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Characterization of Dowelled Cross-Laminated Timber Panels Made of Uruguayan Fast-Grown Species

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Abstract

In recent decades, the development of adhesive-free engineered timber products has become one of the primary research areas in timber construction systems. This paper studies the structural behaviour of Dowelled Cross-Laminated Timber (DCLT) panels made of Uruguayan fast-growing *Pinus taeda*, connected by hardwood dowels. Two series, each comprising three structural-size panels were constructed using C14 and C22 classes timber, joined by 20 mm *Eucalyptus grandis* dowels. Shear tests on dowelled-cross connections and four-point bending tests on DCLT panels were performed, and the slip modulus and bending properties, respectively, were obtained. Results indicated that DCLT-C22 panels showed significantly higher bending strength (16.1 MPa) and stiffness (3,091 MPa) values than DCLT-C14 panels (10.7 MPa; 2,228 MPa), suggesting that the quality of lamellae had influence on the panel's structural properties. The typical failure mode occurred under tension exclusively in the bottom lamellae, with fractures attributed to the presence of knots along the drilled holes and near the load application area. Wooden dowels exhibited minor visible fractures and crushing along their length. These findings suggest that adhesive-free cross-laminated timber panels made from Uruguayan pine are a promising alternative for residential floors and roof uses, advancing more sustainable construction systems.

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1. Introduction

The construction industry accounts for approximately 40% of global CO_2 emissions, with building materials such as steel and concrete contributing an additional 9% of energy-related emissions (Huang et al., 2024). Urbanization and population growth are driving a notable rise in demand for residential construction, emphasizing the importance of adopting sustainable and environmentally responsible solutions (Abed et al., 2022). Therefore, developing materials and construction systems, such as mass timber, is crucial for addressing the industry's challenges.

Mass timber refers to a family of engineered wood products made of multiple wood elements that are nailed or glued together, designed for structural use. Within mass timber, Cross-Laminated Timber (CLT) is widely produced as panels and utilized for floors, roofs, and walls, in Europe, North America, and Asia (Younis and Dodoo, 2022; De Araujo et al., 2023). CLT is composed of layers, orthogonally staked and bonded together with industrial adhesives. Over the last decade, CLT has been questioned regarding the adhesives used in its production, primarily urea-formaldehyde and phenol-formaldehyde, as well as the release of volatile organic compounds that are harmful to the environment during production and final disposal (Świrska-Perkowska et al., 2022). Moreover, in general, the use of adhesives has a significant impact on end-of-life disposal and overall sustainability. Therefore, mechanical joining methods involving wooden dowels and wooden nails in multi-layered timber products are resurging as sustainable alternatives to traditional bonding methods (Han et al., 2023).

Dowelled Cross Laminated Timber (DCLT) is an innovative development in mass timber made of crosswise timber layers joined by hardwood dowels. Dowels having low moisture content (7 ± 1% MC) are inserted in pre-drilled holes to join layers with typical superior MC, and as the dowel gains moisture, it creates a tight, adhesive-free bond.

The literature on DCLT mainly reports on panels (Pereira et al., 2019, 2021; Bui et al., 2020; Paroissien et al., 2023; Paroissien et al., 2024) (Guan et al., 2019; Sotayo et al., 2020; Xu et al., 2022; Han et al., 2023). These studies explore aspects such as the fabrication process (i.e., lamellas and dowels), structural properties, and modelling. To determine the effective section properties of DCLT elements, it is essential to evaluate the stiffness of the connections between lamellas. Since the structural performance of DCLT depends on these connections, understanding the interaction between lamellas and dowels is crucial for its effective design. Recent studies have investigated the mechanical response of dowel–lamella interfaces under various material combinations and moisture conditions, highlighting their impact on the connection behavior (Han et al., 2025).

Over the past decade, Uruguay has launched several research projects exploring mass timber products, including Glued Laminated Timber, Cross Laminated Timber, Dowel Laminated Timber, Nail Laminated Timber with wooden nails, and Nail Laminated Timber with steel nails. However, no national research has been conducted on Dowelled Cross Laminated Timber (DCLT). This study aims to assess the load-bearing capacity of DCLT connections and the bending performance of structural size DCLT panels made of Uruguayan fast-growing species.

2. Materials and Methods

The experimental design consisted of manufacturing and analysing the mechanical behaviour of dowelled cross-laminated timber connections and structural size panels.

2.1. Materials

The timber used in this study came from a *Pinus taeda* plantation. Thirty boards, also called lamellae, graded as C14 and thirty boards graded as C22 (EN 338, 2016), with a cross-section of 147 x 36 mm^2, were purchased from a local supplier. All lamellae were equilibrated to a MC of 16% (±1%). *Eucalyptus grandis* dowels with 20 mm diameter and 110 mm long were prepared, and stored in a climate chamber until they reached 7 ± 1% MC.

