SHEAR STRENGTH AND STIFFNESS OF CLT SPECIMENS WITH DIFFERENT SPECIES-ADHESIVES COMBINATIONS

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ABSTRACT: Cross Laminated Timber (CLT) is used in several countries in Europe and North America and also in Brazil. Its bending design is governed by the rolling shear effect, which occurs with the rolling of the layers of the central wooden lamellae that form the element due to shear stresses. This manuscript presents a study on strength (f_{vt}) and stiffness (G_{vt}) related to rolling shear in CLT specimens made with 4 species of Brazilian wood and glued with polyurethane adhesive (PUR). The tests were carried out on two models of shear test specimens (vertical and inclined) obtained from CLT panels, and also on CLT elements subject to bending. The results showed that there were no major differences between rolling shear strength (f_{vt}) values, with the greatest differences observed for stiffness values (G_{vt}). Rolling shear strength results ranged from 2.05 MPa to 3.90 MPa and stiffness results from 81 MPa to 368 MPa. These values exceeded normative recommendations that propose general variations between 0.8 and 1.2 MPa for strength f_{vt} and 50 MPa for stiffness G_{vt}.

KEYWORDS: timber, etc (max 5 keywords)

1 – INTRODUCTION

Cross Laminated Timber panels are high strength and stiffness elements, manufactured with 90º crossed layers (usually in odd numbers: 3, 5 or 7). CLT panels have lengths between 3 m and 18 m and thicknesses ranging from 57 mm to 400 mm, limits imposed according to the manufacturer. Fig. 1 shows the details of a CLT panel.

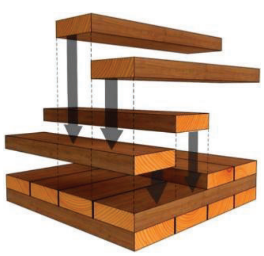

Figure 1. Arrangement of sawn wood lamellae in the assembly of a CLT panel. Source [1]

When the CLT panel is subjected to out-of-plane loading, failure occurs in the transverse layers due to shear, an effect known as rolling shear (Fig. 2), which causes deformations through shear stress. Therefore, it is important to know the properties related to rolling shear because it is a potential failure mechanism for these elements, especially when they have short spans and are subject to out-of-plane stresses, as occurs in bending tests.

Figure 2.Rolling shear failure in a CLT specimen subjected to bending. Search: [2].

The procedures for determining strength (f_{vt}) and stiffness (G_{vt}) related to rolling shear are standardized in Brazil by [3]. Furthermore, several models of test specimens, whether direct shear or bending, are found in the literature to determine these parameters [2].

The Brazilian standard [3] recommend a test to determine the strength (f_{vt}) and stiffness (G_{vt}) properties, using a

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vertical specimen, whose geometry is determined based on an inclination of 14º, but does not include procedures for testing inclined samples of specimens as observed in some works of literature. Furthermore, the differences between the values of the G_{vt} and f_{vt} parameters provided by different models of shear and bending specimens are not known exactly. The European standard [4], recommends design values between 0.8 and 1.2 MPa for f_{vt} and 50 MPa for G_{vt}.

Therefore, this work aimed to experimentally evaluate the strength (f_{vt}) and stiffness (G_{vt}) properties of CLT elements using two different models of shear test specimens and a bending model, made with four different species of Brazilian reforestation wood: Pinus elliottii, Eucalyptus grandis, Toona ciliata and Acrocarpus fraxinifolius, glued with PÙR (polyuretane adhesive)

1.1 TYPES OF WOOD IN BRAZIL

Tropical woods

Brazil has almost 1/3 of the planet's humid tropical forests, which is equivalent to 300 million hectares. These woods have high density, few or almost no defects, in addition to being less prone to attack by termites and other insects. Woods that fit this pattern typically have striking colors from yellowish-beige to dark red. However, high-density wood presents greater difficulty in gluing.

Planted forest wood

Wood plantations, called reforestation wood, are huge industrial monocultures with exotic woods (those coming from trees that are not native to the region in which they are used) such as eucalyptus, pine, teak and cedar. Furthermore, genetically identical (cloned) trees of the same age are found in endless rows and are treated with fertilizers and pesticides. The estimated area of planted forests in Brazil totaled 9.5 million hectares in 2021. Nowadays, reforestation plantations provide large quantities of wood for the civil construction industry as well as paper and cellulose.

Wood from the Pinus and Eucalyptus genera have already been widely studied and are widely used in Brazil, not only for the manufacture of CLT and glulam, but also in other sectors of the wood industry. However, other species have been evaluated for industrial use, in the search for alternatives to Pinus and Eucalyptus wood.

