	Pass			
	2	A	8.80	60	Pass	10.88	58	Pass
		B	9.46	10	Fail			
		C	11.53	60	Pass			
		D	13.74	100	Pass			

VG5	1	A	12.34	85	Pass	13.36	46	Pass
		B	12.12	20	Pass			
		C	13.64	30	Pass			
		D	15.33	50	Pass			
	2	A	16.40	90	Pass	13.52	38	Fail
		B	12.55	20	Pass			
		C	13.81	30	Pass			
		D	11.30	10	Fail			

Table 3-17: ***Shear test on GLT beams N (new timber)***

Glulam beam	Specimen	Cross wise	Shear strength					
			Shear strength N/mm^2	Wood failure %	Req. 14080	Shear strength N/mm^2	Wood failure %	Req. 14080
VG7	1	A	12.44	5	Fail	12.58	4	Fail
		B	13.24	10	Fail			
		C	13.85	0	Fail			
		D	10.78	0	Fail			
	2	A	8.64	20	Fail	11.89	29	Fail
		B	13.52	40	Pass			
		C	11.48	50	Pass			
		D	13.91	5	Fail			
VG8	1	A	16.34	60	Pass	15.21	64	Pass
		B	15.08	30	Pass			
		C	17.34	95	Pass			
		D	12.06	70	Pass			
	2	A	14.95	10	Fail	11.69	25	Fail
		B	14.18	10	Fail			
		C	15.07	50	Pass			
		D	2.57	30	Fail			
VG9	1	A	4.87	90	Fail	13.19	53	Pass
		B	16.79	50	Pass			
		C	14.72	40	Pass			
		D	16.39	30	Pass			
	2	A	16.62	20	Pass	15.56	48	Pass
		B	13.82	60	Pass			
		C	15.65	80	Pass			
		D	16.14	30	Pass			
VG10	1	A	12.05	0	Fail	12.11	23	Fail
		B	15.72	30	Pass			
		C	6.89	10	Fail			
		D	13.78	50	Pass			
	2	A	11.93	0	Fail	14.10	35	Fail
		B	14.19	90	Pass			
		C	14.39	10	Fail			
		D	15.88	40	Pass			
VG11	1	A	15.62	5	Fail	14.53	49	Pass

		B	13.96	90	Pass			
		C	11.92	90	Pass			
		D	16.62	10	Fail			
	2	A	17.00	70	Pass	15.58	65	Pass
		B	9.89	20	Fail			
		C	15.57	80	Pass			
		D	19.86	90	Pass			
VG12	1	A	17.29	50	Pass	13.68	23	Fail
		B	8.75	20	Fail			
		C	12.60	10	Fail			
		D	16.07	10	Fail			
	2	A	13.38	50	Pass	12.71	23	Fail
		B	14.11	20	Pass			
		C	9.00	10	Fail			
		D	14.35	10	Fail			

Analysing the results of the previous tables, in the case of shear test on GLT beams manufactured from recovered timber (Table 3-16), 90% of the specimens passed the shear test. In the case of GLT manufactured from new timber (

Table 3-17), 42% of the specimens passed the test. Regarding shear test values, shear strength was high in both cases, on average 11.99 N/mm^2 (9.92 N/mm^2 of 5th percentile) for recovered timber beams and 13.57 N/mm^2 (11.69 N/mm^2 of 5th percentile) for new timber beams. These values are really high; comparing the 5th percentile values with the values expected according EN 14080 (2013) for a GLT beam GL30h (3.5 N/mm^2).

3.3.3. Conclusions of Spanish Study:

Based on the measured delamination and shear strength of specimens from recovered and new hardwood timber, the following conclusions are drawn:

- The delamination tests on specimen recovered from CLT specimens showed a pass rate of 75% for bond lines between recovered timber, 50% for bond lines between recovered and new timber and only 16% for bond lines between new timber. Even though the surface preparation was identical for new and recovered timber, the recovered timber had a rougher surface after planing, which may explain the difference in performance.
- For the specimens extracted from GLT manufactured from recovered oak and new oak, all glue lines failed the delamination test. This may be due to the test method used, the adhesive selection, surface treatment, or manufacturing parameters or a combination of these and will require further investigation.
- For the case of GLT beams manufactured from recovered oak, 90% passed the shear test based on the wood failure percentage compared to 42% for those from new oak. Nevertheless, the shear strength achieved by both was high and well in excess of the requirement in EN 14080.

3.4. Shear Testing of GLT specimens from recovered timber: UK study

Marlene Cramer, Daniel-Ridley Ellis

GLT specimens manufactured from recovered spruce timber as part of another research project provided specimens for additional shear testing. For these specimens only shear strength tests were performed.

3.4.1. Materials and Methods

Materials

Six glulam beams were manufactured from recovered spruce timber as part of the CIRCuIt project. The material was taken from a 10-year old floor of a bingo hall that was being demolished. Details of the material collection and GLT manufacturing can be found in Bergsagel *et al.* (2021). The GLT beams were conditioned and tested in bending according to EN 14080 (2013) Annex F (EN 408 (2012) four-point bending) at Edinburgh Napier University, but the bending test results are not reported here. Afterwards, the undamaged beam ends were removed (beams were cut into three sections: one with and two without bending failure). Glue line shear tests according to EN 14080 (2013) Annex D were performed on specimens from the failure-free sections. One undamaged end section per beam was used to produce specimens of the full cross section area. Two specimens from either end of each section were cut, one which was close to the beam end and one which was close to the middle of the beam, where bending failure had occurred but in the undamaged wood (Figure 3-6). Each full cross section yielded two test bars of approximately 40 x 40 mm^2. In two beams, two replicates of one end were produced, so that in total 28 test bars were obtained. Each test bar contained 4 or 5 glue lines, since five glulam beams with 6 lamellas and one glulam beam with 5 lamellas were tested.

Figure 3-6: Glulam sections after bending test. Sections without bending failure were used for producing shear specimens.

Methods

The test bars were conditioned at 20 °C and 65 % relative humidity. Then, the dimensions of the shear plane were measured with 0.01 mm accuracy using a calliper.

Shear tests were performed using a universal testing machine (Zwick Roell Z050) and the holding device shown in Figure 3-7. The holding device is fastened on the sample using two nuts and bolts that tighten a steel bar on top of the sample (a in Figure 3-7). The nuts were tightened by hand or using a wrench. The self-aligning load head distributes the force equally along the sample width. Care was taken to ensure that both the load bar on top of the specimen and the steel plate underneath the specimen (b and c in Figure 3-7) had a distance of no more than 1 mm to the glue line. Load was applied in the direction of the grain and all glue lines in each test bar were tested until failure, while load and deformation were recorded. In total, 134 tests were conducted successfully. Two glue lines could not be tested, as failure when testing the previous glue line had occurred close to the middle of the lamella, and not enough material was left to apply the force from above.

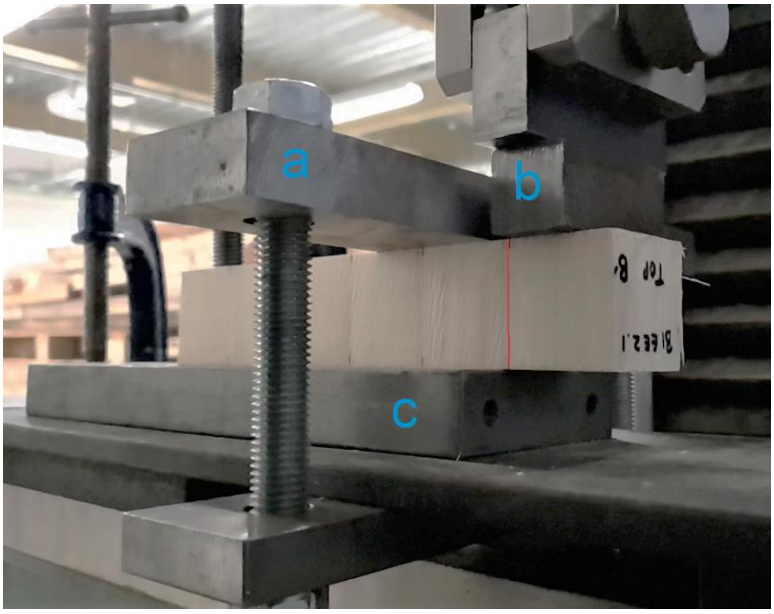


Figure 3-7: Test set-up. Holding device (a) consisting of two steel bars tightened by two nuts and bolts. Load head with steel bar (b) and support steel plate (c) in less than 1 mm distance to shear plane. Glue line marked in red.

Immediately after testing, the mass of each specimen was measured with an accuracy of 0.01 g. All shear planes were examined visually, and the percentage of wood failure was estimated. Any other observations regarding the failure were documented. The specimens were dried at 103 °C to mass consistency and the mass was recorded again. Moisture content at the time of testing was between 11.9 % and 13.0 % average per test bar, in line with EN 14080.

The shear strength of each shear plane was calculated using Equation D.1 of EN 14080 Appendix D, shown below.

$$f_v = k_v \frac{F_u}{A} \tag{3.4}$$

where F_u is the ultimate load, A is the sheared area and k_v is an adjustment factor for thicknesses below 50 mm:

$$k_v = 0{,}78 + 0{,}0044\ t; \tag{3.5}$$

where t is the thickness of the shear plane.

3.4.2. Results and discussion

The average shear strength was 3.5 N/mm^2 with a standard deviation of 0.9 N/mm^2. All results are presented in Table 3-18.

Table 3-18 Shear test on GLT beams (recovered timber)

GLT beam	Specimen	Cross wise	Stick 1			Specimen	Cross wise	Stick 2			Cross section specimen		
			Shear strength	Wood failure	Req. 14080			Shear strength	Wood failure	Req. 14080	Shear strength	Wood failure	Req. 14080
			N/mm^2	%				N/mm^2	%		N/mm^2	%	
B1	1	A	3.82	100	Fail	1	A	4.90	100	Pass	3.41	92	Fail
		B	2.41	90	Fail		B	3.80	100	Fail			
		C	2.03	100	Fail		C	3.28	100	Fail			
		D	3.38	100	Fail		D	3.72	100	Fail			
		E	3.03	75	Fail		E	3.74	50	Fail			
	2	A	4.45	100	Pass	2	A	2.70	90	Fail	3.25	97	Fail
		B	3.36	100	Fail		B	2.58	100	Fail			
		C	3.25	100	Fail		C	2.51	90	Fail			
		D	4.48	100	Pass		D	3.31	100	Fail			
		E	No record				E	2.65	95	Fail			
	3	A	2.51	75	Fail	3	A	3.86	100	Fail	3.95	96	Fail
		B	3.45	80	Fail		B	4.24	100	Pass			
		C	3.09	100	Fail		C	4.47	100	Pass			
		D	4.97	100	Pass		D	4.63	100	Pass			
		E	4.80	100	Pass		E	3.49	100	Fail			
B2	1	A	3.91	100	Fail	1	A	1.97	100	Fail	3.01	100	Fail
		B	3.49	100	Fail		B	3.44	100	Fail			
		C	4.12	100	Pass		C	4.36	100	Pass			
		D	2.26	95	Fail		D	2.64	100	Fail			
		E	1.72	100	Fail		E	2.17	100	Fail			
	2	A	2.66	100	Fail	2	A	4.50	100	Pass	3.71	86	Fail

