REVISTA FLORESTA
Universidade Federal do Paraná
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BENDING PROPERTIES OF CROSS-LAMINATED TIMBER PANELS PRODUCED WITH *Pinus taeda* FROM A MOUNTAIN REGION IN SANTA CATARINA, BRAZIL

Rodrigo Figueiredo Terezo[1*], Carlos Augusto de Paiva Sampaio[2], Altevir dos Santos Castro[3], Ângela do Valle[4], Poliana Dias de Moraes[5]

[1*]Universidade do Estado de Santa Catarina, Departamento de Engenharia Florestal, Lages, Santa Catarina, Brasil – rodrigo.terezo@udesc.br
[2]Universidade do Estado de Santa Catarina, Departamento de Agronomia, Lages, Santa Catarina, Brasil – carlos.sampaio@udesc.br
[3]Universidade Estadual do Oeste do Paraná, Departamento de Engenharia Agrícola, Cascavel, Paraná, Brasil – altevir.santos@unioeste.br
[4]Universidade Federal de Santa Catarina, Departamento de Engenharia Civil, Florianópolis, Santa Catarina, Brasil – angela.valle@ufsc.br
[5]Universidade Federal de Santa Catarina, Departamento de Engenharia Civil, Florianópolis, Santa Catarina, Brasil – poliana.moraes@ufsc.br

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Resumo

Propriedades de flexão de painéis em madeira lamelada cruzada produzidos com Pinus taeda proveniente da serra de Santa Catarina, Brasil. O presente trabalho teve como objetivo estudar a resistência à flexão de 6 painéis Madeira Laminada Colada Cruzada (MLCC) produzidos em laboratório utilizando adesivo estrutural de poliuretano reativo e madeira serrada de Pinus taeda. A metodologia do teste foi baseada nas recomendações da norma britânica BS EN 16351 (2015), com amostras medindo 140 x 100 x 4,7 cm. Foi obtido um valor médio de 9640 MPa para o módulo de elasticidade, 30,24 MPa para a resistência à flexão característica e 0,79 MPa para a resistência ao cisalhamento característico. Os custos de produção apresentaram um valor de R $ 89,76 por m², abaixo do custo dos painéis de alvenaria em cerâmica e blocos de concreto. Os testes preliminares com os painéis de CLT atenderam parcialmente aos requisitos da norma, sendo necessária no processo de produção a classificação mecânica da madeira serrada com módulo de elasticidade acima de 12000 MPa.
Palavras-chaves: Painéis; madeira estrutural; madeira colada.

Abstract

The present work had the objective to study the bending strength of 6 Cross-Laminated Timber (CLT) panels produced in the laboratory using reactive polyurethane structural adhesive and *Pinus taeda* lumber. The test methodology was based on the recommendations of the British standard BS EN 16351 (2015), with samples measuring 140 x 100 x 4.7 cm. An average value of 9,640 MPa was obtained for the modulus of elasticity, 30.24 MPa for the characteristic bending strength and 0.79 MPa for the characteristic shear strength. Production costs showed a value of R$ 100.93 per m², below the cost of masonry panels in ceramics and concrete blocks. The preliminary tests with CLT panels partially attended the standard requirements, with the mechanical classification of the lumber with a modulus of elasticity above 12,000 MPa being necessary in the production process.
Keywords: Boards; structural wood; glued wood.

INTRODUCTION

The civil construction sector has negatively contributed to the environment by using materials that consume a lot of energy on a large scale, such as concrete and steel. Wood has a low environmental impact and can be used on a larger scale. The use of new technologies for producing slabs, beams and columns with glued laminated wood can technically replace or coexist with conventional materials, with the final consumption price being a differential (Abed *et al.*, 2022).

Cross-Laminated Timber (CLT) is produced from the juxtaposition of transverse layers of solid wood sheets bonded with a structural adhesive to form large panels, generally consisting of three, five or seven sheet layers with thicknesses ranging from 0.6 cm to 4.0 cm (BS EN 16351, 2015). It is considered a relatively new system for wood construction, introduced in early 1990 in Austria and Germany (MOHAMMAD, 2010).

