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MECHANICAL PERFORMANCE OF ADHESIVE BONDED JOINTS WITH 1C-PUR ADHESIVE AT DIFFERENT ANGLES

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ABSTRACT

Reforestation trees are an alternative to meet industrial needs, and one potential application is their use in prefabricated structures, such as glued laminated timber (glulam). This study aimed to evaluate the shear strength of *Pinus* sp. bonded joints made using a single-component polyurethane adhesive (1C-PUR). The joints were produced varying the angles between the wood fibers ranging from 0º to 90º and were tested subjected to shear under compression load and to shear under torsional load. The use of the Hankinson's equation as an estimator of shear strength of glued joints and the percentage of wood failure were also evaluated. A total of 144 specimens were tested. Half of the total was subjected to shear test under compression load while the other half was subjected to shear test under torsional load. The wood laminates used to make the joints were previously divided into eight groups according to their apparent density. The results showed that the shear strength was affected by the bonding angle, especially for those tested under compression loads. The mechanical behavior of the shear test under compression was considered different from that of the test under torsion for six of the nine angles used in the study. It was also found that Hankinson's equation can be used as an estimate of the shear strength of joints bonded on different angles when the tests are performed under compression loads. However, the equation was not appropriate for estimating the test results when shear was caused by torsional loads. Overall, the bonded joints presented satisfactory shear strength and low percentage of wood failure. Furthermore, the results of this research were in accordance to those found on similar research where other adhesives were used.

Keywords: Glulam; Strength; Adhesion

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DESEMPENHO MECÂNICO DE JUNTAS COLADAS COM ADESIVO 1C-PUR EM DIFERENTES ÂNGULOS

RESUMO – As árvores de reflorestamento são uma alternativa para suprir as necessidades industriais, e uma das possíveis aplicações é o seu emprego em estruturas pré-fabricadas, como é o caso da madeira lamelada colada (MLC). Este trabalho teve como principal objetivo avaliar a resistência ao cisalhamento na compressão e na torção de juntas de *Pinus* sp. coladas com adesivo poliuretano monocomponente (1C-PUR), tendo-se realizado a colagem com diferentes ângulos em relação às fibras da madeira. Também foi avaliado o emprego da fórmula de Hankinson como estimadora da resistência ao cisalhamento de juntas coladas e o percentual de falha na madeira. Foram confeccionados 144 corpos de prova, sendo metade destinada ao ensaio de resistência ao cisalhamento sob compressão e a outra metade para o ensaio de resistência ao cisalhamento sob torção. As lâminas de madeira foram separadas em oito grupos conforme a sua densidade aparente. Constatou-se que a resistência ao cisalhamento foi afetada pelo ângulo de colagem no ensaio de compressão. O desempenho mecânico no ensaio sob compressão mostrou-se diferente do desempenho obtido no ensaio sob torção para seis dos nove ângulos estudados. A fórmula de Hankinson pode ser empregada como estimadora da resistência ao cisalhamento na compressão de juntas coladas à diferentes ângulos. Contudo, para estimar a resistência ao cisalhamento na torção não é recomendado o uso desta fórmula. As juntas coladas apresentaram valores satisfatórios em relação a resistência ao cisalhamento e baixos valores de percentual de falha na madeira. De modo geral, os resultados desta pesquisa foram compatíveis aos encontrados em pesquisas similares onde utilizou-se outros adesivos.

Palavras-Chave: Madeira lamelada colada; Resistência; Adesão

1. INTRODUCTION

The use of wood in the most diverse applications has been standing out in a global scenario, especially considering the replacement of products from non-renewable sources (Longue Jr e Colodette, 2013). In this way, planted forests emerge as an alternative to meet industrial needs, usually using exotic wood species (Bolgenhagen et al., 2015).

Although Brazil has a native forest area that represents 58.5% of its territory, only 2% of this territory is equivalent to planted forests (SFB, 2019). In this context, reforestation was deployed in Brazil, with emphasis on the genera *Pinus* and *Eucalyptus*, aiming the preservation of native forests. Reforested species are widely used in the forest-timber industry (Araujo et al., 2017).

One of the possible applications of wood from reforestation is its use in structures. In addition to being a renewable material, wood exhibits excellent structural properties, mainly because it has significant tensile and compressive strength, and is considered one of the best materials for this use (Pigozzo et al., 2018a; Pigozzo et al., 2018b).

Compared to other structural materials, wood exhibits similar compressive strength to simple concrete and both have lower strength than steel. However, wood has a lower density when compared to these other materials, exhibiting an excellent strength/density ratio (Ramage et al., 2017). Furthermore, wood exhibits other advantages such as beauty, low energy processing, good thermal insulation and easy workability (Vidal et al., 2015). These characteristics highlight wood as an efficient structural material.