Among these species are Toona ciliata (*T. ciliata*, also known as Australian Cedar) and Acrocarpus fraxinifolius (*A. fraxinifolius*, known as Indian Cedar), which despite being promising in obtaining solid wood products, have been little studied to date. Fig 3 shows the main reforestation woods most common in Brazil.

Figure 3. Brazilian reforestation woods: a) Pinus elliottii; b) Eucalyptus grandis; c) Toona ciliata; and d) Acrocarpus fraxinifolius. Source: [5]

The authors [6] and [7] studied the manufacture of glulam from A. fraxinifolius and T. ciliata with castor oil-based polyurethane adhesive, respectively. The authors verified a good quality of wood bonding with the adhesive and its viability in the manufacture of structural elements for application in civil construction, thus justifying the investigation of the use of these species in the manufacture of CLT. Table 1 shows some properties of these woods.

Table 1: Some properties of planted forest wood. Source: [4].

Woods	Density (kg/m^3)	$f_{c0,k}$ (MPa)	E_{M0} (MPa)	$f_{M0,k}$ (MPa)
P. elliottii	360-520	23-33	7496	40-76
E. grandis	490 - 690	30-40	15600	78-86
T. ciliata	330 -640	27	5105	46
A. fraxinifolius	440 - 680	32	7506	50

$f_{c0,k}$ = compression strength parallel to the fibers (characteristic values); E_{c0} = average elasticity modulus in bending; $f_{M0,k}$ = bending strength (characteristic values).

2 – MATERIALS AND METHODS

The reforestation wood species used in the manufacture of CLT panels were Pinus elliottii (*P. elliottii*, strength class C20 and density equal to 383 kg/m^3), Eucalyptus grandis (*E. grandis*, D30, density 413 kg/m^3), Toona ciliata (*T. ciliata*, D20, density 357 kg/m^3) e Acrocarpus fraxinifolius (*A. fraxinifolius*, D40, density 480 kg/m^3). The adhesive used to glue the panels was two-component polyurethane (AG101) produced by the company KEHL® in a 1:1 ratio, with a curing start time of approximately 30 minutes. The manufacturing pressure used in the panels was 0.7 MPa. All wood used to make the CLT panels was visually and mechanically classified [8]. Subsequently, shear and bendig test specimens were removed from the CLT panels for laboratory testing [3].

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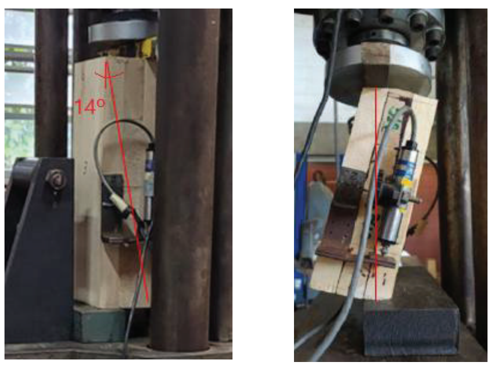
2.1 SHEAR TESTS

The methodology used in the vertical and inclined shear tests of the CLT specimens followed the recommendations of the Brazilian standard [3]. The vertical test specimen used had dimensions of 301 mm x 110 mm x 75 mm (Fig. 4a), considering the angle of 14º between opposite vertices, being the same angle required by [9] and [10] in stiffness tests (rolling shear). The inclined test specimen considered the same bonded area admitted for the vertical specimen. To control the applied load and respective displacements during the tests, a load cell with a capacity of 25 t and two LVDT transdures with a maximum travel of 100 mm on each side of the specimens were used. The sample size tested was 20 specimens of each type.



a) Vertical specimen *b) Inclined specimen*

Figure 4. Test specimens for shear tests.

For the vertical and inclined specimens, the stiffness (G_{vt}) and strength (f_{vt}) to rolling shear were obtained through equations (1) and (2), respectively.

$$G_{vt} = \frac{(F_{40\%} - F_{10\%}) \cdot h_2}{(\delta_{40\%} - \delta_{10\%}) \cdot w \cdot L} \quad (1)$$

$$f_{vt} = \frac{F_{max} \cdot \cos 14°}{w \cdot L} \quad (2)$$

Where:

F_{max}: is the maximum load obtained for the test specimen, in N; $F_{40\%}$: is the load applied to the specimen up to 40% of the estimated maximum load, in N; $F_{10\%}$: is the load applied to the specimen up to 10% of the estimated maximum load, in N; $\delta_{40\%}$: is the displacement referring to the load applied to the specimen up to 40% of the estimated maximum load, in mm; $\delta_{10\%}$: is the displacement referring to the load applied to the specimen up to 10% of the estimated maximum load, in mm; h_2: is the height of the internal layer, which undergoes rolling shear, in mm; w: is the width of the CLT specimen, in mm and L: is the length of the CLT specimen, in mm.