According to D'Amico *et al.* (2020), the hybrid use of CLT with concrete and steel can reduce the number of greenhouse gas emissions in the construction of residential buildings by around 22%. It is uncertain whether the cost of building with CLT is greater than with other traditional materials.

According to FPInnovations (2011), CLT manufacturing requires a classification of the wood quality used and control of the parameters which influence the performance of the glue line. The most used species in Europe and Canada are Spruce-pine-fir and Norway spruce, and Douglas fir-Larch in the United States (HE *et al.*, 2018; HEMATABADI *et al.*, 2020)). Hochreiner *et al.* (2014) and Sciomenta *et al.* (2021) describe that these species are more commercialized in the main producing countries and that industries classify the boards mostly as C24, C18 or C16 according to EN 338 (2016). However, some hardwood species such as beech, oak and cedar can be used, among others (KARACABEYLI; DOUGLAS, 2013; SCIOMENTA, 2021). When studying tropical woods from Southeast Asia applied for CLT, Corpataux *et al.* (2020) verified that the *A. mangium* and *A. macrophyllus* species obtained superior resistance to the class C24. Although hardwoods have superior quality, softwoods are still the most used in the production of CLT due to their technological development of processing. According to Calil Junior (2014), the most commonly used adhesive is polyurethane. This adhesive is a monocomponent which reacts with the air humidity and the material to be bonded, and the bonding time is an average of 30 minutes.

The CLT industry in Europe practices quality control over raw material in strength classes. This classification guarantees that the mechanical performance of the CLT will occur within strength and stiffness standards as per Eurocode 5 (HOCHREINER et al, 2014; PANG and JEONG, 2019). However, it is not known if there is compatibility of *Pinus taeda* wood planted in Brazil for the CLT product. It is believed that there are different qualities of wood for strength, rigidity and defects between Brazil and Europe.

The bending strength and modulus of elasticity are important parameters for a CLT panel due to their relationship with the dimensioning for transverse loads of slabs and structural walls, being applied by several researchers (HE *et al.*, 2018; HEMATABADI *et al.*, 2020; SCIOMENTA *et al.*, 2021). Considering the development of a product which is compatible with the mentioned characteristics, the present work aimed to evaluate the performance of CLT panels produced with *Pinus taeda* and reactive polyurethane adhesive in static bending, as well as to estimate its manufacturing costs.

MATERIAL AND METHODS

The *Pinus taeda* wood used came from planted forests of the Santa Catarina plateau, being approximately 28 years old. The logs were sawn into 50 boards with dimensions of 300 x 20 x 2 cm, being conditioned in a covered area for 120 days in the Laboratory of Wood Technology in the city of Lages/SC, until balance in its moisture content at 17%. The boards were visually classified according to Southern Pine Inspection Bureau (1994) into 30 pieces between classes SE (special structural without defects) and S1 (structural use with few defects), and 15 pieces between classes S2 and S3 (structural use with acceptable defects limits). The other 5 boards were used to determine the density and moisture content of the lot according to NBR 7190 (1997) with 12 specimens for each physical property.

