Structural Performance Analysis of Cross-Laminated Timber-Bamboo (CLTB)

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Construction systems based on cross-laminated timber (CLT) have versatility in material development and are an interesting alternative for construction. This study evaluated the structural performance of cross-laminated timber-bamboo produced from wood (*Pinus* spp.) and bamboo (*Dendrocalamus giganteus*). Panels were produced by strips (wood and bamboo) assorted, under non-destructive structural grading, to support a better panel configuration. Small-length pine pieces were also included in the study, considering their low added-value and underutilization in sawmills from Telêmaco Borba, Brazil. Gluing tests of small specimens were performed to evaluate the bonding quality of three adhesives: melamine-urea-formaldehyde (MUF), isocyanate polymeric emulsion (IPE), and castor oil-based resin (COR). Shear stress strength parallel to grain between bamboo and wood showed the best performance for MUF resin. After preliminary gluing testing, eight cross-laminated panels were produced with MUF adhesive in a three-layered configuration, with transversal orientation: two external bamboo layers and a central layer of pine wood. Stiffness and rupture strength values were above those specified by the ANSI/APA PGR 320 (2012) standard. Elasticity and rupture moduli were 13,310 MPa and 65 MPa, respectively, showing good potential of this composite for structural uses.

Keywords: Cross-laminated timber-bamboo; Lignocellulosic material; Wood-bamboo construction; Structural panels

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INTRODUCTION

The sustainable profile of wood is a strong advantage in light of recent environmental policies that aim to reduce carbon dioxide emissions, considering that civil construction is responsible for a third of all CO_2 emissions released to the atmosphere (Pereira 2014). The construction sector has tried to minimize the production costs and environmental impact related to its activity, whereas environmental standards are more rigid, reinforcing such trends (Silva *et al*. 2012). Thus, sustainability is a normative requirement in several sectors, including in construction. Renewable materials have been developed as a means to minimize environmental impacts (Nogueira 2008). In addition, these new products should contribute to thermal comfort, better utilization of material, and reduction of energy consumption.

Several examples of industrial development are obtained through the adoption of alternative materials from planted areas such as bamboos and its composites (Moizes 2007). Bamboo utilization in construction industry is increasing and contributing to the reduction of deforestation of native forests, due to potentialities as its tropical-perennial character, fast growth, and shorter cycles than woody trees (Pereira and Beraldo 2008).

Bamboo has high productivity per hectare with an 8 culms/clump/year average, having a great capacity to protect soils (Pereira and Beraldo 2008). This plant presents good carbon sequestration level with a low maintenance cost from planting to harvesting.

Bamboos revitalize degraded areas and increase the reforestation system in tropical areas, considering that Brazilian climate is propitious for the development of their several varieties (Pereira and Beraldo 2008; Padovan 2010). There is no other forest species that can compete with bamboo's growth rate or its utilization by area.

Regarding bamboo structural properties and strength/density and stiffness/density ratios, its physical, chemical and mechanical characteristics indicate values that exceed wood and concrete, and in this aspect, it can be compared to steel (Janssen 2000). Thus, bamboo is renewable as wood, and it can be efficiently used in construction (Nogueira 2008). This evergreen grass plant presents visible strength, *i.e*., compression, tensile, and static bending, in comparison to other renewable and non-renewable sources, and it provides more satisfactory results in panels with resin insertion contributing to its adhesion (Moizes 2007; Barbosa *et al*. 2015).

Dendrocalamus giganteus bamboo species has several adjectives for its utilization in civil construction in Brazil, both for specific strength to mechanical stresses with an excellent mechanical behavior, and for its interesting characteristics.

One of the largest planted forest producers of pine lumber is located at Telêmaco Borba, Paraná State, Brazil. Part of the lumber is consumed by the domestic pulp and paper industry, but a portion of sawn wood is usually underutilized and processed by family-owned companies into low added-value raw materials from waste, which are center and slab cuts. Some cuttings are those pieces with less than 120 cm in length and are usually composed by high-quality timber from six-meter logs, which for lumber management and integrity reasons are also intended for firewood (Moura *et al*. 2012).

A good construction alternative is the modular system based on cross-laminated timber (CLT), which is defined by Gagnon and Pirvu (2011) as panel manufactured by timbered parts overlapped and glued in some transversal layers (90°) with structural adhesive, to produce a massive board with structural characteristics. Cross-laminated timber panel was first developed in Austria and Germany in the 1990s (Gagnon and Pirvu 2011). Such panel expands horizons in timber engineering due to its laminated structure, making them ideal for construction in view of its excellent mechanical properties.

CLT is a structural element that is utilized in structural flooring and roofing and in vertical freestanding sealing, as the panels have a high capacity to bear loads and allow two-dimensional load transfer (Rivera 2012). Its robust character and reduced assembly time compared to other systems are other good advantages. Structurally rigid and strong, this low weight raw material is mechanically similar to steel, concrete, or masonry, provides superior dimensional stability, and requires lighter foundation compared to conventional constructions. Cross-laminated timber is gaining popularity in applications in Europe (Gagnon and Pirvu 2011) with presence in Australia and North America (Evans 2013). Recently, new studies are being carried out with this panel based on mixed materials. Alencar (2015) developed a pine-eucalypt cross-laminated panel that showed the technical feasibility of this material.

