DEVELOPMENT OF A MODIFIED STANDARD TERMITE TEST FOR MASS TIMBER PRODUCTS[1]

Tamara S. F. A. França†

Assistant Professor
E-mail: tsf97@msstate.edu

C. Elizabeth Stokes

Associate Professor
Department of Sustainable Bioproducts
Mississippi State University
Mississippi State, MS 39762-9820
E-mail: ces8@msstate.edu

Juliet D. Tang

Research Forest Products Technologist
USDA Forest Service
Forest Products Laboratory
Starkville, MS 39762-9820
E-mail: julietdtang@fs.fed.us

(Received August 2021)

Abstract. US manufacturers are looking to expand the use of cross-laminated timber (CLT) panels into the North American market, including states located in the southeast where termites are important pests. However, there is no current assessment method for determining CLT vulnerability to the highly destructive native termites found in many states across the United States. The impact of damage by these termites is of particularly high interest in areas with suitable climate to their proliferation, such as the southeastern United States. This study evaluated durability of CLT panels and developed a laboratory assay to test susceptibility of this product to termites. Untreated CLT suffered mass losses of up to 5.8% in testing with an average visual rating of 7.2, indicating a moderate to severe attack with 10-30% of the cross section of the product affected by termite intrusion. Recommendations were developed for the inclusion of modifications presented in standardized testing protocols and will be presented to standards organizations. The proposed method may also be applied to evaluate termite resistance of other mass lumber products such as laminated veneer lumber and Glulam.

Keywords: Cross-laminated timber, subterranean termites, laboratory assay, wood durability.

INTRODUCTION

Cross-laminated timber (CLT) has gained attention from the "green" building movement as a renewable prefabricated panel material with excellent thermal insulation, sound insulation, and fire restriction qualities (Laguarda-Mallo and Espinoza 2014). Other advantages include the ease of handling on-site and considerably lower weights than precast concrete. These characteristics make CLT panels ideal for rapid construction of modular buildings, including apartment/condominium structures (Van de Kuilen et al 2011; Smyth 2018).

Construction of numerous single and multilevel buildings in Europe and North America has provided real-world examples of the uses and benefits of CLT products. As investors are always searching for new markets, manufacturers have looked toward expanding the use of this product into the North American market, including the southeastern United States (Grasser 2015). As the adoption of CLT construction expands, so does the need for research focused on specific regional hazards or conditions.

Seismic design factors, R-factor, elastic properties, responses to fire, structural properties, and some

* Corresponding author
† SWST member

https://doi.org/10.22382/wfs-2022-03

strength properties have been examined for CLT (Steiger et al 2008; Frangi et al 2009; Ceccotti et al 2010; Gulzow et al 2011; Popovski and Karacabeyli 2012; Pei et al 2013; Shen et al 2013; Gavric et al 2014; He et al 2020). Durability of panels has been examined regarding the delamination and bonding pressure, with increased bonding pressure resulting in lower incidence of delamination (Lim et al 2020). Durability studies with decay fungi have established that CLT left untreated and unprotected from water intrusion is susceptible to deterioration (Singh et al 2019). In addition, others have investigated the durability of CLT against weathering and wood-decaying fungi (Cappellazzi et al 2020; Sinha et al 2020; Bobadilha et al 2021). However, the extent to which termites may damage CLT in use is still under investigation (Mankowski et al 2018; Oliveira et al 2018).

Subterranean termites are found in most of the United States but are most common in the southern states. The warm and moist environment of the southern United States is the preferable climate for subterranean termites, increasing the chances of termite infestation in wood structures. The continental United States has four hazard zones for the risk of termite infestation, which are based on climate (Peterson et al 2006), and this risk must be taken into account when expanding CLT building to the southern region of the United States. The economic impact of termite damage in wood products in the United States is estimated at $1 billion to $7 billion when repair costs are included (Rust and Su 2012).

Wang et al (2018) summarized the main biological risks related to the use of mass timber. The risk of termite attack should be considered especially now that CLT buildings are being placed in areas of increased termite hazard. However, only preliminary studies have been conducted to evaluate the resistance of CLT to termite attack in laboratory assays (Stokes et al 2017; França et al 2018a, 2018b). Testing wood products for susceptibility to termite attack is standardized by the American Wood Protection Association (AWPA) standard method E1-17 (AWPA 2020) and by the American Society for Testing and Materials (ASTM) standard method D3345 (ASTM 2017). However, neither method offers parameters to accommodate the increased volume of CLT as a material. Although CLT can be tested at many dimensions, based on the preferences of the researcher, this study aims only to provide a starting point for assessing termite attack on commercially available CLT product, with number of lamina and overall thickness as commonly applied in low to midrise construction. At the same time, testing CLT at the specimen size recommended in the standard tests is not feasible, as it would not take into account the volume or multiple layers of material within CLT.

