Physical and Mechanical Properties of Glued Laminated Bamboo

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Certain bamboo species have mechanical properties that are compatible with construction material. Despite this, their low shear strength, the presence of nodes in their culms, and their circular geometry inhibit the expansion of the use of this material as construction material. One technique that can solve these problems is glued laminated bamboo (GLB). Based on such findings, this paper aims to evaluate the physical and mechanical properties of glued laminated bamboo of the *Dendrocalamus giganteus* species. Two glues were used: resorcinol-formaldehyde (PRF) and polyvinyl acetate (PVAc). The following physical and mechanical characterization tests were performed on glued laminated bamboo: water absorption, density, compression parallel to fiber direction, tension parallel to fiber direction, shear parallel to the glue layer, shear parallel to fiber direction, and bending. The results, analyzed using statistical models, showed that the GLB has physical and mechanical properties comparable to those of hardwoods.

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INTRODUCTION

Bamboo is among the first employed and most used materials in civil construction, with its use being recorded for approximately 6000 years (Padovan 2010), and its use is still growing to this day. The use of bamboo seeks to achieve sustainable levels of development, which is achieved by few materials, such as reducing pollution, energy consumption, and conservation of natural resources. Further, it is associated with environmental preservation, which stimulates the development of new techniques for using bamboo raw material.

Despite its formidable physical and mechanical properties, bamboo has not been widely used as a material constituent structure because of its geometric configuration, low shear strength, and the presence of nodes in its culms. The bamboo culms have been utilized in their round form for structural applications. The bamboo culms are round and hollow (Liese 1987) and obviously cannot be directly used for the fabrication of rectangular structural members. Its low resistance to shear does not allow the installation of pins, making it difficult to design larger structures that require connections. Furthermore, bamboo shows nodal structures that generally have inferior mechanical properties (tensile strength parallel to fiber direction) compared with the region internodal culm, and its properties vary greatly depending on the species, soil and climactic condition, silvicultural treatment, age, density, and position in the culm (Lee *et al.* 1994; Yu *et al.* 2008).

The technology of glued lamination is widely used in manufacturing high standard bamboo finished flooring. This technology can be applied to bamboo to eliminate the problems of shear and geometry previously discussed. Furthermore, it can allow a more rational use of this material composing structures.

However, the lack of suitable equipment to complete lamination limits the production of glued laminated bamboo (GLB) (Beraldo and Rivero 2003), with lamination being an important aspect that interferes with the quality of the surface of the material. Another important aspect is the difficulty in bonding the bamboo, which is directly influenced by the adhesive type and pressure used (Carrasco *et al.* 2017). Therefore, the adoption of the thermomechanical process used for wood can reduce or even reverse these limitations because of the decrease in the volume of the empty spaces in the material by compression; hence, promoting increased density.

In this way, it is necessary to split bamboo into small elements that can be used to produce material with varying sizes and cross-sections (Ni *et al.* 2016). Several studies related to bamboo products have been conducted by several authors, such as the analysis of glued laminated bamboo beams under bending (de Lima *et al.* 2014), laminated bamboo lumber production (Nugroho and Ando 2000, 2001), bamboo oriented boards (Sumardi *et al.* 2007), glued laminated bamboo (Nugroho and Ando 2000; Correal and Lopez 2008; Paes *et al.* 2009; Rusch *et al.* 2019; Sulastiningsih *et al.* 2021), heat-treated glued laminated bamboo (Brito *et al.* 2018), bamboo-reinforced composites (Corradi *et al.* 2009), adhesive performance and structural behavior (Correal and Ramirez 2010; Correal *et al.* 2010), laminated bamboo lumber (Mahdavi *et al.* 2012; Kitiyanun *et al.* 2022), parallel strand bamboo (Huang *et al.* 2013), bamboo-bundle laminated veneer lumber (Chen *et al.* 2014), structural performance, and laminated bamboo panels (Rusch *et al.* 2019). In addition, research has been carried out related to the manner in which trusses are prepared from glued laminated bamboo (de Lima *et al.* 2015).

GLB may not be cost-effective compared to timber species, but it can be cost-effective compared to commonly used materials such as steel and concrete (Yang and Wang 2020). However, the idea of using GLBs for structural purposes encounters problems that need more investigation (Bono 1996). Initially, there was a need to develop suitable equipment for laminating bamboo in an artisanal and industrial way. The type of adhesive is also another point that needs to be investigated, because it is essential that it presents low cost, high strength properties, and chemically interacts in an adequate way with the bamboo.

It can be said that the lack of quality and decent housing in rural areas of developing countries is a present problem. In Brazil, particularly in the North and Northeast regions, most low-income constructions are made with sticks of local vegetation covered with clay, without the slightest use of technology. In general, such structures have a bad aesthetic appearance, low resistance to the weather, and a large number of cracks, providing the accommodation of disease-transmitting insects, such as Chagas' disease.

As is true for other woody materials, there is a need to develop an adequate treatment for bamboo against the attack of fungi and insects to guarantee durable material, making it possible to build structures, such as roof trusses and beams, which are more efficient and durable. There are traditional and chemical methods for treating bamboo. Traditional methods do not use chemical protection means and have a relatively low cost; however, they have low efficiency in relation to chemical treatments (Pereira and Beraldo

2016). Additionally, the type of preservative used for bamboo protection can significantly affect the mechanical and bonding properties of GLB depending on: adhesive chemistry; mechanism of bamboo bond formation; bamboo microstructure and anatomical; adhesive penetration in bamboo; physical properties of bamboo; preparation of bamboo elements; surface characteristics; and chemical composition of bamboo elements (Nkeuwa *et al.* 2022).

In this context, GLB is a construction material that can contribute to the improvement of such housing conditions. However, the idea of using the GLB for the purpose of structural elements in northeastern Brazil is recent and still requires further research and documentation. In this perspective, this work aims to evaluate and characterize the physical and mechanical properties of GLB of the *Dendrocalamus giganteas* species, using two types of glues: resorcinol-formaldehyde (PRF) and polyvinyl acetate (PVAc).

