



Nail laminated timber: A sustainable and low - cost alternative for construction

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ABSTRACT. Nail Laminated Timber (NLT) stands out in the construction industry due to its structural characteristics, environmental benefits, and ease of fabrication. It is an engineered wood panel composed of lamellae arranged side by side and joined using nails, which can be either metallic or wooden, without the use of adhesives. This panel can be manufactured using any wood species. The use of NLT, already well - established in North America, offers a sustainable alternative, as the utilization of timber from plantation forests reduces environmental impact compared to traditional construction materials. However, its broader application in Brazil requires specific standardization and national studies to evaluate its mechanical properties. This study presents a literature review on the subject, along with the results of experimental tests, including direct shear tests conducted on specimens and bending tests performed on beams and NLT panels. Numerical simulations are also included, highlighting and analyzing the areas subjected to the highest stress demands. Results indicated that NLT shows great potential for use in construction, offering good strength and stiffness properties. However, visual grading of the lamellae is essential, as the natural defects in the wood can compromise the structural integrity of the element under bending.

Keywords: Mechanical properties; sustainable construction; numerical simulation; wood performance.

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Introduction

The increasing demand for sustainable, efficient, and high - performance construction systems has brought engineered wood products to the forefront of civil engineering. Among these systems, the Nail Laminated Timber (NLT) has gained prominence due to its simplicity of manufacturing, absence of adhesives, and use of plantation wood species, supporting sustainable practices (Gong, 2019; Canadian Standards Association, 2019). NLT panels are composed of sawn timber lamellae arranged fastened using nails — either metallic or wooden — without the application of synthetic adhesives (Figure 1). This structure allows the use of various wood species and eliminates the need for specialized equipment, making it suitable for prefabrication or on - site production (Derikvand et al., 2019). The fasteners serve a dual purpose: maintaining lamella alignment and transferring shear between layers. [CSA] (2019), the shear capacity of the nails and their configuration significantly affect the overall mechanical performance of the panel.



Figure 1. Nail Laminated Timber.

Gong (2019).

Unlike Cross Laminated Timber (CLT) and Glue Laminated Timber (GLT) – which rely on adhesives and require industrial processing – NLT is mechanically connected, offering faster production and better reparability. Moreover, its monodirectional arrangement makes it especially efficient for floor and roof slabs where loading is predominantly perpendicular to the plane of the element (Derikvand et al., 2019). When overlaid with an OSB or plywood panel, the composite action enhances stiffness during transportation and improves in - plane rigidity. Despite its consolidated use in North America and its recent emergence in Brazilian construction, as seen in pilot projects (Figure 2) by Rewood Structural Solutions Company, NLT remains unregulated under national and international standards, unlike CLT, which was included in Associação Brasileira de Normas Técnicas [ABNT] (2022e), ANSI / AWC NDS - 2018, CSA O86:19, and EN 1995 - 1 - 1:2014.



Figure 2. Slab of NLT - Caconde Source: Rewood – Structural Timber Solutions (<https://rewood.com.br>), accessed in 2021.

Key aspects that remain underexplored for NLT in Brazil include: slip modulus (k_s) and ultimate shear strength of the nail joints; bending stiffness (EI) and modulus of rupture (f_m) of beams and panels; Influence of natural defects such as knots, splits, and fiber deviation on failure modes; effect of nail spacing, pattern (zigzag or aligned), and penetration depth on connection performance (Imakawa et al., 2022; Advancing Standards Transforming Markets [ASTM], 2013); interaction between wood and sheathing elements (OSB / Plywood) in the composite system; numerical modeling parameters considering orthotropic behavior of wood, validated through experimental tests (Bilesky et al., 2019). Thus, the aim of this work was to generate validated data that supports future standardization, encourages industrial implementation, and promotes the safe, efficient, and sustainable use of Nail - Laminated Timber in Brazilian civil construction.

Materials and methods

In this study, the NLT elements were analyzed using two specimen models: a) double - shear specimens for direct shear tests of the nail joint; b) beam and panel models for bending tests. The panels were constructed using sawn timber laminations from plantation forests (*Pinus ssp*), with base x height x length dimensions of 50 mm x 90 mm x 1700 mm, classified in the laboratory as C20 and treated with CCA (Chromated Copper Arsenate) preservative.

