Parallel Compression to Grain and Stiffness of Cross Laminated Timber Panels with Bamboo Reinforcement

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Four cross-laminated timber (CLT) panels with and without bamboo reinforcement were prepared and evaluated. The goal was to obtain better possibilities of using this lignocellulosic panel, based on their mechanical properties. Stiffness and strength of compression parallel to grain tests were conducted to simulate the utilization of this material as freestanding walls. Panels were produced based on *Pinus elliottii* wood species and glued with castor oil-based polyurethane resin. Half of these structural panels were also reinforced with strips of *Dendrocalamus asper* bamboo species, which were added on the outer layers. There was a significant increase in the parallel compression-to-grain in the configuration of the cross-laminated timber reinforced with bamboo in the longitudinal direction, which concentrates superior resistance.

Keywords: Pinus elliottii; Dendrocalamus asper; Lignocellulosic composite; Freestanding wall

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INTRODUCTION

Currently, industrial sectors have focused their research and products in favor of lower environmental impact manufacturing. This objective renders in the development of new products with a sustainable character, because they are produced with renewable materials. An important example consists in the woody lignocellulosic materials such as wood and bamboo. According to Wherry and Buehlmann (2014), residential construction plays an important role in the forest products' value chain in the U.S. The popularity of lignocellulosic material utilization in construction is growing rapidly. To fully exploit the potential of these raw materials in two- and three-dimensional structures, a consistent knowledge of their mechanical behavior is required. From this, the mechanical tests are the only way to obtain this example of data (de Borst *et al*. 2013; Mvondo *et al*. 2017).

Similar to timber, the optimization of bamboo use also requires comprehensive understanding of its physical and mechanical properties. Thus, bamboo utilization as building material also demands the knowledge of its properties (Ribeiro *et al*. 2017).

Bamboo is a gramineous biomass, which is typical of tropical, subtropical, and temperate regions, and has a singular aspect of rapid and constant growth.

Bamboo protects the soil, absorbs carbon dioxide from the atmosphere, and can be used with wood in reforested areas, contributing to mitigate the native tree harvesting. This material is an important source of raw material for construction and furniture (Janssen 2000; Pereira and Beraldo 2007; Zaia *et al.* 2015; De Almeida *et al.* 2017). Bamboo acts as an option for laminate production, due to low cost, high efficiency, and environmental advantages, presenting a wide market potential to substitute other current raw materials (Huang *et al.* 2015), such as steel, lumber, concrete, *etc*. The utilization of bamboo laminae as reinforcement improved the panel performance (Zaia *et al*. 2015),

Cross-laminated timber (CLT) is a structural panel produced with 90° overlapping wooden layers that can contain 3 to 7 layers of wood (or more, increasing the panel density and cost), always in odd numbers, providing the dimensional stability and allowing the prefabrication of slab and wall panels. This composition offers high stiffness and strength in all directions. The main raw materials used in the production of this panel are from the *Pinus* genus and phenol-resorcinol-formaldehyde as adhesive (Gagnon and Pirvu 2011; Karacabeyli and Douglas 2013; Buck *et al*. 2016).

CLT is used as prefabricated elements for flooring, roofing, and walls, as well as is becoming increasingly common in structures (Fredriksson *et al*. 2015), which has been gaining popularity in Austria, Germany, and North America (Karacabeyli and Douglas 2013). This panel revealed a construction system that originated in the 1990s in Swiss towns of Lausanne and Zurich, but only in 1996 an Austrian industrial-academical joint resulted in this new development (Schickhofer *et al*. 2009; Espinoza *et al*. 2016).

According to Huang *et al*. (2015), the classic theory of multiple laminated boards stated that the composite material with excellent physical and mechanical properties must confer – from the junction of different layers – the increase of mechanical properties.

This study proposes to evaluate the mechanical properties of compression parallel and perpendicular to grain in the strength and stiffness of structural panels of wood-based CLT with and without bamboo reinforcement. This tactic of reinforcement was studied to obtain better possibilities of bamboo utilization, based on its mechanical characteristics, to offer a new strong and resistant raw material for the construction sector.