		B	3.66	100	Fail		B	3.61	85	Fail			
		C	4.95	100	Pass		C	3.12	70	Fail			
		D	4.10	100	Pass		D	3.72	100	Fail			
		E	3.15	100	Fail		E	3.68	5	Fail			
	3	A	1.95	100	Fail	3	A	2.34	100	Fail	3.94	99	Fail
		B	4.92	100	Pass		B	2.97	100	Fail			
		C	3.39	85	Fail		C	4.02	100	Pass			
		D	3.34	100	Fail		D	4.74	100	Pass			
		E	5.78	100	Fail		E	5.93	100	Pass			
B3	1	A	2.65	100	Pass	1	A	4.54	100	Pass	3.88	97	Fail
		B	4.45	80	Fail		B	3.76	100	Fail			
		C	3.72	100	Fail		C	Not recorded					
		D	3.57	100	Fail		D	3.67	90	Fail			
		E	3.21	100	Fail		E	5.30	100	Fail			
	2	A	2.34	100	Fail	2	A	2.92	100	Fail	3.04	100	Fail
		B	2.03	100	Fail		B	2.88	100	Fail			
		C	5.01	100	Pass		C	3.30	100	Fail			
		D	1.67	100	Fail		D	2.33	100	Fail			
		E	3.76	100	Fail		E	4.17	100	Pass			
B4	1	A	4.46	100	Pass	1	A	4.29	100	Pass	3.69	99	Fail
		B	3.89	100	Fail		B	3.15	95	Fail			
		C	4.13	100	Pass		C	3.73	100	Fail			
		D	3.07	100	Fail		D	3.75	95	Fail			
		E	3.25	100	Fail		E	3.14	100	Fail			
	2	A	2.99	100	Fail	2	A	4.02	100	Pass	3.59	99	Fail
		B	3.56	100	Fail		B	3.13	100	Fail			
		C	1.81	90	Fail		C	4.39	100	Pass			
		D	4.49	100	Pass		D	3.40	100	Fail			
		E	4.89	100	Fail		E	3.24	100	Fail			
B5	1	A	3.47	100	Fail	1	A	2.57	70	Fail	3.30	86	Fail
		B	3.64	90	Fail		B	2.32	100	Fail			
		C	3.64	45	Fail		C	4.12	100	Pass			
		D	4.06	90	Fail		D	2.55	90	Fail			
		E	3.57	100	Fail		E	3.07	75	Fail			
	2	A	3.39	90	Fail	2	A	3.97	100	Fail	3.52	96	Fail
		B	3.90	100	Fail		B	3.53	100	Fail			
		C	5.00	90	Fail		C	4.01	75	Fail			
		D	2.72	100	Fail		D	4.32	100	Pass			

		E	2.31	100	Fail		E	2.06	100	Fail			
B6	1	A	2.41	100	Fail	1	A	3.38	100	Fail	3.28	78	Fail
		B	2.65	45	Fail		B	3.73	75	Fail			
		C	1.64	30	Fail		C	5.16	100	Pass			
		D	3.28	85	Fail		D	3.96	85	Fail			
	2	A	3.27	100	Fail	2	A	2.33	90	Fail	3.34	93	Fail
		B	2.21	100	Fail		B	3.41	55	Fail			
		C	4.61	100	Pass		C	4.04	100	Pass			
		D	2.90	100	Fail		D	3.96	100	Fail			

The wood failure percentage was 94% on average, with 75% of specimens showing no glue failure. Individual values obtained in this study were all below 6 N/mm^2, but values between 4 and 6 N/mm^2 are permitted, where the wood failure percentage is 100. With this rule, 25% of specimens met EN 14080 requirements, but 71% of tests resulted in a shear strength below 4 N/mm^2 as seen in Figure 3-8.

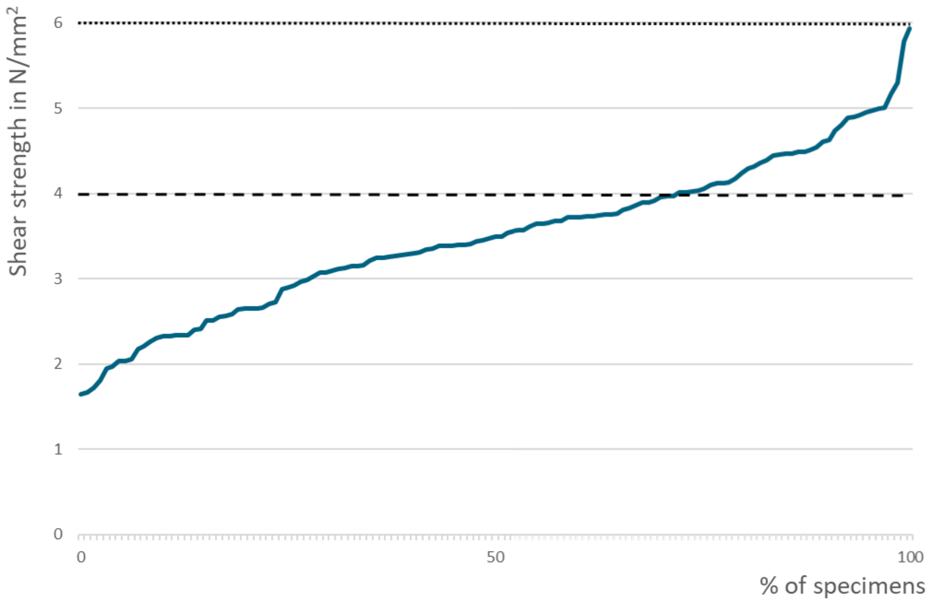


Figure 3-8 Shear strength results. Thresholds of 4 N/mm² and 6 N/mm² marked with dashed lines.

The low shear strength cannot be explained by weaknesses in the glue lines, as only a few specimens showed any glue failure, and many failures occurred in away from the glue line (Figure 3-9). Some specimens showed unusual defects, such as shown in Figure 3-10, which were sometimes only discovered after testing. Fifty of the specimens failed in close proximity to such a defect, along a growth ring, through the pith or close to a knot. However, the average shear strength of these 50 specimens was slightly higher than for the remaining specimens, so that the low shear strength cannot be explained by defects.

Figure 3-9: Specimen after testing. Failure does not always occur in proximity to glue line.

Figure 3-10: Unusual defects can be present in recovered wood, here a screw hole.

It is possible that the shear strength of recovered wood is decreased by ageing effects (such as degradation of the hemicellulose), but the timber in this study was only ten years old and had been used in a protected environment, as the floor of a bingo hall, so effects of aging are expected to be small.

Steiger and Richter (2009) report that the results of shear tests are influenced by the shearing device and the person conducting the test. They describe that the shear procedure of EN 392:1995 (which is now replaced by EN 14080 (2013) with identical procedure) does not only generate shear forces in the specimen, but also a bending moment, which is caused by an uplift of the specimen. When this bending moment is countered by a holding device, bending stresses are added to the shear stresses, which leads to failure at lower loads. The higher the holding force, the lower are the test results.

This explanation seems the most likely one for the low shear strengths measured in this test series. In a video of one of the tests, an uplift of the test bar can be observed (Figure 3-11 and Figure 3-12). The holding device is subjecting the test bar to forces, which are relatively uncontrolled, as the force with which the nuts are tightened is not measured. It is likely that the force varies between tests, between operators and over the specimen width, as it is hard to ensure that both nuts are tightened equally.

Figure 3-11: Specimen uplift during testing, marked with blue arrow. Glue line marked in red.

Figure 3-12: Specimen after failure within the wood, close to holding-down device. Glue line marked in red.

To test the hypothesis that the holding device is affecting the shear results, a new shear test device was developed. The new device combines the holding device and the self-aligning load bar (Figure 3-13), so that the distance between the glue line and the holding device is constant. The holding device is fastened by only one lever (Figure 3-14). The new device is similar to the devices used in Ireland and Spain (see Sections 3.2 and 3.3).

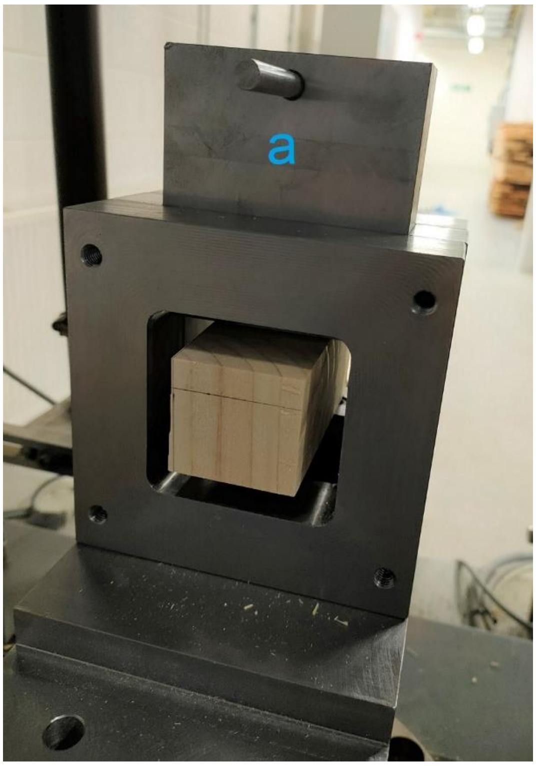


Figure 3-13: New shear test device, front view, with self-aligning load bar (a) positioned on specimen.

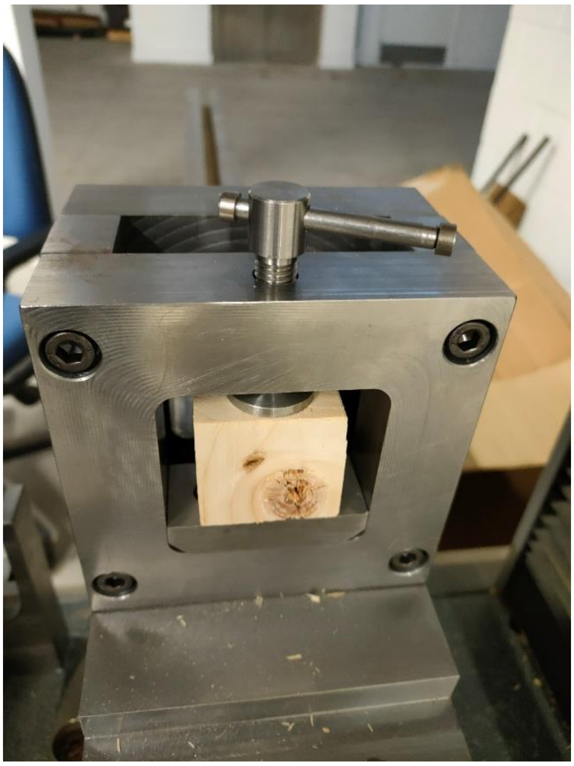


Figure 3-14: New shear test device back view, with holding device securing specimen. Note load bar is not in place.

Eight additional test bars were prepared from four of the beams as described above. All glue lines were tested as described above, by the same operator, but with the new shear test device. The holding device was always fastened by hand only and care was taken to position the specimen centrally, so that the force on the specimen is equally distributed over its width.

The tests resulted in 39 valid shear strength results, with an average of 8.4 N/mm^2 and a standard deviation of 1.58 N/mm^2. One test was not recorded by the universal testing machine. The average wood failure percentage was 87.7% and moisture content was between 11.5 and 11.8 %. All test results are presented in

Table 3-19.

Table 3-19 Shear tests on GLT beams with new device (recovered timber)

GLT beam	Cross wise	Stick 1			Cross wise	Stick 2			Cross section specimen		
		Shear strength	Wood failure	Req. 14080		Shear strength	Wood failure	Req. 14080	Shear strength	Wood failure	Req. 14080
		N/mm^2	%			N/mm^2	%		N/mm^2	%	
B1	A	7.00	100	Pass	A	6.61	50	Pass	7.06	78	Fail
	B	7.93	90	Pass	B	3.33	10	Fail			
	C	6.68	100	Pass	C	6.00	50	Pass			
	D	7.82	100	Pass	D	7.38	80	Pass			
	E	8.59	100	Pass	E	9.27	100	Pass			
B2	A	8.21	95	Pass	A	8.48	100	Pass	8.85	96	Pass
	B	9.34	100	Pass	B	8.86	100	Pass			
	C	7.58	100	Pass	C	8.09	95	Pass			
	D	9.41	90	Pass	D	9.28	90	Pass			
	E	9.40	100	Pass	E	9.83	85	Pass			
B4	A	7.72	100	Pass	A	8.88	85	Pass	8.51	85	Pass
	B	8.69	75	Pass	B	9.04	30	Pass			
	C	7.93	100	Pass	C	6.07	90	Pass			
	D	9.97	100	Pass	D	Not recorded					
	E	9.64	85	Pass	E	8.67	100	Pass			
B5	A	8.73	100	Pass	A	11.27	100	Pass	9.05	92	Pass
	B	10.08	70	Pass	B	9.10	100	Pass			
	C	9.22	100	Pass	C	10.75	100	Pass			
	D	8.25	100	Pass	D	9.38	100	Pass			
	E	4.40	80	Fail	E	9.35	70	Pass			

The majority of individual values (37 of 39) and three of the cross-section specimens met the EN 14080 requirements. The lowest individual value, which is less than 50% of the average, was recorded in a glue line that was visibly glued poorly, with gaps in the glue showing before the test.

A two-sided t-test between the shear strength results of the first and second test series was performed in Excel, with the assumption of unequal variances. The two means are significantly different, with a p-value of 0.000. A comparison between the shear strength in the two test series is shown in Figure 3-15. The wood failure percentage is slightly lower in the second test series, but a significant influence of the test set-up cannot be confirmed (p of 0.076).