One of the structural products manufactured from wood is Glulam (glued-laminated timber), which has been studied in Brazil for several years and usually using reforestation species (Molina et al., 2016). Glulam, which has a long history in developed countries, is a traditional engineering product that consists of a series of sawn wood laminates glued together by means of structural adhesives and the adhesion of the substrate to the adhesive is of great importance (Nadir et al., 2016; Pang et al., 2018). In addition to its industrialized manufacturing process, products made of glulam can be used in the most diverse architectural projects and with different dimensions (Segundinho et al., 2021).

For the manufacture of glulam structures, it is important to first evaluate the adhesion capacity of the wood species. The adhesion mechanism is influenced by the anatomical, chemical, physical and mechanical characteristics of the wood and also by the physical and chemical properties of the adhesive (Albino et al., 2010; Gonçalves et al., 2016). The quality of the wood bonding can be evaluated through standardized tests, evaluating, for example, the shear strength of the glued joints and the percentage of failure in the bonding plane (Bila et al., 2016).

Although NBR 7190 (2022) does not allow the bonding of lamellae at angles other than 0º in relation to the wood fibers, several studies developed in recent years have shown the good structural performance of nodes bonded with the fibers inclined to each other (Couri Petrauski et al., 2016; Stringari et al., 2020; Possa et al., 2022; Filippini et al., 2023). In these studies, some authors highlight the fact that the shear stresses in the bonded planes are caused by different loads: forces and/or moments.

Some recent studies have sought to evaluate the strength of joints bonded at different angles, using exotic species. Petrauski et al. (2020) proposed a methodology for testing glued joints subjected to shear under torsional load. The authors used *Eucalyptus* sp. wood bonded with resorcinol formaldehyde and polyurethane adhesives based on castor oil. The study results pointed to loss of strength with the increase of bonding angles and also a significant difference in the test behavior when shear was caused by compression load or torsional load. Padilha et al. (2023) observed a similar overall behavior when working with *Pinus* sp. and vegetable oil-based adhesive. These researchers recommended conducting similar research, highlighting the need to test other adhesives and wood species.

In this context, this study aimed to evaluate the shear strength under compression load and under torsional load of *Pinus* sp. joints bonded with single-component polyurethane adhesive (1C-PUR), considering nine different angles in relation to the wood fibers. Additionally, the use of Hankinson's formula as an estimator of the shear strength of glued joints and the percentage of wood failure were also evaluated. The methodology used to obtain the shear strengths was the same used by Padilha et al. (2023), researchers who worked with a two-component adhesive based on vegetable oils.

2. MATERIAL AND METHODS

Wood from *Pinus* sp. and the adhesive (1C-PUR) from the company Rendicolla® were used in this study. The wood, purchased in local stores, was stored until it reached hygroscopic equilibrium, with moisture levels close to 12%. The apparent density of the wood ranged from 0.46 to 0.67 g.cm^{-3}, for an average moisture content of 12.4%.

In the glueing process, the adhesive was applied to one of the laminate faces, being spread with the use of a brush. The amount of adhesive applied to the wooden surfaces was measured as 250 g.m^{-2}. Furthermore, a bonding pressure of 0.7 MPa was used, a value based on the study conducted by Tomé et al. (2023).

2.1 Manufacturing of bonded joints

The lamellae for the research were divided into eight groups (G1 to G8) based on apparent density, according to the methodology used by Padilha et al. (2023). Thus, for each density group, were manufactured glulam joints with angles of 0º, 10º, 20º, 30º, 45º, 60º 70º, 80º e 90º relative to the wood fibers. From each joint, two specimens were later extracted for shear under compression load testing and shear under torsional load testing, respectively.

Bonding was performed using 2.1 x 6 x 12 cm³ pieces positioned on 2.1 x 14 x 15 cm³ pieces, allowing the upper piece to be rotated according to the required angle (Figure 1-A and 1-B).

In the bonding process, the open time was zero, and the closed time was approximately 10 minutes. The bonding pressure was applied manually using a Wisterec digital torque wrench. After 20 minutes, a retightening was made in the manual press and the joint remained under pressure for a minimum period of 12 hours.

At the end of the bonding process, an average temperature of 23.8 °C and an average relative humidity of 43.75% were recorded in the environment. The wooden pieces were bonded with moisture content ranging between 11.4% and 13.6% with an overall average of 12.4% and a coefficient of variation of 3.68%. A minimum period of seven days was allowed before the test specimens were prepared and subsequently subjected to the test.

