World Conference on Timber Engineering Oslo 2023

COLLAGE QUALITY OF BRAZILIAN WOODS FOR USE IN GLUED LAMINATED TIMBER BEAMS

Julio Cesar Molina[1], Natália Andrade Bianchi[2], Felipe Dutra Lisboa [3] Nádia Barros Gomes[4]

ABSTRACT: The glued laminated timber industries in Brazil have been looking for alternatives that improve the quality of their products, by choosing the correct wood used in the composition of the structural elements, type of adhesive, as well as by monitoring the quality of the material's manufacturing process. This study evaluated the percentage of delamination and shear strength of glue lines in glulam beams constructed with Brazilian reforestation woods (pine and eucalyptus) and structural adhesives (Cascophen RS 216M and Polyurethane Jowat 686.60). For that, the Brazilian test method [1] based on the [2] was used. To qualify the percentage of failure in the gluing areas, the ImageJ software was used. Complementary microscopy analyzes were used to evaluate the gluing areas. As a result, it was observed that the best bonding quality results were obtained for pine and eucalyptus woods bonded with Cascophen RS 216M adhesive. There were no statistically significant differences between the shear strengths of the glue lines of the cross sections of the tested beams. The wood density and the adhesive viscosity had an influence on the bonding quality of glulam beams. The microscopic analyzes indicated that pine woods have an anatomical structure that allows better bonding quality.

KEYWORDS: Glulam, Delamination, Glue line strength, Image analysis, Microscopy

1 INTRODUCTION

The correct choice of the "specie/adhesive combination" in the manufacture of the glulam elements is fundamental to guarantee the structural quality of the element in service. In the manufacture of glulam elements, different polyurethane structural adhesives and resorcinol-based adhesives are used, as well as different types of Brazilian woods. The most common species of Brazilian reforestation woods are pine and eucalyptus, [9]. In addition, in Brazil there is a great availability of reforestation woods, [10]. There are several factors that can influence the wood glue quality response with structural adhesives. According [3] an important factor is the density of the wood. Denser woods tend to be more difficult for the adhesive to penetrate. The viscosity of the adhesive is another factor to be considered. Higher viscosities result in greater resistance to movement and, consequently, less ability of the adhesive to penetrate the wood. High viscosity values are undesirable due to the difficulty of uniformly distributing the adhesive over the wood. On the other hand, using low viscosity adhesives can result in a hungry glue line or excessive absorption by the wood [3].

The Brazilian test method [1] for evaluating the quality of bonding is based on the delamination and shear strength tests of the glue lines, proposed by the European standard [2] for the external environment.

This study proposed the evaluation of the bonding quality of glulam beams based on the recommendations of the Brazilian test method [1]. In the manufacture of the glulam beams were used two species of reforestation wood (Eucalyptus and Pine) glued with two different types of structural adhesives: one polyurethane and another based on resorcinol. Complementary microscopy and image analysis tests were realized in the evaluation of the bonding regions of the glulam specimens.

2 MATERIALS AND METHOD

The woods used in gluing the glulam beams (dimensions: 50 mm x 100 mm x 1200 mm) were Eucalyptus salligna (C30) and average density equal to 592 kg/m^3 and Pine elliottii (C25), average density equal 447 kg/m^3, without preservative treatment. For gluing the glulam beams, Cascophen RS 216M (bicomponent) and polyurethane Jowapur 686.60 (single component) adhesives were used. The viscosities considered for the adhesives were those indicated by their manufacturers. The viscosity value of Cascophen RS 216M adhesive varied between 500-1000 Pa.s and of Jowat 686.60 polyurethane adhesive between 10200 ± 2500 mPa.s. All tests were carried out at the Materials Properties Laboratory of UNESP in Itapeva,

[1] Julio Cesar Molina, EESC/USP – São Carlos School of Engineering of the University of Sao Paulo, Brazil, julio.molina@usp.br
[2] Natália Andrade Bianchi, FEG - University of Sao Paulo State, Brazil, nataliabianchi95@gmail.com
[3] Felipe Dutra Lisboa, UNESP - University of Sao Paulo State, Brazil, felipe.lisboa@unesp.br
[4] Nádia Barros Gomes, FEG - University of Sao Paulo State, Brazil, nadia.b.gomes@unesp.br

https://doi.org/10.52202/069179-0100

State of São Paulo, Brazil, [4]. Wood characterization tests and tests to evaluate the bonding quality of the four different specie/adhesive combinations were carried out, in this research, as shown schematically in Figure 1.