EXPERIMENTAL

Materials Used

Bamboo is by nature a composite material. Its culm is formed by fibers (50%; responsible for the excellent mechanical properties), vessels (10%), and sap conductors, which are unevenly distributed in the cross-section and embedded in a matrix, named parenchyma (40%). Bamboo culm has a hollow trococonical shape with spaced diaphragms (nodal region), as shown in Fig. 1(a), and it is an anisotropic material (specifically orthotropic) with distinct properties in three directions: longitudinal (fiber direction), tangential, and radial.

(a) (b) (c)

Fig. 1. Cutting and lamination of bamboo products: (a) Outer sidewall of the culm; (b) The inner wall of the culm; (c) Bamboo strips

The bamboo used in this study was of the *Dendrocalamus giganteus* species, obtained from the Cascavel Zoo in Brazil. The culms were 20 m long, and internodes were spaced between 40 and 50 cm. The bamboo culms were between four and five years old and were allowed to dry at room temperature in the shade for three months. Then, the culms were longitudinally sawn with a length of 150 cm, and these pieces were dried at 105 °C until the moisture content reached between 6 and 8%. After drying, the bamboo strips were prepared with a circular saw with nominal dimensions of 150 cm (length), 0.73 cm (thickness), and 3.00 cm (width), as shown in Figs. 1a, b. Subsequently, the strips were sanded with a three-stage electric sander according to the thickness of the walls of the bamboo culm (Fig. 1c).

Two glues were used (manufactured by Henkel Ltda., São Paulo, Brazil): resorcinol-formaldehyde (PRF RS-216-M; CASCOPHEN) and polyvinyl acetate (PVAc; CASCOREZ). These adhesives are suitable for cold pressing. The PRF adhesive was chosen because of the effective shear strength and for waterproofing. Additionally, the PVAc adhesive presents low toxicity and is 15 to 20 times cheaper than PRF; however, this adhesive presents low mechanical strength.

The GLB was prepared from randomly chosen bamboo strips, in order to seek to standardize the properties of the GLB, since the fiber density in the bamboo culm wall varies so that they are more concentrated externally (Ghavami and Marinho 2003). After cleaning, the bamboo strips were coated with adhesives to spread at a coverage equal to 215.5 g/cm^2 using a nylon paintbrush and arranged in the same parallel direction to the bamboo fibers. For gluing, under ambient temperature of 25 °C and relative humidity equal to 50%, the slats were placed in the pressing device (Fig. 2a, b) under a pressure of 6.2 MPa, controlled by means of the properties of the pressing screws (number of screws, type of thread, screw pitch, average diameter, number of turns applied to the nut and coefficient of friction between the screw thread and the nut). After the adhesive had cured, according to the manufacturers' recommendations, duration of 2 hours for PRF and 24 hours for PVAc, the BLC was removed from the pressing equipment, and the finishing was carried out using a circular saw to trim the ends and a planer to remove the glue burrs on the side faces (both Skill, Bosch Ltda., Brazil). Finally, the GLB samples were prepared following, as much as possible, the dimensional recommendations of ABNT NBR 7190 (1997).

(a) (b)

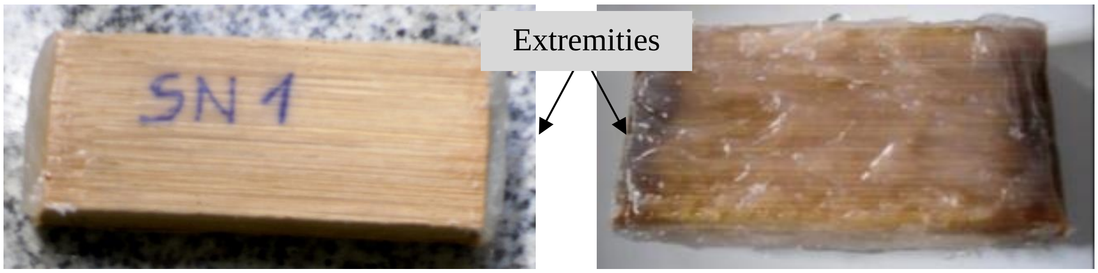
Fig. 2. Pressing process for both glues: a) PVAc; b) PRF

Physical Properties

Bamboo water absorption

To perform the water absorption test, 30 samples of bamboo strips were prepared: 15 were from the nodal region, and the other 15 were from the internodal region. The samples were 0.78 cm thick, 3.09 cm wide, and 5.59 cm long. The absorption test was divided into three phases, using 5 samples of each region for each phase. In the 1st phase, 10 samples were used without any waterproof treatment; in the 2nd phase, faces perpendicular to the fiber direction were rendered impermeable with silicone (Fig. 3a); and finally, in the 3rd phase, faces parallel to fiber direction were rendered impermeable with silicone (Fig. 3b).

The experiment was conducted in a climatic chamber, with an average temperature and humidity of 23.3 °C and 61%, respectively. The samples were dried in an oven at 100 °C for 48 h. Then, waterproofing treatment (2nd and 3rd phases) was applied, and oven dry mass samples were evaluated using an analytical balance. The specimens were immersed in water and weighed after 1 min, 2 min, 3 min, 4 min, 5 min, 10 min, 15 min, 20 min, 25 min, 30 min, 1 h, 2 h, 3 h, 4 h, 5 h, 6 h, 12 h, and 24 h.



(a) **(b)**

Fig. 3. Impermeabilization of samples using silicone: (a) Extremities impermeabilized; (b) Sides impermeabilized

Density of GLB

Eight varieties of GLB, made with adhesive PRF, with the following average dimensions were used: 13.44 mm thick, 27.56 mm wide, and 49.46 mm long. These dimensions correspond to specimens with an average initial moisture content of 7.0%. The samples were dried in an oven at 100 °C for 48 h. Mass samples were evaluated after 4, 9, 24, 27, and 32 h using an analytical balance. The mass evaluated at the final time was considered the oven dry mass.