For side fastening along the length of the laminations, 35 - millimeter - long and 3 - millimeter - diameter ring - shank nails were used, nail in a zigzag pattern. An 11.1 - mm - thick OSB (APA Structural) panel was fixed to the top surface of the sawn laminations using metal staples. The direct shear tests were conducted at the Laboratory of Timber and Timber Structures (LaMEM) of the São Carlos School of Engineering (EESC) at USP.

The wood used in the structural elements was donated by a company specializing in wooden structures. The moisture content of the wood was $12\% \pm 1\%$, and the wood was classified as strength class C20, according to the Associação Brasileira de Normas Técnicas [ABNT] (2022a) standard. These minimum characteristics were sufficient for the performance tests and evaluation. All the material received from the supplier has been kept in a dry place at LaMEM / EESC / USP until the time of the tests.

Shear test of nlt specimens

Shear tests were conducted to determine the maximum load (F_{max}) and the slip modulus (K_s) of the connection (nail). Each specimen was made up of three lamellae, as shown in Figure 3. The tests were performed using an AMSLER Universal Testing Machine with a 25 - ton capacity (Figure 4).

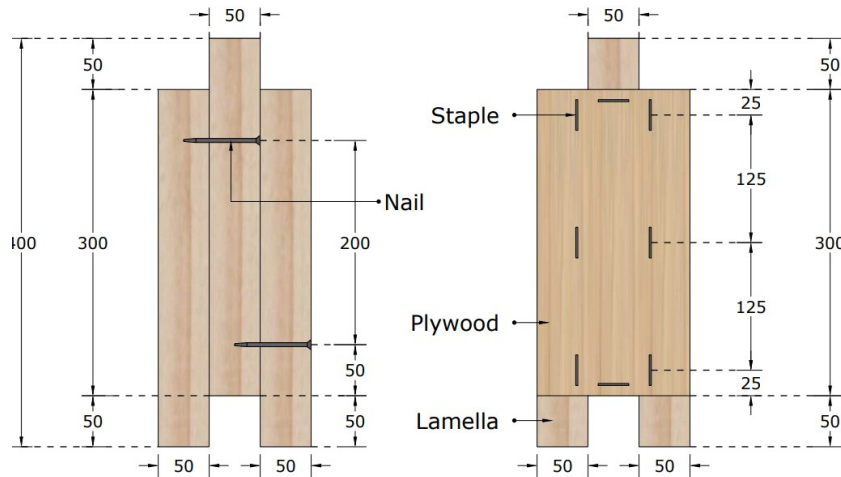


Figure 3. Test specimen configuration with dimensions in millimeters (mm).
Own authorship.



Figure 4. Instrumentation of the test specimen.
Own authorship.

The applied load was controlled by a load cell with a 25 - ton capacity, and displacements were measured using two LVDT displacement transducers with a maximum stroke of 100 mm. The load cell and the two displacement transducers were connected to a 4 - channel data acquisition system. The shear test followed

the procedure outlined in the Associação Brasileira de Normas Técnicas [ABNT] (2022d) standard for determining joint strength and stiffness (Figure 5). The load applied to the test specimen was performed with a loading and unloading cycle between 10% and 40% of the $\mu L_{ultimate}$ strength, with the second cycle applied until the failure load for the connection was reached. The failure of the nail connection occurred either due to the maximum load obtained in the test or a displacement of 15 mm, whichever occurred first. A total of six shear test specimens were tested, as shown in Figure 6.

