FIELD EVALUATION OF PHYSICAL BARRIERS AGAINST SUBTERRANEAN TERMITES AND AMBROSIA BEETLES IN A CLT WALL ENVELOPE SYSTEM

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Abstract. The effectiveness of physical barriers against subterranean termites was evaluated in a 34-wk field test in coastal Mississippi by installing Obex11, a commercial polyethylene flashing, and Termimesh, a stainless-steel mesh in 3-ply 280 mm (width) × 450 mm (length) cross laminated timber (CLT) walls. Damage showed that both barriers performed significantly better than the no barrier control with respect to termite damage as evaluated by visual rating and mud tube length. Obex11, however, like the no barrier

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control, was more vulnerable to attack by *Ambrosiodmus minor* (Stebbing), an invasive ambrosia beetle, with both treatments exhibiting significantly longer bore trails than those found in Termimesh.

Keywords: Cross laminated timber, building envelope, termite barrier, invasive beetle, timber durability.

INTRODUCTION

Cross laminated timber (CLT) is an engineered wood product consisting of layers of lumber products perpendicular to each other that are glued using structural adhesives and pressed to form a solid panel. The introduction of the CLT product standard, ANSI/APA PRG 320 (ANSI/APA 2018) in 2011 and its incorporation in the International Building Code (IBC) (International Code Council 2021) and National Design Specification for Wood Construction (American Wood Council 2018) in 2015 has focused people's interest in CLT as an alternative and hybrid material for steel and concrete. As a biodegradable product, CLT is susceptible to subterranean termite attack, especially in warmer regions that have high humidity and dampness. These termites depend on moisture to attack wood and thus, maintain contact with the soil or locate near areas where water collects. Improper detailing and poor building construction design make conditions favorable for termite infestations and should be prevented at any cost (Peterson et al 2006). This problem also currently limits the use of CLT walls to aboveground conditions.

Hybrid construction system using steel and concrete for ground contact and timber for remaining stories have been a common practice in mass timber construction to overcome biodeterioration and moisture problems. CLT manufactured from lumber boards treated with preservatives can be a potential method to be used in ground contact or close to the foundation to protect the buildings from decay and termites. For wood preservation, chromated copper arsenic (CCA) was a commonly used biocide until 2003, when residential sales of CCA-treated wood were discontinued due to the adverse effects of arsenic and chromium on human health and the environment. This led to the introduction of water-based preservatives like micronized copper azole (MCA), which has low corrosion and leaching rates (Lebow 2004). Research has shown that the mechanical properties of CLT and the bonding performance of adhesives can be degraded due to preservative treatment (Lim et al 2019; Lim et al 2020).

Water-shedding materials like simple paint films, water repellents, urethane coatings, and others can be used to prevent fungal and insect attacks. However, they must be chosen and utilized cautiously as their performance depends on the application and their durability (Wang et al 2018). Such materials can fail over time when the wood gets exposed to leaks and/or external weather conditions and thus, render the wooden members more susceptible to termites and fungal decay. A study to investigate the effectiveness of using polyurea coatings against termites was conducted in Hawaii. Results showed that such coatings provided limited protection against termites, as the coatings degraded over time due to weathering (Konkler et al 2019).

