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Number of laminae on the mechanical behavior of glued laminated timber (glulam) of *Toona ciliata* produced with vegetable polyurethane adhesive

Número de lâminas no comportamento mecânico de madeira laminada colada (MLC) de *Toona ciliata* produzidas com adesivo poliuretano vegetal

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ABSTRACT

The glued laminated timber (glulam) is a composite material obtained from the bonding of wood laminae arranged with parallel fibers put together. The purpose of this paper was to evaluate the influence of the number of laminae on the mechanical behavior of glulam of *Toona ciliata* produced with vegetable-based polyurethane adhesive. The glulam beams were produced with lamellae in the dimensions of 6.0 x 1.5 x 120.0 cm, with 3 beams being made per treatment, which were structurally composed by 5, 7 and 9 laminae. The polyurethane adhesive based on castor oil was used, applying a grammage of 350 g m^{-2}. For the technological characterization of the wood the moisture in the dry base, bulk density, chemical characterization, compressive strength parallel to the fibers, shear and modulus of elasticity (MOE) and rupture (MOR) in the static bending test. While the properties of modulus of elasticity (MOE), modulus of rupture (MOR), shear strength, delamination and visualization of the glue line through photomicrographs of the laminated wood samples were determined for glulam beams. The results showed that the beams with 5 laminae presented values similar to solid wood. The increase in the number of laminae provided lower values for stiffness and strength of the beams. The photomicrographs showed the quality of the bonding and the satisfactory values for shear strength and delamination, indicating the viability of the species under study for situations with high moisture content.

Index terms: Composite; wood; bond resistance; flexural strength.

RESUMO

A madeira laminada colada (MLC) é um material compósito obtido a partir da colagem de lâminas de madeira dispostas com as fibras paralelas entre si. O objetivo deste trabalho foi avaliar a influência do número de lâminas no comportamento mecânico de MLC de *Toona ciliata* produzidas com adesivo poliuretano de base vegetal. As vigas de MLC foram produzidas com lamelas nas dimensões de 6,0 x 1,5 x 120,0 cm, sendo confeccionadas 3 vigas por tratamento, os quais foram estruturalmente compostos por 5, 7 e 9 lâminas. Foi utilizado o adesivo poliuretano à base de óleo de mamona, sendo aplicada gramatura de 350 g m^{-2}. Para a caracterização tecnológica da madeira determinou-se a umidade na base seca, densidade aparente, caracterização química, resistência a compressão paralela às fibras, cisalhamento e os módulos de elasticidade (MOE) e ruptura (MOR) no ensaio de flexão estática. Enquanto para as vigas de MLC foram determinadas as propriedades de módulo de elasticidade (MOE), módulo de ruptura (MOR), resistência ao cisalhamento, delaminação e visualização da linha de cola por meio de fotomicrografias das amostras de madeira laminada colada. Os resultados mostraram que as vigas com 5 lâminas apresentaram valores semelhantes a madeira sólida. O aumento do número de lâminas, proporcionou menores valores para rigidez e resistência das vigas. As fotomicrografias comprovaram a qualidade da colagem e os valores satisfatórios para resistência ao cisalhamento e à delaminação, indicando a viabilidade da espécie em estudo para situações com alto teor de umidade.

Termos para indexação: Compósito; madeira; resistência de ligação; resistência à flexão.

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INTRODUCTION

Glued laminated timber (Glulam) is an engineering product consisting of laminae juxtaposed in a straight or curved manner, with the grain of all parts essentially parallel to the longitudinal axis of the element (Stark; Cai; Carll, 2010). The use of glulam has been growing abroad, with several structural and architectural applications, because it is a product where the limitation is solely due to the size of the machinery used, its use in Brazil is restricted due to the high cost of production (Zangiácomo; Lahr, 2007; Cunha; Matos, 2010).

Among the quality parameters of the production, the number of laminae can result in beams of greater strength when compared to an individual lamina. This increase in the material performance is fundamental for the industry, since usually the quality control measures to determine the lamination quality are dependent on this magnitude (Falk; Colling, 1995).

It is important to know the behavior of the wood beams in the conditions that will be used, and for this, tests based on the modulus of elasticity (MOE) and modulus of rupture (MOR) are required (Issa; Kmeid, 2005). For Vital, Maciel and Della Lucia (2006), the strength, stability and service life of a bonded structure depend to greater strength, rigidity and durability of bonds.