This study considered the production of a structural lignocellulosic composite based on wood and bamboo through the principles of crossed lamination. Thus, cross-laminated timber-bamboo (CLTB) panels were prepared from wood (*Pinus* spp.) and bamboo (*Dendrocalamus giganteus*). The first research part, directed to adhesion quality, was carried out with three different resins, whose results from preliminary stage helped in the selection of best adhesive to be applied for panel bonding. Panels were produced with strips (wood and bamboo), which were assorted under non-destructive structural grading.

EXPERIMENTAL

Materials

Dendrocalamus giganteus bamboo and *Pinus* spp. were the woody raw materials used in the panel production. Bamboo culms were collected from the Botanical Garden of Londrina city, Paraná State, Brazil. In addition, pine pieces from the State University of Londrina (Londrina, Brazil) were obtained from dried boards, which were machined as sawn timber to this study.

Methods

Raw material preparation

To mitigate insect attacks after the collection of lignocellulosic materials, their treatment was based on an insecticide with Cypermethrin, propellant and solvent (Jimo Cupim, Jimo Quimica Industrial, Cachoeirinha, Brazil). These materials were stored in a closed shed from State University of Londrina (Londrina, Paraná State, Brazil) up to their moisture content stabilization level of 12%, according to NBR 11700 (1990) and ASTM D245 (2002) standard documents, and Moura *et al*. (2012) prescriptions. To the specimen production, according to Moura *et al*. (2012), free-defect *Pinus* spp. wood parts were selected without knots, cracks, warping, splintering, cupping, gum, twisting, *etc*.

In addition, the bamboo visual grading followed the standardized parameters from ISO 22156 (2004), NSR 10 (2010), and IS 6874 (2008). Pieces with insect attack and borers (*Dinoderus minutus*), degradation, and defects (blue spots, twisting, splintering, cracks, cupping, etc.) were discarded to panel utilization.

Three-year old mature culms were harvested from those with thick walls. In this case, ASTM D905 (2008) prescribes a minimum thickness of 16 mm for panels, but the maximum thickness was 9 mm, demanding an adaptation to this experiment. Thus, the selected culms were as straight as possible.

In order to choose the best adhesive for the production of cross-laminated timber-bamboo panels (CLTB), defect-free specimens were produced according to ASTM D905 (2008) and NBR 7190 (1997) for shear test in the glue line. ASTM D905 (2008) requires specimen dimensions of 50.8 × 50.8 × 19 mm. Due to thickness limitation of collected bamboo, the specimens had final dimensions of 50 × 50 × 9 mm.

To define specimen thickness and, consequently, width sizes of strips to compose cross-laminated timber-bamboo panel, preliminary perpendicular compression tests were conducted on bamboo strips. Several dimensions were tested up to a safe sizing, in which bamboo strips did not present any cracks during compression testing. To utilize the bamboo curvature, the tested dimensions were 45 to 70 mm (width) × 400 mm (length) × 9 mm (thickness). In the parts with 45 mm width, some cracks were observed. Under a 3 ton loading, the minimum dimension without cracks was 50 mm.

After sizing and cutting lumber and bamboo strips, the more regular and uniformed specimens were selected. Next, wood and bamboo parts were sanded to flatten their surface slightly. Defect-free parts were selected for specimen production. Lumber was converted into wooden strips through a conventional table saw. The same table saw with a special device to support irregular cylindrical culms was used to convert bamboo culms into regular strips. In the performance of glue line shear test, specimens were grouped in sets with 13 units and according to raw material (bamboo and bamboo or bamboo and pine), arrangement of raw material (external part bonded to external part, external bonded to internal, and internal bonded to internal), grain direction (parallel or perpendicular), and resin type (castor oil-based adhesive, melamine-urea-formaldehyde, and isocyanate polymeric emulsion). In total, 312 specimens were produced and equally divided into three groups of 104 specimens per each resin.

Castor oil-based two-component adhesive (Imperveg, Aguaí, Brazil), isocyanate polymeric emulsion and melamine-urea-formaldehyde with liquid emulsifier (Akzonobel, Guarulhos, Brazil) were considered, whose glue contents were 100 $g.m^{-2}$, 300 $g.m^{-2}$, and 450 $g.m^{-2}$, respectively. All specimens were glued at 20 °C temperature. Glued specimens were processed in a press at 1 MPa (Fig. 1) that supports 156 specimens at a time. These pressed materials were kept under pressure for 24 h before shear testing according to ASTM D 905 (2008), through a manual press, specially designed for this purpose.

Afterwards, all specimens were tested with the help of a manual press and the failure percentage was evaluated. For failure analysis, some principles of Alencar (2015) were considered: deep fractures with piece pullout, average fractures with low piece pullout, and shallow fractures with superficial grains on the rupture surface.

