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Load-bearing capacity of pine timber connections using different types of connectors

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ABSTRACT: This study evaluates the load-bearing capacity of pine timber connections using different connectors and two timber strength classes. The connections consisted of pine lamellae (C14 and C22) joined with 20 mm wooden dowels (DLT), 5.3 mm wooden nails (WNLT) and 3.2 mm steel nails (NLT). Shear tests perpendicular to the grain were conducted to determine the shear capacity and slip modulus. The shear properties were influenced by the connector type and timber quality. Timber quality significantly enhanced the stiffness and shear capacity of NLT connections, while in DLT connections, it affected only the stiffness. No significant differences were observed in WNLT connections, probably due to a uniform load distribution. Analytical models based on shear test results were developed to predict the load-bearing capacity under bending. Their validation against experimental tests showed good agreement, demonstrating the potential to optimize the design of timber structures.

Keywords: DLT, NLT, WNLT, load-bearing capacity, timber connections

1 INTRODUCTION

The construction industry plays a significant role in global climate change, accounting for approximately 21% of worldwide greenhouse gas emissions. Buildings contribute about 34% of global energy consumption and are responsible for 37% of carbon dioxide emissions associated with energy use and industrial processes (BPIE & UCL 2024). Therefore, it is crucial to explore sustainable solutions for the design and construction of buildings. In the last two decades, the emergence of engineered wood products (EWPs) such as cross laminated timber (CLT), laminated veneer lumber (LVL), and glued laminated timber (GLT) has significantly contributed to reduce environmental impacts and CO_2 emissions during their production, construction, and operational stages. EWPs offer improved and uniform mechanical properties, making them suitable for structural applications (Abed et al. 2022).

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EWPs are predominantly assembled with synthetic adhesives, that can negatively impact the environment and the human health due to the emission of volatile organic compounds (Han et al. 2023). To mitigate these effects, adhesive-free EWPs have been developed, including dowel laminated timber (DLT), wooden nail laminated timber (WNLT), and nail laminated timber (NLT). Academic research on adhesive-free engineered wood products are gaining interest, particularly focussing on timber connections, as they play an essential role in the performance of timber structures. Most research has focused on the use of steel connectors, considering different types, diameters, spacings, and nail patterns (Sosa Zitto et al. 2013, Zhu et al. 2021, Li et al. 2023). However, the use of steel fasteners in EWPs affects their end-of-life disposal, reusability, recyclability and the overall sustainability (Sotayo et al. 2020). EWPs require suitable connections to join the different elements of the buildings. In recent years, adhesive and metal-free timber connections have been the focus of multiple research. Several studies have been conducted on dowelled laminated timber connections, particularly shear behaviour (Ceraldi et al. 2017, Frontini et al. 2018, Bruzzone et al. 2023, Tétreault et al. 2023) and bending performance (Guan et al. 2018, Dourado et al. 2019, Giordano et al. 2023) on small-scale specimens, using different species, diameters, spacing, nailing patterns of wooden dowels. A disadvantage of using dowel timber connections is the requirement to pre-drill holes before inserting the wooden dowels. In contrast, connections with wooden nails facilitate the direct insertion of the nails using pneumatic guns. During the manufacturing process, the friction between the wooden nail and the surrounding surfaces induces lignin solidification, thereby enhancing the bonding of the timber pieces (Korte et al. 2018). However, published works are scarce, highlighting the works 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. Fink et al. (2019), Ruan et al. (2021) and Ruan et al. (2022) performed shear and bending tests on timber connections with wooden nails, focusing on nail dimensions, orientations, and geometric design. Zhu et al. (2023) performed simple shear and bending tests on small connections and laminated products with wooden nails.

This paper aims to study the load-bearing capacity of pine timber connections made of C14 and C22 pine timber and three different types of fasteners: wooden dowels, wooden nails and steel nails. Shear tests perpendicular to the grain on timber connections were conducted and the shear capacity and slip modulus were obtained. Based on the shear results, analytical models to predict the bending resistance of the connections were proposed, and were experimentally validated.