Mechanical Properties

Tension strength parallel to bamboo fiber direction

Ten specimens were tested, 5 from the nodal region and 5 from the internodal region. Tests were conducted in a computer-controlled, hydraulic-servo universal testing machine (SHIMADZU UH-I SERIES 2000 kN, Tokyo, Japan) by displacement control equipped with grip jaw holders. Specimens were 45 cm long, divided into two wide extreme regions (12 cm long) and a narrowed central region (21 cm long), 0.70 cm thick and average width, at the narrowed region, which is equal to 0.50 and 0.84 cm for specimens with and without nodes, respectively (Fig. 4).

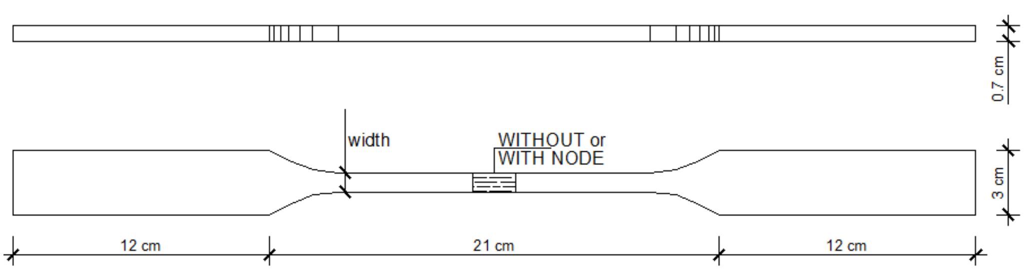


Fig. 4. Tension specimen drawing

Because of the lower tensile strength parallel to fiber direction in the nodal region in relation to the internodal region, it was necessary to apply different areas of cross-sections of the specimens with and without nodes. The specimens were made with dimensions similar to those established by reference ABNT NBR 7190 (1997).

Compression strength parallel to fiber direction of GLB

The compression test was completed in two phases. For both phases, specimens with bamboo nodes randomly distributed within the specimen were used. In the first phase, the behavior of specimens of GLB, with nominal dimensions of 2.75 x 3.00 x 5.00 cm^3, composed of 4 strips of bamboo glued together, was evaluated. These specimens were nominated by the letter "P". Figure 5 shows orthographic views and isometric views of the specimen compression "P". Twenty-two specimens were tested under displacement control, 11 were produced with PRF adhesive, and 11 were with PVAc adhesive. Six specimens were instrumented with two strain gauges parallel to bamboo fiber direction (Fig. 6), because it is intended to obtain the modulus of elasticity (MOE) of the composite material, with the limitation that the strain gauge was installed in one of the adhered materials and that it is supposed to show the behavior of the composite material.

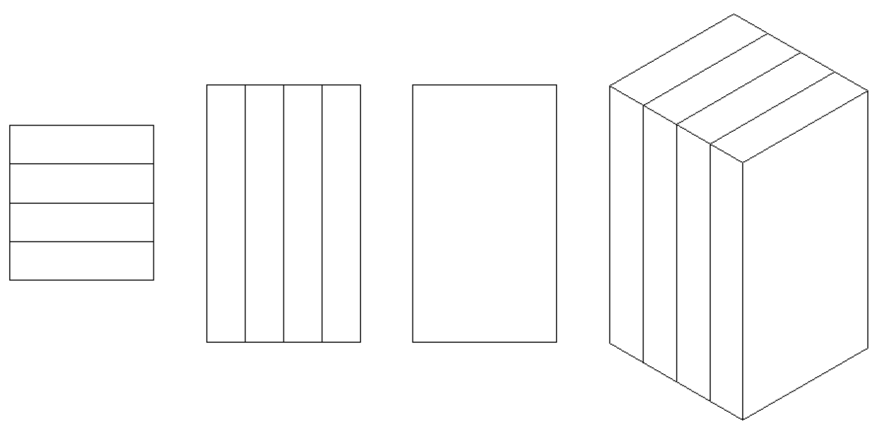


Fig. 5. Characteristics of the compression specimen “P”

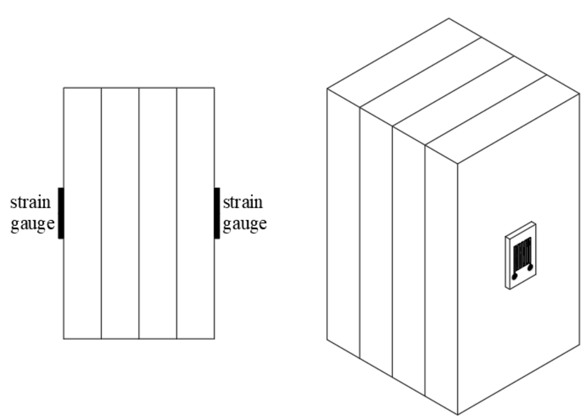


Fig. 6. Arrangement of strain gauges in the specimen compression

The behavior of GLB specimens, with nominal dimensions of 5.00 x 5.00 x 15.00 cm^3, composed of 15 bamboo strips glued together, was also evaluated. These specimens were named by the letter "G". Figure 7 shows orthographic views and isometric views of specimen compression "G". This specimen followed the recommendations of ABNT NBR 7190 (1997). Six specimens were tested, 3 produced with PRF adhesive and 3 with PVAc adhesive. Two specimens were instrumented with two strain gauges in opposite faces and were also tested under displacement control.