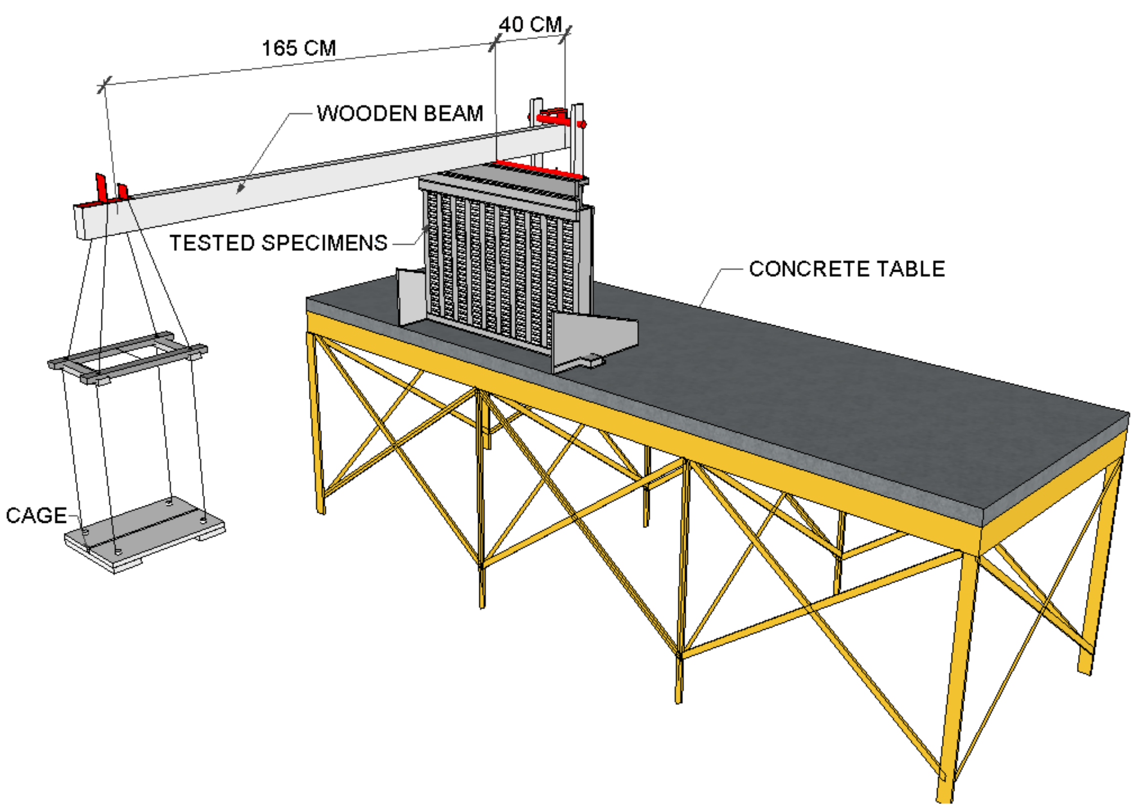


Fig. 1. Manual press to bond shear specimens

Cross-laminated timber-bamboo production under non-destructive grading of strips

Initially, the determination of moisture content was carried out according to NBR 7190 (1997), which requires the moisture content to be around 12% before panel production. Furthermore, this determination was performed before non-destructive testing of each bamboo and wood strip (or lamina) directed to panel production.

Subsequently, ultrasonic non-destructive testing was performed on every piece (timber and bamboo) to obtain the dynamic modulus of elasticity (MOEd). Bamboo strips were cut with 900 mm long (external longitudinal layer) and pine with 320 mm long (internal and transversal layers) according to ASTM D198 (2009), which prescribes that panel width should be greater than 305 mm and its length about thirty times the piece height. Each strip was sized with 40 mm of width, and since the next multiple after 300 mm is 320 mm, that was the finished dimension adopted. Panel was built with three layers of 9 mm each, totaling 27 mm of finished thickness. The length was 810 mm with 45 mm overs in each side to meet the static bending test requirement. The final panel dimensions were 900 × 320 × 27 mm.

For this non-destructive testing, two groups were created: pine wood with 40 mm (width), 320 mm (length) and 90 mm (thickness); and, bamboo with 40 × 900 × 9 mm.

Thus, the non-destructive structural grading of parts (wood and bamboo) followed the guidelines from ASTM D4761 (2013). After this grading by ultrasound method, such wood and bamboo strips were sorted, from lowest to highest value, under the obtained dynamic modulus of elasticity (MOEd), among which were arranged in a frame for assembly of groups. The main objective of this method was to create homogeneous groups, whose average and standard deviation values of the mechanical properties – in this case expressed by MOEd – were similar. Panels were designed with outer layers of bamboo strips and an inner layer of wood strips. The first group was composed of 184 wooden pieces and the second one of 128 bamboo pieces, the quantity is required to assemble 8 cross-laminated timber-bamboo panels.

Panel thickness was determined by the average size of bamboo pieces obtained in their machining, resulting in the average of 9 mm of thickness. Pine wood pieces were machined with this same size. Thereby, panel was composed of 3 mixed layers, in the bamboo-wood-bamboo configuration, with a total sizing of 27 mm (thickness) × 320 mm (width) × 900 mm (length). Considering the optimal performance in static bending, the central panel region requires greater mechanical strength than border parts, due to static bending prescriptions from NBR 7190 (1997), in which a point load is applied in the central part of the panel. Thus, MOEd values grow from the ends to the central part of panel, both for internal and external layers of CLTB panel.

