ISSN impresa 0717-3644
ISSN online 0718-221X

Maderas. Ciencia y tecnología 2024 (26): 2, 1-12

DOI: 10.22320/s0718221x/2024.02

CROSS LAMINATED TIMBER BONDING QUALITY FOR DIFFERENT BRAZILIAN SPECIES AND PRESSING LEVELS

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ABSTRACT

The proper choice of raw materials and manufacturing parameters for Cross Laminated Timber is essential to promote the proper bonding of the lamellas, aiming at their application in construction. However, few Brazilian species are currently used in the production of Cross Laminated Timber. The aim of this work was to characterize the bonding quality of four Brazilian reforestation species (*Pinus elliottii* (pino ellioti), *Eucalyptus grandis* (eucalipto), *Toona ciliata* (toona) and *Acrocarpus fraxinifolius* (lazcar)) in the manufacture of Cross Laminated Timber with two-component polyurethane adhesive and five different pressure levels (from 0,1 MPa to 1,3 MPa). Bonding quality was evaluated through delamination and glue line shear tests based on the European standard. Delamination was affected by the wood species, and the best adhesion occurred for the Cross Laminated Timber manufactured with *Pinus elliottii* (pino ellioti) and *Acrocarpus fraxinifolius* (lazcar) at the bonding pressure of 0,7 MPa. Cross Laminated Timber bonding pressure did not affect the percentage of wood in the shear test fractured surface, whereas higher density Cross Laminated Timber showed higher percentages.

Keywords: Bonding quality, Cross Laminated Timber, delamination, glue line shear strength, reforestation species.

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Received: 18.04.2021 Accepted: 02.08.2023

INTRODUCTION

Cross Laminated Timber (CLT) are rigid, plate-shaped elements, manufactured in layers with 90º fiber alternation, usually in odd numbers (3, 5 or 7) (Jeleč *et al.* 2018, Brandt *et al.* 2019).

The interaction between the various layers and adjacent lamellae of the CLT promotes the homogenization of its mechanical properties, reducing the effect of cracks, grain deviation, nodes and growth rings, so that the stiffness of the final product is compared to the stiffness of reinforced concrete slabs (Buck and Hagman 2018, Pereira and Calil-Junior 2019). These characteristics make CLT a multilayer composite with a plate-like configuration widely used in the civil construction market, especially as elements of slabs, walls and floors (Li 2015, Wang *et al.* 2018).

Large-scale production of CLT in Europe and North America uses almost exclusively coniferous wood and structural adhesives (*e.g.* phenol-resorcinol / melamine formaldehyde, polymeric isocyanate emulsion and mono component polyurethane) (Grandmont *et al.* 2019, Moya *et al.* 2019). On the other hand, in Brazil it is still a new product and CLT is only manufactured with *Pinus* or *Eucalyptus* wood and mono component polyurethane adhesive (Vilela 2020).

However, other species have been evaluated for industrial use as alternatives to *Pinus* and *Eucalyptus* woods (Christoforo *et al.* 2020). Among these species are toona (*Toona ciliata* M.Roem.) and lazcar (*Acrocarpus fraxinifolius* Arn.) which, despite being promising in obtaining solid wood products, have been little studied so far (Braz *et al.* 2013, Faria *et al.* 2019, Oliveira *et al.* 2020a).

Regarding the level of bonding pressure to be used in the manufacture of the CLT elements, there is still no consensus in the Brazilian national industry on the optimum value to be used. Pressing levels can be increased or decreased (*e.g.* when the panel has different raw material from the usual one) as long as the best bonding quality is justified (Grandmont *et al.* 2019). There is also the issue of pressing equipment available, as it could limit CLT's area due to the necessary pressure required for manufacturing.

The bonding pressure is related to the wood species and the adhesive (Oliveira *et al.* 2020b, Yusof *et al.* 2021). Phenol based adhesives require bonding pressure between 1,4 MPa to 2,0 MPa and polyurethane adhesives between 0,01 MPa and 1,0 MPa, according (Oliveira 2018). Thus, new studies are required on levels of bonding pressure of CLT, aiming especially at the effects its properties according to the wood species, for later application at an industrial level. (Brandner *et al.* 2016, Sikora *et al.* 2016, Grandmont *et al.* 2019, Yusof *et al.* 2021).

It is worth mentioning that there is no specific Brazilian standard recommendation for bonding quality tests involving CLT elements. Besides, the bibliography on this subject in the country is still under development.

