# Bonding Durability and Rolling Shear Strength of Commercially Produced Southern Yellow Pine Cross-laminated Timber Treated with Micronized Copper Azole (MCA)

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Presently, structural grade cross-laminated timber (CLT) panels are manufactured for interior applications. To expand the use of CLT to exterior applications, there is a need to protect the panels from biodegrading agents such as fungi and termites. Pressure treatments are effective methods of increasing the durability of wood and wood-based products. There are limited studies on the influence of micronized copper azole (MCA) treatment on the rolling shear modulus and rolling shear strength of a commercially produced 3-ply southern yellow pine CLT panel Grade V3. It was found that MCA treatment didn't have a significant effect on the rolling shear strength of the CLT panels, with the rolling shear strength being 2.19 and 2.31 MPa for the untreated and treated CLT panels, respectively. The bonding durability of the CLT panels had mixed results, with the control specimens measuring a significantly lower wood failure percentage (WFP) of 32% as compared to approximately 75% for the MCA treated specimen. The measured block shear strength (BSS) was approximately the same for the treated and the untreated shear block specimen except for one manufacturing group. The average delamination for the treated specimens was 11% while the average delamination for the untreated specimens was 13.2%.

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## INTRODUCTION

Cross-laminated timber (CLT) is an engineered wood product manufactured mostly from softwood dimension lumber or structural composite lumber. CLT is made by laminating and gluing adjacent layers of lumber together with the layers bonded at 90-degrees to each other (Wang *et al.* 2018). CLT panels are typically manufactured with 3 to 9 layers. CLT, which was first developed in Austria and Germany in the 1970s and 1980s, has enjoyed a major level of success in the European construction market and is establishing a presence in North America construction projects (Brandner *et al.* 2016). The southern region of the United States is experiencing growth in the CLT market with the location of CLT plants in this region. The southern region of the United States has an abundant supply of plantation-grown southern yellow pine lumber to be used as feedstock for a CLT manufacturer (Gaby 1985). A disadvantage to the use of wood products such as southern pine in this region of the United States is its susceptibility to infestation by subterranean termites. Building with preservative treated CLT will be paramount in this region for its sustainability (Wang *et al*. 2018).

One of the limiting factors of CLT in certain structural applications is its low rolling shear strength. Sandoli and Calderoni (2020) give a detailed description of rolling shear phenomenon in CLT panels. There are several methodologies used to investigate the rolling shear properties of CLT. Rolling shear values have been published using short-span four-point bending tests, modified planar shear (MPS) tests with timber sandwich plates, and MPS tests with steel sandwich plates (Nero *et al*. 2022). The method used has an effect on the rolling shear property values. The rolling shear strength specified in PRG-320 for CLT prepared from southern yellow pine is 1.2 MPa. The European standard EN 16351 (2015) specifies a characteristic rolling shear strength of 1.1 MPa for common softwood species. Cao *et al*. (2019) reported rolling shear strength values for untreated southern pine CLT between 1.95 MPa to 2.33 MPa using a short-span bending test. Nero *et al.* (2022) reported a mean rolling shear strength value for radiata pine of 2.07 MPa using a short span four-point bending test. Nero's study showed how the sawing pattern on the laminates significantly influences rolling shear strength and modulus.

Lim *et al.* (2020) studied the influence of micronized copper azole (MCA-C) on the rolling shear strength and modulus on 3-ply southern yellow pine CLT produced in a laboratory setting using the short span four-point bending tests according to EN 16351 (2015). Lim *et al*. (2020) reported rolling shear strength values of 2.16 MPa and 1.87 MPa for untreated and MCA-C treated 3-ply southern pine CLT panels, respectively. The present study uses the methodology presented in the publication by Lim *et al*. (2020) but focuses on treated and untreated CLT panels produced by a commercial CLT manufacturer. There are limited data on the durability and rolling shear strength and modulus of 3 -ply CLT panels constructed with kiln-dried after drying (KDAT) southern yellow pine.

In addition to durability concerns, the integration of preservative treatments such as MCA-C into CLT manufacturing introduces complexities related to adhesive bonding (Alade *et al.* 2022). MCA treatments may alter the surface chemistry and wettability of the wood, which can compromise adhesive bond integrity and increase the risk of delamination (Vick *et al.* 1990; Frihart 2003). Adhesive performance is a critical parameter in the structural reliability of CLT, particularly when used in load-bearing applications where mechanical performance is paramount. Additionally, while preservative treatments aim to enhance biological durability, they may inherently impact the mechanical properties, including the rolling shear modulus and strength of the treated panels. Understanding these trade-offs is essential for optimizing CLT for exterior and semi-exposed applications where both biological durability and mechanical performance are critical.