Several papers aim to associate the improvement in the production processes and composition of glulam (Calil Neto et al., 2014; Christoforo et al., 2014; Lahr et al., 2015; Icimoto et al., 2016), where the adhesives most used in industrial scale for glulam production and wood based panels have formaldehyde in their constitution, as resorcinol-formaldehyde, urea-formaldehyde; phenol-formaldehyde; phenol-resorcinol-formaldehyde; melamine-formaldehyde; melanine-urea-formaldehyde and tannin-formaldehyde (Guimarães et al., 2014; Scatolino et al., 2017; Martins et al., 2018; Martins et al., 2019).

However, a restriction in these adhesive is the formaldehyde gas released in the environment, which is a colorless gas with a strong offensive odor that causes significant environmental issues, as increased pollution (Que et al., 2007; Santos et al., 2014). In addition, formaldehyde could lead to skin and eye irritation (Mohsin et al., 2014), headaches (Mohsin et al., 2013), as well as being considered carcinogenic to humans (Mohsin et al., 2016).

An alternative would be the use of polyurethane, a polymeric adhesive that effectively wets the surface of most substrates and develops excellent adhesion to many materials including textile fibers, metals, plastics, wood, ceramics, rubber and leather (Kong; Liu; Curtis, 2011). Polyurethane vegetable adhesive can be also based on castor oil, which is classified as impermeable and not aggressive to the environment (Dias; Lahr, 2004).

The use of this adhesive was used by Azambuja and Dias (2006) and Miotto and Dias (2011) in glulam, where efficacy was evidenced in relation to the structural performance view, besides the viability of the adhesive application in glulam. From this, the objective of this paper was to evaluate the effect of the number of laminae on the physical and mechanical behavior of glulam of *Toona ciliata* (Australian cedar) produced from polyurethane adhesive based on castor oil.

MATERIAL AND METHODS

Collection and characterization of the properties of *Toona ciliata* wood

In order to carry out this study, three seven-year *Toona ciliata* tree species were cut in a plantation located in Campo Belo, Minas Gerais state, Brazil. These trees showed average DBH (stem diameter at 1.30 m height from the ground) of 25 cm. From each tree, logs were removed from the base with a length of 1.50 m and discs at 0, 25, 50, 75 and 100% of the commercial height. The logs were unfolded and turned into planks. The discs and planks were conditioned in laboratory using an air-conditioning chamber at a temperature of 22 ± 2 °C and 65 ± 5% relative humidity. After moisture stabilization, the discs were divided into four wedges, where two opposing wedges were used to obtain the physical properties and the other two opposite wedges were used for chemical analysis.

In order to evaluate the physical and mechanical properties of the wood, tests were carried out according to the Brazilian standard NBR 7190 (ABNT, 1997). For the determination of the physical and mechanical properties of the wood, twelve specimens were used, the dimensions of which are shown in Table 1.

After the milling in a willey mill, the sawdust was separated with overlapping sieves of 40 (0.420 mm) and 60 mesh (0.250 mm), being considered for the analysis only the fraction retained in the 60 mesh sieve. The following standards were used for the analysis NBR 14853 (ABNT, 2010) for total extractives; NBR 7989 (ABNT, 2010) for insoluble lignin; NBR 13999 (ABNT, 2017) for ashes. In addition, the holocellulose content was obtained by subtracting the sum of the other components considering a total of 100%.

Table 1: Specimens for physical and mechanical tests of *Toona ciliata*, dimensions standardized according to NBR 7190 (ABNT, 1997).

Property	Dimensions (mm)
MOE and MOR in static bending	50 x 50 x 1150
Compression strength parallel to grain	50 x 50 x 150
Shear strength parallel to the grain	50 x 50 x 64
Moisture content	20 x 30 x 50
Bulk density	

Where: MOE - Modulus of Elasticity; MOR - Modulus of rupture.

Production of the glued laminated timber beams

From those planks, 80 pieces were obtained with dimensions of 20 x 70 x 1200 mm which were dried until reaching the moisture of 12%. Subsequently, the faces were planed until reaching the final dimensions of 15 x 60 x 1200 mm. The pieces were classified by the impulse excitation technique with the *Sonelastic* machine (Sonelastic, ATCP, Brazil). For production of the glulam, the pieces were classified according to the MOE value, being those pieces higher than 1000 MPa for the beam faces, and other pieces lower than 1000 MPa placed in the beam core. Three glued laminated timber beams were produced for each treatment, totalizing 9 beams (Table 2). Each beam was glued with polyurethane (from castor oil), bi-component, in proportion 1 to 1.5 from the component A to the component B, respectively (Table 3).

Table 2: Experimental design.