Considering that non-destructive testing showed a large amplitude of MOEd values, and for a better comparison among eight studied panels, this methodology was developed to MOEd value distribution in each panel layer, reaching average values of MOEd and standard deviation in each part of each panel. External layers followed a standard, which was different than the internal layer, aiming the proximity of MOEd and standard deviation values in each panel parts (Fig. 2 and Table 1).

Each panel had 8 bamboo strips per external longitudinal layer (totaling 16), and 23 wood strips in the internal transversal layer. In this way (Table 1), the distribution of strips followed the suchlike averages of MOEd and standard deviation, which were also similar in the eight panels.

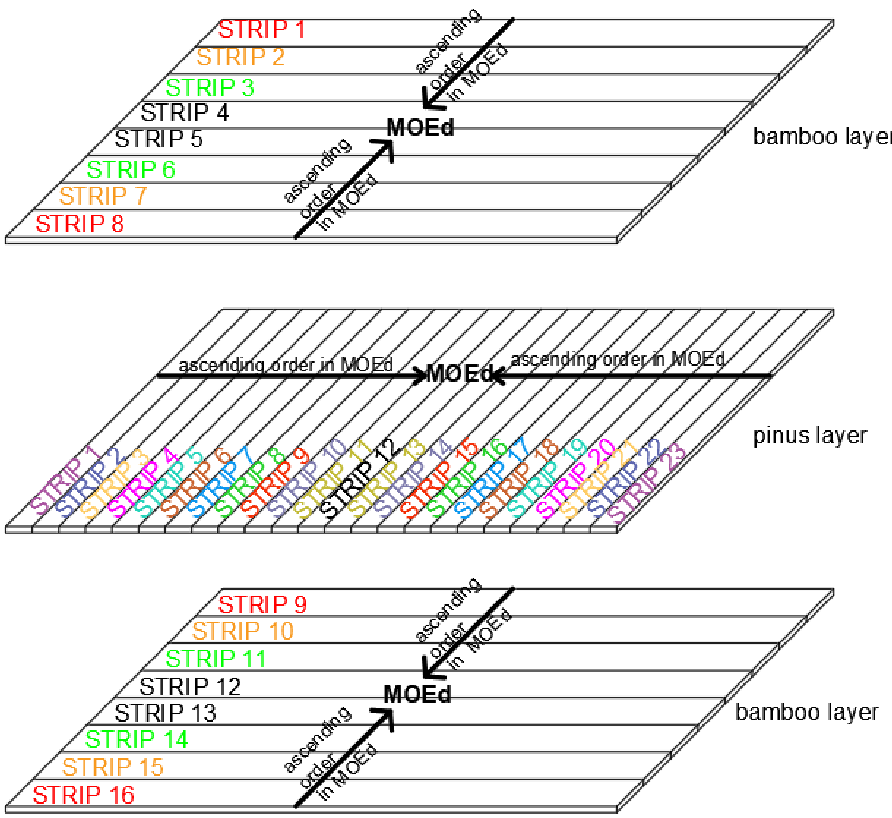


Fig. 2. Bamboo and timber strips (lamellae) lay-up

Table 1. Values of MOEd and Standard Deviation per layer

Dynamic Modulus of Elasticity – MOEd (MPa)								
Condition	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8
A	7760	7706	7693	7674	7568	7546	7475	7486
B	20463	20620	20710	20792	20722	20826	20776	20732
C	7471	7470	7442	7471	7502	7527	7518	7562
D	11898	11932	11948	11979	11931	11966	11923	11926
E	7419	7525	7588	7632	7614	7672	7666	7625
A: bamboo external layer; B: wood internal layer; C: bamboo external layer; D: average MOEd per panel; E: standard deviation								

After the strip organization, the lay-up procedures was performed in the company "Madeplak Comercio de Compensado de Madeiras" at Londrina, Brazil (Fig. 3a), which provided the plywood equipment and professional support in panel bonding and pressing.

According to manufacturer's prescriptions, melamine-urea-formaldehyde (MUF 1242/2542, Akzonobel, Guarulhos, Brazil) was mixed following the proportion of 100 parts of resin for 20 parts of liquid emulsifier. The prescribed pressure was 1.0 MPa with a 3 h pressing time and 400 g.m^{-2}, which are common for tough hardwoods as bamboos.

Panels were pressed according to manufacturer's prescription and ASTM D198 (2009). The pressing time was 18 h at 1 MPa, in a cold condition to avoid formaldehyde emissions. All panels were simultaneously pressed under the same weather conditions. The cross-laminated timber-bamboo panels were conditioned for a week in a dry and airy closed shed to complete resin curing (Fig. 3b). After this procedure, the panels were tested in static bending at the Structure Laboratory at the State University of Londrina.

Fig. 3. Panel production: (a) gluing of strips, and (b) finished cross-laminated timber-bamboo

Destructive testing of cross-laminated timber-bamboo panels based on assorted strips

A universal testing machine (EMIC, Instron Brazil, São José dos Pinhais, Brazil) of 30-ton load capacity was used to test all finished CLTB panels (Fig. 4a). This method was prescribed by NBR 7190 (1997) and ASTM D198 (2009). Load was applied by two wooden beams perpendicular to the panel surface as four-point static bending (Fig. 4b).

