Mechanical Behavior of Cross-Laminated Timber Panels Made of Low-Added-Value Timber

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Abstract

The cross-laminated timber (CLT) construction system has recently emerged as an excellent alternative for civil construction. The objective of this work is to analyze the structural performance of CLT panels using plantation lumber, especially eucalyptus (*Eucalyptus grandis*) heartwood and pine (*Pinus taeda*). After visual grading, all boards were mechanically graded through the ultrasonic nondestructive testing method. Boards were organized to compose four types of three-layered CLT panels: 1) exclusively eucalyptus heartwood (EEE), 2) eucalyptus in the outer layers and pine in the central layer (EPE), 3) exclusively pine (PPP), and 4) pine in the outer layers and eucalyptus in the central layer (PEP). Three panels with graded timber were manufactured for each type, and one more panel was made out of ungraded timber, so each group had four panels altogether. Panels containing eucalyptus in the outer layers (EEE and EPE) were stiffer than the ones with pine in outer layers (PPP and PEP). However, the first two groups presented lower bending strength than the second ones. Modulus of elasticity and modulus of rupture results were compared to values observed in the literature and to the international standard that regulates CLT (American National Standards Institute/American Plywood Association PRG 320). From the four types studied, only panels containing mostly eucalyptus (EEE and EPE) could meet the PRG 320 E2 class. Panels containing mostly pine (PPP and PEP) did not reach the thresholds of any class in terms of stiffness although their resistance was much higher than that specified in the standard.

Plantation pine and eucalyptus sawn wood is often underutilized for civil construction in Brazil. In general, short-length pieces (up to 1.20 m) are undervalued and intended for use as charcoal and firewood. In the case of eucalyptus, low density, low-quality mechanical properties, and high shrinkage characteristic of the heartwood make this lumber mainly suitable for firewood.

The cross-laminated timber (CLT) system consists of boards glued in transverse layers, resulting in a massive panel with structural features. Initially developed in Austria and Germany in the 1990s, these panels have been used in various types of buildings, both commercial and residential. Furthermore, CLT panels can be used in several ways: exclusively for structure, or in combination with other construction systems such as steel and concrete.

As the main characteristic of CLT panels is their outstanding structural performance in all directions, thus being considered an isotropic structural element (Rivera 2012), the utilization of low-graded timber in CLT could be a way to lower production costs and add value to both eucalyptus heartwood and pine short cuts.

Literature Review

Traditionally, solid wood systems have used wood fibers oriented in one direction, both in vertical and horizontal applications. However, CLT panels are built with superposed layers of timber pieces in a transverse direction in order to increase rigidity and stability. The panel thickness can be three or more layers, as illustrated in Figure 1.

The American National Standards Institute/American Plywood Association (ANSI/APA) PRG 320 (APA 2018) provides grading values of species available in the United States according to their strength in tension, bending, compression, and shear. Based on these figures, the standard

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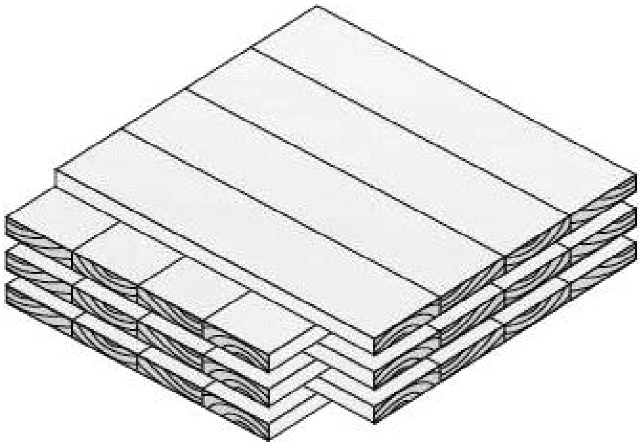

Figure 1.—Configuration of the layers of cross-laminated timber panels. Source: FPInnovations (2011).

requires a minimum structural capacity of CLT panels. Modulus of elasticity (MOE) and modulus of rupture (MOR) must be obtained through mechanical tests on specimens.

A factor that affects the CLT strength is the type of adhesive used in the manufacture of panels, which, according to FPInnovations (2011), is the second most important component of a CLT building system.