Therefore, this work aimed to evaluate the bonding quality, of the different wood species, to determine the bonding pressure with the best structural efficiency for CLT. This work also intends to contribute with data for the proposition of the test method PN 02.126.010-6 (2021), related to CLT, which is currently under discussion in the Study Commission - CE 002 126 010, of the Brazilian Association of Technical Standards.

MATERIALS AND METHODS

CLT raw materials and manufacturing process

The wood species used in the manufacture of the CLT came from the city of Riberão Branco - SP, which are: pino ellioti (*Pinus elliottii* Engelm.), eucalipto (*Eucalyptus grandis* W.Hill ex Maiden), toona (*Toona ciliata* M.Roem.) and lazcar (*Acrocarpus fraxinifolius* Arn.). The structural adhesive used was a two-component polyurethane (AG101) produced by KEHL®, with the same chemical properties described by Silva *et al.* (2021).

Five levels of bonding pressure (0,1 MPa, 0,4 MPa, 0,7 MPa and 1,3 MPa) were tested for each wood species, totalizing twenty CLT boards with dimensions of 500 mm x 50 mm x 75 mm (total of 3 layers with lamellae of thickness equal to 25 mm each) manufactured.

The lamellae used were obtained from commercial dimensions planks (3000 mm x 140 mm x 75 mm). These planks were planed and cut-to-length until they reached a cross section of (110 x 50) mm² and a length of 500 mm. The lamellae were conditioned in an environment with controlled temperature and humidity until they reached a moisture content of 12 %. On the day of manufacture of the CLT, the lamellae were planed until they reached sectional dimensions of (100 x 25) mm².

The lamellae were cleaned with compressed air, in order to remove dirt and dust from the planning procedure, and thus, it was ensured that the surfaces were clean before applying the adhesive. The two-component polyurethane adhesive was spread to the surfaces of the lamellae with the use of a brush, in the proportion of 200 g/m², as indicated by Gomes (2018).

The position of the lamellae (outer and central layers) on the board panel was determined according to their visual and mechanical grading, as the ones with best performance and visual grading were positioned on the outer layers. The pressing of the boards were carried out in a mechanical press with pressure controlled by torque wrench.

The pressing step was carried out at room temperature with monitoring and compensation of the applied pressure, whenever necessary, in the first 24 h of gluing in order to maintain the initial value of pressure applied to the boards. Finally, CLT was sanded in a belt sander (grain 120) and had their edges sectioned to remove excess adhesive. Some of the CLT manufacturing procedures are shown in Figure 1.

Figure 1: CLT manufacturing procedures: (a) Adhesive application; (b) CLT pressing; (c) CLT board after sanding; (d) CLT specimens cutting.

Delamination tests

The delamination tests were performed according to the European standard EN 14080 (2013), for outdoor environments, and also based on the recommendations of Betti *et al.* (2016), who suggested the maximum dimensions of the specimens of (80 x 80) mm².

The delamination tests (Figure 2) were performed in an autoclave at room temperature with the application of vacuum and pressure cycles. The test specimens (80 x 80) mm², obtained from the CLT boards, were subjected to the test cycle consisting of: initial vacuum of 80 kPa for 30 minutes; pressure application of 550 kPa for two hours; removal of the autoclave and drying in a drying oven with air and temperature circulation control (65 °C) until their mass reached 100 % to 110 % of its initial value.

Before the pressure and vacuum cycles in the autoclave, all of the delamination specimens had their masses measured as well as all the lengths of the glue lines. Once the delamination tests were finished, the lengths of the glue line openings of the specimens were measured using a caliper with sensitivity of 0,01 mm.

The percentages of delamination for each species and pressure levels evaluated were compared with the limit of 10 % by EN 14080 (2013) for total delamination of the specimen. The delamination percentages were also compared with the limits of 4 % (for hardwoods, *i.e.* toona (*Toona ciliata* M.Roem.), lazcar (*Acrocarpus fraxinifolius* Arn.) and eucalipto (*Eucalyptus grandis* W.Hill ex Maiden) and 6 % (for softwood, *i.e.* pino ellioti (*Pinus elliottii* Engelm.) recommended by the draft standard ABNT NBR PN 02: 126.10-001-5 (2021).

Figure 2: (a) CLT specimen before testing; (b) Autoclave; (c) Specimens drying after pressure cycles; (d) CLT specimen with delamination.

Glue line shear tests

The glue line shear test also followed the methodology recommended by standard EN 14080 (2013), and the specimens had the same dimension as the delamination tests (Figure 2a). The dimensions used for the specimens in the glue line shear tests considered the shear area as well as the capacity of the test metallic device, which was made specifically for this purpose.