AWPA E1 calls for 400 individual termites per test container, with no more than 10% soldiers (AWPA 2020). Matching the increased scale of the test piece would require approximately 27,000 termites for each container. Since that would require collection of a termite population of nearly 675,000 individuals for a test with five treatments and five replicates, this scale is not feasible. Therefore, data to support a modified testing method is needed while still attempting to follow an existing protocol (Hassan and Morrell 2021).

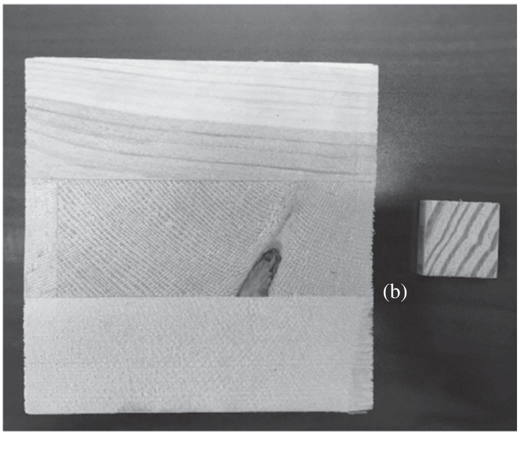
Expanding the range of use for mass timber products throughout the United States requires research into the product's resistance to specific regional hazards. In addition, because CLT is a new product to the United States, there is also a need to develop new methods to measure termite damage, and to be sure that traditional testing methods are still applicable. However, modifications are necessary to accommodate the larger CLT dimensions, and the procedures should be repeatable and reliable. The objectives of this study were to 1) evaluate the resistance of untreated CLT to termite damage and 2) provide a baseline of adjusted methodology for testing CLT panels exposed to termites under laboratory conditions.

MATERIALS AND METHODS

Test Preparation

AWPA E1-17 (AWPA 2020) was used as a basis for this study with modifications to the sample and container size, amount of sand and water substrate, number of termites, and test duration. CLT samples were prepared from sections of 3-ply spruce/pine/fir CLT panels obtained from a western US commercial manufacturer. To minimize the variability present in the material, samples within a test were taken from the same large block providing each test with samples in all treatments that had similar properties. For this test, panels were cut to 10 cm × 10 cm × 2.5 cm (length × width × thickness). This sample size was chosen to demonstrate CLT in its full thickness as shown in Fig 1. When placed in the test containers, the widest face of the CLT sample was placed in contact with the sand surface in the test containers.

Native subterranean termites (species of *Reticulitermes*) were collected from logs found in the Sam D. Hamilton National Wildlife Refuge, Mississippi. For each phase of testing, termites were collected from one population and used within 2 wk of collection. Termites were separated from woody debris by the cleaning methods recommended in AWPA E1-17 (AWPA 2020) and maintained temporarily on dampened coarse paper towel in covered containers.



(a)

Figure 1. Comparison between cross-laminated timber (CLT) and standard test samples: (a) CLT test block face with dimensions of 10 cm × 10 cm × 2.5 cm (length × width × thickness); (b) American Wood Protection Association (AWPA) E1-17 with sample size of 2.5 cm × 2.5 cm × 0.6 cm (radial × tangential × longitudinal).

Prior to this series of tests, preliminary tests were conducted to select an appropriate container size, and 4-L clear polycarbonate containers with a tight-fitting lid were selected. A $1/4''$ hole for air exchange was drilled in each lid. These holes were then plugged with sterile cotton. Before starting the test, samples were oven-dried at 60°C to a constant weight. Five replicate CLT samples were used for each set of conditions. Following testing, blocks were again oven-dried at the same temperature to a constant mass to determine mass change. The variables evaluated in this test series included 1) variation of number of termites, 2) amount of sand substrate and water, and 3) duration of test. For each test phase, replicate control containers were also prepared without the presence of termites, to assess the impact of the test conditions on the CLT samples. For every variable tested, a total of five replicates were used and one container per replicate. Each test container received the same soldier:-worker ratio (not to exceed 10% soldiers) specified in the AWPA E1-17 (AWPA 2020) standard.

Variable 1: Termite number variation test. Termites were separated from the wood as described earlier. Groups of 400, 600, 800, and 1000 termites were each counted three times and weighed. The average weight was calculated. Termites were added to test containers based on weight, which created some variation in the actual number of termites per container. All containers were prepared with 1500 g sand and 180 mL sterile distilled water and exposed for 4 wk, but each treatment received a different number of termites. The first group received the number of termites stipulated by AWPA E1 (AWPA 2020), which is 400 termites (approximately 1 g), and the other containers received 600, 800, or 1000 termites (1.8, 2.4, and 3 g, respectively).

