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BENDING STRENGTH ANALYSIS OF NAIL-CROSS-LAMINATED TIMBER PANELS ASSEMBLED WITH WOODEN NAILS

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ABSTRACT: Engineered Wood Products (EWPs) are increasingly used in construction due to their sustainability and structural efficiency. Among them, Nailed-Cross Laminated Timber (NCLT) is a promising alternative to conventional Cross-Laminated Timber (CLT), using mechanical fasteners instead of adhesives. This study investigates the mechanical properties of NCLT panels assembled with densified wooden nails, focusing on their bending strength and modulus of elasticity. NCLT prototypes were fabricated using Scots pine (*Pinus sylvestris*) laminations from the Catalan Pre-Pyrenees, graded as C22 and C27 according to UNE-EN 1912, and assembled with beech wood nails treated with phenolic resin. The panels were tested under static bending conditions following UNE-EN 408, showing that NCLT panels exhibit bending strength comparable to that of the wood species used, while their modulus of elasticity remains relatively low. Shear deformation was observed between layers, affecting overall stiffness. These findings highlight the potential of NCLT with wooden nails as a sustainable construction material, further reducing carbon emissions by eliminating synthetic adhesives and metal fasteners. Future research should explore optimised nailing configurations and alternative densification methods to enhance mechanical performance for load-bearing applications.

KEYWORDS: wood, panel, stiffness, rolling shear, structural

1 – INTRODUCTION

The construction sector is increasingly shifting towards engineered wood products (EWPs) due to their ecological advantages. EWPs are wood-based materials created by binding smaller components to form larger, stronger, and more durable elements. These materials can replace traditional options like concrete or steel in structures, providing the same functionality. Additionally, constructing with EWPs optimises the inherent structural properties of wood, resulting in a more homogeneous product.

A significant benefit of EWPs is their ability to be prefabricated in factory settings before construction begins. This process enables better material classification, leading to higher-value products, reduced waste, and more efficient on-site assembly, which is faster, more precise, and easier.

The most used EWPs incorporate adhesives in their manufacturing process, such as glue-laminated timber (GLT), structural composite lumber (SCL), and cross-laminated timber (CLT). However, there are also adhesive-free alternatives, including Dowel-Laminated Timber (DLT), Nail-Laminated Timber (NLT), Nail-Cross-Laminated Timber (NCLT), and Interlocking Cross-Laminated Timber (ICLT). EWPs that use adhesives are more rigid, but they may be more complex to manufacture and, in particular, contain synthetic adhesives derived from petroleum-based chemicals. Moreover, they cannot be disassembled as easily as those that use mechanical fastening elements.

Nailed-Cross Laminated Timber (NCLT) panels combine characteristics of CLT and NLT. Like CLT, NCLT consists of layers of laminations arranged perpendicular to adjacent layers, but nails are used to fasten them instead of adhesives. While there is extensive literature on CLT panels, very few studies have examined the mechanical properties of NCLT. Research on this product has focused on the flexural performance and rolling shear of panels with nails or dowels, analysing factors such as the type and number of nails, their angle of insertion, the number of layers, and the use of different wood species [1, 2, 3, 4, 5, 6, 7, 8]. Therefore, this

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research focuses on a better understanding of the mechanical properties of NCLT and optimising its application in load-bearing structures.

Typically, wooden nails are manufactured using mechanical or chemical densification processes. Densification reduces porosity while increasing density, strength, hardness, and dimensional stability. In the case of wooden nails, chemical densification is achieved using phenolic resins (phenol-formaldehyde), which impregnate the wood and enhance its physical and mechanical properties. Recent studies have explored the applications of densified wood in nails, demonstrating significant improvements in their physical and mechanical characteristics [9, 10, 11, 12, 13].

Nailed-Cross Laminated Timber with aluminium nails avoids the emission of 0.52 t CO2eq per tonne of wood when compared to traditional brick construction [14]. Therefore, the use of NCLT with wooden nails, by replacing metal, offers an even greater opportunity to reduce emissions in the construction industry.

2 – OBJECTIVES

To determine the behaviour and properties of nail-cross-laminated timber (NCLT) panels, assembled with wooden nails, under static bending for their use in load-bearing structures.

3 – MATERIALS AND METHODS

The NCLT panels were fabricated using Scots pine (Pinus sylvestris) wood laminations from the Catalan Pre-Pyrenees. The laminations were graded as ME1 and ME2, corresponding to strength classes C27 and C22, respectively, according to the UNE-EN 1912 standard [15]. The majority of the laminations were of ME2 quality, although a small proportion of ME1 wood was also used.