This study aimed to address these knowledge gaps by evaluating the bonding durability and rolling shear modulus and strength of commercially produced 3-ply southern yellow pine CLT panels treated with MCA. The objectives of this study were (1) to assess the adhesive bond performance of MCA-treated southern yellow pine CLT through delamination and shear block tests in accordance with ANSI/APA PRG 320 (2019) and ASTM D905 (2021) standards, respectively; (2) to evaluate the rolling shear modulus and strength of treated and untreated panels through mechanical tests according to EN 16351 (2015); and (3) to analyze the effects of MCA treatment on the mechanical behavior of the CLT panels. By addressing these objectives, this research contributes to advancing the understanding of preservative-treated CLT, supporting its broader adoption in sustainable construction practices.

## EXPERIMENTAL

### Materials

Six 3-ply southern pine (SYP) cross laminated timber (CLT) panels were procured from a commercial engineered wood products manufacturer in the United States. The CLT Grade was V3 according to the ANSI/APA PRG 320 (2019) standard for CLT manufacturing in the US and Canada. The V3 Grade allows for No. 2 Southern Pine lumber laminates in all longitudinal layers and No. 3 Southern Pine lumber laminates in all transverse layers. The allowable bending stiffness and shear stiffness of V3 Grade CLT is 894 x $10^9$ N-mm$^2$/m of width and 7.15 x $10^6$ N/m of width, respectively. The dimensions of the CLT panels as received were 0.11 m x 2.34 m x 4.17 m. The laminates were fabricated from No. 2 2 x 6 (30 mm x 140 mm) SYP dimension lumber. The panels were manufactured with a commercial grade single-component polyurethane adhesive (PUR). Three of the CLT panels were manufactured with micronized copper azole (MCA) treated laminates. The laminates were treated to a target retention of 2.4 kg/m$^3$. This retention level is specified by AWPA U1-22 (2022) for UC4A (ground contact or freshwater) applications. Three or four billets (0.11 m x 0.305 m x 1.37 m) were cut from each CLT panel for testing according to EN 16351 (2015) specifications for determining rolling shear strength and stiffness from bending tests. A span-to-depth ratio of 12 as specified in the standard was used for testing. A total of twenty billets were prepared for testing (ten MCA treated billets and ten untreated billets). Another group of billets (0.11 m x 0.404 m x 0.676 m) were cut in order to prepare shear block and delamination specimens according to ANSI/APA PRG 320 (2019). The billets stayed under the breezeway at the Department of Sustainable Bioproducts at Mississippi State University in Starkville, MS for approximately 3 months before testing. The equilibrium moisture content (EMC) under breezeway was approximately 16.5%. Table 1 shows the mean MC and the $SG_{oven-dry}$ after testing for the treated and untreated specimens prepared from the shear block specimens. The average moisture content of each condition was approximately 15% with a small coefficient of variation (COV). The mean $SG_{oven-dry}$ for each condition was 0.46. Included in our test data set by permission of the manufacturer, thirty-six shear block specimens and thirty-two delamination specimens were prepared and tested by a commercial CLT manufacturer from kiln-dried after treatment (KDAT) dimension lumber received from four different MCA treatment manufacturers. The different manufactures are coded in this study as manufacturer 1 (MT1), manufacturer 2 (MT2), manufacturer 3 (MT3), and manufacturer 4 (MT4). Additional shear block and delamination specimens were prepared from the MT4 specimen group as described in the following section. Per a conversation with our industry contact, the full-sized CLT panels received at our laboratory were prepared with the KDAT lumber received from MT4.

**Table 1.** Summary Statistics of MCs and SGs of Untreated and Treated Laminates from CLT Panels

| Condition | Sample Size (n) | MC | | $SG_{oven-dry}$ | |
|---|---|---|---|---|---|
| | | Mean (%) | COV (%) | Mean | COV (%) |
| Untreated | 74 | 15.09 | 5.43 | 0.46 | 11.89 |
| Treated | 75 | 14.96 | 5.88 | 0.46 | 10.44 |

MC is the moisture content (%); $SG_{oven-dry}$ is the oven dried specific gravity; COV(%) is the coefficient of variation.

## Methods

*Block shear test method*

The billets prepared for shear block and delamination testing were cut into 15 square blocks measuring 133 mm x 133 mm x 104 mm. The shear block specimens were prepared according to the PRG-320 protocol. The shear block specimens were stair-stepped with a shearing area of 51 mm x 38 mm. The specimens were then conditioned at 21°C and 65% RH for at least 2 weeks before testing.

