Rolling shear modulus and strength of cross-laminated timber treated with micronized copper azole type C (MCA-C)

Hyungsuk Lim [a], Sachin Tripathi [b], Minghao Li [c]

[a] Faculty, Department of Sustainable Bioproducts, Mississippi State University, 201 Locksley Way, Starkville, MS, 39759, USA

[b] Graduate student, Department of Sustainable Bioproducts, Mississippi State University, 201 Locksley Way, Starkville, MS, 39759, USA

[c] Faculty, Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800 Christchurch, New Zealand

Abstract

The effect of micronized copper azole type C (MCA-C) treatment on rolling shear (RS) strength and RS modulus of cross-laminated timber (CLT) was evaluated. The CLT test specimens were either constructed with untreated 2 x 6 (38 mm x 140 mm) No. 2. southern yellow pine (the United States grown) laminations or MCA-C treated laminations. The shear-free modulus of elasticity (E_{sf}) and longitudinal-radial shear modulus (G_{LR}) of the laminations were non-destructively measured prior to CLT manufacturing. The average E_{sf} and G_{LR} of the untreated lumber were 11.08GPa and 231.42MPa, respectively, while those of the treated lumber were 9.60GPa and 236.01MPa, respectively. Four-point bending test described in EN 16351 standard along with the Shear analogy method was adopted to measure the RS properties. The preservative treatment decreased the mean RS strength, while it increased the mean RS modulus. However, the differences in the means were not significant based on one-way analysis of variance and Kruskal-Wallis H test, respectively. The experimentally obtained bending stiffness of the CLT test specimens and the RS strength estimated using the simplified method described in the CLT Handbook were compared against the values obtained based on the Shear analogy. The agreement between these two approaches indicates that the short-span test setup

implemented in this study and the simplified method can be used for measuring bending stiffness and estimating RS strength of 3-ply CLT.

1. Introduction

Cross-laminated timber (CLT) is a wooden panel product consisting of orthogonally oriented timber laminations typically bonded by structural adhesives. The use of cross-laminations in CLT provides some level of homogeneity in mechanical properties and high in-plane dimensional stability. Since the development of commercial CLT product in early 1990s, it has successfully penetrated the European construction market [1]. The first North American CLT standard, ANSI/APA PRG 320, was developed by APA-The Engineered Wood Associations and FPInnovations in 2011, which was accredited by the American National Standards Institute (ANSI) [2]. The scope of this standard applies to structural CLT products used in dry service conditions [3]. However, the demand for industrial applications such as ground protection and site accesses, where exposure to biodeterioration is inevitable, has been the one of the major drivers of the North American CLT market [4]. Also, additional protection against biological degradation will be required when CLT is used in places with high humidity, such as tropical regions, or environments with high risks of insect infestation. One of the effective methods against the biodegradation risks is to manufacture CLT using preservative-treated laminations [5].

As CLT is made out of timber laminations, it inherits strength and weakness of timber such as low rolling shear (RS) strength and stiffness. In some building applications, RS properties may govern the design of CLT when subjected to high out-of-plane bending or concentrated loading [6]. Thus, RS properties of CLT should be well understood [7]. In European standard EN 16351 [8], for edge-glued CLT manufactured by common softwood, characteristic RS strength ($f_{v,R}$) of 1.1 MPa is specified. In North America, $f_{v,R}$ =1.2 MPa is specified for CLT made out of southern pine [3].

There are multiple test methods for determining RS properties of CLT [9]. Fellmoser and Blass [6] used the beam vibration method to determine RS modulus (G_R) of spruce which lies between 40 MPa and 80 MPa. It was found that shear deformation contributed significantly to the total CLT beam deflection with decreasing span-to-depth (l/d) ratios due to low G_R of timber. Zhou et al. [10] used two-plate shear tests to measure the $f_{v,R}$ and G_R of visually graded No. 3 black spruce (*Picea mariana*) wood which were found to be 1.09 MPa and 136 MPa, respectively. A torsional shear testing method was implemented to evaluate $f_{v,R}$ of spruce-pine-fir (SPF) CLT in which cross layers were machined to have an annular cross-section to facilitate RS failure mechanism [11,12]. Meanwhile, the RS property evaluation methods found in the European and North American CLT standards are short-span bending tests. The bending tests results are analyzed with theoretical models such as the Shear analogy [13] and Gamma [14] methods. For instance, center-point bending tests along with the Shear analogy method were conducted on Radiata pine CLT to evaluate its $f_{v,R}$ of and the influence of different lamination aspect ratios on such property [15,16]. Several studies have confirmed that Shear analogy method is more accurate in deriving $f_{v,R}$ than other analytical models including the Gamma method, Timoshenko beam theory, and Composite theory [17–19].

Previous studies on CLT mechanical properties were mainly focused on untreated CLT [20], and very little research has been conducted to study the mechanical properties of preservative treated CLT. It is well recognized that preservative treatments often adversely affect mechanical properties of wood. The degrees of changes in mechanical properties depend on several factors including species, chemistry of preservatives, and size of material [21].

Chromated Copper Arsenate (CCA) treatment can reduce short-term bending strength of southern pine lumber but has a negligible effect on the bending strength for 12-week duration at the stress level of 40% of short-term strength [22]. Micronized copper azole (MCA) treatment decreased bending strength of rubberwood as the preservative retention increased while its effect on bending stiffness was not evident [23]. Preservatives can also chemically and physically interfere with adhesives during bonding processes [24,25]. Interactions between preservatives, adhesives, and wood fibers are complex, which makes experimental evaluation of bonding performance compulsory for development of preservative treated wood composites. Thus, prior to the presented study, the authors conducted an experimental study to determine the most compatible adhesive system for manufacturing CLT composed of MCA-type C (MCA-C) treated southern yellow pine (SYP) laminations[26].

This experimental study investigates the effect of MCA-C treatment on RS properties, $f_{v,R}$ and G_R, of SYP CLT by conducting the four-point bending tests recommended by EN 16351 standard [8]. Basic properties of timber laminations are pre-assessed before the manufacturing of the CLT specimens. The RS properties of untreated CLT specimens as a control group are also evaluated by the same test setup. The Shear analogy method for composite beams is used to evaluate the RS properties of the treated and untreated CLT specimens. In addition, the validity of a simplified method for $f_{v,R}$ estimation was examined.