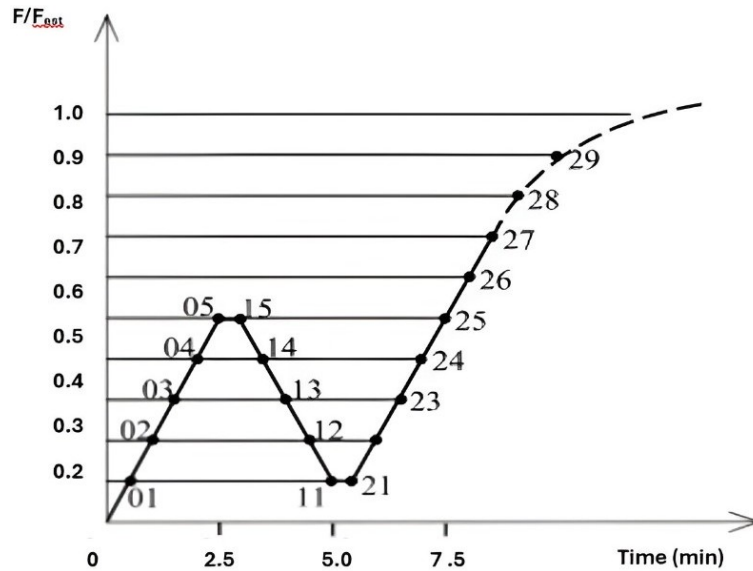


Figure 5. Load versus time curve. Modified of [ABNT] (2022d).

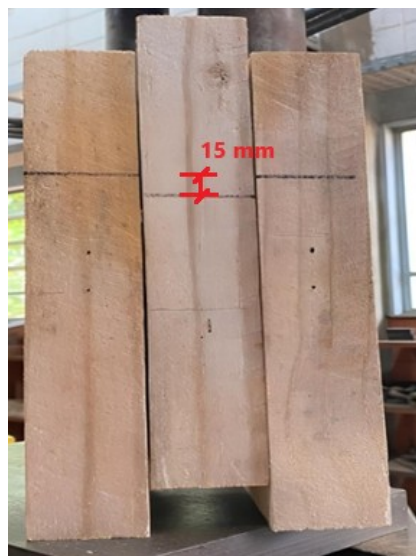


Figure 6. Application of load on specimen test in displacement of 15 mm. Own authorship.

Bending test of nlt beams

The NLT beams used in this study were manufactured with dimensions of 100 mm x 90 mm x 1700 mm (width x thickness x length). Each NLT beam was composed of two sawn timber lamellae. The nails were arranged in a zigzag pattern along the length of the beam, as shown in Figure 7, since a literature review indicated that this fastening method is more efficient (Canadian Wood Council [CWC], 2019; Imakawa et al., 2022; [ASTM]., 2013). The same nailing template was used for the bending test of the NLT panel. The loading and unloading cycle scheme for the bending tests of the NLT beams was identical to that shown in Figure 5. A total of six NLT beams in the bending were tested, considering a support span of 1600 mm, (Figure 8b).

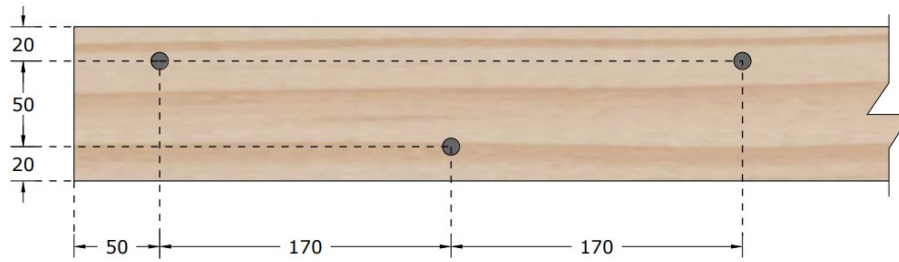


Figure 7. Nail fixing distances along the length of NLT beams and panels. Dimensions in millimeters (mm).
Own authorship.

The vertical displacement measurements at the mid - span of the beams were taken using an LVDT displacement transducer with a maximum stroke of 100 mm, and the applied load was controlled by a 25 - ton load cell, as shown in Figure 8b. The test was performed with loads applied at the thirds of the beam span, following the recommendations of Associação Brasileira de Normas Técnicas [ABNT] (2022c). One twin beam was previously broken to determine the μ Ltimate load. A metal frame with a capacity of 300 kN was used for load application.

a) Cross-section of the beam. b) Detail of the beam test and instrumentation.

