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FABRICATION AND TESTING OF GLUED-LAMINATED TIMBER FRAMES WITH REINFORCED CONNECTIONS

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KEYWORDS

timber structures, adhesives, mechanical performance, *Araucaria angustifolia*.

ABSTRACT

Materials from renewable sources have been increasingly used in construction to assist in sustainable development. Therefore, the use of timber becomes an environmentally advantageous solution, especially if used for long-term purposes, such as in structures. In this sense, this study aimed to evaluate the performance of glued-laminated timber frames reinforced in their main connections. The structures were made using timber from the *Araucaria angustifolia* species and polyurethane adhesive based on vegetable oils. The frames, on a reduced scale, had a pillar height and free span of 2 m and were reinforced in the connections between the roof beams and pillars. The rupture strength values of the structures averaged 38.02 kN, approximately 5.47 times the design load, and represented a 32% increase in strength compared to non-reinforced structures. The displacements did not reach the normative limit for the design load and presented a linear behavior for strengths higher than three times those of the design. The structures presented satisfactory structural behavior and had an improvement in resistance and rigidity caused by the addition of reinforcements.

INTRODUCTION

The use of timber for structural purposes is historical, especially because of its mechanical properties, natural availability, and easy workability. In addition, the need to use materials from renewable sources and sustainable production processes makes the timber market grow every year (Almeida et al., 2013; Santos et al., 2015).

However, the exacerbated use of the native forest led to the tightening of environmental legislation, making it difficult to obtain this massive material in large dimensions. In this sense, several techniques have been developed aiming at prefabrication to allow and rationalize the use of timber in structural systems. One of them is the so-called glued-laminated timber (GLT), which is a composite that consists of laminating and gluing parts with fibers parallel to each other (Segundinho et al., 2017; Faria et al., 2019).

This structural product supports high levels of loading and can be considered light when compared to steel and concrete of the same structural capacity, in addition to distributing natural defects of the parts more homogeneously, allowing the execution of more resistant and reliable elements (Miotto & Dias, 2010; Depieri et al., 2020).

The sheets should be classified and arranged according to their characteristics and glued using appropriate adhesives under pre-established pressure to obtain quality GLT pieces. Moreover, the combination between the wood species and the adhesive must be in accordance with the purpose for which the piece will be applied so that the structure has a satisfactory performance against the straining, temperature, and moisture content to which it will be subjected (Molina et al., 2016; Almeida et al., 2020).

The increased demand for the application of natural products must be considered among the adhesive for timber available on the market. Polymers obtained from renewable sources can compete with or even surpass compounds produced from petroleum both in

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environmental terms and the cost/benefit ratio (Lligadas et al., 2013). Azambuja (2006) used an adhesive produced from castor oil to manufacture glued-laminated timber and concluded that it can be indicated as a technically viable alternative for use in GLT and joints.

Frames stand out among the structural systems that can be constructed using GLT, as they are versatile systems that can be used for the most diverse purposes. The construction of sheds, such as those for laying aviaries, is one of the segments with the highest demand for frame structures in western Paraná State (Stringari et al., 2020).

Couri Petrauski et al. (2016) studied the behavior of wooden frames by building and testing five units using GLT made with *Eucalyptus* spp. and polyurethane adhesives based on castor oil and resorcinol-formaldehyde. The authors stated that the structures presented satisfactory mechanical performance and deformations lower than those allowed by the standard.

Stringari et al. (2020) designed, built, and tested five GLT frames made with the *Araucaria angustifolia* species and vegetable oil-based adhesive, with a geometry similar to that used in frames used for laying aviaries in western Paraná State. The authors attested that these combined materials could result in structures with satisfactory behavior considering strength and stiffness requirements.

Possa et al. (2022) also executed and tested four cable-stayed frames with 3/8″ threaded bars in GLT made with *Pinus* sp. and adhesive based on vegetable oils for use in laying aviaries. The authors concluded that the use of cables contributed positively to increasing the mechanical performance of the structures when compared to structures without their use.