Physical barriers like Termimesh, a commercial product made from stainless steel with fine openings, have been tested in the past and proven to be effective against termites. Grace et al (1996) conducted a 1-yr field test in Hawaii in 1995 using susceptible 250 mm × 85 mm × 18 mm wood specimens in closed bags made out of Termimesh and found that the steel mesh had protected the wood from attack by *Coptotermes formosanus* Shiraki, an introduced species of aggressive subterranean termite. Various stainless-steel mesh tests were conducted in Arizona, FL, Mississippi, and South Carolina in 1993 (Kard 1998). After running the test for 4-5 yr, no termite damage was seen on the 50 mm × 100 mm × 450 mm southern yellow pine (SYP) wood specimens that were fully wrapped with stainless-steel mesh up to 375 mm height and inserted 225 mm deep into termite-infested soil while exposing 75 mm wood at the top. Similarly, in another setup designed to simulate access created by pipes passing vertically through a concrete slab foundation, no termite attack was seen after 5 yr of exposure (Kard 1998). In this setting, each pine sapwood block was placed inside a PVC pipe (100 mm diameter) that passed through the center of a small concrete slab (50 mm × 500 mm × 500 mm). Thus, the only layers separating the pine sapwood block from the soil was the standard vapor barrier (600 mm × 600 mm) directly under the slab and the stainless-steel mesh (600 mm × 600 mm) placed between the vapor barrier and the soil (Kard 1998).

Plastic physical barriers can prevent termite attacks and have been researched for a long time, but this method seems to work until the membranes start to wear and tear by weathering. Various forms of plastics were studied against termites in the laboratory in Australia (Gay and Wetherly 1969). The research showed that polyvinyl chloride in their rigid or semirigid forms and high-density polyethylene membranes were very resistant to termites but vulnerable when plasticized to use as tape or insulant. Research conducted in Japan using a new laboratory method of testing the termite resistance of plastics showed that nylon polyamides were resistant to termites (Tsunoda et al 2010). While plastic membranes have been seen to be effective against termites in these tests, they can cause moisture to accumulate, which promotes decay and other moisture-related problems. Recently, various forms of self-adhering and nonadhering plastic membranes such as TERM, Pango wrap, and so on are being manufactured to protect wood against moisture and termite attack. However, limited independent field studies have been conducted to investigate their utility and feasibility for mass timber building construction.

A few other studies have been conducted to assess termite damage on CLT, but the prevalent data are limited to small-scale specimens. For example, a laboratory study (Franca et al 2018) using *C. formosanus* collected from Mississippi was conducted on 100 mm × 100 mm × 25 mm (4″ × 4″ × 1″) CLT specimens following modifications from the American Wood Protection Association (AWPA) E-1 standard (AWPA 2020). The modifications related to the size of samples, containers, termite numbers, and duration of the test, all of which were necessary to incorporate the heterogeneous design elements of the CLT into the test sample compared with plain sawn lumber. This 8-wk laboratory study showed that CLT made from spruce-pine-fir exhibited slightly less percent mass loss (6.0%) than untreated SYP sapwood (7.0%) but both products had greater mass loss than that recorded for CCA-treated pine (3.9%) (Franca et al 2018). AWPA E-21 (2015) provides guidelines to conduct a full-size commodity field test that evaluates performance of wood products set on the open ends of concrete blocks against termites for interior applications. Stokes et al (2019) used the E-21 test to expose 3-ply CLT specimens (16″ × 4″) at a coastal Mississippi field site with inspections at 12 and 24 mo. Visual ratings of the CLT showed increasing levels of attack over time by subterranean termites (primarily native *Reticulitermes* species). By 24 mo, termite mud tubes covered the base of the CLT, and attack was severe enough that a putty knife could be manually pushed through the wood. These laboratory and field tests show that CLT is highly susceptible to damage by subterranean termites.

The standard building envelope described in the North American CLT handbook consists of rain screen cladding/siding, insulation, weather-resistant barrier (WRB), and self-adhering flashing from the exterior to the wall's interior (FPInnovations 2010). IBC Section 2304 (International Code Council 2021) and International Residential Code (IRC) Sections R317 and R318 (International Code Council 2021) and recommend, but do not require, the use of multiple protection systems against termites, such as preservative treatment and/or physical barriers. Untreated CLT walls are suited for interior above-ground use but building codes do not have enough field data to incorporate such physical barriers in the wall envelope to ensure protection against termites. Therefore, the goal of this experiment was to conduct a field performance evaluation of two types of physical barriers (plastic membrane and stainless-steel mesh) against insect attack in a simplified CLT wall envelope system. Only physical barriers, spacers, and sidings were used to represent the CLT building envelope. To accelerate the experiment, the concrete blocks required in the AWPA E-21 were not used, and sill plates used to anchor the CLT walls to the ground were taken off the CLT panels after 18 wk of installation. Because of the large size of the specimens and the short field exposure (34 wk), the length of termite tubes, beetle trails, and number of beetle holes were reported in addition to visual rating scores. The results suggest that the selection of physical barrier and proper installation method can be a solution against insect attack in mass timber construction that places CLT on a foundation near the soil line instead of using insecticide and preservative treatment. In addition, the installation methods developed here, could provide insights on producing CLT panels with built-in physical barriers during the manufacturing process.

