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Experimental Study of Adhesive and Metal-Free Laminated Timber Products Made of Uruguayan Pine

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Abstract
This study presents the experimental results of adhesive and metal-free laminated timber products made of Uruguayan pine. Dowel laminated timber (DLT) and wooden nail laminated timber (WNLT) were prepared using C22 pine lamellas and joined by wooden dowels or nails with diameters of 20 mm and 5.3 mm, respectively. For comparison, laminated timber products joined with 3.2 mm steel nails (NLT) were manufactured. Two nailing patterns, straight horizontal and zigzag, and three spacing between fasteners, 300, 250 and 150 mm were analysed. Shear tests on timber connections and four-point bending tests on structural size panels were performed, and the slip modulus and bending properties, respectively, were obtained. DLT connections showed significantly higher slip modulus values compared to WNLT and NLT connections. The bending stiffness (9.7 - 11.5 kN/mm^2) and strength (35.4 – 57.4 N/mm^2) of the DLT, WNLT and NLT panels did not show significant differences, suggesting that the connector material (wood or steel) and the diameter did not influence the load-carrying capacity of the panel. In general, the failure mode in the panels was in tension, probably attributed to pronounced fibre deviations and the presence of knots near the load application area. These findings suggest that adhesive and metal-free laminated timber products made of Uruguayan pine have structural properties that allow their use in residential floors, advancing towards more sustainable construction systems.

Keywords
Dowel laminated timber, Timber products, Wooden nail laminated timber.

1 Introduction

The construction industry plays a key role in reducing the use of non-renewable resources, given the growing concerns about global warming and the impact of human activities on the environment. The construction sector is estimated to account for approximately 40% of global CO_2 emissions (Abergel et al. 2017). An effective strategy to reduce the carbon footprint is to promote the use of renewable materials, with wood being a sustainable option that stands out for its low embodied energy and high carbon storage capacity (Abed et al. 2022). Over the past two decades, the use of wood in construction has increased due to the development of engineered wood products (EWPs), which allow large volumes of wood to be used in structural elements such as beams, columns, slabs and walls. EWPs are predominantly assembled with synthetic adhesives or metal connectors, which production is energy intensive and has negative implications for the reuse of timber components at the end of their life cycle, as well as for the emission of Volatile Organic Compounds (Sotayo et al. 2020). Currently, the academic and some forest industries are focusing on adhesive and metal-free EWPs since they reduce the negative impact on the human health and the environment. Dowel laminated timber (DLT) and wood nail laminated timber (WNLT) are a "green" alternative for joining the timber components in muti-layer beams and panels (Han et al. 2023). In Uruguay, government policies are promoting the use of timber construction systems to reduce the housing shortfall and comply with the requirements established in international agreements (Naciones Unidas 2020). Forest projections for 2030 indicate the availability of a minimum of 3 million m^3year^{-1} of pine (*Pinus elliottii* and *P. taeda*) for mechanical transformation (Uruguay XXI 2023). Therefore, there is an opportunity to add value to the Uruguayan forest-timber construction chain, for using the raw material and developing adhesive and metal-free EWPs for the production of social housing. This study aims to experimentally evaluate the structural behavior of adhesive and metal-free laminated timber products made of Uruguayan pine. The influence of different types, number of wooden fasteners, nailing patterns, and spacing between connecting elements on the mechanical properties of DLT and WNLT connections and panels, are analysed. Finally, the results are compared with laminated timber products joined with steel nails (NLT), suggesting the feasibility of using wooden fasteners for sustainable building systems.