2 MATERIALS AND METHODS

2.1 *Materials*

The lumber for this study was supplied by a national sawmill specialised in the mechanical processing of *Pinus taeda*. The commercial plantations are located in the Tacuarembó province (31°44′54” S, 56° 02′16” W) in the northeast of Uruguay. The lamellas were dried in conventional kilns and planed on all four sides. Lamellas measuring 36 x 147 x 2850 mm^3 were selected and structurally classified as C14 and C22 according to EN 338 (CEN 2016). All lamellas were equilibrated to a target moisture content (MC) of 16% (±1%).

Three types of connectors were used in the timber connections: a) *Eucalyptus grandis* wooden dowels of national origin, with 20 mm diameter and 120 mm length, b) *Fagus sylvatica* L. wooden nails of European origin, with 5.3 mm diameter and 9 mm length, LIGNOLOC brand and c) spiral steel nails of 3.1 mm diameter and 100 mm length. The wooden dowels were stored in a climatic chamber until they reached 7% (±1) MC.

Each connection consisted of three lamellas connected by wooden dowels or nails. In the DLT connections, the wooden dowels were inserted manually with a rubber hammer, in 19 mm holes previously drilled with a conventional drill. In the WNLT and NLT connections, the wooden and steel nails were mechanically nailed using pneumatic nailers.

2.2 *Shear tests*

Test series for shear are summarized in Table 1. The specimens loaded perpendicular to the grain direction were prepared according to the geometric configuration described by Sandberg et al. (2000), and are shown in Figure 1. Shear tests were performed using a Controls testing machine equipped with a 300 kN load cell, following the loading procedure described in EN 26891 (CEN 1991). Four extensometers were employed: two mounted on the external wooden elements and two on the central element, to measure the relative dis-placement of the connection. The loading parameters, based on the estimated maximum load (*Fmax,est*), were determined from preliminary destructive tests conducted on three specimens per series. Initially, the specimens were loaded up to 40% of *Fmax,est* maintaining the head position for 30 seconds. Subsequently, the load was reduced to 10% of *Fmax,est* and the position was maintained for an additional 30 seconds. Finally, the specimens were re-loaded at a constant rate of 0.05 mm/s. The slip modulus (*K*s) was determined by Equation (1) established in 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 defined as the maximum load recorded during the tests.

$$Ks = \frac{3}{4}\frac{F04}{\left(\frac{v04}{v01}\right)} \tag{1}$$

where $v01$ is the slip equivalent to load 0.1 $F_{max,est}$; $v04$ is the slip equivalent to load 0.4 $F_{max,est}$.

After the tests were finished, a complete cross-section of each specimen (including the three components comprising the connection) was extracted close to the failure zone for moisture content (MC) and density determination in accordance with EN 13183-1 (CEN 2002). The experimental setup for perpendicular to the grain tests is shown in Figure 1.

Table 1. Summary of the test specimens for the shear test.

Denomination	Type of connector	Strength class	Number of connectors	Spacing between connectors [mm]	Number of specimens
DLT-C14	Wooden dowels	C14	1	-	12
DLT-C22		C22	1	-	12
WNLT-C14	Wooden nails	C14	4	150	9
WNLT-C22		C22	4	150	10
NLT-C14	Steel nails	C14	4	150	9
NLT-C22		C22	4	150	10

2.3 *Bending tests*

Test series for bending tests are summarized in Table 2. Four-point bending tests were carried out on timber connections to determine mechanical properties according to EN 408 (CEN 2010). The connections were arranged symmetrically with three lamellas, therefore with two shear planes. The objective was to mimic the behaviour under two loads applied across the full width of the connection until failure, following the procedure described by Ruan et al. (2022). The tests were carried out on a universal testing machine with a load cell of 250 kN, at a constant rate of 1 mm/min. Deformations were recorded by four extensometers, two mounted on the external wooden elements and two on the central element. until the 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 geometric configuration and the test setup are illustrated in Figure 2.