The determination of the shear strength in the glue line was carried out in the fabricated metallic device coupled (Figure 3) to a universal testing machine (INSTRON EMIC - 300 kN), ensuring that the failure of the test piece, in the glue line, occurred with a minimum time of 20 seconds.

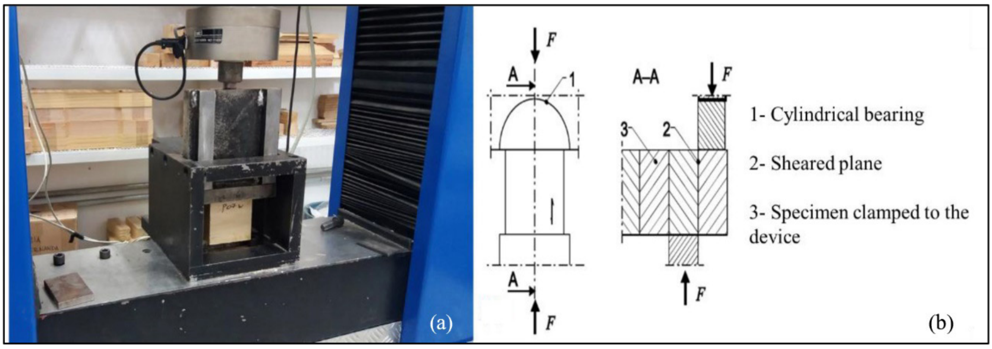

Figure 3: (a) Glue line shear test in progress; (b) Glue line shear strength test proposed by EN 14080 (2013).

Characterization of the shear-broken surface in the bonding region

It was not possible to visually identify the percentage of failure at wood and adhesive (bonding regions) after the shear tests on the glue line, since the polyurethane adhesive becomes translucent after curing. Therefore, a digital image method was required for identifying the amount of wood in the shear broken surface of the bonding region. ImageJ software (Rasband 2021) was used for image processing, after scanning (Figure 4) of the broken bonding regions.

The scanned image was separated into three parts, according to the color spectrum, which were in red, green and blue. It was observed that only the blue color of the spectrum clearly highlighted the region of the image that contained the adhesive. Therefore, only this image was used to determine the percentage of adhesive in the bonding region. Finally, a threshold was performed using the Otsu algorithm, as it presents a better division of the regions with adhesive in relation to the other available algorithms.

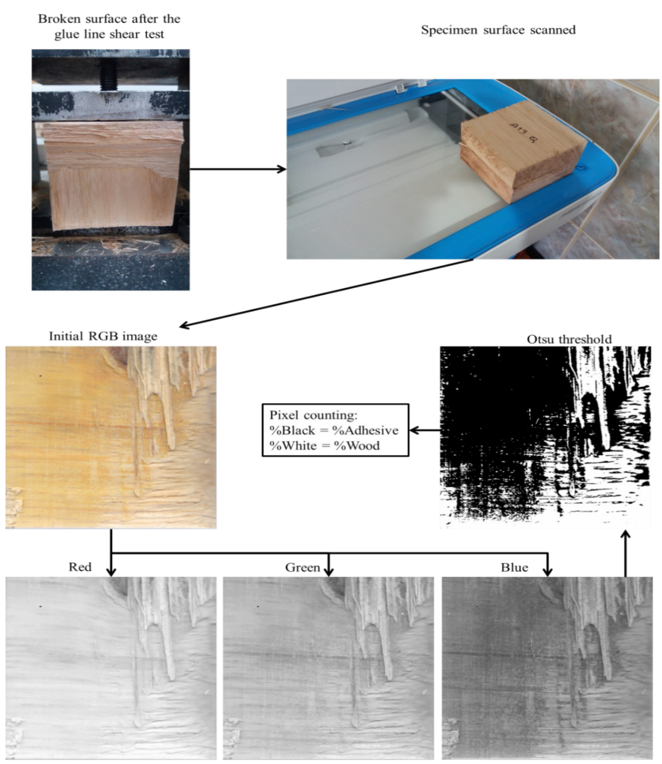

Figure 4: ImageJ method for determining the percentage of failure at wood and adhesive on the broken surface by shearing the glue line.

The percentage of white pixels was counted and considered to be the percentage of wood failure. Special attention should be paid when using this image methodology, because in some cases, regions containing knots or cracks (which have darker tones) can be identified as regions with adhesive.

