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THE REUSE POTENTIAL OF RECLAIMED LOGS FOR OPTIMISED ENGINEERED WOOD PRODUCTS

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ABSTRACT: The research presented in this paper aims to optimally use reclaimed logs to produce new engineered wood products. The process involved preparing the source material, mapping its geometry, and determining the strength and stiffness properties of the resulting boards through visual inspection and non-destructive mechanical testing. The non-destructive testing included four-point bending tests conducted on two faces of the lamellae to calculate the overall modulus of elasticity for the entire element. Additionally, tests were performed at six points to identify the strongest and weakest sections of the lamellae. After measuring, grading, and conducting non-destructive testing of the lamellae, the aim was to optimize the selection and assembly of the best-performing lamellae into three "super beams" that exhibited superior strength and stiffness. The remaining lamellae were used to produce regular beams. The performance of the final products was assessed by testing the stiffness and strength of the glulam beams, the shear strength of the bond line, and the integrity of the bond line in fire conditions.

KEYWORDS: reclaimed timber, bond line integrity, glulam, material quality assessment

1 - INTRODUCTION

As a renewable resource, Timber holds significant promise for recycling, particularly given the scalability and versatility of wood reprocessing techniques. When structural timber reaches the end of its load-bearing lifespan as-is, it can be repurposed into glued laminated timber (GLT), cross laminated timber (CLT) or further processed for non-structural uses, such as panels derived from wood chips or fibres. This study adopts an innovative, applied experimental method to assess the feasibility of recycling century-old spruce (*Picea abies*) timber lamellae from Norway. These lamellae, originally part of an aged barn structure, were extracted from round logs and passed through a planer to achieve more even surfaces suitable for gluing.

The novelty of this research lies in its non-destructive bending tests conducted on the reclaimed specimens. By conducting 4-point non-destructive bending tests on two sides and at six distinct points along the lamellae, the authors were able to identify the side exhibiting the highest modulus of elasticity (MoE), a key parameter of stiffness, as well as the calculation of the average MoE across different zones of the specimen, rather than just the middle span. This method offers the potential, for example, to strategically remove the weaker regions at the beam's ends in longer spans or the placement of areas with higher MoE in sections subject to greater applied loads. Moreover, this method enables the analysis of localized defects and their impact on overall structural performance. Instead of discarding an element due to a single defect, this technique allows the defect to be removed or repositioned to a lower-stress area, thereby optimizing material usage.

The implications of this research go beyond structural analysis and contribute to the growing focus on environmental sustainability within the construction industry. This study demonstrates how recycling aged

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timber can reintroduce decommissioned wood into construction, reducing waste, conserving resources, and lowering carbon emissions. It supports sustainable practices and promotes a circular economy, showing the potential of innovative recycling in the construction industry.

2 - BACKGROUND

Building construction, use, and renovation require substantial energy and raw materials (e.g., sand, gravel, cement). Buildings account for 40% of the total energy consumption [1] This encompasses a significant and broad issue, for which various measures already exist to address or at least mitigate the problem. However, innovative solutions for reducing the environmental footprint of the construction sector are always sought. This research contributes to this effort by focusing on the production of new engineered wood products from old, reclaimed timber.

Some studies on related topics have been conducted, but they are relatively scarce. Despite the limited number of studies, the results have generally been encouraging, providing justification for further in-depth research on the topic, for instance, in an article by Carrasco et al. [2] CLT panels were fabricated using reclaimed railway ties, yielding positive results. The manufacturing process employed an automatic press and varied pressure values, with hardwood incorporated into the CLT panels. The mean density of the panels was 840 kg/m³. The findings from these tests showed that the production of new engineered timber products from reclaimed wood is a viable and feasible approach.

Another study explored the potential of using reclaimed timber in the transverse layers of CLT panels. They employed MUF glue for production and found no issues with the bonding quality of reused timber. The study examined 226 pieces, and the results show that recycled timber is highly suitable for CLT production when appropriately managed during the end-of-life process [3]

In the study by Daniel F. Llana et al. [4] 12 CLT panels made from reclaimed timber were analysed for rupture sections, amongst other properties. The results showed that all panels failed due to timber tension failure in the central section, like CLT made from new timber. No significant differences were observed in the MoE between reclaimed and new timber panels. Although the bending strength of reclaimed timber was slightly lower, it was still sufficiently high (at least 35 N/mm²) for all structural uses.

