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Mechanical Behavior of GFRP Dowel Connections to Cross Laminated Timber-CLT Panels

Amanda Ceinoti de Almeida [1,*] and Jorge Daniel de Melo Moura [2]

1 Architecture and Urban Design-PPU, Maringá State University–DAU, Colombo Avenue, 5790, Maringá 87020-900, Brazil
2 Architecture and Urban Design–PPU, Londrina State University–CTU, Celso Garcia Cid Highway, km 380, Londrina 86057-970, Brazil; jordan@uel.br
* Correspondence: amanda-ceinoti@hotmail.com or pg54287@uem.br

Abstract: Sustainability issues are driving the civil construction industry to adopt and study more environmentally friendly technologies as an alternative to traditional masonry/concrete construction. In this context, plantation wood especially stands out as a constituent of the cross-laminated timber (CLT) system, laminated wood glued in perpendicular layers forming a solid-wood structural panel. CLT panels are commonly connected by screws or nails, and several authors have investigated the behavior of these connections. Glass-fiber-reinforced polymer (GFRP) dowels have been used to connect wooden structures, and have presented excellent performance results; however, they have not yet been tested in CLT. Therefore, the objective of this study is to analyze the glass-fiber-reinforced polymer (GFRP)-doweled connections between CLT panels. The specimens were submitted to monotonic shear loading, following the test protocol described in EN 26891-1991. Two configurations of adjacent five-layer panels were tested: flat-butt connections with 45° dowels (x, y, and z axes), and half-lap connections with 90° dowels. The results were evaluated according to the mechanical connection properties of strength, stiffness, and ductility ratio. The results showed higher stiffness for butt-end connections. In terms of strength, the half-lap connections were stronger than the butt-end connections.

Keywords: GFRP dowel connections; timber constructions; cross-laminated timber (CLT); design methodology

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1. Introduction

Cross-laminated timber (CLT) has been gaining prominence in civil construction worldwide for being an efficient, sustainable, and ecologically friendly prefabricated solution, and is a great alternative to conventional concrete and masonry construction [1].

CLT is manufactured with timber boards placed side by side, glued at 90 degrees to the adjacent layer, composing a structural panel (Figure 1). The CLT panels are manufactured in odd layers, with at least three and at most nine layers. The positioning of the boards is strategically designed to optimize the mechanical properties of the panel [2].

CLT panel connections are commonly made using nails, screws, and metal connectors. Panel-to-panel connections are normally made by three types of joints: (1) half-lap joints; (2) single-surface splines, in which a laminated veneer lumber (LVL) plywood sheet is fixed on one face by screws; and (3) double-surface splines, in which two LVL laminations are fixed on both sides by screws. The connectors responsible for the connections between CLT panels, as well as in other wooden structures, need to have adequate strength, rigidity, and ductility capacity to fulfill their function [3].

Therefore, several studies on CLT have been performed in recent decades. Studies have investigated connections between CLT panels with metal nails, screws, and connectors, as well as the performance of these connections in different loading situations. The highlight is the behavior of the connections between CLT panels in seismic areas, in which the ductility of the connections is of significance in the dissipation of energy, since the CLT panels are very rigid [3–8].

Figure 1. Building made with CLT technology; project by MAPA Architects.

However, metal connections have some disadvantages. Under exposure to high temperatures, the steel elements deform, compromising the wooden structure; they are also corroded in aggressive environments, and during the wood expansion process due to humidity or its absence, the metal elements can damage the structure, such as by cracking of the components [9].

An alternative found to overcome some of these disadvantages is the connection of wooden elements made with dowels and, in particular, those made of Glass-fiber-reinforced polymer (GFRP). GFRP dowels have been tested on different wooden structures to analyze their structural performance in terms of strength, stiffness, and ductility, in addition to the analysis of their mechanical characterization.

One previous study [10] aimed to analyze the performance of GFRP dowels in connections of laminated veneer lumber (LVL) elements. In the tests, the dowels were subjected to double-shear loading, with different diameters and orientations in relation to the plane of the wood fibers. The performance of GFRP dowels reached the expectations of the research.

In another study [11,12], the objective was to analyze the performance of densified veneer wood (DVW) plate connections with GFRP dowels. The spacing between the GFRP dowels according to Eurocode 5 [13], as well as the strength, stiffness, and ductility of the connections, were investigated. The GFRP dowels achieved resistance capacity and ductility of 65% and rigidity of 75% compared to the steel pin values.