EXPERIMENTAL

Materials

The cross-laminated timber (CLT) panels had constituents of sustainable origin, and the panels tested in this paper were produced using *Pinus elliottii* wood species and castor oil-based polyurethane resin (Plural Química, Cerquilho (SP), Brazil). Then, the CLT panels reinforced with bamboo had similar layer-formation, with only an external addition of bamboo strips of *Dendrocalamus asper* species (Betania Farm, Itapeva (SP), Brazil), to stiffen the standard CLT panels.

Methods

Bamboo strip preparation

To obtain bamboo strips, the method from Beraldo and Rivero (2003) was used, with the adequacy of machinery primarily used for wood machining from São Paulo State University (UNESP), Campus of Itapeva, Brazil. The strips were oven-dried to 100 °C ± 3 °C for 72 h. These dried strips were machined to 600 mm × 10 mm × 20 mm sections.

Wooden lamella preparation

Lamellas with 150 mm × 20 mm × 600 mm of *P. elliottii* wood species were used to produce standard CLT panels. This pine wood was obtained from a donation (Cagema Sawmill, Itapeva (SP), Brazil). A visual classification was realized to obtain 48 lamellas with a lower incidence of anatomical defects.

Panel production

Four three-layer panels of CLT were produced with *P. elliottii* wood, using four lamellas by layer, with 90° direction from the wood grain, and were glued with castor oil-based polyurethane adhesive, formed by two-component based on polyol and prepolymer (1:1). Half of these panels were produced to be tested in a standard condition, and the other two were reinforced with bamboo strips in their main external surfaces, which were glued with the same adhesive. The panel production was supported by a hydraulic hot press (PHH, Araraquara (SP), Brazil) at 80 bar and 160 °C. This heat pressing accelerated the resin curing during 4 h. After this pressing stage, all of the panels were square-shaped (600 mm × 60 mm × 600 mm for standard CLT and 600 mm × 80 mm × 600 mm for bamboo-reinforced CLT panels).

Methodology for parallel compression to grain test

Tests of parallel compression to grain were conducted according to the Brazilian standard document ABNT NBR 7190 (1997). These tests were selected because it was a preliminary study. The tests were performed in Material Properties Laboratory at São Paulo State University, campus of Itapeva (Itapeva (SP), Brazil). For the performance of tests, a universal testing machine at 30 ton, provided with speed control at 10 MPa/min of loading rate (EMIC, Instron Brasil, São José dos Pinhais (PR), Brasil).

Specimen extraction

The specimen dimensions were based on the Brazilian standard document ABNT NBR 7190 (1997), which prescribes the characterization of parallel and perpendicular compression to grain that the width is equal to thickness, and the length equal to three times this thickness. This standard ABNT NBR 7190 (1997) also prescribes that 12 randomly extracted specimens need to be tested.

Standard panels (without bamboo reinforcement) were divided into two samples with 12 specimens by panel, where these specimens of the first sample (Fig. 1a) had two lamellas in the longitudinal direction, *i.e.*, predominance of compression parallel to grain in two lamellas and perpendicular to grain in a lamella. The specimens from the second sample (Fig. 1b) presented a lamella in the longitudinal direction, and two perpendicular lamellas, *i.e.*, predominance of perpendicular compression to grain.

Bamboo-reinforced panels were also divided into two samples with 12 specimens, where the specimens of the third sample (Fig. 1c) presented two bamboo lamellas and a wood lamella in the longitudinal direction, *i.e.*, predominance of compression parallel to grain in three lamellas and perpendicular to grain in two lamellas. Then, specimens from the fourth sample (Fig. 1d) presented two wood lamellas in the longitudinal direction, and two bamboo and two wooden lamellas in the transversal direction, *i.e.*, predominance of perpendicular compression to grain.

Statistical analysis

From the data obtained in the tests, a statistical analysis was performed with software R (R Foundation for Statistical Computing, Version 3.3.3, Vienna, Austria) to check the normality of data with Shapiro-Wilk test and the variance homogeneity with the application of Bartlett test. For strength, variance analysis was realized through an F-test, and the Tukey test was used to compare the treatment means; both tests were carried out at 5% of probability. To evince the difference among the treatments, letters (a, b, c, …) were adopted to compare the means through the Tukey test, where the means with the same letters in the table do not statistically differ from each other at a 5% significance level. For stiffness, the Kruskal-Wallis test was applied to compare the means, due to the heterogeneity of variances at 5% of probability.