The tests were carried out per ASTM D905 (2021). An illustration of the test setup is presented in Fig. 1. The shearing tool applied a vertical force through adjacent laminations (at the adhesive bondline) at a rate of 5.08 mm/min until failure. Images of the failure shear plane were photographed with a Canon EOS Rebel T6 camera. The shear plane was analyzed using ImageJ2, an image processing software. Block shear strength (BSS) ($f_v$) was calculated as follows,

$$f_v = F_u/A \tag{1}$$

where $F_u$ is the failure load (N) and $A$ is the sheared area (mm$^2$). The percentage of wood failure (WFP on the shear block failure plane was measured using ImageJ2 software (Rueden *et al.* 2017)). The shear blocks were analyzed for the modes of failure; adhesive failure (AD), failure parallel-to-grain (PAR), and failure perpendicular-to-grain (PER, rolling shear). The WFP was measured by dividing the wood failure area by the tested shear bonded area. The WFP was estimated per ASTM D5266 (2020).

*Delamination test method*

Delamination specimens were prepared and tested according to the PRG-320 protocol. The delamination specimens were cut to 83 mm x 83 mm followed by conditioning at 21°C and 65% RH for at least 2 weeks before testing. Two sides of each specimen were photographed with a Canon EOS Rebel T6 camera.

The delamination specimens were weighed to the nearest 1 gram before testing. The specimens were placed in a wire mesh basket. The wire mesh basket was then placed in the pressure vessel. The pressure vessel was sealed and filled with water at a temperature of 21°C and placed under vacuum for 30 minutes at 0.207 MPa. After the vacuum was released, the specimens were placed under air pressure for 2 hours at 0.517 MPa. The specimens were removed from the pressure vessel and placed in a drying oven with forced air circulation at 71°C until the specimen weight was approximately between 110% and 115% of its initial weight. After drying the specimens to the proper weight, delamination was measured along the test bond lines, and recorded. Knots, grade defects, and wood failure were excluded from the delamination measurements.

The total delamination, Delamtot, of a test specimen was calculated as follows,

$$Delamtot\ (\%) = \frac{l_{tot,\ delam}}{l_{tot,\ glue\ line}} \times 100 \tag{2}$$

where $l_{tot,\ delam}$ is the total delamination length and $l_{tot,\ glue}$ is the sum of the glue lines.

The difference in the bond line lengths shown in Table 4 is a result of the difference in the number of specimens for each group. Each specimen had two bond lines that were added together to make a total bond line length of 635 mm. The length of each individual bond line was 317.5 mm.

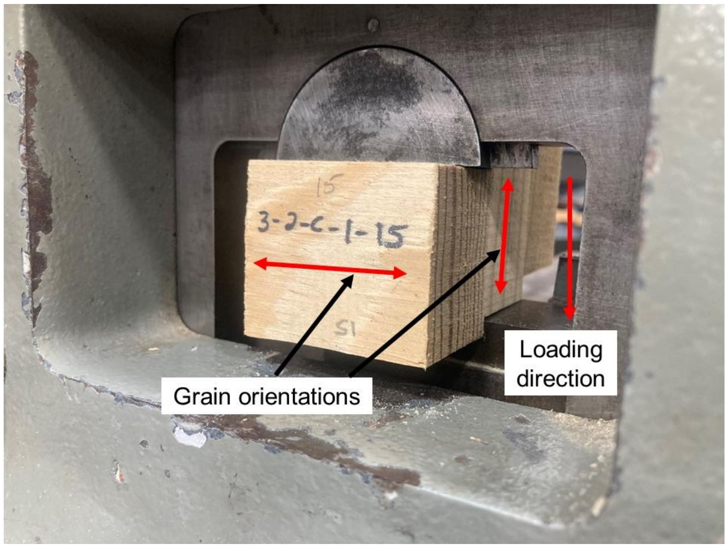


**Fig. 1.** Block shear specimen in block shear test setup.

*Rolling shear test method*

The twenty billets (Figs. 2 and 3) were tested in four-point short span bending tests according to EN 16351 (2015) to determine the rolling shear strength and stiffness. The test support span was 1.26 m with a loading span of 0.63 m and a shear span of 0.315 m. Three linear variable differential transformers (LVDTs) were used to measure the deflection of the panel's neutral axis during testing. One LVDT was located at midspan, while the other two LVDTs were located at 0.025 m inside the two loading heads to measure the shear free zone deflection.


**Fig. 2.** Ten untreated CLT rolling shear test specimen


**Fig. 3.** Ten treated CLT rolling shear test specimen.

**Fig. 4.** Four-point CLT bending test setup

To prevent damage to the LVDTs during testing, the LVDTs were removed at approximately 55.5 kN, which was within the elastic-range of the panel (Figs. 8 and 9). The maximum loads of the CLT panels were estimated based upon calculations presented in Lim *et al.* (2020). After removal of the LVDTs, the panel was continually testing until failure. Figure 4 shows a billet in the testing setup. The testing speed was 1.27 mm/min. Data were collected using an Instron Universal Testing Machine with a data collection rate of 5 Hz. The calculations used for determining rolling shear strength ($f_{v,R,sm}$) and rolling shear modulus ($G_{R,exp}$) were described in a publication by Lim *et al.* (2020).