According to Thomson [11], the spacing between the GFRP dowels is smaller than that of metal dowels and wooden dowels. The length of the shear dowel and, hence, the dowel spacing, clearly influences the ultimate connection capacity. An in-line spacing and end distance of three times the dowel diameter (3d) provides a low level of dowel yield resistance. However, for a dowel spacing and end distance of 4d, significant post-yield deformation and load resistance was observed, and might therefore be considered as the minimum in-line spacing for GFRP dowels.

A method for mechanical characterization of GFRP dowels has also been proposed by Thomson [12] based on the yield moment $M_{y,Rk}$ from Eurocode 5 [13] and the "short beam" test of ASTM D4475-2 [14]. The researcher considered that the deformation of the GFRP dowel in double-shear loading has plasticity at four points along the length of the dowel—that is, the perfect elastic–plastic behavior. The empirical flexural capacity of the GFRP bolts can be determined by equating the internal energy dissipated by rotating the dowel at the four points, thus estimating the yield moment $M_{y,Rk}$, called M_{eff}, and determined through Equation (1) as follows:

$$M_{eff} = \frac{3P_p\ d}{8} \quad (1)$$

where M_{eff} is the yield moment connection, P_p is the plasticity load resistance, and d is the dowel diameter (mm).

Other researchers have studied the performance of GFRP dowels for connections in wooden structures, aiming to analyze their behavior at elevated temperatures [6–8]. The results demonstrated that the GFRP dowels manufactured with a thermosetting polyester matrix, and without fire-resistant additives, presented quick degradation at high temperatures, and failure in a short period.

Other researchers [15–17] have studied the performance of GFRP dowels for connections in wooden structures, aiming to analyze their behavior at elevated temperatures. The results showed that GFRP dowels made with a phenolic matrix, and without fire-resistant additives, may be designed to perform appropriately during fire, and failure of the metal connections occurred faster than failure of the non-metal connections under sustained loads of 20 and 40% of the connection capacity.

The characterization method proposed by Thomson et al. [11,12] was used in the research by Palma et al. [18] to test three types of GFRP dowels: glass fibers and polyester matrix (GP), glass fibers and epoxy matrix (GE), and carbon fibers and epoxy matrix (CE). The results showed that the GE dowels had higher strength and ductility than the CE dowels, whereas the GP reached lower values of resistance, stiffness, and ductility. In the calculation of $M_{y,Rk}$, the resistance of the GFRP dowels was 50% lower than that of the metal dowels. However, GE dowels (epoxy resin matrix and fiberglass) performed better compared to the others. The GFRP-GE dowels were used to test the connections between densified veneer wood (DVW) plates. The resistance of the GFRP-GE dowels was 20–28% lower than that of the metal dowel connections. The stiffness of the connections with GFRP-GE dowels was also inferior, while the ductility was superior for the GFRP-GE dowels.

Thus, the performance of GFRP dowels in wooden structure connections proved to be a viable alternative to overcome some disadvantages of metal connections. However, no studies could be found on GFRP-doweled connections to CLT panels. Therefore, the objective of this research was to analyze the structural performance of such connections as an alternative to upgrade the industrial process of on-site building of the CLT construction system with greater structural efficiency.

2. Materials and Methods

2.1. Specimen Description

The materials used in this study were air-dried yellow pine (*Pinus* spp.) boards, previously oven-dried, averaging 12% moisture content (MC). The MC was measured using a Digisystem DUC 2050L hygrometer at three points of the boards—each end, and the center (center of the upper face)—according to the Brazilian Standard [19]. The pine boards were purchased at a market, coming from Brazilian plantations. The materials were stored in the Laboratory of Structures at the Londrina State University. All boards were cut (cross-section 100 mm × 20 mm), mechanically laminated, and machined to eliminate particles on the surface of the pieces. This process allowed for the opening of the wood pores, thus facilitating the process of absorption and anchoring of the adhesive.

2.1.1. NDT Ultrasonic Test

To guarantee that the panels had homogeneous mechanical properties, the whole set of boards were graded through NDT ultrasonic testing. The equipment used was the Agricef USLab model. The output was 700 V through metal-encapsulated transducers, which operated at a frequency of 45 kHz to directly measure the propagation velocity of the waves in microseconds (μs).