2. Materials

Two lumber stacks, each consisting of 128 pieces of 3 m-long visually graded No. 2 2×6 (38 mm x 140 mm) SYP lumber, were supplied by Shuqualak Lumber Co. located in Mississippi. One lumber stack was commercially treated with MCA-C preservative system, which is composed of 96.1% copper, 1.95% propiconazole, and 1.95% tebuconazole [27], using a modified full-cell treatment process at a commercial facility (Tri-state Lumber Co., Fulton, MS), while another stack was stored indoors. The modified full-cell treatment is essentially the same as the full-cell treatment except that it comprises a low-intensity initial vacuum cycle and an additional final vacuum cycle [28]. The lumber were preservative-treated to a target retention level of 2.40 kg/m^3, which is required for UC4A (ground contact or fresh water) applications [27]. Following the AWPA Standard A9-18 [29], the retention level was measured using X-ray fluorescence spectroscopy, which came out to be 2.88 kg/m^3. The preservative treated lumber were kiln-dried at the maximum dry-bulb temperature of 65ºC which was lower than the threshold post-treatment kiln-drying temperature of 74ºC specified in Wood Handbook [30]. The dry-bulb temperature was gradually raised from ambient to 65ºC in the first 5 hours, maintained for 11 hours, and ramped down to 54ºC in the last 8 hours, while the wet-bulb temperature was ramped from ambient to 43ºC in the first 2 hours, maintained for 3 hours, ramped down to 27ºC in the following 11 hours, and maintained for the last 8 hours. Then, the treated lumber were stored indoors for at least two weeks prior to CLT manufacturing. The untreated and treated lumber were visually inspected to discard the ones with significant distortions (bow, crook, or twist), which would cause large variations in the results of the non-destructive bending tests described in the next section. A total of 81 untreated and 80 treated lumber were selected and cut to two 1.37 m-long pieces for shear-free modulus of elasticity (E_{sf}) and longitudinal-radial shear modulus (G_{LR}) measurements. Also, a 26 mm x 26 mm x 38 mm block was cut for moisture content (MC) and oven-dry specific gravity ($SG_{oven\text{-}dry}$) measurements in accordance with ASTM D4442 [31] and ASTM D2395 [32] standards, respectively. The summary statistics of MC and $SG_{oven\text{-}dry}$ of the untreated and treated lumber are provided in Table 1. The average MC and $SG_{oven\text{-}dry}$ of the untreated lumber were 10.87% and 0.50, respectively, while those of the treated lumber were 9.18% and 0.49, respectively. The MC or $SG_{oven\text{-}dry}$ means were not significantly different (p>0.05) from each other based on the ANOVA test described in a later section. This statistical analysis results confirmed the consistency in quality of the lumber. These average MCs were within the optimum MC range of 12±3% recommended in the CLT Handbook [33].

Table 1. Summary statistics of MCs and SGs of untreated and treated lumber

Condition	Sample size (n)	MC		$SG_{oven\text{-}dry}$	
		Mean (%)	COV (%)	Mean	COV (%)
Untreated	81	10.87	7.71	0.50	11.04
Treated	80	9.18	5.61	0.49	9.39

After conducting the non-destructive tests described in the next section, 13 of each untreated and treated panels were manufactured to the final dimensions of 1370 mm (length) × 305 mm (width) × 105 mm (depth) made using 113 and 112 lumber, respectively. The lumber were planed to a lamination of final dimensions of 35 mm (thickness) x 137 mm (width). EN 16351 [8] standard, which was adopted for the CLT bending tests, requires at least two laminations in the face layers, while ANSI/ APA PRG 320 [3] suggests the net width of a face lamination not to be less than 1.75 times its thickness. The width of the CLT panels was determined to be 305 mm which is the minimum width specified in ANSI/ APA PRG 320 Standard [3]. Thus, two thirds of the surface laminations were cut to 84 mm in width, while the cross laminations were cut to 305 mm in length. Each layer of the CLT specimens was composed of laminations with similar apparent modulus of elasticity (E_{app}) to avoid significant variations in mechanical properties between the laminations. Each CLT panel was composed of 6 surface laminations and 10 cross laminations as illustrated in Fig. 1. A commercial primer solution [34] diluted at 5% with water by weight was applied at a rate of 20 g/m^2 to gluing faces of the lamination planed within six hours. One component polyurethane (1C-PUR) adhesive supplied by Henkel was applied at a single-face rate of 150 g/m^2 to the gluing faces 30 minutes after the primer application. Then, the laminations were pressed under 690 kPa for two hours following the adhesive product specifications [35,36]. The manufactured CLT panels were stored indoors for at least a week before conducting the bending tests described in the next section.

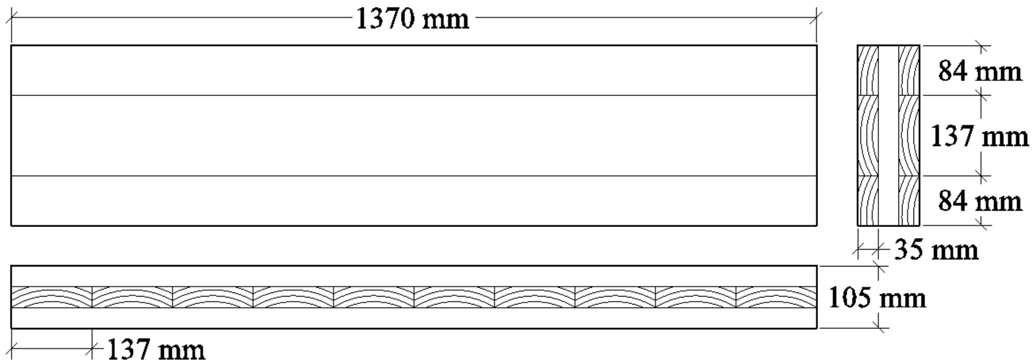


Fig. 1. Orthographic views of a CLT panel

3. Methods

3.1 Non-destructive bending test

Non-destructive edge-wise four-point bending tests were conducted to measure the lamination E_{sf} and G_{LR} properties following ASTM D198 [37]. The 1.37 m-long lumber selected for the CLT manufacturing were tested at a span-to-depth ratio of 9 with a support span (l), loading span, and shear free span (l_{sf}) of 1.26 m, 0.65 m, and 0.53 m, respectively, as shown in Fig. 2. Linear Variable Differential Transformers (LVDTs) were placed 57 mm away from the loading heads towards the center of the test specimen to avoid the influence of stress concentration on shear-free deflection (Δ_{sf}) measurements. The global deflection (Δ_g) was measured using a deflectometer placed at the midspan. The maximum load ($F_{est.max}$) of the lumber was estimated to be 37.4MPa based on the median modulus of rupture (MOR) of No. 2 2× 6 southern pine lumber at MC of 15%, which was reported by Dahlen et al. [38]. The lumber were tested at a loading rate of 1.78 mm/min until the load reached 40% of $F_{est.max}$ (i.e. 12.2 kN) to ensure that the lumber did not undergo permanent deformations before the CLT manufacturing. The changes in Δ_{sf} and Δ_g between 10% and 40% of $F_{est.max}$ were used to calculate

E_{sf} and G_{LR} of each tested lumber, respectively, using the flexure formulas provided in ASTM D198 [37].

Fig. 2. Non-destructive edge-wise four-point bending test set-up

3.2 Bending test of CLT panels

A four-point bending test setup was implemented to evaluate rolling shear (RS) strength ($f_{v,R}$) and RS modulus (G_R) of the CLT specimens as described in EN 16351 [8]. The beam support span was 1.26 m with a span-to-depth ratio of 12, while its shear span, loading span, and shear-free span were 0.63m, 0.63m and 0.53m, respectively. The CLT specimens were simply supported with an overhang of 55mm from each end, and the loads were applied through two loading heads at a constant rate of 1.27 mm/min as shown in Fig. 3. LVDTs were located at center and each end of the shear-free span to measure global (Δ_g) and shear-free (Δ_{sf}) deflections, respectively, along the neutral axis of the specimen, which were used to estimate G_R. The untreated and treated CLT specimens were loaded to 40% of the estimated maximum loads of 76.3kN and 53.4kN, respectively, before the LVDTs were removed. Then, the tests were resumed until failure. The estimated maximum load of the untreated CLT was calculated based on the 5th percentile MOR of No. 2 2× 6 southern pine lumber reported by Dahlen et al. [38], which was 22.2MPa, while that of the treated CLT was calculated based on 70% of the reference MOR of the untreated CLT considering potential strength reduction reported by Barnes [39]. These loads were calculated using Eq. (1) derived based on the simplified method described in CLT Handbook [33]. The panel cross-sections were assumed to be symmetric along their neutral axes and composed of the surface-layers with average E_{sf} parallel to grain presented in Table 2 and the core-layers with E_{sf} perpendicular to grain equal to 1/30 of the E_{sf} parallel to grain [3].

$$P_{est.max} = \frac{4F_b EI_{eff}}{E_1 h\, a} \qquad (1)$$

where F_b is the reference MOR of the outermost layer (i.e. 22.2MPa and 15.5MPa for the untreated and treated CLTs, respectively); E_1 is the is the modulus of elasticity of the outermost layer; h is the thickness of panel; a is the one-half of the shear span; EI_{eff} is the effective bending strength calculated using Eq. (2).