2.2 BENDING TESTS

The variable span bending test, used to determine the stiffness (G_{vt}) and strength (f_{vt}) parameters related to rolling shear, was based on the methodology described by the American standard [11], which is based on a beam model with load applied in the center of the span between supports. The procedure for determining the stiffness G_{vt}, associated with the rolling shear effect in bending, consisted of measuring the apparent modulus of elasticity ($E_{M,app}$) obtained in bending in six different span measurements: 400 mm, 540 mm, 680 mm, 820 mm, 960mm and 1100 mm. The deflection (δ) in the middle span was measured with an LVDT displacement transducer with maximum travel of 100 mm fixed to a magnetic base. The deflection limit to guarantee behavior within the linear section was equal to $L_0/300$ (L = span). The apparent modulus of elasticity for all spans was calculated according to Equation (3)

$$E_{m,app} = \frac{L_0^3 \cdot (F_{30\%} - F_{15\%})}{48 \cdot I_{eff} \cdot (\delta_{30\%} - \delta_{15\%})} \quad (3)$$

Where:

$F_{30\%}$: is the load in the middle of the span with deflection equal to 30% of the span, in N; $F_{15\%}$: is the load in the middle span with deflection equal to 15% of the span, in N; I_{eff}: is the moment of inertia of the CLT element, in mm^4; $\delta_{30\%}$: is the deflection in the middle span due to the application of $F_{30\%}$, in mm and $\delta_{15\%}$: is the deflection in the middle span due to the application of $F_{15\%}$, in mm

The G_{vt} value was calculated based on the angular coefficient of the line presented in Fig.5, with its value defined by Equation (4), where K = 1.5 was adopted in accordance with the American standard [11].

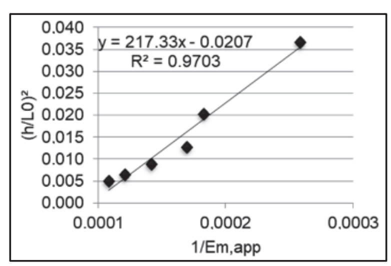


Figure 5. Determination of the shear modulus by the angular coefficient.

$$G_{vt} = K \cdot \frac{\Delta\left(\frac{h}{L_0}\right)^2}{\Delta\frac{1}{E_{m,app}}} \quad (4)$$

Where:

G_{vt}: is the rolling shear shear stiffness, in MPa; K: is the shape factor of the shear coefficient; h: is the total height

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of the CLT specimen, in mm; L_0: is the distance between supports, in mm; $E_{m,app}$: is the apparent elastic modulus of the specimen, in MPa.

Finally, the load was applied to the CLT beam until its failure, with a span of 450 mm, so that the rolling shear strength (f_{vt}) was calculated based on Equation [5] proposed by [5].

$$f_{vt} = \frac{3}{4} \cdot \frac{F_{max}}{w \cdot h} \quad (5)$$

Where

F_{max}: is the rupture load obtained for the test specimen, in N; w: is the width of the CLT cross senction, in mm and h: is the height of the CLT cross section, in mm.

The sample size considered for each specimen model (vertical and inclined shear and bending) was equal to 20.

2.3 STATISTICAL ANALYSIS

The comparison of experimental results obtained for G_{vt} and f_{vt} from different methods were carried out using analysis of variance (ANOVA) according to the Tukey test, with a 5% significance level. Data normality and variance homogeneity tests were performed using the Shapiro-Wilk and Bartlett tests, respectively. All analyzes were performed using Minitab software for statistical analyses.

3 – RESULTS

The average stiffness values (G_{vt}) of the CLT panels of each species, associated with the rolling shear effect, are presented in Table 2, together with the standard deviations (in parentheses), coefficient of variation (in brackets) and analysis of variance. The same letters (capital letters vertically and lowercase letters horizontally) indicate that there were no significant differences at the 5% significance level.

Table 2: Gvt stiffness results of the CLT associated with rolling shear

Method	P. elliottii	E. grandis	T. ciliata	A. fraxinifolius
Bending	291Ab (45) [15.32%]	329Aab (19) [5.83%]	254Ab (8) [3.05%]	368Aa (61) [16.49%]
Vertical shear	82Ca (6.8) [8.30%]	122Ca (7.3) [6.01%]	97Ca (28.1) [29.00%]	81Ca (13.5) [16.66%]
Inclined shear	157Bc (37) [23.46%]	269Ba (34) [12.55%]	134Bbc (117) [87.25%]	241Bab (58) [2.92%]

The wood of E. grandis and A. fraxinifolius presented higher G_{vt} stiffness values than the other species analyzed in this study for all test methods evaluated, except for the vertical shear test, where there was no significant difference between the species.

