3
Materials and Experimental Procedures

This research was developed in the Laboratorio de Ensaios Mecânicos ITUC PUC – Rio with the objective of determining the values for E_t, G_t and τ_t of six types of test specimens and bending properties of unidirectional bamboo-laminated beams.

3.1.
Material used

For this dissertation the bamboo species used was *Dendrocalamus giganteus* taken from the campus of PUC – Rio. 3 culms were cut in November 2013, approximately 40 cm above ground level. After curing and drying, bamboo culm was divided in three parts along its length (Bottom, Middle and Top) approximately 2.5 to 3.5 m each part. Then transversal sections were split radially obtaining 5 to 8 strips 3 to 4 cm width and cut longitudinally 120 cm length. Those strips were processed in order to remove knots and irregular surfaces. All the segments were labeled: Bottom-Outer (BO), Middle-Outer (MO), Top-Outer (TO), Bottom-Inner (BI), Middle-Inner (MI) and Top-Inner (TI). Their longitudinal labeling and cross section location are shown in Figure 15.
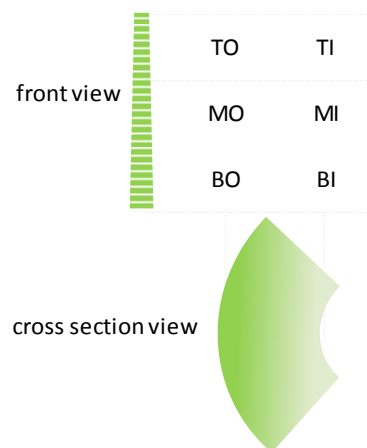

Figure 15 Segments of analysis depending on the longitudinal and cross section location.

3.1.1.
Density and specific gravity

For calculating density and specific gravity, 4 internode samples were taken from different longitudinal and cross section location. The internode was cut into strips of approximately 22 cm long 3 cm wide and 0.3 cm thick. Mass, dimensions and label were registered in order to obtain density and subsequently SG.

3.1.2.
Humidity

Moisture content determination was made according to the standard procedure ISO/TC 165 N135 dated: 2001-12-07. Five samples of approximately 25mm wide, 25mm length and height were prepared. Each sample was weighed and taken to the oven at 110°C to be dried. The drying process took 24 hours and at the end the weight of samples was read again.

Being m_0 initial weight of each sample and m weight after drying, the moisture M of each sample is calculated with equation:

$$M(\%) = \frac{m_0 - m}{m_0} * 100 \qquad (3.1)$$

3.1.3.
Roughness

Surface roughness of mats was calculated in order to make sure that there was an acceptable variation of the surface to allow an optimal performance of adhesive. This calculation was performed with high accuracy roughness tester Taylor Hobson 50. However, resulted dispensable essential because planner thicknesser generated a finish seemed to a sanding process generating layers very uniforms on thick.

3.2.
Equipment

Process to get bamboo layers was carried out with a table saw in order to divide the culm on strips, and a planner thicknesser was used to get suitable and thin 3-5 mm thickness samples and laminas to assemble beams. Tests for

characterization and bending were carried out in a hydraulic testing machine, using clip and strain gages for strain measure and load cells for load measures.

3.2.1.
Table saw

The saw used was the Makita 2704 table saw 255mm (see Figure 16). The machine saw table has high rigidity, and delivers accurate cutting work in order to obtain strips with standard widths. This fact becomes important when optimizing the material because all strips should have a standard width. Its motor enables ripping 4"x8" wood with telescopic sub table.

Figure 16 Table saw.

3.2.2.
Planner thicknesser

The thicknesser used was a compact thicknesser (see Figure 17) used for dressing rough sawn of bamboo, it has a double-edged HSS blades and automatic feed rollers, which push the material through at 8.5m per/min.

Figure 17 Planner thicknesser.

The machine allows adjusting thickness. After obtaining strips by sawing, they were thinned until reaching required segment.

3.2.3.
Materials testing machines

The properties of the tensile test segments were obtained by using a hydraulic testing machine Instron 5500R (see Figure 18). The capacity was 100kN, for tensile, compression and bending tests. The range of velocity was between 0,01 and 1000 mm/min.

Figure 18 Hydraulic machine testing Instron 5500R.

The machine was equipped with an automatic system reads load values and vertical displacements, by means of an optical sensor built in. This equipment

allows choosing the load application procedure, as a function of load rate or rate of displacement. For the characterization tests (tensile, shear and adhesive strength), the test velocity was 1mm/min. The Instron 5500 machine used wedge-sharped pincer clamps as shown on Figure 18, with a maximum capacity of 5000kgf, tighten by a screw system. Clamps held aluminum plates at ends of samples to improve grip.