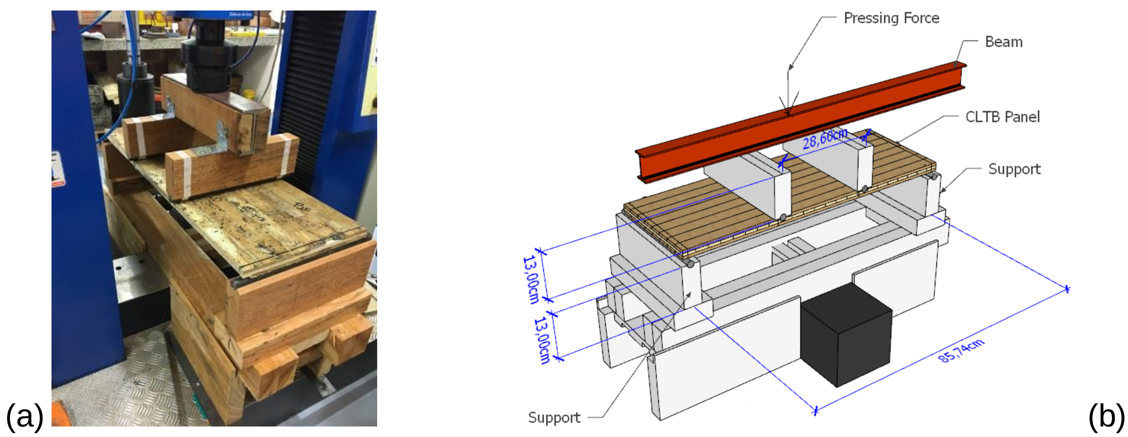


Fig. 4. Panel testing: (a) universal testing machine, and (b) support device schematization

From the ABNT NBR 7190 (1997) and ASTM D198 (2009) standard documents, three modulus were calculated, by Eqs. 1 to 3, for specimens obtained from finished CLTB panels (27 mm × 32 mm × 900 mm). The dynamic modulus of elasticity (MOEd) relates to ultrasonic wave propagation to analyze mechanical quality of any material (Eq. 1), according to its density (ρ in g.cm^{-3}) and longitudinal wave velocity (V in m/s). Static modulus of elasticity (MOEs) is the strain response under static loads (Eq. 2), according to 10% and 50% of estimated maximum load in specimen ($F_{M,10\%}$ and $F_{M,50\%}$ in N), displacement in span for 10 and 50% of maximum load ($V_{10\%}$ and $V_{50\%}$ in m), span (s in m), width (b in m), and height of transversal section of specimen (h in m). Modulus of rupture (MOR) is the capacity of maximum load in a deflected part (Eq. 3), according to maximum load (P_{max} in N), free span (L in m), width (b in m), and height (h in m).

$$\text{MOEd} = \rho \, . \, V \tag{1}$$

$$\text{MOEs} = (F_{M,50\%} - F_{M,10\%}) \, . \, s^3 \, / \, (V_{50\%} - V_{10\%}) \, . \, 4 \, . \, b \, . \, h^3 \tag{2}$$

$$\text{MOR} = (P_{max} \, . \, L) \, / \, (b \, . \, h^3) \tag{3}$$

RESULTS AND DISCUSSION

Adhesive Testing

The results for the glue line shear test concerning the three analyzed adhesives are shown in Fig. 5. Specimens based on *Dendrocalamus giganteus* bamboo and *Pinus* spp. timber using external part of bamboo with wood in parallel direction presented superior bonding values with melamine-urea-formaldehyde (MUF) compared with isocyanate polymeric emulsion (IPE) and castor oil-based resin (COR). The MUF adhesive was 36% superior to the average observed to IPE and 51% greater than COR, showing the best anchorage and resin absorption for MUF in the bamboo and wood interface. Despite better results in shear testing for parallel orientation, to obtain a cross-laminated material, the second best option was selected, which had a normal direction, *i.e.*, the bamboo surface (external part) was glued in direct contact with the central layer of wood.

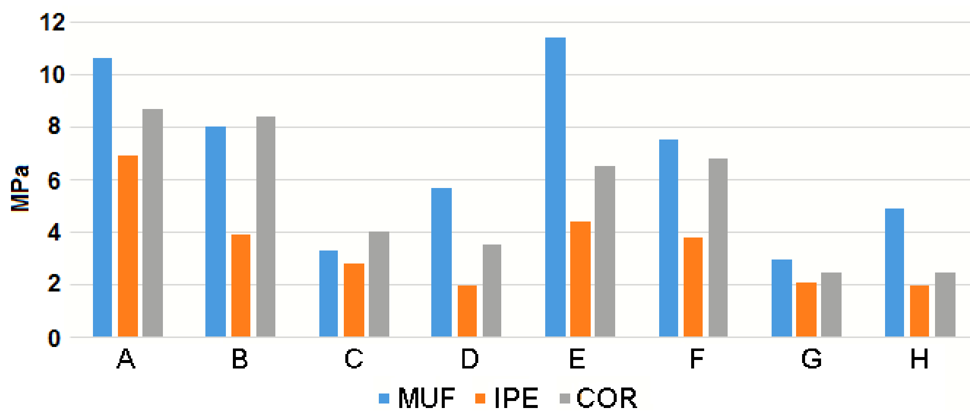


Fig. 5. MOR of gluing test with three adhesives per condition: (a) bamboo/bamboo in external layer (bark to bark) in parallel direction; (b) bamboo/bamboo in internal layer (bark to inside) in parallel direction; (c) bamboo/bamboo in external layer (bark to bark) in perpendicular direction; (d) bamboo/bamboo (inside to inside) in perpendicular direction; (e) bamboo bark to wood in parallel direction; (f) bamboo inside to wood in parallel direction; (g) bamboo bark to wood in perpendicular direction; and (h) bamboo inside to wood in perpendicular direction