The stiffness (G_{vt}) obtained by the bending method presented higher values than the results obtained by the vertical and inclined shear methods.

According to [4] for projects, the G_{vt} value is usually adopted as 50 MPa and some authors [5, 12] propose adopting an average value of 100 MPa for CLT that respects the lamella width/height ratio greater than 4. For numerical modeling, the values adopted for G_{vt} in literature range from 30 MPa to 280 MPa according to each author, generally based on the wood species considered.

Another issue, raised by [13] and Li [14], is that the G_{vt} stiffness characterization results, for high-stiffness CLT, present high coefficients of variation, reaching up to 50%, especially for three-layer CLT. However, the maximum coefficient of variation obtained in the present study was 29% (with the exception of the inclined shear test with T. ciliata), indicating that the methods for obtaining the G_{vt} generated consistent results.

The average strenth values (f_{vt}) of the CLT panels of each species, associated with the rolling shear effect, are presented in Table 3, together with the standard deviation in parentheses, the coefficient of variation in brackets and the analysis of variance. Similarly to Table 2, the same letters (capital letters vertically and lowercase letters horizontally) indicate that there were no significant differences at the 5% significance level.

Table 3: fvt stremgth results of the CLT associated with rolling shear

Method	P. elliottii	E. grandis	T. ciliata	A. fraxinifolius
Bending	2.45Ab (0.30) [12.39%]	3.20Aa (0.34) [10.68%]	2.53Bb (0.15) [5.94%]	3.22Ba (0.35) [10.91%]
Vertical shear	2.14Ab (0.29) [13.34%]	2.74Ba (0.30) [10.94%]	2.05Cb (0.13) [6.13%]	2,98Ba (0.18) [6.23%]
Inclined shear	2.54Ac (0.60) [23.57%]	3.52Aab (0.39) [11.07%]	3.03Abc (0.37) [12.05%]	3.90Aa (0.48) [12.23%]

The rolling shear strength (f_{vt}) results differed significantly from one method to another, with the exception of the results obtained for P. elliottii wood, for which there was no significant difference between the methods. The same order of magnitude was also observed in all tests, indicating that there was no great variation in the results obtained between the methods in the case of determining the f_{vt} strength.

Thus, as in the rolling shear stiffness G_{vt} results, the f_{vt} values of wood from E. grandis and A. fraxinifolius were higher in relation to the other two species (T. ciliata and P. elliottii). It is noteworthy that the f_{vt} values are dependent on the presence of pith in the lamella and proportional to the wood density [14].

The rolling shear strength results (f_{vt}) obtained in the present work agreed with the results published in the literature, which ranged from 0.64 MPa to 8.2 MPa, according to [5].

Regarding the standardization of the f_{vt} value, for CLT projects, there is no consensus among researchers. According to the wood class, [15] specify f_{vt} values ranging from 0.43 to 0.63 MPa, while [16] suggests 1 MPa or 0.77 MPa for special projects. Furthermore, [17] propose the use of an average f_{vt} value of 1.4 MPa for layers with a width/height ratio equal to or greater than 4 and [18] proposes values ranging from 2. 38 MPa to 3.90 MPa.

Figure 6 shows the failure modes obtained in the shear and bending tests of the CLT specimens.

a)Rolling shear (vertical specimen)

b) Rolling shear and crushing (inclined specimen)

c) Rolling shear (bending specimen)

Normal stress - tension (bending specimen)

Figure 6. Failure modes obtained in the test specimens.

The rolling shear strength values (f_{vt}) obtained in this work were close to the normal tensile strength values ($f_{t90,k}$), obtained from the experimental characterization of the woods studied, i.e.: P. eliottii = 2,52 MPa; E. grandis = 2,84 MPa; T. ciliata (cedro australiano) = 3,06 MPa and A. fraxinifolius (cedro indiano) = 2,79 MPa

The failure modes in the shear and bendig tests were related to rolling shear in the central layer of the element. For the bending tests, tensile rupture of the lower lamella was also observed, depending on the type of wood. For vertical shear tests failure due to crushing of external lamella (at the point of support or application of load) was observed.

6 – CONCLUSION

The higher density woods (A. fraxinifolius and E. grandis) showed higher G_{vt} and f_{vt} values in all test methods, except in the vertical shear test, where there was no significant difference between the wood species.

The G_{vt} values obtained were closer to those observed in the literature using the bending and inclined shear method, while for the f_{vt} results, the three test methods generated similar values in terms of order of magnitude.

The failure modes obtained in the rolling shear tests were dependent on the wood species, with failure due to normal stresses being observed in the bending of T. ciliata and failure due to crushing in the vertical shear test for both cedars. For the inclined shear tests, only rolling shear failure was observed in all characterized wood species.

7 – ACKNOWLEDGMENT

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