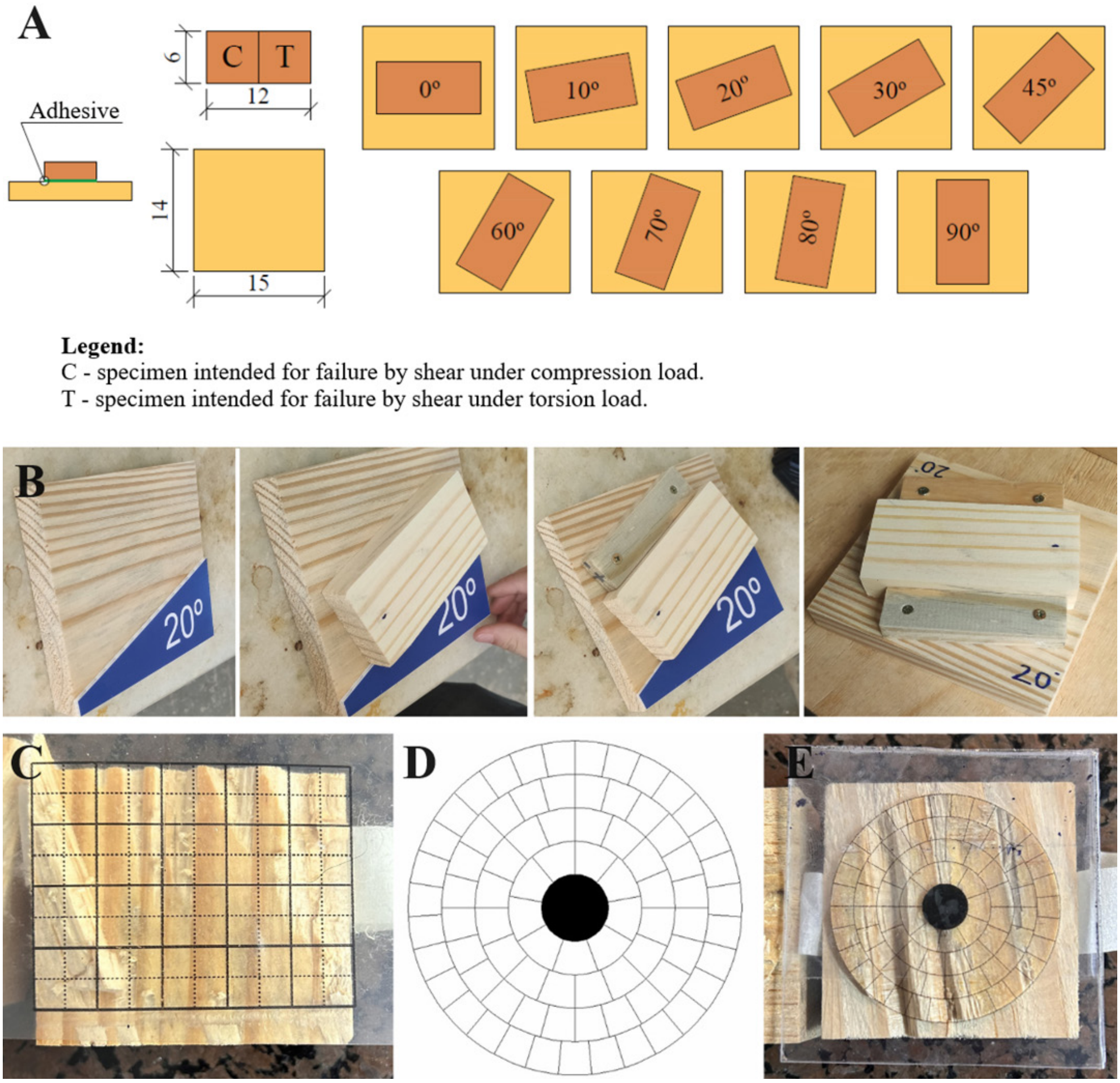

Figure 1. Template used to make the joints with different bonding angles with dimensions in centimeters (A), gluing method (B), rectangular template to analyze wood failure percentage (C) and circular template to analyze wood failure percentage (D-E)

Figura 1. Gabarito utilizado para a confecção das juntas com as fibras coladas com diferentes ângulos com as dimensões em centímetros (A), modo de colagem das juntas (B), lâmina retangular (C) e lâmina circular (D-E) para análise do percentual de falha da madeira

2.2 Shear strength

The shear strength test under compression load was performed according to ASTM D 905-08 (2013). For determining the shear strength under torsional load, the test was conducted following the methodology suggested by Petrauski et al. (2020). Each test specimen was placed in the specific apparatus and tested using a servo-controlled press, model UH501-NS 14009 by Intermetric. After the failure was observed, part of the test specimen was used to determine the moisture content.