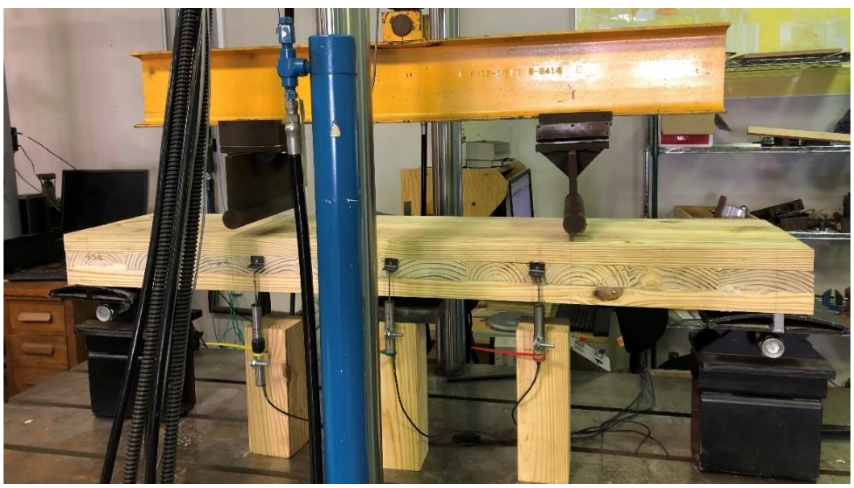


Fig. 3. Four-point CLT bending test setup

3.2.1 Rolling shear modulus and strength calculation according to the Shear analogy method

The Shear analogy method developed by Kreuzinger [13] was implemented for estimating the shear properties of the CLT specimens. The details of this method are provided in numerous publications [40,41]. This method idealizes a CLT panel as a composite system consists of two virtual beams (i.e. Beam A and B) rigidly connected to each other, which displace equally upon out-of-plane loads. Beam A takes the contribution of the flexural stiffness of individual layers into account, while Beam B is responsible for the shear stiffness and the Steiner's component of the moment of inertia of each layer. Thus, the method estimates an effective bending stiffness (EI_{eff}) of a CLT panel using Eq. (2).

$$EI_{eff} = \sum_{i=1}^{n} E_i b_i \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i b_i h_i z_i^2 \qquad (2)$$

where n is the number of layers, E_i is the E_{sf} of the ith layer; b_i is the width of the ith layer; h_i is the depth of the ith layer; z_i is the distance from the neutral axis of a cross-section to the centroid of ith layer.

Since the method assumes that the effective shear stiffness (GA_{eff}) of the composite system comes from Beam B only, it can be calculated using Eq. (3).

$$GA_{eff} = \frac{d^2}{\frac{h_1}{2G_1 \times b_1} + \sum_{i=2}^{n-1} \frac{h_i}{G_i \times b_i} + \frac{h_n}{2G_n \times b_n}} \qquad (3)$$

where d is the distance between the centroids of the outermost layers; G_i is the shear modulus of the ith layer.

GA_{eff} can be also experimentally obtained using Eq. (4), which is established by reorganizing the flexural formula for shear-free MOE provided in ASTM D198.

$$GA_{eff} = \frac{3(P_1 - P_2)}{5\left(\frac{(\Delta g1 - \Delta g2)}{a} - \frac{(3l^2 - 4a^2)(P_1 - P_2)}{48\, EI_{eff}}\right)} \qquad (4)$$

where P_1 is the 40% of $P_{est.max}$ calculated using Eq. (1); P_2 is the 20% of $P_{est.max}$; Δ_{g1} is the global deflection corresponds to the P_1; Δ_{g2} is the global deflection corresponds to the P_2.

Thus, rolling shear modulus, G_R , of a three-layered CLT can be calculated using Eq. (5).

$$G_R = \frac{h_2}{b_2\left(\frac{d^2}{GA_{eff}} - \frac{h_1}{2G_1 \times b_1} - \frac{h_3}{2G_3 \times b_3}\right)} \qquad (5)$$

where GA_{eff} is obtained using Eq. (4); G_1 and G_3 are longitudinal-tangential shear modulus (G_{LT}) of the first and third layers, respectively, which are assumed to be the same as the G_{LR} values obtained from the non-destructive bending test described in the previous section [30]

Rolling shear strength, $f_{v,R}$, of a three-layered CLT can be calculate using Eq. (6), which is derived according to the Shear analogy method as described in details by Winter et al. [41].

$$f_{v,R} = \frac{V_A}{B_A} E_2 \left(\frac{{z_2}^2}{2} - \frac{{h_2}^2}{8}\right) + \frac{V_B}{B_B} E_1 z_1 h_1 \quad (6)$$

where B_A and B_B are the bending stiffness of Beam A and Beam B, respectively; V_A and V_B are the shear forces distributed to Beam A and Beam B, respectively.

3.2.2 Rolling shear strength calculation according to the simplified method using experimentally obtained EI_{eff}

The four-point bending test setup allows to measure Δ_{sf} , which can be used to directly assess $EI_{eff,exp}$ using the flexure formula Eq. (7) in ASTM D198 [37], instead of using the Shear analogy method.

$$EI_{eff,exp} = \frac{(P_1 - P_2)\, a{l_{sf}}^2}{(\Delta_{sf1} - \Delta_{sf2})16} \quad (7)$$

where P_1 is the 40% of $P_{est.max}$ calculated using Eq. (1); P_2 is the 20% of $P_{est.max}$; Δ_{sf1} is the shear-free deflection corresponding to the load P_1; Δ_{sf2} is the shear-free deflection corresponding to the load P_2.

As thoroughly described in CLT Handbook [33], the simplified method can be implemented to calculate effective (Ib/Q) using Eq. (8).

$$(Ib/Q)_{eff} = \frac{EI_{eff}}{\sum_{i=1}^{n/2} E_i h_i z_i} \quad (8)$$

where Q is the first moment of area; z of the layer that consists the neutral axis of the CLT is the distance from the neutral axis to the centroid of the layer's cross section above the neutral axis.

Then, the rolling shear strength, $f_{v,R,\mathrm{sm}}$ can be calculated using Eq.(9) based on the shear formula.

$$f_{v,R,sm} = \frac{P_{max}}{2(Ib/Q)_{eff}} \quad (9)$$

where P_{max} is the maximum load recorded from the four-point bending test.

3.3 Statistical Analysis

The effects of MCA-C preservative treatment on the mechanical properties of 2x6 SYP lumber and three-layered CLT were analyzed using SPSS version 25.0 [42]. The assumptions on normality and homogeneity of variance of the collected data were confirmed by implementing Shapiro-Wilk and Levene's tests, respectively, at $\alpha = 0.05$. If the assumptions were met, one-way analysis of variance (ANOVA) was performed to compare the means of the data sets. Otherwise, the Kruskal-Wallis H test, a non-parametric equivalent of one-way ANOVA, was performed. Both types of analyses were performed at $\alpha = 0.05$.