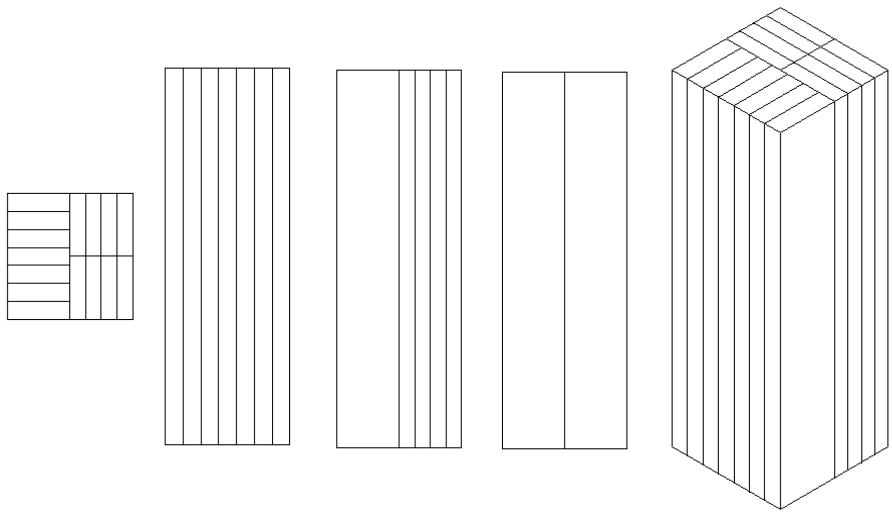


Fig. 7. Characteristics of the compression specimen “G”

Shear parallel to bamboo fiber direction

Eight specimens were tested with average dimensions of 6.1 x 4.2 x 2.8 cm^3. They were composed of 6 bamboo strips that were 0.73 cm thick and were glued together by PVA-based adhesive (PVAc). The size of GLB specimens followed the proportions established by ABNT NBR 7190 (1997). Figure 8 shows orthographic views and isometric specimen views. In addition, the tests were designed to avoid shear in the glue plane, and the average shear area was equal to 2.8 x 5.0 cm^2 (Fig. 9a, b). The shear tests were conducted under displacement control.

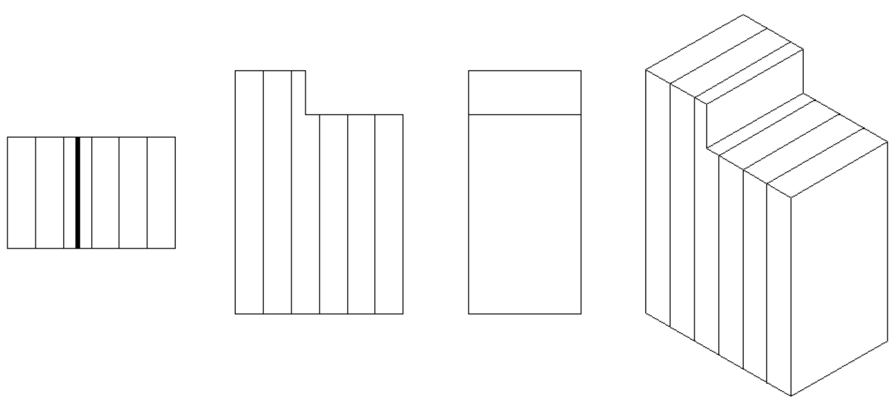
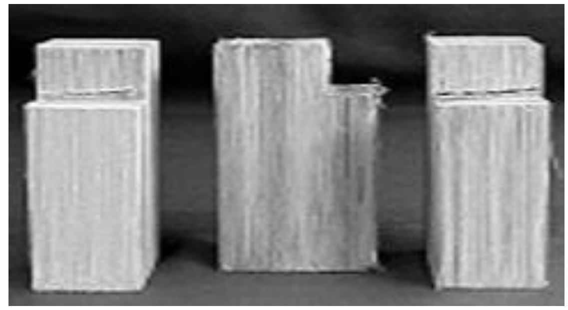


Fig. 8. Features specimen shear parallel to bamboo fiber direction



(a) (b)

Fig. 9. Shear specimens: a) Close-up Front view; b) Multiple views

Shear parallel to the GLB glue layer

Nineteen specimens with dimensions of 6.1 x 4.2 x 2.8 cm^3 composed of 6 strips of bamboo internodal region that were 0.73 cm thick were tested; 9 were manufactured with the adhesive PVAc, and the other 10 were manufactured with the adhesive PRF. A shear plane coincided with the plane of glue, and the average shear area was 2.8 x 5.0 cm^2. Figure 10 shows orthographic views and isometric views of the specimen shear parallel to the glue surface of the GLB.

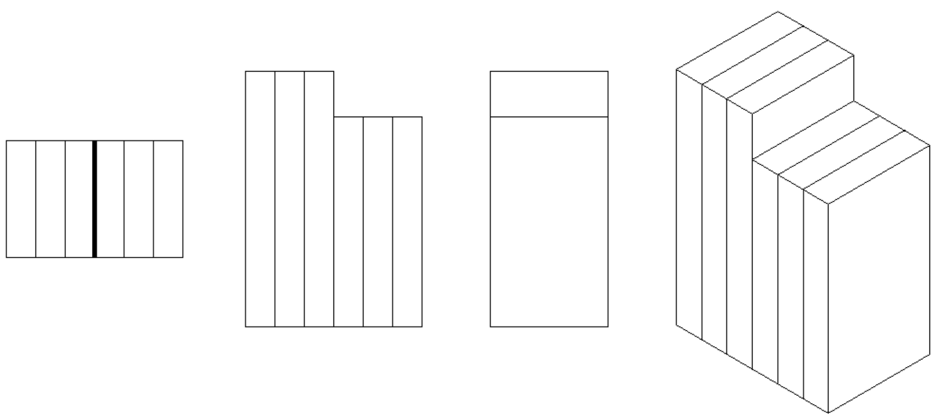
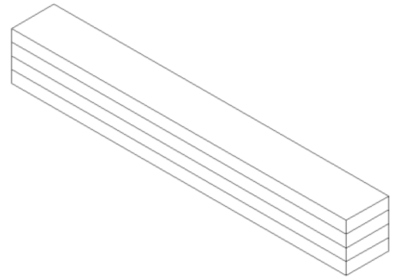


Fig. 10. Features specimen shear parallel to glue surface of GLB

Bending of GLB

The GLB was tested with a simply supported beam, with a range from 18.0 cm, in a flexural test of three points, with one point being the active load (P) at the mid-span and supporting the two reactive ends. The test was conducted using a hydraulic load, which had been coupled to the load cell with a capacity of 100 kN (Fig. 11a). Six test specimens were made, each of which was composed of 4 strips of bamboo glued together (Fig. 11b), three made using the PRF adhesive, and three with the PVAc adhesive. The specimens had the following average dimensions: 2.66 cm (base), 3.00 cm (height), and 25.0 cm (length).