These studies are promising and point to the search for safer and more economical solutions in similar structures. Thus, the present study aimed to build and test frames similar to those executed by Stringari et al. (2020) but with reinforcements in the connections between roof beams and pillars.

METHODOLOGY

The experiments were carried out at the Laboratory of Technology and Timber Structures (LATEM) of the Western Paraná State University (UNIOESTE), campus of Cascavel – PR (Brazil). The timber was of the *Araucaria angustifolia* species from trees that were 30 years old when cut, obtained in the local market and from the same lot as Stringari et al. (2020). The timber characterization was carried out according to normative prescriptions following the recommendations of NBR 7190 (ABNT, 1997). The adhesive consisted of a vegetable oil-based bicomponent purchased from the company KEHL Indústria e Comércio (São Carlos – SP, Brazil).

Project

The geometry used in the structures was the same as that adopted by Stringari et al. (2020), who performed a small-scale project based on real structures used in laying aviaries by Cooperativa Agroindustrial LAR, in Medianeira – PR (Brazil). Figure 1 shows the final geometry of the scaled-down frame already designed for wood construction. The pillars (AC and EG) and beams (CD and DE) were composed of five sheets each and the thickness of the sheets was standardized at 1.5 cm, as shown in Figure 1.

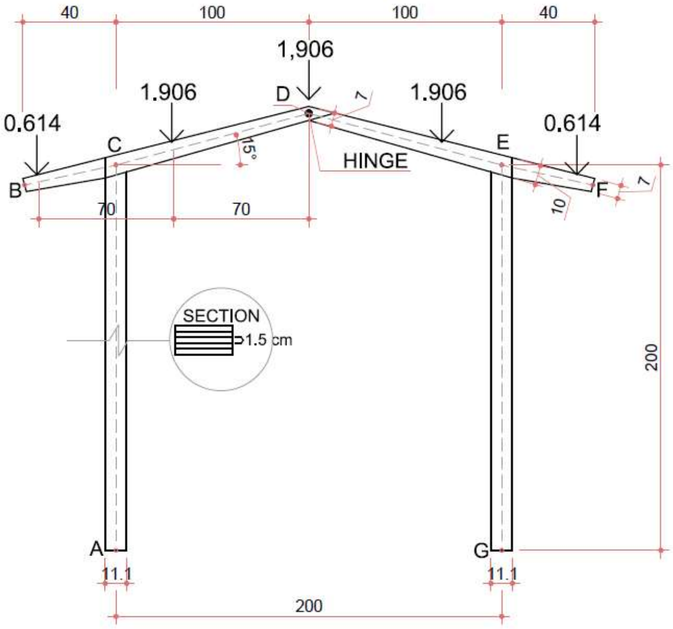

FIGURE 1. Final scaled-down geometry of the frame with design load (in kN), dimensions in centimeters.
Source: adapted from Stringari et al., 2020.

Reinforcements in connections C and E, applied exclusively to the pillar bars at their upper ends and consisting of two additional sheets, were added to the geometry of Stringari et al. (2020). These sheets were 30 cm long, 11.1 cm wide, and identical in thickness to the other sheets. Importantly, this increase in the number of parts and adhesive was equivalent to approximately 3.0% more material, representing a low investment if the total cost of the structure is considered.

A two-sheet overlap from the pillar with three sheets from the roof beam was idealized at this location to make the rigid bonded connection viable at nodes C and E. The design load of the structures is shown in Figure 1. All ruptures occurred in the region of the glued-rigid connection (nodes C or E) in the research by Stringari et al. (2020). However, a rupture was very often observed due to traction perpendicular to the fibers of the sheets coming from the roof. Therefore, in this research, we decided to try to reduce this type of occurrence by extending these bars to the eaves region. Possa et al. (2022) adopted the same procedure. Figure 2 shows the final solution used for the implemented reinforcements.