For the bending tests, an Amsler 57/497 was used to bring layered bamboo beams to failure. Test machines had a load capacity of 20Ton, and are designed for tensile, compression and bending tests. However, this machine presented a wider effective span for bending tests since beams were approximately 55 cm long. Despite test machine measured load, load cell were used in order to synchronize all sources reads at acquisition system. A Linear Variable differential transformer (LVDT) sensor located at the bottom of the sample beams was used to measure vertical displacement in the middle of the sample. Test velocity was 2.4mm/min.

Figure 19 Hydraulic test machine Amsler 57/497.

Gadgets for bending test are shown on Figure 19, they have a maximum spam length of 100cm. For the four point bending test, a distance of 16,7cm between restrains was used as it can be seen on test arrangement.

3.3.
Samples

This research used two types of specimens, test specimens and beam specimens. Test specimens were thin individual layers 200 mm length to determine tensile modulus of elasticity E_t and shear modulus G for each segment of analysis (BI, MI, TI, BO, MO and TO). Beams specimens were elements composited by layers exclusively from a segment of analysis to determine bending modulus of elasticity E_b.

3.4.
Test specimens

There were obtained 18 test specimens for the modulus of elasticity and 18 more for shear modulus tests (3 samples for each segment of analysis), those were obtained from bamboo culms by a radial-symmetrical cut in the cross section along the culm. This provided strips with an accurate isosceles trapezium cross-shape. As a first step, planner thicknesser was used to remove both curve parts in order to get plane surfaces, as shown on the Figure 20. After that, the planner saw polished layers edges, shaping a square form for the transversal section, as can be seen in the final strip on Figure 20. The laminated vertically was used in this research, applying loads on the stack direction.

Inner and outer segments compose the final strip. Outer layer was obtained by sanding inner surface layer outwards until get 3mm thickness and the same process was carried out for the outer wall. Final thickness of layers was approximately 3mm (Figure 22), and from these layers to cut samples and layer to assemble beams.
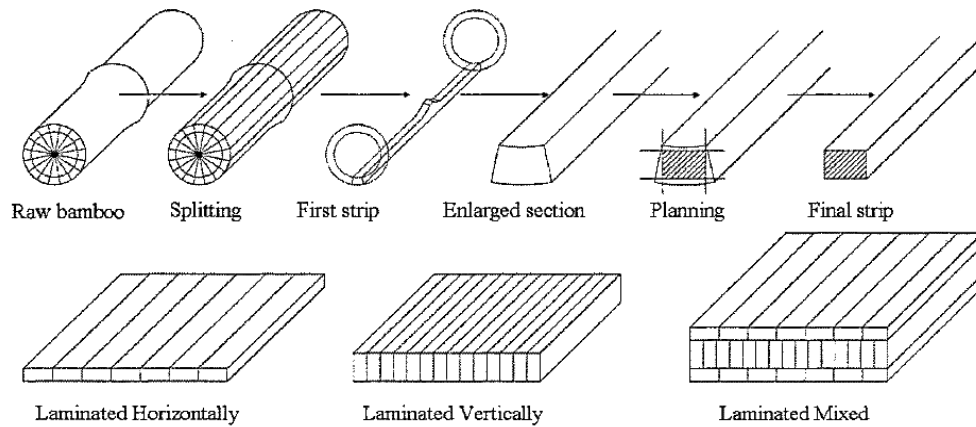
Figure 20 Strip obtaining process, from bamboo culm to final composite (inner-outer) strip.

In previous works, tensile tests carried out by Ghavami in bone shaped samples with aluminum plates at edges, where the clamps act. In the following tests, he suggested to use straight shapes due to the orthotropic nature of the bamboo.

