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Evaluation of the durability of mass timber products against termites (Reticulitermes spp.) using choice testing.

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By

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Evaluation of the durability of mass timber products against termites (Reticulitermes spp.) using choice testing

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Mass timber products are rapidly growing in fascination and popularity across the North American construction market, in which wood products are tested for durability and resiliency according to standards set by the American Wood Protection Association. Presently, the American Wood Protection Association (AWPA) E1 Standard calls for a test sample size of 2.54cm x 2.54cm x 0.64cm, which may be too small to encompass the large spacing between the bond lines of CLT, a multilayered mass timber product composed of layers of kiln-dried lumber alternating in grain direction. The objective of this study was to evaluate the resistance of untreated CLT against subterranean termites (*Reticulitermes* spp.) found in the southeastern United States using two-sample choice testing and extend the AWPA E1-17 Standard to accommodate the larger building material. Choice-testing methods were evaluated over a 4-week period for mass loss, visual rating, mold formation, and termite mortality.

DEDICATION

I dedicate my thesis work to my family and many friends. To my father of whose many authentic gray hairs were caused by myself. To my sisters Corleia, Kiara, Tierney, and Jameshia that have never left my side and are very special to me. To T-Chell thanks for being only a phone call away to fuss at me for motivation and true mentorship. To my nieces and nephews, thank you for thinking so highly of me as your favorite aunt and being constant reminders to never stop coloring outside the lines. A special thanks to my close friends Aliyah, ATL, and Jasmine for being there for me throughout the entire master's program. You have all served as my best cheerleaders and the medication for my sanity, and I am so blessed to maneuver through this crazy adventure of life with you all.

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CHAPTER I

INTRODUCTION

Cross-Laminated Timber (CLT) is a renewable, pre-fabricated panel material and is regarded as a highly desirable construction material as a part of the green building movement (WoodWorks, 2019). In addition, CLT has been deemed admirable for its thermal, sound, seismic, and fire performance qualities (Karacabeyli and Brad, 2013). As of March 2019, there are plans for 545 mass timber buildings across the US with approximately 132 mass timber projects located in southeastern regions of the United States, as shown in Figure 1.1 (WoodWorks, 2019).

Figure 1.1 Mass timber projects constructed or proposed/designed in the U.S. Statistics are current as of March 2019. Image courtesy of WoodWorks (2019).

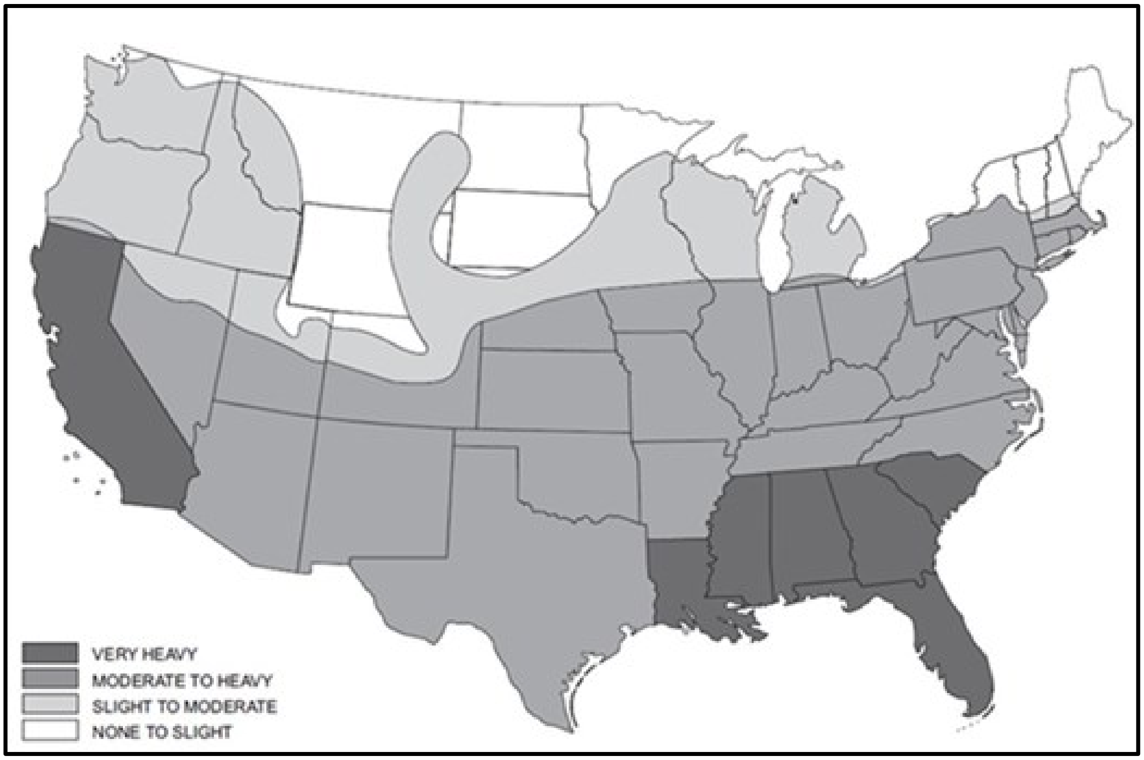

Figure 1.2 Termite infestation probability map. Image courtesy of ABTG, LLC (2018).

Notably, the southeastern United States is in either “very heavy” or “moderate to heavy” termite infestation areas, as shown in Figure 1.2 (ABTG, 2018). This may be problematic for buildings composed of mass timber products that are manufactured without protective measures against termites, either native or invasive. Currently, there is a lack of information regarding deterioration and response to termites for CLT and other mass timber products. With the rapid and constant increase in demand, fascination, and innovation in mass timber products, such information is valuable and imperative to the wood products community.

1.1 Cross-Laminated Timber

Originally developed in Europe, CLT is an innovative engineered wood product that is increasingly becoming popular among North American building designers for residential and commercial use (Karacabeyli and Brad, 2013). CLT panels consist of timber stacked crosswise to create layers, glued together with the grain of the boards in one layer running perpendicular to the grain in adjacent layers (Karacabeyli and Brad, 2013). CLT may also be joined with the use of nails or wooden dowels and the middle layer can be lumber or composite materials and may be labeled as 'nail-laminated timber' or another mass timber product (Crespell and Gagnon, 2011). However, it is common for some layers to run in the same direction that provide double layer for specific building capacities. Typically, CLT is manufactured in 3, 5, 7, and 9 ply panels and more in some cases.

In thickness, the lumber pieces within CLT may vary from 16 mm to 51 mm and 60 mm to 240 mm in width (Karacabeyli and Brad, 2013). The lumber is either visually graded or machine stress rated then kiln dried to a moisture content of 12% ± 2% to reduce dimensional change and surface cracking (Karacabeyli and Brad, 2013). Panel size varies depending on the manufacturer; however, it typically ranges between 0.6 m to 3 m in width, 18 m in length, and up to 580 mm thickness (Karacabeyli and Brad, 2013). Due to its dimensional stability, CLT panels can compete with traditional products in the market such as concrete, steel, and masonry (Crespell and Gagnon, 2011).

In addition, its dimensional stability makes it great for walls and floors, creating an effective lateral load-bearing system. Above all, CLT is recognized as a green building material due to its ability to reduce environmental impact via carbon storage, reduction of greenhouse gas emission in manufacture and use, and reduction of a structure's carbon footprint (Crespell and Gagnon, 2011).

1.2 Mass Plywood Panel

Mass plywood panels (MPP) are massive veneer-based engineered wood products designed to be an alternative to lumber-based CLT. New to the mass timber products, MPP is the first of its kind and has been approved under fire codes for use in buildings up to 18-stories high (Freres, 2019). MPP's prefabricated maximum dimensions are 3.7m (12 ft.) x 14.6m (48 ft.) x 0.6m (2 ft.). The panels are constructed in one-inch increments to ensure maximum strength and performance, and manufactured utilizing veneers in a lower relative grade than traditional lumber (Freres, 2019). To date, mass plywood panels have not been tested for degradation potential by either wood decay fungi or termites. Other similar products such as treated and untreated parallel strand lumber (PSL), untreated laminated veneer lumber (LVL), and similar products have been evaluated in no-choice testing (França et al., 2018). An available supply of MPP for this test led to its inclusion.

1.3 Termites

Subterranean termites, Reticulitermes spp., are native to the Southeastern U.S. area and cause million dollars' worth of damage each year in the United States (Ogg and Ogg, 1990). Issues including loss of strength and potential for mold and fungi infestation occur when termites attack the wooden elements of residential and commercial structures., Termites can attack the internal structure of wood products used in buildings, with their presence often going unnoticed. Subterranean termites are social insects that live in nests or colonies in the soil and function in caste system, which includes reproductives, workers and soldiers (Ogg and Ogg, 1990).