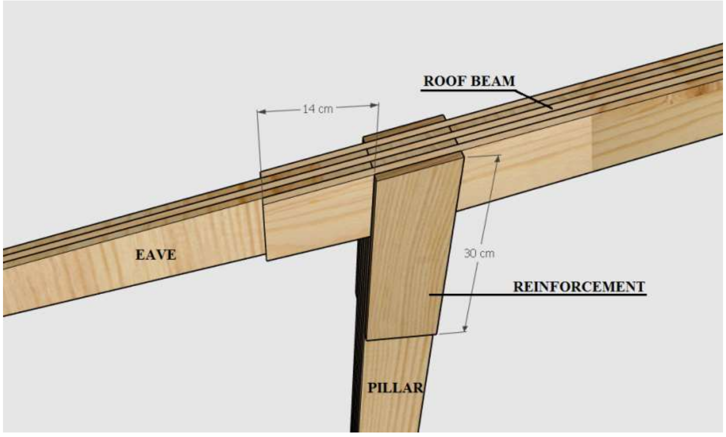

FIGURE 2. Detailing of the overlapping among the nodes C and E.

Execution and testing of structures

Timber pieces with fewer knots, cracks, wanes, and warping and higher density were chosen among those available.

The adhesive preparation followed an isocyanate-to-polyol ratio of 1:1.5. Adhesive consumption was 290 g/m^2 and the bonding pressure adopted was 0.7 MPa. An electronic torque meter was used to control the pressure imposed by the screws on the glued planes. After bonding, the structures were kept under pressure for at least 12 hours, after which they were removed from the pressing table and the minimum time elapsed between the bonding of each frame and the respective test was 24 days, in agreement with that recommended by Couri Petrauski et al. (2016), who suggests a minimum of 12 hours under pressure and 10 days until testing.

The force application system consisted of three vertically fixed hydraulic cylinders, responsible for applying forces to the internal part of the frame, and two trays arranged on the sides of the frames, responsible for applying forces to the eaves. The loading on the trays was performed using previously weighed concrete specimens, as shown in Figure 3.

FIGURE 3. Tray with concrete specimens for structural loading.

The applied forces were indicated using two load cells arranged between the cylinder and the structure at the load application points located internally on the roof beams. The frame displacement readings were taken using six dial gauges with a resolution of 0.01 mm, installed at pre-established points to evaluate the points with the highest displacement. The bracing system was made using a bearing system arranged on the roof beam. The frames were supported using hinges developed for the fixation of the structures at points A and G. Figure 4 shows all these devices.