(a) (b) (c) (d)

Fig. 1. Specimens from: (a) sample 1, (b) sample 2, (c) sample 3, and (d) sample 4

RESULTS AND DISCUSSION

A mean and a standard deviation (σ) were obtained for each sample from tested panels. A comparison amongst these results and the values prescribed by the standards from American National Standards Institute (ANSI/APA PRG 320 2012) and European Technical Approval (ETA 06/0138 2012) were realized, considering the predominance of the compression type of each studied sample (Table 1). Thereby, the values from sample 2 and sample 4 (Table 1) – with a predominance of perpendicular compression to grain – were higher than the minimum value prescribed by ETA 06/0138 (2012). Regarding sample 3, which presented a predominance of parallel compression to grain and bamboo reinforcement, it can be noted that the standard values from ANSI/APA PRG 320 (2012) and ETA 06/0138 (2012) were within the confidence interval obtained in this study.

Table 1. Data Comparison of Strength with Standard Documents

f_c	Sample	Mean ± σ	ANSI/APA 320 (2012)	ETA 06/0138 (2012)	Confidence Interval
f_{c0} (MPa)	2	10.31 ± 1.30	–	2.7	9.48 a 11.14
	4	16.64 ± 1.39			15.75 a 17.53
f_{c90} (MPa)	1	17.24 ± 1.65	19	24	16.03 a 18.82
	3	23.13 ± 2.08			21.80 a 24.45

* f_{c0}: compression parallel to grain * f_{c90}: compression perpendicular to grain

It is important to highlight that, according to Buck *et al.* (2015), in parallel direction to grain the major concentration has higher loads. However, this was not possible for sample 1, which also had predominance of parallel compression to grain, evincing the efficiency of bamboo reinforcement.

In the study performed by Pereira (2014), for the CLT production of five lamellas of *P. elliottii*, the author obtained a mean value of parallel compression to grain of 23.6 MPa. This value was also within the confidence interval obtained in this study by sample 3, and this fact emphasized the efficiency of reinforcement to substitute the external layers in pine wood.

Comparing the CLT reinforced with bamboo from this study with the CLT panel produced by Pereira and Beraldo (2007) that presented a mean strength of 65.5 MPa, it can be verified that the panel in this research reached a lower resistance; whereas the specimens were submitted to the universal testing machine, which has a high sensibility to the first collapse of the material, without its rupture (Fig. 2). Thus, due to its low resistance characteristic, the panel testing of *P. elliottii* wood can be impaired, where only the bamboo properties on the panel would provide higher resistances to the CLT panel.

(a) (b) (c) (d)

Fig. 2. Specimen rupture models from: (a) sample 1, (b) sample 2, (c) sample 3, and (d) sample 4

Statistical analysis

The normality of strength data was first determined by the Shapiro-Wilk test (Table 2). Through the Bartlett test, the homogeneity of variances revealed a P-value of 0.1723.

Table 2. Normality of Sample Data of Strength

Sample	Shapiro-Wilk Testing	Normality
1	W = 0.96, P-value = 0.83	Normal
2	W = 0.96, P-value = 0.74	Normal
3	W = 0.88, P-value = 0.08	Normal
4	W = 0.93, P-value = 0.34	Normal

The analysis of variance showed that there was a significant difference of strength in parallel compression to grain in the four samples (F-value = 99.22; P-value < 0.05). Through the statistical analysis, it can be observed that the mechanical resistance in the compression of specimens from sample 3 was higher than those panels without reinforcement and the reinforced CLT panel with predominance of perpendicular compression to grain. This situation demonstrated that the increasing in the resistance can be noted with the bamboo mechanical stress in parallel compression to grain.

Huang *et al*. (2015) indicated that when bamboo was tested in the grain direction, this material presented high resistance, and when it was used as external reinforcement, it offered high quality with strong and flexible levels.