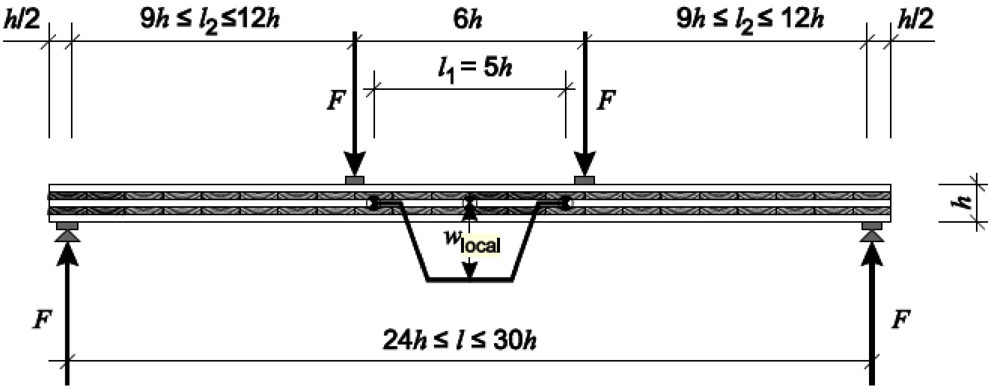
The boards were planed over 24 hours, with a final average thickness of 1.6 cm according to the BS EN 16351 (2015) before gluing in order to open the wood pores. The composition of the CLT occurred with 10 SE pieces to S1 in the first and third layer and 5 pieces of S2 to S3 in the second layer, being randomly distributed in their respective region. No finger-joints were used on the boards.

The Modulus of Elasticity (MOE) of each board was determined by a 3-point non-destructive bending test. A load variation of 70 N was used, corresponding to the estimated elastic regime of the *Pinus taeda* boards.

The adhesive used in the manufacturing was PUR glue from the Kleiberit® company with a weight of 0.2 kg/m² based on reactive polyurethane. The application was in accordance with the manufacturer's specifications and topic 5.1.6.1 of EN 16351 (2015). The bond pressure was controlled with a load cell and HBM® data acquisition system with an average value of 0.6 MPa.

The pressing was in natural temperature with manual grading of the bonding pressure. After being positioned in their respective layers, the boards were restricted laterally to prevent their sliding during pressing. The pressing time was 24 h, followed by 72 h with no pressure to guarantee the adhesive curing.

The final size of the 3 CLT panels was 280 x 100 x 4.7 cm in length x width x thickness. They were subsequently sectioned in the middle, resulting in 6 squared test pieces being produced with final dimensions of 140 x 100 x 4.7 cm. These specimens were submitted to bending tests at four points according to the British standard BS EN 16351 (2015), Figure 1.



In wich: F – load; h – thickness; l – span; and W local – central displacement.

Figure 1. Bending test with cross laminated timber with loads perpendicular to the plane. Adapted from BS EN 16351 (2015).
Figura 1. Teste de flexão em madeira laminada colada cruzada com carregamento perpendicular ao seu plano. Adaptado de BS EN 16351 (2015).

The global Modulus of Elasticity was calculated with the referred equation:

$$MOE = \frac{23}{108} \times \left(\frac{L}{b}\right)^3 \times \left(\frac{\Delta F}{\Delta e}\right) \times \frac{1}{d}$$

In which: L is the span of the sample; b is the thickness of the sample; ΔF is the load increase; Δe is the displacement increase; and d is the width of the sample.

The material and labor inputs were quantified at each production stage of the 3 CLT panels to determine their respective coefficients of productivity and final unit value per m². The material price was taken from the local commerce. Those values were obtained in Lages city, Santa Catarina state on March 2021.

RESULTS

The basic density of the lot was 516.48 kg/m³, having a mean moisture content of 17.31%. The MOE of the boards had an average of 9,472 MPa corrected to the value of 12% of moisture content. The classification representativeness of the board is: 13.33% were classified as SE with an average $MOE_{(12\%)}$ of 10,858 MPa compatible with C22 class strength of EN 338 (2016); 53.33% were classified as S1 with a mean $MOE_{(12\%)}$ of 9,976 MPa as C20 class; 22.22% classified as S2; and 11.11% as S3 with $MOE_{(12\%)}$ of 8,418MPa (C16) and 7,502 MPa (C14), respectively. The mechanical properties of the CLT specimens are listed in Table 1.

Table 1. CLT bending strength values.
Tabela 1. Valores de resistência à flexão do CLT.