Six structural size DCLT panels, three made of C14 lamellae (DCLT-14) and three made of C22 lamellae (DCLT-22), were prepared. Each panel (441 x 3230 x 108 mm^3) consisted of three layers, two external with longitudinal lamellae and one internal with transverse-oriented lamellae. The mean values of the dynamic modulus elasticity parallel to the grain (E_0) of C14 and C22 outer lamellae were 10077 Nmm^{-2} and 13057 Nmm^{-2}, respectively. The corresponding values of E_0 for C14 and C22 inner lamellas were 8818 Nmm^{-2} and 11915 Nmm^{-2}, respectively. The staked layers were joined with 66 dowels, evenly spaced @ 73.5 mm o.c., that were manually inserted using a rubber hammer in pre-drilled holes (Figure 1). After manufacturing, panels were stored in a service Class 1 environment for two weeks to allow moisture to migrate from the lamellas to the dowels, causing the dowels to expand and lock into place.

Two series of connections, ShDCLT-14 and ShDCLT-22, each comprising 12 specimens, were prepared to evaluate the shear behaviour of the dowelled-cross timber connections. The geometric configuration followed Pereira et al. (2021), as shown in Figure 2. The shear tests were designed to simulate the forces acting on the dowels under loading conditions, replicating the stresses experienced by the panel in bending. To create two shear planes, the central pieces were bonded together with polyvinyl acetate (PVAc) adhesive solely for positioning purposes. Each central piece was then joined to the parallel and perpendicular laminations using a single wooden dowel per shear plane.

Fig. 1. Fabrication of structural-size DCLT panels.

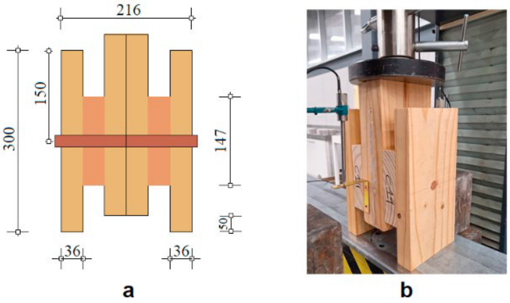

Fig. 2. Shear properties of ShDCLT connections. (a) Specimen dimensions (mm); (b) Test setup.

2.2. Experimental Procedure

2.2.1 Double-shear tests

The connection between lamellae and dowel was evaluated through double-shear tests, according to the loading procedure described in EN 26891 (1991). Tests were conducted using a Controls testing machine with a 300 kN load cell. Two extensometers, each placed on the central piece and on opposite sides of the connection, enabled the measurement of the relative displacement of the connection in both shear planes. The test set up is shown in Figure 2.

The parameters of the loading procedure, based on the maximum estimated load (Fmax, est), were obtained from previous destructive tests conducted on three specimens per series. First, the specimens were loaded until 40% $F_{max,est}$, was reached, and the crosshead position was held for 30s. After this step, specimens were unloaded until 10% $F_{max,est}$, and the crosshead position was once again maintained for an additional 30s. Finally, specimens were reloaded at a constant rate of 1.5 mm/min. The slip modulus (K_s) was calculated in accordance with EN 26891, based on the gradient of the line corresponding to the initial points of 10% $F_{max,est}$ and 40% $F_{max,est}$ on the load-slip curve. The shear capacity (F_s) 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 near the failure zone for MC and density determination, in accordance with EN 13183-1 (2002).

2.2.2 Bending tests

Four-point bending tests on structural size DCLT panels were conducted in accordance with EN 16351 (2021). The bending strength (f_m), local ($E_{m,l}$) and global ($E_{m,g}$) modulus of elasticity were estimated according to EN 408 (2012). DCLT panels were flatwise oriented to represent a typical floor and loaded by two equally separated line loads acting across the entire width of the specimen until failure.

The tests were performed using a universal testing machine equipped with a 300 kN load cell, under constant displacement rates of 0.200 mm/s for DCLT-C14 and 0.283 mm/s for DCLT-C22 panels. Deformations were recorded by extensometers located at the mid span of the underside of the panel until reaching 40% $F_{max,est}$, ensuring that the load cycle and its corresponding deformation fell within the elastic range. At that point, the extensometers were removed and loading continued until failure. The ultimate load was recorded by the load head displacement. The test configuration is illustrated in Figure 3. For each panel, MC and density of the central and outer lamellae were determined.