Variable 2: Substrate variation test. The amount of sand and water recommended by AWPA E1-17 is 150 g and 27 mL, respectively (AWPA 2020). In the chosen 4-L container, this amount of water and sand could not provide enough sand substrate and moisture for termite survival. Four variations were selected for comparison in this second phase of testing: 375, 750, 1125, and 1500 g of sand with proportional increases of water (45, 90, 135, and 180 mL, respectively). For this phase of testing, the number of termites was kept constant at 1000 termites (3 g) in each container, and the test duration was 4 wk.

Variable 3: Variation in duration of test. In the third phase of testing, containers were prepared using the amount of sand (1125 g) water (135 mL), and termites (1000 termites) determined from phases 1 and 2, and three test periods were compared (4, 8, and 12 wk). The recommended length of testing in AWPA E1-17 is 4 wk (AWPA 2020). This phase of testing was included to examine whether the larger test container and larger wood specimen would allow the termite population to remain healthy and active for longer than the standard test period, and whether a longer test period would result in increased damage to the CLT test samples. This test was designed to identify the significant differences between durations of exposure for the visual rating and mass loss variables.

Analysis of Tested Material

Test containers were incubated in a dark room at 21°C and 64% RH. Containers were inspected weekly throughout each phase of testing for signs of mold or secondary fungal contamination, and to verify that the termite populations were active. At the end of each test phase, CLT samples were removed and photographed. Living termites were carefully knocked out of the blocks and counted using an aspirator to collect the individuals. Test samples were then cleaned of mud tubes and debris and oven-dried under the same conditions as the pretest (60°C to a constant weight). Samples were photographed and each sample was examined and visually rated using the AWPA E1-17 (AWPA 2020) visual ratings (Table 1).

Images taken from tested materials were grouped into a single reference image, presented here in Fig 2. These images are presented here to clarify positioning and surface exposure and serve as guidelines for future research. CLT specimens from test series shown in Fig 2 include the following: termite number variation test, sand-adjacent face (a) and nonadjacent face (b); sand variation test, sand-adjacent face (c) and nonadjacent face (d); time variation test, sand-adjacent face (e) and nonadjacent face (f). Figure 3 demonstrates the damage observed on multiple sides of CLT samples from the termite number variation test, indicating an active, foraging termite population. CLT images shown in Fig 3 include the narrow faces of a single specimen, with the top and bottom of the original panel (a and c), and the cut edges (b and d).

Table 1. Visual rating system according to AWPA Standard E1-17 (AWPA 2020).

Visual rating classification	Rating
Sound	10
Trace, surface nibbles permitted	9.5
Slight attack, up to 3% of cross-sectional area affected	9
Moderate attack 3-10% of cross-sectional area affected	8
Moderate/severe attack, penetration, 10-30%, of cross-sectional area affected	7
Severe attack, 30-50% of cross-sectional area affected	6
Very severe attack, 50-75% of cross-sectional area affected	4
Failure	0

AWPA, American Wood Protection Association.

Statistical Analysis

Statistical Analysis System Version 9.4 (SAS Institute, Cary, NC) was used to analyze the differences in termite number, substrate level, and duration on response variables. Assumptions of normality and homogeneity of variance (HOV) were tested on raw data using the Shapiro–Wilk test and Levene's test, respectively. The threshold for significance for all tests was set at $\alpha = 0.05$. If assumptions were met, one-way analysis of variance (ANOVA) was performed using PROC GLM and then mean comparison was done with LSMEANS. If assumptions were not met, logarithmic transformation was used to normalize the data. For visual rating data and data that could not be normalized, Kruskal–Wallis H test, a nonparametric equivalent of one-way ANOVA, was performed. If the effect being analyzed proved to be significant at $\alpha = 0.05$, then mean rank separation was done using a Wilcoxon rank pairwise test adjusted by the Bonferroni correction.