Figure 6 shows the performance for MUF gluing compared to other resins, that is, IPE and COR. After the shear testing, each specimen was visually analyzed with respect to ruptures. The analysis was based on Lobão and Gomes (2006) to detect percentage of shallow, average, and deep fractures (Fig. 6). MUF resin reached the best performance, both in material anchorage (wood and bamboo) and strength, because interconnections among distinct materials were more stable. Thus, MUF was used for panel bonding.

Panel Production

Static bending testing was carried out in three loading/unloading cycles to obtain grain accommodation according to NBR 7190 (1997). Table 2 shows the modulus of elasticity (MOE) and rupture (MOR) of eight cross-laminated timber-bamboo panels, comparing grading values by ultrasound (MPa) and rupture (N). The static modulus of elasticity (MOEs) ranged from 10263 to 16999 MPa, resulting in an increase of 65%, whose average value was 13310 MPa. The coefficient of variation was 14.3%, which was considered low for sawn timber, but it was relatively high for industrialized forest products. Uncertainties related to manual production of panel samples could explain it.

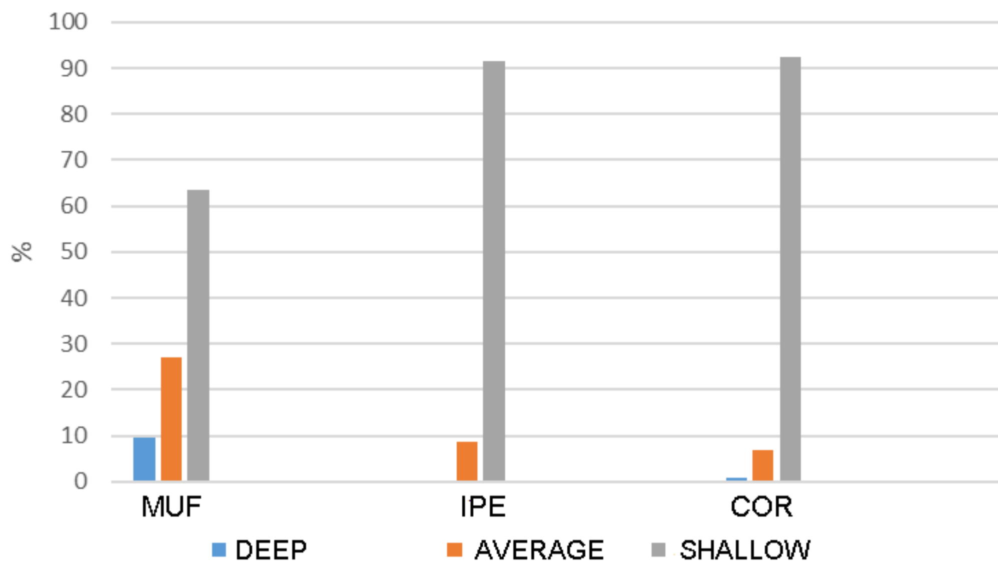
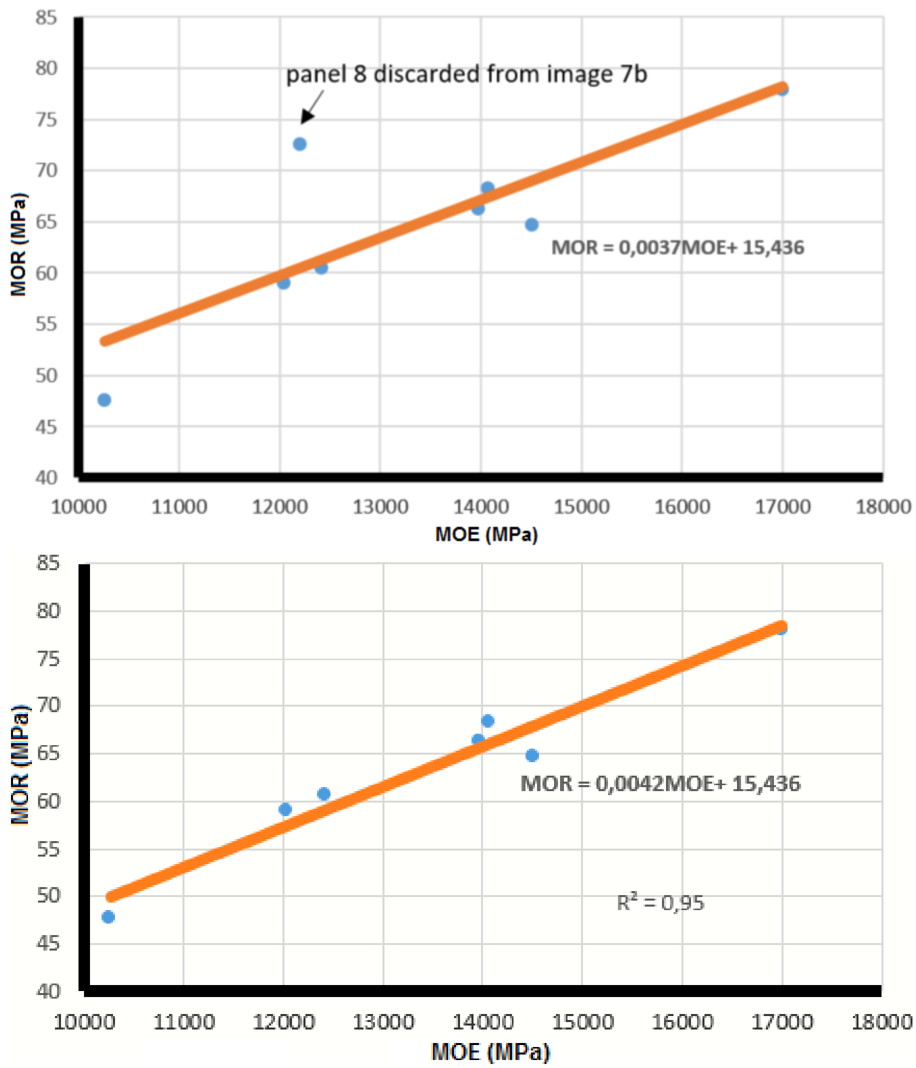