Figure 21 Splitting longitudinally bamboo culm to obtain strips.
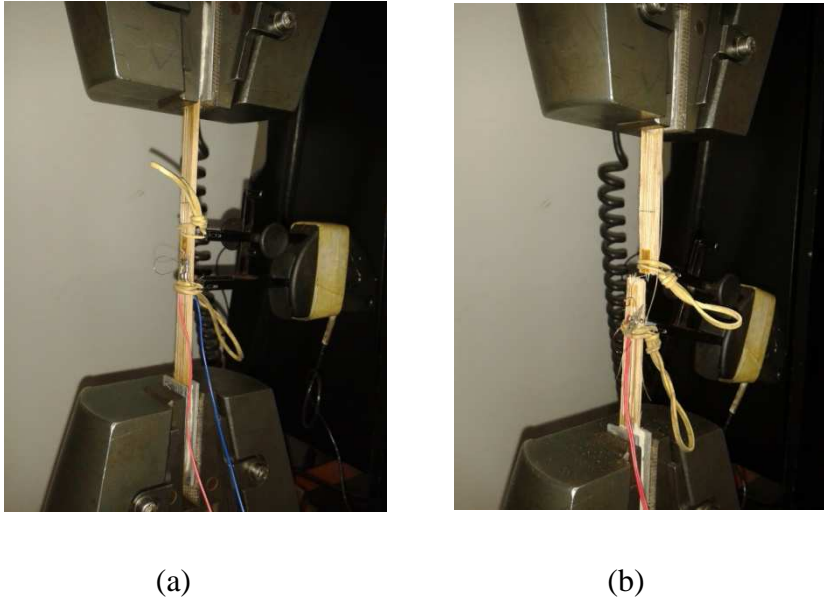
(a)   (b)

Figure 24 Tensile test for modulus of elasticity determination (a) detailed strain and clip gage location before rupture in straight shape (b) sample rupture.

Simple tensile test is shown on Figure 24, shows the location of strain-gage in the middle of the sample. During the tests read load values, vertical displacement and deformation were measured with the purpose of determining the stress-deformation curve for each specimen. Rusinque suggested installing corrugated aluminum plates with epoxy adhesives Sikadur in both sides of samples, to improve grip with clamps (Rusinque, 2009).

3.6.
Determination of shear modulus G

Shear tests were performed to calculate shear corrected modulus of elasticity, indicated by ASTM D198. It was determined on pieces of approximately 3 mm thick, 200 mm long and 20 mm width in order to establish shear resistance and its variation regarding the volume fraction along the thickness of the culm. The test procedure followed the steps proposed by Ghavami & Suoza, which modify the sample indicated by standard ISO N134, suggesting a simple test specimen as shown below in Figure 28 (Ghavami & Souza, 2000) Therefore, shear test is led to failure as a simple tensile test..

Test specimens were cut with a scalpel and processed on the planner thicknesser oriented to obtain constant thick. Thickness was measured with

pachymeter along the sample in six different points to define an accurate average thickness to calculate area under shear stresses.
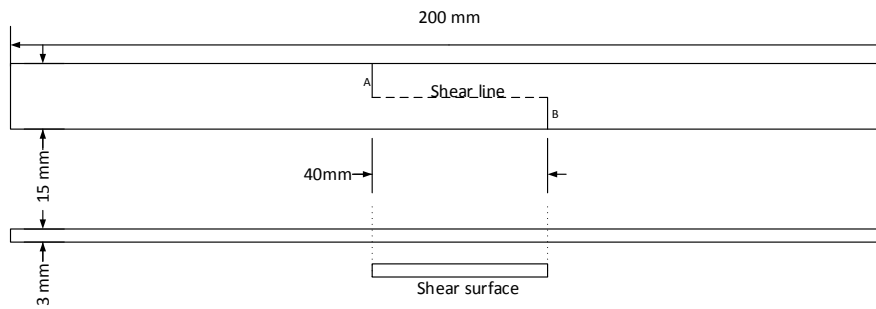

Figure 25 Samples dimensions and opposite transverse cuts A and B made on specimen to define shear zone approximately of 40mm long and 3mm width.
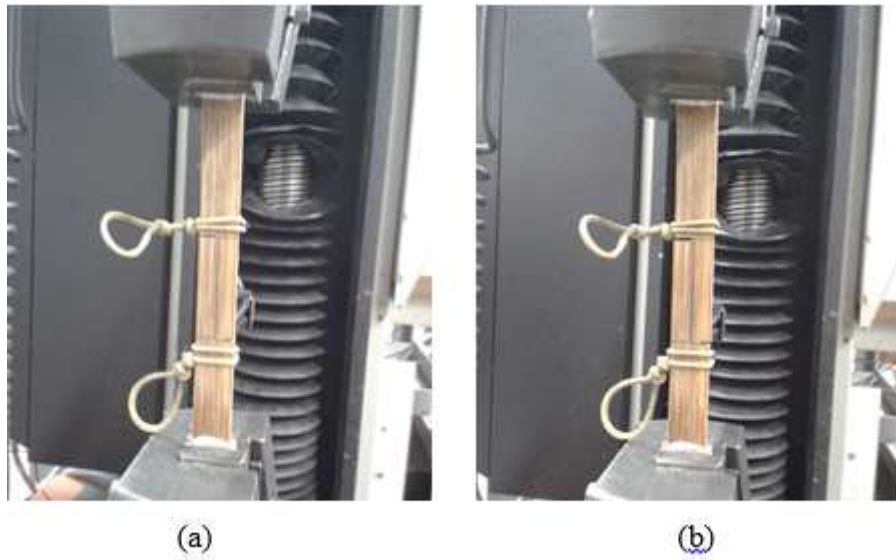

Figure 26 Tensile test for shear modulus determination (a) detailed clip gage location before rupture in straight shape and opposite transversal cuts (b) sample rupture along the shear line.