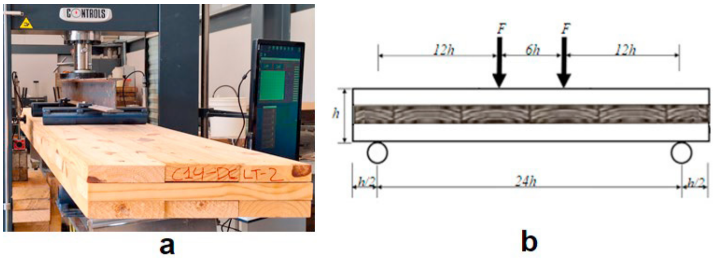

Fig. 3. Test setup for bending properties of DCLT panels. (a) Actual test; (b) Configuration according to EN 16351.

3. Results and Discussion

3.1. Dowelled Cross-Laminated Connections

The results of the shear tests on DCLT connections are summarized in Table 1.

Table 1. Test results for DCLT connections. Mean values and SD.

ID	ShDCLT-C14	ShDCLT-C22
n	12	12
Density (Kg/m^3)	439 (15.7)	518 (19.3)
F_s (kN)	7.96 (0.89)	8.16 (0.43)
K_s (kN/mm)	0.61 (0.20)	0.62 (0.14)

Student's t-test on ShDCLT-C14 and ShDCLT-C22 connections did not show significant differences ($p > 0.05$) between the two strength classes. This suggests that the shear properties of timber-to-timber connections are primarily governed by the mechanical behaviour of the wooden dowel rather than the quality of the base timber.

Figure 4 shows the load-slip behaviours observed in shear tests of dowelled cross-laminated timber connections. For comparison purposes, four representative responses were identified: a. Progressive slip, where the connection exhibits a stable response with a continuous load increase, followed by a gradual failure at the end of the test; b. Failure with partial recovery, characterized by a sudden load drop followed by a regain in load-bearing capacity; c.

Progressive slip with localized failures, characterized by a continuous load increase with small intermittent drops throughout the test; d. Premature failure, characterized by an abrupt loss of load-bearing capacity near the maximum slip, leading to the total collapse of the connection.

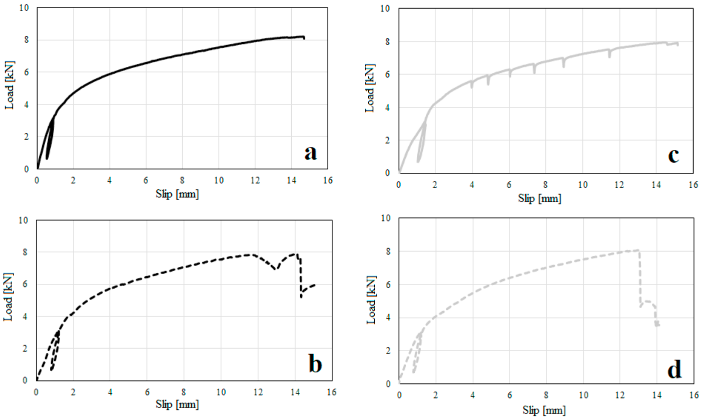

Fig. 4. Load-slip responses in shear tests of ShDCLT connections with different failure behaviours.

Figure 5 illustrates the typical failure modes observed in ShDCLT specimens during shear tests. The observed failure modes can be classified as follows: i) Slip at the connection interface, associated with the rotation of the cross layers and bending deformation of the dowels; ii) Splitting failure along the dowel rows and shear failure in the cross layers and iii) Shear failure, bending deformation, and embedment failure in the wooden dowels. Additionally, localized crushing was observed in the dowel holes. These observations align with the findings reported by Pereira et al. (2021) and Pereira et al. (2023) on dowelled cross-laminated timber

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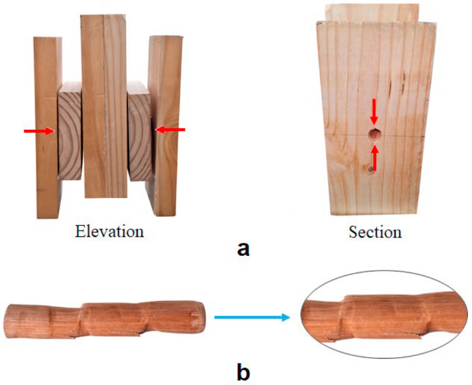


Fig. 5. Typical failure modes in DCLT under shear tests. (a) Connection (elevation and section views); (b) Wooden dowel.