To experimentally evaluate the load-bearing capacity of timber connections with different types of fasteners (i.e., wooden dowels, wooden nails and steel nails) subjected to bending stresses, the bending moment resistance (*Mb.exp*) was determined by:

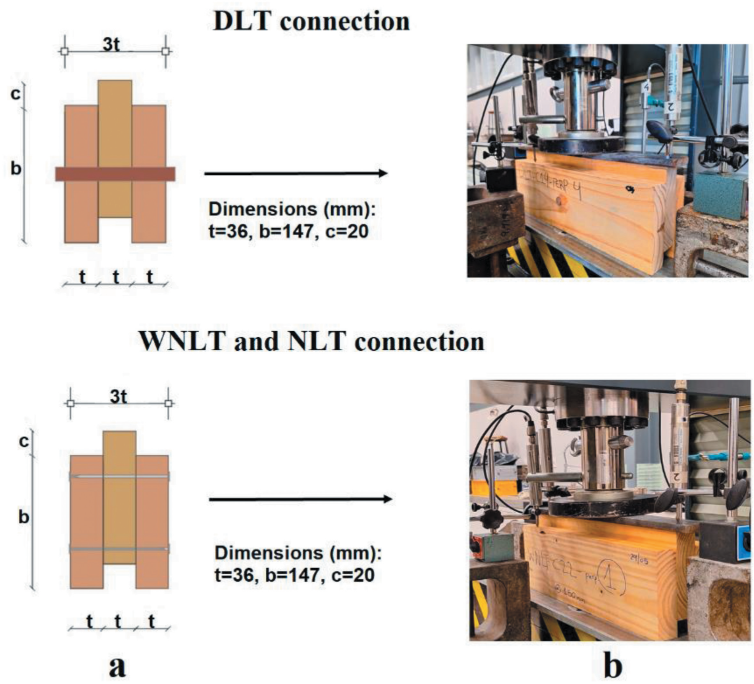

Figure 1. Shear tests on timber perpendicular to the grain connections. a. Geometric configuration. b. Test setup.

Table 2. Summary of the test specimens for the bending test.

Denomination	Type of connector	Strength class	Number of connectors	Nail spacing a_1 [mm]	Nail spacing a_m [mm]	Number of specimens
DLT-C14	Wooden dowels	C14	2	-	300	5
DLT-C22		C22	2	-	300	5
WNLT-C14	Wooden nails	C14	8	75	125	5
WNLT-C22		C22	8	75	125	5
NLT-C14	Steel nails	C14	8	75	125	5
NLT-C22		C22	8	75	125	5

$$M_{b\cdot\exp} = \frac{Fb * lb}{6} \tag{2}$$

where: *Fb* is the maximum load obtained from the bending tests and *lb* is the span.

2.4 *Analytical model*

To predict the moment resistance of DLT, WNLT and NLT with different types of connectors, analytical models were employed and were validated through experimental tests (see Section 2.3).

In DLT connections, the predicted moment resistance (*Mb.mod*) was determined by:

$$M_{b\cdot\mathrm{mod}} = 2 * Fs * d \tag{3}$$

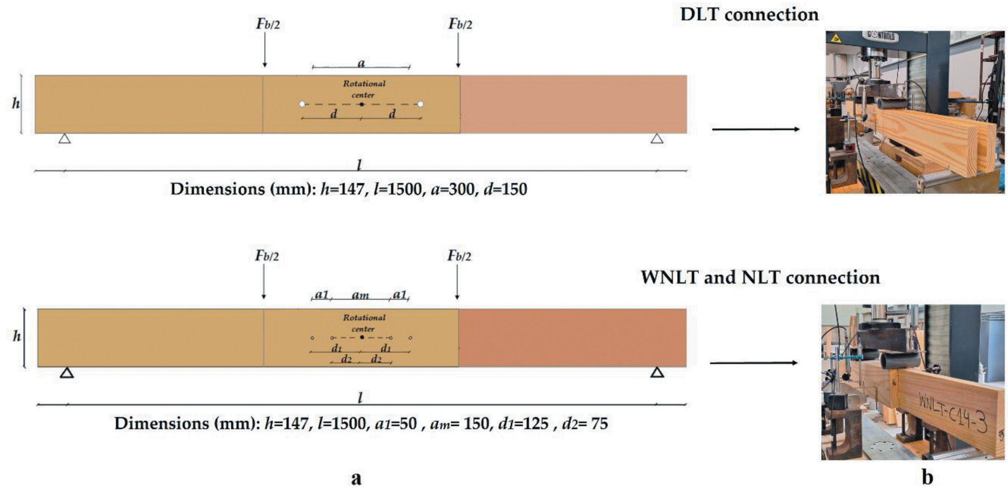

Figure 2. Bending tests on timber connections. a. Geometric configuration (adapted from Ruan et al. 2022). b. Test setup.

where: *Fs* is the shear capacity of the wooden dowel and *d* is the distance between each wooden dowel and rotational centre.

In WNLT and NLT connections, Mb.mod was determined according to Ruan et al. (2022), by:

$$M_{b\cdot\,\mathrm{mod}} = 2\sum_{i}^{2} Fs, i/d_{i,\max} \tag{4}$$

where: *Fs*,*i* is the shear capacity of the nail pairs and *di* is the distance between each nail pair and the rotational center.

3 RESULTS AND DISCUSSION

3.1 *Shear properties*

The mechanical properties and density of the timber connections are given in Table 3.

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

Test series	n	Density [kg/m^3]	F_s [kN]	K_s [kN/mm]
DLT-C14	12	450 (12.4)	7.99 (1.13)	1.47 (0.10)
DLT-C22	12	522 (30.2)	8.76 (1.00)	3.79 (0.55)
WNLT-C14	9	438 (6.1)	6.28 (0.58)	2.79 (0.72)
WNLT-C22	10	507 (10.4)	7.00 (0.90)	2.46 (1.06)
NLT-C14	9	430 (37.3)	14.20 (0.78)	1.37 (0.23)
NLT-C22	10	511 (19.3)	17.59 (2.49)	2.11 (0.89)

Non-parametric tests on DLT (wooden dowel) and WNLT (wooden nails) connections revealed no significant differences ($p > 0.05$) in shear capacity (*Fs*) between strength classes C14 and C22 for each connector type. This suggests that the shear capacity of timber-to-timber connections is primarily governed by the mechanical behavior of the wooden connectors rather than the base timber quality. However, NLT-C22 connections exhibited significantly higher ($p \leq 0.05$) shear capacity compared to NLT-C14. This result indicates that in NLT connections, the failure mechanism is predominantly influenced by the mechanical properties of the base timber, as the steel connectors do not fail under the applied loads.

Regarding the slip modulus (Ks), DLT-C22 connection was 158% higher compared to the DLT-C14 connection. This increase is likely attributed to the higher density of C22 timber, which enhances initial stiffness and load transfer through the single wooden dowel in DLT connections. In contrast, Student's t-test revealed no significant differences ($p > 0.05$) in stiffness between C22 and C14 for WNLT connections. The use of four smaller wooden connectors likely resulted in a more uniform load distribution, reducing the influence of timber density on the connection's stiffness. Nevertheless, NLT connections exhibited significantly higher stiffness in C22 compared to C14, likely due to the higher mechanical strength of steel nails, which improved load transfer and increased the influence of timber density. This finding suggests that the interaction between the connector type and the timber density plays a key role in the structural behaviour of the connections.

3.2 *Bending moment resistance*

The bending moment resistance and density are shown in Table 4.