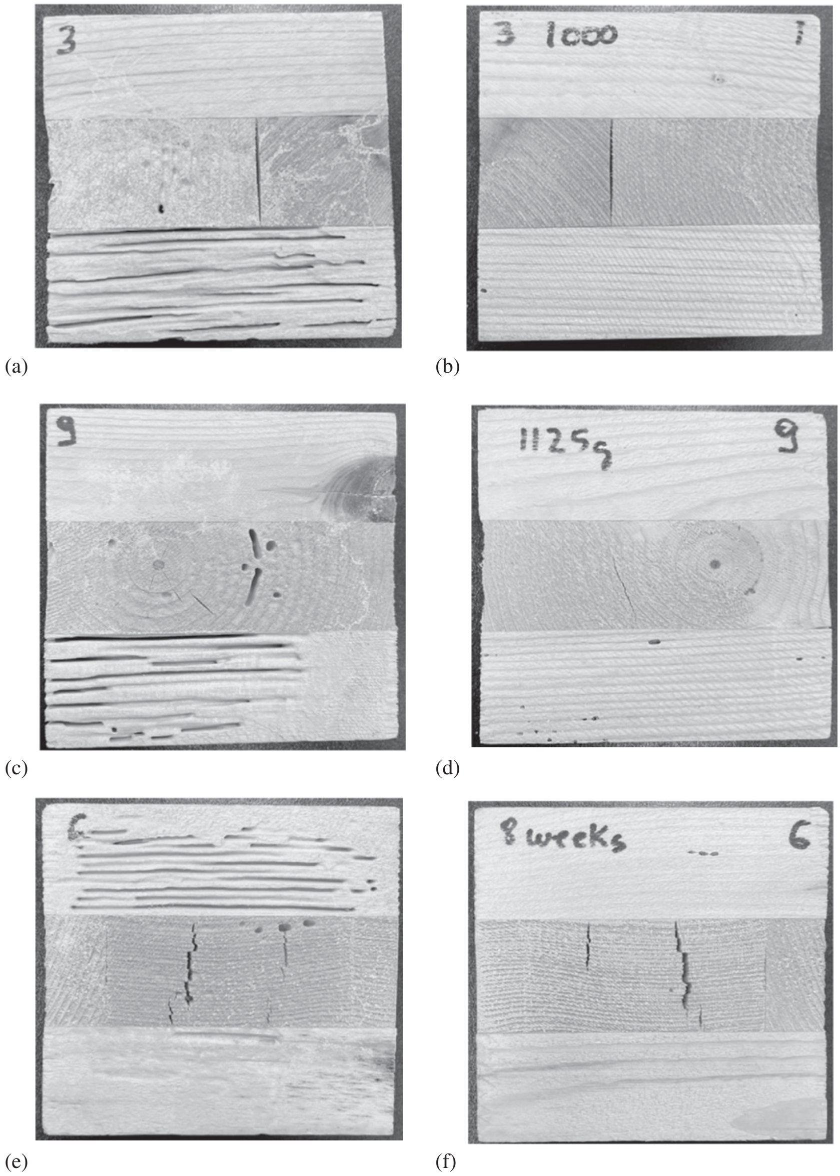
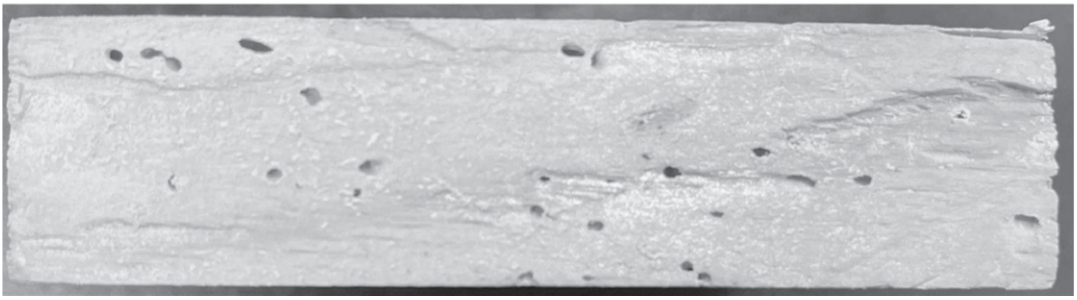


Figure 2. Cross-laminated timber (CLT) specimens from tests series: termite number variation test, sand-adjacent face (a) and nonadjacent face (b); sand variation test, sand-adjacent face (c) and nonadjacent face (d); time variation test, sand-adjacent face (e) and nonadjacent face (f).

RESULTS AND DISCUSSION

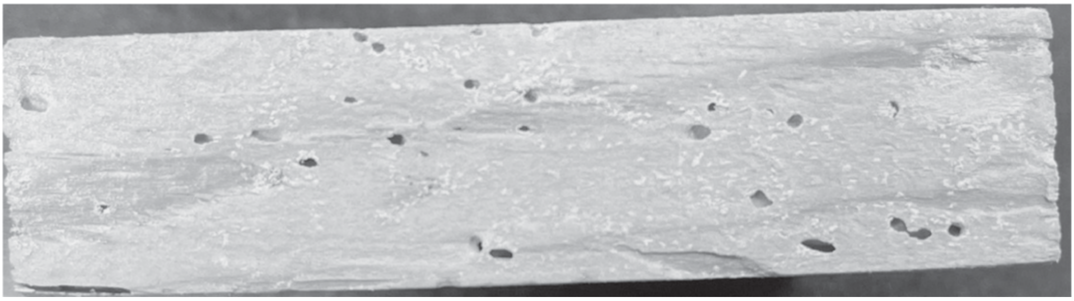
Variable 1: Termite Number Variation Test

Table 2 summarizes mass loss, visual rating, and termite mortality. The data set for mass loss on phase 1 passed normality and HOV tests, so a one-way ANOVA was used to compare the effect of number of termites on mass loss. The average mass loss of samples exposed to 1000 termites per container (1.7%) was significantly higher than the other treatments. There was no statistical difference between the samples exposed to 800 and



(a)

(b)



(c)

(d)

Figure 3. Example of termite damage on all sides of cross-laminated timber (CLT) samples from the test to evaluate termite number: with the top and bottom of the original panel (a and c), and the cut edges (b and d).