2 Literature Review

Most research on engineered wood products has focused on products using adhesives or metallic elements, such as cross laminated timber (CLT), glued laminated timber (GLT) and nail laminated timber (NLT). In the last decade, different works have begun to be reported on adhesive and metal-free EWPs, joined by wooden dowels or nails. In the 1970s, dowel laminated timber (DLT) was developed in Switzerland, and is characterized by a series of sawn timber boards (called lamellae) laid edgewise and parallel to each other, connected with wooden dowels (Haller 2008). The lamellae are usually made of softwood, 20-45 mm thick, with a moisture content (MC) of 12 to 16 %. The dowels are usually made of hardwoods, with diameters of 12 to 24 mm, and 6-8 % MC. The dowels are placed in pre-drilled holes halfway up the lamellae and nailed evenly spaced at 200 - 300 mm. The dowels tend to equilibrate to the MC of the lamellae, expand and as they do so the lamellae form a unique element. In the industrial sector, several companies in Central Europe and North America are involved in the manufacture of DLT. Most of the technical information on DLT are provide by the manufacturing companies due to the limited or lack of standards. In Europe for example, the technical information is specified in the European Technical Assessment (ETA) on a case-by-case basis (Han et al. 2023). At the academic level, research on DLT covering design, manufacturing process, structural properties, and modelling of structural elements, are available. Several authors have focused on the study of horizontal panels (Plowas et al. 2016; Bell 2018; Ogunrinde 2019; Bruzzone et al. 2023; Giordano et al. 2023), vertical panels (Sandhaas et al. 2018) and beams (Sotayo et al. 2020; Derikvand et al. 2021; Yeh and Yeh 2024). Another product under study is wood nail laminated timber (WNLT), which is similar to DLT yet the lamellae are jointed by wooden nails using pneumatic guns. In the manufacturing process, the friction between the wooden nail and the surrounding surfaces generates a solidification of the lignin, allowing the wood pieces to be joined (Korte et al. 2018). Literature related to WNLT are limited, standing out the studies carried out by Riggio et al. (2013) and Riggio et al. (2016), who conducted compression and shear tests on densified hardwood nails of European species. The authors concluded that densified nails are a viable alternative as connectors in timber assemblies made of wood medium-densities and with few knots. Fink et al. (2019) and Ruan et al. (2021, 2022) performed shear and bending tests on WNLT, focusing on nail dimensions, nail orientations, and geometric design. The authors found that wooden nails can provide sufficient load-bearing capacity for structural applications, at least for low loaded structures or with low safety requirements. Zhu et al. (2023) performed simple shear and bending tests on small connections and laminated products jointed by wooden nails. The authors reported that the elastic modulus of WNLT exceeded the average elastic modulus value of the constituent timber pieces. At the industrial level, the company BECK (2024) manufactures cylindrical and densified beech wood nails, commercially known as LIGNOLOC®. A wide variety of diameters and sizes are available depending on the application and specific requirements. The physical and mechanical properties of wooden nails are available in technical brochures published by the company.

3 Research Methodology

The experimental design consisted of manufacturing and analyzing the behavior of adhesive and metal-free laminated timber products made with wooden dowels and nails. The adhesive and metal-free specimens were compared with steel nail-laminated timber (NLT). The identification of the timber connections and structural size panels with the type, number of fasteners, nailing pattern, spacing between connectors and number of specimens are given in Tables 1 and 2.

Table 1. Description of timber connections.

Denomination	Type of connector	Nailing pattern	Number of connectors	Spacing between connectors	Number of specimens
DLT	Wooden dowels	straight line	1	-	12
WNLT-250	Wooden nails	zigzag	4	250 mm	10
WNLT-150			4	150 mm	10
NLT-250	Steel nails	zigzag	4	250 mm	12
NLT-150			4	150 mm	10

Table 2. Description of structural size panels.

Denomination	Type of connector	Nailing pattern	Number of connectors	Spacing between connectors	Number of specimens
DLT-sl	Wooden dowels	straight line	8	300 mm	3
DLT-zigzag		zigzag			3
WNLT-250	Wooden nails	zigzag	11	250 mm	3
WNLT-150			18	150 mm	3
NLT-250	Steel nails	zigzag	11	250 mm	3
NLT-150			18	150 mm	3

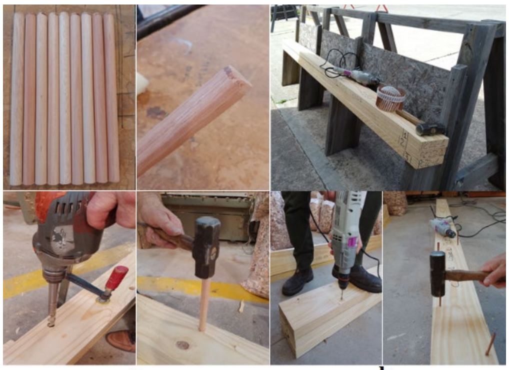
3.1 Materials

One hundred and twenty-eight C22 (CEN 2016) timbers of Uruguayan pine (*Pinus taeda*) with dimensions of 147 x 36 x 2850 m^3, were selected from a commercial sawnmill. The boards (so-called lamellas) had no visible cracks and showed insignificant face knots and/or minimal deformations. All lamellas were equilibrated to a target moisture content (MC) of 16% (±1%).