In the test, the transducers were placed on the center of the flat face of each end of the boards, and a thin layer of approximately 1 mm of alcohol-free gel was applied. The length of the pine boards was 3 m. The dynamic modulus of elasticity (MOE_d) was determined through Equation (2) as follows:

$$MOE_d = \rho_{12\%}.v^2. \tag{2}$$

where MOE_d is the dynamic modulus of elasticity (10^{-6}MPa), $\rho_{12\%}$ is the density of the wood at 12% moisture content (g/cm^3), and v is the longitudinal wave velocity (m/s).

2.1.2. Manufacture of CLT Panels and GFRP Dowels

The design of the panels considered the following conditions: the connection configuration, the location and insertion angles of the GFRP dowels, and the number and dimensions of the panel specimens.

Connection configurations and the inclination of dowel insertion were defined according to the literature findings [13,14]. Butt-end connections showed better results when the dowels were inserted at 45° with respect to the panel surface [3]. However, the most common configuration is the half-lap type: 90° connected. Therefore, the following connections were chosen: butt-end 45° insertion angle dowel connections (x, y, and z axes)—designated T1—and the half-lap 90 ° insertion angle dowel connections, designated T2 (Figure 2).

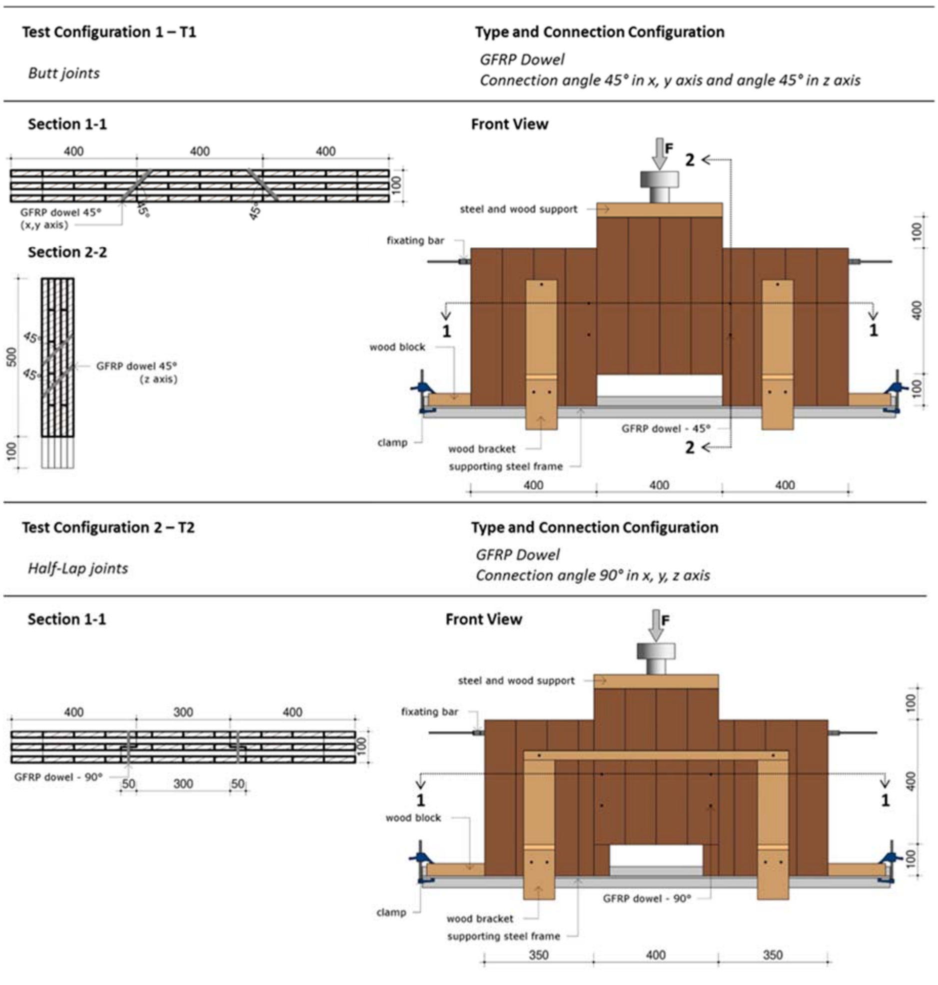

Figure 2. Test setups of configurations T1 and T2 (measures in mm).

Twelve sets of specimens were manufactured, consisting of three five-layered CLT panels each, measuring 500 mm long and 400 mm wide. The laminations were each 19.6

mm thick, and the final panel thickness was 98 mm. The NDT grading procedure permitted the distribution of the laminations in each panel in such a way that the overall MOE average and standard deviation were similar to the whole sets of panels, allowing for comparison.