600 termites per container (1.0% and 0.9%, respectively). Blocks exposed to 400 termites showed a significantly lower mass loss (0.5%) compared with the other treatments. Damage in wood material is often determined by observing mass loss, for which the samples should be oven-dried to a constant mass. The AWPA E1-17 recommendation for drying is 40°C in a forced-draft oven for

Table 2. The effect of termite number on mean and percent coefficient of variation (in parenthesis) of mass loss, visual rating, and termite mortality.[a]

Number of termites	Mass loss[b] (%)	Visual rating[b] (AWPA E1)	Termite mortality (%)
1000	1.7a (15.8)	6.3d (3.9)	0.0 (0.0)
800	1.0b (19.0)	7.2c (3.4)	0.0 (0.0)
600	0.9b (10.6)	7.1c (2.8)	0.0 (0.0)
400	0.5c (43.8)	8.0b (2.8)	0.0 (0.0)
No Termite Control	−0.4d (−25.8)	10.0a (0.0)	N/A

AWPA, American Wood Protection Association.

[a] Test containers were evaluated at 4 wk and contained 1500 g sand and 180 mL of water.

[b] A significant difference among mean values in a column is indicated when no lowercase letters are shared ($\alpha = 0.05$).

solid wood materials and 40°C or 103°C for wood plastic composites (AWPA 2020). After working with CLT specimens during this series of tests, it was found that the CLT posttest specimens could not be dried at 40°C in a reasonable amount of time. Therefore, the recommended oven-drying temperature was increased to 60°C ± 2 for all tests. This temperature allowed CLT samples to dry in a reasonable time but was not high enough to damage samples resulting in cracks, checks, or delamination.

CLT samples exposed to 1000 termites per container received a significantly lower visual rating (6.3) compared with the other treatments (Table 2). According to the AWPA E1-17 visual rating, this attack is classified as severe attack with 30-50% of cross-sectional area affected (AWPA 2020). Blocks exposed to 800 or 600 termites received visual ratings of 7.2 and 7.1, respectively. This damage is classified as moderate attack with 10-30% of cross-sectional area affected. CLT blocks exposed to 400 termites received an average grade of 8.0 and the damage was classified as moderate attack with 3-10% of the cross-sectional area affected. There was no observed mortality in the tested conditions.

Variable 2: Substrate Variation Test

After transforming percent mass loss data using $\log_{10}$, assumptions of normality and HOV were satisfied (Table 3). One-way ANOVA showed that the effect of treatment was significant. A total of 1000 termites per container (approximately 3 g) produced the highest mass loss percentage in phase 1. Wood specimens in containers prepared with 1125 g and 750 g of sand had 2.4% and 2.1% mass loss, respectively, which was statistically higher than containers with 375 g (1.5%) but was not significantly different from containers with 1500 g (1.9%). Containers with 1125 g showed the

Table 3. The effect of amount of sand on mean and percent coefficient of variation (in parenthesis) of mass loss, visual rating, and termite mortality.[a]

Amount of sand (g)	Mass loss[b] (%)	Visual rating[b] (AWPA E1)	Termite mortality (%)
1500	1.9ab (25.4)	8.0b (6.9)	0.0 (0.0)
1125	2.4a (7.2)	7.5b (5.5)	0.0 (0.0)
750	2.1a (12.0)	7.5b (6.0)	0.0 (0.0)
375	1.5b (30.6)	7.8b (5.1)	0.0 (0.0)
1500_C[1]	0.6c (39.9)	10.0a (0.0)	N/A
1125 C[1]	0.6c (36.2)	10.0a (0.0)	N/A
750 C[1]	0.7c (19.5)	10.0a (0.0)	N/A
375_C[1]	0.7c (22.0)	10.0a (0.0)	N/A

AWPA, American Wood Protection Association.

[1] Control = no termites, otherwise containers had about 1000 termites and were evaluated at 4 wk.

[a] Test containers were evaluated at 4 wk and tested with 1000 termites per container.

[b] A significant difference among mean values in a column is indicated when no lowercase letters are shared ($\alpha = 0.05$).

lowest coefficient of variation (CV) among all sand levels tested.

Test blocks in containers with 1500 g of sand received higher average visual ratings (8.0) and were classified as having moderate attack, with 3-10% of the cross-sectional area affected (Table 3). However, no significant differences were observed between sand levels for visual ratings. Containers with 1125, 750, and 375 g of sand (7.5, 7.5, and 7.8 visual rating, respectively) were classified as severe attack, with 10-30% of cross-sectional area affected. No termite mortality was observed in this phase of testing. Even though no significant differences were observed between the three different sand levels (1500, 1125, 750 g of sand), 1125 g of sand was used in the third phase of testing.