The comparison of all results was performed by analysis of variance (ANOVA) according to the Tukey test, with a 5 % level of significance. Tests of normality of data and homogeneity of variance were performed using the Shapiro-Wilk and Bartlett tests, respectively. All analyzes were performed with the use of software R version 4.0.4 (2021).

RESULTS AND DISCUSSION

Cross laminated timber density

Table 1 lists the average results of the densities of the CLT specimens, with the analysis of variance and the standard deviation (in parentheses). Lower case letters equal in horizontal and upper-case letters in vertical indicated that there was no significant difference (p-value > 0,05).

Table 1: Density of CLT specimens.

Species	Pressure level					Average
	0,1 MPa	0,4 MPa	0,7 MPa	1,0 MPa	1,3 MPa	
P. elliottii	401a (39)	413a (38)	399a (25)	401a (24)	407a (34)	404C (32)
E. grandis	427b (16)	434ab (18)	445a (26)	433ab (20)	441ab (19)	436B (21)
T. ciliata	353b (14)	367ab (20)	367ab (9)	377a (22)	369ab (27)	367D (21)
A. fraxinifolius	497a (39)	470b (29)	480ab (24)	487ab (16)	490ab (24)	485A (28)
Average	420a (60)	421a (46)	423a (48)	425a (46)	427a (52)	423 (51)

The mean values of the densities of the CLT samples ranged from 353 kg/m³ to 490 kg/m³, and these values differed significantly for each species, where lazcar (*Acrocarpus fraxinifolius* Arn.) and toona (*Toona ciliata* M.Roem.) showed higher and lower density, respectively.

The minimum density required for the production of CLT, in the United States and Canada, is 350 kg/m³ (Grandmont *et al.* 2019). In Brazil, ABNT NBR 7190 (1997) suggests that lamellae with 12 % apparent density between 400 kg/m³ and 750 kg/m³ should be used.

CLT delamination

The delamination observed for the CLT specimens for all pressure tested are shown in Figure 5.

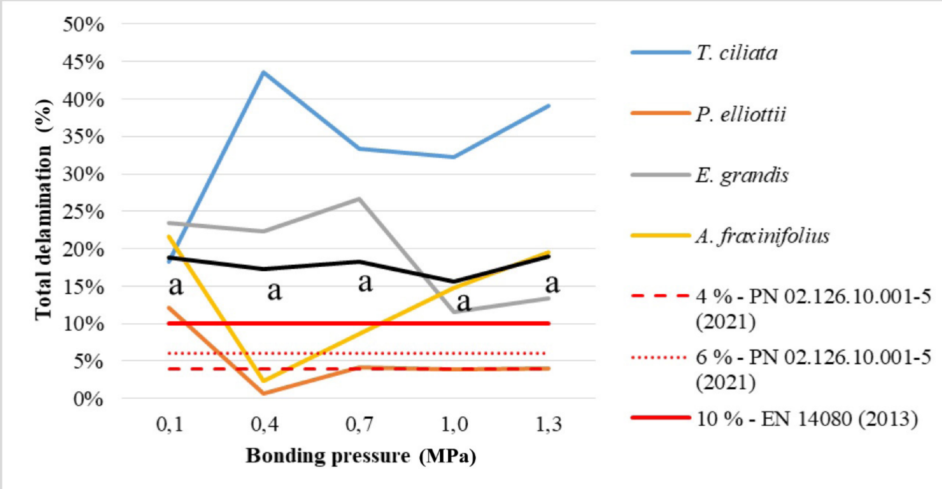

Figure 5: Total delamination of the CLT specimens and standards limits.

The degrees of total delamination varied according to the wood species, being significantly lower in the CLT panels of pino ellioti (*Pinus elliottii* Engelm.) and lazcar (*Acrocarpus fraxinifolius* Arn.). On the other hand, the different pressure levels applied in the manufacture of CLT panels, on tested specimens, did not affect delamination values.

There was a trend of decreased percentage of total delamination, in the pressure range from 0,4 MPa to 1,0 MPa, for CLT made with lazcar (*Acrocarpus fraxinifolius* Arn.) and eucalipto (*Eucalyptus grandis* W.Hill ex Maiden). pino ellioti (*Pinus elliottii* Engelm.) CLT. The total delamination remained practically constant between the pressures from 0,7 MPa to 1,0 MPa. For the CLT made with lazcar (*Acrocarpus fraxinifolius* Arn.), there was a tendency of increase in total delamination from the applied pressure from 0,4 MPa to 1,3 MPa.