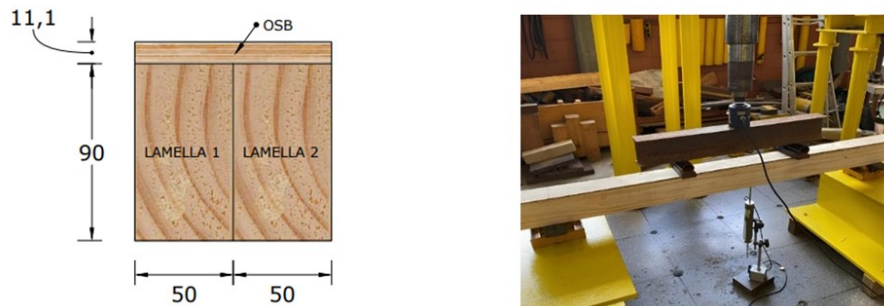


Figure 8. Details of NLT bending beam tests and cross section of the beam. Dimensions in millimeters (mm).
Own authorship.

The modulus of elasticity in bending (E_0) was calculated using (Equation 1), and the bending strength (f_m) was determined using (Equation 2). Four - point bending tests were conducted on the beam.

$$E_0 = \frac{23}{108} \times \left(\frac{L}{h}\right)^3 \times \left(\frac{\Delta F}{\Delta e}\right) \times \frac{1}{b} \tag{1}$$

Where: b is the width of the element (mm); L is the span between supports (mm); ΔF represents the applied load levels, with a maximum of 10% and 40% of the μ Ltimate failure load in (N); Δe are the vertical displacements (mm) corresponding to the applied load levels, respectively.

$$f_m = \frac{F_{rupt} \times L}{b \times h^2} \tag{2}$$

Where: F_{rupt} is the applied rupture load (N); L is the span between supports equal to $18 h$ (mm); b is the width of the specimen's cross section (mm); h is the height of the specimen's cross section (mm).

Bending test on the nlt panel

The NLT panel used in this study was fabricated from 12 sawn lamellae with dimensions of 50 mm x 90 mm x 1700 mm (width x height x length) and an OSB board, as used in the beam models. The loading and unloading cycle scheme for the bending tests was identical to that shown in Figure 5, but with vertical displacement limits of $L/300$ (L = distance between supports). A single NLT panel was tested due to the limited availability of material for the fabrication of the element, as shown in Figure 9.

For load application, a load frame with a cylinder capacity of 300 kN was used. A three - point bending test with a centered load at the mid - span was conducted for the beam. In the panel test, the distance between supports was fixed at 1600 mm. A load cell with a capacity of 30 t was used to control the applied load during the NLT panel test.

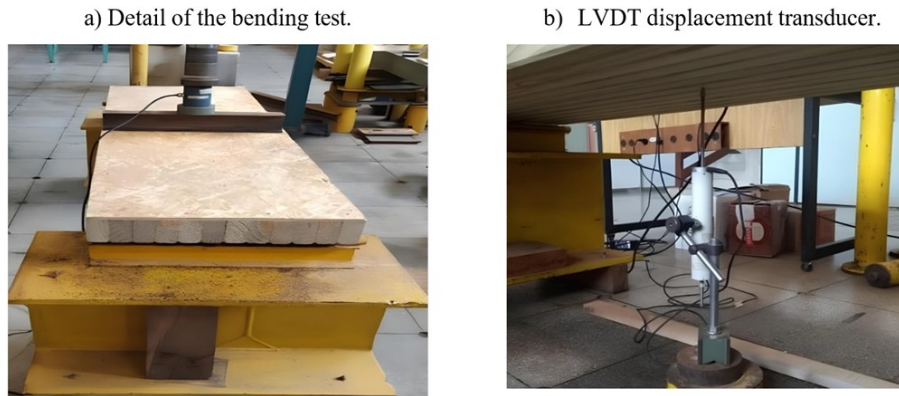


Figure 9. Details of NLT bending panel test.

Own authorship.

The stiffness EI of the NLT panel was determined using (Equation 3), which considers the vertical displacement caused by a concentrated load at the center of the span of the element. The bending strength was obtained using (Equation 4), where the load P was applied on an I - section steel profile to distribute the load along a line in the transverse direction of the panel.

$$EI = \left(\frac{\Delta P \times L^3}{48\Delta\delta} \right) \quad (3)$$

Where: ΔP = applied load within the linear regime in N; L = distance between supports (mm); $\Delta\delta$ = vertical displacement obtained at mid - span (mm); EI = stiffness of the element in bending ($N \cdot mm^2$).

$$f_M = \frac{M_{max}}{W} \quad (4)$$

Where: f_M = ultimate bending strength ($N \cdot mm^2$); M_{max} = maximum moment obtained for the ultimate rupture load ($M_{max} = \frac{P \times L}{4}$) $N \cdot mm$; W = cross - sectional resistance modulus ($W = \frac{b \times h^2}{6}$) mm^3 ; b = total width of the NLT element (mm); h = height of the NLT element (mm).