In their natural habitat, subterranean termites have many methods to avoid desiccation or to maintain their desired level of moisture content. The soil provides a source of moisture that protects termites from drying out, shields termites from predators, and serves as a building material for shelter tubes above ground. Too little water can cause desiccation in termites, but excessive moisture can also have unfavorable effects on termite foraging and survival.

The termites feed on cellulose obtained from wood. This cellulose often includes the wooden portions of buildings, utility poles, fence posts, or other wood products. Termites invade most buildings through wood close to or in contact with the soil including porches, steps, terraces, fences, planters, or cracks in the foundation (Ogg and Ogg, 1990). After contact is established with an aboveground moisture and food source, termites can reduce or eliminate contact with the soil. Termites excavate galleries throughout their food and typically favor softer portions of wood, such as springwood (Figure 1.3)

Figure 1.3 Active termite excavation along the springwood layers of growth rings.

Termites feed along growth rings, often leaving behind thin layers of denser wood (Ohio, 2007). Wood products damaged by subterranean termites have numerous distinct features ranging from small holes of initial penetrations to visible shelter or mud tubes made of feces and mud. Occasionally their presence is associated with mold fungi, which promotes wood decay (Ohio, 2007).

Though CLT has great structural durability, there is lack of information geared toward its biodegradation properties, which includes termite damage. Currently, CLT is manufactured without preservatives to prevent biodegradation. But with CLT being introduced in termite-heavy regions of North America, it is important to address the possibilities as a precaution. For example, Nordic Structures manufactured CLT for the building of Candlewood Suites at Redstone Arsenal located North Alabama, which is a heavy termite activity zone (WoodWorks, 2016).

1.4 AWPA E1 Standard Modifications

Currently, the AWPA E1-17 Standard choice test calls for 2.54 x 2.54 x 0.64 cm southern yellow pine (SYP) testing wafer and an 8 x 10 cm glass screw on top jar (AWPA, 2019). However, with the recent growth in demand for mass timber products it is important to start the inclusion of mass timber products into the testing standards to assure the longevity of products. Mass timber products, such as CLT, have multiple layers that should be accounted for during testing, which cannot be represented in a 2.54 x 2.54 x 0.64 cm testing wafer nor fit in an 8 x 10 cm glass. A larger test specimen, as shown in Figure 1.4, requires larger containers than the standard dictates, as well as more substrate and a greater amount of water. All characteristics of the AWPA test should be defined for inclusion in future standard publications.

Figure 1.4 Size comparisons of 3-ply CLT (10.16 x 10.16 x 2.54 cm) and AWPA E1-17 standard testing piece (2.54 x 2.54 x 0.64 cm). CLT blocks of this size were divided in half for choice testing.

1.5 Objectives

The proposed project aims to evaluate the resistance of untreated CLT and mass plywood against subterranean termites (*Reticulitermes* spp.) found in the southeastern United States using two-sample choice testing and extend the AWPA E1-17 Standard to accommodate the larger material. AWPA E1-17 standard test protocol for two-sample choice testing will be increased in scale to accommodate the required increase in test sample volume.

CHAPTER II

MATERIALS AND METHODS

2.1 AWPA Choice Testing

The laboratory choice test consisted of all untreated product pairs as follows: CLT (Hem-fir) vs. solid control (SYP), MPP vs. solid control; and CLT (SYP) vs. solid control; MPP vs. CLT (Hem-fir), as showing in Table 2.1. CLT (SYP) was manufactured at the Department of Sustainable Bioproducts, Mississippi State University, while CLT (Hem-fir) was obtained from SmartLam (Whitefish, MT), solid SYP was purchased through East Mississippi Lumber Company (Starkville, MS), and MPP was obtained from USDA colleagues (Starkville, MS). Prior studies on the development of no-choice testing for mass timber used 8-liter containers with lids, 135 mL of sterile distilled water, and 1125 g of sand with 10.16 x 5.08 x 2.54 cm dimension samples and 3 g of termites – approximately 1000 termites (França et al., 2018). Based on successes in no-choice testing, these parameters were also adopted for choice testing.

Table 2.1 Treatment group combinations included in AWPA E1-17 choice testing, with 'x' indicating paired materials in each treatment group.

Treatment Groups	Untreated SYP	CLT HF	MPP	CLT SYP
A	x		x	
B	x	x		
C	x			x
D		x	x	
E			x	x
F		x		x

For the laboratory choice testing, the dimensions of the testing specimens were approximately 5.08 x 5.08 x 2.54 cm, to allow for placement of multiple specimens within the container. This is smaller than samples used in no-choice testing, with each of the two pieces in choice testing at half the size of a no-choice test piece (França et al., 2018). Samples were cut from bulk pieces of CLT and MPP, sections of dimensional SYP were prepared to a similar size, Oven-dry weights were determined for test specimens prior to use, as described in AWPA E1-17. Test specimens were conditioned to a constant weight as developed by França et al. (2018) prior to testing in an environmental chamber set at 70°F (21°C) and 64% RH, with a calculated equilibrium moisture content (EMC) of 12%. Other than those noted, test conditions from AWPA E1-17 were followed.

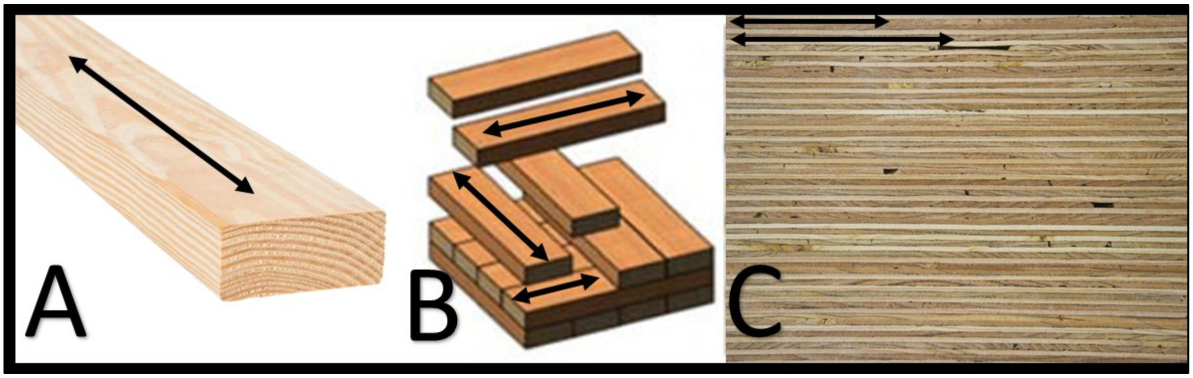

Figure 2.1 Three types of material used in testing: A) SYP dimensional lumber with a single grain direction, B) CLT made from SYP and Hem-Fir dimensional lumber, with alternating grain directions in each layer, and C) mass plywood panel made from layers of veneer, with alternating grain directions in each layer.

Sand substrate was prepared by autoclaving and drying to remove any contaminating microorganisms. Food-safe 8-liter containers were prepared by sterilizing, and distilled water was autoclaved prior to use. Factors developed in the mass timber no-choice tests such as the amount of sand, water, and termites remained consistent for the duration of the project. Samples of each type of material, including the control group, were numbered 1 through 35, and assigned to treatment groups using online integer randomizers. Natural and machining defects were noted for each piece prior to testing. Ten replicate pairings were set up for each treatment group. Treatment groups were staged in time to allow adequate collection and breakdown times. All treatment groups were housed in two environmental chambers, grouped by treatment.

Termites of *Reticulitermes* spp. were obtained from one location found in the Mississippi State University John Starr Forest located south of Starkville, MS. Termites collected were used within two weeks after collection and cleaned as described in AWPA E1-17(AWPA, 2019). After cleaning, termites were counted to determine the mass of 1000 individuals (3 g). Counts were repeated three times for an average weight/1000 termite and the termites were added to the appropriate testing containers by weight. Termite groups included both workers and soldiers, with soldiers making up less than 10% of the overall group. After adding the termites to containers, lids were loosely placed on containers to allow proper air exchange. Test containers were stored in climate-controlled chambers for the full duration of testing (Figure 2.2). Also, a termite starvation test was conducted where termites were placed in a container with sand and water only to estimate the life span of termites in the tested conditions without a food source.

Figure 2.2 Testing containers incubated in climate-controlled incubation chambers set at 70°F with 64% RH and 12% EMC.

The containers were monitored daily for mold growth as well as termite activity for the duration of testing. Container labels included start date of trial, material type, and the sample numbers. At the end of four weeks, specimens were removed from containers and the remaining live termites were counted to determine percent mortality (Figure 2.3).