Although only 6 specimens were used and given the variability of natural bamboo properties and the random choice of slats that make up the GLB, the results of other bending tests carried out by de Lima *et al.* (2014) were considered as a means to corroborate the results of this research.



(a) (b)

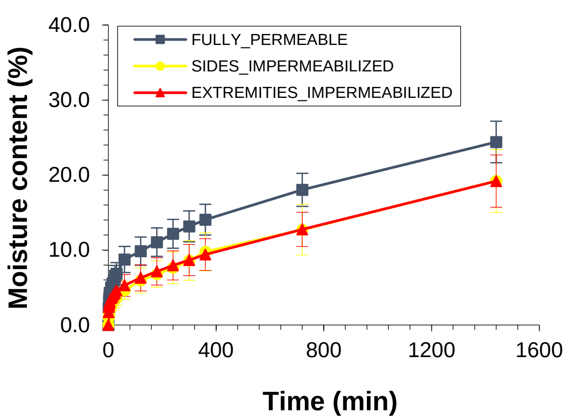
Fig. 11. Bending specimens: a) Front view; b) Isometric perspective

RESULTS AND DISCUSSION

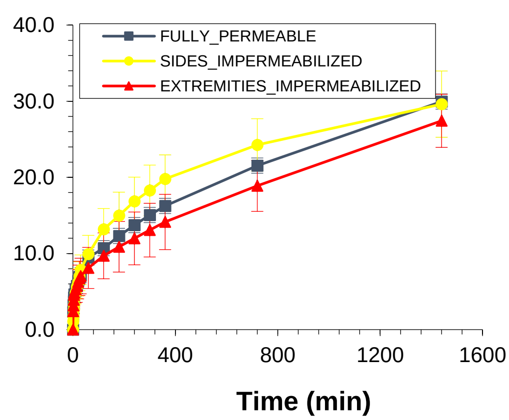
Physical Properties

Water absorption of bamboo

Figure 12a shows the data of the bamboo specimens without nodes, and Fig. 12b shows the data relating to specimens with present nodal regions. Moreover, these results are related to the test samples with and without waterproofing treatment (lateral waterproofing or waterproofing at the extremities). For statistical analysis (Microsoft Excel Office Professional Plus 2016, 2301 version, Albuquerque, NM, USA), a confidence interval was used assuming a probability of 95% using Student's t-distribution.



(a)



(b)

Fig. 12. Diagram moisture content *versus* time: (a) Bamboo without node; (b) Bamboo with node

It can be observed that for samples with and without nodes, the rate of water absorption reached values of 24.4 and 30.0%, respectively, in 1440 min (24 h). These values agree with those found in the literature (Ghavami 2005). It was also observed that the rate of water absorption of the nodal region was approximately 25% higher than in the region without the presence of a node at the time the test ended (24 h), demonstrating that the nodal region has higher porosity. Analyzing the moisture content rate curves of the specimens without nodes, with ends or sides waterproofed, it was observed that these showed the same behavior, albeit the results below the specimens being without waterproofing. For samples with node checks, the specimens with free ends had higher absorption rates during times between 100 and 800 min; however, in 24 h, the test values stabilized and were equal to those of the specimens without waterproofing treatment.

To determine which face (end or side) absorbs more water per unit area, the variations in moisture per unit area in contact with water were calculated. Thus, Fig. 13(a) and (b) show the curves of variation of the moisture content *vs*. the area of exposure to water for the 24 h test. Through analyzing the curves in Figs. 13a and b, it is evident that the end face, perpendicular to the fiber direction, had the highest absorption rate in both regions of the bamboo culm (nodal and internodal). Considering the points corresponding to the durations of 24 h and 60 min, it was observed that the end face was approximately 8 to 10 times more absorbent than the lateral side without and with nodes, respectively. Moreover, the end face of the nodal region was two times more absorbent than the region without a node.

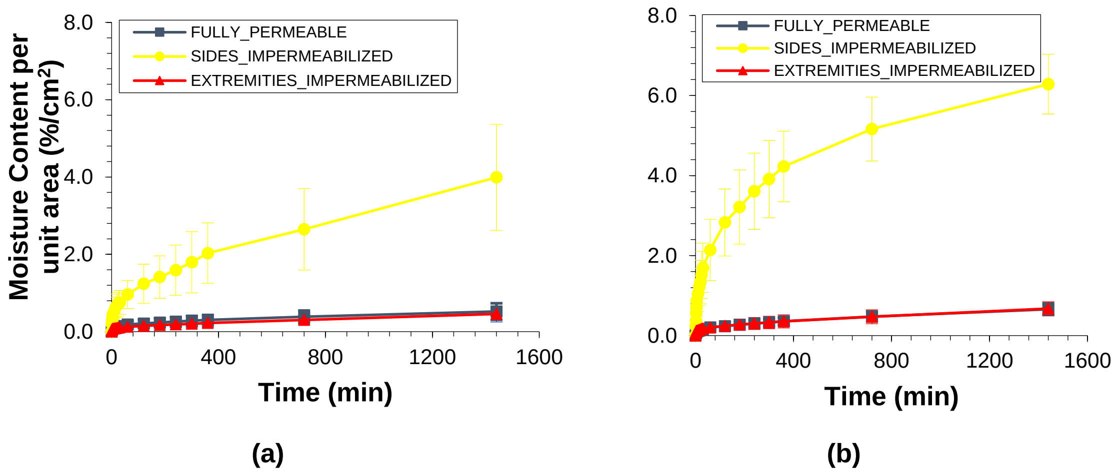


Fig. 13. Diagram of moisture content variation rate per unit area *versus* time: (a) Bamboo without node; (b) Bamboo with node

Figure 14 shows in detail the absorption of water by the end face of the specimens with impermeable sides. Regions of darker shades are observed near the ends of the sample and are characterized by greater water concentrations.