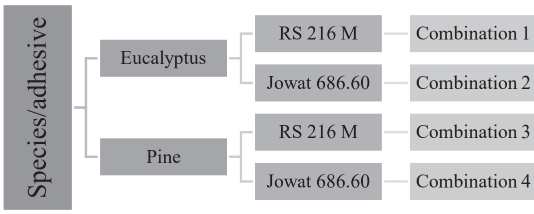

Figure 1: *Specie/adhesive combinations tested in this research*

2.1 GLUING PRESSURE FOR THE BEAMS

The bonding pressures used for the pine and eucalyptus glulam beams with different adhesives were 0.7 MPa (wood density ≤ 0,5 g/cm^3) and 1.2 MPa (wood density > 0,5 g/cm^3), respectively [5]. Pressure values were measured using a torquemeter and the gluing of the beams was made in a floor press (Figure 2). The moisture content of the wooden lamellae at the time of gluing was 12% ± 1% [5]. The glulam beams, after the pressing process, remained at rest for 72 hours for the complete curing of the adhesives and, later, they were machined to remove the specimens for the tests (delamination and shear strength of the glue lines), according to [1].

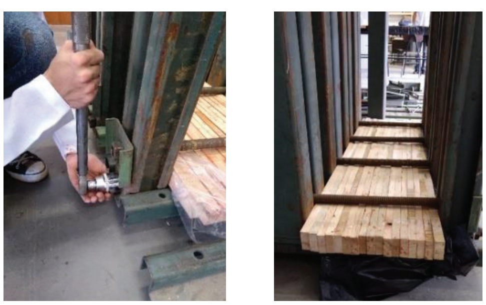

Figure 2: *Pressure control in glulam beams*

2.2 TEST SPECIMENS

All lamellae used in the glulam beams were visually and mechanically graded [5,6]. The lamellae classified in visual Class 1 were positioned at the edge of the cross section (lamellae 1, 2, 4 and 5, Figure 3) while the lamellae classified in visual Class 2 were positioned in the central part of the cross section (lamella 3). Thus, a total of four lines of glue and five lamellae were considered per beam (see Figure 3). The thickness of each lamella was 20 mm [5]. For bonding the glulam beams with the Cascophen RS 216-M adhesive (two-component), the weight considered was 240 g/m^2, applied on a single side of the lamella. A ratio of 10:2 (adhesive:catalyst) was used, i.e., 12 g of adhesive to 2.4 g of catalyst. For the Jowapur 686.60 polyurethane adhesive (one-component), a weight of 200 g/m^2 was used, with the adhesive applied to a single side of the lamella [7].

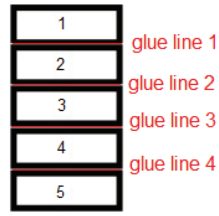

Figure 3: *Cross section of the glulam beams*

The specimens (50 mm x 100 mm x 75 mm) for the delamination and shear strength of the glue lines tests were obtained from the glulam beams, Figure 4. Six glulam beams (B1 – B6) were made for each specie/adhesive combination (total of 24 beams). From each glulam beam, 16 specimens were obtained, 7 for the delamination tests and another 7 for the glue lines shear tests. The two specimens of the edge of the beams were excluded.