Additionally, another 30 test specimens were prepared and tested to obtain the shear strength of solid wood, in accordance with NBR 7190-3 (2022). This complementary test aimed to compare the results with the shear strength of bonded joints at 0°.

2.3 Statistical analysis of strength results

The experiment was conducted in split plots, with the density groups representing the plots. The average density values for each group were: 0.646 g.cm^{-3} (G1); 0.623 g.cm^{-3} (G2); 0.587 g.cm^{-3} (G3); 0.573 g.cm^{-3} (G4); 0.552 g.cm^{-3} (G5); 0.526 g.cm^{-3} (G6); 0.505 g.cm^{-3} (G7) e 0.477 g.cm^{-3} (G8).

A total of 144 test specimens were prepared, with half reserved for the shear strength test under compression load (C) and the other half for the shear strength test under torsion load (T). The objective was to determine whether the strength was influenced by the bonding angle and the type of test. Therefore, the statistical model for shear strength described in the work of Padilha et al. (2023) was adopted.

The least squares estimation process was applied, and the quality of the Hankinson model fit was evaluated through graphical and statistical analyses, investigating the residual sum of squares and the coefficient of determination (R^2) of the model studied.

The analyses in the study were performed using the R software (R Core Team, 2022), version 4.2.1, with the ggplot2 package for creating the graphs and ExpDes package for experiment analysis – ANOVA and Tukey tests.

2.4 Failure percentage in wood

The failure percentage in the wood for the test specimens subjected to shear under compression loads (Figure 1-C) was analyzed using the method specified by ASTM D 5266-92 (2005). For the specimens subjected to shear under torsional load tests the template developed by De Paula (2020) was used, as illustrated in Figure 1-D.

In this work both deep failures (with visible fiber layer removal) and shallow failures (where the presence of fibers on the rupture surface was observed) were considered as wood failure.

3. RESULTS

3.1 Strengths and failure percentages in wood

Table 1 presents the average shear strengths according to the test type and the bonding angle, as well as the average percentage of wood failure with their respective coefficients of variation. The Tukey multiple comparison tests were applied to the strengths obtained for the angle factor, with the analyses conducted independently for each test.

Table 1. Average shear strength results by test type and bonding angle and wood failure percentile

Tabela 1. Resistência média ao cisalhamento segundo ensaio e ângulo de colagem e percentual médio de falha na madeira

Angles	Compression			Torsion		
	Average shear strength (MPa)		Average wood failure (%)	Average shear strength (MPa)		Average wood failure (%)
0º	9.36 (12.93)	a	29.56 (113)	7.42 (13.88)	x	15.62 (82.14)
10º	9.27 (9.06)	a	24.88 (25.84)	7.83 (14.18)	x	27.78 (69.47)
20º	9.56 (15.17)	ab	26.77 (74.60)	7.42 (17.79)	xy	17.94 (85.67)
30º	9.17 (16.79)	ab	26.20 (52.52)	7.91 (11.13)	xy	30.52 (53.01)
45º	7.66 (21.27)	bc	35.20 (60.96)	7.48 (18.85)	xy	25.42 (58.85)
60º	6.36 (20.28)	cd	38.62 (61.37)	6.64 (10.24)	xy	47.28 (50.19)
70º	5.27 (25.05)	de	36.27 (70.43)	6.13 (12.07)	y	38.41 (58.73)
80º	4.75 (22.74)	e	33.75 (70.43)	6.08 (21.71)	y	33.50 (63.91)
90º	4.18 (28.47)	e	46.69 (41.23)	6.07 (7.08)	y	61.25 (23.82)

Note: Average followed by the same letters do not differ statistically, according to Tukey's test at a 5% probability level. Between parenthesis is the coefficient of variation (C.V.%).

Nota: Médias seguidas pelas mesmas letras não se diferenciam estatisticamente, pelo teste de Tukey a 5% de probabilidade. Em parênteses estão os coeficientes de variação (C.V.%).

For both tests, there was a decrease in strength with an increase in the bonding angle. It was observed that the highest coefficients of variation were for the 90° angle for the shear under compression load test and for the 80° angle for the shear under torsional load test.

According to the results obtained in the Tukey test, it was found that in the shear strength under compression load, five levels were established, while for shear strength under torsional load, only two levels were obtained. This indicates that the loss of strength in the shear under torsional load test is less influenced by the bonding angle. When considering the extreme angles of 0° and 90° as a reference, the shear under compression load test showed a 55% loss in strength, while the shear under torsional load test showed only an 18% loss.