4. Results and discussions

4.1 Effect of MCA-C treatment on bending and shear stiffness of lumber

Table 2 provides the summary statistics of the four-point bending test results presented in Figs. 4 and 5. of the untreated and the MCA-C treated SYP lumber used as the laminations of the CLT specimens. The average E_{sf}, E_{app}, and G_{LR} of the untreated lumber were 11.08GPa, 7.11GPa, and 231.42MPa, respectively, while those of the treated lumber were 9.60GPa, 6.46GPa, and 236.01MPa, respectively. Based on the Kruskal-Wallis H test, the mean ranks of E_{sf} were significantly different ($p < 0.001$) from each other, while those of G_{LR} were not ($p = 0.225$). Thus, the MCA-C treatment significantly decreased E_{sf} of the SYP lumber, while it did not significantly affect G_{LR}. The G_{LR}/E_{sf} ratios of both types of lumber were less than 0.027 on average. In this research we assumed that $G_{LR} \approx G_{LT}$ [30], and thus the measured shear modulus values can be used as inputs for determining G_R of the CLT specimens using Eq. (5).

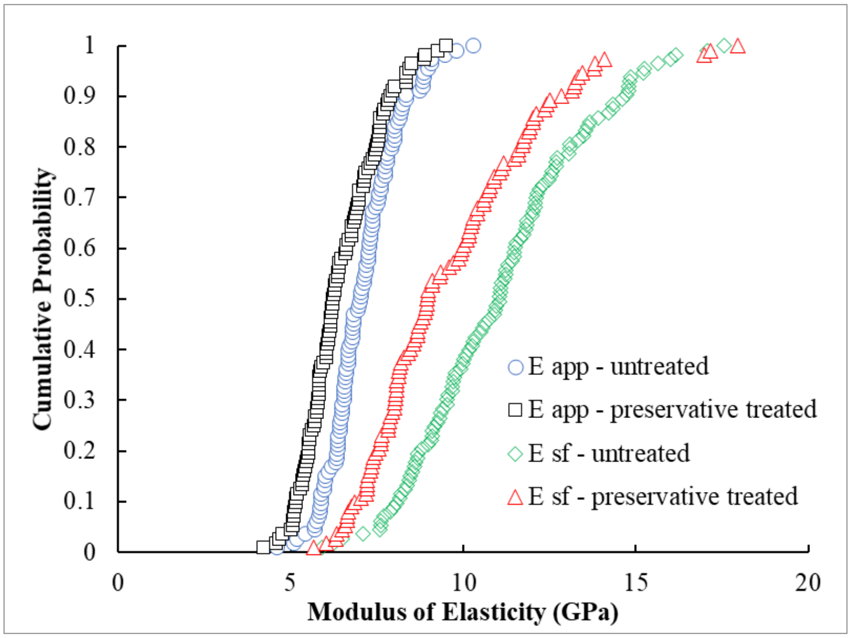


Fig. 4. Cumulative Distribution Function (CDF) plots of the E_{app} and E_{sf} values of the untreated and preservative-treated lumber

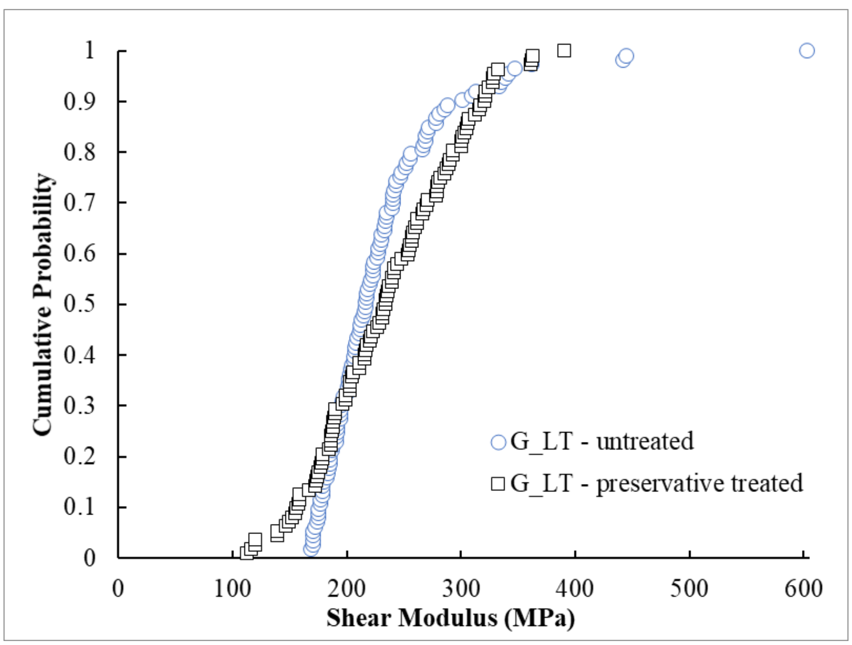


Fig. 5. Cumulative Distribution Function (CDF) plots of the G_{LR} values of the untreated and preservative-treated lumber

Table 2. Summary statistics of bending and shear stiffness of untreated and treated lumber

Condition	Sample size (n)	E_{sf}		E_{app}		G_{LR}	
		Mean (GPa)	COV (%)	Mean (GPa)	COV (%)	Mean (MPa)	COV (%)
Untreated	113	11.08	22.14	7.11	14.38	231.42	27.36
Treated	112	9.60	25.26	6.46	16.87	236.01	26.09

4.2 Effect of MCA-C treatment on RS modulus and strength of CLT

The bending stiffness (EI_{eff}), shear stiffness (GA_{eff}), RS modulus, (G_R), and RS strength ($f_{v,R}$) of the untreated and the treated CLT specimens are presented in Tables 3 and 4, respectively, along with the summary statistics. These mechanical properties were calculated according to the Shear analogy method using Eqs. (2) and (4-6).

Table 3. Mechanical properties of the untreated CLT specimens

Specimen No.	EI_{eff} (10^9 N mm^2/m)	GA_{eff} (10^6 N /m)	G_R (MPa)	$f_{v,R}$ (MPa)
C1	1281.65	9.42	100.85	1.96
C2	954.70	9.52	101.37	1.72
C3	1354.42	12.14	150.22	2.44
C4	967.32	12.64	144.74	2.68
C5	934.01	14.06	181.34	2.35
C6	918.65	10.87	116.90	2.02
C7	862.76	10.25	104.48	1.78
C8	1316.13	12.54	140.39	2.79
C9	1078.68	11.26	116.74	1.70
C10	1231.87	10.67	103.17	2.17
C11	1035.88	12.67	134.90	2.50
C12	821.25	14.78	163.31	1.95
C13	652.14	14.42	159.08	1.96
Mean	1031.50	11.94	132.11	2.16
COV	20.55%	14.99%	20.36%	16.90%

Table 4. Mechanical properties of the MCA-C treated CLT specimens

Specimen No.	EI_{eff} (10^9 N mm^2/m)	GA_{eff} (10^6 N / m)	G_R (MPa)	$f_{v,R}$ MPa
T1	974.37	10.15	122.52	1.62
T2	887.03	12.82	181.39	1.76
T3	996.68	8.96	94.69	1.33
T4	729.67	13.82	172.12	1.81
T5	724.73	16.52	246.36	1.58
T6	1069.07	13.24	157.93	2.06
T7	943.77	9.50	98.26	1.61
T8	900.86	15.59	174.39	1.87
T9	768.84	10.97	115.07	2.24
T10	1028.69	10.92	107.82	1.55
T11	1255.61	7.86	80.89	2.00
T12	865.98	9.48	108.20	2.41
T13	781.59	19.32	260.79	2.51
Mean	917.45	12.24	147.72	1.87
COV	16.55%	27.53%	38.91%	18.98%