MATERIALS AND METHODS

Materials

Two lumber stacks, each consisting of 128 pieces of 2430 mm long visually graded No. 2-2 × 6 (38 mm × 140 mm) SYP sapwood lumber, were supplied by Shuqualak Lumber Co. located in Mississippi. A commercial primer solution diluted with 10% water by volume and Loctite PURBOND polyurethane adhesive were used to glue the CLT laminate (Loctite 2020). Hardie cement board 1200 mm × 2400 mm × 8 mm (48″ × 96″ × 0.312″) was cut to the final size to fit the CLT panels, ie 280 mm × 450 mm (11″ × 18″), and were used as siding for the envelope. Aluminum C-section spacers of 19 mm × 19 mm × 450 mm (3/4″ web × 3/4″ flange × 18″ length) were used to hold the sidings to the CLT panels using 32 mm screws. A 300 mm wide × 16,750 mm long roll of Obex11 was used as the plastic physical barrier. It is a 0.15 mm thick polyethylene membrane that contains a chemical blend called Termirepel to repel termites and consists of a yellow and black surface. According to the manufacturer's installation guide, the membrane's yellow surface was exposed to the exterior. A 914 mm wide × 9140 mm long Termimesh roll was used as steel mesh physical barrier in the second treatment group, which consisted of 0.18 mm thick TMA 725 stainless-steel wire mesh. The apertures on this mesh are 0.45 mm × 0.66 mm wide, through which foraging worker termites cannot penetrate. The specimens installed with Obex11 and Termimesh were labeled with the letters P (for plastic) and S (for steel), respectively, followed by the specimen number (eg P1, P2 and S1, S2). The control specimens with no physical barrier were indicated with the letter C, followed by the specimen number.

Cross Laminated Timber Manufacture

The lumber boards were planed twice by 1.6 mm on each flat surface to a final dimension of 31.75 mm × 140 mm (1.25″ × 5.5″) and subjected to the application of primer within 6 h of planing. Primer was applied at a rate of 21.53 g/m^2 (2 gm/ft^2) to the gluing faces of the laminates. After 10 min of primer application, glue was spread to the primed laminates at a rate of 129.17 g/m^2 (12 g/ft^2). The assembled CLT laminates were pressed under 0.75 MPa (110 psi) for 150 min following the adhesive product specifications (Loctite 2020). Three CLT panels (1 per treatment) were made per batch by dividing lumber boards as shown in Fig 1. Laminates with same color indicate that they were obtained from same board resulting in identical CLT specimens across the treatment groups. The surface laminates were assembled such that the sapwood (as opposed to the pith) was exposed on both sides of the panel as shown in Fig 2.