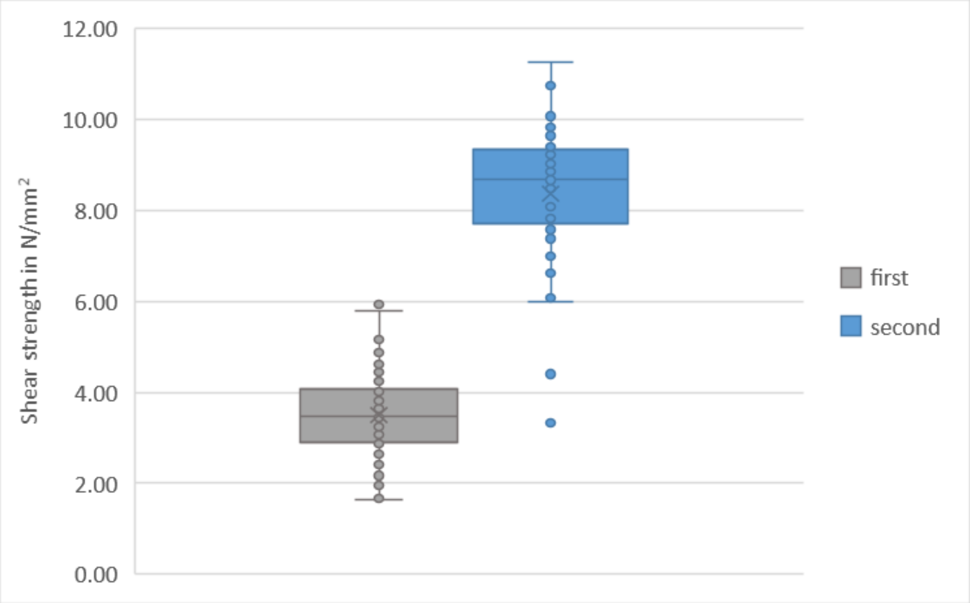


Figure 3-15 Boxplot of first and second test series.

It could clearly be shown that the shear test results are influenced by the shear test device, as much higher results were obtained in the second test series than in the first one. It is likely that this is due to the difference in the holding device, which might subject the specimen to lower forces than the one in the first test series. The force is also applied more equally over the specimen width. In addition, the position of the holding device is fixed quite close to the shear plane, so that bending moments are kept low. Both these factors reduce the influence of bending stresses on the measured loads, so that the results obtained in the second test series are reflecting the actual shear strength more closely than the results of the first test series. The slightly higher glue-failure percentage in the second test series indicates that the stresses were indeed more concentrated in the glue line. Still, the true shear strength could potentially be even higher, as stresses other than shear stress cannot be fully eliminated with this test set-up.

3.4.3. Conclusions of UK Study

Based on the shear strength investigation of specimens extracted from GLT specimens manufactured from recovered timber, the following conclusions are drawn:

- The loading device used in the shear experiments influenced the test results.
- Using the first device, only 25% of the specimens tested satisfied the requirements of EN 14080.
- For the improved loading device, 95% of specimens satisfied the requirements of EN 14080 with respect to shear strength.
- It can be concluded that the recovered wood glulam does, indeed, have a level of performance we expect to see in equivalent glulam from new timber.

4. Embedment Behaviour of Recovered Softwood and Hardwood Timber

Caitríona Uí Chúláin, David Gil-Moreno, Daniel F. Llana, Mitja Plos, Goran Turk, Annette M. Harte

4.1. Introduction

Dowel-type connections are the most commonly used connection type used in timber structures. Design of dowel-type connections requires knowledge of the embedment behaviour of the timber. The embedment strength of new timber may be determined using empirical equations given in Eurocode 5 (EN1995-1-1, 2014). These equations describe the dependency of the embedment strength of the timber on the timber density, the dowel diameter and the loaded direction. The embedment strength can also be established by testing, which is the only option for materials not covered by the standard.

This experimental study assessed the embedment strength of recovered softwood and hardwood timber. Values obtained are compared with published data for new timber and with values from the Eurocode 5 empirical equations. The test programme includes the determination of embedment strength of recovered spruce timber from a demolition project in Ireland and spruce and oak from two different demolition projects in Slovenia. To investigate the influence of diameter, high-strength steel dowels of three different diameters will be used. The specimens were tested by loading in compression parallel, and perpendicular to the grain to capture the influence of loading direction in accordance with EN 383 (2007). In all, 191 samples were tested.

4.2. Materials and Methods

4.2.1. Materials

Recovered timber for embedment testing came from three different demolition sites in Ireland and Slovenia:

Series 1: Recovered European spruce timber was collected from the demolition of a timber roof structure built in the mid-1970’s in Stillorgan, Co. Dublin (Figure 2-1). The truss members had grade stamps indicating they were from boards which were approximately equivalent to grade TR26.

Series 2: Slovenian spruce was obtained during the reconstruction of the roof of one of the buildings of the Faculty of Civil and Geodetic Engineering of the University of Ljubljana (Figure 4-1). The building was built in the years from 1947 to 1949 so the roof structure was approximately 70 years old. During their use in the building, the trusses were protected against rain and not insulated. Therefore, they were not exposed to water, but were subjected to varying temperature estimated between -20° C and 50° C. The strength grade of the timber is unknown as at that time the JUS (Yugoslavian) norms were not yet in use. The density of the timber specimens at moisture equilibrium was between 362 kg/m^3 and 526 kg/m^3, with an average of 426 kg/m^3. All the specimens that were taken from the roof included the pith.

Series 3: Recovered Slovenia oak was obtained during the reconstruction of a wooden bridge over the Sava river supported by concrete pillars. The bridge was constructed in the years from 1930 to 1935. The deconstruction took place in 2019 (Figure 4-2). During their use on the bridge, the timber first served as the driving surface, later they were covered with a new driving surface also made from wood. At first the water and salt from the vehicles would drip onto the specimens directly, later only partially. The whole time they were exposed to moisture from the surrounding moist air over the river, but they were protected from direct rain by the roof of the bridge. The density of the recovered oak specimens at moisture equilibrium was between 609 kg/m^3 and 860 kg/m^3, with an average of 739 kg/m^3.

Figure 4-1: The roof of the faculty building prior to deconstruction.

Figure 4-2: The bridge over the Sava river during deconstruction.

Smooth dowels of high-strength steel to BS 1407 (1970) and having diameters of 10 mm, 12 mm and 14 mm were used.

The specimen geometry for testing in the parallel to the grain and perpendicular to the grain directions are specified in EN 383 (2007) as a function of the dowel diameter. Figure 4-3 shows the specimen dimensions for the two loading directions as specified in the standards. For dowel connections, $a_1 = a_2 = 5d$, $l_1 = l_2 = 7d$ and $l_5 = 20d$, where d is the dowel diameter. The specimen thickness should be in the range $1.5d – 4d$.

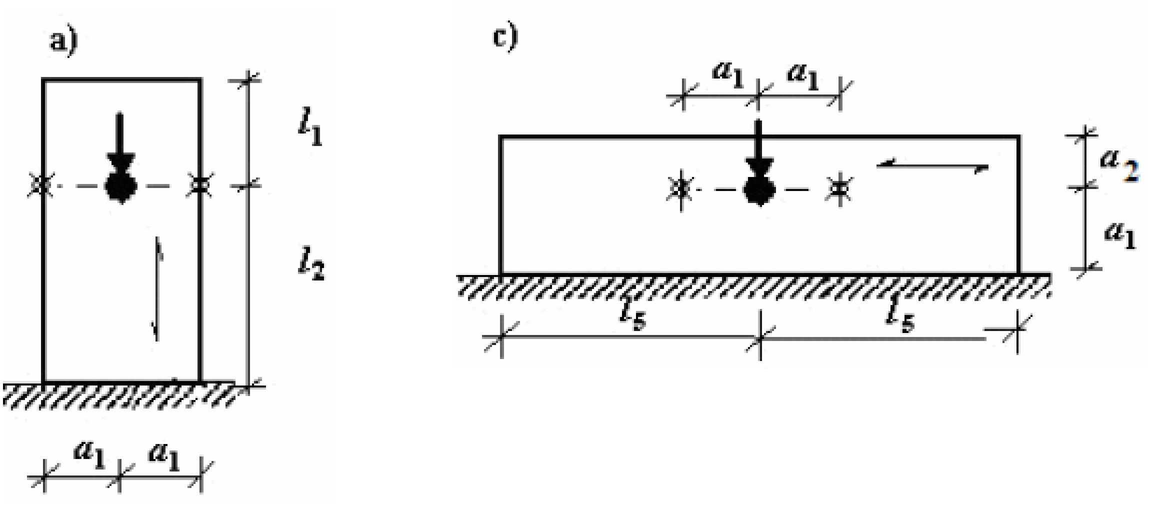


Figure 4-3: Specimen dimension for compression embedment tests a) parallel to the grain and c) perpendicular to the grain (EN 383, 2007)

Dimensions of the test specimens for each series are given Table 4-1 and

Table ***4-2*** for the two loaded directions, respectively, together with the number of specimens tested in each series and the moisture content (MC) at the time of testing.

Table 4-1 Embedment test series: parallel-to-grain

Series	Dowel	Number tests	Specimen dimensions			MC (%)
	d **(mm)**	**#**	***l*** **(mm)**	***b*** **(mm)**	***t*** **(mm)**	**Mean (CoV)**
Irish spruce	10	11	141	61	25	13.0 (5%)
	12	10	169	68	28	
	14	10	197	85	29	
Slovenian spruce	10	12	141	61	31	10.9 (5%)
	12	11	169	73	31	
	14	10	196	85	30	
Slovenian oak	10	12	141	61	30	12.1 (14%)
	12	10	169	73	30	
	14	11	197	85	31	

Table 4-2 Embedment test series: perpendicular to the grain

Series	Dowel	Number tests	Specimen dimensions			MC (%)
	Diameter (mm)	#	h (mm)	d (mm)	t (mm)	Mean (CoV)
Irish spruce	10	10	100	401	30	12.8(3%)
	12	10	119	482	28	
	14	8	140	560	29	
Slovenian spruce	10	11	101	400	27	10.3(6%)
	12	10	120	479	30	
	14	11	139	561	30	
Slovenian oak	10	13	100	401	29	13.0 (7%)
	12	10	120	485	30	
	14	11	140	565	30	

4.2.2. Embedment test set-up:

The tests were carried out in accordance with EN 383 (2007). The test set-up is illustrated in Figure 4-4 and Figure 4-5 for the parallel to the grain and perpendicular to the grain tests, respectively. Each test piece was placed symmetrically in the apparatus and supported such that the influence of friction with the loading apparatus was avoided. High-strength steel dowels were used to avoid bending under test. Each bar was loaded perpendicular to its axis.

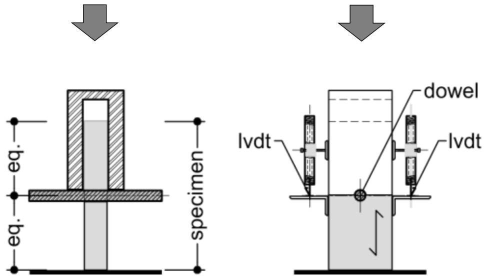


Figure 4-4: Apparatus set-up parallel-to-grain in accordance with EN 383 (2007): a) Section, b) Front elevation

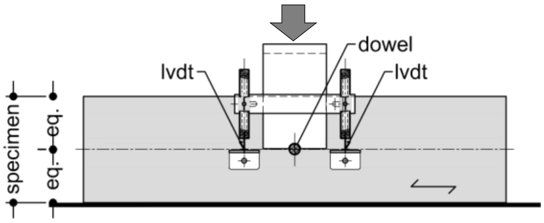


Figure 4-5: Apparatus set-up perpendicular-to-grain in accordance with EN 383 (2007): Front elevation

All embedment tests were carried out in compression. Each dowel was loaded perpendicular to its axis in accordance with the loading procedure outlined in EN 383 (2007) and EN 26891: (1991) as shown in Figure 4-6 and Figure 4-7. The load was recorded, and the corresponding deformation of the dowel relative to the timber at the level centreline of the fastener was measured using two LVDTs. Each test was stopped either when the deformation exceeded 5 mm or when the wood specimen split.