Fig. 14. Water penetration by the end face of the sample

Density of GLB

The average density obtained for the 8 GLB samples was 761 kg/m^3, with a coefficient of variation (CV) equal to 15.7% and an average moisture content of 7.0%. For the samples oven-dried until dry conditions (moisture content equal to 0%), the average density was 733 kg/m^3, and the coefficient of variation was equal to 15.8%. Additionally, using an expression proposed by Logsdon (1998), which relates the density at 12% humidity with the density at any humidity and with the volumetric shrinkage coefficient of the sample (averaged equal to 3.05%), the average density of the GLB equal to 770 kg/m^3 at 12% moisture.

The density at 12% moisture for the wood *Eucalyptus grandis* and *Araucaria angustifolia* were 640 and 580 kg/m^3 (ABNT NBR 7190 1997), respectively. Thus, the GLB (bamboo *Dendrocalamus giganteus* species) had density values larger than the aforesaid wood; however, these values are generally lower than those of dicotyledons wood used in roof structures, such as *Manilkara* spp. with density at 12% and moisture content equal to 1140 kg/m^3. Figure 15 shows the density data using confidence intervals according to a probability Student's t-distribution with a level of confidence of 95%. Finally, it is observed that the values of the density of the GLB in this research are in line with the literature (Oliveira *et al.* 2009).

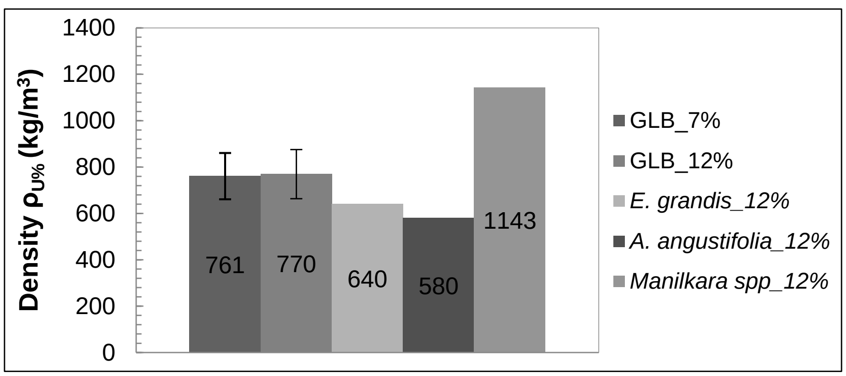


Fig. 15. Density data for GLB and comparative woods

Mechanical Properties

All mechanical properties were evaluated according to an average moisture content of 7%, which corresponds to an average density equal to 761 kg/m^3.

Tension strength parallel to bamboo fiber direction

An average tensile strength parallel to fiber direction of 262 MPa and a coefficient of variation equal to 12.5% were obtained for specimens without nodes (internodal region - SN), and 76.1 MPa and CV equal to 7.0% were obtained for specimens with nodes (nodal region - CN). The tension strength in the internodal region was approximately 3.5 times higher than that in the nodal region. Figure 16 shows the tension strength data using confidence intervals according to a probability Student's t-distribution with a level of confidence of 95%; it also had the following wood types of data (ABNT NBR 7190 1997): *Eucalyptus grandis*, *Araucaria angustifolia*, and *Manilkara* spp. (CV equal to 18%).

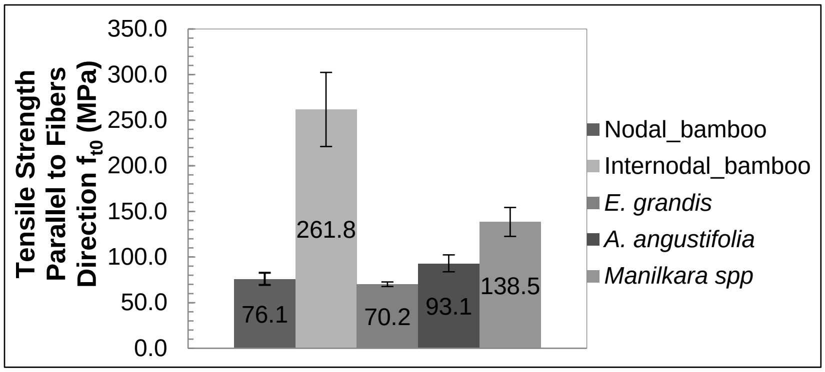


Fig. 16. Tensile strength parallel to bamboo fiber direction data

Compression strength parallel to fiber direction of GLB

Through a hypothesis test with a confidence level of 95%, it is observed that the size of the specimens did not significantly influence the compressive strength parallel to bamboo fiber direction. Additionally, using the hypothesis test with a confidence level of 95%, it was observed that the type of adhesive used did not influence the compressive strength parallel to fiber direction. Figure 17 shows the compression strength parallel to the grain data using confidence intervals according to a probability Student's t-distribution with a level of confidence of 95%, considering both types of specimens differentiated by the type of adhesive used (coefficient of variation of 8.43% and 9.69% for PVAc and PRF, respectively), because the size of the specimen did not influence the strength parallel to GLB fiber direction. Additionally, there are data regarding wood *Eucalyptus grandis* (40.3 MPa), *Araucaria angustifolia* (40.9 MPa), and *Manilkara* spp. (82.9 MPa) (ABNT NBR 7190 1997). It is observed that the compressive strength parallel to GLB fiber direction is 2.4 times greater than the wood *Eucalyptus grandis* and *Araucaria angustifolia*, respectively. Furthermore, f_{c0} GLB was approximately 20% greater than *Manilkara* spp. (coefficient of variation equal to 18%).