Alencar and Moura (2014) tested two adhesives, urea-formaldehyde (UF) and melamine-urea-formaldehyde (MUF), in small shear specimens, as described in ASTM D0905 (American Society for Testing and Materials [ASTM] 1981). Two species and three combinations were tested for the prospective manufacture of CLT panels: pine/pine, eucalyptus/eucalyptus, and pine/eucalyptus. The authors performed tests in both parallel-to-grain and perpendicular-to-grain specimens. Their results showed that UF and MUF had similar shear strength, with MUF having a slight advantage. However, in terms of fracture, and considering only the perpendicular-to-grain glued specimens, MUF outperforms the UF adhesive.

According to the authors (Alencar and Moura 2014), the MUF adhesive was greatly superior to UF in terms of fracture, showing that the penetration of the MUF adhesive in the wood cells was more efficient.

ANSI/APA PRG 320 (APA 2018) determines the values of MOE and MOR for panels made with Canadian and American species. These species are evaluated by both visual and mechanical grading (destructive and nondestructive), also yielding the values of compression and shear according to the two directions of fibers, parallel and perpendicular, to the panel axis.

The minimum design values, according to ANSI/APA PRG 320 (APA 2018), of MOR and MOE in CLT panels made from spruce–pine–fir species, Douglas-fir–larch, and eastern softwoods that are visually and mechanically nondestructively graded, and CLT panels that are only visually graded, are displayed in Table 1.

Table 1.—Bending properties of cross-laminated timber panels.[a,b]

Grading	MOR (MPa)	MOE (MPa)
E1	28.2	11,700
E2	23.9	10,300
E3	17.4	8,300
V1	10	11,000
V2	11.8	9,500

[a] Source: adapted from ANSI/APA PRG 320 (APA: The Engineered Wood Association 2018).

[b] MOR = modulus of rupture; MOE = modulus of elasticity; E = nondestructively graded in parallel layers and visually graded in perpendicular layers; V = visually graded only in both parallel and perpendicular layers.

The resultant minimum values of the MOE and MOR for structural CLT panels issued by ANSI/APA PRG 320 (APA 2018) should not be lower than 8,300 and 10 MPa, respectively.

The use of low-grade timber in CLT has been a concern among researchers. A study by Concu et al. (2014) analyzes the possibility of using low-grade pine for the manufacture of CLT panels. The average dynamic MOE was 8,380 MPa. The average apparent density of the timber was 0.49 g/cm^3. Fifteen five-layer CLT panels were made, and the results obtained in bending tests were 7,913 MPa for MOE and 26.1 MPa for MOR. Concu et al. (2014) believe that these results would be higher if there were no incidence of knots on the boards, as the collapse of the panels corresponds to the alignment of knots.

Sigrist et al. (2014) developed a study using small cuts and full-length pieces of low-grade Australian radiata pine (*Pinus radiata*) to manufacture CLT panels. These pieces, which did not reach the minimum grade for structural use in accordance with the European standards, were placed in different layers of 70 CLT panels, arranged in such a way as to meet the European CLT strength and rigidity requirements that C24 and C16 graded timber classes prescribe.

Four different groups of pine pieces from different regions of the log were organized and graded through both visual and nondestructive methods. Of these four groups, two nonstructural types were used, and one ungraded. The second consisted of only visually graded timber with an average MOE of 7,700 MPa, which reached 12,000 MPa once major defects, such as knots and cracks, were discarded.

The other two groups, having pieces from the densest regions of the log, showed average MOEs of 35,000 and 27,000 MPa for both visually and mechanically graded pieces and for ungraded pieces, respectively. In the study, three-, five-, and seven-layer panels were tested.

The MOR and MOE values obtained in that study for panels with three layers composed of nonstructural pine were 25.5 and 6,251 MPa, respectively. These MOR and MOE results increased to 35.4 and 8,066 MPa, respectively, using the same pieces, but with only visual grading.

The best results were obtained in panels made from mechanically and visually graded lumber, showing 53.1 MPa for MOR and 12,567 MPa for MOE. That study concluded that ungraded nonstructural pine pieces from less dense regions of the log can be used; however, only in the transverse layers of the panels, which are the least important from the mechanical perspective.