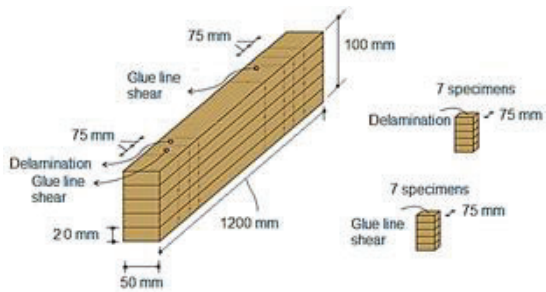

Figure 4: *Specimens for bonding quality tests*

2.3 GLUE LINE SHEAR AS A FUNCION OF POSITION IN THE CROSS SECTION

It was also analyzed whether the glue lines of the glulam beams showed differences of shear strength in relation to the height of the neutral line (LN), as lamellae arrangement shown in Figure 5. Thus, it was verified whether the two lines of glue (2 and 3) from the center of the cross section showed differences with relationship to the two other glue lines (1 and 4) at the edge of the cross section. This analysis was performed with the use of box plots for the values of the pairs of internal glue lines and external, compared to the total number of glue lines in the cross section of each analyzed combination in Figure 1.

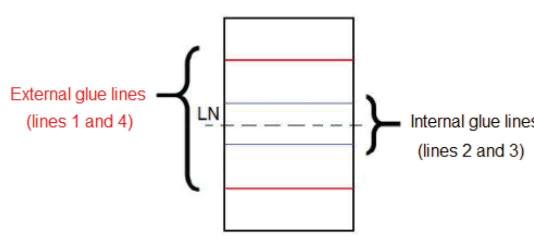

Figure 5: *Internal and external glue lines in the cross section*

https://doi.org/10.52202/069179-0100

2.4 COLLAGE QUALITY TESTS

To evaluate the bonding quality of the specie/adhesive combinations, delamination and shear of the glue lines tests were carried out on the specimens (Figure 4).

2.4.1 Delamination tests

The delamination and shear strength tests of the glue lines were carried out based on the recommendations of the Brazilian test method [1], for external environment, which is based on the European standard [2] and is recommended by the [5]. The delamination specimens initially had their masses determined. At the beginning of the test, the specimens were submerged in water, inside an autoclave, at a temperature of 20 ºC (Figure 6). Then, a vacuum of 80 kPa was applied for 30 minutes. Subsequently, the specimens were subjected to a pressure of 550 kPa for 2 hours. A metallic grid was positioned on the specimens inside the autoclave to ensure that the specimens were submerged in water during the delamination tests. After a single vacuum-pressure cycle, the specimens were placed in a drying kiln at 70 °C. Inside the drying kiln, the air flow had a velocity of 2 m/s and a relative humidity of approximately 8%. During drying, the specimens were spaced 50 mm apart, with the cut cross sections positioned parallel to the air flow. The drying of the specimens continued until the mass of the specimens reached a value between 0% and 10% above the original mass obtained before the autoclave process. The drying process of the specimens in the drying kiln lasted between 19 and 22 hours.

Figure 6: Details of delamination tests

The percentage of total delamination of each specimen was obtained by Equation (1) based on Figure 7.

$$D_T = \frac{L_a}{L_a} x100 \qquad (1)$$

Where:
Dt: total delamination, in %;
La: sum of the length of the opening of all glue lines on the faces of the cross section, in mm;
Lt: total length of all glue lines on the faces of the cross section, in mm.

For all delamination tests, the evaluation of the opening of the glue lines was carried out by measuring the glue lines on the front and back faces of the specimens taken from the glulam element, without considering the delamination of the lateral glue lines. The delamination limit considered for coniferous woods, according to the [1] test method was 4% and 6% for dicotyledonous woods. According to [8] the delamination lengths must be measured on the biggest face of the specimen, which generally correspond to the front and back faces of the cross section of the glulam specimen (Figure 7). In addition, according to method A of the [8] standard, the delamination limit after the third pressure and vacuum cycle is 10%.

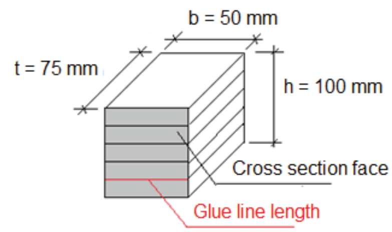

Figure 7: Cross section of the specimen considered in the evaluation of the percentage of delamination

2.4.2 Shear tests of glued lines

The shear strength of the glue lines and the percentage of wood failure in the sheared area were also recorded. The shear strength for the glue lines was obtained through Equation (2). The four lines of glue (Figure 3) were broken by shear for each of the specimens tested. For the shear tests, a metallic device coupled to the EMIC testing machine was used (Figure 8). The percentages of rupture, in the gluing regions, after the shear tests of the glue lines, were quantified using the ImageJ software.

$$f_v = \frac{F_{v,max}}{(b.t)} \qquad (2)$$

Where:
f_v: shear strength of the glue line, in MPa;
$F_{v,max}$: maximum shear load applied to the rupture lamella, in N;
b: width of the specimen, in mm (Figure 7);
t: height of the specimen, in mm (Figure 7).