The connecting elements used in the panels varied in material and diameter. Two types of connectors were used in the adhesive and metal-free panels, a) *Eucalyptus grandis* wooden dowels of national origin, with 20 mm diameter and 350 mm length and b) *Fagus sylvatica* L. wooden nails of European origin, with 5.3 mm diameter and 9 mm length, LIGNOLOC brand. The wooden dowels were stored in a climatic chamber until they reached 7% (±1) MC. For comparison, spiral steel nails of 3.1 mm diameter and 100 mm length were used for the NLT panels.

Prior to the manufacture of all panels, the lamellas were non-destructively tested (NDT) to evaluate the dynamic modulus of elasticity (*E*d) by the impact wave method using a Fakopp equipment (Microsecond Timer). The average values of *E*d and density of one hundred and thirty two lamellas were 13.75 kN/mm² (COV = 15 %) and 527 kg/m³ (COV = 9.2 %), respectively. The lamellas were sorted in four groups according to their modulus of elasticity, and they were used to manufacture the panels assuring that each panel contained lamellas from each group.

Each panel consisted of seven lamellas connected by wooden dowels or nails. In the DLT and WNLT panels, the wooden dowels and nails were inserted manually with a rubber hammer, in holes previously drilled with a conventional drill. In the NLT panels, the steel nails were mechanically nailed using pneumatic nailers. The final dimensions of the DLT, WNLT and NLT panels were 252 x 147 x 2850 mm³. The manufacturing processes are shown in Figure 1.



a b

Figure 1. Fabrication of structural size panels. a. DLT panel. b. WNLT panel.

The five series of timber connections described in Table 1, were prepared to evaluate their mechanical properties in specimens loaded perpendicular to the grain. The geometrical configuration established by Sandberget al. (2000). The dimensions of connections were 108 mm × 147 mm × 450 mm.

3.2 Experimental procedure

3.2.1 Shear connection tests

Shear tests according to the loading procedure described in EN 26891 (CEN 1991) were carried out using a Controls testing machine with a 300 kN load cell. Four extensometers were employed: two mounted on the external timber elements and two on the central element, to measure the relative displacement of the connection.The parameters of the loading procedure based on the maximum estimated load (*Fmax,est*) were obtained from previous destructively tests conducted on three specimens per series. First, the specimens were loaded until 40% *Fmax,est* was reached and the crosshead position held during 30s. Second, specimens were unloaded until 10% *Fmax,est* and the crosshead position again maintained for additional 30s. Finally, specimens were reloaded at a constant rate of 0.05 mm/s. The slip modulus (*Ks*) was calculated in accordance with EN 26891, based on the gradient of the line that corresponds with the initial points of 10% *Fmax,est* and 40% *Fmax,est* on the load-slip curve. The shear capacity (*Fs*) was determined as the maximum load recorded during the tests. After testing, a full cross section of the specimen (including the three pieces that comprised the connection) was cut close to the failure zone for MC and density determination. Test arrangements for perpendicular to the grain tests are shown in Figure 2.

a b

Figure 2. Test setup for shear properties determination in perpendicular to the grain. a. DLT connection. b. WNLT connection.

3.2.2 Bending tests on structural size panels

Four-point bending tests were carried out on structural size panels to determine the flexural strength (*f*m), global modulus of elasticity (*E*m,g) and local modulus of elasticity (*E*m,l) according to EN 408 (CEN 2010). The panels were arranged to mimic the behavior of a floor slab by applying two loads across the full width of the panel until failure. The tests were carried out on a universal machine with a load cell of 250 kN and at a constant rate of 1 mm/min. Deformations were recorded using extensometers located at the mid-bottom of the panel until 40% of the estimated maximum load was reached, ensuring that the loading cycle and its corresponding deformation remained within the elastic range. At that point, the extensometers were removed and loading continued until failure. The maximum load was recorded with the displacement of the loading head. The test setup is illustrated in Figure 3.

a b

Figure 3. Test set up for bending tests. a. DLT panel. b. WNLT panel.

