

Physical and mechanical properties of glued laminated bamboo

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Abstract

Some Bamboos species have mechanical properties 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 this problem is Glued Laminated Bamboo (GLB). Based on these findings, this paper aims to evaluate the physical and mechanical properties of Glued Laminated Bamboo of the species *Dendrocalamus giganteus*. Two glues were analyzed: resorcinol-formaldehyde (CASCOPHEN, commercial name) and polyvinyl acetate (CASCOREZ, commercial name). The following physical and mechanical characterization tests were performed on Glued Laminated Bamboo: water absorption, density, compression parallel to the fiber, tension parallel to the fiber, shear parallel to the glue layer, shear parallel to the bamboo fibers and bending. The results, analyzed using statistical models, showed that the Glued Laminated Bamboo has physical and mechanical properties comparable to those of hardwoods.

1. Introduction

Bamboo is among the oldest and most used materials in civil construction, with its use being recorded for approximately six thousand years (Padovan RB 2010), and its use is still growing to this day. The use of bamboo seeks to achieve sustainable levels of development, which are achieved by few materials, reducing pollution, energy consumption and conservation of natural resources, and being associated with environmental preservation, which stimulates the development of new techniques for using bamboo raw material (de Lima DM, Amorim MM, Lima Júnior HC et al. 2014).

Despite its formidable physical and mechanical properties, bamboo has not been widely used as a material constituent structure due to its geometric configuration, low shear strength and the presence of nodes in its culms. The bamboo culm structure resembles a hollow tubular structure (Liese W 1987), making it impossible to use as usual structural parts, such as beams and columns of generally rectangular cross-sections. 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 (compressive strength, tension strength) compared with the region internodal culm, and its properties vary greatly depending on the species, soil and climatic condition, silvicultural treatment, age, density, and position in the culm (Lee AWC, Bai X, Peralta PN 1994) and (Yu HQ, Jiang ZH, Hse CY et al. 2008).

The technology of glued lamination is widely used in manufacturing high standards of finish flooring bamboo. This technology can be applied to bamboo to eliminate the problems of shear and geometry discussed previously. Furthermore, it can allow a more rational use of this material composing structures. The GLB is a material that can be a factor in improving the housing conditions of low-income housing in northeastern Brazil.

However, the lack of suitable equipment to carry out lamination limits the production of GLB (Beraldo AL, Rivero LA 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 EVM, Smits MA, Mantilla JNR 2017). Therefore, the adoption of the thermomechanical process used for wood can reduce or even reverse these limitations due to the decrease in the volume of the empty spaces in the material by compression; hence, promoting density increase.

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 L, Zhang X, Liu H et al. 2016). Several studies related to bamboo products were analyzed by several authors, such as the analysis of glued laminated bamboo beams under bending (de Lima DM, Amorim MM, Lima Júnior HC et al. 2014), laminated bamboo lumber production (Nugroho N, Ando N 2000) and (Nugroho N, Ando N 2001), bamboo oriented boards (Sumardi I, Ono K, Suzuki S 2007), glued laminated bamboo (Nugroho N, Ando N 2000), (Correal JF, Lopez LF 2008), (Rusch F; Trevisan R; Hillig É et al 2019) and (Sulastiningsih IM, Trisatya DR, Indrawan DA et al. 2021), heat-treated glued laminated bamboo (Brito FMS, Paes JB, Oliveira JTS et al. 2018) bamboo reinforced composites (Corradi S, Isidori T, Corradi M et al. 2009), adhesive performance and structural behavior (Correal JF, Ramirez F 2010) and (Correal JF, Ramirez F, Gonzalez S et al. 2010), laminated bamboo lumber (Mahdavi M, Clouston PL, Arwade SR 2012) and (Kitiyanun K, Kongsong W, Tuprakay S et al. 2022), parallel strand bamboo (Huang DS, Zhou AP, Bian YL 2013), bamboo-bundle laminated veneer lumber (Chen F, Jiang Z, Deng J et al. 2014), structural performance Howe trusses made of glued laminated bamboo (de Lima DM, Amorim MM, Lima Júnior HC et al. 2015), and laminated bamboo panels (Rusch F, Trevisan R, Hillig É et al. 2019).

Therefore, glued laminated bamboo is a low-cost material that can help improve housing conditions. However, the idea of using GLBs for structural purposes falls into problems that need more investigation (Bono CT 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, since it is essential that it presents low cost, high resistance and interacts chemically in an adequate way with the bamboo. The process of gluing bamboo strips must be optimized in terms of cost and generation of miniature interfaces. Finally, there is a need to develop an adequate treatment against the attack of fungi and insects to guarantee durable material, making it possible to build structures, such as roof trusses and beams, that are more efficient and durable.

In this perspective, this work aims to evaluate and characterize the physical and mechanical properties of Glued Laminated Bamboo of the species *Dendrocalamus giganteus*, using two types of glues: resorcinol-formaldehyde (CASCOPHEN, commercial name) and polyvinyl acetate (CASCOREZ, commercial name).

2. Materials And Methods

2.1 Materials Used

The bamboo used in this study was of the *Dendrocalamus giganteus* specie, obtained from the Cascavel Zoo in Brazil.. The culms were 20 m long, and internodes were spaced between 40-50 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 sawed longitudinally 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 extracted with a circular saw with nominal dimensions of 150 cm (length), 0.73 cm (thickness) and 3.00 cm (width), as shown in Fig. 1a and 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: resorcinol-formaldehyde (commercially known as CASCOPHEN) and polyvinyl acetate (commercially known as CASCOREZ). These adhesives are suitable for cold pressing. The CASCOPHEN adhesive was chosen because of the effective shear strength and for waterproofing. Additionally, the CASCOREZ adhesive presents low toxicity and is 15 to 20 times cheaper than CASCOPHEN; however, this adhesive presents low mechanical strength.

Glued laminated bamboo (GLB) was prepared from randomly chosen bamboo strips. After cleaning, the adhesive was distributed between the strips with a paintbrush and arranged in the same parallel direction to the bamboo fibers. Additionally, a device was mounted for pressing and bonding the bamboo strips (Fig. 2). The drying time followed the recommendations of each used adhesive. After drying, the pieces of GLB were prepared for testing.

2.2 Physical Properties

2.2.1 Bamboo Water Absorption

To perform the water absorption test, 30 samples of bamboo strips were extracted: 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 impermeable with silicone (Fig. 3a); and finally, in the 3rd phase, faces parallel to the fiber direction were 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.