3 - PROJECT DESCRIPTION

This study used 39 spruce (*Picea Abies*) wood test specimens sourced from a barn over 100 years old in Norway. Cut initially from round logs, the lamellas were processed into rectangular cross-sections measuring approximately 60x60 mm and around 4 meters in length. Initially, each lamella was labelled on its sides with letters A-D, and the start (S) and end (L) points were marked. The lamellae were then divided into seven equal sections, starting 200 mm from the beginning, with each subsequent section spaced 500 mm apart, as shown in Figure 1. The last section was positioned approximately 300 mm from the end to avoid defects at the lamella ends. This division enabled non-destructive testing at six different points on both sides (A and B) to determine the MoE at each location.

The aim was to assess the variation in stiffness along the lamella length and identify the strongest regions, optimising lamella placement when assembling the glued laminated beams. The strongest lamellae were grouped to form "super beams" while weaker lamellae were used in the central sections of the regular glulam beams. Despite

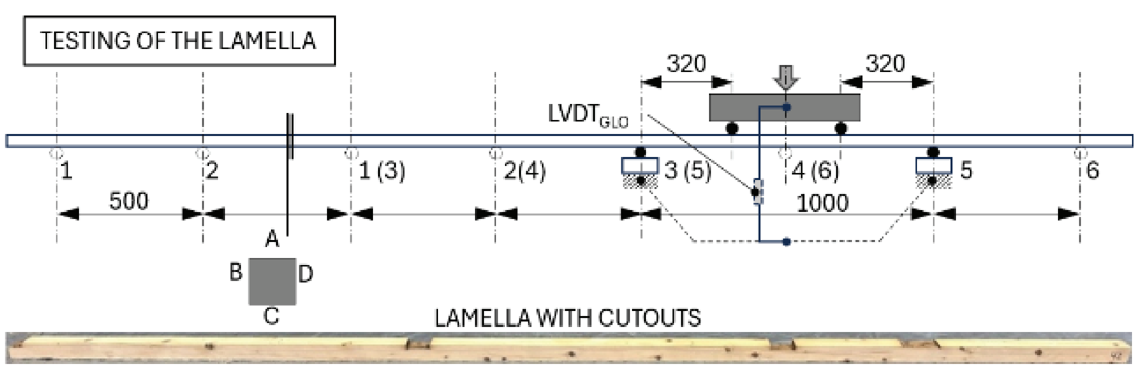

Figure 1 Marking of a test specimen and bending test setup according to the example in point 6.

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having 38 lamellae, 8 glulam beams, each containing 4 lamellae, were produced, as some were excluded due to excessive wane, which would have impaired adhesiveness based on visual inspection.

Three adhesives were employed: one-component PUR and two-component MUF and PRF. These adhesives were selected based on availability to determine which was most effective and easiest to apply in manual conditions for bonding reclaimed wood. Although this manual method was not the most precise, it was considered suitable for the preliminary phase of evaluating the feasibility and challenges of constructing laminated beams from reclaimed wood.

4 - EXPERIMENTAL SETUP

4.1 Modulus of elasticity and bending strength

The global bending MoE was determined and calculated following the guidelines of EN 408:2010+A1:2012 [5], which specifies that the specimen length must be (19±3) times the cross-sectional height, and the span should be (18±3) times the cross-sectional height. The test setup for determining the global bending MoE of the lamellae is illustrated in Figure 1. To minimize local crushing, 50 mm wide steel plates were placed between the load and the beam. The maximum load applied during the non-destructive test was $0.4F_{max,est}$. All 39 specimens were tested with the assumption that $0.4F_{max,est} = 3$ kN.