4 Findings and Discussion

4.1 Shear tests

Results of the tests are given in Table 3 and presented graphically in Figure 4.

Table 3. Results of shear tests. Mean values and SD.

Test series	**DLT**	**WNLT-250**	**WNLT-150**	**NLT-250**	**NLT-150**
n	12	10	10	12	11
Density [kg/m^3]	522 (30.2)	515 (24.3)	507 (10.4)	534 (12.2)	511 (19.3)
*F*s	8.8	6.0	7.0	16.9	17.6

[kN]	(1.00)	(1.27)	(0.90)	(1.34)	(2.49)
*K*s [kN/mm]	3.8 (0.55)	1.7 (0.47)	2.5 (1.06)	1.5 (0.30)	2.1 (0.89)

The nonparametric tests on DLT, WNLT and NLT connections presented significant differences ($p \leq 0.05$) for the three types of connections, regardless of the number and spacing between connectors. NLT connections exhibited significantly higher strength values than DLT and WNLT. Furthermore, DLT showed considerably higher slip modulus values compared to WNLT and NLT. The results suggest that the material of the fasteners (wood or steel) influenced the mechanical properties of the connections. Figure 4 shows the mean values of the mechanical properties for the three types of tested connections.

For WNLT, the spacing pattern (250 and 150 mm) between wooden nails did not show a significant influence on the mechanical properties of the connections.

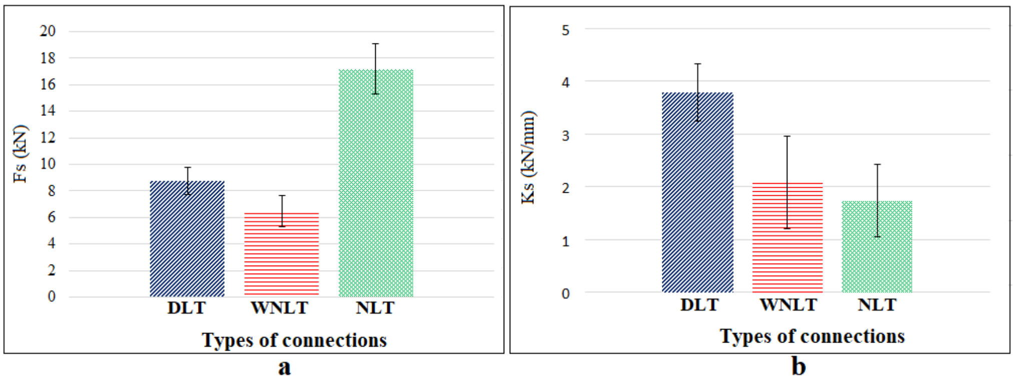


Figure 4. Comparison of shear properties (mean values and SD) of connection types. a. *Fs* and b. *Ks*.

Figure 5 shows the load-slip response from the shear tests for DLT (a), WNLT (b) and NLT (c) connections. All the tested specimens failed within the 15-minute range, and no one reached the 15 mm slip established in the EN 26891. DLT specimens (5a) exhibited a slight, progressive decrease in load after reaching the maximum load, followed by a prolonged plateau before the final drop in load, consistent with findings reported by Ceraldi et al. (2018) and Bruzzone et al. (2023) on dowelled timber connections. WNLT specimens (5b) showed a characteristic load-slip curve with a plastic response that could be attributable to the embedment of the wooden nails in the lamellas, consistent with Ruan et al. (2022). In NLT (5c), an increase in load was observed after reaching the yield point, possibly attributed to the formation of plastic hinges, similar to Sosa Zito et al. (2013) findings.