CLT Panels	MOR (MPa)	MOE (MPa)	*fv* (MPa)
P 1	25.83	8,624.81	0.67
P 2	28.89	7,786.27	0.75
P 3	30.45	7,998.52	0.80
P 4	33.41	10,423.44	0.87
P 5	26.40	8,810.20	0.69
P 6	24.29	8,648.69	0.63
Mean	28.21	8,715.32	0.73
Standard Deviation	3.37	929.11	0.08
Coef. of variation (%)	11.95	10.66	12.16
$MOR_{(12\%)}$	30.24		
$MOE_{(12\%)}$		9,640.54	
$fv_{(12\%)}$			0.79

In which: MOR = characteristic bending strength in longitudinal direction; MOE = bending modulus of elasticity; and *fv* = shear strength in the bending test; (12%) = values corrected to 12% of moisture content.

Figure 2 shows the relationship between the forces and the displacement of the panels on the four-point bending tests, resulting in a $r^2 = 0.99$. This regular linearity shows that the panels deform approximately 10 mm every 5 kN at a 1:2 ratio.

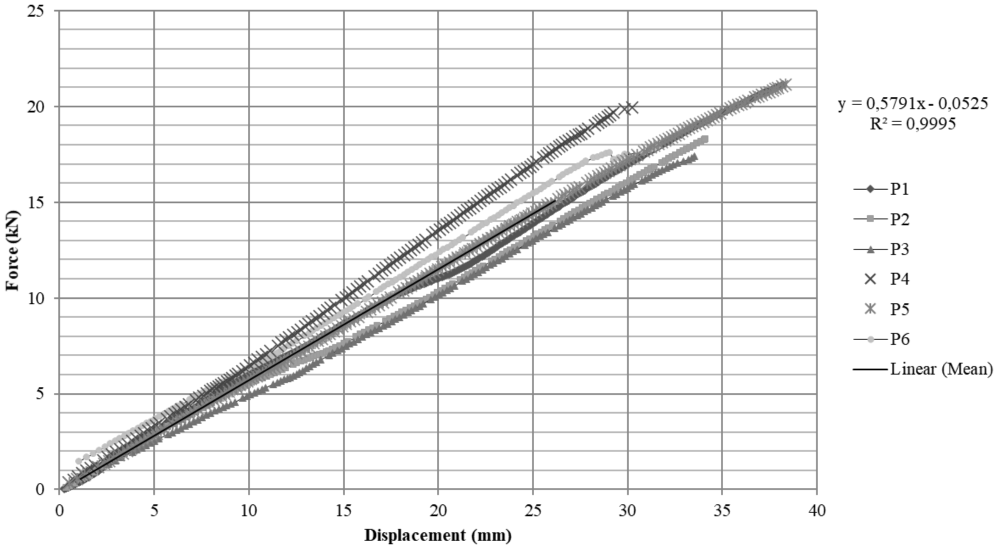


Figure 2. Relation between force and bending displacement in the elastic regime.
Figura 2. Relação entre força e deslocamento na flexão no regime elástico.

Table 2 shows the unit price composition for manufacturing CLT in a laboratorial situation, without considering transport and assembly on construction site.

Table 2. CLT price composition in m².
Tabela 2. Composição de preço por m² para MLCC.

Production Inputs	Unit	Coefficient	Unit Cost (R$)	Total Cost (R$)
Sawn dry pinus wood (piece 2 x 20cm)	m³	0.060	524.69	31.48
PUR Adhesive	kg	0.400	35.00	14.00
Electric Planer	h	0.250	8.89	2.22
Wood Cutting Machine	h	1.500	10.00	15.00
Press bonding	h	0.139	8.00	1.11
Pressing	h	4.000	0.42	1.68
Total Materials and Equipment				65.49
Labor				
Classification	h	0.111	18.75	2.08
Carpenter	h	0.111	18.75	2.08
Assistant	h	0.222	9.38	2.08
Total Labor				6.24
Social Laws	123%			7.68
Indirect Benefits and Expenses	30%			21.52
Overall Cost	R$			100.93