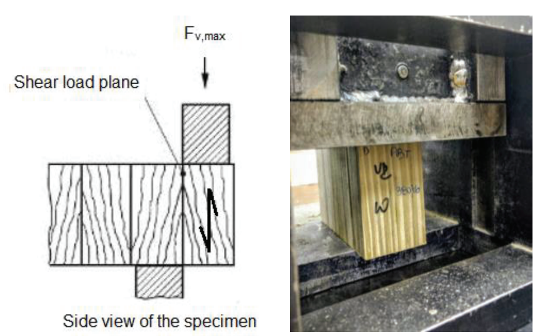

Figure 8: Glue line shear test details

https://doi.org/10.52202/069179-0100

2.4.3 Microscopy analysis

The surfaces of the lamellae before bonding were analyzed using optical microscopy. A LEICA M80 optical microscope with lighting was used.

From lamellas with initial dimensions of 5 x 2 x 120 cm, before gluing the glulam beams, samples with dimensions 50 x 20 x 75 mm were taken to analyze the quality of these surfaces. The variations in the thickness of the glue lines of the glulam specimens were also analyzed by microscopy.

2.5 STATISTICAL ANALYSIS OF THE RESULTS

The delamination and shear strength results of the glue lines were analyzed using the Minitab statistical analysis software. Initially, the normality of the data was verified using the Anderson-Darling test.

Subsequently, an analysis of variance was performed based on Student T test with determination of the p-value. It was verified whether there were significant differences between the means obtained for a significant level of 5%.

3 RESULTS AND DISCUSSION

3.1 DELAMINATION TESTS

Tables 1 and 2 show the delamination results of the glulam beams (eucalyptus and pine) glued with RS 216M and Jowapur 686.6 adhesives, calculated by equation (1).

Table 1: *Average delamination percentages of eucalyptus beams glued with Cascophen RS 216M and Jowapur 686.60 adhesives.*

Beams	Combination 1 (%)	Combination 2 (%)
B1	0.00	6.78
B2	0.42	7.44
B3	1.37	6.95
B4	1.23	6.70
B5	0.00	8.50
B6	0.78	6.91
Average	0.63	7.21

Note: an average of 7 specimens was considered for each glulam beam

Table 2: *Average delamination percentages of pine beams glued with Cascophen RS 216M and Jowapur 686.60 adhesives.*

Beams	Combination 3 (%)	Combination 4 (%)
B1	2.49	0.30
B2	2.40	3.84
B3	2.13	7.99
B4	2.17	1.79
B5	1.70	2.78
B6	2.12	8.97
Average	2.17	4.28

Note: an average of 7 specimens was considered for each glulam beam

The Cascophen RS 216M adhesive showed good delamination results, both for eucalyptus wood (average percentage lower than the 6% limit) and for pine woods (average percentage lower than the of 4%). The Jowapur 686.60 adhesive showed higher viscosity during application on the lamellae. Higher viscosity for the adhesive associated with higher density wood (eucalyptus) resulted in poor bonding quality.

3.2 GLUED LINE SHEAR TESTS

Tables 3 and 4 present the results of shear strength of the glue lines (Equation 2) and respective percentages of failure in the wood obtained for the glued areas (ImageJ).