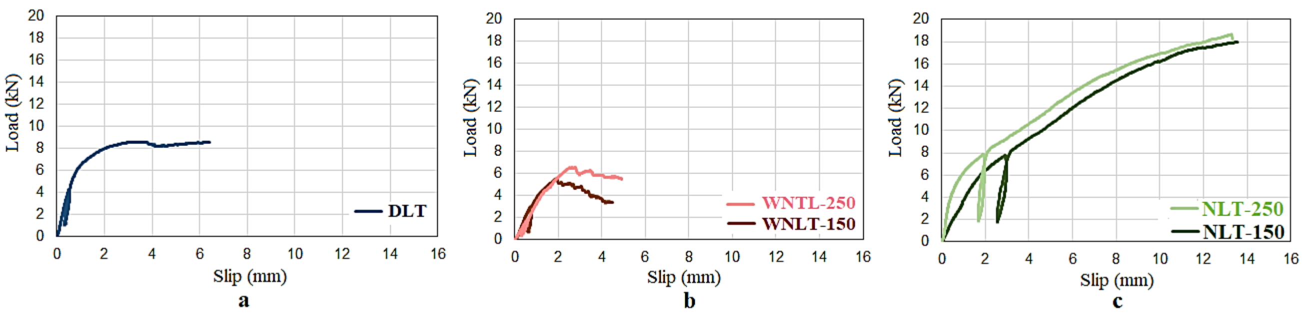


Figure 5. Comparison of typical load-slip curves in perpendicular to grain shear tests of selected: a. DLT, b. WNLT and c. NLT.

4.2 Bending tests

The results of bending tests on structural size panels are summarised in Table 4.

Table 4. Results of bending tests. Mean values and SD.

Test series	DLT-sl	DLT-zigzag	WNLT-250	WNLT-150	NLT-250	NLT-150
n	3	3	3	3	3	3
Density [kg/m³]	528 (41.1)	510 (51.5)	528 (51.6)	522 (41.6)	512 (44.3)	537 (44.5)
*f*m [N/mm²]	57.4 (5.83)	35.4 (1.16)	47.2 (1.95)	46.0 (3.32)	46.3 (5.19)	43.2 (1.17)
*E*m,g [kN/mm²]	11.5 (0.17)	9.8 (0.33)	10.2 (0.22)	10.0 (0.62)	9.7 (1.09)	10.4 (0.70)
*E*m,l [kN/mm²]	12.0 (0.18)	10.2 (0.35)	10.7 (0.23)	10.5 (0.65)	10.1 (1.15)	10.9 (0.74)

Analysis of Variance (ANOVA) of the DLT, WNLT and NLT panels indicated that the values of the bending properties were similar ($p > 0.05$) for the three panel types, regardless of the nailing pattern and connectors spacing. The results suggest that the material of the fastener, wood or steel, and diameter did not influence the load-carring capacity of the panel.

DLT panels with a straight linear nailing pattern showed significantly higher bending strength and stiffness values (62.0 % and 18.5 %, respectively) compared to DLT panels with a zigzag nailing pattern. The values of the structural properties of the DLT-lineal were higher than those reported by Plowas et al. (2016), who performed four-point bending tests on 140 mm x 300 mm x 2520 m^3 DLT panels, composed of 140 x 30 mm *Larix sp.* lamellae (structural class C22) joined with 20 mm diameter *Fagus sp.* dowels spaced at 300 mm in a lineal nailing pattern.

For WNLT panels, the spacing patterns, 250 and 150 mm, between nails did not have a substantial influence on the bending properties.

The load-deformation curves of the DLT, WNLT and NLT panels are shown in Figure 6. All panels exhibited similar behavior, initially a linear up to the proportional limit, followed by a non-linear phase until the maximum load was reached and then failure occurred. The failure pattern was uniform in the six series, with successive ruptures of the lamellae, followed by a load recovery until complete failure of the panel occurred. This behavior is consistent with studies reported by Bell (2018) and Ogunrinde (2019) and could be attributed to the panel configuration, where lamellae with different strength and stiffness were used. In this system, stress is transferred between adjacent lamellae through the connectors; once the strength capacity of a lamella is depleted, the connector transfers the load to the adjacent lamella until failure, and so forth.