The NCLT prototypes were made using wooden nails made from beech wood densified with phenolic resin and sourced from a PEFC-certified supply [16]. Their geometry is presented in Fig. 1. The driving of the wooden nails was carried out using a pneumatic nailer developed by the company FASCO® [17]. This company has successfully implemented technology that enables its equipment to drive wooden nails.

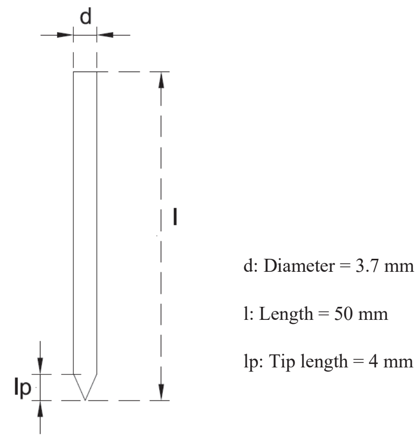

Figure 1. Diagram of a wooden nail

The laminations used to manufacture the NCLT were initially 25×100×1,100 mm in size before planing the faces and edges. A Casadei PFS41 2-in-1 Planer-Thicknesser was used to reduce them to 20×90 mm. Finally, they were cut to lengths ranging from 180 mm to 1,000 mm using a Virutex TM 33-L mitre saw.

Next, the wooden laminations were joined together using wooden nails, driven with an F44 LIGNOLOC pneumatic nailer and the help of clamps to press the laminations together. This ensured maximum contact between the boards, reducing wood deformation and achieving correct penetration. The nails were placed in staggered rows, following the spacing indicated in Fig. 2 and in accordance with the general rules for buildings of the Eurocode 5 [18] (Tab. 1). Due to the length of the nails and the thickness of the laminations, each nail always connected two boards.

Three three-layer NCLT prototypes were manufactured in the laboratory, each containing a total of 110 wooden nails. As the panels consisted of three layers, two levels of nails were required for assembly. Each prototype measured 60×180×1,100 mm. The nailing was performed without prior drilling.

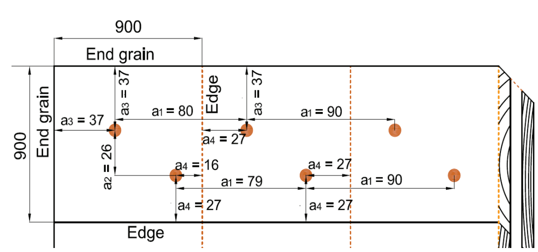

Figure 2. Distribution of wooden nails in the NCLT prototypes according to Table 1 (distances in mm).

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Table 1: Nail placement

Spacings and end/edge distances (mm)		
Spacing or distance	Minimum requirements in accordance with the Table 8.2 of the EN 1995-1-1:2016 [18] for $420 < \rho_k \leq 500$	Used on the NCLT prototypes
a_1	15d = 55,5	79 - 90
a_2	7d = 25,9	26
a_3	15d = 55,5	37
a_4	7d = 25,9	16 - 27
a_1: Spacing between nails in a row, parallel to the grain (mm) a_2: Spacing between rows of nails, parallel to the grain direction (mm) a_3: End distance parallel to the grain between the nail and the edge of the lamination (mm) a_4: End distance perpendicular to the grain between the nail and the edge of the lamination (mm) d: Diameter of the wooden nail (3.7 mm). ρk: Characteristic density (kg/m^3)		

The static bending test was performed in accordance with UNE-EN 408 [19]. The test setup was symmetrical, with a total span of 18 times the panel's section height and two central loading points positioned at one-third of the span. Overall, the panel length had to be 19 times its section height (Fig. 3). A constant loading rate was applied, ensuring that both the maximum load and breakage occurred within 300 ± 120 seconds. The bending strength was calculated using formula (1), and the modulus of elasticity parallel was calculated using formula (2).

$$f_m = \frac{3Fa}{bh^2} \tag{1}$$

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

Where:

f_m: bending strength (N/mm^2)
F: load (N)
a: distance between a loading position and the nearest support in a bending test (mm)
b: width of cross section in a bending test (mm)
h: depth of cross section in a bending test (mm)
$E_{m,g}$: global modulus of elasticity in bending test (N/mm^2)
l: span in bending (mm)
$F_2 - F_1$: increase in load on the regression line with a correlation coefficient of 0.99 or better (N)
$w_2 - w_1$: increase in deformation corresponding to F2 − F1 (mm)
G: shear modulus (N/mm^2)

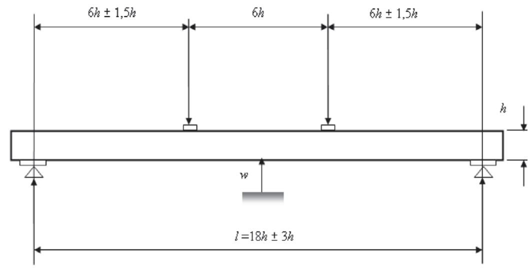

Figure 3. Bending test geometry according to EN 408. h: section depth, l: bending span.