The density has a leading role in the mechanical behavior of the panel, and the presence of connections in laminations also affects the mechanical performance.

ANSI/APA PRG 320 (APA 2018) allows lumber with specific gravity greater than 0.35.

Wang et al. (2014) conducted mechanical tests on CLT panels combining different species. Three species were used: Douglas-fir (*Pseudotsuga menziesii*), radiata pine (*Pinus radiata*), and Euro-American poplar (*Populus* × *euroamericana* (Dode) Guinier), with densities of 0.47, 0.45, and 0.41 g/cm^3, respectively.

Five groups of 2.1-m-long and 1-m-wide CLT panels were manufactured with three layers bonded with polyurethane adhesive. Of these five groups of panels, three used Euro-American poplar in the transverse layer, two had pine and Douglas-fir in the longitudinal layers, and one was manufactured entirely with poplar. The others included one completely made of pine and another entirely of Douglas-fir.

The most significant values of the MOR and MOE obtained by Wang et al. (2014) in the bending tests were 44.5 MPa for panels made entirely of pine and 8,690 MPa for panels with Douglas-fir, respectively. The panels made entirely of less dense poplar showed MOR and MOE results of 41.6 and 5,970 MPa, respectively.

The lowest values were observed in panels composed with Douglas-fir in the longitudinal layers and Euro-American poplar in the cross layers, 31.5 and 8,070 MPa for MOR and MOE, respectively. Compared to the results found in panels with only Douglas-fir (MOR: 34.7 MPa; MOE: 8,690 MPa), it becomes clear that this less dense species (Euro-American poplar) in the central layer caused the panel to lower the bending strength and rigidity. The same result was observed for combinations containing pine and poplar in the transverse layer (MOR: 41.2 MPa; MOE: 6,210 MPa), as compared to panels containing only pine (MOR: 44.5 MPa; MOE: 6,350 MPa).

Juvenile wood in general presents lower density in relation to the rest. This was observed by Lima and Garcia (2010) in their research on 21-year-old *Eucalyptus grandis* trees. The density ranged from 0.51 g/cm^3 close to the pith to 0.75 g/cm^3 close to the bark. Similar results were observed by Lobão et al. (2004), who recorded density values ranging from 0.57 to 0.88 g/cm^3 on *Eucalyptus grandis* lumber. In addition, it was expected that eucalyptus boards would contain an elevated percentage of cross grain, a feature of juvenile wood around the pith.

According to the Forest Products Laboratory (USDA Forest Service 2010), cross grain in sawn products often goes undetected by ordinary visual inspection and can reduce the strength of the wood to the levels as low as 20 percent, as compared with normal wood.

Other authors, e.g., Steiger et al. (2012) and Zhou and Chui (2014), conducted studies on CLT using low-density timber and obtained interesting results.

As a summary of the literature review, it was observed that low-graded timber can be successfully used for CLT.

As an indicator of mechanical properties, density must be a parameter to consider, especially because density of the heartwood containing mostly juvenile wood can reach low values influencing stiffness and strength of the panels.

Of high concern is the incidence of defects in the wood. Knots are the main factor influencing the mechanical properties of the panels. Alignment of knots, especially in the tensioned region of the panel (in bending tests) could significantly reduce the strength of the panels. Cross grain is also a concern as a defect. Being visually undetectable, its presence can reduce the strength of the wood to as low as 20 percent in comparison with clear wood.

Grading is an important tool to assess timber mechanical properties allowing for the manufacture of panels with homogeneous and predictable mechanical behavior.

Several adhesives have been used with success. Among them, MUF has been one of those showing good performance and is suitable for CLT panels.

Objective

This study aims to evaluate the mechanical behavior in bending of three-layered CLT panels made from eucalyptus (*Eucalyptus grandis*) heartwood timber and yellow pine (*Pinus taeda*), bonded with MUF adhesive.