Cubes (25.4 mm × 25.4 mm × 25.4 mm) were cut from each board to calculate the MC and oven-dry specific gravity ($SG_{oven\text{-}dry}$) in accordance with ASTM (2016, 2017) standards, respectively. The average MC and $SG_{oven\text{-}dry}$ of the lumber were 10.2% and 0.45, respectively. The average MC of the boards used in CLT manufacturing was within the optimum MC range of 12 ± 3% recommended in the CLT handbook (FPInnovations 2010). A total of 30 CLT panels of final size 96 mm × 280 mm × 450 mm were

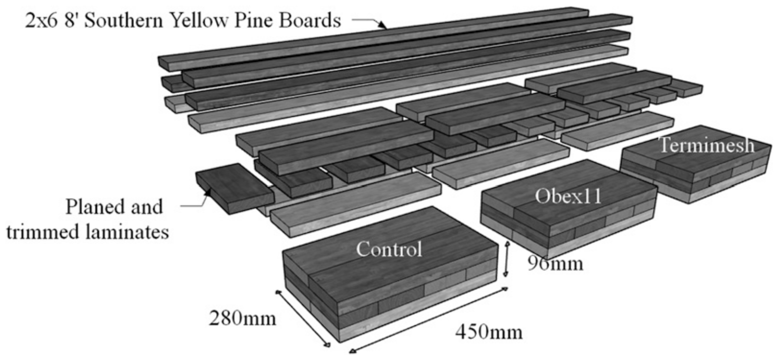


Figure 1. Lumber layout to manufacture one batch of cross laminated timber (CLT) specimens.

manufactured and stored for a week under indoor ambient conditions before the envelope layers were installed.

Envelope Construction

For the purpose of this study, the only envelope layer added to the CLT panels was a cement board siding, installed via aluminum spacers to create a 19 mm air cavity. Instead of treating the two faces of the CLT panels as exterior and interior side of a building, the siding was installed on both sides. This setup gave an advantage of adding extra surface area to test the termite resistance of physical barriers. Also, this configuration simplified the construction process and negated the extra work of building a different interior wall envelope layer on the inner face of the CLT panel. The other standard building envelope layers were omitted from the experiment as they would provide little or no resistance against termites compared with the chosen physical barriers that are manufactured specifically for termite protection. The 30 CLT panels were divided into three