Treatment	Number of layers
T1	5
T2	7
T3	9

Table 3: Parameters for the production of the glued laminated timber beams.

Parameter	Polyurethane
Bulk viscosity (25 °C)	430.63 cP
Solid Content	79.43%
pH	7.0
Grammage	350 g m^{-2}
Pressing / time	1 MPa / 24 h

Properties of the glued laminated timber beams

After pressing, the beams were conditioned in an environment with temperature of 22 ± 2 °C and relative humidity 65 ± 5% until reaching the moisture of 12%. Shear strength and compression parallel to grain tests were performed on the glue line for evaluation of its quality. In total, 12 samples were obtained from the glued laminated timber produced and evaluated according to NBR 7190 (ABNT, 1997) for shear strength and compression parallel to grain. Static bending tests were performed according to the ASTM D198-15 (2015); for determination of the MOE and MOR.

To determine the delamination of specimens extracted from glued laminated timber beams, 6 specimens with 7.5 x 6.0 x A cm (length, width and A = thickness) were drawn in parallel to the fibers, using the methodology described by Lestari et al. (2015).

Eletromicrographs of the SEM glue line

The specimens were 6 mm in diameter and 3 mm thick, with the glue line centered on each specimen. These specimens were covered with a layer of gold in an evaporator and tested in a scanning electron microscopy (SEM) (LEO EVO 40 XPV) at 20 kV to obtain the eletromicrographs of the glue line.

Statistical analysis

The results were submitted to statistical analysis using ANOVA. In significance, the comparison of means was applied through the Tukey test. All tests were performed in the Sisvar 5.6 program at 95% probability (Ferreira, 2014).

RESULTS AND DISCUSSION

Physical characterization of *Toona ciliata* wood

Toona ciliata wood species achieved a mean bulk density of 0.320 g cm^{-3} with a dry base moisture content of 11.29%.

The knowledge of moisture and bulk density of the wood batch are important factors for the manufacture of glulam, since the moisture must be between 8 and 12% and the bulk density influences the pressing time and pressure during the production process of the elements of glulam (FPL, 2010; NBR 7190 (ABNT, 2013); Segundinho et al., 2015). The results obtained for bulk density in this work are same those observed by Almeida et al. (2012), whose author found mean values of bulk density of 0.320 g cm^{-3}.

Chemical characterization of *Toona ciliata* wood species

Figure 1 shows the mean values of the chemical components of *Toona ciliata* wood.

The average total extractive contents obtained for *Toona ciliata* were higher than those observed by Ribeiro et al. (2014), whose author found average extractive contents of 12.81%. Similar values were also obtained by Bufalino et al. (2012), whose authors obtained average values of extractives of 12.87%. According to Fonte and Trianoski (2015), glulam elements produced with species with high extractive values may exhibit deficiency in bonding. Depending on the species and drying conditions of wood, due to the migration and excessive concentration of extractives, a so-called "inactive or contaminated surface" may occur, damaging the adhesive-wood contact (Iwakiri, 2005). High levels of this component may influence the cure time of the adhesive as well as the quality of adhesion (Boa et al., 2014).

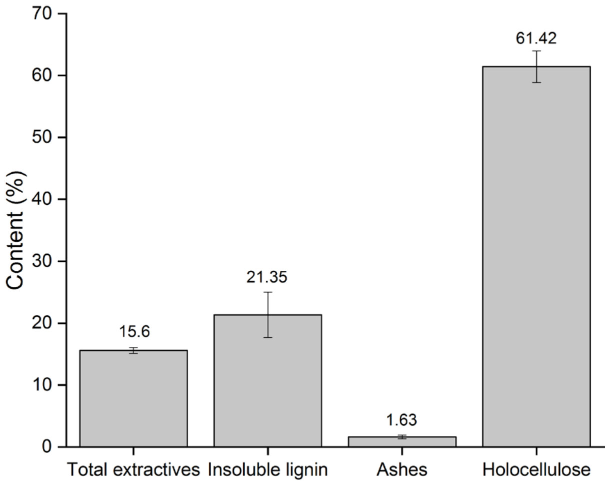

Figure 1: Chemical components of *Toona ciliata* wood.

However, for lignin contents, Ribeiro et al. (2014) observed a mean lignin value of 20.46%, which was higher than the present study. The lower lignin contents obtained in this work can be attributed to the factors such as the age of the trees, characteristics of the region where the trees were collected, climatic conditions and mainly the specificities of the studied clone. Lignin is a natural adhesive, positive for the production of engineered wood elements, giving better mechanical properties and water resistance (Khedari et al., 2004; Bufalino et al., 2012).