2.2.2 Density of GLB

Eight varieties of GLB with the following average dimensions were used: 13.44 mm thick, 27.56 mm wide and 27.56 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.

2.3 Mechanical Properties

2.3.1 Tension Strength Parallel to Bamboo fiber

Ten specimens were tested, 5 from the nodal region and 5 from the internodal region. Tests were conducted in a Universal Testing Machine with displacement control. 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). Due to the lower tensile strength parallel to the fibers 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).

2.3.2 Compression Parallel to the fiber of GLB

The compression test was carried out 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, composed of 4 strips of bamboo glued together, was evaluated. These specimens were nominated by the letter "P". Fig. 5 shows orthographic views and isometric views of the specimen compression "P". Twenty-two specimens were tested under displacement control, 11 produced with CASCOPHEN adhesive and 11 with CASCOREZ adhesive. Six specimens were instrumented with two strain gauges parallel to the bamboo fibers (Fig. 6).

The behavior of specimens of GLB, with nominal dimensions of 5.00 x 5.00 x 15.00 cm, composed of 15 bamboo strips glued together, was also evaluated. These specimens were named by the letter "G". Fig. 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 CASCOPHEN adhesive and 3 with CASCOREZ adhesive. Two specimens were instrumented with two strain gauges in opposite faces and were also tested under displacement control.

2.3.3 Parallel Shear to the Bamboo Fiber

Eight specimens were tested with average dimensions of 6.1 x 4.2 x 2.8 cm. They were composed of 6 bamboo strips that were 0.73 cm thick and were glued together by PVA-based adhesive (CASCOREZ). The size of specimens GLB followed the proportions established by (ABNT NBR 7190 1997). Fig. 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 (Fig. 9). The shear tests were conducted under displacement control.

2.3.4 Parallel Shear to the GLB Glue Layer

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

2.3.5 Bending of GLB

It 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), 3 made using the CASCOPHEN adhesive and 3 with the CASCOREZ adhesive. The specimens had the following average dimensions: 2.66 cm (base); 3.00 cm (height) and 25.0 cm (length).

3. Results And Discussion

3.1 Physical Properties

3.1.1 Water Absorption of Bamboo

Fig. 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, a confidence interval was used assuming a probability of 95% using Student's t-distribution.

It is 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 K 2005). It was also observed that the rate of water absorption of the nodal region is 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 is 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 shows the curves of variation of the moisture content vs. the area of exposure to water for the 24 h test. By analyzing the curves in Fig. 13, 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 is two times more absorbent than the region without a node.

Fig. 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.

3.1.2 Density of GLB

The average density obtained for the 8 GLB samples was 760.85 kg/m^3 , with a variation coefficient equal to 15.69% and an average moisture content of 7.0%. For the samples dried in an oven until dry conditions (moisture content equal to 0%), the average density was 733.11 kg/m^3 , and the variation coefficient was equal to 15.80%. Additionally, using an expression proposed by (Logsdon NB 1998), the average density of the GLB equal to 769.51 kg/m^3 was computed. The density at 12% moisture for the wood *Eucalyptus grandis* and *Araucaria angustifolia* are equal to 640 kg/m^3 to 580 kg/m^3 (ABNT NBR 7190 1997), respectively. Thus, the GLB (bamboo species *Dendrocalamus giganteus*) has 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% moisture content equal to 1143 kg/m^3 . Fig. 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 AK, Paez JB 2006).

3.2 Mechanical Properties

3.2.1 Tension Parallel to the Bamboo Grain

An average tensile strength parallel to the grain of 261.8 MPa and a variation coefficient (VC) equal to 12.5% were obtained for specimens without nodes (internodal region - SN), and 76.1 MPa and VC equal to 7.0% were obtained for specimens with nodes (nodal region - CN). The tension strength in the internodal region is approximately 3.5 times higher than that in the nodal region. Fig. 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.* (variation coefficient 18%).

3.2.2 Compression Parallel to Grain of GLB

Through a hypothesis test with a confidence level of 95%, it is observed that the size of the specimens does not significantly influence the compressive strength parallel to the grain. Additionally, using the hypothesis test with a confidence level of 95%, it was observed that the type of adhesive used does not influence the compressive strength parallel to the grain. Fig. 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 (variation coefficients of 8,43% and 9,69% for CASCOREZ and CASCOPHEN, respectively), since the size of the specimen does not influence the strength parallel to the grain of the GLB. 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 the grain of GLB is 2.4 times greater than the wood *E. grandis* and *A. angustifolia*, respectively. Furthermore, f_{c0} GLB is approximately 20% greater than *Manilkara spp.* (variation coefficient 18%).

Fig. 18 shows the stress–strain diagram of the specimens subjected to parallel compression to the grain. Additionally, a linear approximation of the data by the least squares method is conducted and the compressive modulus of elasticity parallel to the grain of the GLB was found to be numerically equal to the slope of the linear approximation of the data. According to ABNT NBR 7190 (1997), the compressive modulus is equal to the slope of the secant line between points 10% and 50% of the compressive strength parallel to the grain. Therefore, the average compressive modulus of elasticity parallel to fibers (E_{c0}) of GLB is equal to 22.1 GPa and the VC is 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 wood (ABNT NBR 7190 1997) *E. grandis* (12.8 GPa) and *A. angustifolia* (15.2 GPa), respectively.

The behavior of the parallel compression to the grain of the GLB 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 modulus of elasticity parallel to fibers is 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.

3.2.3 Shear Parallel to the Grain of Bamboo

The obtained shear strength parallel to the fibers was 8.42 MPa (VC equal to 14.0%). Fig. 20 shows the exposed sheared surfaces of the specimens after fracture.

3.2.4 Shear Parallel to the Glue Surface of the GLB

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

Fig. 21 shows the shear strength parallel to the grain of bamboo (f_{v0}) and the shear strength parallel to the glue plane of GLB (f_{gv0}). In addition, it is exposed to shear strength parallel to the grain data of the

following woods, *E. grandis*, *A. angustifolia* and *Manilkara spp.*, with a variant coefficient equal to 28% as in ABNT NBR 7190 (1997).

By 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 the grain of the bamboo and shear strength parallel to the glue surface CASCOPHEN of GLB have statistically the same shear strength. However, the shear strength parallel to the glue surface CASCOREZ is considerably less than the shear strength parallel to the grain of the bamboo. The adhesive CASCOREZ presents results of shear strength approximately 60% lower than the BAMBOO and adhesive CASCOPHEN. Finally, it was observed that the shear strength of the bamboo is comparable to the woods *E. grandis* and *A. angustifolia*; however, it represents only 34% of the shear strength parallel to the grain of the wood *Manilkara spp.* It should be noted that this wood has the third (3rd) largest value of shear strength parallel to grain cataloged by ABNT NBR 7190 (1997).