As expected from the non-destructive test results of the lumber, the mean EI_{eff} of the untreated CLT specimens (1031.50 x 10^9 N mm^2/m) was higher than that of the treated CLT specimens (917.45 x 10^9 N mm^2/m). However, the preservative treatment increased the mean GA_{eff} from 11.94 x 10^6 N / m to 12.24 x 10^6 N / m. The mean G_R of the untreated CLT specimens was 132.11 MPa, which is greater than the G_R range of Norway spruce (i.e. 40 to 80MPa) reported by Fellmoser and Blass [6] and close to the one of edge-glued 38mm-thick black spruce cross layer (i.e. 136MPa) [10]. In general, G_R values of the MCA-C treated specimens were greater than those of the untreated specimens, which were characterized with a relatively large coefficient of variation (COV). The mean $f_{v,R}$ of the untreated CLT specimens was 2.16 MPa, which sits between the $f_{v,R}$ values of 3-ply SYP CLT obtained from center-point load bending tests (1.83 MPa) and two-plate shear tests (2.34 MPa) reported by Cao et al. [40]. The MCA-C treatment reduced the mean $f_{v,R}$ by 13% to 1.87 MPa, which is still greater than the $f_{v,R}$ of 3-ply Radiata pine CLT composed of cross laminations with an aspect ratio of 4.1 [16]. Despite the described differences between the shear properties of the untreated and the treated CLT specimens, the preservative treatment did not significantly affect either G_R (p = 0.11) base on the Kruskal-Wallis H test or $f_{v,R}$ (p = 0.06) based on the one-way ANOVA analysis. Also, these experimental results confirmed that the Allowable Stress Design reference G_R of 60.33MPa and $f_{v,R}$ of 0.38 MPa provided in the ANSI/APA PRG 320 standard [3] are conservative.

4.3 A simplified approach for RS strength calculation

The $EI_{eff,exp}$ and $f_{v,R,\mathrm{sm}}$ of the untreated and the treated CLT specimens obtained using Eqs. (7) and (9) are presented in Tables 5 and 6, respectively, along with their comparisons against the ones calculated using the Shear analogy method.

Table 5. Experimentally obtained bending stiffness and RS strength of the untreated CLT specimens following the simplified method

Specimen No.	$EI_{eff,exp}$ (10^9 N mm^2/m)	$f_{v,R,\mathrm{sm}}$ MPa	EI_{eff} /$EI_{eff,exp}$	$f_{v,R}$ /$f_{v,R,\mathrm{sm}}$
C1	1086.94	2.33	1.18	0.84
C2	918.39	1.81	1.04	0.95
C3	1377.36	2.06	0.98	1.18
C4	948.62	2.38	1.02	1.13
C5	940.33	2.27	0.99	1.04
C6	826.73	2.16	1.11	0.94
C7	856.40	1.77	1.01	1.01
C8	1231.26	2.68	1.07	1.04
C9	921.03	2.22	1.17	0.77
C10	1213.26	2.16	1.02	1.01
C11	944.28	2.38	1.10	1.05
C12	859.93	1.90	0.96	1.03
C13	684.30	2.09	0.95	0.94
Mean	1010.38	2.17	1.05	1.00
COV	18.91%	11.69%	7.12%	11.01%

Table 6. Experimentally obtained bending stiffness and RS strength of the MCA-C treated CLT specimens following the simplified method

Specimen No.	$EI_{eff,exp}$ (10^9 N mm^2/m)	$f_{v,R,\mathrm{sm}}$ MPa	EI_{eff} /$EI_{eff,exp}$	$f_{v,R}$ /$f_{v,R,\mathrm{sm}}$
T1	896.35	1.84	1.09	0.88
T2	873.44	1.84	1.02	0.96
T3	901.13	1.54	1.11	0.87
T4	767.93	1.76	0.95	1.03
T5	730.79	1.59	0.99	0.99
T6	1008.95	2.26	1.06	0.91
T7	804.70	1.96	1.17	0.82
T8	922.36	1.87	0.98	1.00
T9	728.61	2.44	1.06	0.92
T10	1308.78	1.27	0.79	1.23
T11	1148.03	2.35	1.09	0.85
T12	777.80	2.82	1.11	0.86
T13	899.17	2.22	0.87	1.13
Mean	905.74	1.98	1.03	0.94
COV	18.61%	21.33%	10.34%	12.46%

Although the test setup was recommended for examining shear properties of CLT [8], the $EI_{eff,exp}$ values of both treated and untreated CLT specimens were in a good agreement with those obtained using the Shear analogy method as presented in Tables 3 and 4. The differences between the $EI_{eff,exp}$ and EI_{eff} values of 85% of the untreated and treated CLT specimens were less than 15%, while the differences between their mean values were 2.09% and 1.29% for the untreated and treated CLT specimens, respectively. Similarly, the differences between the $f_{v,R,\mathrm{sm}}$ and $f_{v,R}$ values of 77% of the untreated and treated CLT specimens were less than 15%, while the differences between their mean values were 0.59% and 5.43% for the untreated and treated CLT specimens, respectively. Also, based on one-way ANOVA analysis, the mean $EI_{eff,exp}$ and $f_{v,R,\mathrm{sm}}$ values were not significantly different from EI_{eff} and $f_{v,R}$, respectively. Thus, the test setup adopted in this study can be reliable for measuring effective bending stiffness and estimating rolling shear strength of 105mm-thick 3-ply CLT along with the simplified method.

4.4 Failure modes

The core layers within the shear zones of all untreated and treated CLT specimens experienced typical RS failure as shown in Fig. 6, which progressively occurred following the general sequence described in Cao et al.[40]. As illustrated in Fig. 7 and Fig. 8, the load-deflection curves of the untreated and the treated CLT specimens were linear up to approximately 70% of their maximum loads. Then, the curves became nonlinear as shear cracks formed in the core layers at inclined angles. The nonlinearity became more severe as the shear cracks propagated towards the glue lines. Eventually, the wood fibers surrounding the cracks fractured in a brittle manner, which caused the sudden load drops.

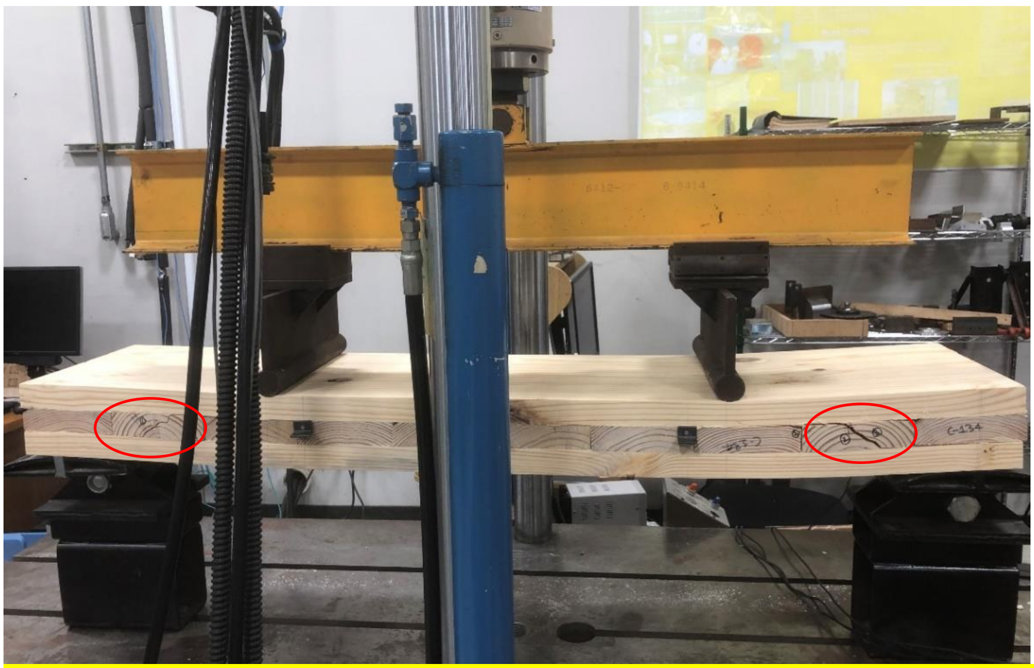


Fig. 6. Rolling shear failures at the shear zones of untreated CLT test specimen C5