In view of the holocellulose values, the present study is superior to those observed by Bufalino et al. (2012), whose authors obtained mean values for this compound of 41.87%. Holocellulose values can affect the physical properties of engineered wood elements due to the hygroscopicity of these structures because they refer to free hydroxyl groups that can adhere to water (Iwakiri, 2005).

Regarding ash content, Ribeiro et al. (2014) obtained 0.91%, lower values than those observed in this study. The presence of higher amounts of minerals and some apolar extractives may result in the blockage of chemical groups reactive for adhesion, thus affecting the quality of the bonding and the mechanical performance of the glulam elements (Ndazi et al., 2007). With this, *Toona ciliata* wood may present problems in the bonding, due to the presence of more than 1% of ash in its constitution.

Mechanical characterization of the glued laminated timber beams of *Toona ciliata*

Table 4 below shows the mean values observed for the fiber parallel compression and shear strength tests for solid wood and for glued laminated beams.

Table 4: Mean values of parallel fiber compression, shear and flaw in wood for solid wood and glued laminated beams.

Treatment	Parallel compression (MPa)	Shear strength (MPa)	FM (%)
Solid wood	24.38 (1.99)A*	6.56 (1.61)A	-
Glulam	22.86 (1.59)A	6.95 (1.99)A	75.20

*Values followed by the same letter do not differ from each other by the Tukey test at 5% significance. Standard deviation between parentheses. FM: Flaw in the wood.

Table 4 showed that there was no significant statistical difference for the properties of parallel compression to the fibers and shear strength for solid wood and for the glued laminated beams. The close values for both evaluated properties can be explained by the efficiency of laminae gluing, since the final strength of the bonded part is expected to have resistance close to wood in its natural status.

Similar behavior to this work for parallel compression to the fibers was observed by Segundinho et al. (2018), whose authors did not verify significant statistical differences studying the properties of glued laminated wood (glulam) produced with wood of *Eucalyptus sp.* The authors found 47.77 MPa for solid wood, 50.90 MPa for glulam produced with polyurethane (PUR) adhesive and 48.15 MPa for glulam produced with resorcinol-phenol-formaldehyde adhesive.

The property of compressive strength parallel to the fibers is important for the success of the glulam structural element. Since the element is in service in the function of beam, the same will have lower fibers tensioned and upper fibers compressed, thus making the need of good strength to withstand the applied load. Even though the part is acting as a pillar, the structural element will be under load in the direction parallel to the fibers, and a good bonding of the laminae is necessary to withstand the requesting stress.

For shear strength parallel to the fibers, the values were statistically the same for solid wood and for glued laminated beams, confirming the efficiency of the part bonding. This behavior was also observed by Segundinho et al. (2015), which evaluated the adhesion efficiency of glued laminated timber of *Acacia mangium* species and structural adhesives, resulting statistically in the same values for the pieces bonded with PUR adhesive, and those from solid wood with close values, being 8.66 and 8.64 MPa, respectively.

The results for shear strength (Table 4) indicate the adhesive quality for external applications, when submitted to high moisture and weathering conditions, thus satisfying adhesive conditions for structural application according to NBR 7190 (ABNT, 1997).

In relation to the value for glue line flaw of bonded specimens, it can be inferred that a higher percentage of flaw in the wood is related to a greater efficiency of the adhesive. The mean values observed in this study (75.20%) are higher than those results from Segundinho et al. (2015), which obtained the highest mean values for the melanin-urea-formaldehyde adhesive in the dry test condition (65.08%). For the polyurethane adhesive in the dry condition, the authors found average results of 26.63%. The difference of the values – between results obtained here and those observed by the aforementioned authors - is due to the fact that the type of adhesive used is of different origin, since the adhesive used in the research has vegetable origin based on castor oil and other used by those authors presents an oil source. According to the Standard JAS 234 (2003), the minimum percentage of wood flaw is 60%. Thus, the results obtained in this work for adhesive bond strength of the glue line agreed with the standard.

The satisfactory bonding of the glued laminated beams was observed not only in the mechanical tests, but also in the photomicrographs obtained by scanning electron microscopy (SEM), where the presence of an intact glue line was observed, showing a constant thickness. Figure 2 below shows photomicrographs obtained from the glue line of the laminated timber beams.

Table 5 shows the average values for the rupture and elasticity moduli for solid wood and for three evaluated glulam treatments.