3.2.5 Bending of GLB

Among the 6 specimens tested, only 1 broke by tension due to bending, with another broken by shear parallel to the glue surface between the bamboo strips. The shear strength to the glue surface was equal to 7.0 MPa (VC = 8.3%) and 8.8 MPa (VC = 9.0%) for specimens fabricated with the adhesives CASCOREZ and CASCOPHEN, respectively. The tension parallel to grain for bending was equal to 97.3 MPa (VC = 8.7%) and 123.5 MPa (VC = 12.5%) for specimens fabricated with the adhesives CASCOREZ and CASCOPHEN, respectively. It should be noted that the tension parallel to the grain-to-bending values is not the bending strength of the GLB (f_M) because the mechanism of rupture was parallel shear. Fig. 22 verifies the parallel shear failure between the 2nd and 3rd strips and the failure tension due to the presence of the bamboo nodal region.

4. Conclusion

1. The nodal region of bamboo is more absorbent than its internodal region;
2. The face perpendicular to the fibers of bamboo (top) is more absorbent than the bamboo side surface;
3. The density of the GLB is greater than that of the woods *Eucalyptus grandis* and *Araucaria angustifolia*. However, the density of the GLB is smaller than the density of the woods commonly used in the construction of roofs in Brazil, such as *Manilkara spp.*
4. Bamboo *Dendrocalamus giganteus* has excellent tensile strength parallel to the fibers, comparable to steel yield, as ASTM A36;
5. It is observed that the compressive strength parallel to the fiber of GLB is 2.4 times greater than the woods *E. grandis* and *A. angustifolia*, respectively. Furthermore, this compressive strength is approximately 20% greater than that of *Manilkara spp.*

6. The shear strength parallel to fiber of the bamboo *Dendrocalamus giganteus* is comparable to that of woods *E. grandis* and *A. angustifolia*; in contrast, it represents only 34% of the shear strength parallel to the fiber of the wood *Manilkara spp.*

7. It is verified that the test samples shear strength parallel to the grain of bamboo and shear strength parallel to the glue surface CASCOPHEN of GLB have statistically the same shear strength. Therefore, it is not necessary to use adhesives with higher shear strength because the rupture of GLBs is limited by the shear strength of the bamboo. The adhesive CASCOREZ showed low shear strength parallel to the glue surface.

8. The failure mode of the bending specimen test was governed by shear parallel to the glue plane due to the high compressive strength parallel to the grain and tension strength parallel to the grain of bamboo.

Declarations

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Author contributions DML: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. HCLJ: Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision. ISM: Visualization, Writing – original draft, Writing – review & editing.

Financial interests The authors declare they have no financial interests.

References

1. ABNT NBR 7190 (1997) Projetos de estruturas de madeira, Rio de Janeiro.
2. Beraldo AL, Rivero LA (2003) Bambu laminado colado. *Floresta e Ambiente* 10:36-46.
3. Bono CT (1996) Madeira Laminada Colada na Arquitetura: sistematização de obras executadas no Brasil. Dissertação, Universidade de São Paulo.
4. Brito FMS, Paes JB, Oliveira JTS et al (2018) Physico-mechanical characterization of heat-treated glued laminated bamboo, *Constr Build Mater* 190:719-727. <https://doi.org/10.1016/j.conbuildmat.2018.09.057>.
5. Carrasco EVM, Smits MA, Mantilla JNR (2017) Resistência ao cisalhamento da ligação bambu-bambu: influência da pressão de colagem. *Matéria* 22:e11914.
6. Chen F, Jiang Z, Deng J et al (2014) Evaluation of the uniformity of density and mechanical properties of bamboo-bundle laminated veneer lumber (BLVL). *BioResources* 9:554-565.

<https://doi.org/10.15376/biores.9.1.554-565>

7. Corradi S, Isidori T, Corradi M et al (2009) Composite boat hulls with bamboo natural fibres. *Int J Mater Prod Tec* 36:73-89.
8. Correal JF, Lopez LF (2008) Mechanical properties of Colombian glued laminated bamboo. In: *Modern Bamboo Structures*, Paudel SK, Xiao Y, Inoue M (eds.), Taylor & Francis, London, pp 121-127.
9. Correal JF, Ramirez F (2008) Adhesive bond performance in glue line shear and bending for glued laminated guadua bamboo. *J Trop Forest Sci* 22:433-439.
10. Correal JF, Ramirez F, Gonzalez S et al (2010) Structural behavior of glued laminated guadua bamboo as a construction material. *Proceedings of the 11th World Conference on Timber Engineering*, Riva del Garda, Italy.
11. de Lima DM, Amorim MM, Lima Júnior HC et al (2014) Avaliação do comportamento de vigas de bambu laminado colado submetidas à flexão. *Ambiente Construído* 14:15-27.
<https://doi.org/10.1590/S1678-86212014000100003>
12. de Lima DM, Amorim MM, Lima Júnior HC et al (2015) Avaliação do desempenho estrutural de treliças Howe de Bambu Laminado Colado. *Ambiente Construído* 15: 85-102.
<https://doi.org/10.1590/s1678-86212015000300028>
13. Ghavami K (2005) Bamboo as reinforcement in structural concrete elements. *Cement Concrete Comp* 27:637-649. <https://doi.org/10.1016/j.cemconcomp.2004.06.002>
14. Huang DS, Zhou AP, Bian YL (2013) Experimental and analytical study on the nonlinear bending of parallel strand bamboo beams. *Constr Build Mater* 44:585-592.
<https://doi.org/10.1016/j.conbuildmat.2013.03.050>
15. Kitiyanun K, Kongsong W, Tuprakay S et al (2022) Mechanical Properties of Parallel TDG Bamboo Laminated Columns with Tough and Grove Joints, *Designs* 6:107.
<https://doi.org/10.3390/designs6060107>
16. Lee AWC, Bai X, Peralta PN (1994) Selected physical and mechanical properties of giant timber bamboo grown in South Carolina. *Forest Prod J* 44:40-46.
17. Liese W (1987) Research on bamboo. *Wood Sci Technol* 21:189-209.
<https://doi.org/10.1007/BF00351391>
18. Logsdon NB (1998) Influência da umidade em propriedades da madeira. Tese, Universidade de São Paulo.
19. Mahdavi M, Clouston PL, Arwade SR (2012) A low-technology approach toward fabrication of laminated bamboo lumber. *Constr Build Mater* 29:257-262.
<https://doi.org/10.1016/j.conbuildmat.2011.10.046>
20. Ni L, Zhang X, Liu H et al (2016) Selected and mechanical properties of glued bamboo laminates. *BioResources* 11:4459-4471.
21. Nugroho N, Ando N (2000) Development of structural composite products made from bamboo I: Fundamental properties of bamboo zephyr board. *J Wood Sci* 46:68-74.