## Statistical Analysis

The effects of MCA treatment on RS modulus ($G_R$), RS strength ($f_{v,R}$), block shear strength (BSS), wood failure percentage (WFP), and delamination were analyzed using SAS version 9.4. Assumptions of normality and homogeneity of variance were tested on the raw data using the Shapiro-Wilk test and Levene's test at $\alpha$=0.05, respectively. Details on data handling that did not follow the assumptions of normality and homogeneity of variance are described in detail in the statistical analysis section of other publications (Lim *et al.* 2020; Quin *et al.* 2024).

# RESULTS AND DISCUSSION

## Block Shear Test

The descriptive statistics of the calculated BSS and WFP for the MCA treated groups and untreated group are shown in Table 2. The major governing failure mode for the treated CLT shear blocks was shear perpendicular-to-grain (rolling shear), while the major mode of failure for the untreated (control) CLT shear blocks was adhesive failure. The average BSS of the control specimens ranged from 1.96 to 5.23 MPa with a COV of 22.8%. The treated CLT shear blocks from the MT3 group measured the lowest mean BSS of 2.93 MPa, while the treated CLT shear blocks from the MT2 group measured the highest BSS of 3.95 MPa with a COV of 21.3%. This was a difference of approximately 21%. The average wood failure percentage for the treated specimens ranged from 70.4% to 88.9%. The average wood failure percentage for the control specimens was 32.7%. A large percentage of the control specimens had wood failure that was less than 80%. Satir *et al.* 2024 reported an average wood failure of 58.1% for 3-ply southern pine CLT because of a large percentage of adhesive failure. The BSS of 3-ply southern pine CLT reported by Satir was 2.92 MPa.

The only CLT groups that passed the WFP of 80% as specified in PRG-320 were MT1 and MT2. The BSS values reported for the treated and untreated are like the results reported by Lim *et al.* (2020), which reported a mean 3.68 MPa BSS for untreated specimens and a mean of 4.03 MPa for the MCA-C treated specimens. Lim *et al.* (2020) reported WFP over 90% for both untreated and MCA-C treated specimens. For the BSS and the WFP, a one-way ANOVA was used to compare the CLT groups, since the datasets passed the normality and homogeneity of variance tests. The one-way ANOVA revealed a significant difference between the BSS and WFP of the CLT groups ($p=0.0006$) (Fig. 5) and ($p<0.0001$) (Fig. 5), respectively.

**Table 2.** Descriptive Statistics of BSS (Block Shear Strength) and WFP (Wood Failure Percentage) for Five CLT Groups

| CLT Group | Sample Size | BSS (MPa) Mean [95% CI] | BSS (MPa) Median [range] | BSS (MPa) COV (%) | WFP (%) Mean | WFP (%) Median [range] | No. <80% WFP |
|---|---|---|---|---|---|---|---|
| MT1 | 18 | 3.70 [3.45-3.81] | 3.72 [2.86-4.70] | 13.0 | 88.9 | 92.5 [50.0-100.0] | 2 |
| MT2 | 18 | 3.95 [3.35-4.35] | 3.80 [2.96-6.46] | 21.3 | 80.3 | 87.5 [30.0-100.0] | 4 |
| MT3 | 18 | 2.93 [2.61-3.14] | 2.83 [1.91-4.35] | 20.8 | 60.3 | 65.0 [5.0-100.0] | 10 |
| MT4 | 68 | 3.57 [3.14-4.08] | 3.57 [2.01-5.60] | 18.8 | 70.4 | 72.5 [5.0-100.0 | 34 |
| C | 50 | 3.50 [3.01-3.96] | 3.50 [1.96-5.23] | 22.8 | 32.7 | 25.0 [0-100.0] | 45 |