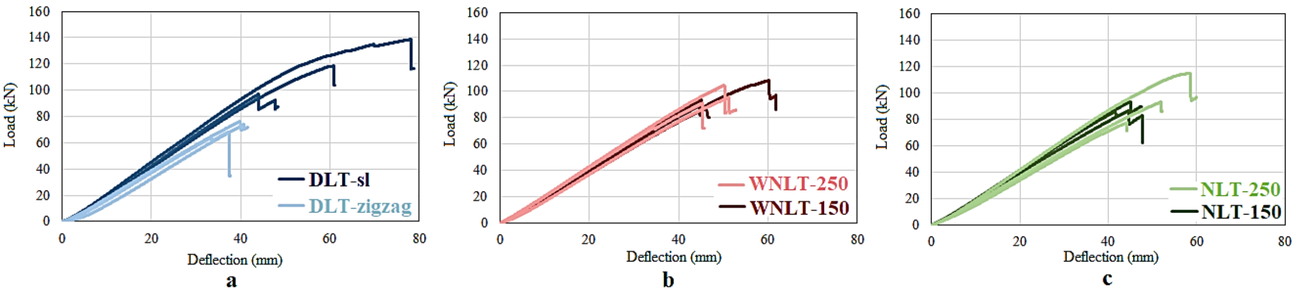
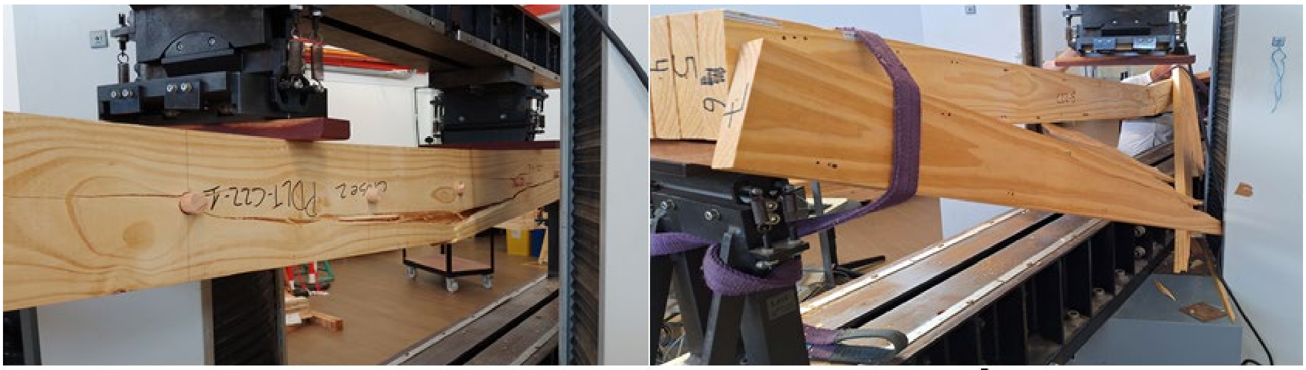


Figure 6. Load-deflection curves of structural size panels. a. DLT panel. b. WNLT panel. c. NLT panel.

The failure pattern observed in the six series of panels was sequential and occurred in the tensioned area of the panel, possibly due to the presence of knots or fibre deviation. Delamination and rupture of the wooden nails in the WNLT panels were observed, in accordance with Zhu et al. (2023). In the DLT panels, most of the breaks were seen to propagate along the dowelled connection line, in agreement with Bruzzone et al. (2023) and Giordano et al. (2023). In addition, visible fractures in the wooden dowels were observed. Figure 7 shows a typical bending failure of DLT and WNLT panels.



a b

Figure 7. Typical bending failure in structural size panels. a. DLT panels. b. WNLT panels.

5 Conclusions and Further Research

The performance of the connections under double shear tests was evaluated and the strength and stiffness were obtained. The following conclusions can be made:

- NLT connections exhibited significantly higher strength values compared to DLT and WNLT connections. DLT connections showed considerably higher stiffness values compared to WNLT and NLT connections. The results suggest that the material of the fasteners (wood or steel) influenced the mechanical properties of the connections.

- In the WNLT connections, the spacing patterns (250 and 150 mm) between wooden nails did not have a significant influence on the mechanical properties.

The bending properties of structural size panels were evaluated under four-point bending tests. From the test results, the following conclusions can be drawn:

- The bending properties of DLT, WNLT and NLT panels were similar, regardless of the nailing pattern and connector spacing. These results suggest that the material and diameter of the connectors (wood or steel) do not significantly affect the load-carrying capacity of the panels.