Faria *et al.* (2019), using the same delamination method, did not observe delamination in “Glulam elements” manufactured with toona (*Toona ciliata* M.Roem.) and polyurethane adhesive, indicating that the fiber direction of the lamellae in the CLT bonding may affect delamination performance.

The stresses generated due to the swelling and shrinkage of the wood in CLT elements are higher than in Glulam elements, due to restriction of its dimensional variation of the orthogonally arranged layers (Grandmont *et al.* 2019). This increase in stresses can cause a higher level of delamination compared to Glulam samples. Besides, the bonding of wooden elements arranged orthogonally to each other may not be as effective as the bonding of elements arranged in the same direction as the fibers.

According to Oliveira (2018), the CLT with three layers are not watertight, which may have caused a high percentage of delamination in the specimens. On the other hand, according to Betti *et al.* (2016) and Grandmont *et al.* (2019), the levels of retraction and swelling of the wood generate stresses in the glue lines, which are proportional to the sample size. Thus, the high delamination values are also justified by the sample size being larger than those generally used in Glulam specimens.

Shear strength of CLT glue lines

Figure 6 shows the relationship between the pressure level applied in the manufacture of the panels and the characteristic value of the shear strength in the glue line, for each of the species / pressure combinations.

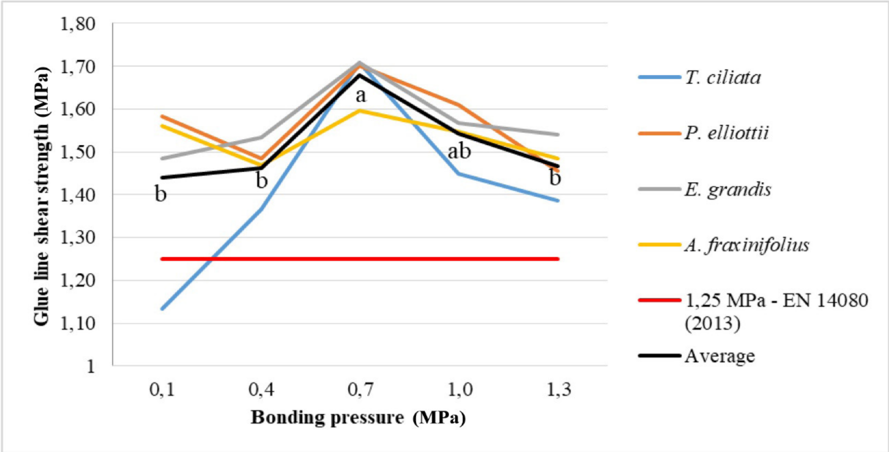

Figure 6: Shear strength in the glue line of CLT specimens.

Unlike the delamination tests, the results of shear strengths in the glue lines were influenced by the manufacturing pressure used. CLT panels bonded with pressures of 0,7 MPa obtained higher glue line shear strength compared to boards manufactured with other pressure values (0,1 MPa, 0,4 MPa and 1,3 MPa). CLT bonded with pressure of 1,0 MPa obtained intermediate results of shear strength on the glue lines.

According to Vilguts *et al.* (2015), the pressure required for the production of CLT must be at least 0,6 MPa, in order to promote an adequate binding of the glue lines. On the other hand, all the wood used in making the panels, in this research, presented apparent densities, for the 12 % moisture content, less than 500 kg/m³. In this context, the revision project of the Brazilian standard for wooden structures ABNT NBR 7190 (1997) recommends to use a bonding pressure of 0,7 MPa, for wooden elements glued with structural adhesives (Glulam and CLT). The percentages of failure at wood, in the bonded region of the CLT specimens, are shown in Figure 7.

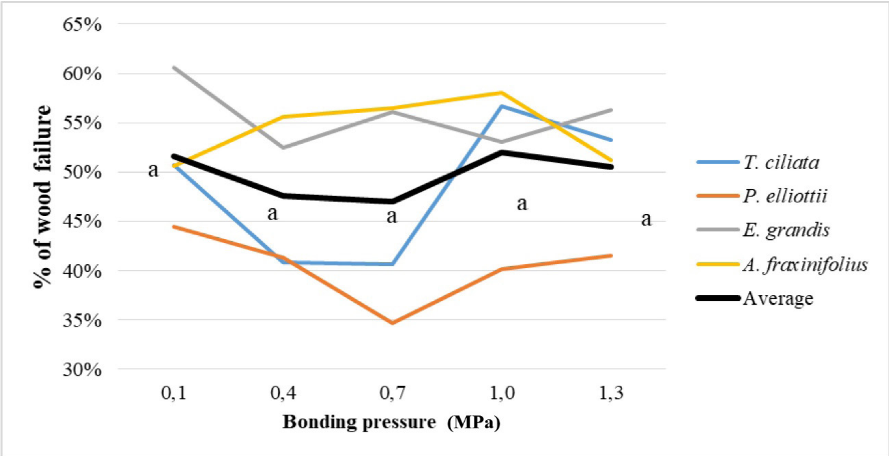

Figure 7: Percentage of rupture in the wood in the bonded region.