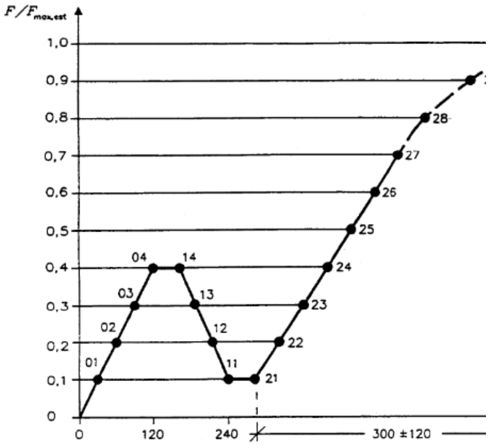


Figure 4-6: Loading procedure in accordance with EN 383 (2007)

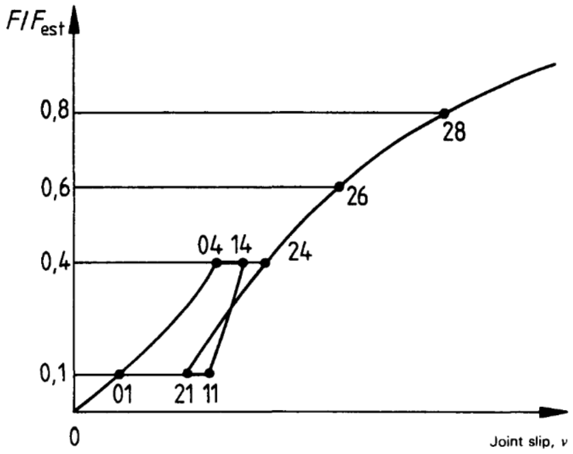


Figure 4-7:Test protocol in accordance with EN 26891 (1991)

4.3. Embedment test results

4.3.1. Load-displacement response

Figure 4-8 and Figure 4-9 show mean load-displacement curves for 10 mm steel dowels loaded parallel-to-grain and 14 mm steel dowels loaded perpendicular-to-grain, respectively.

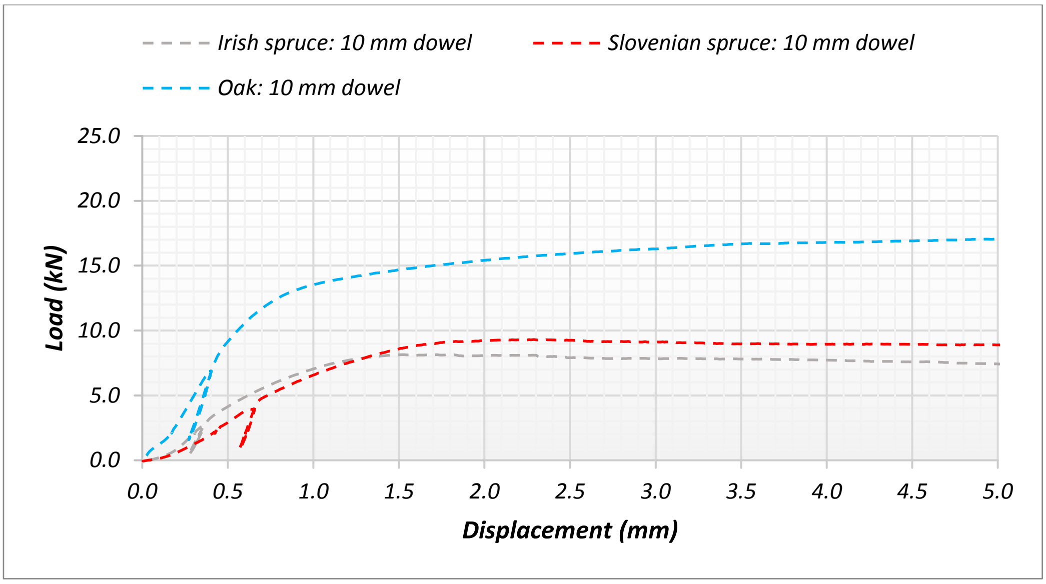


Figure 4-8: Mean-value load-displacement curves recovered timber loaded by 10 mm steel dowels parallel-to-grain

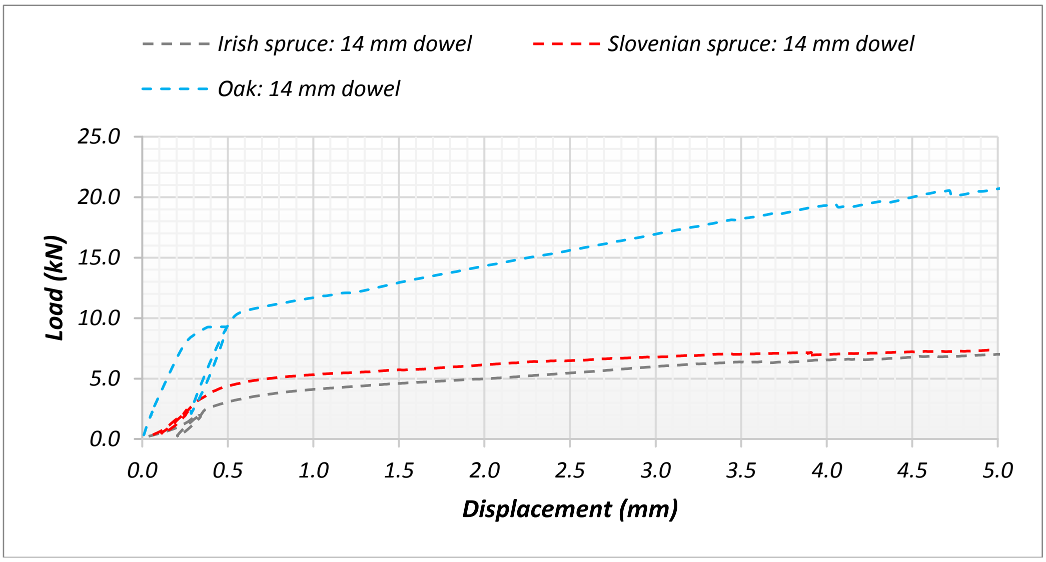


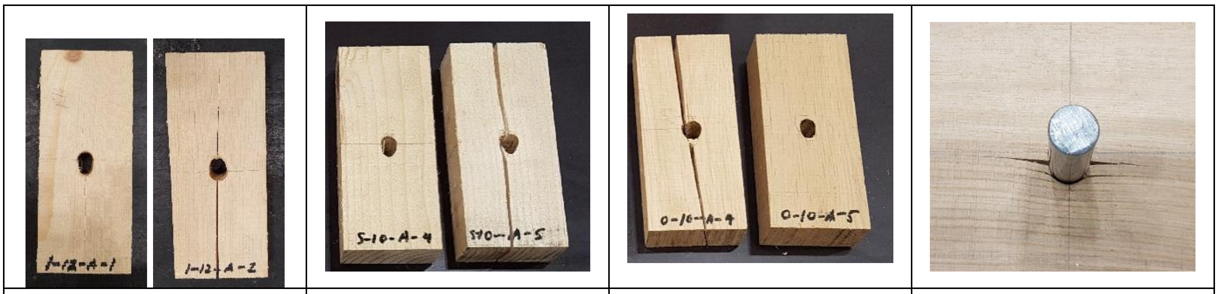
Figure 4-9: Mean-value load-displacement curves for recovered timber-loaded by 14 mm steel dowels perpendicular-to-grain

The loading of the dowels in the different wood species showed the same trend with respect to deformation behaviour. However, the oak specimens bore a greater load per displacement in comparison to the spruce samples. There was little difference between the Irish and Slovenian spruce results with respect to load-displacement values.

In the case of the test series parallel-to-grain, the maximum load was reached within 2 mm displacement. Most tests resulted in embedment to 5 mm, however, 27% of the Irish spruce, 33% of the Slovenian spruce and 33% of the Slovenian oak specimens failed due to splitting before reaching the target embedment value using 10 mm dowels. This splitting rate reduced to 10%, 18%, and 20% for 12 mm dowels, respectively and to 10%, 10%, and 18% for the 14 mm dowel tests, respectively.

In the case of the perpendicular-to-grain embedment tests, an embedment of 5 mm was reached in all but one Slovenian spruce specimen that failed due to splitting before reaching 5 mm embedment using a 10 mm diameter dowel.

Figure 4-10 shows sample embedment and splitting failure modes from the test series loaded parallel-to-grain and perpendicular-to-grain.



a) Irish recovered spruce

b) Slovenian recovered spruce-

c) Slovenian recovered oak

d) Slovenian recovered oak

Figure 4-10: Embedment failure in recovered timber

4.3.2. Summary Test Results

A summary of the embedment test results for the three series and three dowel diameters is given in Table 4-3. Mean values and coefficients of variation of density and embedment strength are provided.

Table 4-3:Summary test results

Series	Test	Dowel diameter mm	Number of Specimens	f_h N/mm² Mean (CoV)	Density kg/m³ Mean (CoV)
Irish spruce	Parallel	10	11	29.6 (18%)	415 (8%)
	Parallel	12	10	25.6 (3%)	402 (5%)
	Parallel	14	10	29.6 (18%)	426 (9%)
Slovenian spruce	Parallel	10	12	28.8 (9%)	368 (5%)
	Parallel	12	11	28.1 (15%)	377 (12%)
	Parallel	14	10	28.8 (12%)	372 (6%)
Slovenian Oak	Parallel	10	12	56.2 (16%)	631 (9%)
	Parallel	12	11	48 (18%)	591 (12%)
	Parallel	14	11	52 (14%)	611 (9%)
Irish spruce	Perpendicular	10	10	20.6 (9%)	416 (6%)
	Perpendicular	12	10	17.8 (23%)	378 (6%)
	Perpendicular	14	8	16.6 (12%)	400 (8%)
Slovenian spruce	Perpendicular	10	10	23.7 (16%)	402 (4%)
	Perpendicular	12	10	16.5 (13%)	368 (3%)
	Perpendicular	14	11	17.9 (21%)	394 (8%)
Slovenian Oak	Perpendicular	10	13	48.1 (28%)	633 (10%)
	Perpendicular	12	10	51.5 (21%)	656 (10%)
	Perpendicular	14	11	49.1 (19%)	670 (7%)

4.3.3. Influence of density

The influence of density on embedment strength both parallel and perpendicular to the grain is seen in Figure 4-11.

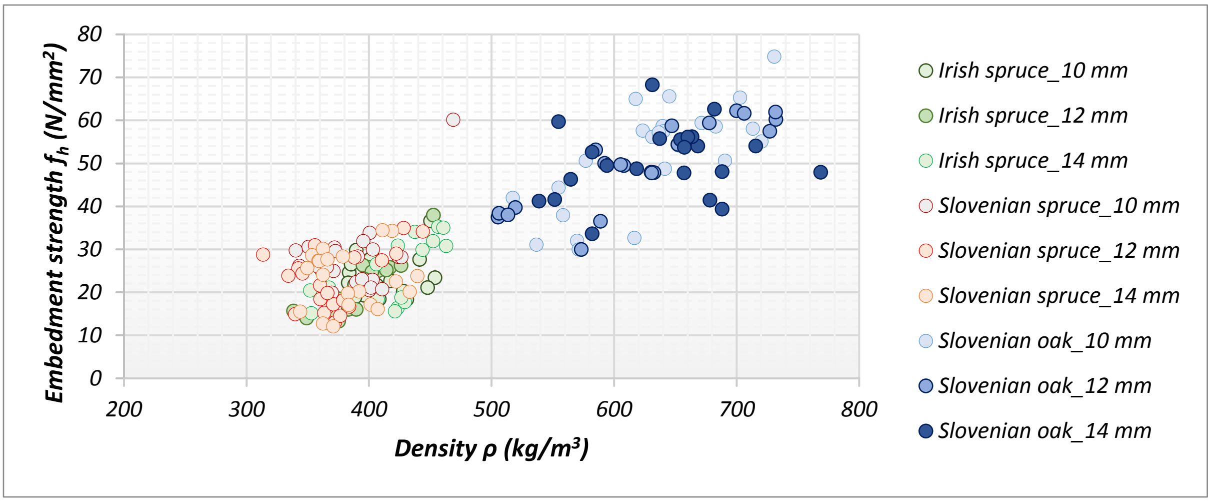


Figure 4-11: Embedment strength N/mm^2 relative to wood density kg/m^3 (parallel-& perpendicular-to-grain)

The empirical equations given in Eurocode 5 (EN 1995-1-1, 2014) for the characteristic embedment strength parallel to the grain $f_{h,0,k}$ and perpendicular to the grain $f_{h,90,k}$ are given in Equations (4.2) and (4.3)

$$f_{h,0,k} = 0.082\,(1-0.01d)\rho_k \tag{4.2}$$

$$f_{h,90,k} = f_{h,90,k}\,/k_{90} \tag{4.3}$$

where ρ_k is the characteristic density in kg/m^3 and d is the dowel diameter in mm. k_{90} is (1.35+0.015d) for softwood and (0.9+0.015d) for hardwoods.