Variable 3: Variation in Duration of Test

The variation in exposure duration is presented in Table 4. Since mass loss data in phase 3 were not normal and did not pass HOV even after transformation, differences in time duration were tested using the Kruskal–Wallis H test. Treatment was significant and a Wilcoxon multiple comparisons test was performed. Containers exposed to termite infestation for 12 or 8 wk had significantly higher mass losses (5.8% and 5.2%, respectively) than those exposed for only 4 wk (3.6%). No termite mortality occurred on wood in containers exposed for 4 and 8 wk; however, a high termite mortality (68.6%) was observed in containers exposed for 12 wk.

Although no statistically significant differences were observed in mass loss data between test samples exposed for 12 and 8 wk, the 8-wk duration had other advantages: 1) it was shorter, thereby providing a faster turnaround time for test results, 2) it produced lower CV values (4.2% vs 20.7% for 12 wk), and 3) it showed much lower termite mortality (0% vs 68.6% for 12 wk).

Table 4 also shows the companion visual rating data for exposure duration. Containers exposed for 4 and 8 wk had significantly higher mean visual ratings (7.4 and 7.0, respectively) compared with containers exposed for 12 wk (5.6). Containers exposed for 4 and 8 wk had termite damage classified as moderate/severe attack with penetration and 10-30% of the cross-sectional area affected. Containers exposed for 12 wk had severe attack with 30-50% of the cross-sectional area affected.

The results suggest that adjustments should be made to the existing standard tests to provide a basis for lab-scale testing of CLT, or that this material requires such different handling that a new standard should be developed. AWPA E1-17 (AWPA 2020) was selected as the basis for this test design since this standard is commonly used to evaluate the resistance of solid and composite wood products to subterranean termites. AWPA E1, however, was originally developed for wood products of a uniform composition, for which a small sample size is viable. CLT panels are a massive and heterogeneous product that should be tested at a size representative of use conditions. Table 5 describes the conditions from this series of testing that were

Table 4. The effect of exposure time on mean and percent coefficient of variation (in parenthesis) of mass loss, visual rating, and termite mortality.[a]

Treatment (weeks)	Mass loss[b] (%)	Visual rating[b] (AWPA E1)	Termite mortality (%)
4	3.6b (3.9)	7.4b (6.6)	0.0 (0.0)
8	5.2a (4.2)	7.0b (0.0)	0.0 (0.0)
12	5.8a (20.7)	5.6c (14.3)	68.6 (58.0)
4_C[1]	2.0c (6.5)	10.0a (0.0)	N/A
8_C[1]	1.6d (6.1)	10.0a (0.0)	N/A
12_C[1]	2.1c (5.8)	10.0a (0.0)	N/A

AWPA, American Wood Protection Association.

[1] Control = no termites, otherwise containers had 3 g or about 1000 termites and 1125 g sand.

[a] Test containers had 1000 termites and contained 1125 g sand and 135 mL of water.

[b] A significant difference among mean values in a column is indicated when no lowercase letters are shared ($\alpha = 0.05$).

Table 5. Recommended modifications to the AWPA Standard E1-17 test method for evaluating termite damage to CLT material.

Testing conditions	AWPA standard	Modifications for CLT samples
Oven-drying temperature	40°C ± 2 or 103°C ± 2	60°C ± 2
Wood sample size	2.5 cm × 2.5 cm × 0.6 cm	10 cm × 10 cm × 2.5 cm
Test container	80 mm × 100 mm glass screw-top jars	4-L food-safe container
Sand and water	150 g/27 mL	1125 g/135 mL
Number of termites	400	1000
Test duration	4 wk	Up to 8 wk

AWPA, American Wood Protection Association; CLT, cross-laminated timber.

determined to be suitable for the evaluation of termite damage on CLT at the bench scale.

When considering mass loss of CLT in an AWPA E1 style test, and the mass losses typically derived from testing solid wood in this test, a trend in the end results has been observed. With solid wood specimens of pine, spruce, and fir using standard test dimensions, values obtained in other studies were 40%, 23%, and 25%, respectively (Arango et al 2006; Kose and Tylor 2012; França et al 2016). In the AWPA E1 modified test presented here, with CLT at larger dimensions than the standard sample, the greatest mass loss achieved was 5.8%. Mass loss results from standard solid wood tests are much higher than the values obtained in this study, possibly due to the larger sample size used, or perhaps due to the laminate characteristic of CLT.

It is clear, however, that testing CLT in this manner should not be directly correlated to solid wood tests conducted at standard sample dimensions. Due to these differences and the lack of laboratory-scale testing of CLT products to date, it is unclear whether mass loss over time is a true indicator of change in CLT due to termite feeding behavior. It is also unclear whether mass loss is a true indicator of MC in CLT, as wood layers and glue lines exist at different moisture contents and may have distinct variations in drying. Perhaps, application of more precise technologies to measure volume loss and moisture changes should be combined with mass loss for better evaluation of termite damage on CLT samples.