The panels were manufactured at Compensados Ideal Ltd. (Londrina, Brazil)—a local plywood manufacturing company. The panel layers were phenol-formaldehyde-resin-bonded, (brand name FF-109), and donated by the Bonardi Indústria Química Ltd. (Colombo, Brazil). To comply with the indications in the literature, the bonding pressure was 1 MPa applied by a hydraulic press [20].

Five sets were half-lap-connected and five sets were butt-end-connected. In order to estimate the F_{max}, duplicates of both types were prepared, thus totaling 12 sets. The butt-end-connected specimens were numbered from 1 to 5 (SP1 to SP5), while the half-lap-connected specimens were designated from A to E (SPA to SPE). The grouping of the panels in the specimens was carried out according to the values obtained from the NDT ultrasonic grading test (MOE_d), in order to guarantee that the panels had homogeneous mechanical properties, as shown in Table 1.

Table 1. Graded NDT ultrasonic test MOE_d and grouping of panels.

Configuration	Specimen	Grouping of Panels	MOE_d [10^{-6} MPa]	
			Mean	COV (%)
T1—Half-lap	SPA	Panel 1 + Panel 5 + Panel 3	5584	9
	SPB	Panel 4 + Panel 2 + Panel 6	5452	11
	SPC	Panel 7 + Panel 14 + Panel 9	5402	17
	SPD	Panel 8 + Panel 10 + Panel 12	5340	11
	SPE	Panel 11 + Panel 13 + Panel 15	5316	12
	Twin half-lap	Panel 16 + Panel 20 + Panel 18	5434	12
T2—Butt-end	SP1	Panel 17 + Panel 19 + Panel 21	5321	2
	SP2	Panel 22 + Panel 23 + Panel 24	5422	13
	SP3	Panel 27 + Panel 29 + Panel 30	5310	9
	SP4	Panel 25 + Panel 26 + Panel 28	5321	2
	SP5	Panel 31 + Panel 34 + Panel 35	5416	2
	Twin butt-end	Panel 32 + Panel 33 + Panel 36	5403	11

The materials used to manufacture the GFRP dowels were Huntsman's epoxy polymer resin—composed of Araldite® LY 1564 BR resin and Aradur 2963 hardener—and Owens Corning's E-CR GLASS Advantex® fiberglass. The glass fibers were unidirectionally oriented and continuous. The percentages of fiberglass and epoxy resin were 63% and 37%, respectively.

The production method for GFRP dowels was pultrusion, performed manually and individually; the portions of fiberglass and epoxy resin were separated into a container, and the fibers were bathed in the resin and then pulled into a mold, where they cured for 24 h as recommended by the resin manufacturer.

The dowels' minimum diameter was 6 mm, so as to comply with the provisions of Eurocode 5 [13]; the dowels were 150 mm long for the butt-end connections and 100 mm for the half-lap connections (Figure 3). The CLT specimens were pre-drilled, with a diameter of 6 mm.

Figure 3. GFRP dowel specimens.

2.2. Testing

The tests were performed at the Londrina State University Structure Laboratory. The specimens were subjected to monotonic shear loading according to the test method described by EN 26891 [21]. The specimens were tested on an EMIC model DL-30000 Universal Testing Machine with 300 kN maximum loading capacity. Two support rods were inserted into the head of the set to prevent panel rotation around the Y axis. In the same way, two wooden blocks guaranteed locking of the panels on the X axis, and prevented gaps between panels during the test.

On the center panel, a steel I-type bar with wooden sides sitting on a metal plate was used to evenly distribute the applied load. In accordance with the EN 26891 [21] provisions, a dial gauge was positioned on the center panel to measure vertical displacements (Figure 4). This process was replicated for both butt-end connections and half-lap connections.

Figure 4. Experimental setup T1 and T2.

According to the literature [6,7], the mean estimated ultimate failure load (F_{est}) for the T1 configuration was calculated to be 15 kN. These references [6,7] were later used in the comparison between screws, nails, and GFRP dowels, which can be found in Section 4.2. Thus, according to the EN 26891 load x displacement graph [21], the testing was initiated by the twin specimens of both types of connections.

Concerning the butt-end connections, at 30% F_{est} the displacement reached the maximum 15 mm stipulated by EN 26891 [21]. The maximum load F_{max} observed was 5 kN. Thus, for this test, the new threshold had to be adjusted to 5 kN.