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

Test series	n	Density [kg/m^3]	F_b [kN]	$M_{b.exp}$ [kN·m]	$M_{b.mod}$ [kN·m]	Relative error [%]
DLT-C14	5	451 (1.6)	9.99 (2.13)	2.50	2.40	-4.00
DLT-C22	5	531 (21.5)	10.33 (2.50)	2.58	2.63	1.94
WNLT-C14	5	450 (14.1)	4.59 (0.45)	1.15	1.07	-6.96
WNLT-C22	5	515 (24.3)	5.16 (0.36)	1.29	1.19	-7.75
NLT-C14	5	451 (2.9)	11.34 (1.19)	2.83	2.41	-14.84
NLT-C22	5	534 (12.2)	11.45 (1.02)	2.86	2.99	4.54

Student's t-tests suggested that the timber quality (C14 and C22) did no significantly affect the bending properties ($p > 0.05$) of the DLT, WNLT, and NLT connections. Furthermore, the DLT and NLT connections exhibited significantly higher strength values ($p \leq 0.05$) compared to the WNLT connections. Other factors, such as the characteristics of the connectors, stress redistribution, and the interaction between the connectors and the timber, possibly had a substantial influence on the performance of the connections.

In general, a concordance between the bending moment resistance obtained from the analytical model and the experimental results for DLT, WNLT, and NLT connections, was

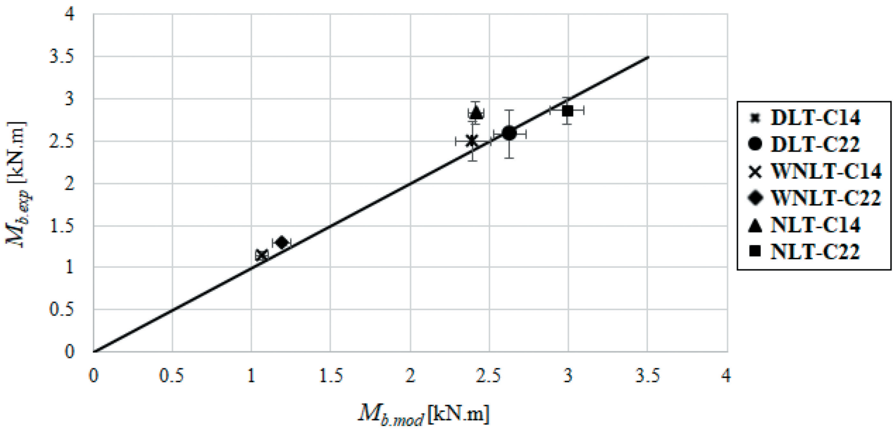

Figure 3. Comparison of the predicted versus experimental moment resistance.

observed regardless of the timber class. These findings are consistent with those reported by Ruan et al. (2022). A more detailed analysis showed that the analytical model slightly overestimated the experimental bending moment resistance in the DLT-C22 and NLT-C22 connections (with differences of 0.05 to 0.13 kN·m), while in the remaining test series (DLT-C14, WNLT-C14, WNLT-C22 and NLT-C14), the model slightly underestimated the experimental results with errors ranging from 0.10 to 0.42 kN·m. These small discrepancies can be attributed to the unaccounted interaction of additional rotation and horizontal loads on the connectors, and the diverse stiffness values of the different types of connectors. Figure 3 depicts the comparison of the experimental bending moment resistance (*Mb*) and the analytical model predictions.

4 CONCLUSION

Based on the results and observations, the following conclusions can be drawn:

The structural performance of timber connections varied depending on the connector type and the timber strength class (C14 and C22). In DLT connections, the slip modulus was significantly higher for C22, suggesting that timber density enhances stiffness and load transfer through the wooden dowel. In WNLT connections, no significant differences were observed in shear capacity or stiffness between timber classes, probably due to the uniform load distribution provided by multiple wooden connectors which minimized the influence of timber density. In contrast, NLT connections exhibited significantly higher shear capacity and slip modulus for C22, attributed to the superior mechanical properties of steel nails and the increased contribution of timber density. These results highlight the critical role of the interaction between connector type and timber density in determining the structural behavior of timber connections.

A good agreement between the bending moment resistance estimated by analytical models and the experimental results was observed. This finding suggests that the analytical models could effectively optimize the design of timber structures using different types of connectors and timber qualities.

Future research evaluating the influence of the amount and size of dowels or nails, and the nailing pattern on the structural properties of timber connections will be highly valuable. This approach will enable a more precise optimization of the design of timber structures.

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