- In DLT panels, the nailing pattern (lineal or zig-zag) had a significant influence on the bending properties. In WNLT panels, the connector spacing (250 and 150 mm) had no substantial influence on the bending strength and stiffness.

- Most of the panels, regardless of lamella-connector combination, had similar behavior. The most common failure pattern suggests that some lamellas within the panel are weaker than others, and as they fail, mainly due to tension in the bottom side of the panel, the stress is transferred through the connectors to the adjacent lamellas until complete panel failure occurs.

- Delamination and fractures of the wooden nails were detected in the WNLT panels. A similar trend was observed in the DLT panels, where visible fractures in the dowels were observed.

Based on the preliminary results, it can be concluded, that the adhesive and metal-free laminated timber products made of Uruguayan pine are a promising alternative for floor uses. Further on-going research on embedment strength and dimensional stability of wooden nails would shed light on the overall performance of WNLT products.

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7 References

Abed, J., Rayburg, S., Rodwell, J., and Neave, M., 2022. A review of the performance and benefits of mass timber as an alternative to concrete and steel for improving the sustainability of structures. *Sustainability*, 14 (9), 5570. https://doi.org/10.3390/su14095570

Abergel, T., Dean, B., and Dulac, J., 2017. Global Status Report 2017: Towards a zero-emission, efficient, and resilient buildings and construction sector. Nairobi, Kenya: *United Nations Environment Programme*.

BECK, 2024. Lignoloc®. Building sustainably-nail by nail. [online]. Available from: https://www.beck-fastening.com/en/innovation/lignoloc [Accessed 3 August 2024].

Bell, T., 2018. A detailed investigation into the engineering properties and challenges affecting the potential introduction of a UK grown Dowel-laminated timber floor panel into the domestic construction market. Thesis (PhD). University of Strathclyde.

Bruzzone, G., Godoy, D., Quagliotti, S., Arrejuría, S., Böthig, S., and Moya, L., 2023. Experimental investigation on dowel laminated timber made of Uruguayan fast-grown species. *Forests*, 14 (11), 2215. https://doi.org/10.3390/f14112215

CEN European Committee for Standardization, 1991. EN 26891. Timber structures. Joints made with mechanical fasteners. General principles for the determination of strength and deformation characteristics, Brussels, Belgium.

CEN European Committee for Standardization, 2002. EN 13183-1. Moisture content of a piece of sawn timber-part 1: Determination by oven dry method. Brussels, Belgium.

CEN European Committee for Standardization, 2010. EN 408:2010+A1:2012. Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties, Brussels, Belgium.

CEN European Committee for Standardization, 2016. EN 338. Structural timber-strength classes. Brussels, Belgium.

Ceraldi, C., Lippiello, M., D'ambra, C., and Prota, A., 2017. The influence of dowel-bearing strength in designing timber pegged timber joints. *International Journal of Architectural Heritage*, 12(3): 362–375. https://doi.org/10.1080/15583058.2017.1323249

Derikvand, M., Serveh, H., and Fink, G., 2021. Mechanical properties of dowel laminated timber beams with connectors made of salvaged wooden materials. *Journal of Architectural Engineering*, 27 (4). https://doi.org/10.1061/(ASCE)AE.1943-5568.0000513

Fink, G., Ruan, G., and Filz, G., 2019. Sustainable design concepts for short span, timber-only structures. In: Proceedings of the IASS Annual Symposium 2019 - Structural Membranes 2019: Form and Force, 7-10 October 2019, Barcelona, Spain. International Association for Shell and Spatial Structures (IASS), 8 p.

Giordano, L., Derikvand, M., and Fink, G., 2023. Bending properties and vibration characteristics of dowel-laminated timber panels made with short salvaged timber elements. *Buildings*, 13 (1), 199. https://doi.org/10.3390/buildings13010199

Haller, P., 2008. Eminent structural engineer: Julius Natterer. *Structural Engineering International*, 18 (2), 207-209. https://doi.org/10.2749/101686608784218815

Han, L., Kutnar, A., Sandak, J., Šušteršič, I., and Sandberg, D., 2023. Adhesive-and metal-free assembly techniques for prefabricated multi-layer engineered wood products: A review on wooden connectors. *Forests*, 14 (2), 311. https://doi.org/10.3390/f14020311

Korte, H., Koch, G., and Krause, K.C., 2018. Wood nails to fix softwoods: characterization of structural deformation and lignin modification. *European Journal of Wood and Wood Products*, 76, 979-988. https://doi.org/10.1007/s00107-018-1288-x

Naciones Unidas, 2020. United nations sustainable development cooperation framework in Uruguay 2021-2025. [online]. Available from: https://uruguay.un.org/es/125526-marco-de-cooperaci%C3%B3n [Accessed 4 August 2024].