Table 3: *Results of shear tests of glue lines of glulam beams with eucalyptus woods.*

Beams	Combination 1		Combination 2	
	$f_{v,m}$ (MPa)	FW (%)	$f_{v,m}$ (MPa)	FW (%)
B1	8.94	96.00	8.33	91.00
B2	8.15	95.00	7.13	92.00
B3	9.13	97.00	6.41	92.00
B4	8.51	95.00	7.51	91.00
B5	8.45	95.00	8.98	92.00
B6	8.21	94.00	5.81	89.00
Average	8.41	95.33	7.02	91.20
$f_{v,k}$	5.99	66.73	5.15	63.84
DP	0.36	0,94	1.08	1.07
CV (%)	4.28	0,99	15.38	1.17

Notes: an average of 7 specimens was considered for each glulam beam. $f_{v,m}$= average value of shear strength of the glue lines of the beams; FW= wood failure (ImageJ); CV= coefficient of variation (DP/mean*100); DP = standard deviation; $f_{v,k}$ = characteristic value of shear strength according to [3].

Table 4: *Results of shear tests of glue lines of glulam beams with pine woods.*

Beams	Combination 3		Combination 4	
	$f_{v,m}$ (MPa)	FW (%)	$f_{v,m}$ (MPa)	FW (%)
B1	7.15	86.00	4.26	79.00
B2	434	83.00	4.06	78.00
B3	6.39	85.00	4.71	80.00
B4	8.64	87.00	5.39	81.00
B5	9.10	88.00	5.73	81.00
B6	6.16	84.00	6.13	82.00
Average	7.18	85.50	4.93	80.20
$f_{v,k}$	4.87	59.85	3.54	56.14
DP	1.60	1.71	0.76	1.34
CV (%)	22.28	2.00	15.41	1.67

Notes: an average of 7 specimens was considered for each glulam beam. $f_{v,m}$= average value of shear strength of the glue lines of the beams; FW= wood failure (ImageJ); CV= coefficient of variation (DP/mean*100); DP = standard deviation; $f_{v,k}$ = characteristic value of shear strength according to [3].

For all specie/adhesive combinations (Figure 1), the failure in the collage area occurred in the wood, indicating good gluing results. The average values of the shear strengths of the glue lines were higher for the eucalyptus beams glued with the Cascophen RS 216M adhesive (combination 1) when compared to the values obtained for the beams glued with Jowapur 686.60 adhesive (combination 2). However, from a statistical point of view these differences were not significant (p-value equal to $0.08 > \alpha = 0.05$). For the combinations of the glulam beams with pine woods (combinations 3 and 4), the average shear strengths of the glue lines were statistically significant (p-value equal to $0.03 < \alpha = 0.05$).

3.3 GLUE LINE SHEAR AS A FUNCION OF POSITION IN THE CROSS SECTION

The box-plot graphs for the values of the pairs of internal and external glue lines, compared to the number of total glue lines in the cross section of each analyzed combination are show in Figures 9 to 12.

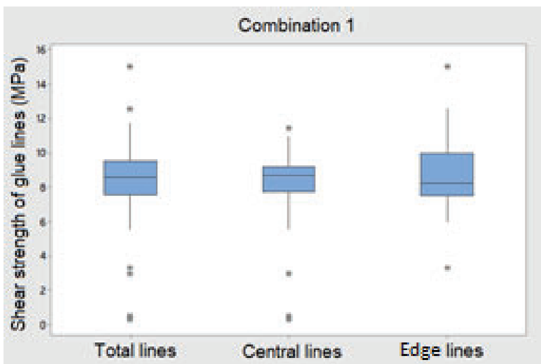

Figure 9: *Box plot of the shear strengths of the glue lines as a function of their location in the cross section (Combination 1).*

For combination 1, the central portion of the graphs showed a median (8.67 MPa) very similar to the glue lines of the extreme regions (8.26 MPa) and the total (8.30 MPa). In addition, the central value showed lower data dispersion (1.46 MPa).

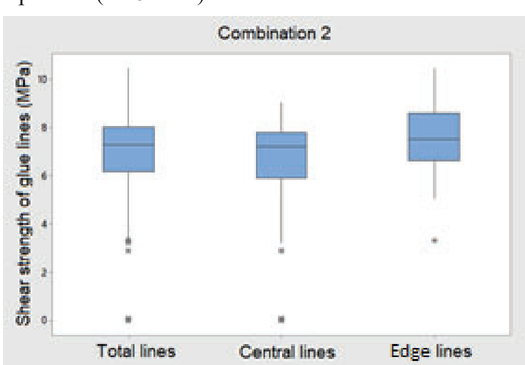

Figure 10: *Box plot of the shear strengths of the glue lines as a function of their location in the cross section. (Combination 2)*

For combination 2, the lines in the central part presented median (7.21 MPa) like the edge lines (7.52 MPa) and total (7.28 MPa). The lines in the central part showed lower data dispersion (1.88 MPa).