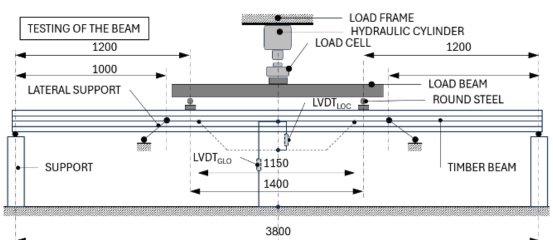

Figure 2 Four-point test setup for lamella and beam.

The lamellae were loaded in two transverse directions at half-meter intervals along a one-meter span. The span was repositioned six times along the element, resulting in 12 measurements across both directions. The symbols A–D in the figure indicate possible loaded sides - either B or D and A or C. A walter + bai LFM 600 universal testing machine was used for loading, and the global vertical displacement at midspan was recorded using an LVDT. It should be noted here that the lamellae had cutouts from the original log, which acted as weaknesses in the cross-section. These cutout areas were left within the flexural zone during the bending tests, potentially influencing the mechanical response and reducing the effective bending strength.

The glued beams with a span of 4 m were loaded using a manually operated Enerpac RC506 hydraulic cylinder. The applied load was measured with a Zemic BM24R-C3-60t-15G load cell. To mitigate the risk of lateral-torsional buckling, the beams were laterally supported at two points along the span (see Figure 3). Global and local vertical displacements at the midspan were recorded using LVDTs. Data was acquired with an HBM Quantum MX840B universal amplifier and Catman DAQ Software. The measurement points are indicated in the schematic diagram in Figure 2.

Figure 3 Photograph of a beam undergoing bending tests, showing supports designed to prevent lateral-torsional buckling.

4.2 Assembly of the glulam beams

After conducting non-destructive bending tests on each lamella at 6 points across two faces, the MoE was calculated for each section. The assembly of the glulam beams was based on the average MoE of the lamella's middle points (3 and 4) on both faces, with the results also being compared to the overall average MoE of the lamella to identify any potential defects, such as beams being strong in the centre but weak at the ends. To ensure uniform strength, the three strongest specimens were selected as base lamellas for each ‘’super beam’’, followed by the next strongest lamellae, etc. This approach was also applied to the standard beams, ensuring consistency and homogenization in glulam strength.

In addition to MoE, the lamellae’s appearance and quality were considered; specimens with high MoE but excessive wane or other defects were rejected. When a lamella's MoE was slightly higher on one side (e.g., side A), but that face’s surface was unsuitable for gluing, the weaker side (side B) was selected. Furthermore, elements with multiple cuts or irregular shapes were excluded as they could not be glued in their untreated form.

Three different adhesives were used for gluing: PRF, MUF, and PUR. Three beams were glued with both PUR and MUF, and two with PRF. The two-component adhesives were blended until homogeneous and applied manually with a paintbrush. The quantity of adhesive applied was close to the manufacturer's guidelines; however, accurately calculating the precise amounts was challenging. This is due to the potential reduction in adhesive surface area caused by the presence of wanes, while a higher amount of adhesive is required due to manual application. Additionally, the surfaces are generally less uniform compared to those of fresh wood, further complicating the estimation.

All lamellas were pressed together after the application of the adhesive using at least 16 lace screws, spaced 250 mm apart as shown in Figure 4. The recommended adhesive handling time was considered and was never exceeded. All glulam beams were kept under pressure following the adhesive manufacturer's guidelines.

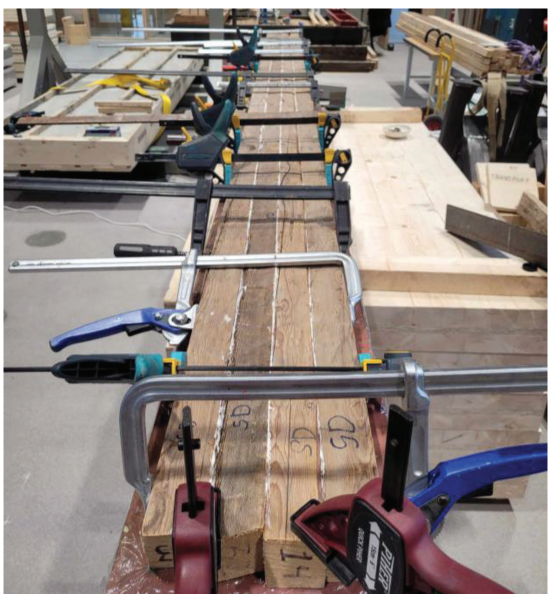

Figure 4 Assembly of freshly bonded glulam beam, secured with lace screws.