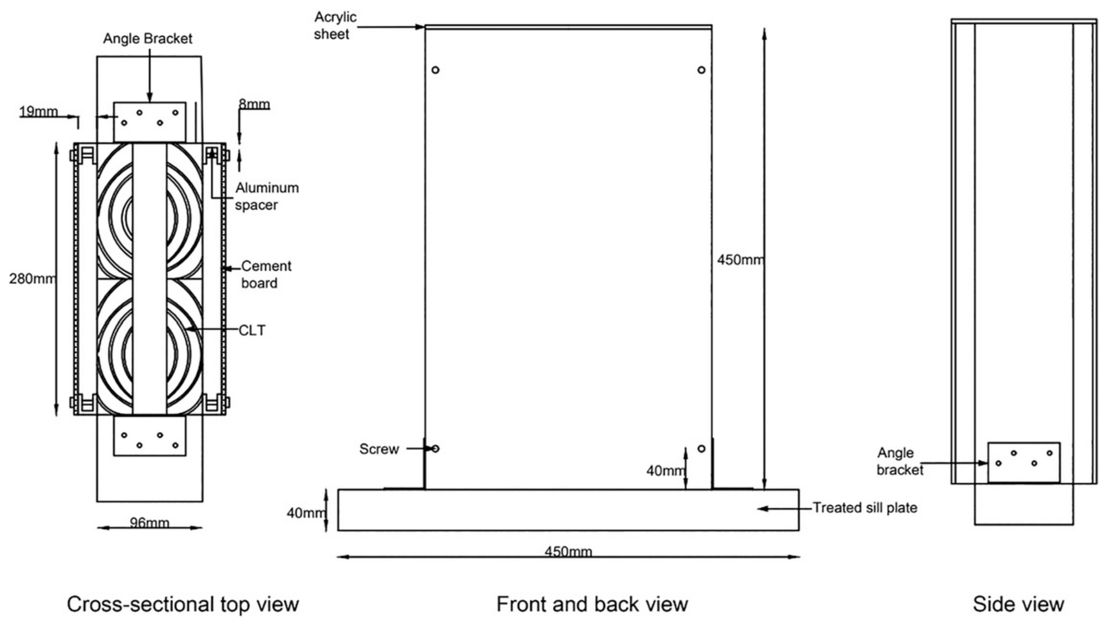


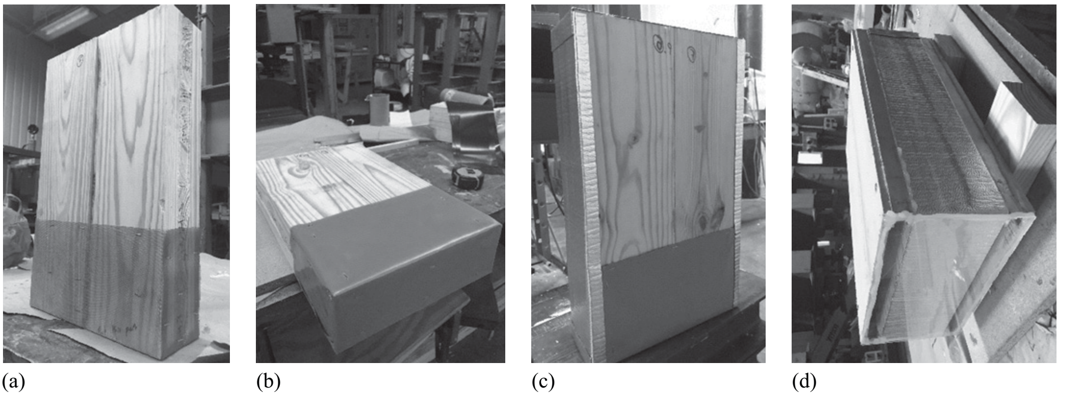
Figure 2. 2D drawing of a CLT envelope specimen.

treatment groups: Obex11, Termimesh, and control (no barrier). The physical barriers were cut to two final sizes: 150 mm × 580 mm (6″ × 23″) and 300 mm × 400 mm (12″ × 16″) for easier wrapping. The 150 mm × 580 mm wide piece was wrapped along the narrow edge of the panel and the 300 mm × 400 mm piece was wrapped along the wider faces of the panel to a height of 150 mm and stapled. The two pieces of barrier overlapped the 95 mm thickness of the CLT at the bottom and 25 mm at the corners where spacers were screwed afterward. This height was chosen based on the Obex11 manufacturer specification of 152-178 mm vertical fold after laying the membrane underneath the sill plates/brick ledger of the wall (Obex11 2023). A self-adhering aluminum tape was used to seal the edges of the CLT, which limited termite exposure only to the faces of the panels. Spacers and sidings were screwed to the CLT panels using two screws per spacer: one on the top and one on the bottom. All the joints between spacers and CLT and spacers and siding were sealed with silicone. The top of the specimen was covered with an acrylic sheet, which was also glued to the panel with silicone for easier inspection from the top without moving the panels. The CLT envelope installation procedure is demonstrated through Fig 3(a)-(d). The control specimens were prepared similarly to the treatment groups except that they did not have any physical barrier. To keep the CLT specimens upright, sill plates made from MCA-treated SYP lumber were entirely wrapped with the self-adhering aluminum tape and fixed to the CLT specimens using angle brackets and screws.

Field Installation and Damage Evaluations

A timeline of field activities is depicted in Table 1. The finished CLT envelope specimens were anchored to the ground using edge metal stakes and deployed at the USDA Forest Service Harrison Experimental Forest, Saucier, MS, near the Gulf Coast, where risk hazard for subterranean termite infestation is typically severe (Peterson et al 2006). The CLT specimens (n = 10 per treatment) were laid out in a randomized complete block (RCB) design as shown in Fig 4. Surface investigations were carried out during each inspection to look for damage to physical barriers and the presence of mud tubes. Specimens were also overturned to evaluate termite activities at the soil level. As there was no evidence of termites or mud tubes on specimens at 18 wk, sill plates were removed, and specimens were reinstalled in their original positions. For the final inspection at 34 wk, specimens were taken back to the laboratory, and envelope layers were carefully dismantled. Physical barriers were visually examined for wear and tear, and the CLT was evaluated for attack from subterranean termites and wood-boring beetles.