It was observed that the specimens with predominance of parallel compression to grain were statistically similar. Moreover, it can be concluded that an appropriate form of the use of this material should be planned, whereas the predominance of the directions of the mechanical stresses determine the panel efficiency, through the right configuration of use. Figure 3a illustrates the medians of the resistances of sample 1 to sample 4.

Next, the normality of data of the stiffness through the Shapiro-Wilk test was proved (Table 3). Through the Bartlett test, the homogeneity of variances was verified, with P-value = $9.736.\ 10^{-05}$. The non-parametric test of Kruskal-Wallis was realized with a significance level of 5%, checking the existence of statistical differences among the samples. Then, the analysis showed that there were significant difference for stiffness in the four samples (P-value = $3.049 \times 10^{-07} < 5\%$).

Table 3. Normality of the Sample Data of Stiffness

Samples	Shapiro-Wilk	Normality
1	W = 0.92, p-value = 0.26	Normal
2	W = 0.93, p-value = 0.42	Normal
3	W = 0.92, p-value = 0.27	Normal
4	W = 0.92, p-value = 0.33	Normal

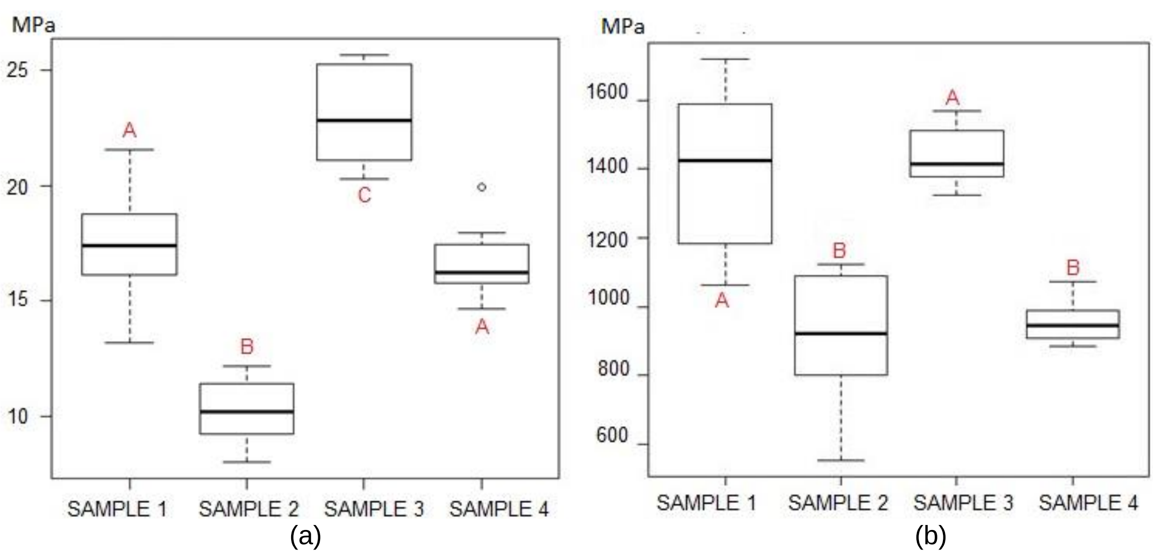

Fig. 3. Comparison graph of means (in MPa): (a) strength and (b) stiffness

Through the mean comparison analysis, it was observed that, for perpendicular predominance samples, the obtained means did not differ from each other in stiffness. The same situation occurred for the samples with predominance in parallel compression, which indicated that the utilization of reinforcement did not influence the pine panel stiffness. Figure 3b represents the graph of medians of stiffness of sample 1 to sample 4.

CONCLUSIONS

1. The main objective of this study was achieved with the characterization of parallel compression to grain of CLT panels and the increase in this property with the bamboo reinforcement in the external layers. This effect aimed to contribute to a better use of this panel in situations that require this kind of mechanical stress, *e.g.*, construction.
2. The CLT panel was produced with the minimum level of overlapping lamellas of wood, *i.e.* three layers directed in 90° among them according to the wood grain, which reached similar values from analyzed standard documents.
3. There was a significant increase in the strength in the parallel compression to grain when the panel presented the bamboo reinforcement in the longitudinal direction, which had greater resistance suitable for freestanding walls.

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