The individual embedment test results relative to the density for the parallel-to-grain tests using 10 mm, 12 mm and 14 mm dowels are given in Figure 4-12, Figure 4-13 and Figure 4-14. Also, included in these figures is Eurocode 5 relationship and mean embedment strength test data from tests on new timber reported in the literature.

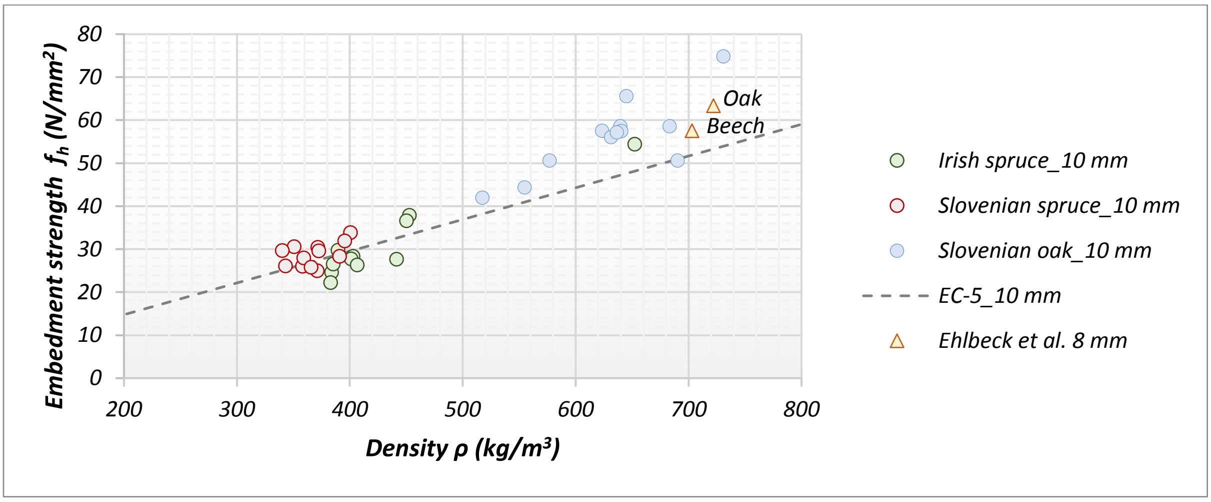


Figure 4-12: Embedment strength v density (10 mm dowel parallel-to-grain)

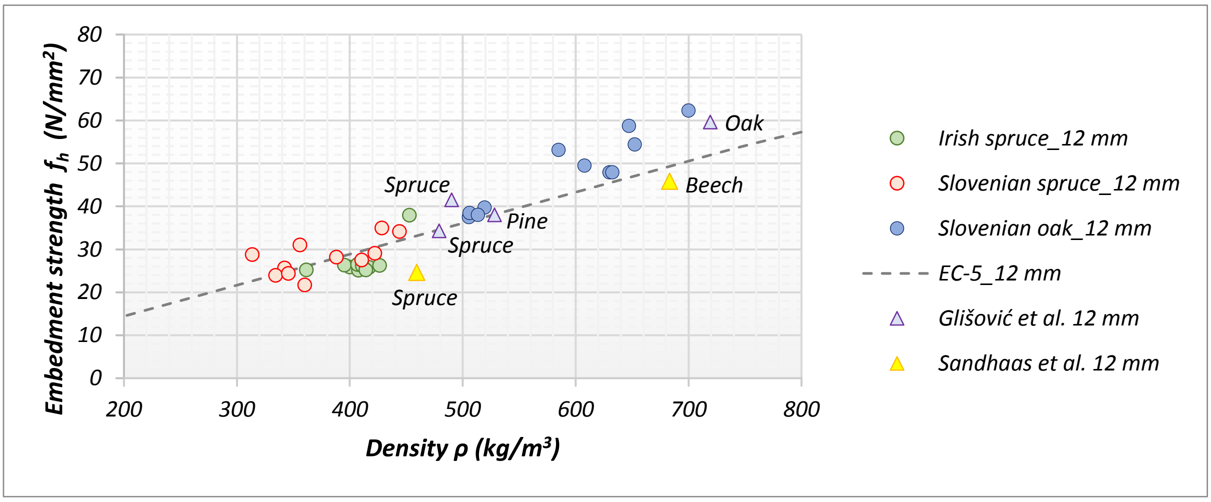


Figure 4-13: Embedment strength v density (12 mm dowel parallel-to-grain)

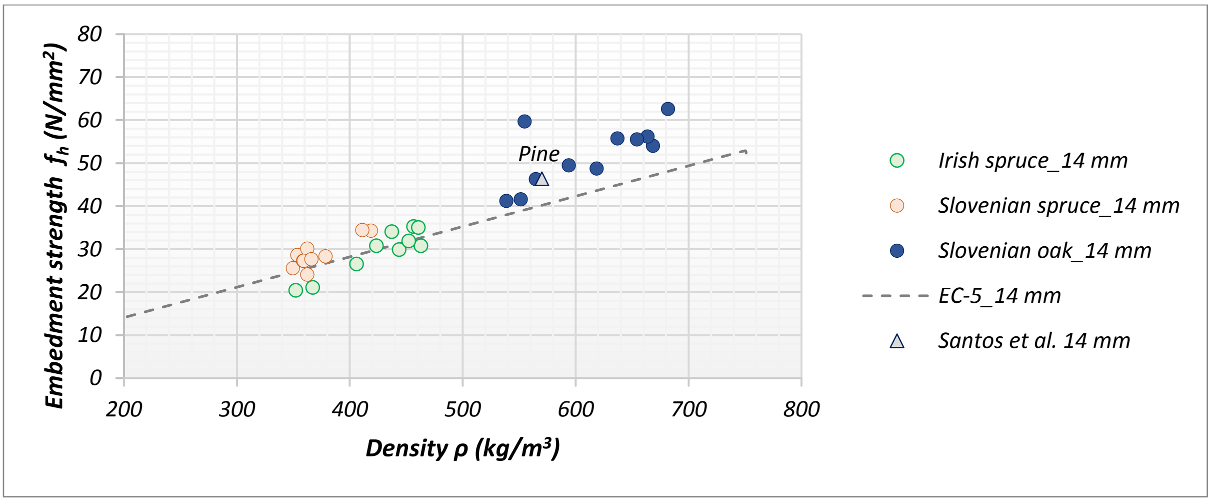


Figure 4-14: Embedment strength v density (14 mm dowel parallel-to-grain)

It is clear from the results of this experimental study on recovered timber that the embedment strength is strongly influenced by the wood density as has been reported in the literature for new timber. The embedment test results for Irish- and Slovenian-sourced recovered timber were comparable with mean values for new timber. The results for the specimens loaded parallel-to-grain were generally in line with the current Eurocode 5 (EN 1995-1-1, 2014) predictions. However, the Irish sourced recovered spruce values tended to be lower than the Slovenian spruce. The predictions for hardwood embedment strength were conservative.

Overall, the tests carried out in the parallel to the grain direction show that the embedment behaviour of the recovered timber is the same as new timber and the Eurocode 5 empirical models are a good predictor of the embedment strength of recovered softwood and hardwood. It is important to point out that the number of specimens tested was comparatively small and further testing is needed to confirm these findings.

Figure 4-15, Figure 4-16 and Figure 4-17 show the embedment test results of the specimens loaded perpendicular-to-grain for dowel diameters 10 mm, 12 mm, and 14 mm, respectively. The comparative mean values from the literature for new-timber and the EC-5 empirical embedment strength equations for softwood and hardwood are also shown. Similar to the findings from the parallel to the grain tests, the embedment strength of the recovered softwood and hardwood timber in the perpendicular to the grain direction is the same as new timber and the Eurocode models are appropriate.

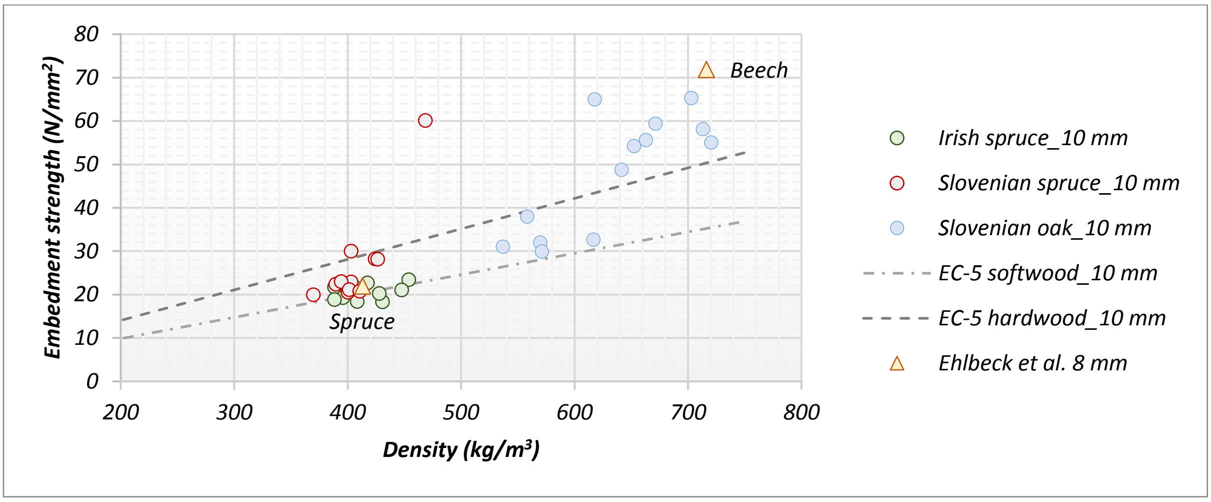


Figure 4-15: Embedment strength v density kg (10 mm dowel perpendicular-to-grain)

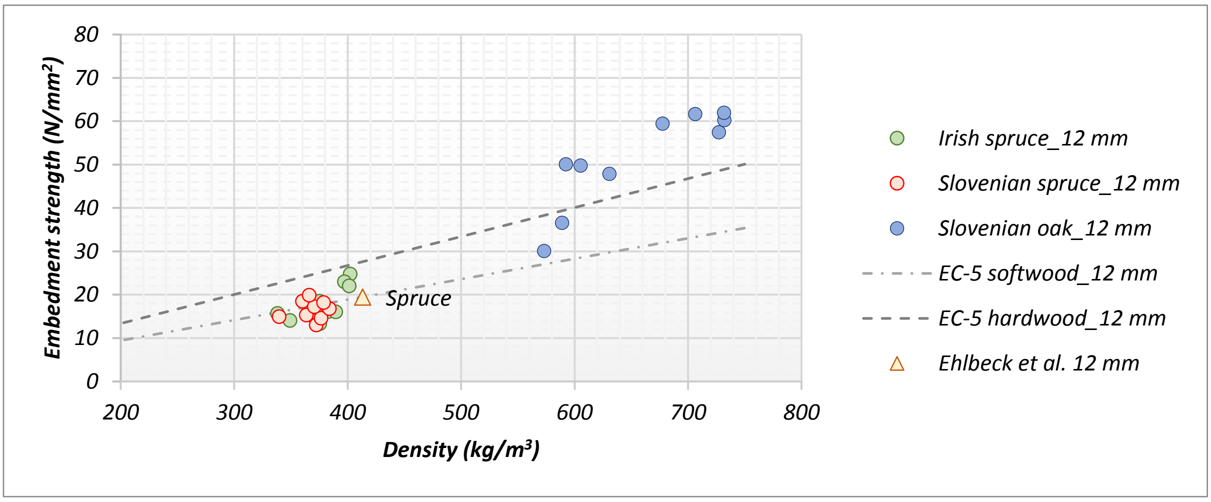


Figure 4-16: Embedment strength v density (12 mm dowel perpendicular-to-grain)

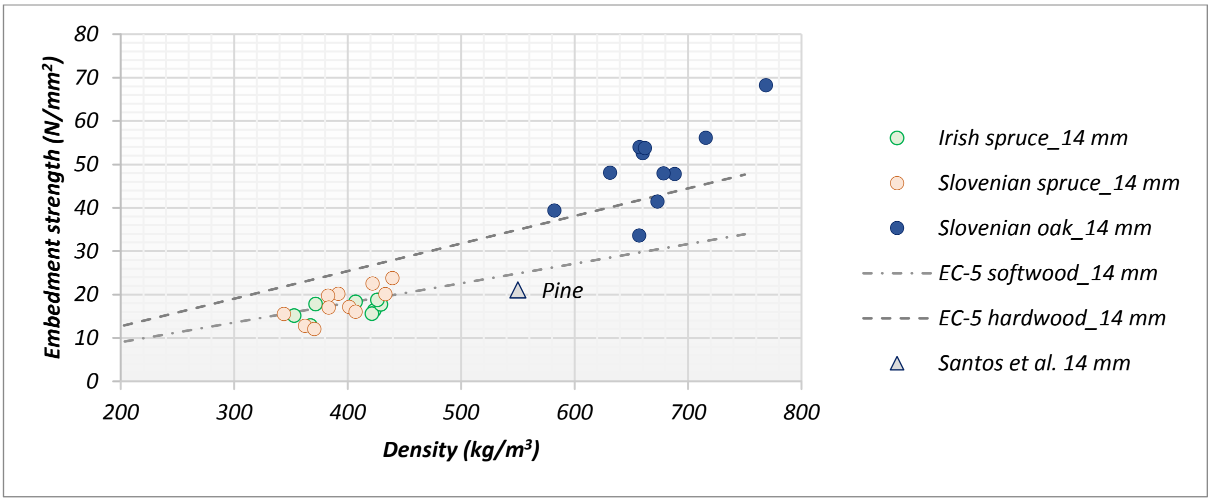


Figure 4-17: Embedment strength v density (14 mm dowel perpendicular-to-grain)

4.3.4. Influence of dowel diameter and species

To examine the differences between series tested parallel to the grain, boxplots of the embedment strength by diameter and species are presented in Figure 4-18. The oak series is clearly different to the two spruce series and there appears to be an influence of diameter. To statistically test the influence of diameter and species on the relationship between embedment strength and density, an analysis of variance was conducted on a linear model. It showed that the slope of the relationship is not significantly different for the three series examined. The higher embedment strength for the oak series is likely to be a consequence of the higher density. A one-way analysis of variance showed that there was no significant difference in embedment strength between the Irish spruce and Slovenian spruce series.