Numerical simulation on the nlt panel

The numerical simulation of the panel's flexural behavior was conducted using the ANSYS software, academic version 11, which is based on the Finite Element Method (FEM). Wood was considered an orthotropic material with properties defined along its three orthogonal directions: longitudinal (L), radial (R), and tangential (T). In ANSYS, the x - axis was defined as the longitudinal fiber direction of the wood, the y - axis as the radial direction, and the z - axis as the tangential direction.

For the discretization of the sawn wood lamellae and the OSB panel (components of the NLT panel), the Solid45 element was used. This element was chosen for its ability to accurately represent the behavior to be simulated. The OSB panel was modeled as an isotropic element with a Poisson's ratio of 0.23 and a modulus of elasticity of 4474 MPa.

The geometric configuration of the numerical model followed the experimental dimensions of the panel tested in bending, using the material properties determined experimentally. Hexahedral elements were used in the composition of the finite element mesh. The bending test simulation was performed by applying a load at the mid - span, distributed over 392 upper central nodes of the model, based on the rupture value obtained from the experimental analysis.

At one end of the panel, all translation movements (in x, y, and z) of the support - line nodes were constrained. At the other end, the x - direction was left free for the line nodes, while the other degrees of freedom (y and z) were restricted (Figure 10).

The mechanical properties of pine wood were considered for the numerical simulation of the NLT panel, (Table 1):

The numerical simulation was performed only for the NLT panel to analyze the behavior of the most commonly used application of the material, which is as a panel in bending. While the NLT beam is also a relevant application, the numerical simulation focused on the panel provided a more accurate and detailed view of the material's behavior under the most common usage conditions.

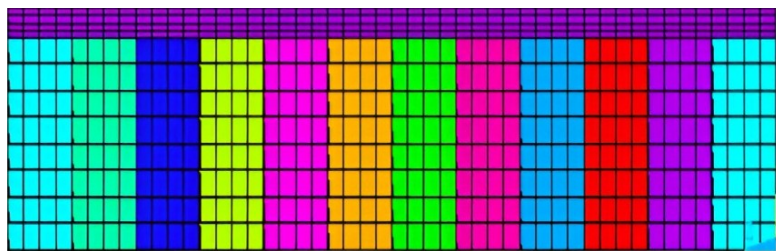


Figure 10. Detail of the finite element mesh of the numerical model of the panel. ANSYS.

Table 1. Properties of pine wood used in the numerical model.

Property	Symbol	Value
Modulus of elasticity (x - direction)	E_x	3500 MPa
Modulus of elasticity (y - direction)	E_y	350 MPa
Modulus of elasticity (z - direction)	E_z	350 MPa
Poisson's ratio (xy - plane)	ν_{xy}	0.013
Poisson's ratio (yz - plane)	ν_{yz}	0.23
Poisson's ratio (xz - plane)	ν_{xz}	0.013
Shear modulus (xy - plane)	G_{xy}	17.5 MPa
Shear modulus (yz - plane)	G_{yz}	17.5 MPa
Shear modulus (xz - plane)	G_{xz}	17.5 MPa

Results and discussions

This section presents the main experimental results for strength and stiffness obtained for the shear connections in the test specimens, as well as for the NLT beams and panels. Additionally, the stress distribution results in the regions of greatest demand in the NLT panels, as analyzed using ANSYS, are also provided.

Shear test on nlt specimens

The average slip modulus (k_s) obtained experimentally for the six test specimens for each shear plane of the nail connection was $3353 \text{ N m}^{-1} \text{ m}$. The maximum load (F_{\max}) recorded was 4.98 kN per shear plane. These values were relatively low, given that the nails' primary function in this case is to hold the panels laterally together. The observed failure mode for the nail connection was ductile, characterized by nail bending associated with embedding of the nail into the wood, reaching the displacement limit of 15 mm, as shown in Figure 6.