The same procedure was followed with respect to the half-lap connection specimens. However, in this configuration there was a twofold increase in the failure load compared to the prior test (F_{max} = 10 kN), which required adjustments of the test threshold to 10 kN.

3. Results

The performance analysis of GFRP-doweled connections was based on the methodology presented in EN 26891 [21]. The same guidelines were followed in testing. The mechanical properties analyzed (from the linear regression line between the 0.1 to 0.4 F_{est} curve) were the connection resistance capacity F_{max}, the maximum displacement D_{max}, and the stiffness k_{ser}. The k_{ser} linear regression aims to compare the values obtained by calculation with those observed during testing.

3.1. Butt-End Connections Results

The load x displacement curve of configuration T1 for the butt-end connections is shown in Figure 5. In accordance with EN 26891 [21], the load was applied up to 0.4 F_{est} and maintained for 30 s. The load was then be reduced to 0.1 F_{est} and maintained for 30 s. Thereafter, the load was increased until the ultimate load or a slip of 15 mm was reached.

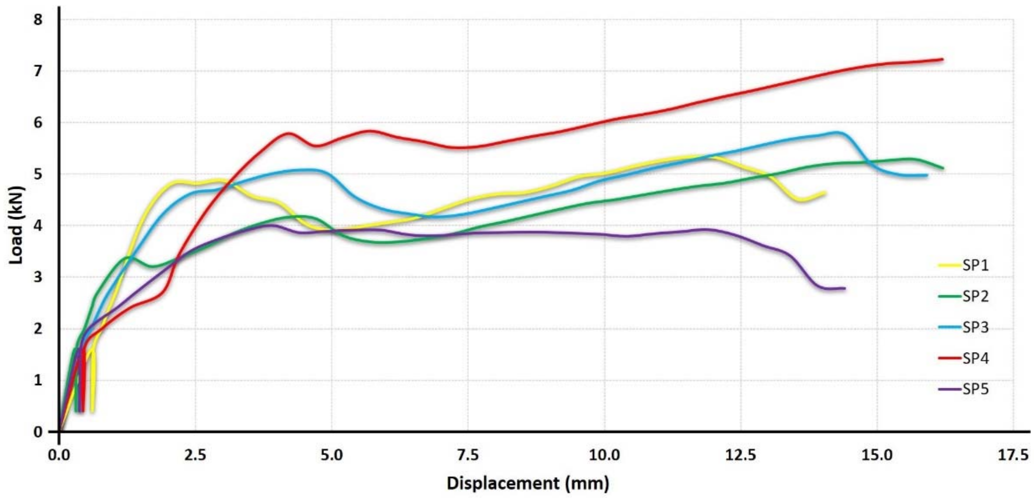

Figure 5. Load x displacement curves of butt-end connections (T1).

The mechanical properties of the whole set of butt-end connections are displayed in Table 2. All but one (D_{max}) of the coefficients of variation (COVs) were high (greater than 20%).

Table 2. Butt-end connections' mechanical properties (T1).

Specimen	F_{est} (kN)	F_{max} (kN)	D_{max} (mm)	k_{ser} (kN/mm)	
				EN 26891 (1991)	Regression
SP1		5.33	11.54	1.97	2.66
SP2		5.22	14.71	3.87	5.51
SP3	5	5.77	14.41	3.00	4.32
SP4		6.97	14.75	2.73	3.63
SP5		3.92	11.91	3.20	4.44
Mean		5.44	13.46	2.95	4.11
COV (%)		20.17	11.87	23.50	25.64

The average maximum displacement D_{max} was 13.46 mm—close to the maximum 15 mm allowed by the EN. The proximity to the displacement limit points to a good energy dissipation capacity and high degree of ductility.

The instantaneous sliding modulus or stiffness k_{ser}, was similar concerning COVs calculated following EN 26891 [21] and those observed in the experimental test—23.50% and 25.64% (columns 5 and 6, respectively). However, the averages of the calculated k_{ser} and that obtained by the regression line are quite divergent. This divergence can be explained by how stiffness is obtained, according to EN 26891 [21], by Equation (3), as follows:

$$k_{ser} = \frac{0.4\ F_{est}}{v_{i,mod}} \text{ where } v_{i,mod} = \frac{4}{3}(v_{04} - v_{01}) \tag{3}$$

where F_{est} is the estimated ultimate failure load, $v_{i,mod}$ is the value of the initial slip, and v_{04} and v_{01} are the values of the displacements registered for 0.4 F_{est} and 0.1 F_{est}, respectively. The stiffness obtained by the linear regression is an adjustment to the force–displacement response between the values of 0.1 F_{est} and 0.4 F_{est}. Therefore, this divergence is the result of the dependence displayed by this variable on possible geometric deviations or errors verified in the manufacturing of the connections.