22. Nugroho N, Ando N (2001) Development of structural composite products made from bamboo II: Fundamental properties of laminated bamboo lumber. *J Wood Sci* 47: 237-242.
23. Oliveira AK, Paez JB (2006) Caracterização físico-mecânica de laminado colado de bambu (*Dendrocalamus giganteus*) para revestimento de pisos. BRASIL NOCMAT - Salvador.
24. Padovan RB (2010) O bambu na arquitetura: design de conexões estruturais. Dissertação, Universidade Estadual Paulista.
25. Rusch F, Trevisan R, Hillig É et al (2019) Physical-mechanical properties of laminated bamboo panels. *Pesquisa Agropecuária Tropical* [online] 49:e53714. <https://doi.org/10.1590/1983-40632019v4953714>
26. Rusch F; Trevisan R; Hillig É et al (2019) Physical-mechanical properties of laminated bamboo panels, *Pesq Agropec Trop* 49:e53714. <https://doi.org/10.1590/1983-40632019v4953714>
27. Sulastiningsih IM, Trisatya DR, Indrawan DA et al (2021) Physical and mechanical properties of glued laminated bamboo lumber. *J Trop Forest Sci* 33:290-297. <https://doi.org/10.26525/jtfs2021.33.3.290>
28. Sumardi I, Ono K, Suzuki S (2007) Effect of board density and layer structure on the mechanical properties of bamboo oriented strandboard. *J Wood Sci* 53:510-515.
29. Yu HQ, Jiang ZH, Hse CY et al (2008) Selected physical and mechanical properties of moso bamboo (*Phyllostachys pubescens*). *J Trop Forest Sci* 20:258-263.

Figures

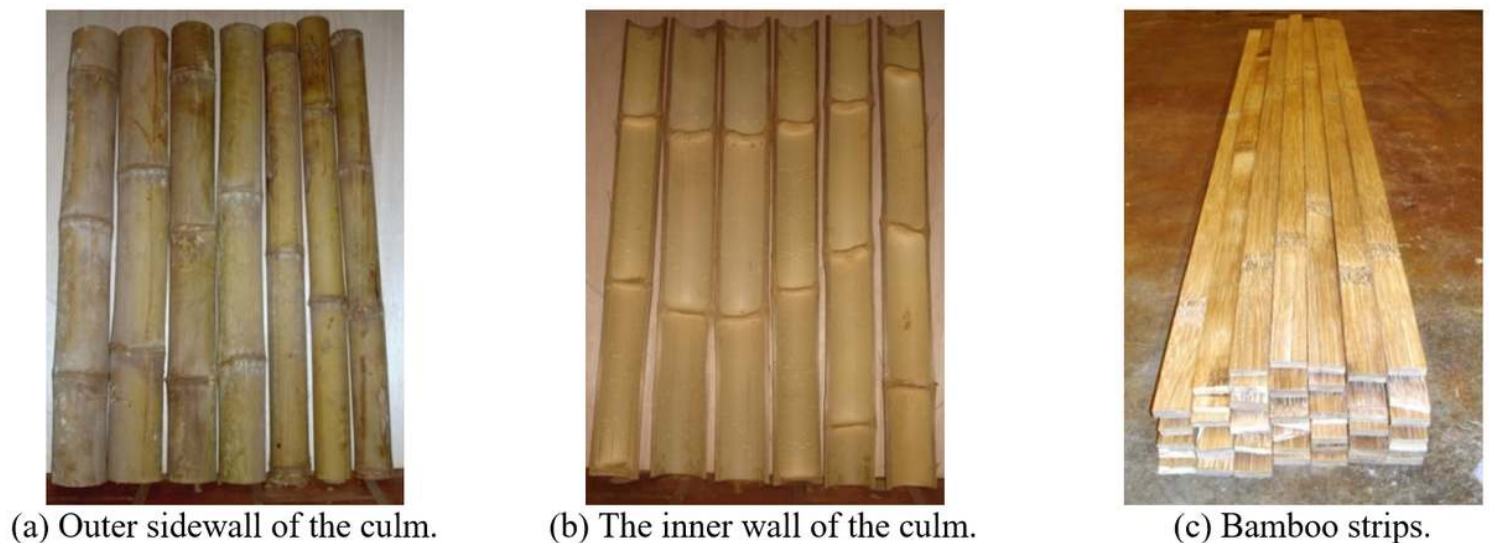


Figure 1

Cutting and lamination of bamboo products.



(a)



(b)

Figure 2

Pressing process.



(a) Extremities impermeabilized.



(b) Sides impermeabilized.

Figure 3

Impermeabilization of samples using silicone.

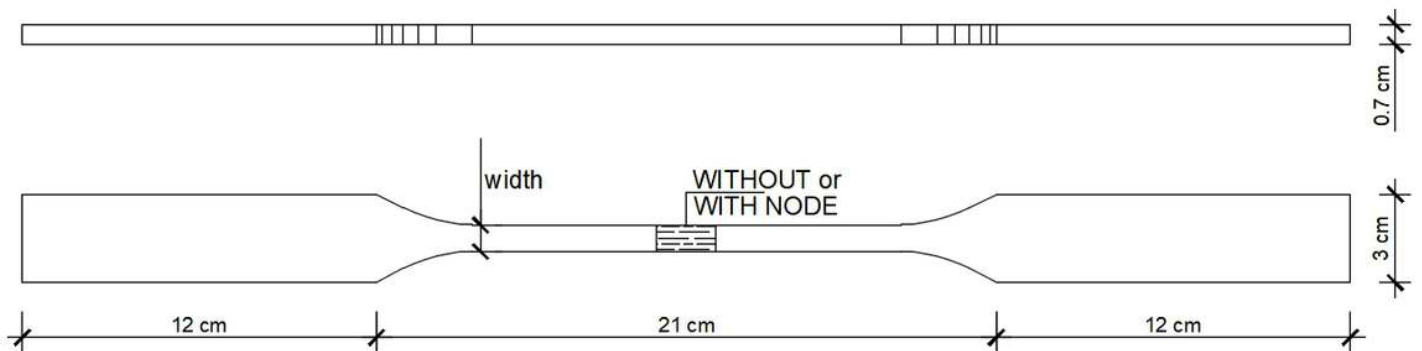


Figure 4

Tension specimen.