No relationship was observed between the glue line shear strength and the percentage of failure at wood in the bonded region, which the values varied from 35 % to 60 %. On the other hand, denser woods lazcar (*Acrocarpus fraxinifolius* Arn.) and eucalipto (*Eucalyptus grandis* W.Hill ex Maiden) showed a higher percentage of failure at wood. The fact that the adhesive is translucent may have contributed to the variability of the results obtained for the determination of the failure percentage at wood. It becomes clear that the use of a dye (when using an adhesive without distinctive tone after its curing) is recommended to better visualize the glue regions, and as long as it does not impair the adhesive bonding performance.

In general, there was no relationship between the density of the species and the quality of the bonding in the manufacture of the CLT, both in the delamination tests and in the shear bond strength tests in the glue line. Other factors may have been predominant in the results obtained, such as the anatomy and the chemical compounds present in each wood species (Vick 1999).

Failure modes obtained in the shear tests of the glue lines

Three types of specimen failures were obtained experimentally after the shear tests of the glue lines (Figure 8), as follows:

Type I failure: Separation of the bonded region (the only ones used in the analysis of the results, ranging from 8 to 24 samples per treatment, totaling 75 % of all the glue lines analyzed);

Type II failure: Failure by compression perpendicular to the grain in one of the layers, that is, there was no separation of the lamellae in the bonded region (totaling 19 % of the glue lines analyzed);

Type III failure: Failure due to incorrect positioning of the specimen at the test device (totaling 6 % of the glue lines analyzed).

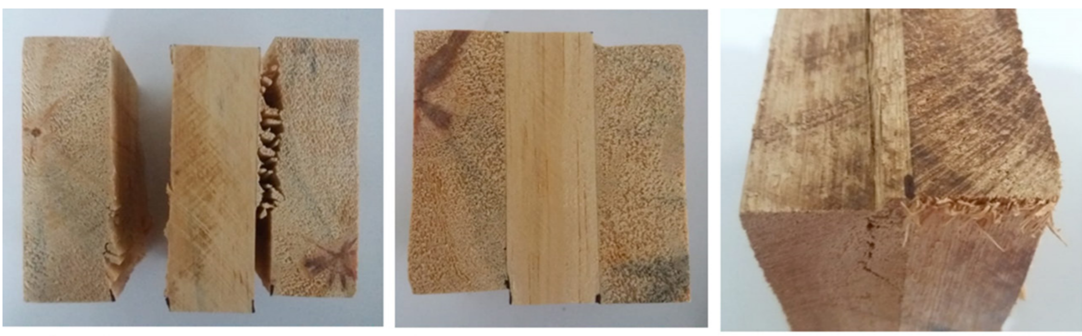

Figure 8: Types of failures observed on specimens after the shear tests of the glue lines.

CONCLUSIONS

The percentages of total delamination on the CLT panels made with *Pinus elliottii* and *Acrocarpus fraxinifolius* woods were lower than the limits (4 % for hardwoods and 6 % for softwoods) established by standard EN 14080 (2013), thus indicating a good species-adhesive interaction. However, the limit of 10 % was shown to be more representative for the analysis of the delamination of the CLT panels when compared with the limits of 4 % and 6 % proposed by the draft standard PN ABNT 02.126.10.001-5 (2021) for Glulam, which is based on standard EN 14080 (2013).

The bonding pressure used in the fabrication had no significant effect on the delamination percentages of the CLT. However, this parameter affected the glue line shear strength, which had a superior performance for the 0,7 MPa pressure value. No relationship was observed between the percentage of wood failure and the bonding pressure applied in the manufacture of the panels, although higher density of CLT specimens showed predominant percentage of failure at wood in the bonding region.