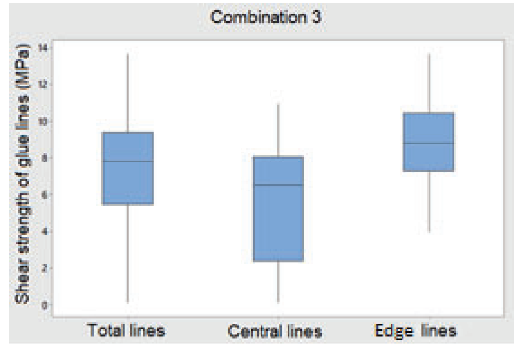

Figure 11: *Box plot of the shear strengths of the glue lines as a function of their location in the cross section. (Combination 3)*

In combination 3 (Figure 12), the median value of the center lines (6.52 MPa) was below the median of the edge lines (8.81 MPa) and total (7.81 MPa). The central lines showed the greatest dispersion (5.67 MPa).

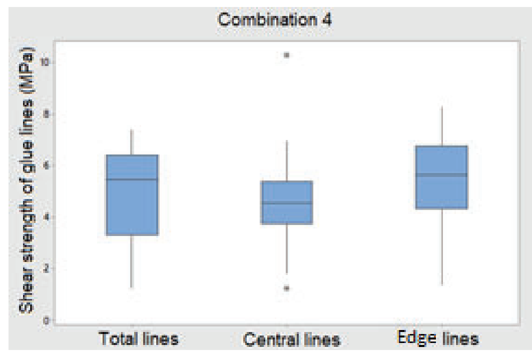

Figure 12: *Box plot of the shear strengths of the glue lines as a function of their location in the cross section. (Combination 4)*

For combination 4, the total glue lines dataset showed a median (5.45 MPa) very close to the edge glue lines (5.62 MPa). However, the central glue lines showed lower data dispersion (1.62 MPa) and median (4.52 MPa) a little lower than the others.

3.4 MICROSCOPIC ANALYSIS

Figure 13 shows the microscopy details of the surfaces of the machined lamellae before bonding.

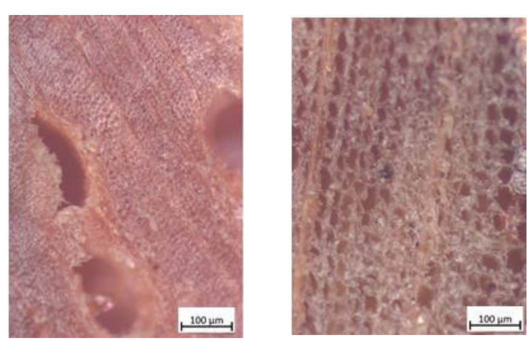

Figure 13: *Microscopy of lamellae surfaces before bonding.*

https://doi.org/10.52202/069179-0100

In the enlarged images of the lamellae surfaces, it was observed that the eucalyptus lamella presented open vessels with irregular shapes. The pine lamella exhibited a more homogeneous surface due to the presence of early and late wood tracheid's distributed throughout the lamella bonding area. The average variation of the thicknesses of the glue lines on the glulam beams are presented in Table 5.

Table 5: *Variation of glue line thickness for different specie/adhesive combinations*

Adhesives	Thickness of glue lines (μm)	
	Eucalyptus	Pinus
RS 216-M	112.8 – 119.9	69.2 – 155.0
Jowapur 686.60	225.1 – 319.0	89.6 – 211.8

When gluing pressure is applied to the glulam element, the adhesive layer acquires a narrow and continuous thickness which should obtain thicknesses between 76 and 152 μm [3]. From the analysis of Table 5, it was observed that, except for glulam elements made with eucalyptus wood and glued with Jowapur 686.60 adhesive (combination 2), all other specie/adhesive combinations (1, 3 and 4) showed variations in the thickness of the glue lines in agreement with the results of the literature [3].