Materials and Methods

The materials used in the study were air-dried yellow pine (*Pinus taeda*) boards and ovendried eucalyptus (*Eucalyptus grandis*) boards, both with measured values of 10 percent moisture. The eucalyptus boards were sawn from the heartwood (Fig. 2) of logs coming from planted forests in Telêmaco Borba County, Paraná, Brazil, and were provided by the Tecnomade sawmill. The pine boards were purchased in the market, but also came from Brazilian plantations. The material was stored in the Laboratory of Structures at the Londrina State University. No finger-joined connection was admitted in the laminations. All the laminations were machine surfaced prior to bonding to allow full contact between the layers.

Nondestructive ultrasonic test

The nondestructive (NDT) ultrasonic test was performed on both pine and eucalyptus pieces. The equipment used was the Agricef–USLab model. The output was 700 V through metal-encapsulated transducers, which operated with a frequency of 45 kHz to directly measure the propagation velocity of the waves in microseconds.

In the test, the transducers were placed on the center of the flat face of each end of the boards with an application of a thin layer of approximately 1 mm of gel without alcohol. The length of the eucalyptus and pine boards was 3 m. The dynamic MOE (MOE_d) was determined through the following equation:

$$MOE_d = \rho_{12\%} \cdot V^2$$

where MOE_d = dynamic MOE (10–^{6}MPa); $\rho_{12\%}$ = density of wood at 12 percent moisture (g/cm^3); and V = longitudinal wave velocity (m/s).

Manufacture of CLT panels

The three-layered panels were 1.80 m in length and 0.60 m in width. Each lamination was 19.6 mm thick, totaling a panel thickness of 59 mm. Four types of panels were manufactured, including two single-species types: one composed exclusively of pine (PPP) and another exclusively of eucalyptus (EEE). Two other types combined the two species: one with eucalyptus in the central layer and pine in the outer layers (PEP), and the second having pine in the central layer and eucalyptus in the outer layers (EPE).

The distribution of boards in the panels was performed in such a way as to assemble boards with similar MOE obtained from NDT grading on the boards within each group (Fig. 3). One more category of panels was manufactured from ungraded wood to study the influence of grading on the mechanical behavior of the panels. Altogether, each group

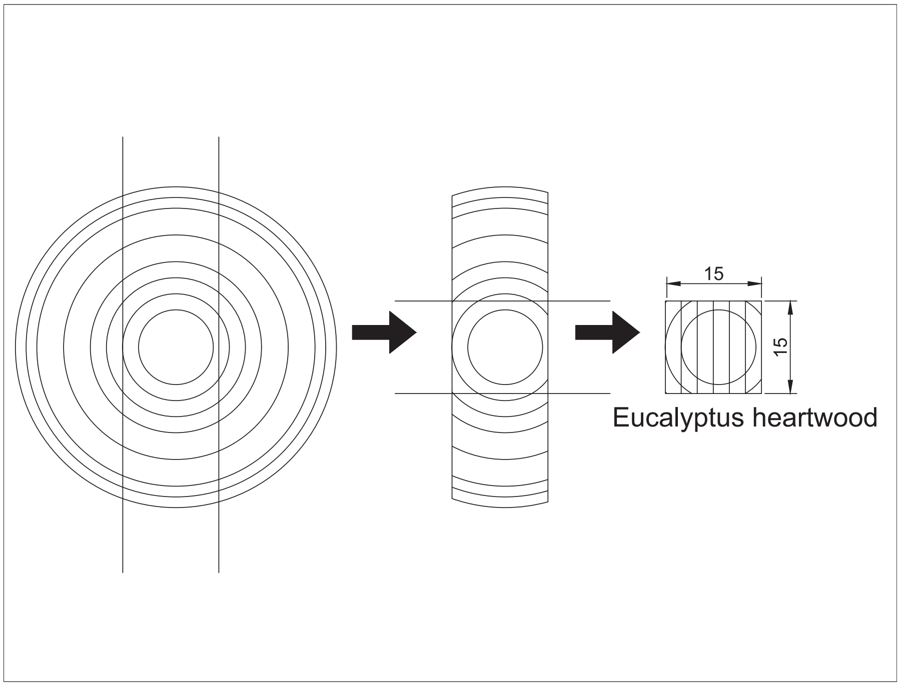

Figure 2.—Eucalyptus heartwood sawing pattern.

had three specimens made from graded timber and the fourth one made of ungraded timber, totaling four specimens per group and 16 panels altogether.