There was significant variability in the wood failure percentages across both tests, including the results by different angles. The overall average percentage for the shear under compression load test was 33.10%, and for the shear under torsional load test, it was 33.08%, yielding very similar results. The average coefficients of variation observed were greater than 60% for both tests.

By subjecting the obtained strength values to analysis of variance, the conditions of normality and homogeneity were not rejected. Evaluating the factors of interest using the F-test from ANOVA, it was found that there was a significant interaction between the type of test and the bonding angle. Consequently, as the angle and the type of test change, the strength is also substantially modified.

When analyzing the strengths by angle, it was observed that there is a considerable difference between the shear under torsional load test and the shear under compression load test for six of the nine angles studied (Table 2). It was found that specimens with wood fibers bonded at angles of 45°, 60°, and 70° exhibited statistically equal strengths, regardless of the test performed. This appears coherent since, from the 45° angle onwards, the strengths from the shear under torsional load tests approach those from the shear under compression load tests. Furthermore, from the 60° angle onwards, the shear under torsional load strengths are higher than the shear under compression load strengths. As shown in Figure 2, the curves corresponding to the tests intersect near the 50° angle.

Table 2. ANOVA considering the test type fator within the bonding angles

Tabela 2. Resumo da ANOVA dado o desdobramento do fator ensaio dentro de ângulo

Sources of Variation	df	Sum of Squares	F-Test	p-value
Test/ angle: 0°	1	15.02	16.06	<0.001
Test/ angle 10°	1	8.20	8.77	0.004
Test/ angle: 20°	1	18.40	19.67	<0.001
Test/ angle: 30°	1	6.37	6.81	0.011
Test/ angle: 45°	1	0.12	0.13	0.722
Test/ angle: 60°	1	0.31	0.34	0.564
Test/ angle: 70°	1	2.97	3.17	0.079
Test/ angle: 80°	1	7.13	7.63	0.007
Test/ angle: 90°	1	14.24	15.23	<0.001
Error (subparcel)	63	58.92		

The sample strength values by test type and angle are presented in Figure 2. The smaller points represent the sample values, while the larger points indicate the average values. It is evident that shear under torsional load strength is less sensitive to angle variation compared to the shear under compression load strength.

For the solid wood shear test according

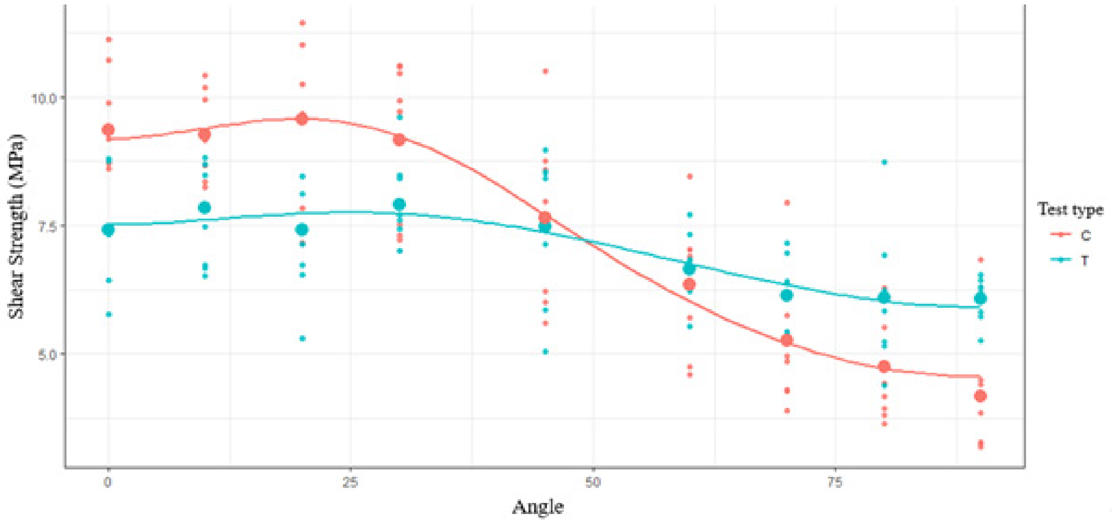

Figure 2. Sample shear strength and average shear strength considering the bonding angle and test type

Figura 2. Resistência amostral e resistência média de acordo com o ângulo de colagem e ensaio

to NBR 7190 (2022), the wood exhibited an average shear strength of 12.17 MPa, with a coefficient of variation of 12.16%, a value higher than that obtained in this research for the shear under compression load tests with fibers glued parallel to each other, which resulted in an average strength of 9.36 MPa.