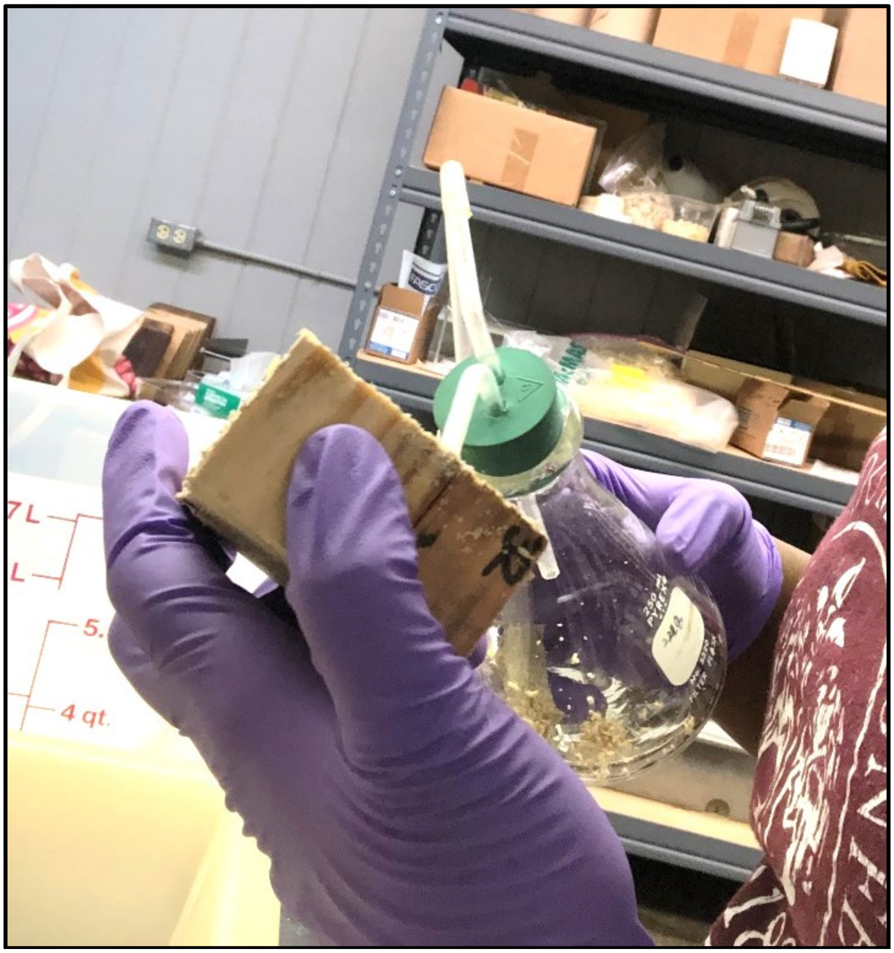

Figure 2.3 Removal and counting of termites at the end of testing using a vacuum aspirator.

The tested mass timber pieces were then cleaned of external mud tubes, termites, and other debris, photographed, re-weighed, and placed back in the environmental chamber. After the materials equilibrated, mass loss was determined for each specimen by determining oven-dry weights as previously described based on AWPA E1-17. Visual assessments were performed according to AWPA E1-17 visual ratings system (Table 2.2). Assessments were performed only on the exposed face (in contact with sand substrate) of each test block, which will be discussed in the following chapter.

Table 2.2 AWPA E1-17 visual grading system.

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

2.2 Data and Analyses

Data collected from the series of choice tests includes mass change for each tested block, termite mortality for each treatment container, and AWPA visual rating. Qualitative data includes photographs of each test piece following testing, descriptions of termite activity including patterns of attack for each block, and general observations of each block following testing.

The equation used to calculate the change in mass (%), and termite mortality:

$$\Delta\, Mass\ (\%) = \frac{(w_1\ -\ w_2)}{w_1} \times 100 \qquad (2.1)$$

Where w_1 is Initial conditioned mass prior to testing (g), w_2 is the final conditioning weight post testing (g).

Termite mortality was calculated for each testing setup by counting the number of living termites at the end of test, subtracted from the original goal of 1000 termites, as shown here:

$$Termite\ mortality\ \% = \frac{(1000 - \#\ of\ living\ termites)}{1000} \times 100 \tag{2.2}$$

2.3 Visualizing Damage

Assessment of termite damage was determined from mass change and from visual ratings assigned to the sand-adjacent face of each test block. To get more information on what termites may have damaged inside the blocks, we also attempted to scan representative blocks using the Nikon XTH 225 x-ray CT (Brighton, MI), located at MSU's Institute for Imaging and Analytical Technologies. It is possible to calculate porosity or void volume for a block using the associated analytical software myVGL® version 3.2 from Volume Graphics, Inc (Charlotte, NC).

CHAPTER III

RESULTS

For the control treatment group, it was found that the mass timber specimens had variations in water retention with the maximum being roughly 3 grams with visual ratings of 10 and without any mold or fungi present (Figure 3.1).

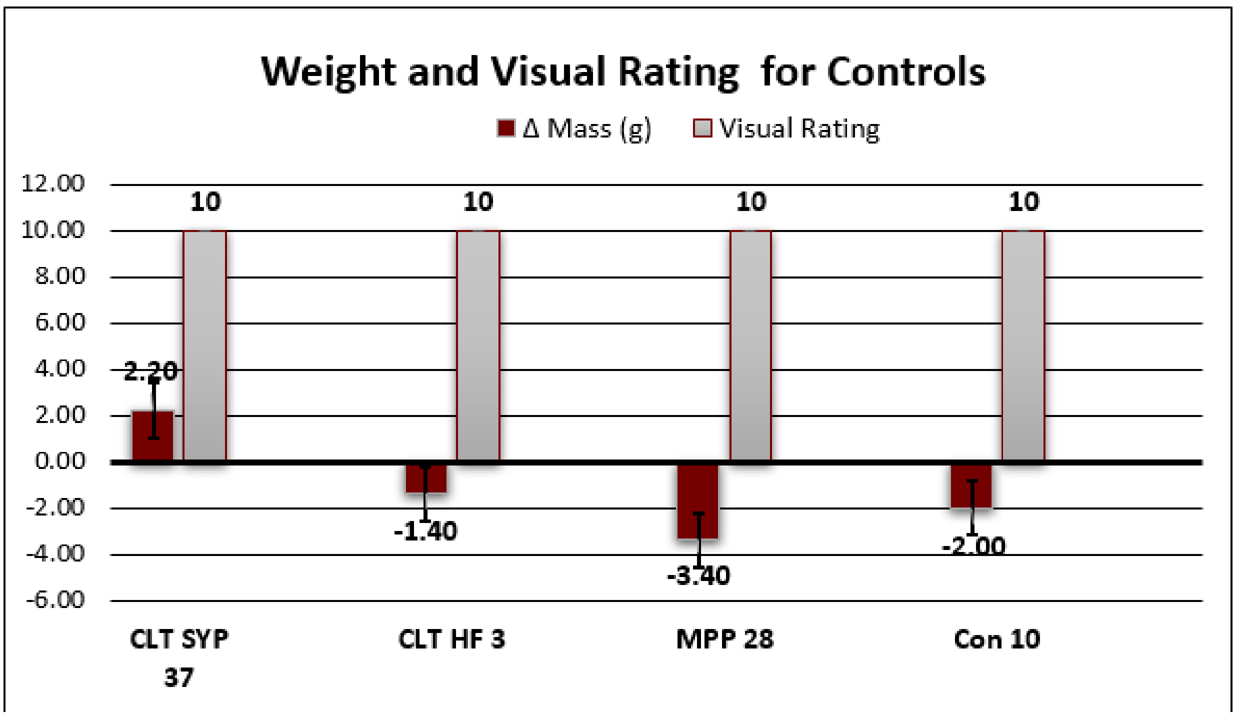

Figure 3.1 Mass change and visual rating for numbered controls of each type of material tested without termites with standard error bars. Labeling includes material and sample number.

The controls were for the individual materials, and do not serve as a reflection of each treatment. This provided a rough estimate of how much water each material may absorb for the duration of 4 weeks without competition.

For the starvation test, termites were placed in a container with sand, water, and no food source in and environmental controlled environments like treatments and controls. The termites survived under said conditions for an average of 9 days with the termites of container #1 surviving for 12 days (Figure 3.2).