All CLT produced with the four wood species (softwood and hardwoods) presented apparent density (12 % moisture content) less than 500 kg/m³. *Pinus elliottii* and *Acrocarpus fraxinifolius* woods showed good interaction with the bi component polyurethane adhesive in the manufacture of CLT panels, being the most suitable woods for the manufacture with this adhesive.

AUTHORSHIP CONTRIBUTIONS

J. V. F. S.: Conceptualization / Formal Analysis /Funding acquisition / Writing - original draft / Investigation. K. A. D. O.: Methodology / Investigation. C. A. B. O.: Formal Analysis / Writing - review & editing. M. F. F. S.: Methodology / Writing - review & editing. J. C. M.: Conceptualization / Supervision / Funding acquisition / Project administration.

ACKNOWLEDGEMENTS

The authors acknowledge FAPESP (grant #2020/00555-6, São Paulo Research Foundation - Brazil) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - (Finance Code 001) for funding the development of this study.

REFERENCES

ABNT. 1997. Projeto de estruturas de madeira. ABNT 7190. Rio de Janeiro, Brazil.

ABNT. 2021. Madeira laminada colada estrutural: método de ensaio. PN-02:126.10-001-5. Rio de Janeiro, Brazil.

ABNT. 2021. Madeiras - Madeira Lamelada Colada Cruzada estrutural (Cross Laminated Timber): método de ensaio. PN-02:126.10-001-6. Rio de Janeiro, Brazil.

Betti, M.; Brunetti, M.; Lauriola, M.P.; Nocetti, M.; Ravalli, F.; Pizzo, B. 2016. Comparison of newly proposed test methods to evaluate the bonding quality of Cross-Laminated Timber (CLT) panels by means of experimental data and finite element (FE) analysis. *Construction and Building Materials* 125: 952-963. https://doi.org/10.1016/j.conbuildmat.2016.08.113

Brandner, R.; Flatscher, G.; Ringhofer, A.; Shickhofer, G.; Thiel, A. 2016. Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products* 74(3): 331-351. https://doi.org/10.1007/s00107-015-0999-5

Brandt, K.; Wilson, A.; Bender, D.; Dolan, J.D.; Wolcott, M.P. 2019. Techno-economic analysis for manufacturing cross-laminated timber. *BioResources* 14(4): 7790-7804. https://doi.org/10.15376/biores.14.4.7790-7804

Braz, R.L.; Oliveira, J.T.S.; Rodrigues, B.P.; Arantes, M.D.C. 2013. Propriedades físicas e mecânicas da madeira de *Toona ciliata* em diferentes idades. *Floresta* 43(4): 663-670. http://dx.doi.org/10.5380/rf.v43i4.30559

Buck, D.; Hagman, O. 2018. Production and in-plane compression mechanics of alternatively angled layered cross-laminated timber. *BioResources* 13(2): 4029-4045. https://doi.org/10.15376/biores.13.2.4029-4045

Christoforo, A.L.; Aquino, V.B.M.; Govane, J.S.; Dias, A.M.P.G.; Panzera, T.H.; Lahr, F.A.R. 2020. Alternative model to determine the characteristic strength value of wood in the compression parallel to the grain. *Maderas. Ciencia y Tecnología* 22(3): 281-290. https://doi.org/10.4067/S0718-221X2020005000303

EN. 2013. Timber structures – glued Laminated timber and glued solid timber – requirements. EN 14080. Brussels, Belgium.

Faria, D.L.; Cruz, T.M.; Mesquita Júnior, L.; Duarte, P.J.; Mendes, L.M.; Guimarães Júnior, J.B. 2019. Number of laminae on the mechanical behavior of glued laminated timber (glulam) of *Toona ciliata* produced with vegetable polyurethane adhesive. *Ciência e Agrotecnologia* 43: e014819. https://doi.org/10.1590/1413-7054201943014819

Gomes, N.B. 2018. Análise de elementos estruturais de MLC na flexão com base na versão de revisão da norma ABNT NBR 7190:2013. Master Degree Thesis, Universidade Estadual Paulista. Guaratinguetá, Brazil. http://hdl.handle.net/11449/153503

Grandmont, J.F.; Yeh, B.; Dagenais, C. 2019. Introduction to cross-laminated timber. In: *Canadian CLT Handbook*. Karacabeyli, E.; Gagnon, S. (Eds.). FPInnovations: Pointe-Claire, Canada. https://web.fpinnovations.ca/clt/

Jeleč, M.; Varevac, D.; Rajčić, V. 2018. Cross-laminated timber (CLT): a state of the art report. *Journal of the Croatian Association of Civil Engineers* 70(2): 75-95. https://doi.org/10.14256/JCE.2071.2017