3.2 Validity of the hankinson model

When modeling the Hankinson curve for the shear under compression load test and the shear under torsional load test, Equations 1 and 2 were obtained, respectively.

$$\hat{y}_{iC} = \frac{9.18 \times 4.56}{9.18\left(sen(\alpha_i)\right)^{2.68} + 4.56\left(cos(\alpha_i)\right)^{2.68}} \quad \text{(Eq. 1)}$$

$$\hat{y}_{iT} = \frac{7.51 \times 5.90}{7.51\left(sen(\alpha_i)\right)^{2.31} + 5.90\left(cos(\alpha_i)\right)^{2.31}} \quad \text{(Eq. 2)}$$

Although the equations appear to be suitable for both tests performed, the coefficient of determination was low for the shear under torsional load test (T), with R_C^2=0,732 and R_T^2=0,333. In Table 3, the estimated coefficients for the Hankinson model, their respective confidence intervals, and the coefficients of determination can be observed.

4. DISCUSSION

The adoption of density as a control factor in experimental planning was appropriate,

Table 3. Estimated coefficients for Hankinson's equation considering the test type, confidence intervals and coefficients of determination

Tabela 3. Coeficientes estimados para o modelo de Hankinson por ensaio, intervalos de confiança e coeficiente de determinação

Test type	**Parameters**			
	$\hat{f}_{w0_j}$	$\hat{f}_{w90_j}$	$\hat{b}_j$	R_j^2
Compression	9.18 [8.58; 9.81]	4.56 [4.10; 5.03]	2.68 [2.37; 3.00]	0.732
Torsion	7.51 [7.03; 8.01]	5.90 [5.47; 6.36]	2.31 [2.03; 2.60]	0.333

considering that the physical and anatomical characteristics of wood can influence the obtained strengths. This reality has already been recognized by other researchers, such as Mendes et al. (1999), Albino et al. (2012) and Soares et al. (2021). Another relevant factor to control this variable is the high variation in density across different growth directions of the tree in softwood species, as is the case with *Pinus* sp., as reported by Melo et al. (2010) and Rios et al. (2018).

According Pimentel-Gomes (2022), the coeficient of variation (C.V.), although it does not account for the number of repetitions, is a statistic associated with the precision of the experiment, with a low value being desirable. The NBR 7190 (2022) standard allows coefficients of variation of up to 28% for results involving shear stresses. In this research, considering the shear under compression load tests, coefficients of variation between 9.06% and 28.47% were obtained, respectively, for angles of 10° and 90°, with an average of 19.13% for the nine angles. Except for the 90° angle, which had a result slightly above 28%, the coefficients calculated for all other angles were below 28%. For the shear under torsional load tests, the values ranged between 7.08% and 21.71%, respectively, for the angles of 90° and 80°, with an average of 14.10%. Therefore, in general, the experimental variability obtained can be considered within the expected range. Comparatively, Padilha et al. (2023) and Petrauski et al. (2020) found average coefficients of variation below 28% for shear under compression load and shear under torsional load results.

In the shear under compression load test, there was a correlation between the bonding angle and the coefficients of variation (CVs) found, indicating a possible loss of precision with an increase in the angle. In this study, a correlation coefficient of 0.94 was obtained. However, despite this result, the evidence is not confirmed in similar studies. The results presented by Padilha et al. (2023), using a two-component polyurethane adhesive, indicate a correlation coefficient of 0,69. Additionally, for the values presented by Petrauski et al. (2020), working with *Eucalyptus* and two adhesives, the correlation coefficients were around 0.5.

In this research, it was observed that the strength decreases as the bonding angles increases for both test types, with the highest and lowest strength values occurring in shear under compression load tests. As a result, for this kind of test, a greater decrease in strength was observed when compared to the shear under torsional load test. Additionally, these tests were statistically different for six of the nine angles studied. The shear strength obtained under torsional loads exhibited average strengths with a smaller range of variation and, consequently, more consistent results.

Figure 3 aims to illustrate the geometric differences in the tests conducted, particularly regarding the angles between the shear stresses causing failure and the fiber orientation of the involved parts.