For termites, final evaluations included number of live termites observed and a wood damage visual



(a) (b) (c) (d)

Figure 3. Envelope installation (a) CLT with Termimesh barrier, (b) CLT with Obex11 barrier, (c) CLT edges sealed with aluminum tape, and (d) a complete CLT envelope specimen with spacers and cement board cladding.

Table 1. Timeline of field activities.

Events	Date	Week	Activities	Observations
Installation	04/01/2021	0	1. Randomized complete block (RCB) design 2. Specimens anchored to the ground using metal stakes	None
First inspection	07/02/2021	12	1. Specimens overturned 2. Surface inspection around the corners and bottom	Termites present underneath the sill plates
Second inspection	08/16/2021	18	1. Inspection 2. Sill plated removed 3. Specimens reinstalled at original position	No termite damage on panels; termites active underneath specimens
Third inspection	10/15/2021	26	1. MC of control specimens measured using pin-type moisture meter 2. The top acrylic cover removed	Termite tubes, patches of termite damage, and moisture damage seen in specimens
Final inspection	12/09/2021	34	1. Samples dismantled for visual rating assessment 2. Live termites and beetles counted and collected for identification	Termite damage on control panels and one steel mesh panel; beetle damage on all groups; Obex11 punctured by beetles

rating ($VR_{termite}$) based on the grading system outlined in the AWPA E21 full-size commodity test for interior use applications given in Table 2 (AWPA 2015). Specifically, each panel was rated on both vertical faces, then averaged to give one visual rating for the replicate. In addition, the length of mud tubes on both vertical faces sides was recorded, then summed to give one mud tube length ($MTH_{termite}$) per panel replicate. For wood-boring beetles, the number of holes observed

Figure 4. Field installation of CLT specimens in an RCB design (3 × 10 rectangular array with 1200 mm spacing between specimens and rows) at the test site in Saucier, MS.

Table 2. Visual ratings of termite damage according to AWPA E21 (AWPA 2015).

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

from both vertical faces and the base was recorded then summed to give one value (NH_{beetle}) per panel replicate. BB_{beetle} and AB_{beetle} were the number of holes below and above barrier (or 150 mm for controls), respectively. The length of visible bored trails was also recorded and summed to give one value (BTL_{beetle}) per panel replicate. Termite soldiers and adult beetles were collected and preserved in 70% ethanol for taxonomic identification. Termite soldiers were identified to genus using a key (Scheffrahn and Su 1994), whereas adult beetles were identified to species by Terence Schiefer, Curator of the Mississippi Entomological Museum at Mississippi State University.

Nonparametric Statistical Analysis

The effect of treatment on measured responses ($VR_{termite}$, $MTH_{termite}$, NH_{beetle}, BTL_{beetle}, BB_{beetle}, and AB_{beetle}) were analyzed in SAS 9.4 (SAS Institute 2013) using the Kruskal–Wallis test of Wilcoxon scores (rank sums). Once the Kruskal–Wallis test showed a significant difference in mean ranks among the three groups, a pairwise, two-sided, and multiple comparison test was conducted using Dwass, Steel, Critchlow–Fligner method at a significance level of $p < 0.05$.