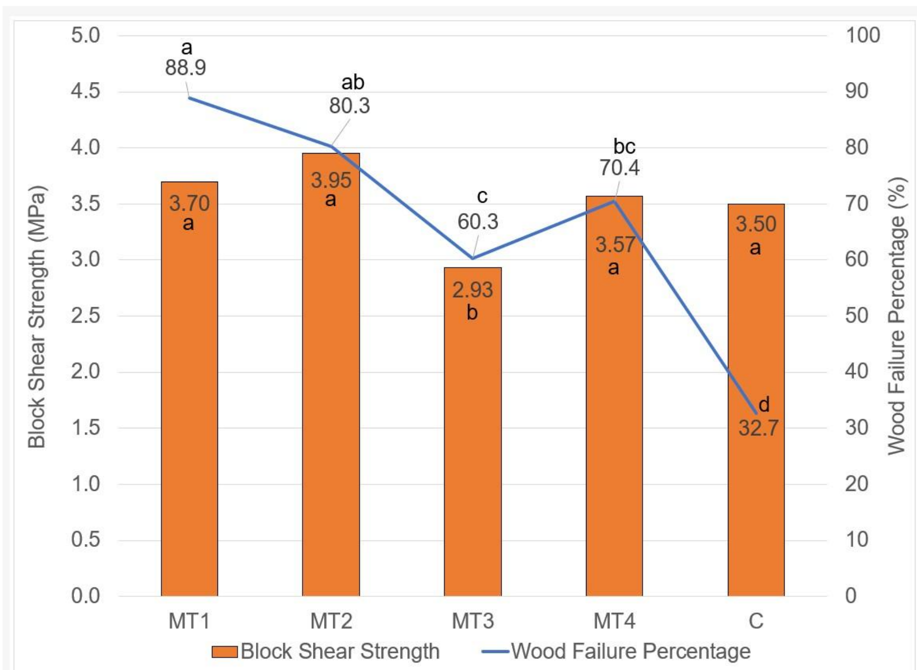


**Fig. 5.** Mean block shear strength (BSS) and wood failure percentage (WFP) (different letters above or between the numbers indicate significant differences (p<0.05) amount the CLT groups. Tukey Honestly Significant Difference (HSD) Test for multiple comparisons found the means values of BSS and WFP to be significantly different between some CLT groups.

## Delamination Test

Internal stresses in wood during shrinking and swelling of the adherents influence the adhesive bonding capacity. Delamination as defined in the literature as the separation of layers at the interface between an adhesive and the adherent (Gong *et al.* 2016). Since wood is orthotropic, the dimensional changes are dependent upon its grain orientation. Shrinkage and swelling in the longitudinal direction are significantly lower than in the radial and tangential directions. The delamination criteria were based upon PRG-320. A 0.08 mm feeler gauge was used to determine adhesive bond line separation. Only failure in the adhesive or at the bondline with no sign of wood failure was counted as delamination.

**Table 3.** Summary of Delamination Test Results

| CLT Group | Sample Size | Bondline Delamination (mm) | Bondline Length (mm) | Delamination(%) |
|---|---|---|---|---|
| MT1 | 8 | 406.2 | 5080 | 8.1 |
| MT2 | 8 | 752.0 | 5080 | 15.2 |
| MT3 | 8 | 17.9 | 5080 | 0.4 |
| MT4 | 28 | 3437.6 | 17780 | 19.3 |
| C | 20 | 1674.8 | 12700 | 13.2 |

Table 3 shows the results of the delamination test. The delamination percentages ranged from 0.4% (MT3) to 19.3% (MT4). The delamination specimens fabricated KDAT lumber from MT3 recorded the lowest delamination of 0.4%. The control group recorded an intermediate delamination rate of 13.2%. The delamination percentage for the untreated CLT is similar to data published by Quin *et al.* 2024 for untreated 3-ply CLT panel which reported an average delamination rate of 7.0%. Lim *et al.* (2020) reported a 0% delamination rate for 3-ply untreated and treated southern pine CLT when using a one-component polyurethane (PUR) adhesive.

## Rolling Shear Test

Tables 4 and 5 present the results for the bending stiffness, shear stiffness, RS modulus, and RS strength of the untreated CLT panel specimens and the treated CLT panel specimens, respectively. The mechanical properties were calculated according to the Shear Analogy, Simplified Method (Cao *et al.* 2020) along with an experimental method for calculating $EI_{eff,exp}$ and $GA_{eff,exp}$ described in Lim *et al.* 2020.