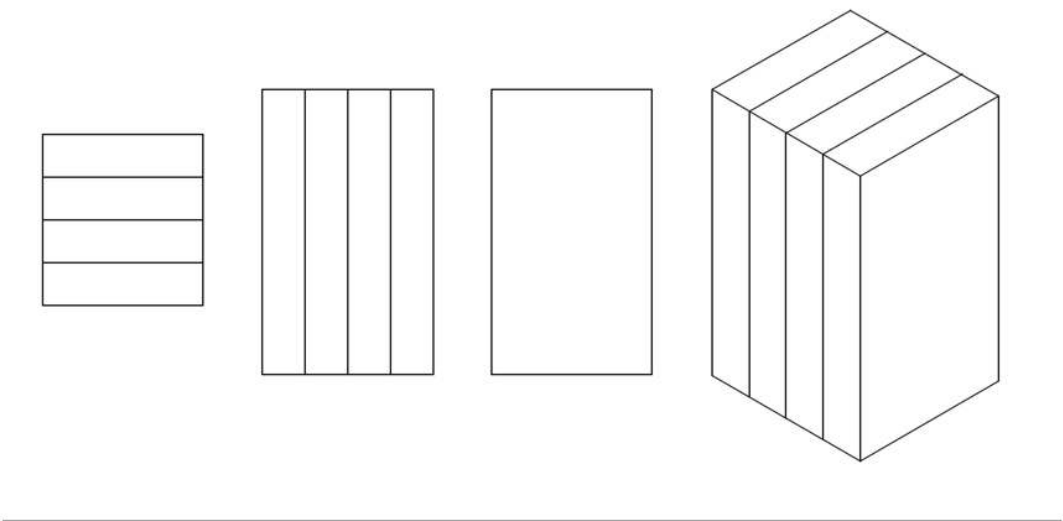


Figure 5

Characteristics of the compression specimen “P”.

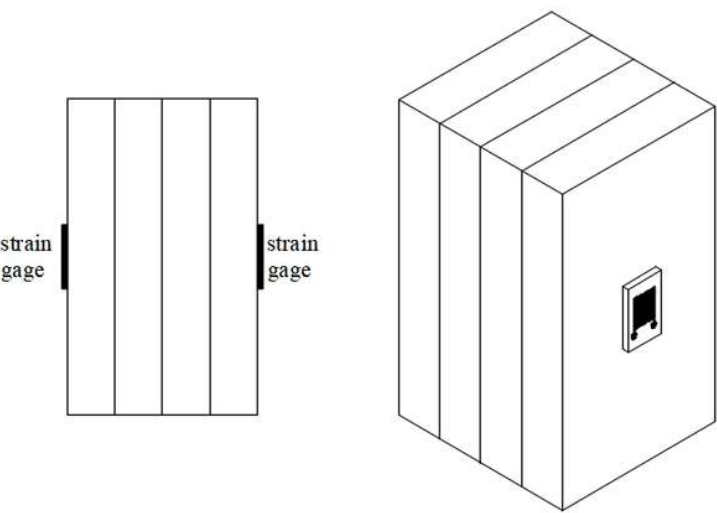


Figure 6

Arrangement of strain in the specimen compression.

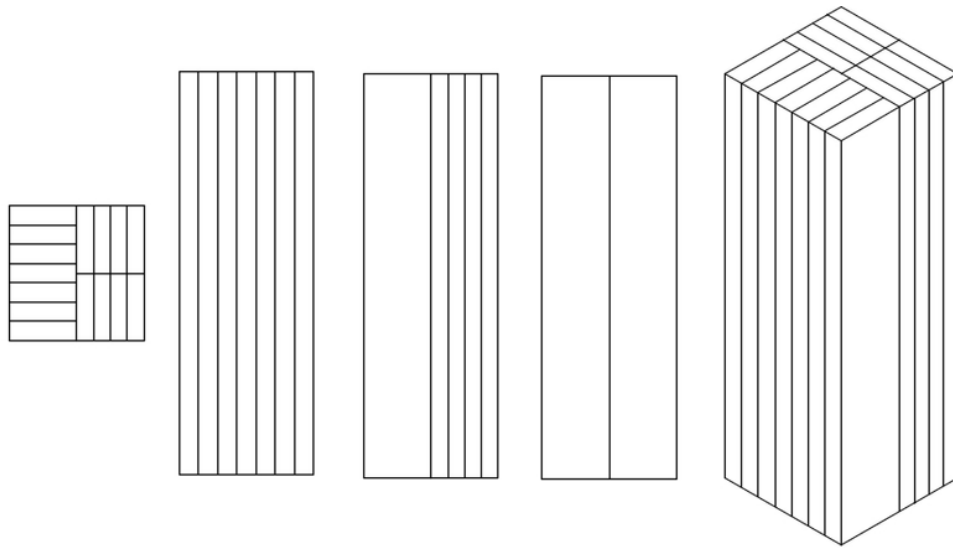


Figure 7

Characteristics of the compression specimen "G".