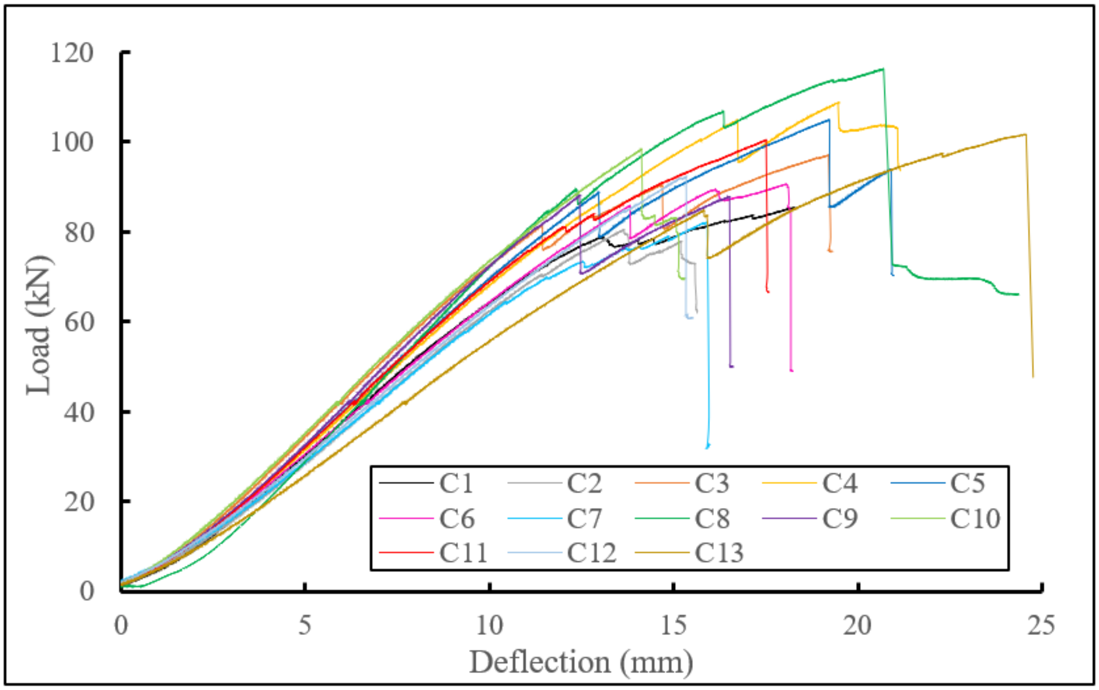


Fig. 7. Load-deflection curves of the untreated CLT specimens

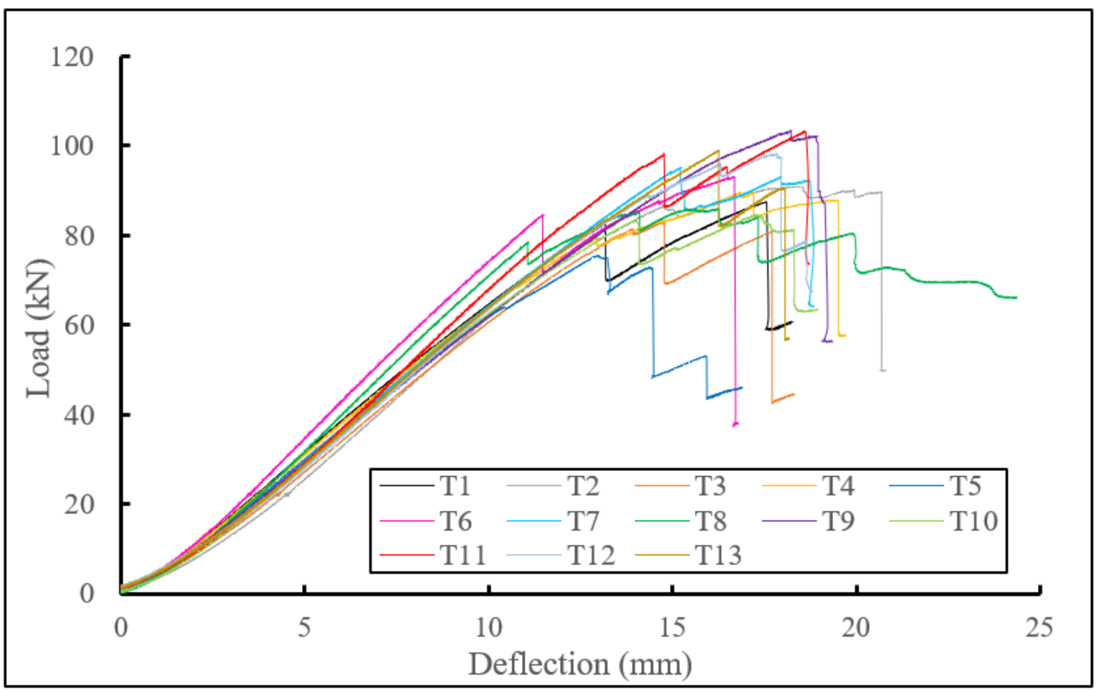
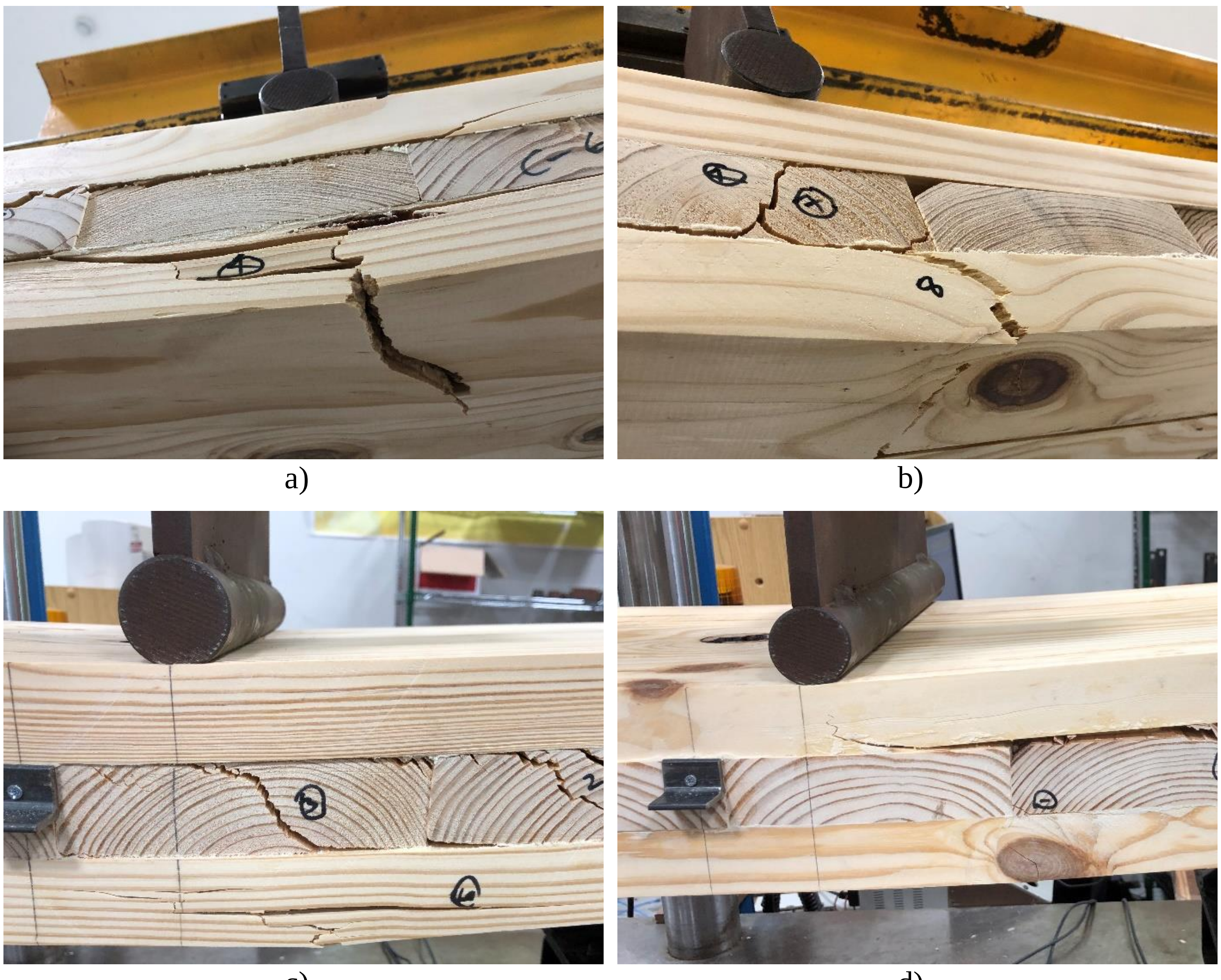
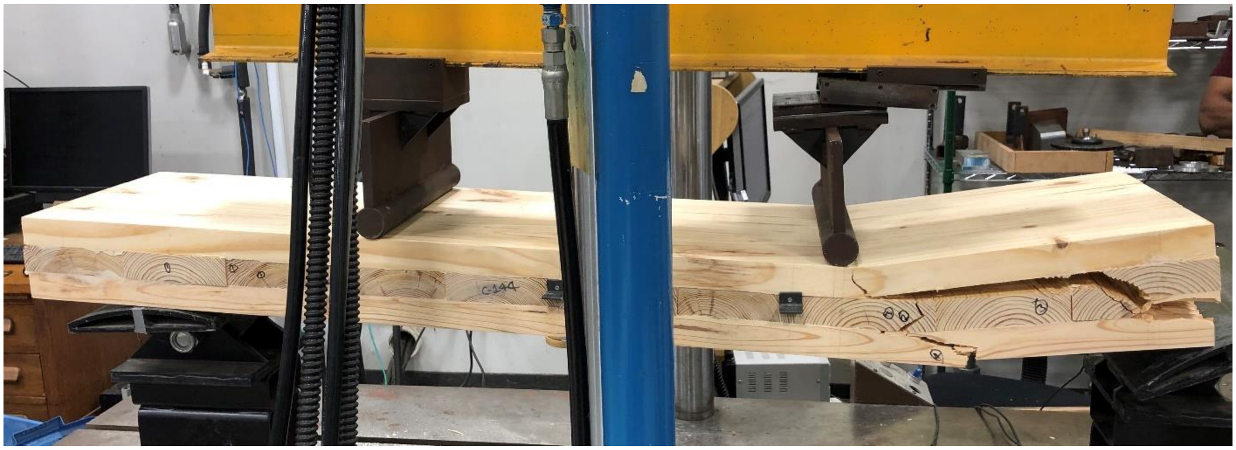