Therefore, the k_{ser} proposed by the standard is quite conservative. The calculations underestimate the actual values, pointing to a reconsideration of the parameters adopted in the equations proposed by the EN 26891 standard [21].

3.2. Half-Lap Connections Results

The load x displacement curves of the T2 configuration for half-lap connections are shown in Figure 6. In accordance with EN 26891 [21], the load was applied up to 0.4 F_{est} and maintained for 30 s. The load was then reduced to 0.1 F_{est} and maintained for 30 s. Thereafter, the load was increased until the ultimate load or a slip of 15 mm was reached.

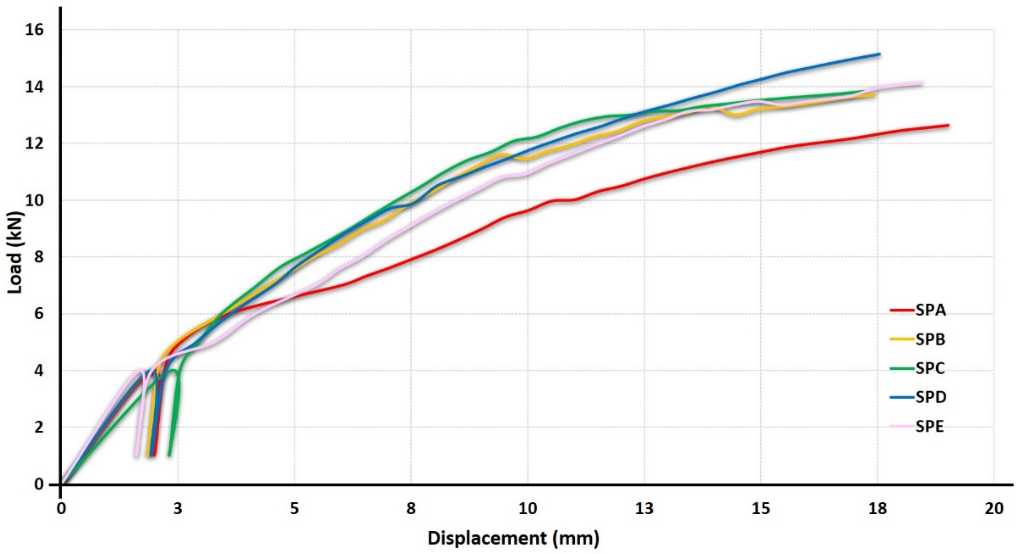

Figure 6. Load–displacement curves from half-lap connections (T2).

The maximum loads F_{max} of these connections are very close, resulting in a COV equal to 7.26%. The results show that the average maximum 14.73 mm displacement was even closer to 15 mm compared to the butt-end connections (T1), indicating greater ductility of this configuration (Table 3).

Table 3. Mechanical properties of half-lap connections (T2).

Specimen	F_{est} (kN)	F_{max} (kN)	D_{max} (mm)	k_{ser} (kN/mm)	
				EN 26891 (1991)	Regression
SPA	10	11.54	14.51	1.51	2.03
SPB		13.20	14.94	1.56	2.08
SPC		13.47	14.70	1.27	1.68
SPD		14.07	14.55	1.56	2.11
SPE		13.47	14.95	1.79	2.38
Mean		13.15	14.73	1.54	2.06
COV (%)		7.26	1.42	12.05	12.17

The results of the instantaneous slip modulus k_{ser} were very similar, showing calculated and observed coefficients of variation 12.05 and 12.17%, respectively. Furthermore, for this configuration, the experimental results for stiffness were greater than those calculated by 25.2% on average. The same observation can be made for the revision of the equations suggested by EN 26891 [21].

4. Discussion

4.1. Comparison between Butt-End Connections and Half-Lap Connections

Comparing the results of butt-end connections (T1) to those of half-lap connections (T2), the ultimate load shows a considerable difference (Figure 7). T1 strength was 41% greater than that of T2 connections, averaging 13.15 kN and 5.44 kN, respectively.