The highest value found for MOR was for solid wood (30.51 MPa), being statistically equal to T1 and T2 as well as the lowest evaluated value was T3 (19.87 MPa) with statistical significance equal to T2. For MOE, the highest value was found in T1 (2798.72 MPa), although it was statistically equal to solid wood. The lowest value was found for T3 (597.98 MPa). The results showed a significant reduction of the MOE and MOR values of the glulam beams with the increase of the number of laminae. Icimoto et al. (2016) found similar behavior, obtaining higher values of MOE and MOR with lower number of laminae. This behavior could be justified by the results observed by Melo, Souza and Costa (2015), who obtained lower MOE and MOR values in *Toona ciliata* specimens with a decrease in length/height ratio (l/h), that is, greater thickness in relation to the span.

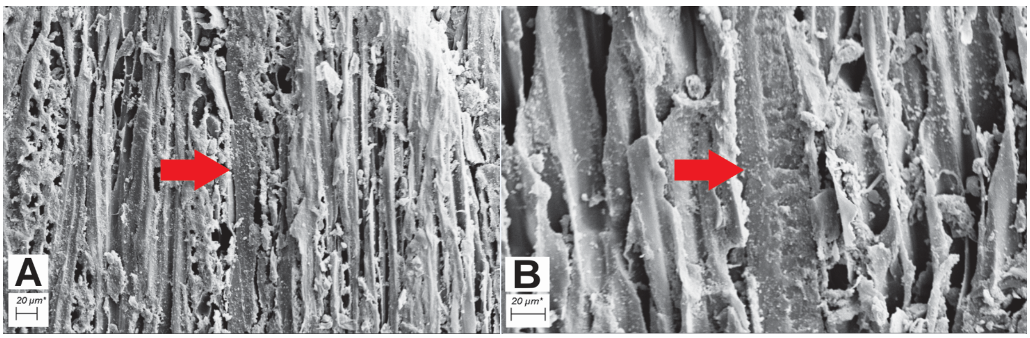

Figure 2: A and B - SEM of the glue line of the laminated wood beams. Observation: Red arrows indicate the glue line.

Table 5: Mean values of modulus of elasticity (MOE) and rupture (MOR) to static bending for solid wood and glulam beams.

Treatment	MOR (MPa)	MOE (MPa)	Delamination (%)
Solid wood	30.51 (3.45)B*	2558.19 (417.24) C	-
T1	28.21 (3.72)B	2798.72 (29.84) C	0
T2	24.10 (2.60)AB	1306.92 (88.14) B	0
T3	19.87 (1.56)A	547.98 (148.22) A	0

*Values followed by the same letter do not differ from each other by the Tukey test at 5% significance. Standard deviation between parentheses.

In relation to delamination test of glued laminated timber, the specimens did not present delamination slits as indicated by visual verification of glue lines (Figure 3); it was found that the percentage of delamination was zero (Table 5). Segundinho et al. (2015) also obtained a zero percentage of delamination, studying the behavior of structural beams of *Acacia mangium* wood species glued with polyurethane adhesive. Results close to zero were also observed by Calil Neto et al. (2014), finding a percentage of delamination of 0.5 and 0.6% for *Pinus spp* glued laminated timber produced with polyurethane and resorcinol-formaldehyde adhesives, respectively.

Figure 3: Absence of cracks in samples after delamination test.

The percentage of delamination observed in this study was lower than the 10% maximum prescribed by European Standard EN 386 (European Standard, 2001), and lower than the 5% maximum allowed by Standard JAS 234 (2003). When subjected to variations in moisture, pressure and temperature, the evaluation of the efficiency of these adhesives is important to ensure the integrity of the structural element in glued laminated timber during service use (Fiorelli; Dias, 2005).

CONCLUSIONS

The results for the chemical constituents of *Toona ciliata* wood were close to those of the literature, and despite high levels of total extractives and ash, they did not affect the bonding of the laminae. For the mechanical properties, similar values were observed for solid wood and glued laminated timber in the tests of parallel compression to the fibers and shear of the glue line. The quality of the bonding can be verified by the photomicrographs that presented uniform glue line and constant thickness. The increase in the number of lamina significantly affected the strength and stiffness of glulam pieces, where the pieces produced with 5 lamina presented the highest average values, where this behavior is a result of the decrease in length/height ratio (l/h). These results indicate the feasibility of using pieces with lower number of lamina, thus resulting in wood and adhesive savings, lowering the final value of the composite. Regarding the delamination test, the species presented satisfactory results, indicating the potentiality of glued laminated timber in structural use, such as pillars and beams used for roofing.

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