Fig. 6. Visual analysis of fracture percentage in shear testing

Table 2. Average Values of Mechanical Properties of Studied Panel

Panel	Rupture Loading (N)	MOEd (N)	MOEs (MPa)	MOR (MPa)
1	17654.8	11898.8	13979.3	66.2
2	16641.1	11932.4	12041.3	59.0
3	16483.7	11948.7	12420.0	60.5
4	14446.6	11979.6	10263.0	47.6
5	15873.6	11931.1	14507.5	64.7
6	17585.9	11966.8	14069.6	68.2
7	18412.5	11923.6	16994.8	77.9
8	19800.0	11926.9	12206.4	72.6
Average	17112.3	11938.0	13310.2	64.6
sd	1528.5	24.0	1902.0	8.6
cv (%)	8.93	0.20	14.29	13.35
sd: standard deviation; cv: coefficient of variance				

Dynamic modulus of elasticity (MOEd) estimated by ultrasound grading revealed a very short variation (0.2%). The average MOEd values (11938 MPa) and MOEs (13310 MPa) indicated a coherence between dynamic grading and the mechanical testing, being the MOEd slightly overestimated with relation to MOEs (Table 2). The results confirmed the importance of previous grading to obtain structural components with more predictable mechanical properties. They also suggest that further studies on non-destructive testing methods relating to solid sawn wood to panels based on solid wood should be developed. Regarding MOR, the variation observed was lower than those obtained for static modulus of elasticity. The relationship between MOEs and MOR was indicated to all panels (Fig. 7a) and without panel 8 (Fig. 7b), that is, the most distant point. Two moduli were highly correlated, 0.66 and 0.95 (Figs. 7a and 7b), which makes it possible to state that there is a good predictability of rupture through static bending non-destructive test. The mechanical behavior was similar to all tested CLTB panels (Fig. 8), showing initial elastic phase with posterior plastic deformation and eventual rupture. In terms of failure mode, no gap was observed between layers. All panels had ruptures by tensile stress to grain (Fig. 9a,b).



(a)

(b)

Fig. 7. MOEs x MOR relationship: (a) eight panels (b) seven panels (without panel number 8)

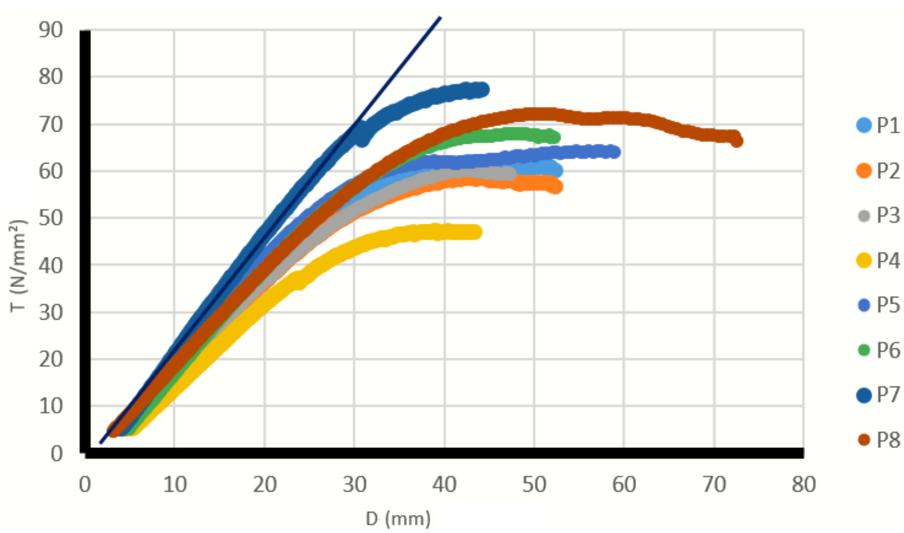


Fig. 8. Comparison of tension (T) x displacement (D) curves to the whole group of CLTB panels

(a) (b)

Fig. 9. Tested CLTB panels: (a) deflection, and (b) rupture in fibers (bottom part of panel).