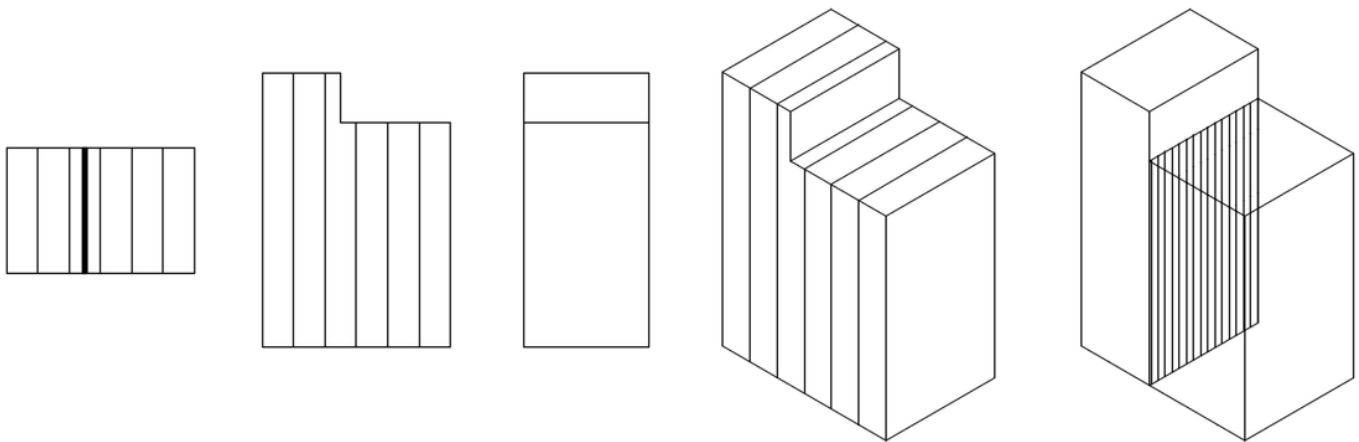
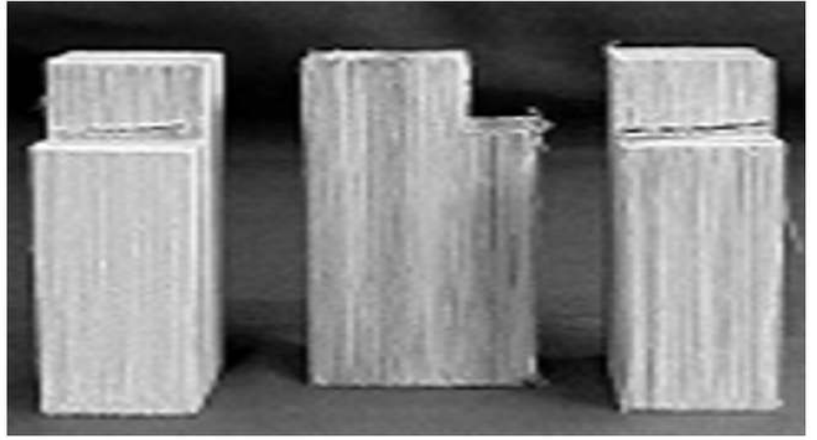


Figure 8

Features specimen shear parallel to the fibers of bamboo.



(a)



(b)

Figure 9

Shear specimens.

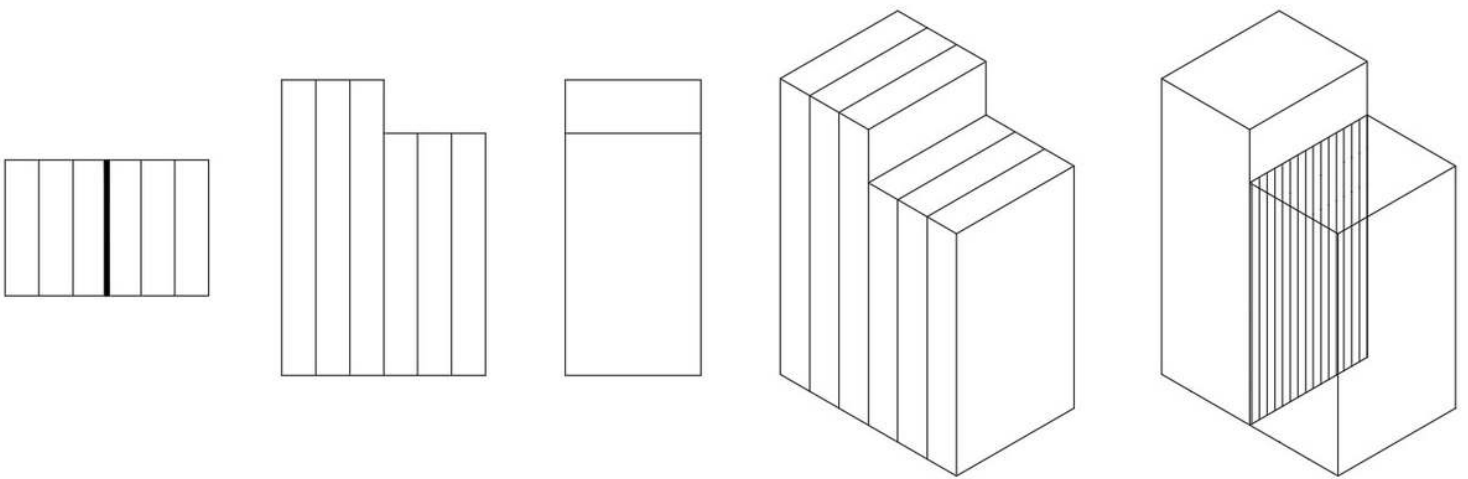
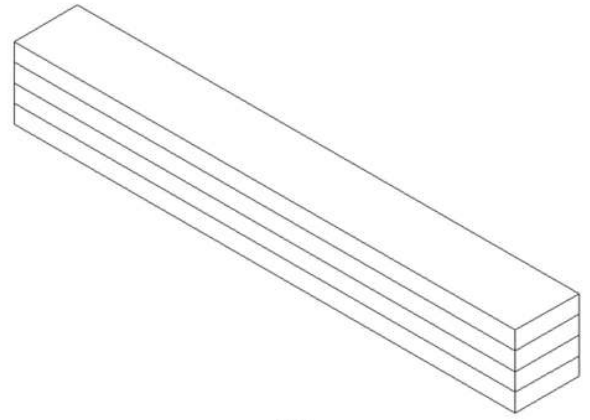


Figure 10

Features specimen shear parallel to glue surface of GLB.



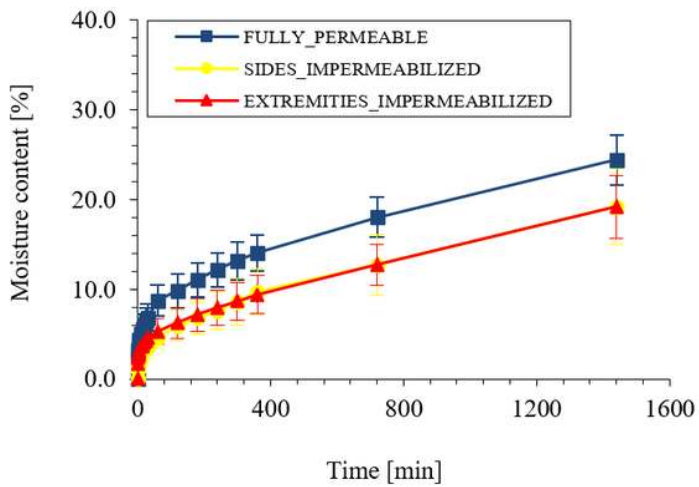
(a)