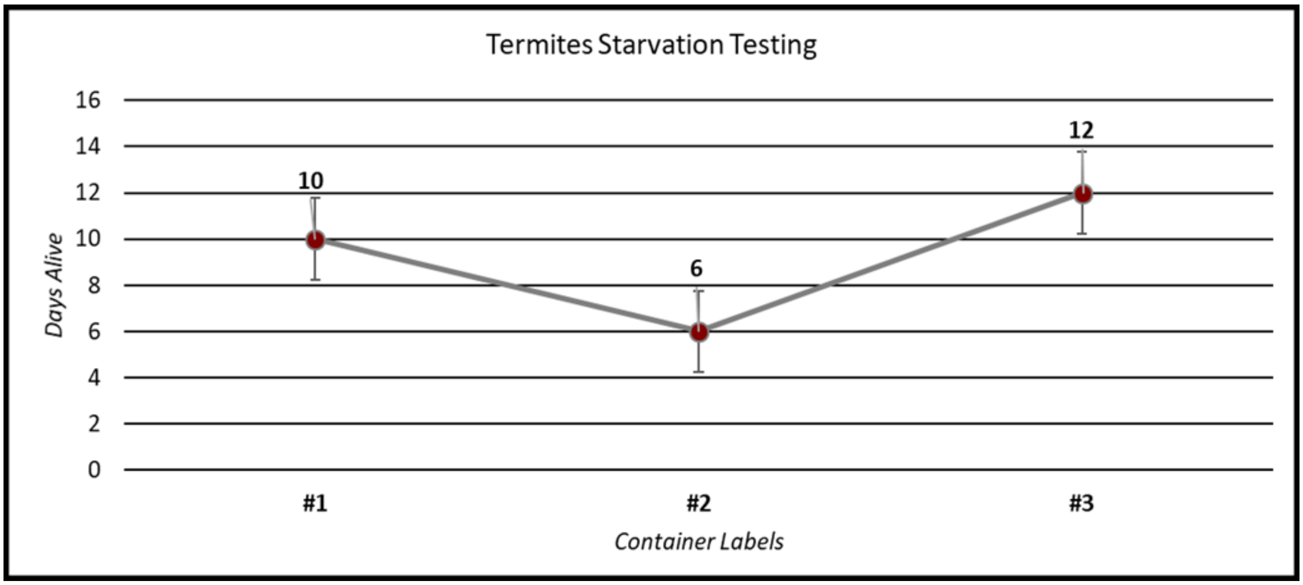

Figure 3.2 Starvation test data showing the number of days the termites survived with standard error bars.

For treatments A through F, the lowest average mass loss was CLT HF of treatment D with 0.256 g and the highest mass gain was solid SYP control in treatment A with 1.904 g (Figure 3.3). The highest visual rating average was found in MPP of treatment D and CLT SYP with 9.95 and the lowest being CLT HF of treatment B with 5.4 (Figure 3.3).

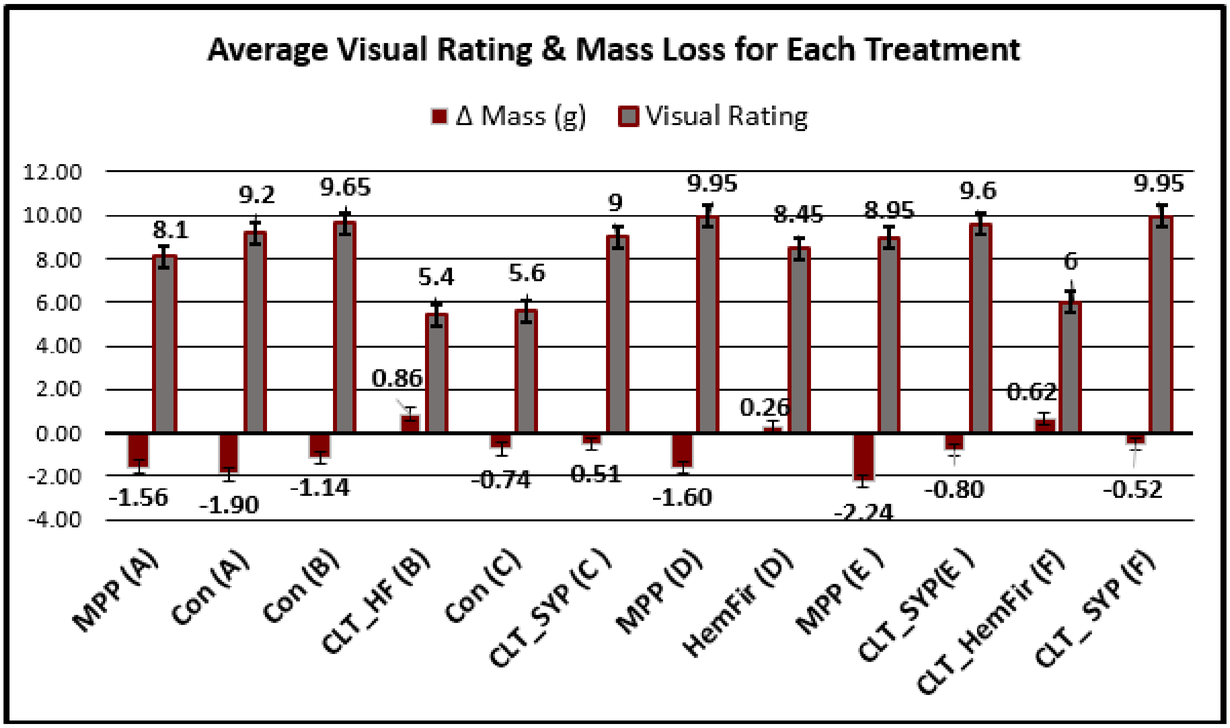

Figure 3.3 Visual rating (left bar) and mass change (right bar) for each treatment group (A) – (F). Negative mass change indicates a gain in mass after post-test oven drying, while positive mass changes indicate a loss in mass after oven drying.

As compared to the control blocks without termites, which had an average visual rating of 10 and -1.15 mass change (gain in mass by 1.15 g), paired choice tests averaged an 8.3 visual rating and -0.773 g mass change (gain in mass by 0.773 g). As for the change in mass, the mass gain is not an accurate reflection of termite damage since results reflects that the samples gained mass instead of losing mass due to termite excavation (Figure 3.4, Table 3.4).

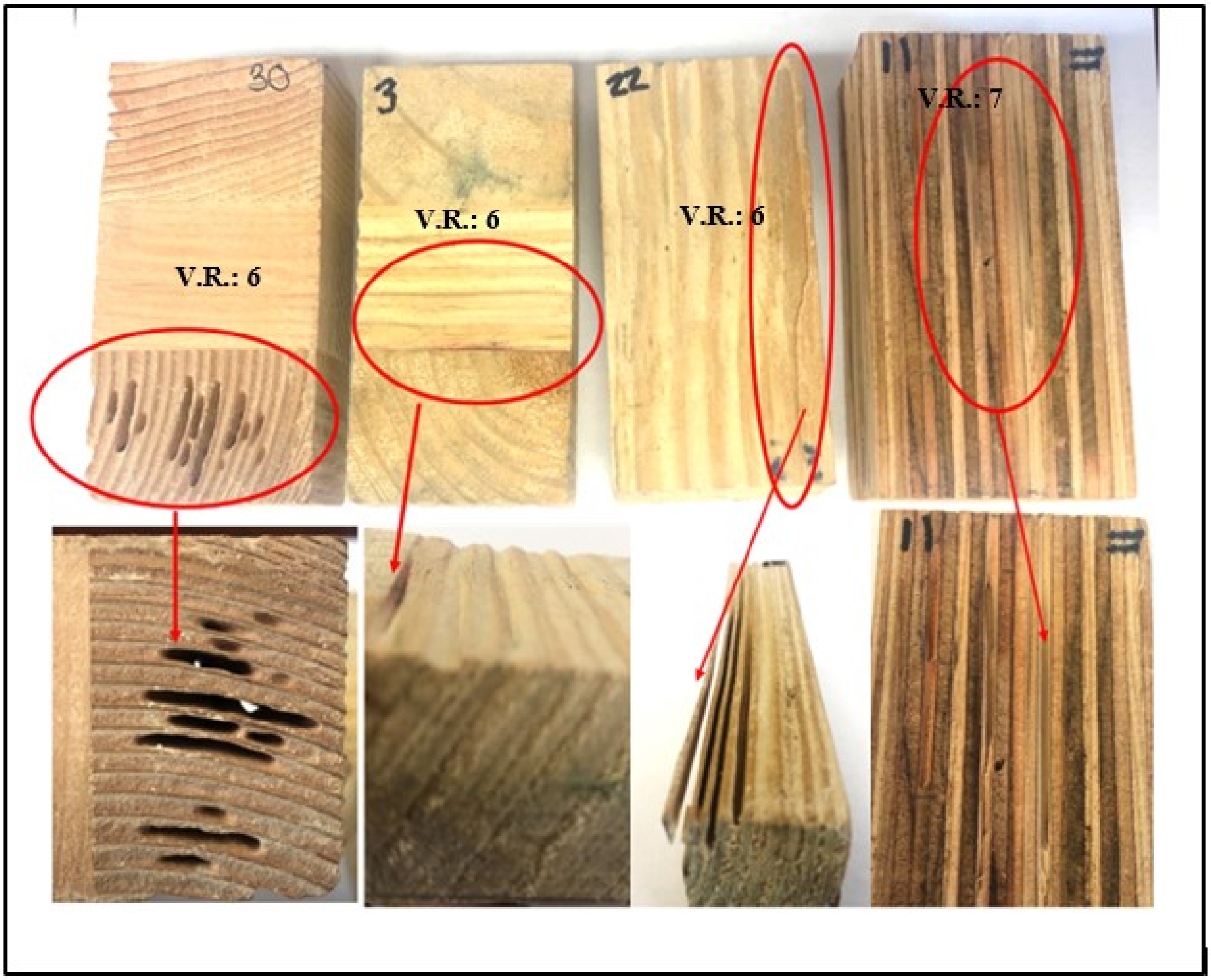

Figure 3.4 Examples of the exposed surface and the variations depth of attack for each material with visual rating (V.R.).