Fig. 8. Load-deflection curves of the MCA-C treated CLT specimens

Five untreated CLT specimens experienced bending failure at their loading points simultaneously with the rolling shear failure described above. C6, C7, and C8 specimens had tensile failures in the edge laminations of their bottom layers, while the edge lamination of C12 specimen's top layer experienced compressive failure as shown in Fig. 9a to 9d, respectively. C13 specimen had compressive failure on its top surface layer and tensile failure on its bottom layer as shown in Fig. 9e. Stress concentrations below the loading heads and natural defects (i.e. knot and pocket) primarily caused such failure modes. Also, increased load distributions to the surface layers due to the fracture of the core layers would possibly cause these secondary failure modes as well.



a) b) c) d)



e)

Fig. 9. Bending failures of untreated CLT specimens: a) C6, b) C7, c) C8, d) C12 and e) C13.

5. Conclusions

The effects of MCA-C treatment on RS properties of 3-ply SYP CLT were investigated by conducting four-point bending tests. The preservative treatment reduced the mean RS strength from 2.16 MPa to 1.87 MPa, while it increased the mean RS modulus from 132.11 MPa to 147.72 MPa. However, the differences in the RS properties of the untreated and the treated CLT specimens were not statiscally significant. Besides, the preservative treatment significantly decreased E_{sf} of the SYP lumber, but the effect was less evident for EI_{eff} of CLT specimens due to the large dispersion in their data. All treated and untreated CLT specimens failed in rolling shear, while secondary bending failure modes were observed only in the untreated CLT specimens near their loading locations.

The RS strength values estimated using the simplified method of the CLT Handbook based on the experimentally obtained bending stiffness ($EI_{eff,exp}$) were in a good agreement with those calculated based on the Shear analogy method. The $EI_{eff,exp}$ values obtained using the short-span test setup described in the EN 16351 standard were also agreed well with the EI_{eff} values estimated based on the non-destructively measured E_{sf} of the CLT laminations using the Shear analogy method. Thus, the bending test setup adopted in this study, along with the simplified method, can be implemented to examine the bending stiffness and RS strength of 3-ply CLT over the Shear analogy method.

Acknowledgment

The authors wish to acknowledge the support of U.S. Department of Agriculture (USDA), Research, Education, and Economics (REE), Agriculture Research Service (ARS), Administrative and Financial Management (AFM), Financial Management and Accounting Division (FMAD) Grants and Agreements Management Branch (GAMB), under Agreement No. 58-0204-6-001 and McIntire-Stennis project under accession number 1014025. This publication is also a contribution of the Forest and Wildlife Research Center, Mississippi State University. The authors also would like to thank Shuqualak Lumber Co., Henkel, and Hexion Inc. for providing materials and Tri-State Lumber Co. for treating the lumber.

References

[1] R. Brandner, G. Flatscher, A. Ringhofer, G. Schickhofer, A. Thiel, Cross laminated timber (CLT): overview and development, Eur. J. Wood Wood Prod. 74 (2016) 331–351. doi:10.1007/s00107-015-0999-5.

[2] B. Yeh, S. Gagnon, T. Williamson, C. Piruu, C. Lum, D. Kretschmann, The North American Product Standard for Cross- Laminated Timber, Wood Des. Focus. 22 (2012) 13–21.

[3] ANSI/APA PRG 320, Standard for Performance-Rated Cross-Laminated Timber, APA - The Engineered Wood Association, Tacoma, 2018.

[4] G. Schwarzmann, Establishing New Markets for CLT - Lessons Learned, Oregon State University, 2017. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/41687p08g.

[5] J.Y. Wang, R. Stirling, P.I. Morris, A. Taylor, J. Lloyd, G. Kirker, S. Lebow, M.E. Mankowski, H.M. Barnes, J.J. Morrell, Durability of Mass Timber Structures : a Review of the Biological Risks, Wood Fiber Sci. 50 (2018) 110–127.

[6] P. Fellmoser, H. Blaß, Influence of rolling shear modulus on strength and stiffness of structural bonded timber elements, CIBW18 Meet. (2004) 1–8.