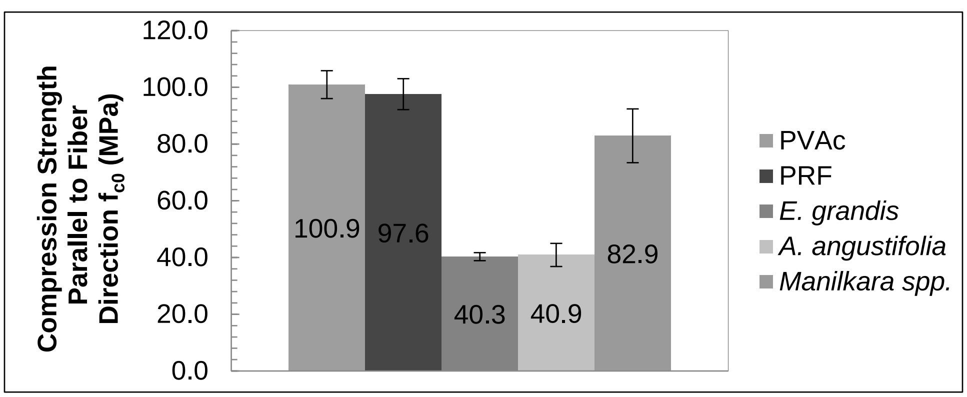


Fig. 17. Compression strength parallel to fiber direction data

Figures 18a and b show the stress–strain diagram of the specimens subjected to parallel compression to fiber direction. Additionally, a linear approximation of the data by the least squares method was conducted, and the compressive MOE parallel to GLB fiber direction was numerically equal to the slope of the linear approximation of the data. According to ABNT NBR 7190 (1997), the compressive modulus was equal to the slope of the secant line between points 10% and 50% of the compressive strength parallel to fiber direction. Therefore, the average compressive MOE parallel to fibers (E_{c0}) of GLB was equal to 22.1 GPa and the CV was equal to 13.2%; this value is similar to E_{c0} timber *Manilkara* spp. (22.7 GPa) and is approximately 72% and 45% higher than the timbers *Eucalyptus grandis* (12.8 GPa) and *Araucaria angustifolia* (15.2 GPa), respectively.

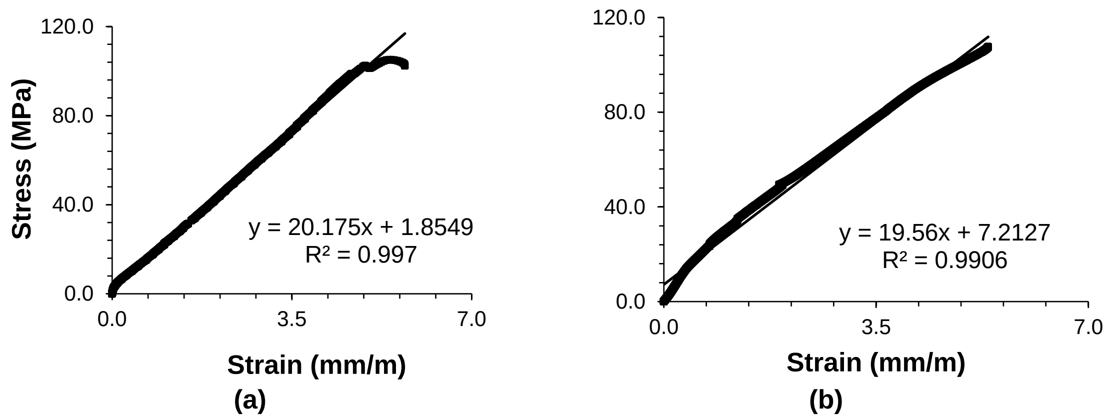


Fig. 18. Stress–strain diagram of GLB to compressive parallel to fiber direction: (a) Adhesive PVAc; (b) Adhesive PRF

The behavior of the parallel compression to GLB fiber direction was linear up to the proportional limit. Then, the stress–strain diagram was nonlinear due to buckling of the fibers from the bamboo. Thus, the compressive MOE parallel to fibers was calculated for the linear part of the stress–strain graph. Figure 19 shows the compressive failure mode of the specimens, which starts the detachment of the adhesive followed by rupture by compressive buckling of the strips composing the specimen.

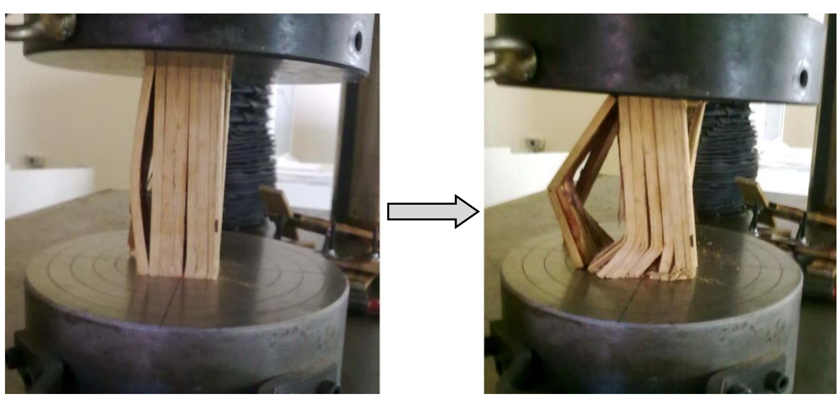


Fig. 19. Compressive failure mode

Shear parallel to bamboo fiber direction and the GLB glue surface

The obtained shear strength parallel to fiber direction was 8.42 MPa (CV equal to 14.0%). Figure 20a shows the exposed sheared surfaces of the specimens after fracture.

These values statistically corroborate the results obtained by Lima and Dias (2001), who tested 10 specimens formed by five bamboo slats glued with PFR adhesive (dimensions of 6.4 x 5.0 x 3.0 cm^3), in that the average shear strength with the respective standard deviation was 7.81 and 1.06 MPa, respectively.