Table 3.2 Average mass change and visual rating for each material and the combined average termite mortality in treatments A through F.

	Average		
treatment	Δ Mass (%)	Visual Rating	Termite Mortality
MPP_A	-1.50%	8.1	88%
$control_A$	-2.24%	9.2	
$control_B$	-1.28%	9.65	37%
CLT_HF_B	1.04%	5.4	
$crontrol_C$	-0.77%	5.6	56.69%
CLT_SYP_C	-0.78%	9	
MPP_D	-1.55%	9.95	100%
$HemFir_D$	0.27%	8.45	
MPP_E	-1.63%	8.95	100%
CLT_SYP_E	-1.21%	9.6	
CLT_HFir_F	0.66%	6	90%
CLT_SYP_F	-0.89%	9.95	

CHAPTER IV

DISCUSSION

Through this experiment, one conclusion is that mass timber products are not compatible with the current AWPA E1-17 protocol. The efforts of upscaling the standard proved to be highly challenging due to the complexity of the mass timber products. These complexities include moisture, insect attack patterns, the determination of damage, and variation of quality within products.

4.1 Moisture

Lumber is known to absorb water from the cross-sectional face. The termites' survival is dependent on moisture, but they were out-competed for this resource throughout the study by the timber (Figure 4.1.) The wood samples absorbed much of the moisture, and the termites did not always have adequate moisture to survive the test. This alone has proven to be a problem with using mass timber products in this protocol. Both MPP and CLT specimens have multiple exposed cross-sectional faces which could explain the mass gain and high water uptake. With moisture apparently being a key component during choice testing, it may be recommended to up-scale the amount of water used when testing mass timber products in this way, or to determine a testing condition that would minimize water uptake by the mass timber sections during the test.

Figure 4.1 MPP sample #33 of Treatment D (MPP paired with Hem-Fir CLT) with dried termites on the exposed surface.

As shown previously in Figure 3.1, the MPP material that was tested has a high water-retention ability. During the experiment it was observed that depending on the match up of the products, some treatments will still dry out before the end of testing due to the variations of absorption rates, even when kept at consistent conditions of 70°F with 64% RH and 12% EMC. Correspondingly, treatments that include either type of CLT against MPP dried out within 2 – 3 weeks, such as treatment D which paired MPP against CLT HF, as seen in Figure 4.2.

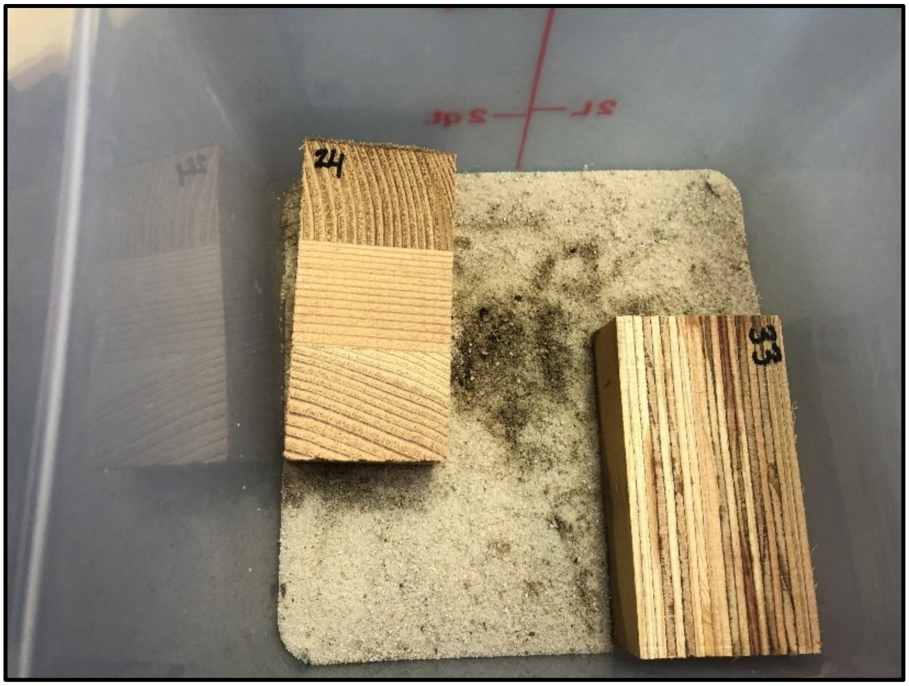

Figure 4.2 Treatment D at the end of testing; note the completely dry substrate.

Not only did the specimens absorb a lot of water during the duration of the study but also the high variation in water retention made it extremely hard for the specimens to return to a constant weight post-test. Even after being left in the environmental chamber at the test settings for multiple weeks, many samples remained with higher masses than documented at the start of the study. On the contrary, when mass timber products were paired up with the solid SYP specimens, the treatments' moisture levels were sustainable for the duration of the 4-week testing period, with healthy termite activity present during the removal of samples from containers (Figure 4.3). However, the mass timber products still exhibited some water retention after being reconditioned.

Figure 4.3 Presence of healthy and active termites when CLT is paired with solid SYP.

4.2 Attack Pattern

Termites excavate galleries throughout their food as they consume it. They tend to favor consuming the softer wood resulting in feeding along the grain, and generally attack larger portions of available earlywood over denser latewood. Termite feeding behavior during this series of tests tended to follow this trend, but termites also fed across both earlywood and latewood on some faces. Attacks sometimes resulted in complete penetration or deep excavations (Figure 4.4).

Figure 4.4 CLT HF specimen with active termites attacking between narrow and wide growth rings.

The attacks varied from slight to heavy and the termites did not show much of an attraction to southern yellow pine when hem-fir CLT was an optional food source. However, in treatments where CLT SYP was paired with solid SYP the termites favored the solid SYP with consistent presence of greyish green discoloration and some unidentified mold (Figure 4.5).

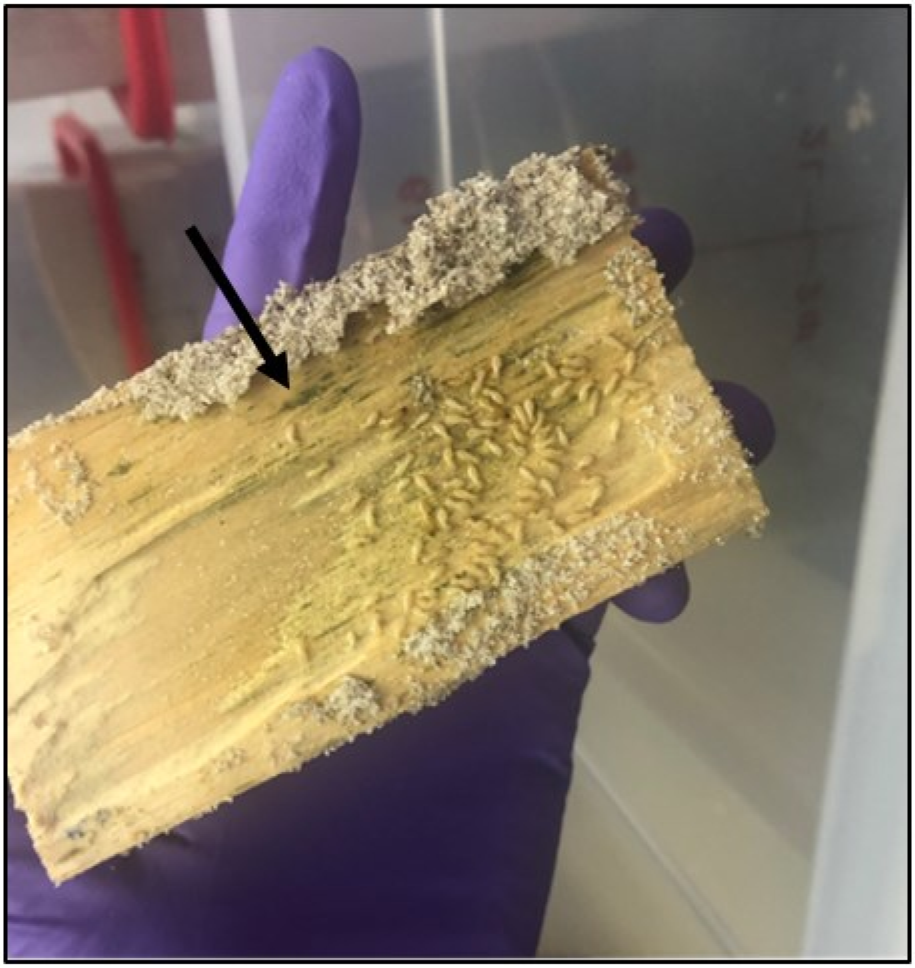

Figure 4.5 Solid SYP sample with active termites present along with discoloration (indicated at arrow) in treatment C where solid control was paired with SYP CLT.