The adhesive used was MUF, and this choice was based on the prior research by Alencar and Moura (2014). The composition of the mixture was 100 parts of resin and 20 parts of the catalyst. The yield suggested by the manufacturer was 400 g/m^2. The layup of the panels was carried out on a metal surface before pressing. To avoid bonding of the boards and metal surface due to excess glue, a plastic sheet was placed underneath the panel.

The first longitudinal layer was composed of six laminations, each 100 mm wide (0.60 m total), placed side by side. The amount of the adhesive per layer was weighed using a precision scale. The adhesive was spread out manually with a spatula. Afterwards, the second layer of perpendicular laminations was added, as shown in Figure 4. Immediately after the placement of the second transverse layer, the adhesive was applied again, and the final layer laid up perpendicularly to the second one.

The ambient temperature at the time of the preparation of the panels was 28°C, and the assembly time was completed in 30 minutes on average (the MUF adhesive manufacturer specifies open time ranges from 50 min at 30°C to 150 min at 15°C). There was no gluing or pressing on the edges of the laminations. Once laid up, the panels were placed on the press trays. The pressing time was 6 hours, and the set pressure was 0.8 MPa according to the standard prescriptions (ANSI/APA PRG 320; APA 2018). Pressing was performed at the ambient temperature.

Testing of CLT panels

The three-layered panel dimensions were 1.80 m in length and 0.60 m in width. The testing equipment was an EMIC DL-30000 model with a 3-ton load capacity (300 KN). The tests were performed at the Londrina State University Laboratory of Materials according to the methodology prescribed in NBR 7190 (Associação Brasileira de Normas Técnicas [ABNT] 1997) Annex B. The testing span was

Figure 3.—Nondestructive grading of timber according to the dynamic modulus of elasticity.

Figure 4.—Layup of the panel.

1.77 m, 30 times the total thickness of the panel (59 mm), according to ANSI/APA PRG 320 (APA 2018).

The loading rate was 10 MPa/min. The load was applied by two twin wooden pieces, perpendicular to the face of the panel, according to the third-point load method described in ASTM D0198 (ASTM 2000), as shown in Figure 5. The loading was performed in three cycles of loading/unloading: in the first two, the load reached the threshold corresponding to 50 percent of the estimated failure load according to Figure 6. This procedure aimed to settle the fibers during the test. The third and last cycle led the panels to failure. The MOE was calculated within the elastic range at 50 percent of the failure load in the second cycle. The whole test time ranged from 10 to 15 minutes for each panel.

Figure 5.—Full-scale bending tests.

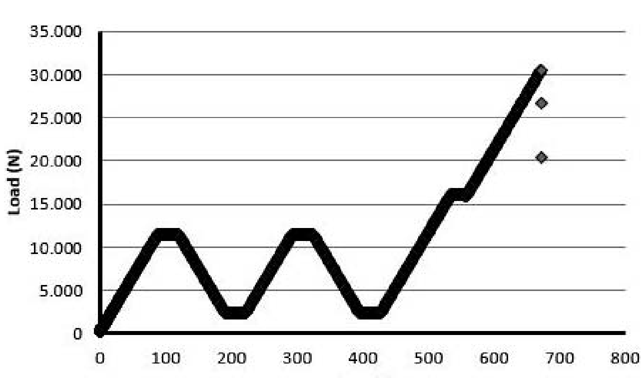

Figure 6.—Cyclic loading pattern.

Results and Discussion

Table 2 shows the results obtained in the NDT ultrasonic grading on pieces of pine and eucalyptus.

Eucalyptus shows a higher average MOE_d than pine (13,216 and 12,502 MPa, respectively), indicating that panels containing eucalyptus in the outer layers should be stiffer than the ones with pine in the outer layers. The eucalyptus timber density was lower than the published values as this material came from the heartwood of logs. Table 3 depicts the result of the MOE and MOR for all panels. As expected, the results show that the two groups with mostly eucalyptus (EEE and EPE) were the stiffest.

In the four groups, it was observed that the ungraded panels presented very similar MOE to the others within the same group, showing that for CLT, defects have a minor impact on the panel stiffness (Table 3: columns 2, 4, 6, and 8).