4.3 Bond line integrity in fire

Fire test specimens of glulam with a size of 100 x 100 x 60 mm were subsequently prepared from these blocks. The specimen consisted of two layers and the bond line in between. The thickness of the upper lamella was 20 mm and lower lamella 40 mm. A notch was cut on all sides using a thin band saw to define the tested bond line surface, reducing the surface area to 50 mm x 50 mm. Testing was performed with the heat flux 50 kW/m^2. The method is described in [6]. Specimens with all three different adhesives were assessed.

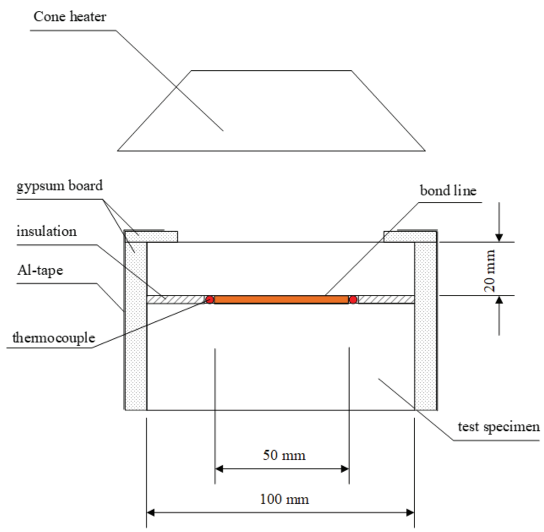

Figure 5 Test specimen setup under the cone heater.

The specimen was heated until the average temperature at the bond line reached 290°C. Then, it was removed from under the cone, the protective gypsum casing gently removed, and loaded in shear until failure. The failure load and mode were recorded for all specimens. Shear capacity was always conducted along the grain direction.

5 - RESULTS

5.1 Bending stiffness of the lamellae

Since the bending tests of the lamellae left weaknesses in the form of cuts within the tested area, the calculated MoE is conditional, representing the effective bending stiffness of the cross-section. Therefore, the value can vary along the length of the element by up to three times in the worst case. The difference in the average MoE when loading the cross-section in the two transverse directions differed, in some cases, by up to 49 %. Figure illustrates the stiffness values of the lamellae in the ‘’super beam’’ SB1-PUR beam as an example, where the number indicates the lamella, and the letter indicates the loaded side.

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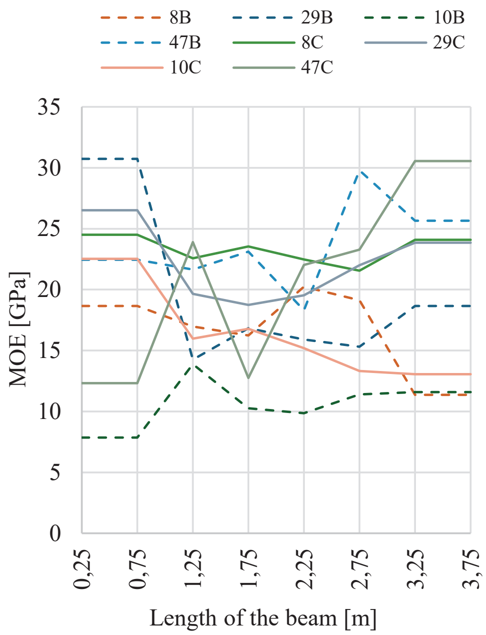

Figure 6 Stiffness values of the SB1-PUR beam lamellae.

After sorting the lamellae according to their modulus of elasticity and evaluating the adhesiveness of the corresponding surfaces, 32 lamellae were selected for eight beams. The variability of the MoE of this group was 27.1%.

The lamellae were distributed among the beams based on the average MoE from the mid-zone of the lamellae, which corresponds to the pure bending zone of the glued beams test. When comparing the mid-zone stiffness values with the overall beam stiffness, which accounts for the entire beam length, the results show a strong correlation, as illustrated in **Error! Reference source not found.**.