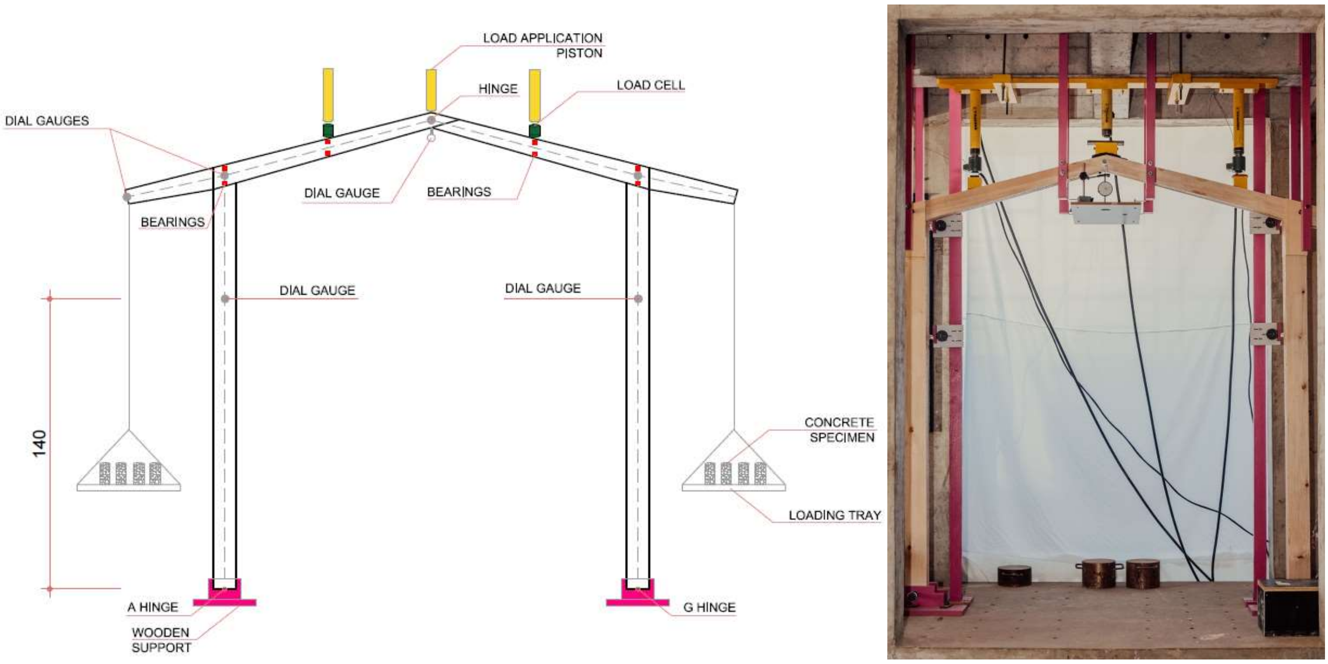

FIGURE 4. (a) Arrangement of the test apparatus; and (b) arrangement for real-world testing.

The tests were conducted starting with an application of total force, close to 2 kN, to allow an initial structure accommodation and instrument checking. Removing the initial load, an increasing load was applied up to the level corresponding to the design load, including the loading of the eaves (6.946 kN), with the reading of displacements on the dial gauges and subsequent structure unloading. This sequence was repeated. Finally, an increasing load was applied, aiming at rupture, with the reading of the dial gauges up to an approximate load of 20 kN, with no application of load on the eaves. The equipment was removed above these loading levels for safety reasons and the tests continued until rupture.

RESULTS AND DISCUSSION

Strength of structures

Table 1 shows the information regarding the strength of the frames obtained in the tests.

TABLE 1. Strenght of the frames in the tests.

Frame	Rupture point	Rupture load (kN)	Design load (kN)	Ratio of rupture load to design load
1	Node C and D	36.585	6.946	5.27
2	Node C and D	41.295	6.946	5.95
3	Node C and D	36.975	6.946	5.32
4	Node E	38.40	6.946	5.53
5	Node C and D	36.855	6.946	5.30
Average	-	38.022	6.946	5.47
Frame averages Stringari et al. (2020)		28.79	6.946	4.14

The average quotient between the rupture load of the frames and the design load was 5.47, showing satisfactory performance in terms of safety. The positive influence of the reinforcements on the strength can also be noticed if compared with the mean value of the quotient of rupture load and design load of the structures by Stringari et al. (2020), which was 4.14. That is, the reinforcement in the critical connections (C and E) resulted in an average increase of 32% in strength.

The quotient found in the structures also surpassed the quotients found by Couri Petrauski et al. (2016), which were 4.42 on average for the two units bonded with castor bean adhesive and 4.63 for the three units bonded with resorcinol formaldehyde. These results confirm the good performance regarding the strength of the tested structures.

Stiffness of structures

Data from six dial gauges, arranged as shown in Figure 5, were used to analyze the stiffness presented by the structures. Importantly, this arrangement was chosen to prioritize the analysis of points with higher levels of displacements indicated by the Ftool Software. Table 2 shows the displacement values presented by the structures during the tests for the design load. The average values are presented for dial gauges 2 and 4, as well as 3 and 5.