The mean $EI_{eff,exp}$ of the untreated CLT specimens (1710 x $10^9$ N mm$^2$/m) was lower than that of the treated CLT specimens (1810 x $10^9$ N mm$^2$/m). This differs from the results reported by Lim *et al*. (2020), which reported a higher value for the untreated CLT specimens as compared to the treated CLT specimens. Lim *et al.* (2020) and Barnes (1985) reported that preservative treatment lowers the modulus of rupture (MOR) of SYP lumber at high retentions. The modulus of elasticity (MOE) was not adversely affected according to Barnes (1985). The mean $GA_{eff,exp}$ of the untreated CLT specimens (4.57 x $10^6$ N/m) was also lower than that of the treated CLT specimens (5.82 x $10^6$ N/m). The increase in the $GA_{eff,exp}$ for the treated CLT panel specimens was also reported by Lim *et al*. (2020). The mean $G_R$ (75.8 MPa) for the untreated CLT specimen was significantly less than the mean $G_R$ reported by Lim *et al.* (2020) of 132 MPa for untreated Southern Pine CLT panels. The $G_R$ values reported in this study are in line with results reported by Fellmoser and Blass (2004) on Norway spruce. The mean $G_R$ (82.4 MPa) for the treated CLT was higher than the mean $G_R$ for the untreated CLT. The mean $f_{v,R}$ for the treated CLT specimens (2.31 MPa) was slightly higher than the mean $f_{v,R}$ for the untreated CLT specimens (2.19 MPa). Cao *et al.* 2020 reported similar results the RS strength of 3-ply untreated SYP CLT panels.

For the RS modulus and the RS strength, a one-way ANOVA was used to compare the effect of the preservative treatment, since the datasets passed the normality and homogeneity of variance tests. The one-way ANOVA revealed no significant difference between the RS modulus (p=0.0575) and the RS strength (p=0.3473). This is the same as the results by Lim *et al.* (2020).

The mode of failure for all specimens was rolling shear failure in the core layers within the shear zone (Fig. 6). One of the treated CLT specimens had failure in the bottom laminate along with rolling shear failure (Fig. 7). The CLT panels had some gaps between the laminates in the face and the core layers. According to APA PRG-320, edge gaps in the face layers should not exceed 6.4 mm, while the adjacent laminations edges should not exceed 9.5 mm in the core layers. Some of the CLT panels exceeded these laminations. A study by Gardner *et al.* (2020) showed that the presence of gaps in the CLT panel introduces stress riser effects, which decreases shear strength. The study showed that a 6.0 mm gap could exhibit a drop in shear strength of 13%. These results were based upon a 5-ply CLT panel constructed with Spruce-Pine-Fir (SPF) lumber.

Figures 8 and 9 show the load deflection curves for the untreated and treated CLT panels, respectively. The load deflection curves are linear up to a point where rolling shear cracks started to appear in the core layer. These shear cracks continue to propagate until the panel experiences a brittle failure with a sudden load drop. The load deflection curves were similar in behavior for both the treated and untreated CLT panels. This is similar to the results reported by Lim *et al.* (2020).

**Table 4.** Experimentally Obtained Bending Stiffness, Shear Stiffness, RS Modulus, and RS Strength of Untreated CLT Specimens along with Bending Stiffness and Shear Stiffness Estimated from the Shear Analogy Method

| Specimen No. | $EI_{eff}$ ($10^9$N mm$^2$/m) | $EI_{eff,exp}$ ($10^9$N mm$^2$/m) | $GA_{eff}$ ($10^6$N/m) | $GA_{eff,exp}$ ($10^6$N/m) | $G_R$ (MPa) | $f_{v,R}$ (MPa) |
|---|---|---|---|---|---|---|
| C1 | 894 | 1317.77 | 7.15 | 4.57 | 60.12 | 2.72 |
| C2 | 894 | 1384.48 | 7.15 | 4.84 | 64.68 | 2.61 |
| C3 | 894 | 1780.07 | 7.15 | 5.32 | 73.03 | 1.84 |
| C4 | 894 | 1657.76 | 7.15 | 5.23 | 71.53 | 2.18 |
| C5 | 894 | 1782.88 | 7.15 | 5.91 | 84.02 | 2.09 |
| C6 | 894 | 1758.00 | 7.15 | 5.33 | 73.24 | 2.32 |
| C7 | 894 | 1759.18 | 7.15 | 5.56 | 77.51 | 1.99 |
| C8 | 894 | 1761.05 | 7.15 | 5.06 | 68.43 | 2.44 |
| C9 | 894 | 1915.59 | 7.15 | 6.15 | 88.83 | 1.85 |
| C10 | 894 | 1937.70 | 7.15 | 6.02 | 86.33 | 1.81 |
| Mean | | 1707.36 | | 4.57 | 74.75 | 2.19 |
| COV | | 11.98% | | 9.55% | 12.58% | 15.02% |