Ogunrinde, O., 2019. Evaluation of bending performance of nail laminated and dowel laminated timber. Thesis (MSc). University of Alberta.

Plowas W., Bell, T., Hairstans, R., and Williamson, J., 2016. Understanding the compatibility of UK resource for dowel laminated timber construction. *TH Building construction*, 12 p. http://researchrepository.napier.ac.uk/id/eprint/10195

Riggio, M., Pauliny, D., Sandak, J., and Sandak, A., 2013. Novel Nail-like Wood Connectors. *Advanced Materials Research*, 778: 647–654. https://doi.org/10.4028/www.scientific.net/AMR.778.647

Riggio, M., Sandak, J., Sandak, A., 2016. Densified Wooden Nails for New Timber Assemblies and Restoration Works: A Pilot Research. *Construction and Building Materials*, 102 (2), 1084–1092. https://doi.org/10.1016/j.conbuildmat.2015.06.045

Ruan, G., Filz, G.H., and Fink, G., 2021. An integrated architectural and structural design concept by using local, salvaged timber. In: Proceedings of the IASS Annual Symposium 2020/21 and the 7th International Conference on Spatial Structures: Inspiring the Next Generation, 23-27 September 2021, Guilford, UK. International Association for Shell and Spatial Structures (IASS), 536-545.

Ruan, G., Filz, G. H., and Fink, G., 2022. Shear capacity of timber-to-timber connections using wooden nails. *Wood Material Science and Engineering*, 17 (1), 20-29. https://doi.org/10.1080/17480272.2021.1964595

Sandberg, L., Bulleit, W. M., and Reid, E., 2000. Strength and stiffness of oak pegs in traditional timber-frame joints. *Journal of Structural Engineering*, 126 (6). https://doi.org/10.1061/(ASCE)0733-9445(2000)126:6(717)

Sandhaas, C., Schädle, P., and Ceccotti, A., 2018. Innovative timber building systems: Comparative testing and modelling of earthquake behaviour. *Bulletin of Earthquake Engineering*, 16, 1961-1985. https://doi.org/10.1007/s10518-017-0264-x

Sosa Zitto, M., Köhler, J., and Piter, J. 2013. Load-carrying capacity of timber-to-timber joints of fast-growing Argentinean Eucalyptus grandis with nails of small diameter laterally loaded in double shear: Analysis according to the criterion adopted by European standards. *European Journal of Wood and Wood Products*. 72 (1), 21-31. https://doi.org/10.1007/s00107-013-0748-6

Sotayo, A., Bradley, D., Bather, M., Oudjene, M., El-Houjeyri, I., and Guan, Z., 2020. Development and structural behaviour of adhesive free laminated timber beams and cross laminated panels. *Construction and Building Materials*, 259, 119821. https://doi.org/10.1016/j.conbuildmat.2020.119821

Uruguay XXI, 2023. Forestry sector in Uruguay. Investment, export and country brand promotion agency [online]. Available from: https://www.uruguayxxi.gub.uy/es/centro-informacion/articulo/sector-forestal-en-uruguay/ [Accessed 3 August 2024].

Yeh, Y.H., and Yeh, Y. C., 2024. Bending behaviour and failure modes of non-glue-laminated timber beams composed of wooden dowels and self-tapping screws. *Buildings*, 14 (2), 394. https://doi.org/10.3390/buildings14020394

Zhu, X., Xue, Y., Qi, P., Lan, Q., and Qian, L., 2023. Flexural properties of wooden nail friction welding of laminated timber. *BioResources*, 18 (1), 1166-1176. DOI:10.15376/biores.18.1.1166-1176