RESULTS AND DISCUSSION

A first inspection at 12 wk showed some termite activity on 14 specimens. The termites had not yet attacked the wood even in the case of control panels. The aluminum flashing, which wrapped the sill plate, was preventing moisture movement between soil and wood and appeared to deter termites due to heat build-up from the summer sun. Since this was intended to be a short-term field test, the sill plates were removed at 18 wk. Mud tubes were seen during the third inspection at 26 wk. A few of the top acrylic sheet covers were cracked and came off during the inspection, so all acrylic sheets were removed. Five of the control specimens were attacked by termites, and mud tubes were seen on panel surfaces. Specimens with Obex11 did not show any signs of termite damage, whereas in one of the specimens installed with Termimesh, one mud tube was seen that traveled from the soil level up the full height of the barrier and onto the upper wood face of the CLT specimen. A pin-type moisture meter was used to measure the MC of the control specimen panels, which was 16% and 28% at the top and the bottom, respectively (Table 3). Thus, even though subterranean termites in laboratory studies prefer wood with high MC greater than 79% (Nakayama et al 2005; Gautam and Henderson 2011) and cannot sustain feeding on wood with less than 24% MC, attack and conspicuous damage in the field are possible as long as the wood is close to FSP (about 23% for SYP).

Termite Damage

The two soldiers collected were identified (Scheffrahn and Su 1994) as *Reticulitermes* species and were most likely either *R. flavipes* or *R. virginicus,* both of which occur in abundance at the test site. At test termination (34 wk), only the control specimens had active live termites with up to 10 termites in a specimen and an average of two termites per panel. The average $VR_{termite}$ of the control, Obex11, and Termimesh groups were: 8.9, 10,

Table 3. Percent MC at top and bottom surfaces of control specimens at 26 wk.

Specimen	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Average MC (%)
MC at top (%)	14	15	17	19	16	14	17	14	18	16	**16**
MC at bottom (%)	26	25	26	28	29	29	28	27	30	28	**28**

and 9.9, respectively, with Obex11 and Termimesh showing significantly less damage than the control (Fig 5[a]). All control specimens except one showed signs of termite damage indicating greater susceptibility of CLT panels without physical barriers to termite infestation. Summing mud tube length provided another measure of the differences in termite activity among the three treatments. The average $MTH_{termite}$ of the control, Obex11, and Termimesh groups were: 24.5, 0.5, and 5.5 cm, respectively (Fig 5[b]). This suggests that there was little to no termite activity on the Obex11 compared with the Termimesh treatment, and the greatest termite activity on the controls. Statistical analysis, however, only detected significantly lower $MTH_{termite}$ in the control group with no significant difference between Obex11 and Termimesh treatments. Since nonparametric statistics tends to have lower sensitivity, it is possible that differences between the Obex11 and Termimesh may have been resolved with more replication and longer field exposure.

Figure 6(a) shows typical termite damage seen on the CLT from the control treatment. After scraping away the mud tubes (traces of the mud tube outline remain in the photo), the wood damage was revealed and began at the bottom of the CLT near the soil line and progressed upward with channels eaten through the sapwood. Damage was quite conspicuous in almost all of the control specimens but because of the large size of the panels, the assigned visual rating values were always less than 10% of surface area affected.

Figure 6(b) shows one Termimesh specimen that was found with a mud tube that ran from the soil line all the way to the top of the CLT panel, a distance of 55 cm. This was atypical since no mud tubes were found on any of the other Termimesh specimens. Therefore, even though termites could not penetrate Termimesh, they were capable of finding their way to the wood—in this case, by climbing 150 mm across the barrier upwards to the unprotected wood. The wooden specimens tested in Hawaii showed that the termites were able to make their way to the wood through a gap created by a fold in the corner of a wooden specimen wrapped with Termimesh (Grace et al 1996). However, the termite attack was due to an