In static bending tests, a horizontal shear displacement occurs between the layers of the cross-laminated timber panel due to the differing stress conditions. The bottom layer elongates under tensile stress, while the top layer shortens under compressive stress. To measure this relative movement, vertical red lines were drawn at 50 mm intervals along the edge of the panel before testing. These markings helped visualize the shear slippage between the layers during loading, as shown in Fig. 4.

a)
b)

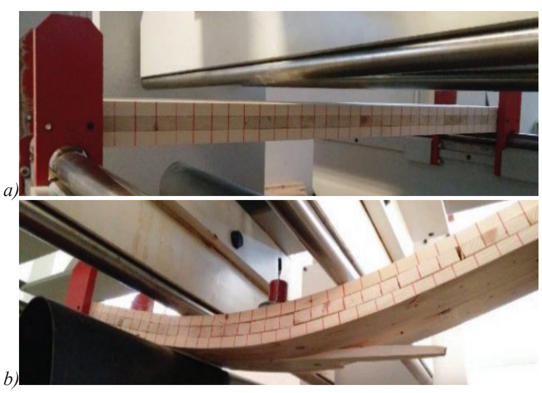

Figure 4. a) NCLT prototype placed in the bending test machine. b) Detail of the breakage of a NCLT prototype

4 – RESULTS

The results of the perpendicular bending tests indicate that the manufactured NCLT prototypes exhibit the bending strength of the wood species used. However, the modulus of elasticity values are relatively low (Tab. 2 and Tab. 3).

Table 2: Bending strength test: raw results

NCLT	Density ρ (kg/m^3)	Deflection w (mm)	Breakage load F_{max} (N)
1	491,16	79,47	8.609,00
2	539,81	84,06	10.021,00
3	507,32	46,91	6.364,00

Table 3: Bending strength test: calculated results

NCLT	Considering the total thickness of the panel		Considering only the thickness of the longitudinal layers	
	MOR (N/mm^2)	MOE (N/mm^2)	MOR (N/mm^2)	MOE (N/mm^2)
1	14,35	2.362,38	32,28	7.973,03
2	16,70	1.820,25	37,58	6.143,36
3	10,61	2.590,67	23,87	8.743,52

5 – DISCUSSION

The main difference in the bending behaviour between the glued EWPs and those assembled with nails, screws, or dowels is their stiffness. According to Han *et al*. [20], dowel-laminated timber can provide adequate load-bearing capacity but exhibits relatively low stiffness, approximately 10–20% lower than GLT or CLT of the same size. Likewise, Sotayo [21] observed that the bending strength of DLT is about half that of CLT. As a result, reductions in the modulus of elasticity of between 20% and 75% can be expected [20, 21].

This big difference in stiffness is due to the accumulation of displacements between the different layers, caused by the rolling shear. In CLT, the glued joint is rigid, and any sliding between two layers results solely from their shear deformations. In contrast, in dowelled or nailed products, deformation arises from both the lack of rigidity in the dowelled or nailed joint and the shear displacements between the layers [21]. This explains why the sliding that occurs between every layer is more significant in DLT or NCLT than in CLT, leading to a reduction in flexural stiffness.

As seen in the Fig. 5 up to 5.500 N all the prototypes show a similar stiffness. From this load on the slope of the curve load-deflection changes and all the panels start to yield. However, the breakage load varies considerably between panels, with a difference of approximately 40%. Prototype 1 failed at around 8,000 N, Prototype 2 at 6,000 N, and Prototype 3 at 10,000 N.

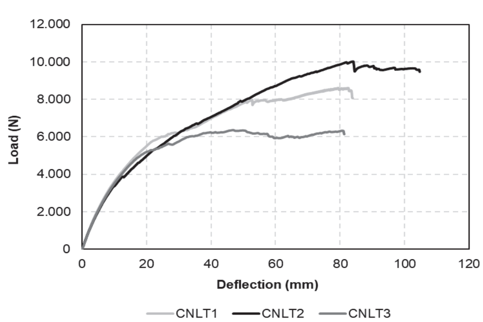

Figure 5. Load-Deflection curve of the three prototypes

The collapse of the manufactured prototypes was caused by tensile failure in the lower layer, the area of highest stress in the panel. Damage originated at weak points within this tensile zone, such as knots and wood defects, leading to stress concentration and crack formation, which ultimately caused the failure of the lower wooden boards. During testing, the specimens deformed as the spacing between layers increased, reducing nail embedment depth and weakening the nailed connections between layers [6, 21].