For example, Arango et al (2016) evaluated the resistance of laser marking on wood to termite attack. Samples of solid southern pine wood and plywood samples measuring 75 mm × 37 mm × 9 mm were marked with a laser and the laser-marked surface was exposed to termites. In this study, termite damage to the longitudinal wood face, marked by a laser, was evaluated using percent surface attack as analyzed by ImageJ software rather than by mass loss. The larger scale of the samples required a change in evaluation methods. França et al (2019) used ImageJ to determine percent cross-sectional area affected on CLT samples subjected to termite attack. Percent cross-sectional area affected by termite feeding, in conjunction with mass loss and visual rating, resulted in a more accurate determination of overall termite damage in CLT than mass loss alone was able to describe.

This study outlines guidance for the laboratory-scale testing of CLT. These recommendations are meant to serve as a beginning for further testing of CLT and other mass timber products, each with their own characteristics that must be considered. In addition, test protocols for CLT exposure to termites under laboratory conditions should continue to be refined from the starting point provided here with comparison of other variables such as MC of wood, MC of adhesive, thickness of glue line, wood density, and wood grain orientation included.

CONCLUSIONS

A termite assay was developed for testing 3-ply CLT, a product that is heterogeneous in composition. This methodology can be used as a starting point for the development of standardized procedures to asses termite damage on CLT panels.

The evaluation of appropriate conditions to compare the number of termites, amount of substrate and moisture, and duration of testing was completed. Adjustments to test conditions are presented as a comparison with standard test conditions in Table 5. Further testing is underway, and additional testing is recommended to continue the examination of all variables that may influence testing, such as adhesive thickness and type, MC, preservative treatment of wood lamina, and wood species included in CLT.

ACKNOWLEDGMENTS

The authors acknowledge the support from USDA Forest Service Forest Products Laboratory (FPL) in Madison, WI, as a major contributor of technical assistance, advice, and guidance to this research. This paper was approved as journal article SB 1042 of the Forest & Wildlife Research Center, Mississippi State University.

REFERENCES

Arango RA, Green F, Hintz K, Lebow PK, Miller RB (2006) Natural durability of tropical and native woods against termite damage by *Reticulitermes flavipes* (Kollar). Int Biodeterior Biodegradation 57(3):146-150.

Arango RA, Woodward BM, Lebow ST (2016) Evaluating the effects of post dip-treatment laser marking on resistance to feeding by subterranean termites. *In* Proc IRG Annual Meeting (ISSN 2000-8953), The International Research Group on Wood Protection, 19-22 July 2016, Lisbon, Portugal; IRG/WP 16-10854; Section 1 Biology.

American Society for Testing and Materials (ASTM) (2017) D 3345-17: Standard test method for laboratory evaluation of solid wood for resistance to termites, American Society for Testing and Material International, West Conshohocken, PA.

American Wood Protection Association (AWPA) (2020) E1-17: Laboratory methods for evaluating the termite resistance of wood-based materials. American Wood Protection Association Book of standards. American Wood Protection Association, Birmingham, AL.

Bobadilha GS, Stokes CE, Kirker G, Ahmed SA, Ohno KM, Lopes DJV (2021) Effect of exterior wood coatings on the durability of cross-laminated timber against mold and decay fungi. BioResources 15(4):8420-8433.

Cappellazzi J, Konkler MJ, Sinha A, Morrell JJ (2020) Potential for decay in mass timber elements: A review of the risks and identifying possible solutions. Wood Mater Sci Eng 15(6):351-360.

Ceccotti A, Sandhaas C, Yasumura M (2010) Seismic behavior of multistory cross-laminated timber buildings. *In* Proc International Convention of Society of Wood Science and Technology, Geneva, Switzerland CSA S-16. Design of Steel Structures. Ottawa, Canada: Canadian Standards Association.

França TSFA, França FJN, Arango RA, Woodward BM, Arantes MDC (2016) Natural resistance of plantation grown African mahogany (*Khaya ivorensis* and *Khaya senegalensis*) from Brazil to wood-rot fungi and subterranean termites. Int Biodeterior Biodegradation 107:88-91.

França TSFA, Stokes CE, Tang JD (2018a) Durability of cross laminated timber against termite damage. *In* Proc 61st international convention of society of wood science and technology and Japan wood research society. Monona, WI: Society for Wood Science and Technology. 10 pp.

França TSFA, Stokes CE, Tang JD (2018b) Evaluation of cross-laminated timber resistance to termite attack. *In* Proc American Wood Protection Association Annual Meeting, 22-24 April 2018, Seattle, WA. 114:266-271.