For this test, corrugated aluminum plates were attached at sample ends with epoxy adhesive Sikadur to improve grip on clamps.

3.7.
Beam specimens - Laminated Glued Bamboo (LGB)

There were used 18 beam specimens, 3 by each segment of analysis. They were assembled stacking randomly 10 to 14 layers of 550 mm approximately and

effective span of 500 mm. Layered bamboo arrangements glued with any kind of adhesives have been named with many terms, depending on adhesives and the types of wood arranging them. Layers obtained in previous steps were arranged in sets with similar conditions, before being stacked using mamona resin as adhesive laminator.
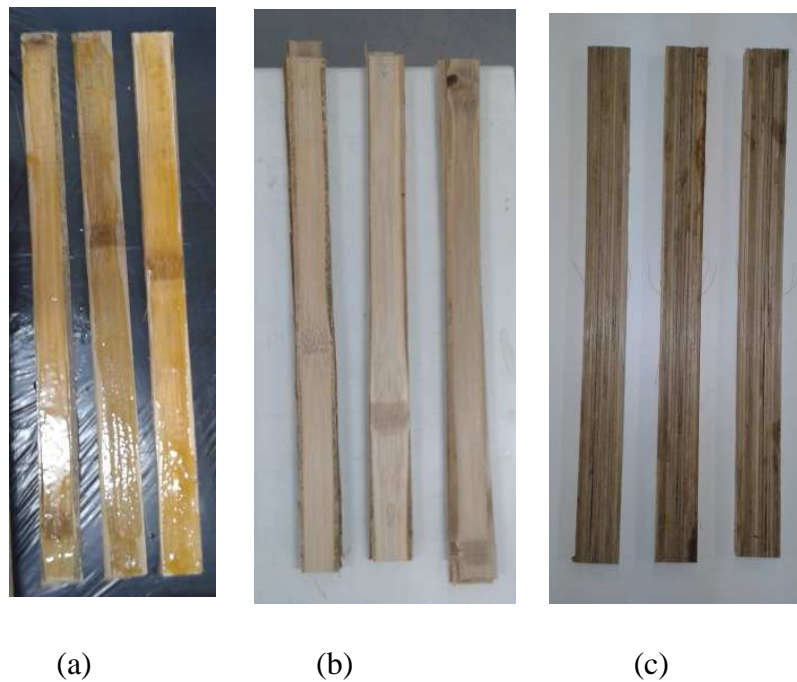

(a)   (b)   (c)

Figure 27 (a) 3mm thick bamboo mats with a coat of mamona's resin (b) strips stacked arranged for stick (c) final beams casted after adhesive drying and polishing edges.

Strips were divided into groups of the same analysis segments, as seen on Figure 23 (a). First layers were arranged to spread resin uniformly, then second layers were placed aligned to the first ones, and this process was until having a stack of 8 to 12 pieces, as can be seen on Figure Figure 23 (b). As the chemical reaction involved is exothermic, the drying process does not need heating. However, a pressure ranging between 15 to 20 kPa was applied during 24 hours after applying the adhesive. Blocks were polished in order to remove resin excesses and to shape longitudinal and cross-sections. Final beams ready to test are shown on Figure 23 (c).