4 CONCLUSIONS

The results obtained from the delamination and shear strength tests of the glue lines indicated that the wood density and the adhesive viscosity are important factors in the gluing of glulam beams.

In general, bonding the wooden lamellas with Cascophen RS 216M adhesive resulted in better bonding quality for the glulam beams. Except for combination 2 (eucalyptus glued with Jowapur 686.60 adhesive), all other combinations presented acceptable delamination limits (< 4% for gluing coniferous wood and < 6% for gluing dicotyledons) according to the Brazilian test method [1].

For all specie/adhesive combinations evaluated, the predominant failure in the specimens' bonding areas, in the shear tests of the glue lines, occurred due to failure in the wood.

In general, the shear strengths (in the glue lines of the glulam specimens made with eucalyptus wood were higher than those obtained for the specimens with pine wood.

There were no statistically significant differences between the shear strengths of the glue lines evaluated in the same cross-section of the specimens. Thus, the number of analyzes in the shear tests of the glue lines can be reduced since the test in the central region of the cross section of the specimen is prioritized, due to the higher concentration of shear stresses.

The microscopic analysis of the surfaces of the wooden lamellae indicated that the pine woods, due to their anatomy, present a greater regularity of the surface with greater porosity provided by the presence of the tracheids of the early and late wood, which facilitates the penetration of the adhesive with respect to eucalyptus woods.

The microscopy analyzes also indicated that, in general, the thickness of the glue lines for the specie/adhesive combinations analyzed agreed with the values in the literature (76 and 152 μm) except for gluing eucalyptus wood with Jowapur 686.60 adhesive.

ACKNOWLEDGEMENT

The authors thank FAPESP (São Paulo State Research Support Foundation, Brazil) for its financial backing of this work. Process number 2017/19974-6.

REFERENCES

[1] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 7190-6: projeto de estruturas de madeira – métodos de ensaio para caracterização de madeira lamelada colada estrutural, 2022.

[2] BRITSH STANDARD INSTITUTION. EN 14080: Timber structures – glued Laminated timber and glued solid timber – requirements, 2013.

[3] Juliana J. B., Angelica C. O. C., João P. S. L., Ana P. M. T., Flavia A. P., Bráulio S. O.: Shear strength in the glue line of Eucalyptus sp. and Pinus sp. wood Revista Árvore, 40(6):1109-1117, 2016.

[4] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 7190-3: projeto de estruturas de madeira – métodos de ensaio para corpos de prova isentos de defeitos para madeiras de florestas nativas, 2022.

[5] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 7190-1: projeto de estruturas de madeira, 2022.

[6] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 7190-2: projeto de estruturas de madeira – métodos de ensaio para classificação visual e mecânica de peças estruturais de madeira, 2022.

[7] BIANCHI, N. A. Avaliação da delaminação e da resistência da linha de cola de elementos de MLC com base no projeto de revisão da norma ABNT NBR 7190:2013 considerando madeiras de reflorestamento tratadas com CCA e sem tratamento preservativo. Dissertação (Mestrado em Engenharia Mecânica). Faculdade de Engenharia de Guaratinguetá, Universidade Estadual Paulista. 77f. Guaratinguetá. 2020.

[8] EUROPEAN STANDARD. EN 391: Glued laminated timber – delamination tests of glue lines, 1995.

[9] Soares, L. S. Z. R.; Fraga, I. F.; Paula, L. S.; Arroyo, F. N.; Ruthes, H. C.; Aquino, V. B. M.; Molina, J. C.; Panzera, T. H.; Branco, L. A. M. N.; Chahud, E.; Christoforo, A. L.; Lahr, F. A. R.: Influence of moisture contente on physical and mechanical properties of cedrelinga catenaeformis wood Bioresources, 16(4):6758-6765, 2021.

[10] Karina, A. O., Carolina A. B., Julio C. M.: Physical, chemical and mechanical characterization of Acrocarpus Fraxinifolius cultivated in Sao Paulo. Maderas-Ciencia y Tecnologia, v. 24, 1-8, 2022.

https://doi.org/10.52202/069179-0100