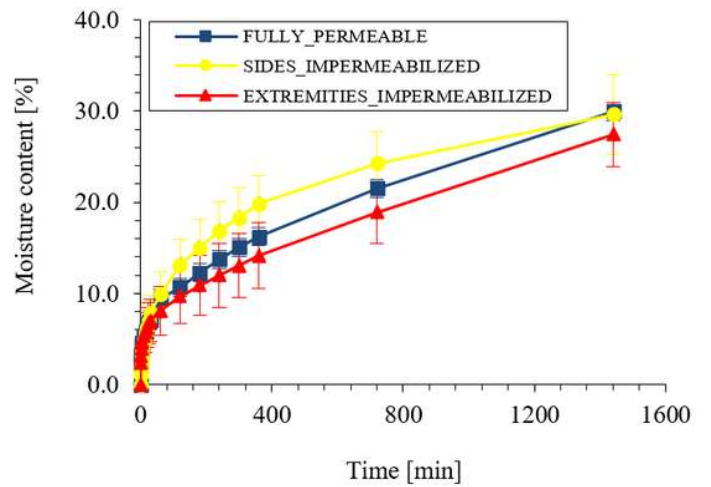
(b)

Figure 11

Bending specimens.



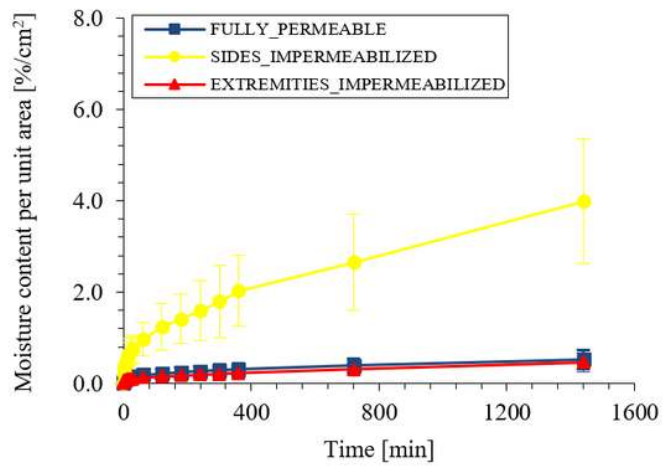
(a) Bamboo without node.



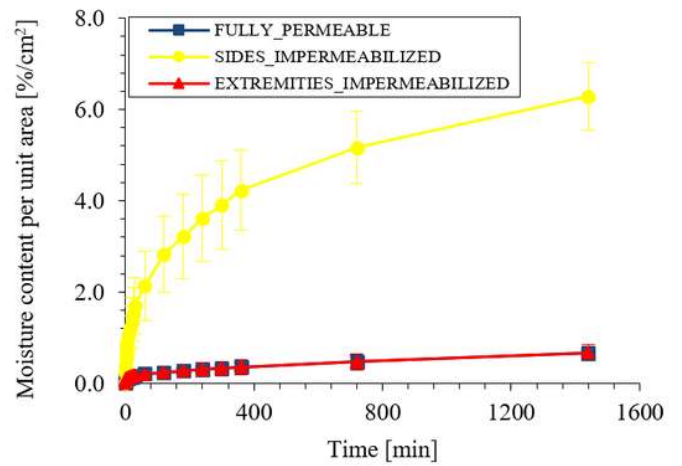
(b) Bamboo with node.

Figure 12

Diagram moisture content versus time.



(a) Bamboo without node.



(b) Bamboo with node.

Figure 13

Diagram of moisture content variation rate per unit area versus time.



Figure 14

Water penetration by the end face of the sample.

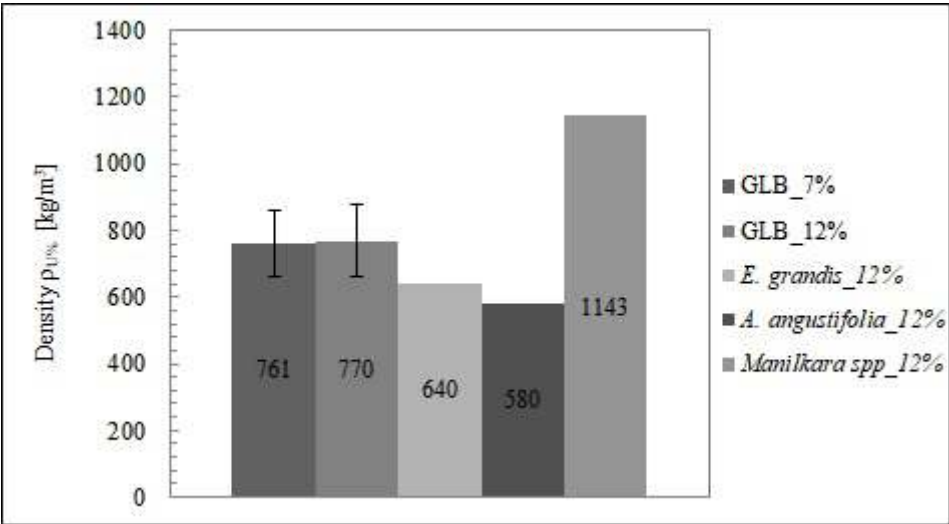


Figure 15

Density data.

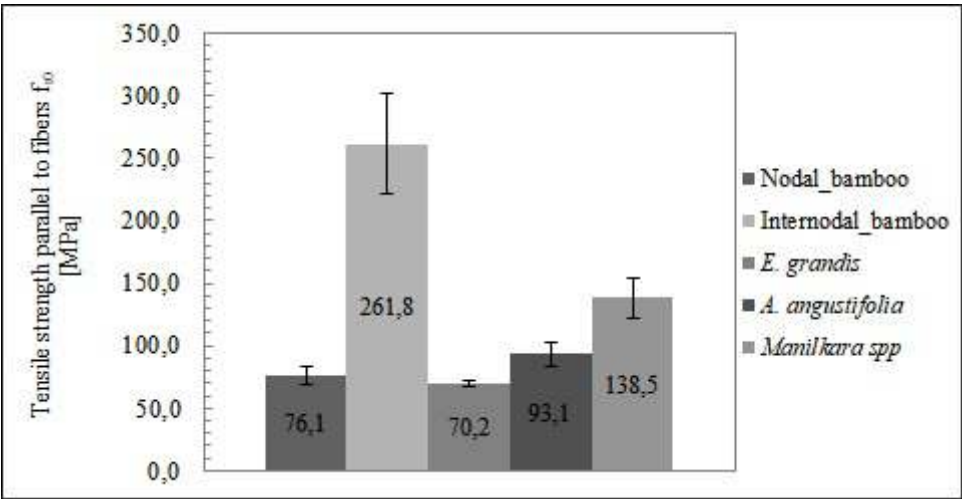


Figure 16

Tensile strength parallel to bamboo fibers data.