The obtained shear strength parallel to the GLB glue surface was 5.07 MPa (CV = 9.0%) and 8.05 MPa (CV = 11.4%) for the PVAc and PRF glues, respectively. Again, Fig. 20(b) shows the exposed sheared surfaces of the specimens after fracture.

Fig. 20. Shear failure mode: (a) Shear parallel to bamboo fiber direction; (b) Shear parallel to GLB glue surface

Figure 21 shows the shear strength parallel to bamboo fiber direction (f_{v0}) and the shear strength parallel to the GLB glue plane (f_{gv0}). In addition, it is exposed to shear strength parallel to fiber direction data of the following woods: *Eucalyptus grandis*, *Araucaria angustifolia*, and *Manilkara* spp.; with a coefficient of variation equal to 28% as in ABNT NBR 7190 (1997).

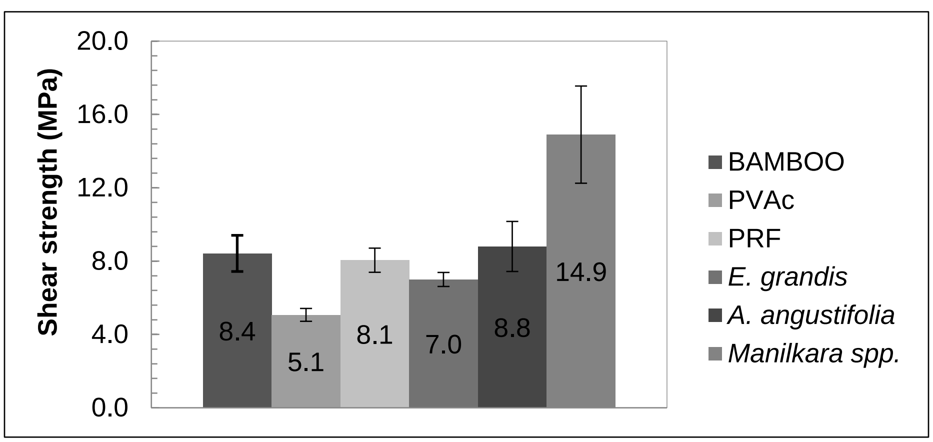


Fig. 21. Shear strength data for GLB, adhesives and comparatives woods

Through analyzing the graph of Fig. 21 and evaluating the shear data through hypothesis testing with a confidence level of 95%, it is verified that the test samples' shear strength parallel to bamboo fiber direction and shear strength parallel to the PRF glue surface had statistically the same shear strength. However, the shear strength parallel to the

PVAc glue surface was considerably less than the shear strength parallel to bamboo fiber direction. The adhesive PVAc presents results of shear strength approximately 37% lower than the bamboo and adhesive PRF. Finally, it was observed that the shear strength of the bamboo is comparable to the woods *Eucalyptus grandis* and *Araucaria angustifolia*; however, it represents only 56% of the shear strength parallel to wood fiber direction *Manilkara* spp. It should be noted that this wood has the third largest value of shear strength parallel to fiber direction cataloged by ABNT NBR 7190 (1997).

Bending of GLB

Among the 6 specimens tested, only 1 ruptured by tension due to bending, and all of the rest ruptured by shear parallel to the glue surface between the bamboo strips. The shear strength to the glue surface was equal to 7.0 MPa (CV = 8.3%) and 8.8 MPa (CV = 9.0%) for specimens fabricated with the adhesives PVAc and PRF, respectively.

The tensile stresses parallel to fiber direction for bending was equal to 97.3 MPa (CV = 8.7%) and 123.5 MPa (CV = 12.5%) for specimens fabricated with the adhesives PVAc and PRF, respectively. It should be noted that the tension parallel to fiber direction-to-bending values is not the GLB Modulus of Rupture (MOR), because predominantly the mechanism of rupture was longitudinal shear to adhesive surface in specimens tested. The results of other GLB bending tests can be seen in the literature (de Lima et al. 2014), which corroborate the fact of the predominance of rupture by longitudinal shear on the adhesive surface.

Figure 22 verifies the interlaminar shear failure between the second and third strips and the onset of failure due to tensile in bending due to the presence of the bamboo nodal region in the middle section of the lower strip.

Fig. 22. Bending specimen rupture

CONCLUSIONS

1. The nodal region of bamboo was found to be more absorbent than its internodal region.
2. The face perpendicular to the fibers of bamboo (top) was more absorbent than the bamboo side surface.
3. The glued laminated bamboo (GLB) density was found to be smaller than the density of the woods commonly used in the construction of roofs in Brazil, such as *Manilkara* spp.

4. Bamboo *Dendrocalamus giganteus*, in internodal region, has excellent tensile strength parallel to fiber direction, comparable to steel yield, as per ASTM A36 (2019).
5. It was observed that the compressive strength parallel to GLB fiber direction was 2.4 times greater than the woods *Eucalyptus grandis* and *Araucaria angustifolia*, respectively.
6. It was observed that the type of adhesive (PFR or PVAc) used did not significantly modify the compressive strength parallel to fiber direction, being statistically equal.
7. The shear strength parallel to fiber direction of the bamboo *Dendrocalamus giganteus* was found to be comparable to that of *Eucalyptus grandis* and *Araucaria angustifolia*; in contrast, it represented only 34% of the shear strength of the *Manilkara* spp.
8. It is verified that the test samples' shear strength parallel to the bamboo fiber direction and shear strength parallel to the PRF glue surface have statistically the same shear strength.
9. The adhesive PVAc presented results of shear strength parallel to the GLB glue surface 37% lower than adhesive PRF.
10. It is not necessary to use adhesives with shear strength much greater than that shear parallel to bamboo fiber direction, as failure of the GLBs will be limited by the bamboo.
11. The failure mode of the bending specimen test was governed by shear parallel to the glue plane because of the high compressive and tension strengths parallel to the bamboo fiber direction, even in bending tests.

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