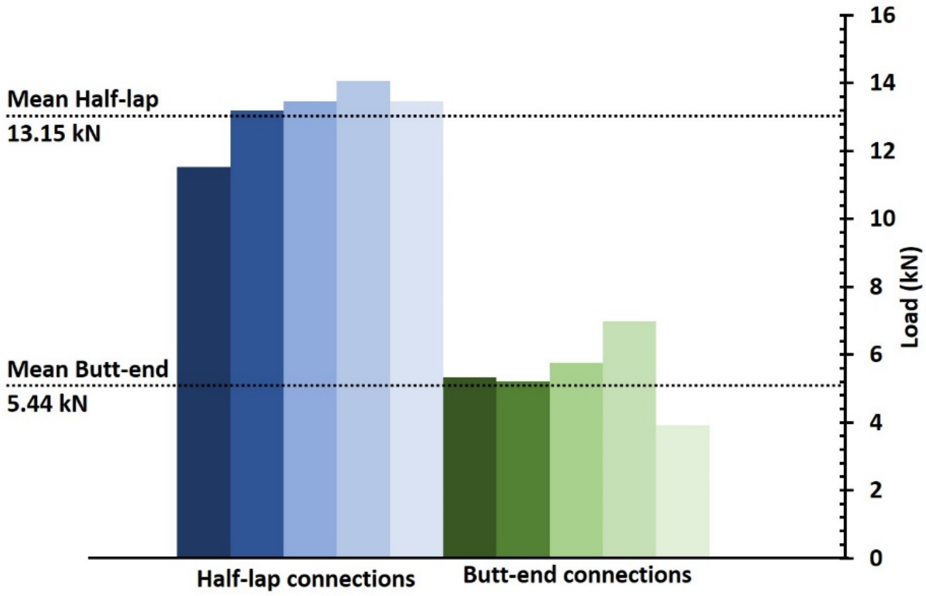

Figure 7. Comparison of mean maximum load (F_{max}) of butt-end and half-lap connections.

In contrast to the results reported in the literature regarding nailed and screw connections, the 45° butt-end connections (T1) presented lower performance than the 90° half-lap connections (T2). This phenomenon can be explained by the behavior of the GRFP as a function of the fiber orientation with respect to the plane of stress application, as shown in Figure 8.

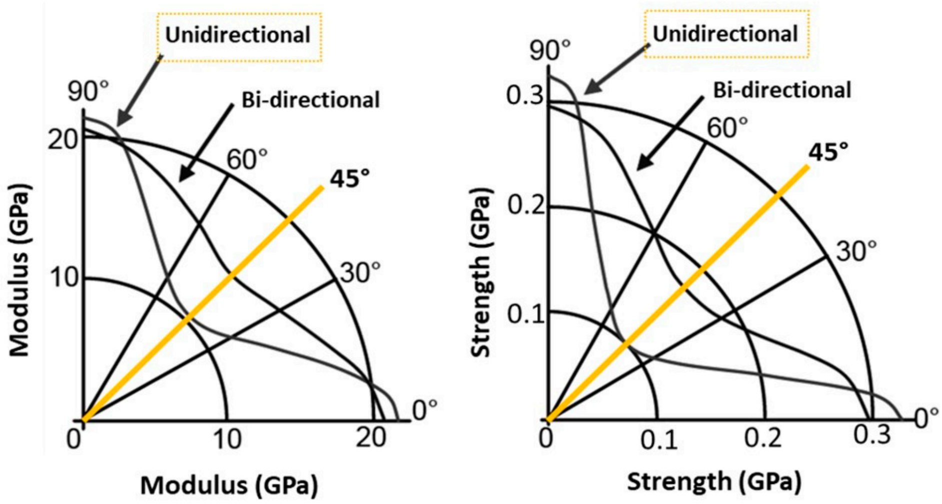

Figure 8. GFRP modulus of elasticity (MOE) and modulus of rupture (MOR) diagram as a function of the fiber orientation; source: Piggot [22].

The diagram of the moduli of elasticity and rupture (Figure 7) demonstrates that the GFRP materials composed of unidirectional fibers oriented in the longitudinal (0°) and transverse (90°; the present case) directions show similar performances; however, at 45° the response is much lower [17]. This also explains the better results concerning 90° half-lap connections (T2). Therefore, the experimental observations are justified by the literature.