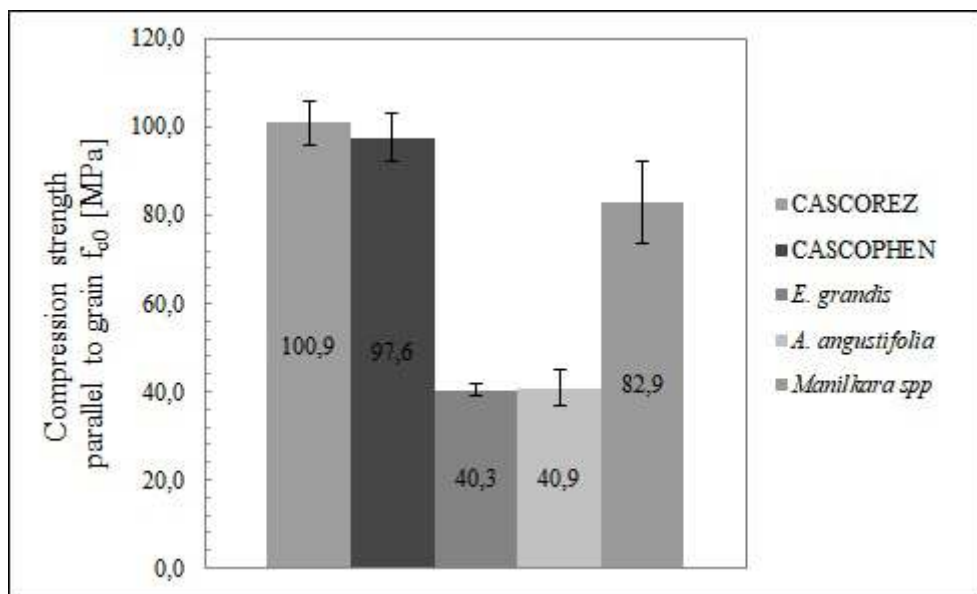
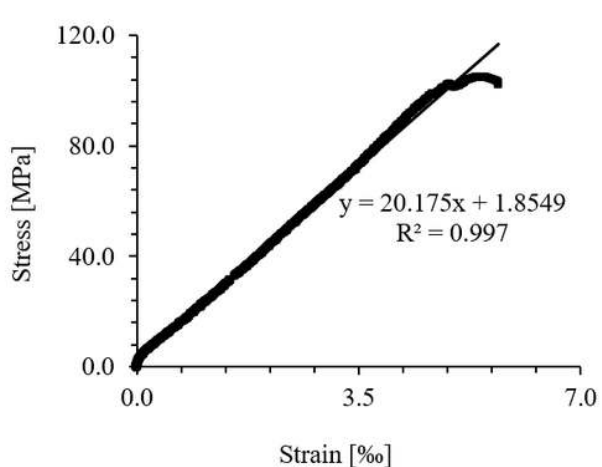
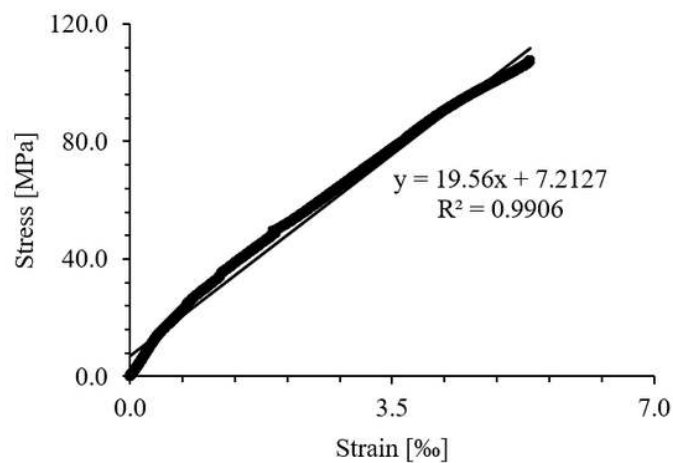


Figure 17

Compression strength parallel to grain data.



(a) Adhesive CASCOREZ.



(b) Adhesive CASCOPHEN.

Figure 18

Stress-strain diagram of GLB to compressive parallel to grain.



Figure 19

Compressive failure mode.



(a) Shear parallel to grain of bamboo.



(b) Shear parallel to glue surface of GLB.

Figure 20

Shear failure mode.

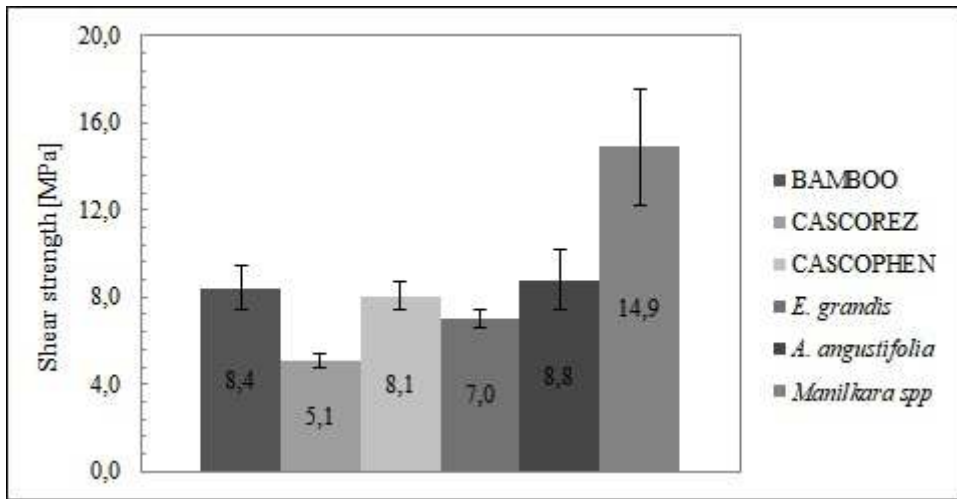


Figure 21

Shear strength data.



Figure 22

Longitudinal shear failure mode.