The experimental values obtained for the average slip modulus and for the maximum load indicated a moderate capacity to resist lateral movement between the lamellae connected by nails. Since the primary function of the nails in NLT systems is to maintain the lateral cohesion of the panels rather than to resist significant structural loads, the values obtained are consistent with this intended role. The observed ductile failure mode, characterized by nail bending and embedding into the wood, confirms the desirable behavior of the system under displacement, allowing for deformation without abrupt failure.

Bending test on nlt beams

The average modulus of elasticity in bending ($E_{0, m}$) for the sawn lamellae in the NLT beams was approximately 3500 MPa (C20 wood class according to Associação Brasileira de Normas Técnicas [ABNT] (2022a)). The experimental rupture load obtained in the bending test for the NLT beam was 11,402 N, with a corresponding vertical displacement of L 200-1 equal to 12.1 mm in the material's linear phase.

The beam model was observed to be more flexible than the panel model with 12 associated beams. This is because the NLT panel behaves like a plate, constraining displacements in the transverse width direction in addition to its longitudinal stiffness, which does not occur in the beam model. The observed failure mode in the NLT beams occurred due to tension in the lower lamellae (Figure 11), which exhibited natural defects, such as knots. The average stiffness (EI) and bending strength (f_m) values for the NLT beams were $3.02 \times 10^{10} \text{ N. mm}^2$ and 23.41 MPa, respectively. The OSB plate, in the case of the beams, did not significantly influence the EI stiffness or the strength results, as the beam predominantly bends in the direction of its longer span.



Figure 11. Predominant failure mode for NLT beams in bending.
Own authorship.

Bending tests on nlt panels

The average modulus of elasticity in bending ($E_{0, m}$) for the sawn lamellae of the NLT panel was approximately 3500 MPa (C20 wood class according to [ABNT], 2022a).

The experimental rupture load obtained in the bending test for the NLT panel was 18, 742 N, with a corresponding vertical displacement of $L 200^{-1}$ equal to 8 mm in the material's linear phase.

The observed failure mode in the NLT panel also occurred due to tension in the lower lamellae (Figure 12a), particularly in those with knots (natural defects). This highlighted that during bending, the lamellae failed in the areas of greatest wood fragility, i. e., where defects were present, as the lamellae were not subjected to a visual grading process.

It can be inferred that since the panel is composed of multiple lamellae, when one lamella fails, the system redistributes the load to the lateral lamellae, preventing complete panel failure.

The remaining lamellae continue to support the load. Additionally, part of the panel's stiffness is ensured by the OSB element, which restricts lateral movement of the lamellae.

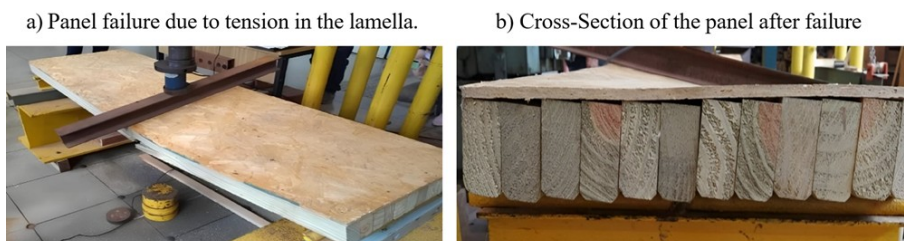


Figure 12. Failure mode obtained for NLT panel in bending.
Own authorship.

In this way, it is observed the need to use the visual classification of the laminas before the panels are made, in order to increase their strength and minimize localized strength issues. This visual classification can be done using the Associação Brasileira de Normas Técnicas [ABNT] (2022b) standard. The values of stiffness (EI) and bending strength (f_m) of the NLT panel obtained from equations (3) and (4) were $13.8 \times 10^{10} \text{ N} \cdot \text{mm}^2$ and 8.63 MPa, respectively. The stiffness (EI) was higher than the stiffness of the NLT beams. On the other hand, the bending strength of the NLT panel was lower than that of the NLT beam. The OSB panel mainly contributed to the increase in stiffness (EI) of the panels.