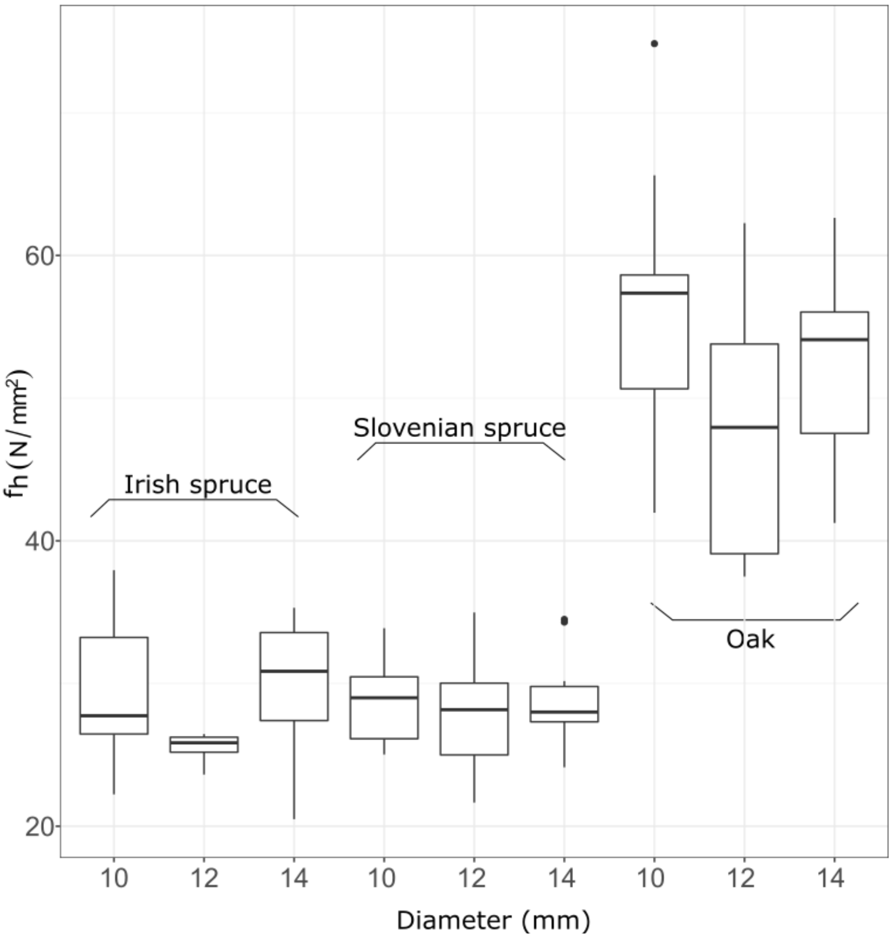


Figure 4-18 Boxplots of embedment strength by species and diameter – parallel tests

For the embedment tests conducted perpendicular to the grain, boxplots of the embedment strength by diameter and species are presented in Figure 4-19. Analysis of variance of a linear model shows that there is no significant influence of species on the relationship between embedment strength and density. The dowel diameter did not influence the slope of the relationship but did have an effect on the intercept, showing that with 14 mm diameter dowel, embedment strength was lower than the 10 mm and 12 mm dowel tests.

A one-way analysis of variance showed that there was a statistically significant difference between the embedment strength of the Irish and Slovenian spruce. The Tukey post-hoc test found that the 10 mm Slovenian spruce test results were different to the other five spruce groups and there was no difference between the other five groups. This finding is likely due to the small number of tests in each group and would need to be checked by further testing.

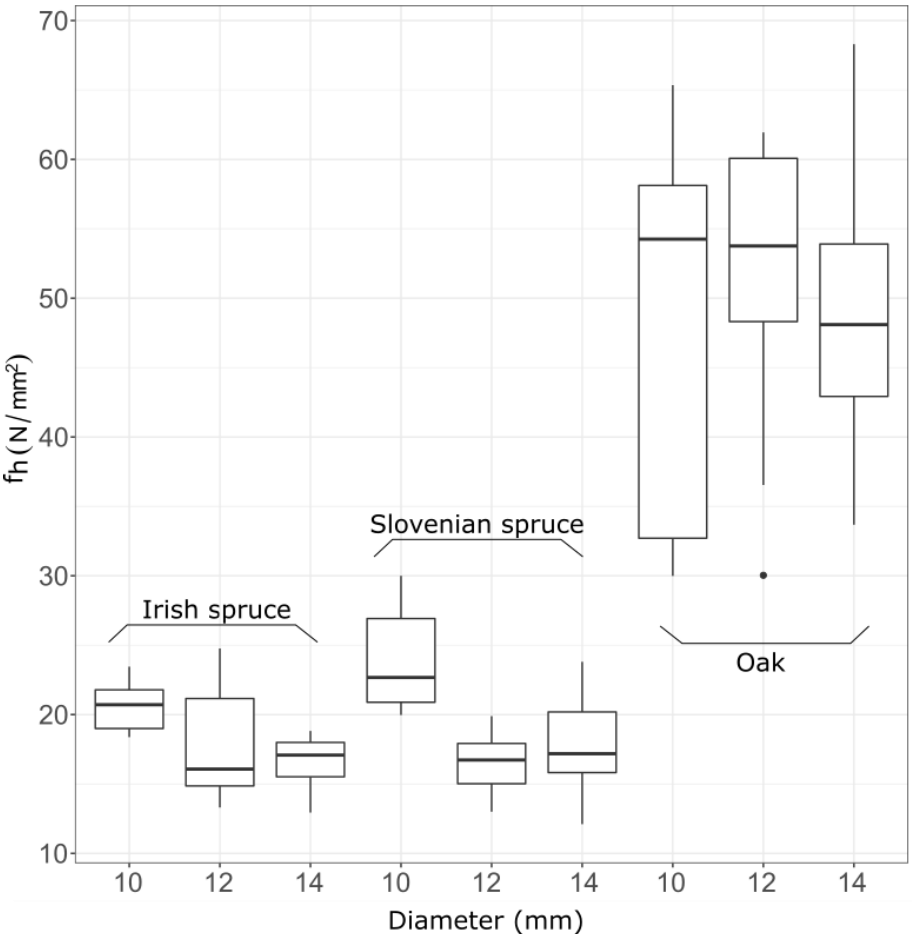


Figure 4-19: Boxplots of embedment strength by species and diameter – perpendicular tests

4.4. Conclusions of embedment testing programme

The embedment strength of Irish sourced recovered spruce, Slovenian sourced recovered spruce and recovered oak timber with high-strength steel dowels of three different diameters was measured. The specimens were tested in compression parallel, and perpendicular to the wood grain in accordance with EN 383 (2007) and EN 26891 (1991)**.** In all, 191 specimens were tested, comprising 59 and 65 specimens of Irish and Slovenian spruce, respectively, and 67 specimens of Slovenian oak. The results were compared with published data on the embedment strength of new timber and were also assessed with respect to the current structural hardwood and softwood design values prescribed in EN 1995-1-1 (2014) for embedment performance. The following observations on the test results were made:

- The wood density strongly influenced the embedment strength results.
- No significant difference in embedment strength parallel to the grain was found between the Irish and Slovenian sourced spruce.

- For the perpendicular to grain embedment strength, one of the Slovenian spruce groups was found to be significantly different to the other Slovenian spruce group and to the three Irish spruce groups. This may be due to the small number of tests carried out.
- In the parallel to grain tests, 33% of Slovenian spruce and oak specimens and 27% of Irish spruce specimens failed by splitting before reaching 5 mm displacement.
- In the case of the perpendicular-to-grain embedment tests, an embedment of 5 mm was reached in all but one Slovenian spruce specimen in a 10 mm dowel test.
- The 14 mm dowel tests perpendicular to the grain results in lower embedment strength than the 10 mm and 12 mm dowel tests.
- The embedment strength values for the recovered Irish- and Slovenian-sourced timber were comparable with mean values for new timber reported in the literature.
- The embedment test results were generally in line with the current Eurocode 5 (EN 1995-1-1, 2014) predictions.

5. Comparison of the environmental impacts of CLT made from recovered and primary timber

Michael Risse, Michael Stemmer, Raphaela Ivanica, Klaus Richter

5.1. Introduction

The conversion of the European economy towards a bio-based economy, using renewable resources as main feedstock for the production of material and energy goods, will likely increase demand for wood resources. A common strategy to contribute to the increasing demand while respecting the sustainability principle of forest management, is the concept of wood cascading. Wood cascading is defined as the sequential use of one unit of a resource in multiple material applications with the energy recovery as final step (Risse, 2019). The use of recovered wood in high value applications such as CLT, can contribute to the implementation of the wood cascading concept into practice. However, wood recycling in material applications may not *per se* result in the expected reduction of environmental impacts, compared to alternative utilisation options or functionally equivalent products. Therefore, to avoid a misleading technology development and political or industrial decisions, an analysis of the environmental impacts of the recycling of recovered wood in CLT products is of great importance. The analysis can further identify the key factors contributing to the overall environmental impacts and thereby highlight the potential for technological improvement.

This section provides a brief summary of the comparison between the environmental impacts of CLT from recovered and primary wood using LCA methodology. The work was conducted within work package 6 of the InFutUReWood project. Further methodological details, scenarios and results from the analysis can be found in the associated report from WP 6.

5.2. Goal and scope definition and inventory modelling

The LCA analysis is based on the technological development and testing of CLT from recovered wood as presented in this report. However, as the technological development is conducted on lab scale, which is not comparable to industrial manufacturing, the modelling of the recovered wood processing within the LCA was adjusted to industrial scale.

For the environmental impact assessment of the CLT from recovered wood, a Life Cycle Assessment was performed in accordance with the DIN EN ISO 14040:2021-02 and DIN EN ISO 14044:2021-02 standards. The CLT from recovered wood is compared with a functionally equivalent CLT panel from primary wood of the same dimensions. Since a CLT panel is primarily used in building construction as wall and floor element, the functional unit is defined as 1 m² of wall area with a thickness of 115 mm, composed of three layers, with an additional generation of 342 MJ of electricity and 1026 MJ of heat. The choice of wall area as functional unit would further allow the comparison of a CLT panel with functionally equivalent non-wood products used in wall constructions (e.g. concrete, brick), also under the consideration of other properties, such as heat transmission.