Confronting Tables 2 and 3, it becomes clear that even though NDT ultrasound overestimates MOE, it still remains a good reference to assess the mechanical properties of timber.

As for the strength, the panels containing mostly pine (PPP and PEP) presented higher bending strength than those containing mostly eucalyptus (EEE and EPE), with 24 MPa average for the first two groups versus 32 and 39 MPa for the third and fourth groups, respectively.

This can be explained by the fact that the eucalyptus wood in this study came from the heartwood of the logs and likely contained a high percentage of visually undetected cross grain. MOR is the mechanical property sensitive to defects, especially knots and cross grain. As higher stresses in bending are concentrated in the external layers, the presence of defects in that position is a determining factor of the ultimate panel load.

Cross grain is caused by winding or spiral growth of wood fibers around the trunk of the tree instead of vertical growth. Depending on the angle of the grain slope, the strength with respect to the parallel-to-grain strength can be as low as 20 percent.

Ungraded timber produces panels whose mechanical behavior becomes somewhat difficult to predict in terms of rupture. Ungraded panel MOR within the PEP group was much lower than MORs of the others in the same group, (19 MPa vs. 39 MPa average, Table 3, column 9), and similar within the others: 22 MPa versus 24 MPa (EEE group;

Table 2.—Dynamic modulus of elasticity (MOE_d), pine and eucalyptus.[a]

Species	Density at 12% moisture (g/cm^3)	V (m/s)	MOE_d (MPa)
Eucalyptus			
Max.	0.57	5,800	19,115
Min.	0.40	3,543	5,029
Mean	0.52	5,033	13,216
SD	0.08	723	3,493
COV (%)	16.2	14.4	26.4
Pine			
Max.	0.55	5,878	18,991
Min.	0.39	3,614	5,096
Mean	0.52	4,849	12,502
SD	0.07	650	3,504
COV (%)	12.8	13.4	28.0

[a] V = longitudinal wave velocity; MOE_d = dynamic modulus of elasticity; COV = coefficient of variation.

Table 3.—Modulus of elasticity and modulus of rupture.[a]

Panel	Group 1 MOE	EEE MOR	Group 2 MOE	EPE MOR	Group 3 MOE	PPP MOR	Group 4 MOE	PEP MOR
1	10,873.5	25.5	10,201.6	24.3	8,604.4	35.8	8,604.4	44.1
2	10,390.7	26.5	10,337.1	21.5	8,354.7	37.9	6,854.0	41.8
3	9,545.9	21.2	9,894.1	24.7	7,373.2	22.0	6,261.3	31.7
Average	10,270.1	24.4	10,144.3	23.5	8,110.8	31.9	7,239.9	39.2
SD	672.0	2.8	227.0	1.7	650.8	8.6	1,218.3	6.6
COV (%)	6.5	11.4	2.2	7.3	8.0	27.0	16.8	16.9
Ungraded	10,115.7	22.1	10,402.1	25.4	8,631.7	32.6	6,265.6	19.2

[a] EEE = eucalyptus–eucalyptus–eucalyptus; EPE = eucalyptus–pine–eucalyptus; PPP = pine–pine–pine; PEP = pine–eucalyptus–pine; MOR = modulus of rupture; MOE = modulus of elasticity; COV = coefficient of variation.

Table 3, column 3); 26 MPa versus 24 MPa (EPE group; Table 3, column 5), and 32 MPa versus 33 MPa (PPP group; Table 3, column 7).

This fact highlights the importance of the grading processes, both visual and nondestructive. The procedure of grading allows improvement in the structural behavior of panels, as well as the predictability of mechanical properties of the components. In terms of predictability, it is important to notice that groups with eucalyptus in the external layers (EEE and EPE) presented lower coefficients of variation for both MOE and MOR, as compared to the ones with pine in the external layers (PPP and PEP). The highest variation concerning MOR was observed in the fourth group (PPP), in which the coefficient of variation was 27 percent.

For the sake of comparison with other studies, Table 4 shows the results reported in the literature. The results observed in this study were consistent with those found in the literature. Although the densities were higher in general (0.51/0.52; Table 2), the MOE and the MOR met the same range of the results reported in Table 4.