[7] S. Gagnon, C. Pirvu, CLT Handbook-Canadian Edition, Libr. Arch. Canada Cat. Publ. Quebec, Canada. (2011).

[8] EN 16351, Timber Structures - Cross Laminted Timber - Requirements, European Committee for Standardization (CEN), Belgium, 2015.

[9] T. Ehrhart, R. Brandner, Rolling shear: Test configurations and properties of some European soft- and hardwood species, Eng. Struct. 172 (2018) 554–572. doi:10.1016/j.engstruct.2018.05.118.

[10] Q. Zhou, M. Gong, Y.H. Chui, M. Mohammad, Measurement of rolling shear modulus and strength of cross laminated timber fabricated with black spruce, Constr. Build. Mater. 64 (2014) 379–386. doi:10.1016/j.conbuildmat.2014.04.039.

[11] M. Li, F. Lam, Y. Li, Evaluating Rolling Shear Strength Properties of Cross Laminated Timber by Torsional Shear Tests and Bending Tests, in: Proc. 13th World Conf. Timber Eng., Quebec City, Canada, Canada, 2014.

[12] F. Lam, Y. Li, M. Li, Torque loading tests on the rolling shear strength of cross-laminated timber, J. Wood Sci. 62 (2016) 407–415. doi:10.1007/s10086-016-1567-2.

[13] H. Kreuzinger, Platten, scheiben und schalen - Ein berechnungsmodell für gängige statikprogramme (in German), Bau. Mit Holz. 1 (1999) 34–39.

[14] EN 1995-1-1, Eurocode 5: Design of timber structures - Part 1-1: General - Common rules

and rules for buildings, European Committee for Standardization (CEN), Brussels, Belgium, 2004.

[15] M. Li, Evaluating rolling shear strength properties of cross-laminated timber by short-span bending tests and modified planar shear tests, J. Wood Sci. 63 (2017) 331–337. doi:10.1007/s10086-017-1631-6.

[16] M. Li, W. Dong, H. Lim, Influence of Lamination Aspect Ratios and Test Methods on Rolling Shear Strength Evaluation of Cross-Laminated Timber, J. Mater. Civ. Eng. 31 (2019) 1–11. doi:10.1061/(ASCE)MT.1943-5533.0002977.

[17] I.P. Christovasilis, M. Brunetti, M. Follesa, M. Nocetti, D. Vassallo, Evaluation of the mechanical properties of cross laminated timber with elementary beam theories, Constr. Build. Mater. 122 (2016) 202–213. doi:https://doi.org/10.1016/j.conbuildmat.2016.06.082.

[18] J. Zhou, Y.H. Chui, M. Gong, L. Hu, Elastic properties of full-size mass timber panels: Characterization using modal testing and comparison with model predictions, Compos. Part B Eng. 112 (2017) 203–212. doi:https://doi.org/10.1016/j.compositesb.2016.12.027.

[19] T. Bogensperger, G. Silly, G. Schickhofer, Comparison of Methods of Approximate Verification Procedures for Cross Laminated Timber, Institute for Timber Engineering and Wood Technology Management. Holzbau Forschungs gmbh, Graz, Austria, 2012.

[20] X. Sun, M. He, Z. Li, Novel engineered wood and bamboo composites for structural applications: State-of-art of manufacturing technology and mechanical performance evaluation, Constr. Build. Mater. 249 (2020) 118751. doi:10.1016/j.conbuildmat.2020.118751.

[21] J.E. Winandy, Effects of Waterborne Preservative Treatment on Mechanical Properties: A Review, in: Proc. 91st Annu. Meet. Am. Wood-Preservers' Assoc., 1995: pp. 17–34.

[22] L. Soltis, J. Winandy, Long-term strength of CCA-treated lumber, For. Prod. J. 39 (1989) 64–68.

[23] S.R. Shukla, J. Zhang, D.P. Kamdem, Pressure treatment of rubberwood (Heavea brasiliensis) with waterborne micronized copper azole: Effects on retention, copper leaching, decay resistance and mechanical properties, Constr. Build. Mater. 216 (2019) 576–587. doi:10.1016/j.conbuildmat.2019.05.013.

[24] D.C. Maldas, D.P. Kamdem, Surface characterization of chromated copper arsenate (CCA)-treated red maple, J. Adhes. Sci. Technol. 12 (1998) 763–772. doi:10.1163/156856198X00281.

[25] L.F. Lorenz, C. Frihart, Adhesive bonding of wood treated with ACQ and copper azole preservatives, For. Prod. J. 56 (2006) 90–93.

[26] H. Lim, S. Tripathi, J.D. Tang, Bonding performance of adhesive systems for cross-laminated timber treated with micronized copper azole type C (MCA-C), Constr. Build. Mater. 232 (2020). doi:10.1016/j.conbuildmat.2019.117208.

[27] AWPA P62-16, Standard for micronized copper azole type C (MCA-C), American Wood Protection Association, Birmingham, AL, 2018.

[28] S.T. Lebow, Chapter 15: Wood preservation, in: Wood Handb. Wood as an Eng. Mater., FPL-GTR-19, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 2006: p. 508. doi:10.2737/FPL-GTR-190.

[29] AWPA A9-18, Standard Method for Analysis of Treated Wood and Treating Solutions by X-ray Spectroscopy, American Wood Protection Association, Birmingham, AL, 2018.

[30] D.E. Kretschmann, Chapter 05: Mechanical Properties of Wood, in: Wood Handb. Wood as an Eng. Mater., FPL-GTR-19, U.S. Department of Agriculture, Forest Service, Forest

Products Laboratory, Madison, WI, 2010: p. 508. doi:10.2737/FPL-GTR-190.

[31] ASTM D4442-16, Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials, ASTM International, West Conshohocken, PA, 2016.

[32] ASTM D2395-17, Standard Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials, ASTM International, West Conshohocken, PA, 2017.

[33] FPInnovations, CLT Handbook U.S. Edition, FPInnovations, pointe-Claire, 2013.

[34] Purbond, Application instructions: Bonding of SOUTHERN PINE wood with primer LOCTITE PR 3105 and PURBOND HB X adhesives, Sempach Station, Switzerland, 2017.

[35] Purbond, PURBOND HB E452 Single-component polyurethane adhesive for the manufacutre of engineered wood products, 2009.

[36] Henkel, Technical Data Sheet LOCTITE HB X102 PURBOND, Bridgewater, NJ, USA, 2018.

[37] ASTM D198-15, Standard Test Methods of Static Tests of Lumber in Structural Sizes, ASTM International, West Conshohocken, PA, 2015.

[38] J. Dahlen, P.D. Jones, R.D. Seale, R. Shmulsky, Bending strength and stiffness of wide dimension southern pine No. 2 lumber, Eur. J. Wood Wood Prod. 72 (2014) 759–768. doi:10.1007/s00107-014-0848-y.

[39] H.M. Barnes, Effect of steaming temperature and CCA retention on mechanical properties of southern pine, For. Prod. J. 35 (1985) 31–32.

[40] Y. Cao, J. Street, M. Li, H. Lim, Evaluation of the effect of knots on rolling shear strength of cross laminated timber (CLT), Constr. Build. Mater. 222 (2019) 579–587.

doi:10.1016/j.conbuildmat.2019.06.165.

[41] S. Winter, H. Kreuzinger, P. Mestek, Teilprojekt 15 Flächen aus Brettstapeln, Brettsperrholz und Verbundkonstruktionen (in German), Fraunhofer IRB Verlag, Stuttgart, 2009.

[42] IBM Corp., IBM SPSS Statistics for Windows, Version 25.0, (2017).