4.3 Damage determination

As previously stated, the standard AWPA E1-17 standard testing piece size is not suitable for mass timber products, but neither is the grading system. The AWPA system was intended for pieces 6mm (¼ inch) thick, which is not representative of mass timber samples. When evaluating damage, we find with mass timber products that it is important to evaluate at both external and internal levels for mass timber. Based on the thickness of mass timber products, the visual assessment of the surface damage is insufficient when rating damage. Surface damage-only assessments would be equivalent to leaving a restaurant's drive thru window without checking your bag. How is it known for sure that the content in the bag was the right order? Comparatively, how can one truly assess mass timber termite damage without including the internal damage?

One of the greatest marketing points for mass timber is that it can be used as an alternative in applications where concrete, masonry, and steel are implemented as stated in the CLT Handbook. Although this may be true, CLT and other mass timber products, if left untreated, still can be accessible to termite attacks. Said attack can not only be damaging to the surface, but termites may also excavate numerous galleries throughout wood products which can compromise the structural integrity of the products. The current grading system does not adequately take depth of termite damage into consideration. The depth of damage in this set of experiments varied from treatment to treatment as well as from product to product.

In previous studies, imaging mechanisms have been utilized in hope of exposing the internal condition of mass timber products (França et al., 2018). Images were taken of some tested pieces from this experiment using Nikon Xtek's XT H 225GST x-ray system, with the intention of determining void volume per piece. Cutting into samples, even with very small saw kerf, would destroy a portion of the termite galleries. Scanning methods, such as CT or x-ray should be able to provide a clear picture of excavations and allow for volume loss calculations. However, 2-D x-ray is likely to not be a good candidate for this visualization because of its limited resolution. Portable 3-D scanners are not yet viable, but could provide useful information in future development. However, void volume and porosity are still being determined in collaboration with researchers at the Institute for Imaging and Analytical Technologies. The candidates for such scans were samples with complete width and/or thickness penetration (Figures 4.6 and 4.7).

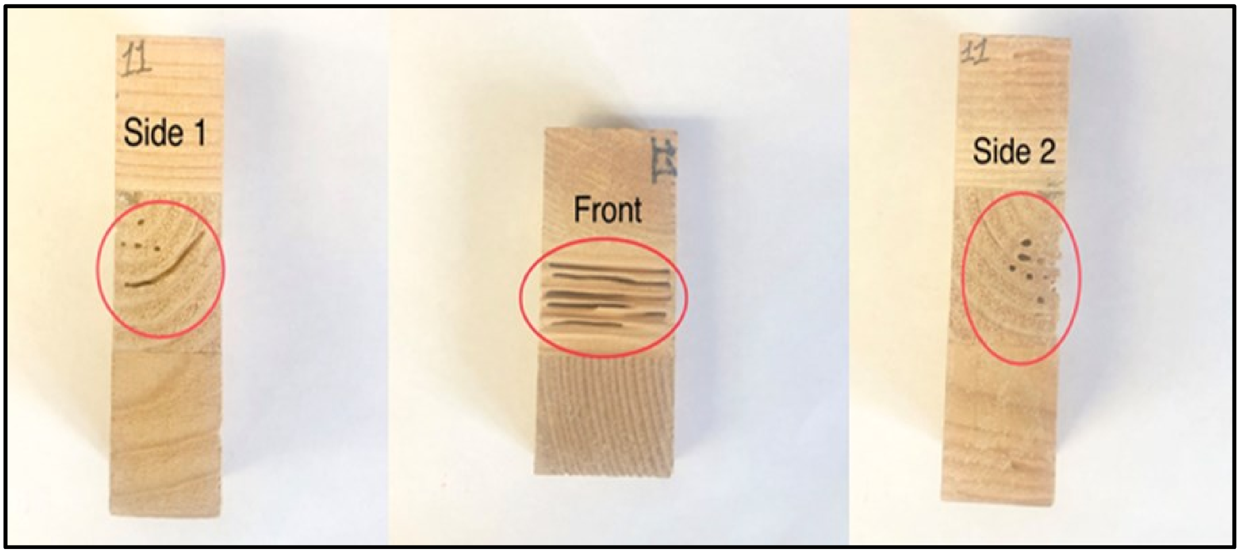

Figure 4.6 Three different views of termite damage with complete width penetration.

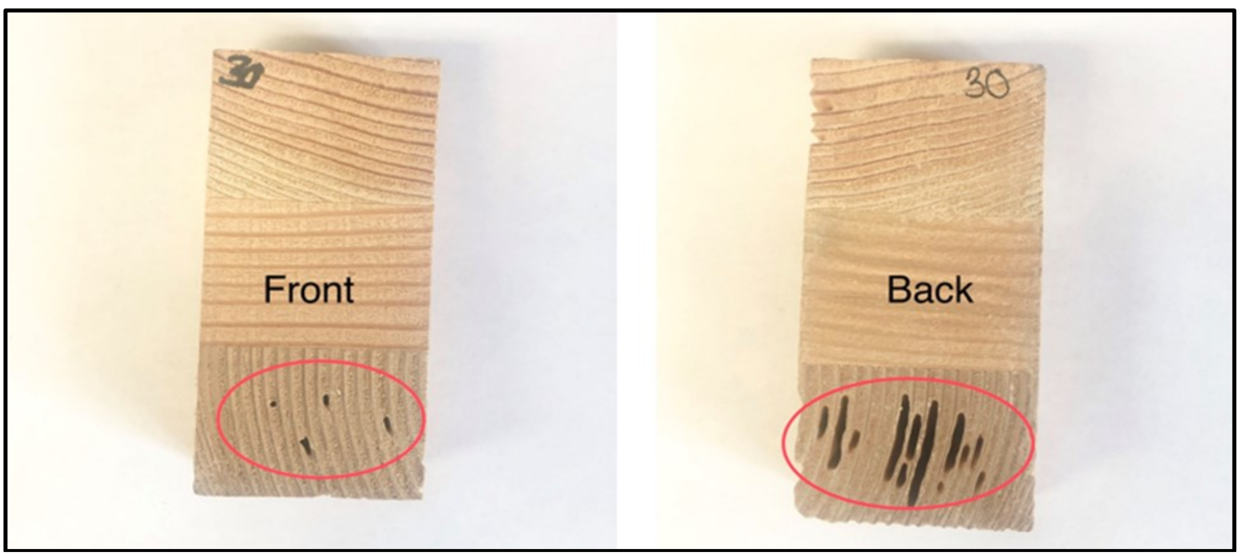

Figure 4.7 Front and back views of complete depth penetration.

4.4 Variation of Wood Quality

Though mass timber is viewed to be durable under different conditions, the lack of attention to consistent wood quality presents its own issue for choice testing. AWPA E1-17 specifies for testing material to be without visible defects, free of sap stain, chemicals, mold, stain, decay, and insect attack prior to testing. The natural defects that may appear in wood used in mass timber include but are not limited to knots, grain direction, shakes, and pitch pockets. Under those circumstances, mass timber products are highly unqualified for use in the AWPA standard. Mass timber products are known to allow some natural defects; however, the defects do not compromise the strength properties of the product (Figures 4.8 and 4.9).

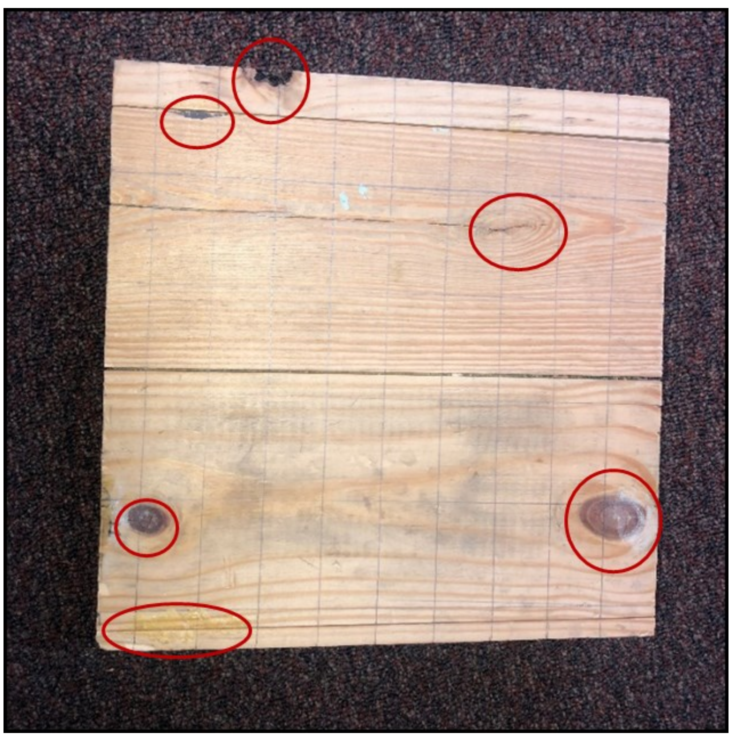

Figure 4.8 SYP CLT used with natural surface defects circled.