3.8.
Determination of bending modulus of elasticity E_b

Beams were instrumented with upper and lower strain gages in the midpoint of the beam to measure strains. A LVDT sensor was located in the middle to read vertical displacement and loads applied by the load applicator. All sensors were connected to acquisition system, which recorded values of each one during the test period. The Figure 24 shows the test arrangement for a 4 points bend test, which is set up in this way to generate pure bending moment at the middle-span.
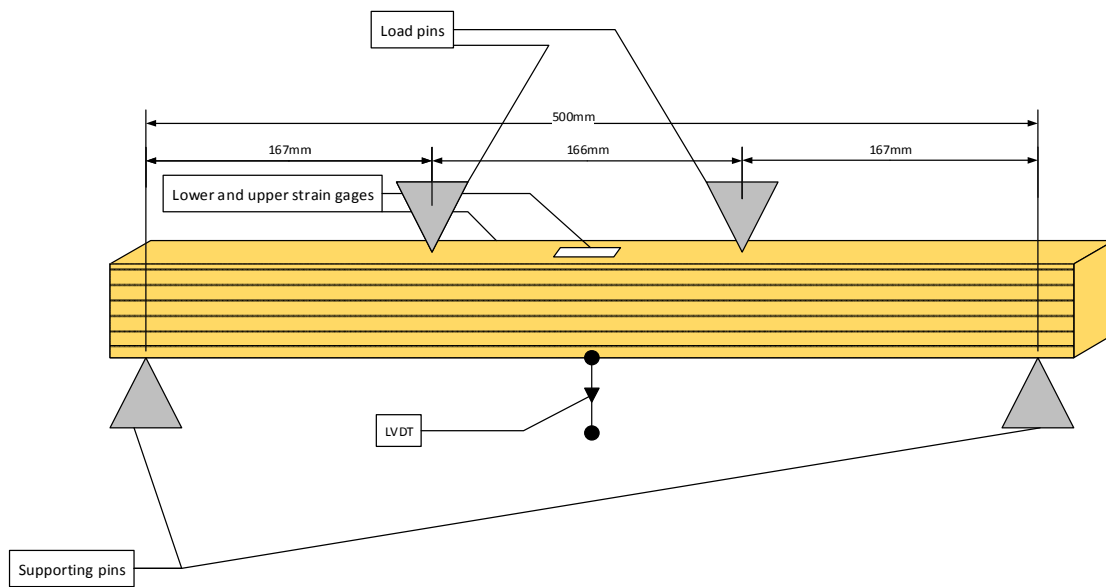

Figure 28 Set up of 4 point bending test.

Figure 29 Picture of a 4 points bending test arrangement showing the load and supporting conditions.

Tests were carried out until failure although strain gages and LVDT in almost all cases were exceeded. However, information recorded was enough to determine the modulus of elasticity and shear modulus for the LBL casted.

Different methodologies were used to establish bending modulus of elasticity. In the first place, modulus was established based on elastic curve equations. Then a methodology based on upper and lower strains on the beams by using strain gages. Finally, the ASTM provides equations to calculate directly the apparent modulus of elasticity and shear corrected modulus (ASTM D198, 2014) on static test for lumber in structural sizes.

3.9.
Mamona resin adhesive

The adhesive used was resin of Mamona. This is a mixture composed by Mamona oil, known as castor oil, extracted from mamona fruit (*Ricinus communis L.*) a popular bush mainly grown in tropical regions. It is used for obtaining a polymer known as Polyurethane, which presents favorable features in terms of strength and sustainability. Due to this, the resin of mamona emerged as an optimal adhesive to use on this research, both for its mechanical performance and biomaterial condition, as it was recognized in (Marques & Rossinoli Martins, 2009).

Mamona's resin is a bi-component material made of a mixture, in a proportion 2:1, of a Polyol (alcohol) and a Pre-polymer (Isocyanate) respectively, as can be seen on Figure 30 Image of mamona components Polyol and Pre-polymer and its respective proportions. Polymerization reaction occurs between an isocyanate and an alcohol; it liberates about 24 kcal/mol of Urethane, in an exothermic reaction. A dense solution was the result, which was applied uniformly in layers of approximately 1 to 0,7 mm over the entire surface stuck. The application had to be done immediately after the alcohol and the isocyanate were mixed, due to its fast drying properties.

The experimental density of the composite was calculated by measuring the weight of 142 ml of resin. The result was $\rho_{mamona} = 131\ gr/142\ cm^3 = 0,92\ gr/cm^3$ Therefore, its experimental specific gravity is 0,92, which conforms the specifications of the supplier

(Proquinor Produtos Quimicos do Nordeste Ltda) who states a range of 0,9 – 1,0 g/cm³.

Figure 30 Image of mamona components Polyol and Pre-polymer and its respective proportions.

In preliminary studies about polyurethanes derived from Mamona oil aimed to obtain mechanical and physical properties as a biomaterial developed for medicinal elements and prosthesis (Loureiro et al, 1998) obtained the following values.

	max load [N]	tensile rupture [KPa]	elongation [%]	Modulus of Elasticity [MPa]
Mamona's resin	8	335,75	105,27	0,36

Table 5 Mamona's resin properties.