França TSFA, Stokes CE, Tang JD, Arango RA (2019) Utility of image software in quantification of termite damage on cross-laminated timber (CLT). *In* Proc 21st International Nondestructive Testing and Evaluation of Wood Symposium, 24-27 September 2019, Freiburg, Baden-Württemberg, Germany. General Technical Report FPL-GTR-272. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. pp. 643-649.

Frangi A, Fontana M, Hugi E, Jübstl R (2009) Experimental analysis of cross-laminated timber panels in fire. Fire Saf J 44(8):1078-1087.

Gavric I, Fragiacomo M, Popovski M, Ceccotti A (2014) Behavior of cross-laminated timber panels under cyclic loads. Pages 689-702 *in* S Aicher, HW Reinhardt, H Garrecht, eds. Materials and joints in timber structures. The Netherlands: Springer.

Grasser KK (2015) Development of cross laminated timber in the United States of America. MS thesis, University of Tennessee, Knoxville, TN. 115 pp.

Gulzow A, Richter K, Steiger R (2011) Influence of wood moisture content on bending and shear stiffness of cross laminated timber panels. Holz Roh-und Werkst 69(2): 193-197.

Hassan B, Morrell JJ (2021) Termite testing methods: A global review. J Test Eval 49(6):20200455.

He M, Sun X, Li Z, Feng W (2020) Bending, shear, and compressive properties of three- and five-layer cross-laminated timber fabricated with black spruce. J Wood Sci 66(38):1-17.

Kose C, Tylor AM (2012) Evaluation of mold and termite resistance of included sapwood in eastern redcedar. Wood Fiber Sci 44(3):319-324.

Laguarda-Mallo M, Espinoza O (2014) Outlook for cross-laminated timber in the United States. BioResources 9(4): 7427-7443.

Lim H, Tripathi S, Tang JD (2020) Bonding performance of adhesive systems for cross laminated timber treated with micronized copper azole type C (MCA-C). Constr Build Mater 232:1-10.

Mankowski M, Shelton TG, Kirker G, Morrell J (2018) Ongoing field evaluation of Douglas-fir cross laminated timber in a ground proximity protected test in Mississippi. *In* Proc 114th American Wood Protection Association Annual Meeting, 22-24 April 2018, Seattle, WA. pp. 132-137.

Oliveira GL, Oliveira FL, Brazolin S (2018) Wood preservation for preventing biodeterioration of cross laminated timber (CLT) panels assembled in tropical locations. Procedia Structural Integrity 11:242-249.

Pei S, Van de Lindt JW, Popovski M (2013) Approximate R-factor for cross-laminated timber walls in multistory buildings. J Archit Eng 19(4):245-255.

Peterson C, Wagner TL, Mulrooney JE, Shelton TG (2006) Subterranean termites—their prevention and control in building. Home and Garden Bulletin 64. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Starkville, MS. 38 pp.

Popovski M, Karacabeyli E (2012) Seismic behaviour of cross-laminated timber structures. Pages 335-344 *in* P Quenneville, ed. Proc World Conference on Timber Engineering, 16-19 July 2012, Auckland, New Zealand.

Rust MK, Su NY (2012) Managing social insects of urban importance. Annu Rev Entomol 57:355-375.

SAS Institute (2013) SAS® software, version 9.4. Cary, NC: The SAS Institute Inc.

Shen Y, Schneider J, Tesfamariam S, Stiemer SF, Mu Z (2013) Hysteresis behavior of bracket connection in cross-laminated-timber shear walls. Constr Build Mater 48:980-991.

Singh T, Page D, Simpson I (2019) Manufactured structural timber building materials and their durability. Construction Structural Timber Building Materials and Their Durability 217:84-92.

Sinha A, Udele K, Cappellazzi J, Morrell JJ (2020) A method to characterize biological degradation of mass timber connections. Wood Fiber Sci 52(4):419-430.

Smyth M (2018) Cross laminated timber for residential construction. MS thesis, KTH Royal Institute of Technology, Stockholm, Sweden. p. 95.

Steiger R, Gülzow A, Gsel LD (2008) Non-destructive evaluation of elastic material properties of cross-laminated timber (CLT). Pages 29-30 *in* WF Gard and JWG van deKuilen, eds. Proc International Conference COST E53, 29-30 October 2008, Delft, The Netherlands.

Stokes CE, Tang JD, Shmulsky R (2017) Potential impact of subterranean termites on cross-laminated timber (CLT) in the Southeastern U.S. *In* Proc American Wood Protection Association Annual Meeting, 09-11 April 2018, Las Vegas, NV. 113:214-219.

Van de Kuilen JWG, Ceccotti A, Xia Z, He M (2011) Very tall wooden buildings with cross laminated timber. Procedia Eng 14:1621-1628.

Wang JY, Stirling R, Morris PI, Taylor A, Lloyd J, Kirker G, Lebow S, Mankowski M, Barnes HM, Morrell JJ (2018) Durability of mass timber structures: A review of the biological risks. Wood Fiber Sci 50(Special Issue):110-127.