The system boundaries for the comparison are illustrated in Figure 5-1. For the recycling of recovered solid wood (RW), it is assumed that the recovered solid wood is composed of fractions from demolition, transportation or packaging, among others. Therefore, the material is very heterogeneous with respect to dimensions, impurities and potential contamination with wood preservatives. As a consequence, a sorting and decontamination process is considered as a first step for the processing of the recovered wood. In the lab work of WP 3, a similar sorting was performed manually in a workshop, whereas for the LCA assessment, an industrial scale was modelled, to be consistent in the comparison with CLT from primary wood. The modelling of the sorting and decontamination of the recovered wood is based on a recycling process of recovered solid wood into clean (i.e. free from impurities and contaminants) and standardised lamellae, developed in a previous research project (Irle et al., 2018; Irle et al., 2015; Privat, 2019; Privat et al., 2016). The obtained lamellae are comparable to sawn timber from primary wood and are kiln dried to reduce the moisture content from 22 % (Privat, 2019) to 13 %. The lamellae are further processed in the CLT manufacturing plant. All discarded pieces (e.g. curved wood), off-cuts, saw dust and chips are considered to be incinerated in a combined heat and power (CHP) plant on site.

For the inventory modelling of the sorting and decontamination process of recovered solid wood, inventory data was used from Risse (2019). The inventory data was specified and adjusted based on the observations from the lab work in WP 3 and expert judgement. For the CLT manufacturing, inventory data for CLT from primary wood was used as basis and modified to the use of recovered wood according to the experiences from the lab work and expert judgement. The modifications relate, for example, to a greater wear of metal tools and a higher glue consumption per m² due to the likely smaller lamellae obtained from recovered wood. The main system modelling considerations are available in Table 5-1.

Table 5-1: Adaptations to the inventory model accounting for the use of recovered wood instead of primary wood. RW = Recovered wood, PW = Primary wood

	RW system	**PW system**	**Source**
Additional wearing of blades/saws in decontamination process in %	25%	-	WP 3 lab work
Additional effort in CLT manufacturing using recovered wood in %	25%	-	WP 3 lab work

In the primary wood (PW) system, the CLT is manufactured from primary roundwood. The roundwood is processed in a sawmill into lamellae and then transported and processed in a CLT manufacturing plant. The modelling covers the current state of the art technology and manufacturing of CLT in Germany. Similar to the recovered wood system, it is also considered that the off-cuts, shavings and sawdust are incinerated in a CHP plant on site.

The inventory for CLT from primary wood as well as all background processes of both systems were modelled using the ecoinvent database v.3.7.1 (Wernet et al., 2016) and partly modified by literature data.

To achieve functional equivalence between both systems, system expansion (SE) was applied. As a consequence of the different amounts of wooden by-products incinerated in the CHP plants of both systems, a larger quantity of energy is generated in the recovered wood system. Therefore, the primary wood system is expanded with the energy provision from a) the German grid mix and b) primary wood, to account for the decisive influence of energy generation modeling in system expansion.

The LCA was conducted using openLCA 1.10.3. For the life cycle impact assessment, the LCIA method ReCiPe (H) 2016 (Huijbregts et al., 2017) at midpoint level was applied.

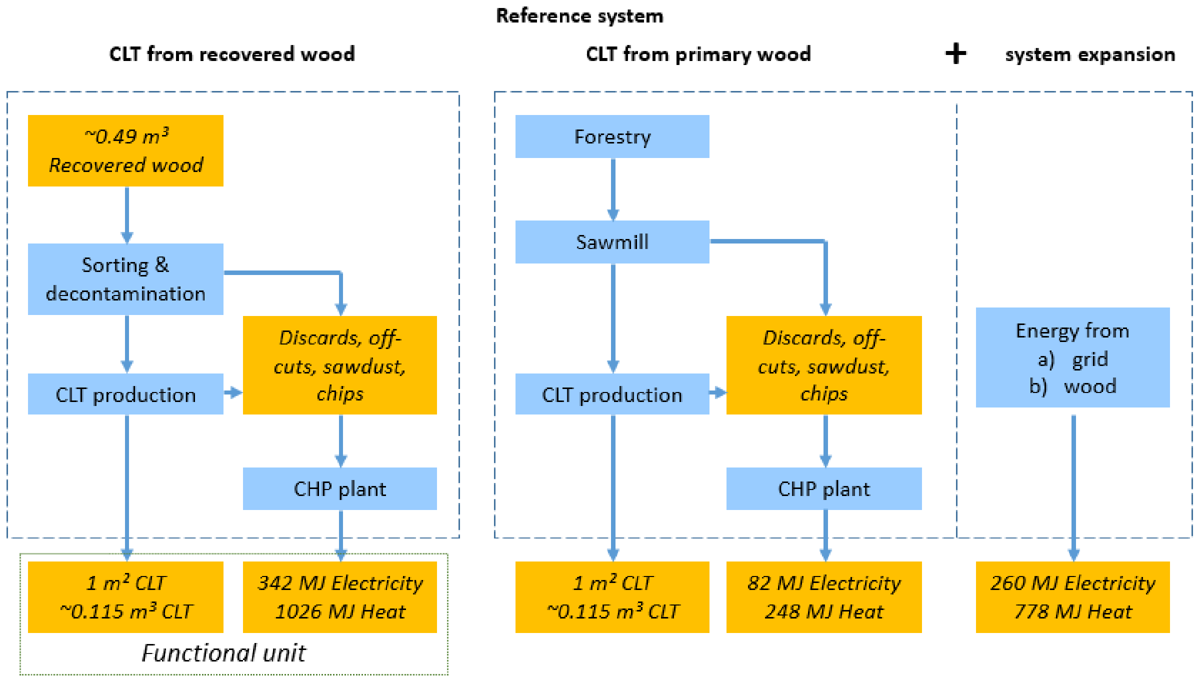


Figure 5-1: System boundary for the comparison between the environmental impacts of CLT from recovered and primary wood.

5.3. Results

5.3.1. Environmental impacts

The overall environmental impacts from the LCA calculation are presented in Figure 5-2. For most impact categories, the recovered wood systems perform better compared to both primary wood systems. In the impact category of Human non-carcinogenic toxicity potential, the recovered wood systems perform worse. The main contributor to the impacts of human non-carcinogenic toxicity is the incineration process, in particular the ash treatment. Due to the potentially high share of toxic substances in the ash from contaminated, i.e. chemically treated or coated recovered wood, the impacts are very high compared to the alternative systems.

The system expansion processes dominate the results of the primary wood system and the comparison. In particular, the fossil-based energy generation in the German grid mix (SEgrid), contributes to high environmental impacts in all categories, in particular the GWP, FRS, SOD and FE. The modelling of the system expansion from primary wood (SEwood) system in contrast follows the assumption of the same resource types as inputs to the systems. Given the higher moisture content of the primary wood used for energy generation, the required quantities are higher compared to the amount required from the drier recovered wood in the RW system. This explains the higher impacts of the SEwood system compared to the RW system.

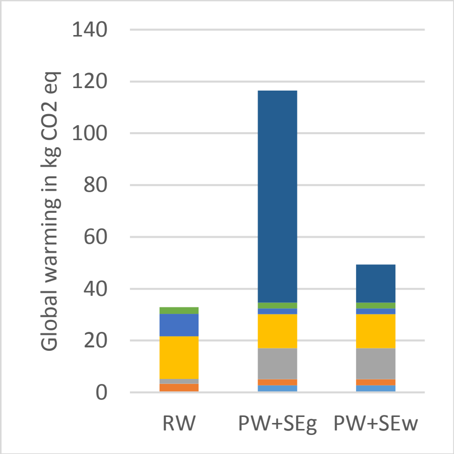
For several impact categories, the comparison of the CLT manufacturing only (without SE) reveals, that the RW system performs worse (FMP, HCT, HNCT, MRS, TA). In these impact categories, the adaptations to the RW system along with the greater emissions from the wood incineration, result in higher impacts. However, this comparison disregards the energy provided from the system.

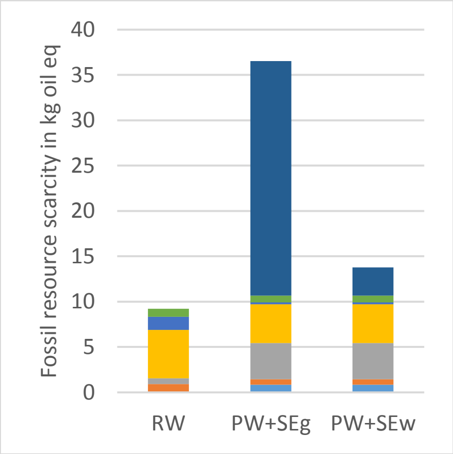
One of the main benefits from the recycling of recovered wood into CLT panels can be observed from the land use impact category. The recycling in material applications avoids the use of large quantities of primary resources, i.e. land resources. As wood is a renewable resource, the roundwood from the saved land resources could be used for alternative applications to further increase the amount of wood products on the market.

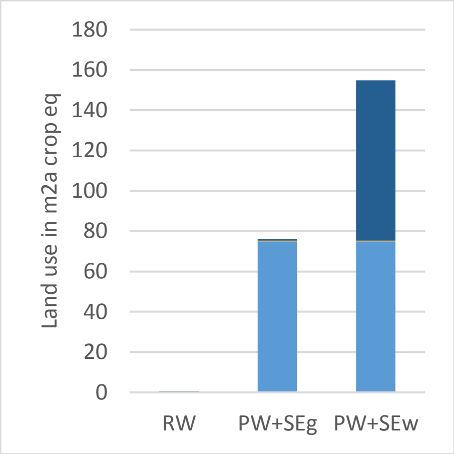
Depending on the impact category, either the incineration or the CLT manufacturing contribute the most to the environmental impacts of the RW system. In CLT manufacturing, the up-stream production of the fossil-based wood glues as well as the energy demand create the highest impacts. As consequence of the modelling choices of a higher input demand during the CLT manufacturing using recovered wood, the total impacts from the CLT manufacturing is 25% higher in the RW system. The contribution to the overall impacts of the CLT manufacturing is similar in the PW systems, when the SE is disregarded. The large contribution of the incineration process to the overall impacts can be attributed primarily to nitrous and phosphorous emissions, large quantities of fine particulate matter emissions as well as the heavy metal flows from ash treatment. In the PW systems, the second highest contribution was the drying process. The drying is of much smaller relevance for the RW system, due to the reduced energy demand. The transportation is of minor relevance in both systems, which can be attributed to the considered transportation distances for the recovered and roundwood only.

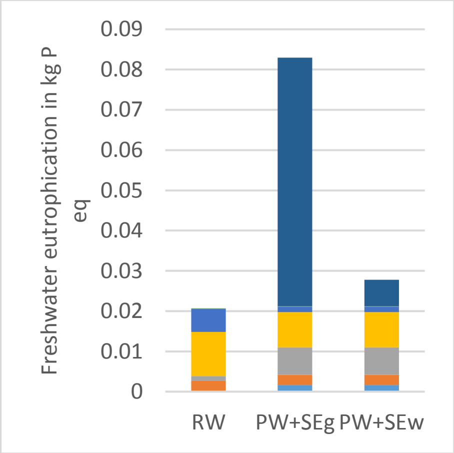
For the provision of the functional unit of 1 m² of CLT and energy, 0.49 m³ of recovered wood are required. The modeling approach of comparing the impacts of recovered and primary CLT follows the assumption, that recovered wood is an alternative resource available for utilization. This perspective is driven by the current momentum in research and industry, which indicates a strong focus on circularity and wood cascading concepts. However, this perspective disregards the current treatment of recovered wood as waste material and thus treatment in incineration or landfilling, depending on the European country.

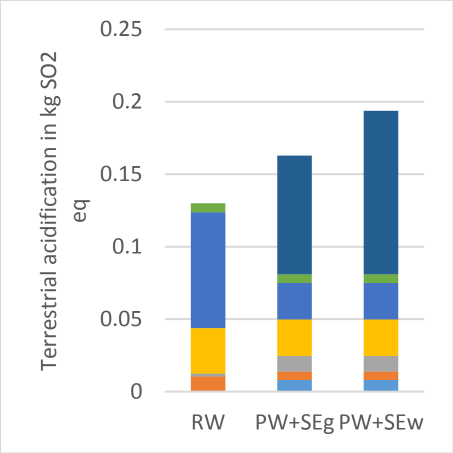
Due to the geographic scope of the modelling of the study, the presented results refer to the conditions in Germany. Adaptions in the energy grid mix as well as the transportation distances (e.g. for Sweden) will influence the results. However, in both cases, the results would affect both systems.