5.2 Bending tests of the beams

The results of the bending tests of the beams are presented in Table 1, ''SB'' in front of the specimen

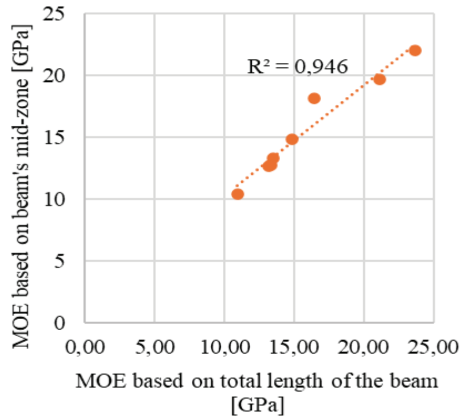

Figure 7 Correlation between the stiffness of the mid-zone and entire beam.

number indicating ''super beam''. Three of the eight beams were tested to failure, while the remaining five were only loaded within the elastic range. The full bending strength potential of the beams was not realized in any case. Two of the three beams failed in shear at the support, while the third experienced a combination of shear and bending failure, though the bending failure was not distinguishable. Notably, the beam with PRF glue exhibited an exceptionally brittle shear failure, which deserves special attention and further investigation.

The partially rounded corners of the lamellae led to an insufficient contact surface between them, which in turn was the primary cause of predominant shear failure – see Figure 8.

Figure 6 Insufficient contact surface between the lamellae.

Table 1 Bending test results of the glulam beams.

Type of glue	Specimen	MoE mid-zone: average of four lamellae [GPa]	MoE total length: average of four lamellae [GPa]	MoE test GLOBAL [GPa]	MoE test LOCAL [GPa]	Bending stress at maximum load level [GPa]	Failure mode
PUR	SB1-PUR	19,71	21,12	14,85	17,11	51,5	Bending/Shear
	PUR1	13,34	13,49	13,80	14,46	-	
	SB3-PUR2	22,03	23,66	12,90	16,35	-	
MUF	SB2-MUF	18,18	16,43	13,89	15,55	26,5	Shear
	MUF1	12,74	13,32	13,07	14,18	-	
	MUF2	12,68	13,16	14,99	15,09	-	
PRF	PRF1	10,40	10,94	11,64	10,45	17,5	Shear
	PRF2	14,88	14,83	12,12	11,23	-	

Among the tested beams, SB1-PUR provides the best indication of its potential if its full bending strength were realized, as the bending stress at failure reached 51.5 GPa. In comparing local MoE, the highest values were observed in the so-called ‘'super beams”, where the lamellae with the greatest stiffness were intentionally positioned. The correlation between the average stiffness of individual lamellae and the measured local MoE reached R=0.72, calculated for both the mid-zone and the entire lamella length – Figure 9. On the other hand, the correlation between the global elastic modulus of the beams and the theoretical result is very weak (R=0.2), probably due to the large shear deformations.

The coefficient of variation of the local MoE for the eight beams was 15.6%. However, it should be noted that the lamellae were not uniformly assigned to the beams based on stiffness ranking; instead, the stiffer elements were selectively grouped into the ''super beam''. Had the lamellae been assigned sequentially, the variation would have been lower, as demonstrated by the density by Tuhkanen et al. [7].

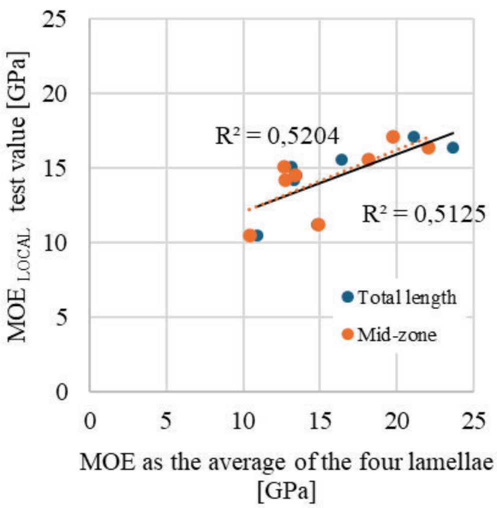

Figure 7 Correlation between the average stiffness of individual lamellae and the measured local MoE.