Wooden nails prevented sliding between layers; however, once the nails began to break, the NCLT prototypes started to yield. Despite this, the load capacity continued to increase due to friction between layers and the nails' withdrawal resistance. At this point the load-deflection slope flattened. Eventually, the load increased until failure occurred in the lower layers. Therefore, the tensile strength of these layers determines the maximum load capacity of the NCLT prototypes.

The ductile behaviour of NCLT, due to the deformations occurring at the joint planes because of the shear resistance provided by the nails, suggests its potential suitability for use in seismic zones [21].

The behaviour of NCLT with aluminium nails follows the same pattern in the load-displacement curve, with an elastic phase followed by a shorter elastic-plastic phase, although it achieves higher breaking load values [3, 4, 6]. In Sotayo's study [21], which involved the development of DLT prototypes, the load-displacement graphs of DLT and CLT were found to be similar. However, their magnitudes differed, with DLT exhibiting greater ductility, lower flexural modulus, and lower resistance compared to cross-laminated panels.

The vertical lines painted on the side of the panel highlight the relative displacement between layers at the ends of the NCLT prototypes. In contrast, at the centre of the span these control lines remain unchanged. Analysing the breakage, it is observed how the effect of the rolling shear causes the separation of the laminations in the inner layer along the edge. Since the laminations are not edge-glued, the tension is released at that point, and no rolling shear fractures occur in the wood of the transversal layer (Fig. 6). Additionally, the load-deflection graph exhibited a non-linear behaviour due to the flexible nature of the nails. These observations align with the conclusions of Pang *et al*. and Moraes *et al*. [4, 7].

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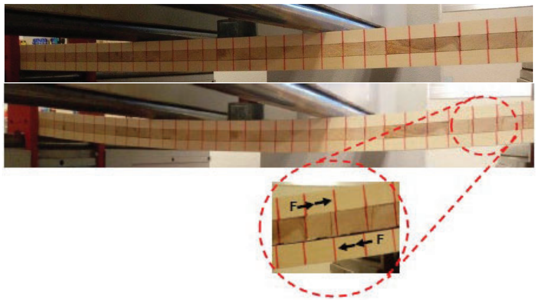

Figure 6. Interlayer in-plane slip displacement, in a panel during the four-point static bending test

Therefore, similar to what happens in DLT, the number of layers in NCLT influences the rigidity of the panels. Five-layer elements experience greater deformation accumulation, leading to more slippage compared to three-layer elements [8, 21]. Furthermore, elements with more layers tend to contain a higher number of natural defects, which reduces their overall rigidity [21].

In contrast to the stiffness of NCLT discussed so far, Zhang [6] analysed whether increasing the number of nails per surface in NCLT could prevent rolling shear failure. The study demonstrated that interlayer integrity could be enhanced by using nailed connections instead of adhesives. Increasing the number of nails improved the interlayer connection strength, which contributed to enhancing the flexural rigidity of NCLT panels. Moreover, flexural rigidity increased with the number of nailed layers, and the strain rate of wood in the lower tensile zone decreased significantly [3, 6].

The nailing angle between layers is also a factor that influences the mechanical properties of NCLT, as a 30° insertion angle increases both the strength and ductility of the product [6]. A joint with a 90° insertion angle deforms under pure shear stress, whereas when the insertion angle is less than 90°, a tighter bond of the wooden boards is achieved under load. However, when the insertion angle exceeds 90°, the boards tend to separate [20].

In dowelled or nailed wood products under load, the joints may weaken over time due to strength loss induced by wood viscoelasticity, stress relaxation, and creep deformation. This justifies the use of densified wood dowels in friction-driven joints, as they offer a solution to overcome these long-term performance issues and improve the mechanical properties of all NCLT systems [20].

In Mehra's research [22], the influence of accelerated ageing under dry and humid cyclic climatic conditions on the extraction strength of densified Scots pine and non-densified European beech dowels was evaluated. The study showed that densified dowels exhibited higher extraction strength and resistance, improving the long-term performance of the dowel-to-wood board bond.

Taking all these considerations into account — that the use of nailed or dowelled timber products is limited, that there are no clear guidelines, and that European standards are lacking — experimental research provides a valuable reference for determining the structural potential of these solutions and contributes to improving the limited knowledge of these products. This, in turn, supports the development of potentially useful design guidelines and standards [21].

6 – CONCLUSIONS

The results of this research demonstrate that NCLT exhibits lower stiffness and bending strength compared to CLT, due to the greater accumulated deformation between layers and the lower rigidity of nailed joints. The use of densified wooden nails improves the strength and durability of the joints, although the number of layers and the arrangement of the nails are key factors influencing the performance of the panels.

Future research should focus on determining the properties of NCLT using wooden nails of varying diameters, lengths, and insertion angles, as well as exploring alternative nailing distributions.

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