In terms of stiffness, all groups in this study presented comparable levels of MOE to those observed by other authors (Table 4). However, for the panels composed mostly of eucalyptus heartwood (EEE and EPE), the individual strength was below that of the panels made from conifers, both graded and ungraded. The panels composed of mostly pine (PPP and PEP) showed an average strength similar to the ones reported.

Considering the results obtained in this research, only panels composed mostly of eucalyptus (EEE and EPE) could meet the E2 and E3 classes defined by PRG 320 (Table 1). Groups PPP and PEP did not reach the minimum stiffness stipulated in the five classes of the standard, although the average flexural strength of both groups exceeded the minimum thresholds significantly (Table 1). That is the case of most results found in the literature (Table 4).

Modes of rupture

Most panels presented failure in the longitudinal laminations located in the tensioned lower layer. Panel 3 (PPP) had the failure in the alignment of knots close to the center of the panel (Fig. 7). That caused the final strength of the panel (22 MPa) to fall significantly below that of the others in the same group, even the ungraded one (Table 3, column 7). The same happened to the ungraded PEP panel (Fig. 8), which recorded a very low MOR of 19 MPa (Table 3). In addition to knots, it also had a high percentage of heartwood lumber (the dark-colored area on the boards).

Panels EPE1 and PPP1 showed failure in the glue line, which apparently did not affect the strength adversely (Fig. 9). That could have happened because of slight differences

Table 4.—Summary of the results found in the literature.[a]

Authors	Species	Density (g/cm^3)	MOE (MPa)	MOR (MPa)
Concu et al. (2013)	*Pinus radiata*	0.49	7,913	26.1
Sigrist et al. (2014)	*Pinus radiata* (ungraded)	Not informed	6,251	25.5
	Pinus radiata (visually graded)	Not informed	8,066	35.4
	Pinus radiata (graded)	Not informed	12,567	53.1
Wang et al. (2014)	*Pinus radiata*	0.45	6,350	44.5
	Pseudotsuga menziesii (finger joined)	0.47	8,690	34.7
	Populus euroamericana (finger joined)	0.41	5,970	41.6
Flaig and Blass (2014)	CLT beams, no finger joint (*Picea abies*)	0.45	12,800	40
		0.40	10,000	32
Steiger et al. (2012)	C24/C20	0.42 0.39	12,000/14,000	—
Zhou and Chui (2014)	Spruce–pine–fir	0.52	10,500	—
Alencar and Moura (present study)	EEE	0.51	10,270.1[b]	24.4
	EPE	0.51/0.53	10,144.3[b]	23.5
	PPP	0.53	8,110.8[b]	31.9
	PEP	0.53/0.51	7,239.9[b]	39.2

[a] MOE = modulus of elasticity; MOR = modulus of rupture; CLT = cross-laminated timber; EEE = eucalyptus–eucalyptus–eucalyptus; EPE = eucalyptus–pine–eucalyptus; PPP = pine–pine–pine; PEP = pine–eucalyptus–pine.

[b] Not including ungraded panels.

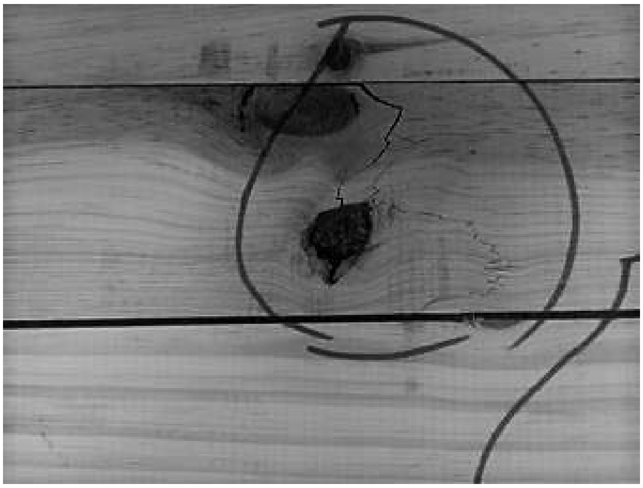

Figure 7.—Panel Group 3 (three layers of pine), rupture in the knot.