In the case of standardized tests with shear caused by compressive forces (Figures 3-A and

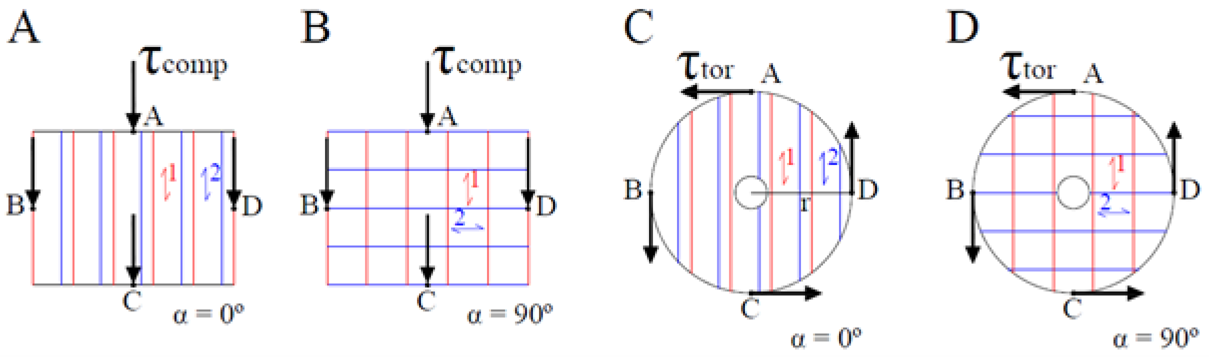

Figure 3. Stress distribution scheme for the shear under compression load test (A-B) and for the shear under torsional load test (C-D)

Figura 3. Esquema de distribuição de tensões para o ensaio de cisalhamento na compressão (A-B) e para o ensaio de cisalhamento na torção (C-D)

3-B), the angle formed between the direction of the shear stresses under compression load (τ_{comp}) and the fiber orientation of one of the bonded pieces will always be the bonding angle (α) itself. Assuming that, hypothetically, the best mechanical performance occurs with bonding at 0° and the worst performance with bonding at 90°, the performance in the shear under torsional load test can be evaluated. Figures 3-C and 3-D aim to illustrate the shear stresses generated by the torsion moment, highlighting that the directions of these stresses (τ_{tor}) are continuously varied and always perpendicular to the radius (r) of the involved circle. Figure 3-C presents the schematic of a 0° bond under torsion. It is noted that only at points B and D will the direction of the stresses be parallel to the fibers, regardless of whether they are in piece 1 or 2. Consequently, only at these two points would maximum strength be achieved. Conversely, at points A and C, the directions of the stresses will be perpendicular to the fibers, with the worst performances expected. This may explain why the shear under torsional load strength for the 0° angle is lower than the shear under compression load strength for the same angle.

Figure 3-D presents the schematic of a 90° bond between the fibers in the pieces. Notice that at points A, B, C and D, the situations will be identical, meaning the shear stress will always be orthogonal to the fibers of one piece and parallel to the fibers of the other. Therefore, it is expected that the shear under torsional load strength will not be as low as the shear under compression load strength for 90° bonds. Following this logic, the expected result was obtained: the strength at 90° is lower in the shear under compression load test. Consequently, the fitting curves of the results tend to intersect at some intermediate point. In this study, this occurred at an angle close to 50°.

Petrauski et al. (2020), when studying the mechanical performance of *Eucalyptus* sp. joints, subjected to shear under compression load tests and shear under torsional load tests for bonding angles of 0º, 15º, 30º, 45º, 60º, 75º and 90º, found a statistical difference between the tests for six angles, except for the 30° angle. Furthermore, the researchers compared the application of two different adhesives, a resorcinol formaldehyde adhesive and a two-component polyurethane adhesive, and observed that the strength behavior was independent of the type of adhesive used. The researchers attributed the statistical difference between the tests to the nature of the forces acting in the region subjected to shear stresses. It is worth noting that studies conducted by Couri Petrauski et al. (2022) and Padilha et al. (2023) reported the same trend of decreasing strength in both shear under compression load and shear under torsional load, with the decrease being less pronounced in the torsion test.

Padilha et al. (2023) investigated shear strength considering a series of nine bonding angles, using a two-component polyurethane adhesive. Similar to this research, the best and worst strengths found by the researchers were in the shear under compression load test. The average strength values for these tests were 10.46 MPa (0°), decreasing to 3.9 MPa (90°), while for the shear under torsional load tests, they ranged from 7.13 MPa to 4.52 MPa for the same bonding angle values.

The strength results from the shear under compression load tests produce a graphic pattern similar to the estimates derived from the application of the Hankinson formula, showing a coefficient of determination of 0.732. Several researchers have observed the trend of decreasing strength in bonded joints subjected to shear under compression loads and have validated the Hankinson formula as a good estimator of this strength (Petrauski et al., 2020; Couri Petrauski et al., 2022, Padilha et al., 2023). The Hankinson formula is already used by NBR 7190 (2022) to determine certain wood strengths at different angles.