DISCUSSION

The boards visually classified as SE, S1, S2 and S3 had mean values of MOE (12%) compatible with C22, C20, C16 and C14 classes respectively, according to the European standard EN 338 (2016). When studying the use of *Eucalyptus nitens* and *Eucalyptus globulus* for CLT, Pangh *et al.* (2019) concluded that the visual classification underestimates the MOE values of the boards when compared to the mechanical classification. Thus, the wood sampling in the present study has compatible mechanical and visual classes for structural use. However, the moisture content of 17.31% is above that recommended for production, which is 12% + or - 3% according to the Kleiberit® manual use, the CLT Handbook and 12% + or - 2% according to ETA 06/0138 (2012). Free air drying was not sufficient to reach the humidity required for CLT manufacturing.

The result of the bending strength determined in this study is higher than described by ETA 06/0138 (2012), which indicates a minimum value of 24 MPa resistance. However, the same document requires a minimum value of 12,000 MPa for the modulus of elasticity. This shows that the mean elasticity values of *Pinus taeda,* acquired in this study are not compatible with that required by ETA 06/0138 (2012).

In using wood of the *Pinus* genus for producing CLTs, Ecker (2017) obtained values of 10,200 MPa for MOE and of 34.21 MPa for MOR, which are similar to this study. Mirski *et al.* (2020) obtained C32, C28 and C24 strength classes for *Pinus sylvestris* L. boards, constituting classes higher than those found in this work. The CLT produced with C24 wood resulted in an overall MOE of 11,710 MPa and MOR 24 MPa. When studying the *Pinus densiflora* and *Larix kaempferi* species, KIM (2020) obtained MOE of 6,500 MPa and 9,800 MPa, and MOR of 27 MPa and 35 MPa, respectively. For LI *et al.* (2020), the CLT panels with the *Pinus radiate* D. Don species obtained results of 10,770 MPa for the MOE and 31 MPa for the MOR. When producing CLT panels with the southern pine species (*Pinus* spp) in the United States, Sharifnia and Hindman (2017) obtained MOE values of 8,450 MPa and MOR of 17.6 MPa. These conifer species studied by other researchers can be used to produce CLT and revealed similar results to the present study.

The NBR 7190 (1997) rule accepts a range of strength values for sawn wood of up to 18% for axial stresses and 28% for shear. The values found here are below 11% for both axial and shear stresses.

The bending shear strength determined in the CLT panels (0.79 MPa) was lower than the characteristic shear strength parallel to the *Pinus taeda* grain (7.7 MPa), according to NBR 7190 (1997). Thus, the CLT rupture did not occur by shear (0.73 MPa), but by axial tension (28.21 MPa) (shown in Figure 2), demonstrating good cohesion between the panel layers with the PUR adhesive.

The production value of 1 m^2 of the CLT was lower when compared to the concrete block fencing panels (R$ 90.47/m²) and ceramic masonry (R$ 116.36/m²) estimated by the Price Composition Table for Budgets (TCPO, 2018). This shows it to be a competitive product compared to conventional materials. Moreover, this value can be reduced if there is production on a large industrial scale, since the manufacturing process in the laboratory was done manually. The industrialization of panels in ceramic masonry or concrete blocks is not common in Brazil.

CONCLUSION

- It can be concluded that *Pinus taeda* belongs to strength classes which are compatible with structural use according to EN 338 (2016) for CLT production. However, the samples produced did not provide enough elasticity for the CLT to obtain a value compatible with the ETA 06/0138 (2012). Nevertheless, it has more bending strength than required by the same standard.
- The classification and correct positioning of the lumber result in low variability of mechanical strength values, providing standard deviation less than 18%, which is required for structural timber use in axial strength (MOR), and less than 28% for transversal strength (*fv*), by the NBR 7190 (1997).
- The estimated price per m² of the CLT production in the laboratory was lower than the estimated price of ceramic masonry and concrete blocks, thus enabling a potential material to be used in construction works.

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