As for D_{max}, the half-lap connections were also responsible for the largest average displacement. However, the most rigid connections were the butt-end connections, averaging 47% (calculated) and 49% (tested) more rigid than half-lap connections (Tables 1 and 2). The k_{ser} coefficients of variation in both cases were close, ranging from 23.50% to 25.64%. These results indicate a lower predictability for butt-end connection with dowels placed in this position. The mode of rupture of the 45° butt-end connections occurred with shear of the dowels (Figure 9), while the dowels at 90° were plasticized.

Figure 9. GFRP dowel failure mode for butt-end connections.

The rupture of the GFRP dowel connection at the butt-end joint at 45° indicates the risk of compromising the overall structure. On the other hand, the plasticity of the GFRP dowel connections in the case of the half-lap joints provides greater resistance before failure.

4.2. Comparison between Experimental Results and Literature Review

The results observed in the present study were compared with those found in the literature [6,7]. In this study [6], the diameter of the dowels was 6 mm, while that of the HBS screws was 8 mm. The length of the GFRP dowels was equal to the thickness of the CLT panels—approximately 100 mm. While the authors of [6] used the commercially produced screw length (80 mm), their CLT panel thickness was 85 mm.

The strength of the GFRP half-lap connections was well above that observed in [6] for the same number of connectors (13.15 × 5.25; Table 4). The maximum displacement was similar to that observed in all studies. However, the instantaneous sliding modulus or stiffness—corresponding to the connection stiffness k_{ser}—was quite different.

Table 4. Experimental GFRP dowel connection vs. literature review.

Properties	Gavric et al. [6]	Branco et al. [7]		Experimental GFRP	
	Half-Lap	Nail 90°	Nail 45°	Half-Lap	Butt-End
F_{max} (kN)	5.25	3.51	2.48	13.15	5.44
D_{max} (mm)	15.98	14.03	13.90	14.73	13.46
k_{ser} (kN/mm)	1.24	1.20	1.37	1.54	2.95
Connections	4 screws	2 nails		4 GFRP dowels	

The tests in [7] were performed on solid wood pieces connected with nails at various angles. The average strength obtained in [7] concerned two-nail connections at a 90° insertion angle. Considering that with fewer than eight connectors, the strength of a connection (nailed or screwed) can be considered as the sum of individual pin strength [19], the equivalent to four nails would be 7.02 kN (3.51 × 2; column 2, Table 4)—well below the 13.15 kN observed in this study. The 90° nailed connections had a stiffness of 2.4 kN—equivalent to a four-nailed connection (1.2 × 2; column 2, Table 4)—stiffer than those of the half-lap GFRP (1.54; column 4, Table 4).

Following the same reasoning, the mean maximum load for the 45° GFRP-doweled connections was greater than that of the 45° nailed connections observed in [7] - 5.44 kN vs. 4.96 kN (2.48 * 2; column 3, Table 4). The same was true of stiffness: 2.95 kN vs. 2.74 kN (1.37 * 2; column 3, Table 4) for dowels and nails, respectively.

5. Conclusions

This study focused on the behavior of CLT panels connected via butt-end (T1) and half-lap (T2) GRFP-doweled connections; and some conclusions could be drawn. The results showed higher stiffness for butt-end connections (T1). In terms of strength, the half-lap connections were 2.4 times stronger than the butt-end connections.

This observation totally diverges from the literature concerning metal-pinned connections (nail and screws), and can be explained by the way the GRFP behaves according to the plane to which the stress is applied—at 45° the response is the poorest. The strength reported for unidirectional GRPF in both longitudinal and transverse directions (0° and 90°) is very close, which explains the superior performance for the 90° half-lap connections. The results demonstrate a lower predictability for butt-end joints placed at a 45° angle, reducing the reliability of the GFRP material.

The use of glass-fiber-reinforced polymer (GFRP) composites as doweled connections for CLT construction systems proved to be a viable technical alternative. Another considerable advantage is the physical resistance of GFRP dowels compared to metal fasteners. In the presence of variable moisture and in coastal areas, metal fasteners can corrode, compromising the CLT structure; this does not happen with GFRP dowels. Further research is necessary, such as the mechanical characterization of the GFRP dowels according to the methods identified in the literature, and studies on greater diameters of GFRP dowels for CLT connections.

Finally, it is worth mentioning the pioneering character of this research since, to date, no study has been found in the literature on the use of GFRP dowels as connections for CLT panels. This research is of great importance for the civil construction sector—especially CLT construction, which is on the rise in Brazil.

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