The value of the coefficient b, the exponent of the sine and cosine in the Hankinson formula, ranged from 2.37 to 3 for the shear under compression load test. NBR 7190 (2022) adopts the use of b equal to 2, a value lower than that found in this study. This indicates that using b = 2 would underestimate the strength values for the studied batch, which favors safety, a desirable outcome in structural design. However, for the shear under torsional load tests, the use of the Hankinson formula is not recommended due to the low coefficient of determination shown by the curve adjustment (R_T^2=0,333). Therefore, the Hankinson formula seems appropriate only for estimating shear strength when it occurs under compression loads, with shear stress distributions in the cross sections similar to those shown in Figures 3-A and 3-B.

Although both curves show a decrease in

strength as the bonding angle increases, it is possible to observe that the behaviors are distinct depending on whether the shear forces occur due to a compression load or a torsional load. Hence, studying both forces is important for the structural design of bonded joints, especially in the construction of frames, as previous research has demonstrated (Couri Petrauski et al., 2016; Stringari et al., 2020; Possa et al., 2022; Couri Petrauski et al., 2022; Filippini et al., 2023).

Regarding the failure modes, ASTM D 2559 (2016) recommends the use of adhesives that exhibit average percentages of at least 75% wood failure. The average wood failure percentages in this study did not exceed 47% for the shear under compression load tests and 61% for the shear under torsional load tests, both below the recommended standard. Tomé et al. (2023), using the same wood species and 1C-PUR adhesive, also found low wood failure percentages, with an average around 28%.

One possible cause of the variability in wood failure percentages could be attributed to the subjectivity of the evaluator during the analysis, as highlighted by Tomé et al. (2023), Lopes et al. (2013) and Pimentel et al. (2021). Additionally, Tomé et al. (2023) mention that there may be some difficulties in determining whether the failure occurred in the wood or in the glue line, especially when the color of the adhesive is similar to that of the wood. As illustrated in Figures 1-C and 1-E, this is the case for the studied specimens.

According to Muller et al. (2009), in a study on the shear strength of 1C-PUR adhesive-bonded planes, polyurethane adhesives have a lower percentage of wood failure due to their chemical structure and the mechanical properties of the adhesive, exhibiting greater ductility and lower stiffness in the glue line. Additionally, they concluded that it is possible, regardless of the low wood failure, to achieve a stable and reliable bond with the use of this group of adhesives.

According to ASTM D 2559 (2016), the average shear strength of the bonded joint must be at least 90% of the value obtained for the shear strength test of solid wood. In this research, the average shear strength of bonded joints with parallel fibers was 9.36 MPa, equivalent to 77% of the strength presented by solid wood (12.17 MPa). Comparing this to the research conducted by Padilha et al. (2023) the percentage obtained was 86%, indicating slightly better performance for the two-component adhesive. Gonçalves et al. (2016), when comparing the shear strength of *Pinus* sp. wood with the mechanical performance of five different adhesives, found that only three adhesives met the above-mentioned standard threshold: urea-formaldehyde, PVA, and melamine-urea-formaldehyde.

The adhesive used, given that it did not allow performance close to the strength of solid wood, requests further investigation in specific studies, particularly those that seek better combinations of adhesive weight and bonding pressure to achieve better mechanical performance.

5. CONCLUSION

Shear strength was affected by the bonding angle, especially when the shear test was performed under compression loads, and the mechanical performance observed in the shear under compression load tests differed from the performance obtained in the shear under torsional load tests.

The Hankinson formula can be used as an estimator of shear strength under compression load for bonded joints at different angles, but it is not recommended for estimating shear strength under torsional load.

Although not the main objective of the research, the mechanical performance of parallel bonded joints reached only 77% of the strength of solid wood, and the observed wood failure percentages were consistently low for all bonding angles, regardless of the test.

Considering this and other similar research conducted previously by other researchers, there is evidence that the mechanical performance of bonded joints at angles is similar, regardless of the adhesive used.

Given the conditions of this research, it is suggested that similar studies be conducted using other adhesives and other wood species, especially those suitable for reforestation, and additionally, to seek correlations between wood failure percentages and wood density.

AUTHOR CONTRIBUTIONS

Possa D.C. (a): Conceptualization, writing, reviewing, analyzing data, conducting and executing laboratory experiments. Petrauski A.: Conceptualization, writing, reviewing, analyzing data, conducting and executing laboratory experiments. Petrauski M.C.: Reviewing, theoretical and methodological support. Santos A. dos: Writing, reviewing and analyzing data. Petrauski S.M.F.C.: Supervising and executing laboratory experiments. Possa D.C. (b): Reviewing, editing and executing laboratory experiments.

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