Li, Y. 2015. Duration-of-load and size effects on the rolling shear strength of cross laminated timber. Ph.D. Dissertation, University of British Columbia. Vancouver, Canada. http://hdl.handle.net/2429/52397

Moya, L.; Gomar, C.P.; Vega, A.; Sánchez, A.; Torino, I.; Baño, V. 2019. Relationship between manufacturing parameters and structural properties of *Eucalyptus grandis* glued laminated timber. *Maderas. Ciencia y Tecnología* 21(3): 327-340. https://doi.org/10.4067/S0718-221X2019005000305

Oliveira, C.A.B.; Silva, J.V.F.; Bianchi, N.A.; Campos, C.I.; Oliveira, K.A.; Galdino, D.S.; Bertolini, M.S.; Morais, C.A.G.; de Souza, A.J.D.; Molina, J.C. 2020a. Influence of Indian cedar particle pretreatments on cement-wood composite properties. *BioResources* 15(1): 1656-1664. https://doi.org/10.15376/biores.15.1.1656-1664

Oliveira, G.L. 2018. Cross Laminated Timber (CLT) no Brasil: processo construtivo e desempenho: Recomendações para o processo de projeto arquitetônico. Master Degree Thesis, Universidade de São Paulo. São Paulo, Brazil. https://doi.org/10.11606/D.16.2019.tde-09012019-144057

Oliveira, R.G.E.; Gonçalves, F.G.; Segundinho, P.G.A.; Oliveira, J.T.S.; Paes, J.B.; Chaves, I.L.S.; Brito, A.S. 2020b. Analysis of glue line and correlations between density and anatomical characteristics of *Eucalyptus grandis* × *Eucalyptus urophylla* glulam. *Maderas. Ciencia y Tecnología* 22(4): 495-504. https://doi.org/10.4067/S0718-221X2020005000408

Pereira, M.C.M.; Calil Junior, C. 2019. Strength and Stiffness of Cross Laminated Timber (CLT) panels produced with *Pinus* and *Eucalyptus*: experimental and analytical comparisons. *Revista Materia* 24(2). http://dx.doi.org/10.1590/s1517-707620190002.0684

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing: Vienna, Austria.

Rasband, W.S. 2021. ImageJ. U.S. National Institutes of Health: Maryland, USA.

Sikora, K.S.; McPolin, D.O.; Harte, A.M. 2016. Shear strength and durability testing of adhesive bonds in cross-laminated timber. *The Journal of Adhesion* 92(7): 758-777. https://doi.org/10.1080/00218464.2015.1094391

Silva, J.V.F.; Silva, M.F.F.; Ferreira, B.S.; Fiorelli, J.; Christoforo, A.L.; Campos, C.I. 2021. Castor oil based polyurethane adhesive content on OSSB produced with soybean straw. *Ambiente Construído* 21(1): 23-36. http://dx.doi.org/10.1590/s1678-86212021000100491

Vick, C. B. 1999. Chapter 9: Adhesive bonding of wood materials. In: *Wood handbook- Wood as an engineering material*. General technical report FPL - GTR-113. Forest Products Laboratory: Madison, United States of America. https://doi.org/10.2737/FPL-GTR-113

Vilela, R. 2020. Structural performance in bending of cross-laminated timber plates. Master Degree Thesis, Universidade Estadual de Campinas. Campinas, Brazil. http://repositorio.unicamp.br/jspui/handle/REPOSIP/339689

Vilguts, A.; Serdjuks, D.; Pakrastins, L. 2015. Design methods of elements from cross-laminated timber subjected to flexure. *Procedia Engineering* 117: 10-19. https://doi.org/10.1016/j.proeng.2015.08.117

Wang, Z.; Zhou, J.; Dong, W.; Yao, Y.; Gong, M. 2018. Influence of technical characteristics on the rolling shear properties of cross laminated timber by modified planar shear tests. *Maderas. Ciencia y Tecnología* 20(3): 469-478. https://doi.org/10.4067/S0718-221X2018005031601

Yusof, N.M.; Tahir, P.M.; Lee, S.H.; Sabaruddin, F.A.; James, R.M.S.; Khan, M.A.; Lee, C.H.; Roseley, A.S.M. 2021. Thermal properties of *Acacia mangium* cross laminated timber and its gluelines bonded with two structural adhesives. *Maderas. Ciencia y Tecnología* 23(2): 1-10. https://doi.org/10.4067/s0718-221x2021000100402