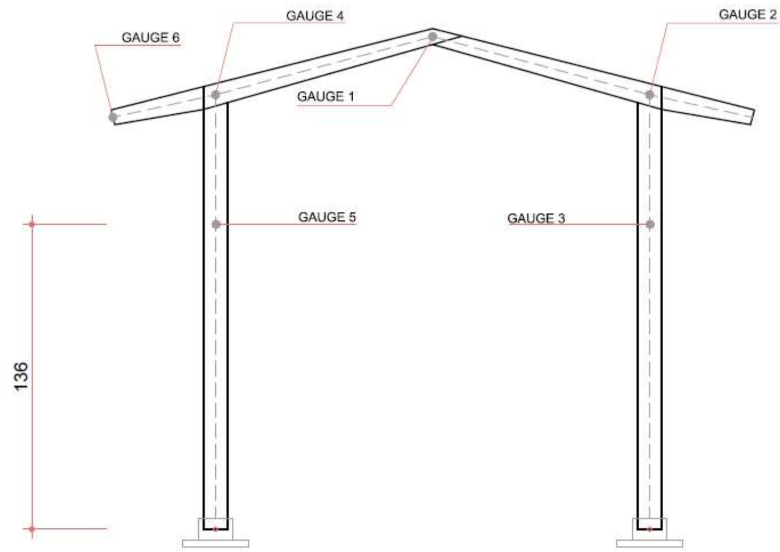

FIGURE 5. Arrangement of the dial gauges.

TABLE 2. Displacements for the design load.

Frame	Dial gauge 1 (vertical)	Dial gauges 2 and 4 (horizontal)	Dial gauges 3 and 5 (horizontal)	Dial gauge 6 (vertical)
1	5.35	1.576	2.2708	0.835
2	6.379	1.922	2.814	1.37
3	5.781	1.901	2.539	1.283
4	5.582	1.584	2.457	1.144
5	5.536	1.629	2.446	1.08
Average	5.726	1.722	2.505	1.142
Variation coefficient	6.18%	9.03%	7.08%	16.14%

The increase in the stiffness of the structures was one of the expected consequences of the use of reinforcements in the connections of the frames. This increase in stiffness can be proven by the comparison shown in Figure 6. This figure shows the displacements theoretically obtained by Ftool for structures with reinforcement, the actual average displacements obtained in the tests by Stringari et al. (2020), and the actual average displacements obtained in this study for reinforced structures. All arrows refer to the design load value, that is, 6.946 kN.

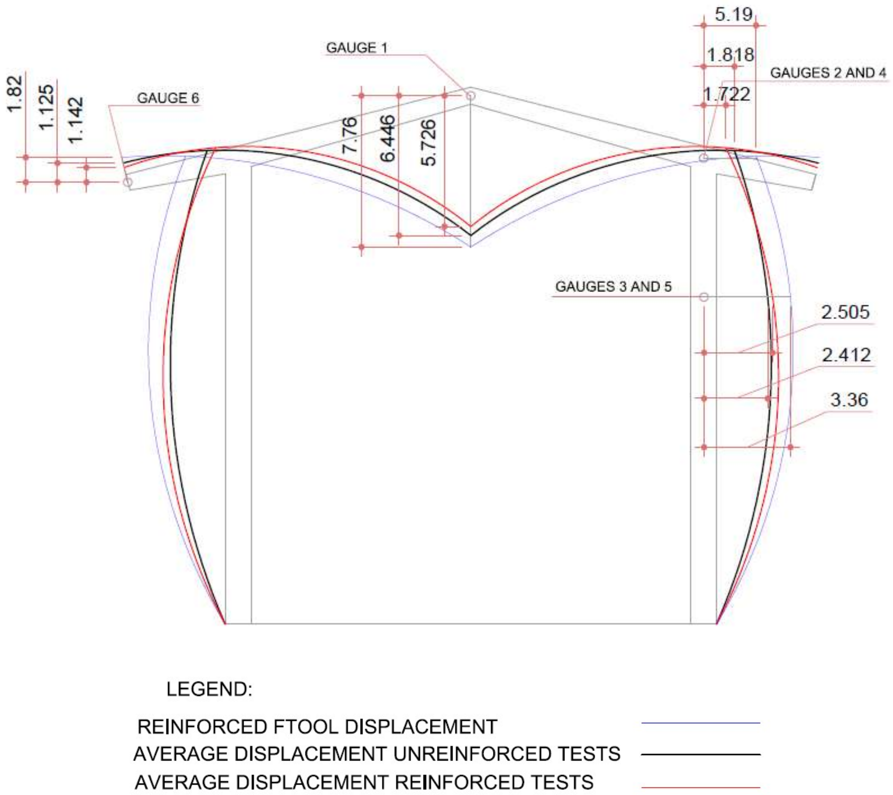

FIGURE 6. Comparison between the displacement estimated by Ftool, average displacements obtained from the unreinforced structures (Stringari et al., 2020), and with reinforcement, in mm, for design loading.