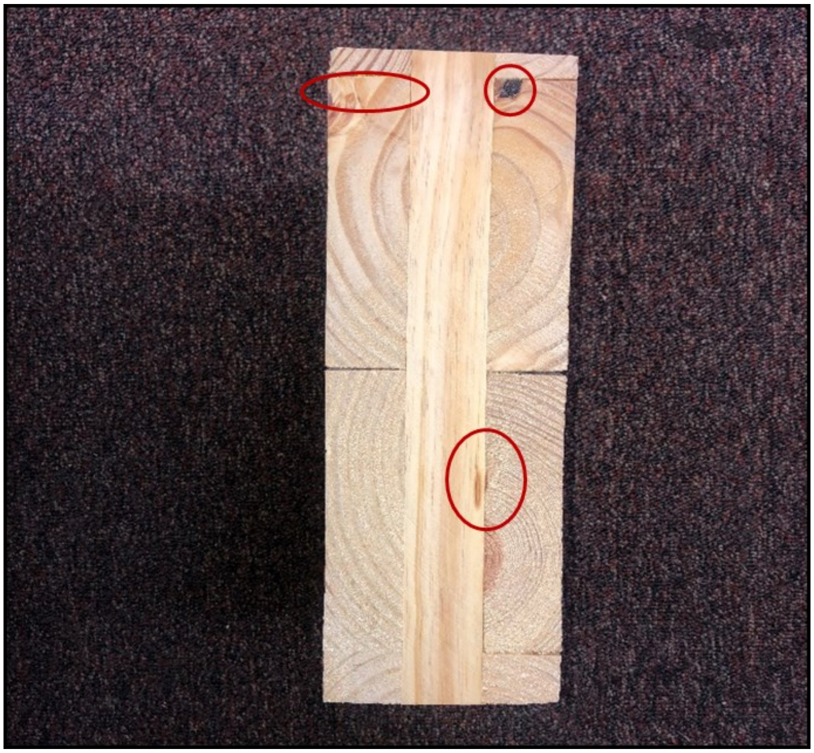

Figure 4.9 Side view of SYP CLT with natural surface defects circled.

4.5 Conclusions

The era of transformation of the building material industry is happening now, beginning with upgrading of traditional building materials as a part of the movement for sustainable 'green' buildings. As an increasingly popular part of said movement, mass timber products in North America, especially those used in the southeastern US, ideal termite habitat, must have protective measures addressed. The choice testing attempted in this series of tests, using a scaled-up test material, proved to be burdensome due to the intricacy of mass timber products. Results from this study propose that unprotected mass timber products are susceptible to attacks by subterranean termites.

However, mass timber products are also vulnerable to water absorption and retention, which have been proven to present significant hurdles when using mass loss as a measure of termite damage. The water retention of the products also presented an issue for the termites' hydration during study. It is recommended that new testing standards for mass timber products should be developed, due its testing complexities. The product does not behave like average building timber products (i.e., dimensional pine lumber). Any new standard that is prepared for this material should also include a visual grading system that takes internal damage and visual bias into consideration. I recommend that more water should be used during set up to help combat the dry out situation. Additionally, it may prove helpful to always include a set of controls for each type of material individually to represent termite feeding likelihood and another set of controls without termites to represent moisture retention by the tested mass timber products

In future studies of mass timber durability against termites, a compression test series should be included to further prove the structural durability of the product after termite infestation. This, along with the internal evaluation of damage, will provide vital information for innovation of engineered timber products. The development of high-quality green building material is in great demand and so we should try to provide insurance of the products' longevity by protecting these materials from biological attacks.

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APPENDIX A

CHOICE TESTING SAMPLE INVENTORY AND SAMPLE DISTRABUTION

Table A.1 The numbering, treatment assignment, mass pre-conditioning mass, and the notation of initial visual defects of materials used. The treatment assignments are expressed by colors.

MPP[1]	mass	defects*	CLT (SYP)	mass	defects*	CLT (HemFir)	mass	defects*	control	mass	defects*
1	90.80	knot layer	1	63.40		1	80.00		1	115.30	
2	99.00	knot layer	2	66.50		2	118.10		2	79.20	
3	102.10	knot layer	3	65.90		3	117.60		3	94.70	
4	87.60		4	63.60		4	78.60		4	101.60	
5	95.60		5	62.00		5	76.60		5	71.30	
6	77.40	knot layer	6	64.20		6	81.40		6	101.90	
7	103.60		7	63.60	warped	7	79.00		7	100.60	
8	104.00		8	61.20	glue middle	8	85.10		8	78.10	
9	107.50		9	78.80		9	81.40		9	87.10	
10	100.10		10	59.80		10	85.40	hole	10	108.90	
11	112.10		11	54.60		11	75.90		11	95.80	
12	11.40		12	65.40	knot hole	12	105.80		12	111.40	
13	101.00		13	59.00		13	102.90		13	89.60	
14	112.80		14	63.60		14	111.00	cracks	14	79.10	
15	110.70		15	65.20		15	101.70		15	83.00	
16	100.60		16	78.20	glue middle	16	100.50		16	110.30	
17	118.70	knot layer	17	61.90		17	99.80		17	82.50	
18	117.50		18	75.20		18	103.90		18	100.30	
19	102.90		19	67.10		19	67.50		19	104.30	
20	109.00		20	63.70		20	94.80		20	103.60	
21	111.70		21	64.40		21	103.20		21	100.30	
22	91.30		22	74.00		22	105.50	gap between glue line	22	76.80	
23	104.90	knot layer	23	69.90	middle crack	23	107.60	gap between glue line	23	75.20	
24	116.40		24	61.00	glue middle	24	80.20		24	83.40	
25	70.10		25	60.20		25	85.60	crack @ top; hole in the side	25	85.60	
26	115.80		26	65.60		26	86.50		26	82.00	
27	98.60	knot layer	27	64.20		27	107.40		27	102.00	
28	104.90		28	79.90	knot layer	28	106.1		28	101.10	
29	104.80	knot layer	29	58.20	glue middle/chip corne	29	76.30		29	86.34	
30	122.00		30	62.50		30	80.40	hole	30	99.97	
31	105.00	knot layer	31	66.80		31	70.20	pitch pocket	31	85.10	
32	94.90		32	74.40		32	103.10	cracks	32	102.86	
33	90.20		33	65.10		33	82.40		33	80.94	
34	107.90		34	77.20	glue on outside	34			34	78.60	
35	107.40		35	59.20		35			35	95.84	
36	114.00	knot layer	36								
37	107.30										

Treatment A = ; Treatment B = ; Treatment C = ; Treatment D = ; Treatment E = ; Treatment F =

APPENDIX B

TREATMENTS' CHOICE TEST DATA

Table B.1 Treatment A: Control v. MPP data for 4-week testing

		Sample #	ICW (g)	FCW (g)	Δ Mass (g)	Δ Mass (%)	Visual Rating	Termite Mortality (%)
Treatment A: Control v. MPP	1*	31	85.42	86.8	-1.38	-1.62%	10	
		2	100.55	100.8	-0.25	-0.25%	9	28%
	2*	32	103.24	104.6	-1.36	-1.32%	9.5	
		6	78.45	79.2	-0.75	-0.96%	8	100%
	3*	8	78.49	79.4	-0.91	-1.16%	8	
		9	108.78	110.6	-1.82	-1.67%	8	100%
	4*	21	100.61	101	-0.39	-0.39%	10	
		11	113.35	115.2	-1.85	-1.63%	7	100%
	5*	6	102.35	104.2	-1.85	-1.81%	9	
		12	112.59	114.8	-2.21	-1.96%	8	100%
	6*	15	75.68	85	-9.32	-12.32%	9	
		13	102.19	104	-1.81	-1.77%	8	48%
	7*	23	75.68	76.6	-0.92	-1.22%	9.5	
		19	104.17	106.2	-2.03	-1.95%	8	100%
	8*	1	115.78	117	-1.22	-1.05%	9	
		23	106.32	107.8	-1.48	-1.39%	9	100%
	9*	27	102.45	103.2	-0.75	-0.73%	10	
		29	106.11	107.8	-1.69	-1.59%	8	100%
	10*	12	111.86	112.8	-0.94	-0.84%	8	
		32	96.09	97.8	-1.71	-1.78%	8	100%
				AVG :	**-1.904**	**-2.24%**	**9.2**	
					-1.56	-1.50%	8.1	**88%**