3.2. Dowelled Cross-Laminated Panels

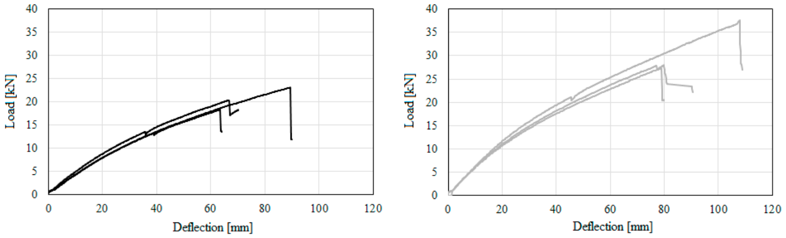
The results of bending tests on DCLT panels are summarised in Table 2.

Table 2. Test results for DCLT panels. Mean values and SD.

ID	DCLT-C14	DCLT-C22
n	3	3
Density (Kg/m^3)	443 (28.5)	520 (46.1)
Strength (MPa)	10.7 (1.25)	16.1 (3.03)
Global MOE (MPa)	2228 (145)	3091 (142)
Local MOE (MPa)	2299 (149)	3189 (146)

The average maximum load for DCLT-C14 and DCLT-C22 was 20.6 kN and 31.0 kN, respectively. The bending properties of DCLT-C14 panels exhibited significant differences ($p \leqslant 0.05$) from those of DCLT-C22 indicating that the quality of the lamellae influenced the structural properties of the panels. This behaviour can be also attributed to a more efficient stress distribution in the DCLT-C22 panels, which favoured an increase in ductility and a higher capacity to absorb deformations prior to failure.

The load-deformation curves of the DCLT panels are shown in Figure 6. All panels exhibited similar behaviour, initially a linear increase up to the proportional limit, followed by a non-linear phase until the maximum load was reached, and then failure occurred. The orthogonal arrangement of the lamellae and wooden dowels as connectors optimizes the stress distribution, being higher in the outer layers (parallel to the fibers) and lower in the middle layer (perpendicular to the fibers), which allows for a greater load absorption capacity. However, the holes generated by the dowels can introduce discontinuities in the fibers, creating stress concentrations that limit the load-bearing capacity in specific areas of the panel. Similar response was reported by Pereira et al. (2019) who studied cross-laminated timber panels made of pine and assembled with pau-roxo dowels.



a

b

Fig. 6. Load-deflection curves of structural size panels. (a) DCLT-C14; (b) DCLT-C22.

The typical failure mode occurred under tension exclusively in the bottom lamellae, with fractures attributed to the presence of knots along the drilled holes and near the load application area. In general, wooden dowels exhibited minor visible fractures and crushing along their length. These observations are consistent with the findings reported by Xu et al. (2022) in adhesive-free cross-laminated timber elements. The typical failure of DCLT panels in bending is shown in the Figure 7.

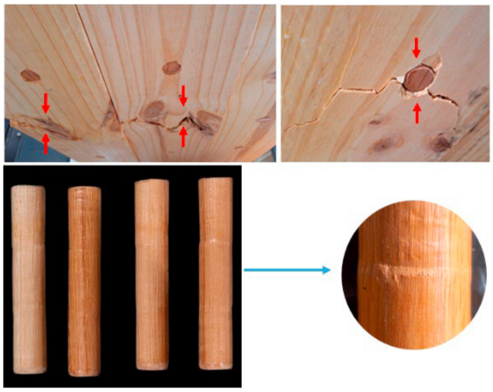


Fig. 7. Failure pattern for DCLT panel in bending.

4. Conclusions

A series of Dowelled Cross-Laminated Timber (DCLT) panels made from fast-growing Uruguayan species were manufactured and tested according to European standards.

Bending performance of DCLT panels:

- DCLT panels with higher-grade lamellae (C22) demonstrated enhanced flexural performance compared to C14, confirming the critical role of lamella quality in overall panel behaviour.
- All panels exhibited a linear–nonlinear response up to failure, typically governed by tension in the bottom lamellae due to natural defects near the dowel path.
- The orthogonal layout and mechanical interlocking of dowels provided reliable performance, although stress concentrations around dowel holes may limit strength in localized areas.

Shear performance of DCLT connections:

- Shear performance was similar for C14 and C22 timber, suggesting that dowel properties primarily govern connection strength and stiffness.
- Four distinct load–slip responses were identified, reflecting the influence of dowel configuration, timber properties, and manufacturing variability.
- Failure modes included dowel embedment and shear, splitting along dowel rows, and slip at the interface, all affecting load-bearing capacity and ductility.

This preliminary study intended to explore that the mechanical behaviour and analyse the failure modes of Dowelled Cross-Laminated Timber made from fast-growing Uruguayan species. Further on-going work including different design configurations (i.e., more dowels, species with higher densities for external layers) would contribute to a better understanding of the DCLT behaviour and would probably improve its performance for complying with floor serviceability criteria. In addition, modelling methods to predict the structural performance of DCLT are being developed. Acknowledgements

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