Numerical simulation of the nlt panel

The calibration of the numerical results of the NLT panel was performed by comparing them with the experimental curve obtained from the bending test (Figure 13), with the displacement measurement point considered as the point where the displacements were read by the LVDT transducer at the bottom of the panel. The numerical and experimental results showed good agreement. Figure 13 shows the distribution of von Mises stresses in the NLT panel tested experimentally. The analysis of von Mises stresses in the longitudinal

x direction, considered as the direction parallel to the fibers in the proposed model, showed the most stressed regions of the model, both in the tension of the fibers in the lower lamella and in the compression of the upper fibers. These corresponded to the regions farthest from the neutral axis of the section (upper and lower fibers).

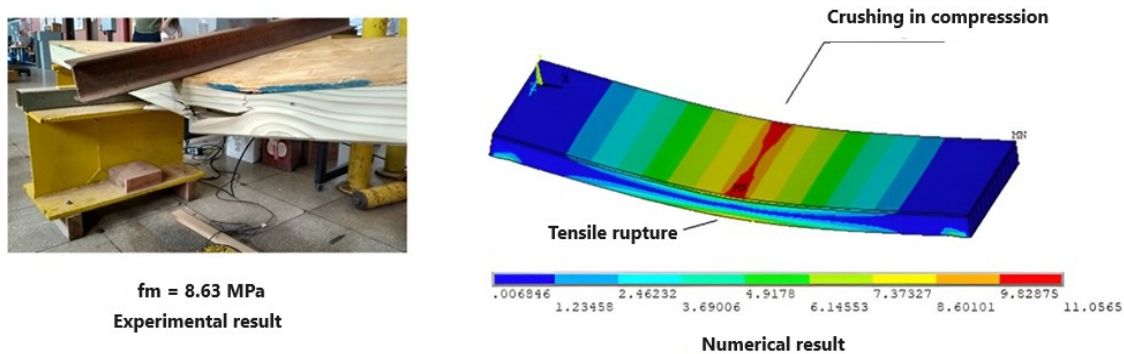


Figure 13. Failure mode in the bending test of the NLT panel.

Own authorship.

The stress distributions explain the failure modes observed in the NLT element. In the upper part of the element, at the point of load application, crushing occurred due to two factors: compression parallel to the fibers, caused by bending, and crushing perpendicular to the fibers, resulting from the localized application of the load in both types of NLT. In addition, the NLT panel showed failure due to tension in the lower lamella, where the greatest concentration of tensile stresses occurred due to the bending effect of the element. By comparing the experimental tensile stresses obtained for the last lower lamella of the panel (i. e., $f_m = 8.63$ MPa) with the maximum numerical tensile stress obtained at that point, it was observed that the longitudinal tensile stress in the x direction was $f = 9.23$ MPa, justifying the failure mode obtained for the panel.

Conclusion

Nail Laminated Timber (NLT) is a relatively new material in the country and presents advantages, potentially expanding solutions in civil construction, especially in timber structures.

The production of NLT does not require sophisticated equipment, and its manufacturing process, combined with a reduced production time, does not use synthetic adhesives. It proposes the use of reforestation timber (plantations), making this material an ally of sustainable construction.

The mechanical and visual classification of the laminas that make up the NLT is fundamental because the presence of wood defects, such as knots, reduces the strength of the element, especially if these defects are located in areas of higher stress concentration due to bending.

The visual classification of wood can be done using the [ABNT] (2022b) standard, while the mechanical classification can be done using the [ABNT] (2022c) document, as both documents are specific for wood from planted forests, which present typical defects and drying issues.

The bending test is the main test for evaluating NLT, but other tests are necessary to evaluate the connections separately. These tests can be carried out using the Associação Brasileira de Normas Técnicas [ABNT] (2022c) and [ABNT] (2022d) standards.

The NLT panel proved to be stiffer than the NLT beams, with the OSB panel contributing mainly to the increase in the system's stiffness (EI).

The stiffness (EI) of the panel was 4.56 times higher than the stiffness of the beams, mainly due to the plate effect (horizontal and transversal stiffness) that occurs in the case of the panel, while the beam only experiences pure bending in the longitudinal direction of the span.

The numerical simulation of NLT behavior under bending, conducted using the ANSYS software, showed good agreement with experimental results. The numerical model was able to simulate the behavior of NLT not only globally, in relation to the force - displacement curve, but also locally, indicating regions of higher stress concentration and justifying the failure modes observed.

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