**Table 5.** Experimentally Obtained Bending Stiffness, Shear Stiffness, RS Modulus, and RS Strength of MCA Treated CLT Specimens along with Bending Stiffness and Shear Stiffness Estimated from the Shear Analogy Method

| Specimen No. | $EI_{eff}$ ($10^9$N mm$^2$/m) | $EI_{eff,exp}$ ($10^9$N mm$^2$/m) | $GA_{eff}$ ($10^6$N/m) | $GA_{eff,exp}$ ($10^6$N/m | $G_R$ (MPa) | $f_{v,R}$ (MPa) |
|---|---|---|---|---|---|---|
| T1 | 884 | 1539.54 | 7.15 | 5.42 | 74.89 | 2.53 |
| T2 | 884 | 2083.11 | 7.15 | 6.16 | 89.13 | 1.87 |
| T3 | 884 | 2115.51 | 7.15 | 6.34 | 92.76 | 2.19 |
| T4 | 884 | 1885.87 | 7.15 | 5.84 | 82.69 | 2.47 |
| T5 | 884 | 1882.32 | 7.15 | 5.71 | 80.32 | 2.35 |
| T6 | 884 | 1836.98 | 7.15 | 5.54 | 77.08 | 2.40 |
| T7 | 884 | 1512.42 | 7.15 | 6.09 | 87.62 | 2.76 |
| T8 | 884 | 1634.53 | 7.15 | 5.28 | 72.36 | 2.31 |
| T9 | 884 | 1885.92 | 7.15 | 6.25 | 90.75 | 1.93 |
| T10 | 884 | 1761.09 | 7.15 | 5.49 | 76.17 | 2.33 |
| Mean | | 1813.73 | | 5.82 | 82.38 | 2.31 |
| COV | | 11.33% | | 6.53% | 8.83% | 11.51% |