The following observations were made on CLTB panels. The bamboo culms of *Dendrocalamus giganteus* from Londrina city, Brazil, had relatively thin walls, which allowed only the utilization of basal part of whole culm. Thus, the greatest thicknesses obtained after machining were about 9 mm, which is below the prescribed by the ASTM D905 (2008). This situation required an experimental adaptation in terms of method approach. Special attention was required for bamboo strip machining to ensure better panel performance avoiding the full elimination of bark – region with higher fiber concentration and density. However, the bamboo bark presents waxy layer, as suggested Pereira and Beraldo (2008). Hence, for the resin penetration, a slight machining was applied for the external bamboo parts to allow a better anchorage among the elements bamboo-resin-wood.

Due to this wall thickness limitation, panels were 27 mm thick, but future studies could focus on thicker bamboo strips. Due to timetable restrictions during the project, the bamboo culms were harvested in December and in February (the rainy local season), that is, a non-recommended period for bamboo harvesting according to Beraldo (2008). This situation was possibly responsible for the visible cracks in the material during drying, due to high moisture content, with impact on material yield. Many culms were discarded.

Table 3 shows the previous results about cross-laminated timber panels reported in the literature, which was mostly focused on low-graded timber.

The results of MOEs and MOR for cross-laminated timber-bamboo observed in this present study were greater than those prescribed by the ANSI/APA PRG 320 (2012) standard document. Comparing to literature, the cross-laminated timber-bamboo panels were structurally efficient (Fig. 9), being more resistant than the most of cited composites (Table 3). In general, CLTB mechanical properties were well above to those reported in the literature, except Steiger *et al.* (2011), especially for MOR. MOE/MOR correlation was high and allowed the maximum loading prediction by non-destructive static bending test with low loading. Despite the insertion of wood in CLTB panel, MOE values were close to natural bamboo ones. Elastic phase behavior was similar to all panels (Fig. 8).

There were difficulties in following ANSI/APA PRG 320 (2012) standard document and Gagnon and Pirvu (2011) handbook prescriptions, considering that these documents are only focused on wood application. Another difficulty was related to visual grading of bamboo strips, due to non-existence of specific standards, whereas ISO 22156 and NSR 10 standard documents were not sufficient to help in this proposal. Then, revisions to these documents could be suggested to include bamboo as highly potential material to compose lignocellulosic panels.

Table 3. Related Results from Literature on Cross-laminated Panels

Author	Wood Species	Density (g/cm^3)	MOE (MPa)	MOR(MPa)
ANSI/APA PRG 320 (2012)	Standard value for woods	–	8300	10
Concu *et al*. (2014)	*Pinus* spp.	0.49	7913	26
Sigrist and Lehmann (2014)	Non-classified *Pinus radiata*	–	6251	26
	Visually classified *Pinus radiata*	–	8066	35
	MGP12 ordering *Pinus radiata*	–	12567	53
Wang *et al*. (2014)	*Pinus radiata*	0.45	6350	45
	Douglas fir (without defect; with finger-joint)	0.47	8690	35
	Populus (without defect and with finger-joint)	0.41	5970	42
Flaig and Blad (2014)	*Picea abies* (without finger-joint)	0.45	12800	40
		0.40	10000	32
Steiger *et al*. (2011)	C24/C20 wood classes	0.42 (outer) 0.39 (inner)	12000 (outer) 14000 (inner)	–
Zhou and Chui (2014)	Spruce-pine-fir	0.52	10500	–
Alencar (2015)	Eucalyptus	0.51	10270	24
	Eucalypt-pine-eucalypt	0.51/0.53	10144	24
	Pine	0.53	8111	32
	Pine-eucalypt-pine	0.53/0.51	7240	39
* This study	Bamboo-pine-bamboo	–	13310	65

Lastly, despite bamboo underutilization in Brazil, its use either with or without pine wood is very promising. Bamboo utilization could play an important role in the composition of panels with high mechanical performance, being competitive with regard to non-renewable materials. Bamboo growth is very fast (five years to reach harvest age), consequently with shorter cycles than wood plantations, opening a wide range of future applications while helping to reduce native timber consumption and deforestation.

CONCLUSIONS

1. The methodology to set up timber and bamboo strips for panel production was based on ultrasound grading, which was used to lay up homogeneous panels with similar mechanical properties and low coefficient of variation.
2. The adhesive with best structural performance from previous analysis was melamine-urea-formaldehyde (MUF). MUF resin was selected for CLTB production, due to its best bonding strength indicated by high percentage of deep fractures on small shear specimens.
3. In the four-point static bending test, cross-laminated timber-bamboo panels revealed superior performance than required by the ANSI/APA PRG 320 (2012), allowing to envision a wide structural application of this composite.

4. The failure mode was quite uniform and common to all samples with parallel tensile stress rupture in the tensioned bamboo layer. No gaps were observed between layers, providing a good anchorage in resin bonding between raw materials as well as a good pressing obtained in the panel production. Delamination study and shear block test were not performed due to material limitations and, however, their importance for a complete panel characterization is recognized and required for future studies.

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