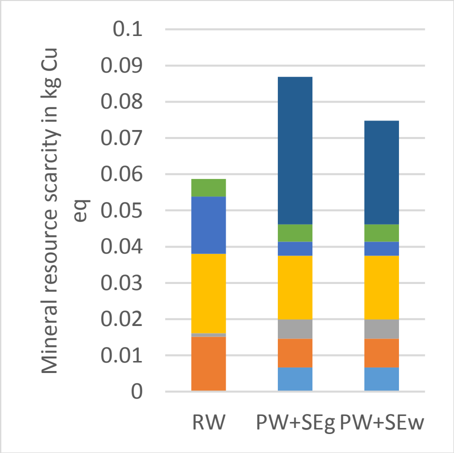

Global warming in kg CO2 eq
140
120
100
80
60
40
20
0
RW
PW+SEg
PW+SEw

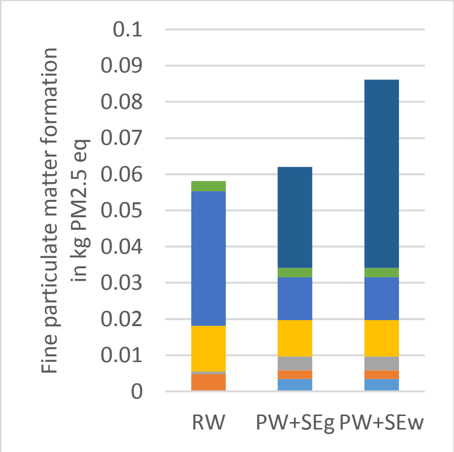

Fossil resource scarcity in kg oil eq
40
35
30
25
20
15
10
5
0
RW
PW+SEg
PW+SEw

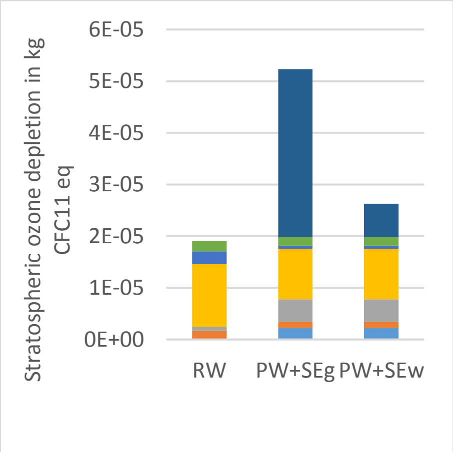

Land use in m2a crop eq
180
160
140
120
100
80
60
40
20
0
RW
PW+SEg
PW+SEw

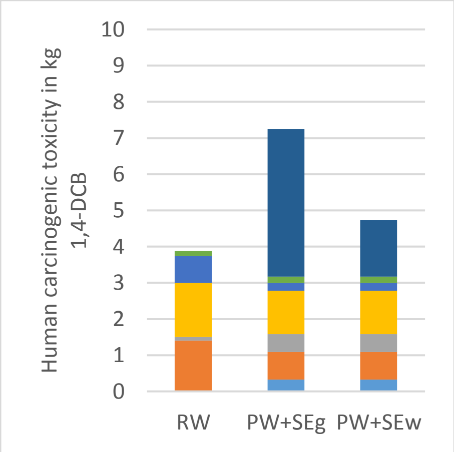

Freshwater eutrophication in kg P eq
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
RW
PW+SEg
PW+SEw


Terrestrial acidification in kg SO2 eq
0.25
0.2
0.15
0.1
0.05
0
RW
PW+SEg
PW+SEw


Mineral resource scarcity in kg Cu eq
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
RW
PW+SEg
PW+SEw


Fine particulate matter formation in kg PM2.5 eq
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
RW
PW+SEg
PW+SEw


Stratospheric ozone depletion in kg CFC11 eq
6E-05
5E-05
4E-05
3E-05
2E-05
1E-05
0E+00
RW
PW+SEg
PW+SEw


Human carcinogenic toxicity in kg 1,4-DCB
10
9
8
7
6
5
4
3
2
1
0
RW
PW+SEg
PW+SEw

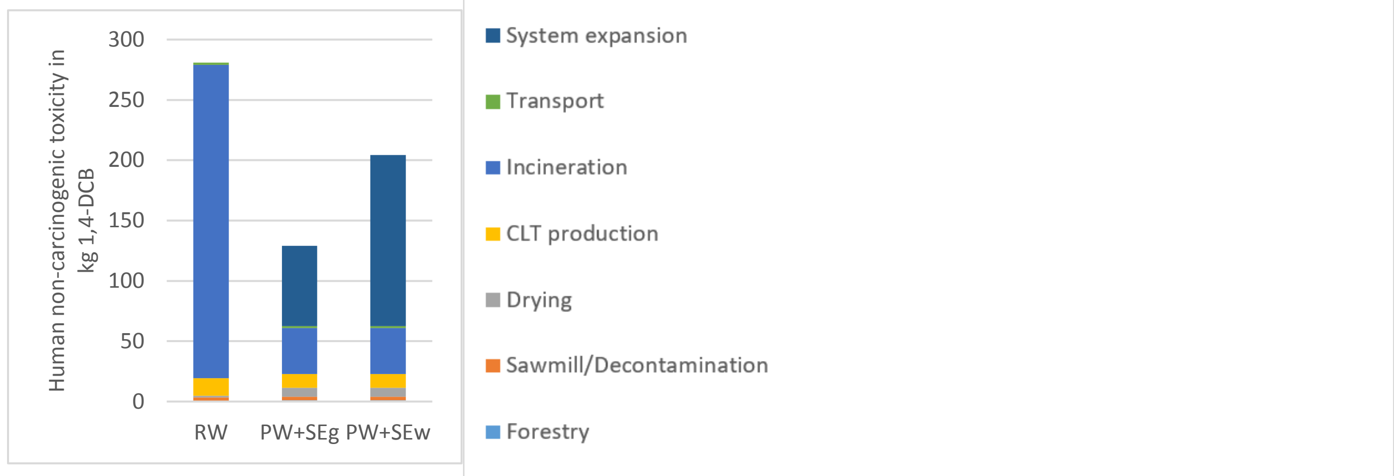


Figure 5-2: Environmental impacts of 1 m² of interior wall made from CLT from recovered wood (RW) and primary wood (PW). SE = System expansion with energy from grid (g) or primary wood (w).

5.4. Conclusions

The LCA comparison indicates that the use of recovered wood in CLT manufacturing is a feasible environmental option, when compared to the use of primary wood. In most categories, the use of recovered wood results in lower or similar environmental impacts, despite the consideration of higher inputs (e.g. glue, metal) for the use of recovered wood. Only the incineration of the contaminated fractions of the recovered wood results in higher environmental impacts in some categories. A reduced utilization of wood preservatives would thus lower the impacts during recycling processes as well as during the end of life treatment. The impact savings from the reduced drying effort for the recovered wood motivate to keep the material dry during disassembly and the recovery process. The use of recovered wood as resource results in the saving of primary resources, of land area, which would be available for further wood production, given the renewability of wood resources. Overall, it can be concluded, that the use of recovered solid wood in high valuable material applications like CLT is to current knowledge an environmentally feasible option and can contribute to the implementation of wood cascading as part of a bio-based economy.

6. Conclusions

One of the key objectives of the InFutUReWood project is to identify potential new construction products using recovered timber. This report presents the results of a number of studies carried out in Ireland, Spain, Sweden, the UK and Germany to achieve this objective. Experimental test programmes were conducted to determine the technical feasibility of producing high-performance mass-timber construction systems from recovered softwood and hardwood. In addition, a life cycle analysis (LCA) study was undertaken to assess the relative environmental impacts of CLT products from recovered and new timber.

6.1. Mass timber products from recovered timber

Mass timber products from recovered and new timber were manufactured, tested and their relative performance assessed. Studies were carried out in Ireland on CLT panels manufactured from recovered spruce and in Spain on CLT panels and GLT beams manufactured from recovered oak. Similar reference CLT panels and GLT beams manufactured from new timber were also tested. Finally, hybrid panels and beams using mixed recovered and new timber were investigated. Testing these products in bending in accordance with European standards has shown no significant difference in the mean flexural stiffness of recovered, new and hybrid CLT panels manufactured from softwood or hardwoods. A similar conclusion can be drawn for the stiffness of GLT beams manufactured from recovered and new oak. No difference was found between the mean bending strength of CLT panels manufactured with recovered and new softwoods with slightly lower values for the hybrid panels. For CLT panels manufactured with hardwood timber, lower values of bending strength were obtained for panels with recovered timber in the longitudinal layers than those with new timber. For all panels tested, strength values were high and suitable for structural applications. Similarly, while the bending strength was lower for GLT beams manufactured from recovered oak, the values were high enough for structural applications. It can be concluded from these two studies that the mechanical performance of mass timber products from recovered softwood and hardwoods is comparable to those of similar products made with new timber and both are suitable for structural applications. It should be borne in mind that the number of specimens tested in both cases was small and validation of these findings on a larger sample size is recommended.

The main issue identified during preparation of the recovered material for reuse was the removal of metal as detection of embedded metal was sometimes a challenge and this Regarding the yield from the recovered timber, for Irish study the yield was only 28% due to the difference in size between the recovered boards and the final dimensions for CLT manufacture. To achieve higher yields, a wider range of recovered timber sizes would need to be available commercially. In the case of Spanish mass timber products, the yield was even lower (around 15%) as the recovered timber was of large cross-section and a significant amount of wood waste was generated in sawing into smaller sizes. In terms of yield, mass-timber products are a good option for recycling medium cross-section recovered timber (e.g. joist and roof rafters). However, for large cross-sections, direct reuse for rehabilitation works will be a more efficient use of the material.

In Sweden, spruce timber recovered from three buildings was used in the manufacture of an IsoTimber wall panel, which was tested in compression. For this panel, recovered timber was used for the uprights and new timber for the structural frame. Compression tests carried out on this panel and panels manufactured using new timber showed that both had minimum load capacities of 400 kN. However, there was a significant stiffness reduction above 270 kN for the panel with recovered timber compared with panels with new timber. As only one panel was manufactured from recovered wood, it is not possible for draw firm conclusions but the following lessons were learnt that will be useful for the company IsoTimber, which intends to use recovered wood in its manufacturing process and to undertake further comparative studies of new and reclaimed wood used as component of a structural elements.

6.2. Quality assessment of adhesive bonding in recovered timber products

As good bonding between the individual lamella is key to structural integrity of mass timber products, experimental investigations were carried out in Ireland, Spain and the UK to characterise the integrity of adhesive bonds in mass timber products using recovered timber. In the Irish study, specimens from the CLT panels manufactured with recovered spruce and the hybrid CLT panels made with recovered and new timber outer layers satisfied all the requirements of the CLT product standard with respect to delamination and shear strength. Delamination and shear tests in the Spanish study showed that recovered oak timber glues better than new oak. The reason for this may be due to the fact that the surface texture of the recovered timber after planing was rougher than that of new. The UK study showed that glue lines in GLT beams manufactured from recovered spruce had a level of performance one would expect to see in equivalent glulam from new timber. The results of these three studies show that designers can be as confident in the use of recovered timber as with new timber with respect to the bond strength of CLT panels.

6.3. Embedment performance of recovered spruce and oak

Having established the potential to produce high-quality mass timber products from recovered timber. The next step was to consider structural connections. Dowel type connections are widely used in timber structures. As the structural capacity of these types of connections depends on the embedment behaviour of the timber, an experimental programme was carried out in Ireland to characterise the embedment strength of recovered spruce and oak sourced in Ireland and Slovenia. In all, 191 samples were tested in embedment parallel to the grain and perpendicular to the grain using high strength dowels of three different diameters. The wood density was found to have a significant influence on the embedment strength. The embedment strength values for the recovered Irish and Slovenian sourced timber were comparable with mean values for new timber reported in the literature. As the embedment test results were generally in line with the current Eurocode 5 predictions for new softwoods and hardwood, it can be concluded that current Eurocode design guidelines for dowel-type connections can be used for connection between timber elements from recovered timber.

6.4. Life cycle assessment of recovered CLT manufacture

The environmental LCA study carried out in Germany concluded that the use of recovered wood in CLT manufacturing is a feasible environmental option, when compared to the use of primary wood. In most impact categories, the use of recovered wood results in lower or similar environmental impacts, despite the consideration of higher inputs (e.g. glue, metal) for the use of recovered wood. Only the incineration of the contaminated fractions of the recovered wood results in higher environmental impacts in some categories. A reduced utilization of wood preservatives would thus lower the impacts during recycling processes as well as during the end of life treatment. The impact savings from the reduced drying effort for the recovered wood motivate to keep the material dry during disassembly and the recovery process. The use of recovered wood as a resource results in the saving of primary resources, in particular of land area, which would be available for further wood production, given the renewability of wood resources.

Overall, it can be concluded, that the use of recovered solid wood in high valuable material applications like CLT is to current knowledge an environmentally and technically feasible option and can contribute to the implementation of wood cascading as part of a bio-based economy.

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