5.3 Bond line integrity in fire

The shear capacities of the tested bond lines were the following:

The specimen with PRF adhesive had wood failure at a shear load of 613N. The specimen with MUF adhesive had 50% wood failure and 50% adhesive failure at a shear load of 467 N. The specimen with PUR adhesive had adhesive failure at a shear load of 39N. Compared to the previous studies [8] it can be concluded that the bond lines with PRF and MUF adhesives indicate the behaviour with bond line integrity maintained in fire. Bond lines with tested PUR will most probably not be maintained in fire.

Figure 10 Specimens after fire test of bond line.

6 - CONCLUSIONS

An important observation from this study is that glulam beam failures predominantly occurred due to shear stress, with one exception exhibiting a combination of both shear and bending failure. To fully realize the potential strength of the beams, it is crucial to ensure uniform contact surfaces between the lamellae, facilitating their complete interaction. While the stiffness values of the cross-section can vary significantly along the beam's length, the combination of lamellae leads to sufficient homogenization, resulting in a more uniform structural response. Therefore, determining the stiffness along the entire lamella is not essential. Since all the beams failed due to shear, it is reasonable to use reclaimed wood in glulam as an additional stiffening element in the structure, meaning they should be designed for serviceability limit state rather than ultimate limit state as primary load-bearing elements. While they have high load-bearing potential, the rounded edges of the old wood pose a risk of shear failure. Therefore, using them as auxiliary elements is advisable, ensuring that their stiffness is fully utilized.

Initially, the authors hypothesized that the assembly of glulam beams from reclaimed timber could serve as an intermediary step toward the production of CLT, due to the perceived complexity of CLT manufacturing. However, after producing the glulam beams, it was suggested that glulam production may, in fact, present more significant challenges than CLT. This is primarily due to the smaller bonding surface in glulam, and the automated process with machinery could be challenging, as the irregular reclaimed timber could distort under the stress, causing the lamellas to shift. Although wanes in certain limits have not been shown to adversely affect the intrinsic MoE of the timber ([9], [10]) they surely appear to negatively influence the integrity of the adhesive bond in glulam, which is crucial to the overall structural

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performance. When considering adhesives, MUF and PUR performed better for manual application. PRF, on the other hand, was the most difficult to apply due to its short handling time and consistency. Additionally, it was the only adhesive to exhibit brittle failure during testing.

Although the assembly of glulam beams can be deemed successful, it is crucial to acknowledge the setbacks and challenges encountered throughout the process. A substantial number of failures can be attributed to handling-related errors, such as non-uniform glue distribution, inadequate glue application, and poor mixing of two-component adhesives, which compromise their efficacy. Furthermore, insufficient clamping force during the compression of the lamellae leads to a reduction in the final product's mechanical properties. These factors collectively suggest that producing glulam beams from reclaimed timber requires a more rigorous level of control and precision and presents greater complexity than initially anticipated.

The assembly process is further complicated by the need to mitigate distortion, which often requires passing the wood through a thickness planer. Such steps significantly increase both time and resource costs. Additionally, the variability of reclaimed wood raises important questions regarding the strength classification of glulam beams produced from reclaimed timber in comparison to newly manufactured beams, prompting the question of who is responsible for ensuring the strength of the final engineered wood product and how to confirm and guarantee its structural integrity effectively.

While nails used in traditional log construction are typically surface-mounted and can be easily removed, indicating the timber's potential for further reuse, this is not always the case with all reclaimed timber. In some instances, eliminating fasteners may require a time-consuming and labour-intensive process. Furthermore, for this research, long lamellae were available for direct use; however, reclaimed wood is often of inconsistent quality and length. Consequently, the next logical step for further research is using old timber for finger-jointing, as reclaimed wood from buildings is typically available in unsuitable lengths. While shorter elements are easier to transport, which reduces transportation costs, they also enable the reuse of a larger volume of wood waste, promoting sustainability in the production process.

7 - ACKNOWLEDGEMENT

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