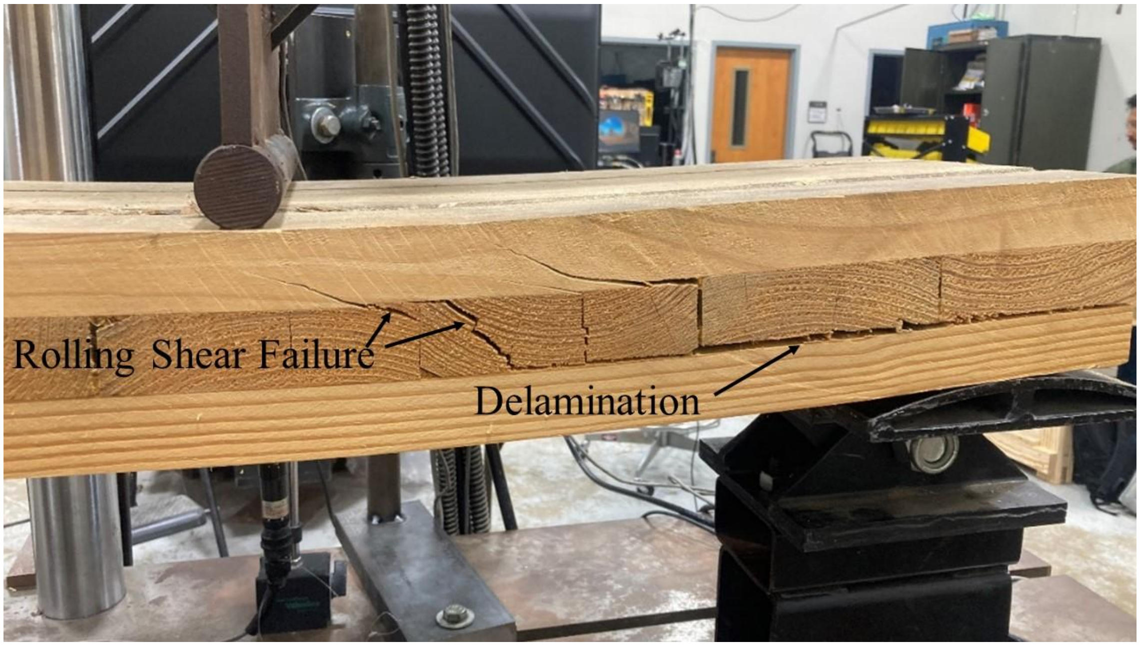


**Fig. 6.** Typical failure mode of treated and untreated CLT specimen

**Fig. 7.** Failure of bottom laminate in bending of one treated CLT specimen

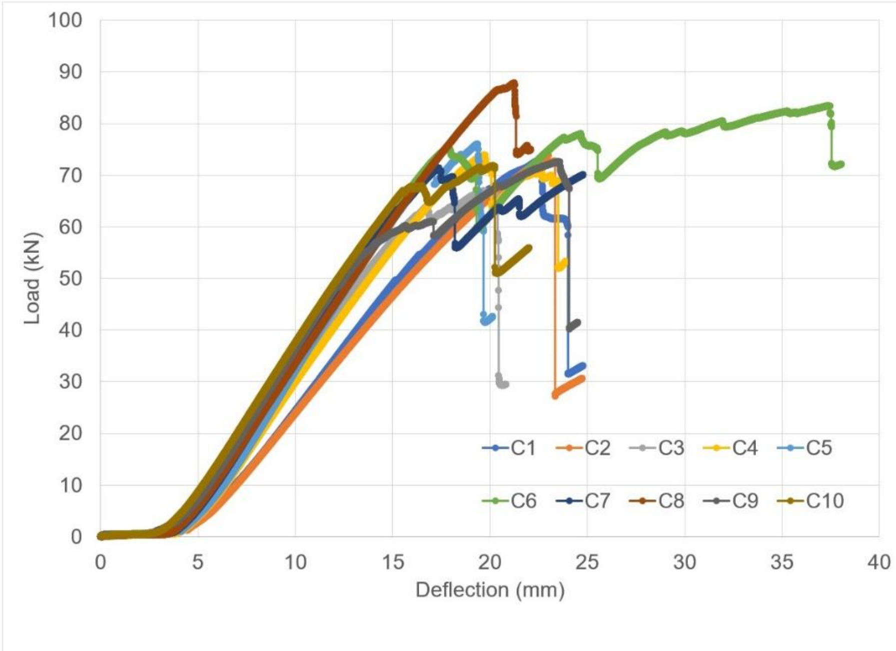


**Fig. 8.** Load-deflection curves of the untreated CLT specimens

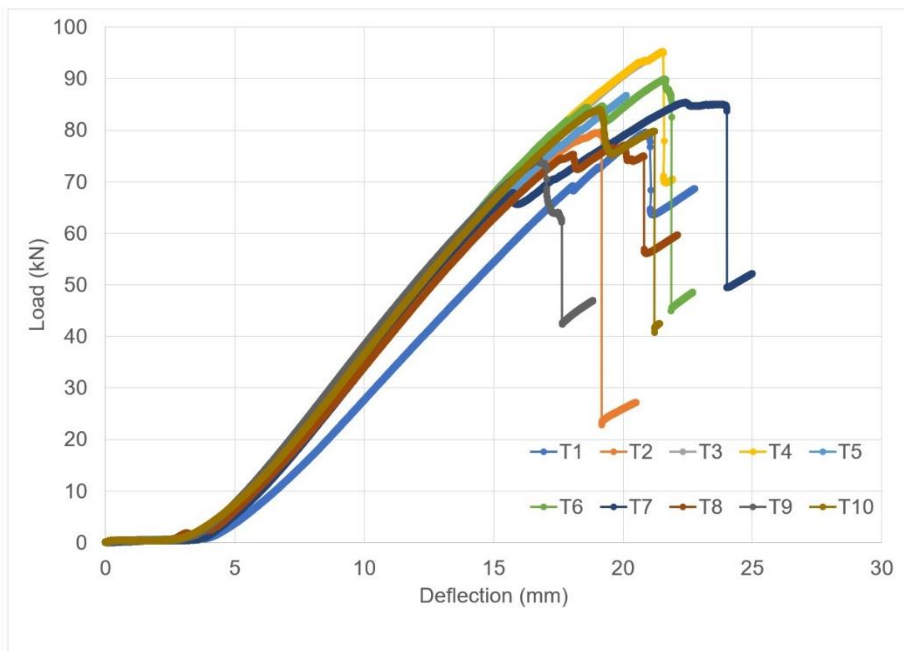


**Fig. 9.** Load-deflection curves of the MCA treated CLT specimens

## CONCLUSIONS

1. This study examined the effect of micronized copper azole (MCA) treatment on a commercially produced 3-ply southern pine cross-laminated timber (CLT) panel during a short span bending test according to EN 16351 (2015) and bonding durability according to APA PRG-320.
2. The results showed that the MCA treatment showed no significant influence on the

block shear strength (BSS) and wood failure percentage (WFP) of the 3-ply southern pine CLT panels.

3. Delamination testing results were mixed, with the control specimens showing delamination along with the MCA specimens. The only CLT group to pass the APA PRG-320 standard of less than 5% delamination was MT3.
4. Rolling shear strength and rolling shear modulus was not significantly influenced by the MCA treatment.
5. The mean rolling shear modulus of the treated panels was 82.4 MPa while the mean rolling shear modulus of the untreated panels was 74.8 MPa. This was an increase in mean rolling shear modulus of approximately 9.3%.
6. The mean rolling shear strength of the treated panels was 2.31 MPa, while the mean rolling shear strength of the untreated panels was 2.19 MPa. The results for the mean rolling shear strength of the untreated panels are the same as the mean rolling strength of untreated CLT panels reported by Lim *et al.* (2020).
7. Both CLT panel configurations recorded values for rolling shear modulus and rolling shear strength above the reference values reported for the allowable stress design values of 60.3 and 0.38 MPa for rolling shear modulus and rolling shear strength, respectively.

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