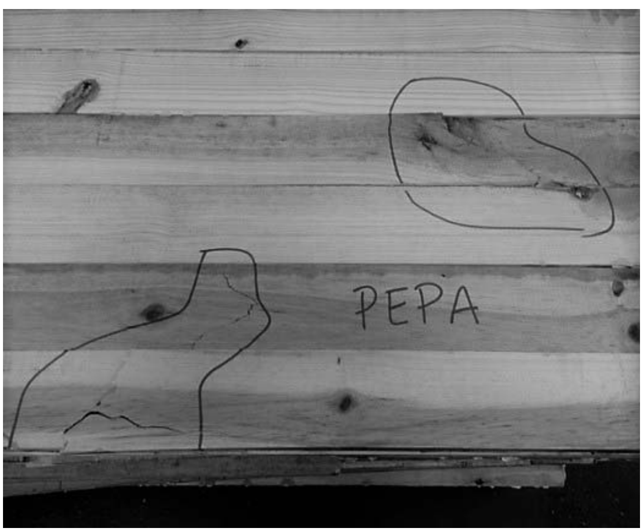

Figure 8.—Ungraded pine–eucalyptus–pine (PEP) panel, failure in the knot.

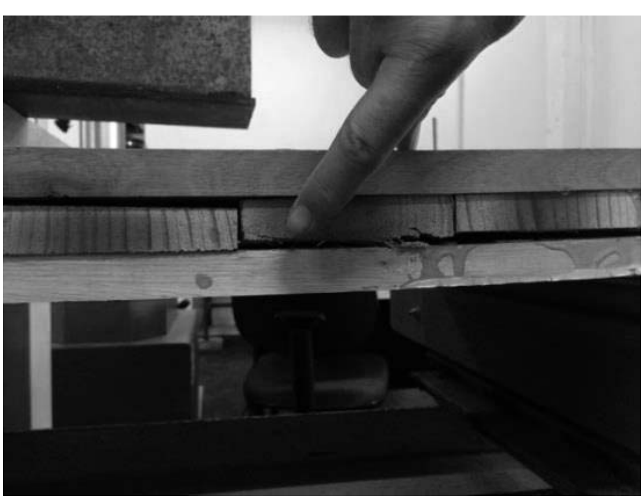

Figure 9.—Failure in glue line of eucalyptus–pine–eucalyptus panel (Panel 1).

in the individual thickness of laminations in the same layer, causing a lack of full contact between the layers.

Conclusion

In this study, 16 CLT panels made from eucalyptus heartwood (*Eucalyptus grandis*) and yellow pine (*Pinus taeda*) timber were submitted to bending tests, and the following conclusions could be drawn.

The results of MOE and MOR observed were comparable to the ones referred to in the literature. The panels made with mostly eucalyptus (EEE and EPE) were stiffer than the ones with mostly pine (PPP and PEP). However, the panels with mostly pine presented higher bending strength. This could be explained by the presence of a high percentage of cross grain in the laminations of eucalyptus.

The results observed indicate that the panels with mostly eucalyptus could meet the E2 and E3 classes established by APA/ANSI PRG 320 (APA 2018). The panels with mostly pine did not reach the thresholds of any of the mentioned standard class in terms of MOE. However, the MOR was much higher than the standard limits.

As most studies found in the literature did not meet any APA/ANSI PRG 320 class, a revision of the standard could be suitable concerning low-graded timber.

The study highlighted the importance of grading the wood. The panels containing ungraded laminations showed unpredictable structural behavior even though the MOE of ungraded panels was similar to or even higher than that of the others in the same group.

Eucalyptus heartwood, a raw material considered inappropriate for structural use by NBR 9487 (ABNT 1986), was confirmed to be technically viable in terms of mechanical behavior in the composition of CLT panels. However, as a function of defects (mostly cracks and knots), the yield was quite low; only 20 percent of the total volume of eucalyptus heartwood timber could be used. Finger-joining laminations could be a means to improve the yield of this material.

Other studies, such as shear, compression, and tensile tests, are necessary to establish low-graded eucalyptus heartwood CLT as a fully engineerable product. Research on the impact of butt-end connected laminations, delamination of panels, the utilization of other varieties of eucalyptus, and the effect of preservation treatments, among other aspects, should be carried out as well.

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