Control = MPP =

Table B.2 Treatment B: Control v. CLT(HemFir) data for 4-week testing

Treatment B: Control v. CLT (HF)		Sample #	ICW (g)	FCW (g)	Δ Mass (g)	Δ Mass (%)	Visual Rating	Termite Mortality (%)
	1	28	107.39	107.20	0.19	0.18%	6	97%
		33	81.25	82.80	-1.55	-1.91%	9.5	
	2	11	76.83	75.40	1.43	1.86%	6	80%
		18	100.78	102.20	-1.42	-1.41%	10	
	3	31	71.06	70.20	0.86	1.21%	6	35%
		30	100.31	100.60	-0.29	-0.29%	9.5	
	4	29	77.71	76.20	1.51	1.94%	6	4%
		25	86.04	87.00	-0.96	-1.12%	10	
	5	30	81.21	80.00	1.21	1.49%	6	0%
		4	102.05	103.20	-1.15	-1.13%	9.5	
	6	14	112.49	112.30	0.19	0.17%	6	100%
		28	101.44	103.40	-1.96	-1.93%	9.5	
	7	5	77.53	76.60	0.93	1.20%	4	13%
		14	79.47	81.40	-1.93	-2.43%	10	
	*8	25	86.71	86.00	0.71	0.82%	4	0%
		2	79.52	81.00	-1.48	-1.86%	9.5	
	*9	32	104.36	103.80	0.56	0.54%	6	33%
		17	82.82	83.20	-0.38	-0.46%	9	
	*10	21	104.42	103.40	1.02	0.98%	6	12%
		35	96.16	96.40	-0.24	-0.25%	10	
				AVG :	0.86	1.04%	5.6	**37%**
					-1.14	-1.28%	9.65	

CLT = [yellow] CLT (HF) = [purple] Dried out = *

Table B.3 Treatment C: Control v. CLT(SYP) data for 4-week testing

		Sample #	ICW (g)	FCW (g)	Δ Mass (g)	Δ Mass (%)	Visual Rating	Termite Mortality (%)	comments
Treatment* C: *Control v. CLT (SYP)	1*	19	104.71	105.6	-0.89	-0.85%	6	99.70%	
		2	67.29	68	-0.71	-1.06%	8		
	2	9	87.58	88.6	-1.02	-1.16%	7	76.60%	
		3	66.8	66.5	0.30	0.45%	6		
	3	13	89.99	91	-1.01	-1.12%	7	54.30%	
		5	62.72	63.4	-0.68	-1.08%	9.5		
	4	16	110.74	111.2	-0.46	-0.42%	4	44.30%	
		8	61.94	62.6	-0.66	-1.07%	9.5		
	5	7	101.17	102.6	-1.43	-1.41%	6	33.20%	
		11	55.35	56.2	-0.85	-1.54%	10		
	6	22	77.3	76.8	0.50	0.65%	6	21.90%	
		16	79.18	80.6	-1.42	-1.79%	10		
	7*	3	95.18	96.6	-1.42	-1.49%	6	88.00%	
		21	65.16	65.4	-0.24	-0.37%	9.5		
	8	11	96.31	97	-0.69	-0.72%	6	74.90%	
		25	61.04	61.4	-0.36	-0.59%	9.5		
	9	34	79.03	79.2	-0.17	-0.22%	4	34.00%	
		27	65.93	65.6	0.33	0.50%	9		
	10	24	83.78	84.6	-0.82	-0.98%	4	40.00%	
		33	65.89	66.7	-0.81	-1.23%	9		
				AVG :	-0.74	-0.77%	5.6	**56.69%**	
					-0.51	-0.78%	9		

Control = CLT =

Table B.4 Treatment D: MPP v. CLT (HemFir) data for 4-week testing.

		Sample #	ICW (g)	FCW (g)	Δ Mass (g)	Δ Mass (%)	Visual Rating	Termite Mortality (%)
Group D: *MPP v. CLT (HF)*	1*	1	92.02	93.4	-1.38	-1.50%	10	
		23	108.99	108.6	0.39	0.36%	8	100%
	2*	4	88.79	89.8	-1.01	-1.14%	10	
		12	107.21	107	0.21	0.20%	8	100%
	3*	5	96.89	98.2	-1.31	-1.35%	10	
		8	86.18	86.2	-0.02	-0.02%	9.5	100%
	4*	8	105.42	107.6	-2.18	-2.07%	9.5	
		17	101.86	101	0.86	0.84%	9	100%
	5*	14	114.27	116.4	-2.13	-1.86%	10	
		33	83.44	83.36	0.08	0.10%	10	100%
	6*	15	112.16	113.8	-1.64	-1.46%	10	
		16	101.86	101.6	0.26	0.26%	8	100%
	7*	16	102.02	103.2	-1.18	-1.16%	10	
		10	86.41	86.2	0.21	0.24%	8	100%
	8*	24	117.88	119.6	-1.72	-1.46%	10	
		13	104.32	104.2	0.12	0.12%	8	100%
	9*	33	91.49	93.2	-1.71	-1.87%	10	
		24	81.12	80.8	0.32	0.39%	8	100%
	10*	35	108.86	110.6	-1.74	-1.60%	10	
		19	68.33	68.2	0.13	0.19%	8	100%
				AVG :	-1.6	-1.55%	9.95	
					0.256	0.27%	8.45	**100%**

MPP = [blue] CLT = [yellow] Dried out = *

Table B.5 Treatment E: MPP v. CLT (SYP) data for 4-week testing

		Sample #	ICW (g)	FCW (g)	Δ Mass (g)	Δ Mass (%)	Visual Rating	Termite Mortality (%)
Group E: *MPP v. CLT (SYP)*	1*	3	103.41	105.6	-2.19	-2.12%	9	
		4	64.44	65.6	-1.16	-1.80%	9.5	100%
	2*	7	104.83	107.6	-2.77	-2.64%	9.5	
		6	65.01	66.2	-1.19	-1.83%	9.5	100%
	3*	10	101.35	103.4	-2.05	-2.02%	9	
		9	79.61	80.6	-0.99	-1.24%	9.5	100%
	4*	17	120.28	122.6	-2.32	-1.93%	9	
		12	66.11	66.8	-0.69	-1.04%	9.5	100%
	5*	18	118.91	120.4	-1.49	-1.25%	9	
		13	59.72	60.6	-0.88	-1.47%	10	100%
	6*	21	113.12	115.4	-2.28	-2.02%	8	
		15	66.6	67	-0.40	-0.60%	9.5	100%
	7*	22	92.45	94.6	-2.15	-2.33%	9	
		23	70.84	72.2	-1.36	-1.92%	9.5	100%
	8*	30	123.6	126	-2.40	-1.94%	9	
		29	58.9	59.8	-0.90	-1.53%	9.5	100%
	9*	26	117.31	119.6	-2.29	-1.95%	9	
		30	63.18	63.2	-0.02	-0.03%	9.5	100%
	10*	34	109.32	111.8	-2.48	-2.27%	9	
		31	67.56	68	-0.44	-0.65%	10	100%
				AVG :	-2.24	-1.63%	8.95	
					-0.80	-1.21%	9.6	**100%**

MPP = (blue) CLT = (green) Dried out = *

Table B.6 Treatment F: CLT (SYP) v. CLT (HemFir) data for 4-week testing

		Sample #	ICW (g)	FCW (g)	Δ Mass (g)	Δ Mass (%)	Visual Rating	Termite Mortality (%)
Group F: *CLT (SYP) v. CLT (HF)*	1	22	106.72	106	0.72	0.67%	6	98%
		7	64.29	65.2	-0.91	-1.42%	10	
	2	20	96.06	95.4	0.66	0.69%	6	100%
		26	66.37	66.8	-0.43	-0.65%	10	
	3*	27	108.69	108.2	0.49	0.45%	6	99%
		10	60.61	61.4	-0.79	-1.30%	9.5	
	4*	26	87.49	87.2	0.29	0.33%	6	100%
		14	64.43	65.6	-1.17	-1.82%	10	
	5*	18	105.35	104.8	0.55	0.52%	6	100%
		19	67.89	69.2	-1.31	-1.93%	10	
	6	15	103.10	102	1.10	1.07%	6	100%
		22	74.82	76.2	-1.38	-1.84%	10	
	7*	4	79.56	79.2	0.36	0.45%	6	100%
		28	86.80	82.2	4.60	5.30%	10	
	8	6	82.40	81.4	1.00	1.21%	6	0%
		32	75.30	76.8	-1.50	-1.99%	10	
	9*	1	81.03	80.4	0.63	0.78%	6	100%
		34	78.03	79.4	-1.37	-1.76%	10	
	10*	9	82.38	82	0.38	0.46%	6	100%
		35	59.90	60.8	-0.90	-1.50%	10	
				AVG :	0.62	0.66%	6.00	**90%**
					-0.52	-0.89%	9.95	

CLT (HemFir) = green CLT (SYP) = yellow Dried out = *

Table B.7 Control Treatment without termites with negative numbers expressing weight gain

	Sample #	ICW (g)	FCW (g)	Δ Mass (g)	Δ Mass (%)	Visual Rating
CLT (SYP)	37	72.20	70.00	2.20	3.05%	10
CLT (HemF)	3	119.00	120.40	-1.40	-1.18%	10
MPP	28	106.40	109.80	-3.40	-3.20%	10
control	10	109.60	111.60	-2.00	-1.82%	10