The recorded displacements were lower than those found by Stringari et al. (2020) and estimated by Ftool, except for the pillars. This evidence confirms a positive reflection of the implemented reinforcements on stiffness. Regarding the pillars, the densest timber with the least presence of defects in the lot worked by Stringari et al. (2020) is believed to have allowed higher stiffness at these points.

The estimates of the Ftool program were more pessimistic in all cases than those obtained in the experiments. The fact that the program does not allow the implementation of the linear variation of the inertia in the inclined bars may be related to this occurrence. In this case, the inertia variations were implemented by subdividing the bars into sections. Finally, the ridge (node D) was treated in Ftool as a hinge, but it is more rigid in the actual structure due to the fitting performed, not allowing a deformation as free as the theoretical hinge.

According to NBR 7190 (1997), the maximum deflection allowed for this type of structure at the midpoint is equal to L/200, where L is the free span of the structure, i.e., 200 cm in this case. Therefore, a deflection of up to 10 millimeters is allowed on the ridge for frames of this geometry for agricultural purposes. Figure 7 shows that the frames did not reach the maximum deflection limit allowed by the standard although all of them are subject to the design load.

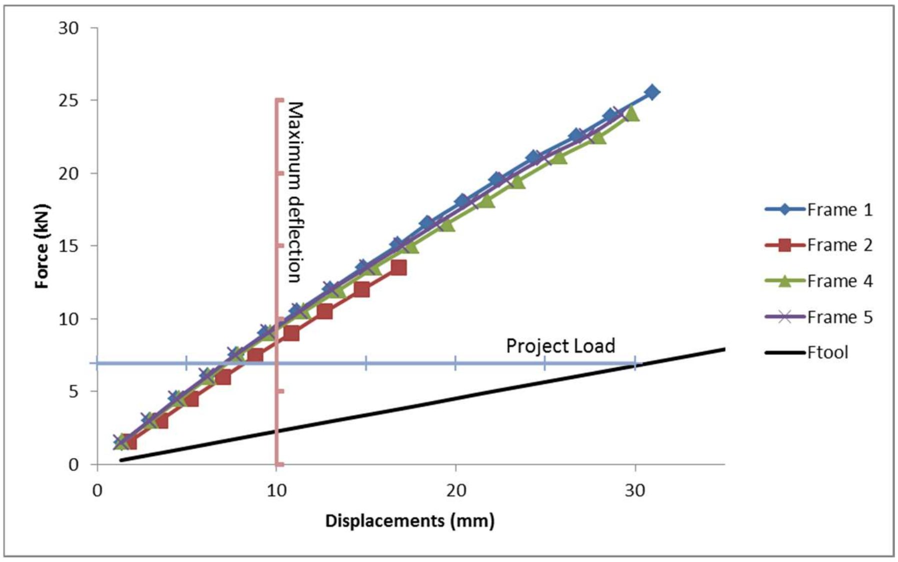

FIGURE 7. Force-displacement diagrams presented by Dial 1, ridge, without loading on the eaves.

CONCLUSIONS

Regarding strength, the structures failed with an average load 5.47 times higher than that of the design. Moreover, an increase in strength of around 32% compared to non-reinforced structures was observed.

As for stiffness, a positive effect was also observed on displacements compared to structures with no reinforcement from a decrease in displacement levels. In addition, the structures reached the maximum deflection prescribed by the standard only at loads higher than the design.

The use of reinforcements in the connections had a positive impact on the strength and stiffness of the built and tested structures, with a low investment in timber and adhesive in the order of a 3% increase. Therefore, the application of reinforcements at key points is a viable and economical option for optimizing the performance of these structures.

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