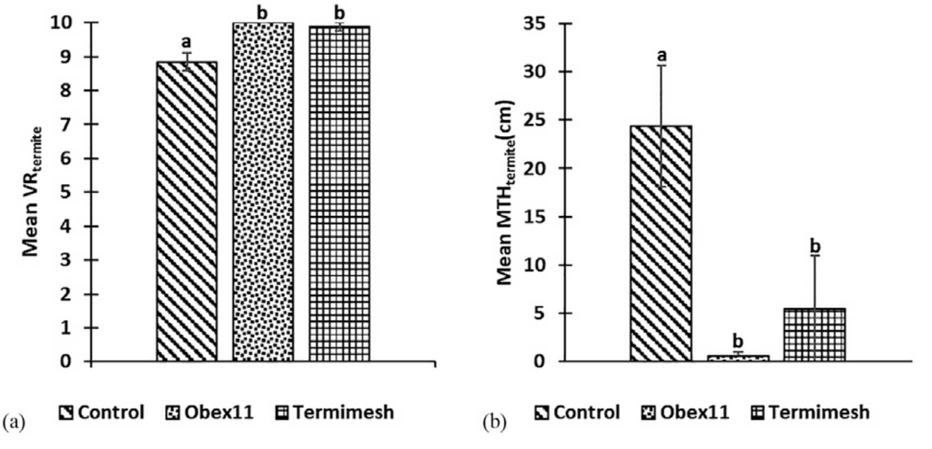


Figure 5. Mean termite (a) VR and (b) MTH. Different lowercase letters within a plot indicate significant differences among treatments. Bars denote ± SE.

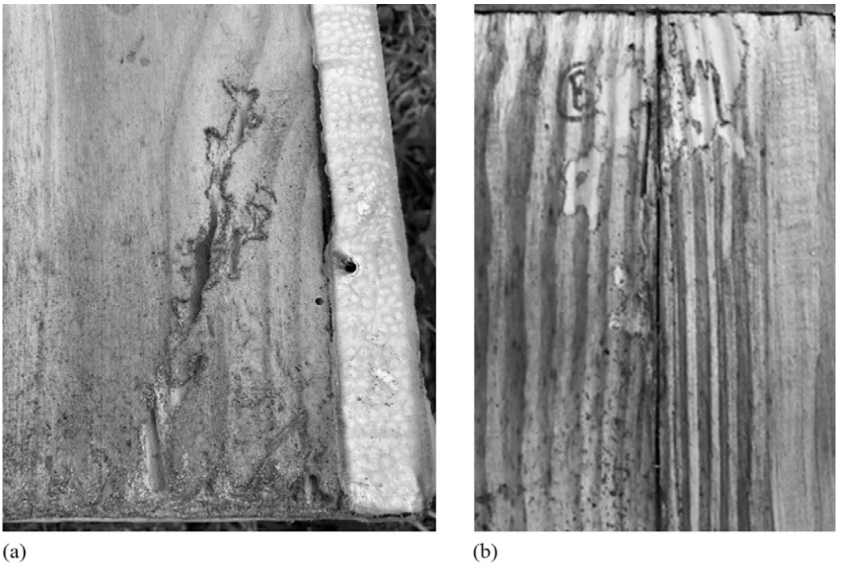


Figure 6. Damage (a) from a typical control specimen and (b) in one Termimesh specimen, where termites had constructed a mud tube from the soil line up to the top of the panel and attacked the wood at the top of the CLT.

installation error and not related to the barrier's height. A better comparison in terms of barrier height is a 5-yr field test deployed in Arizona, FL, Mississippi, and South Carolina within the United States by Kard (1998). Kard (1998) used 450 mm long wooden stakes wrapped with stainless-steel barrier to a height of 150 mm above ground and found no termite damage, as assessed by percentage attack on wooden blocks, at any of their field sites. One possible explanation for the difference between our Termimesh results with that of Kard's (1998) could be the presence of the outer wall envelope in our study. The wall envelope created a closed dark space (air cavity) with increased dampness, thereby protecting the termites from the sun and desiccation while they constructed their mud tubes and consumed the underlying wood. Regardless of test method, proper installation of the stainless-steel mesh barrier is essential when designing building envelope layers. In addition, the barrier height needs to be further researched as 150 mm did not guarantee termite resistance in all Termimesh specimens when the CLT was in contact with the soil.

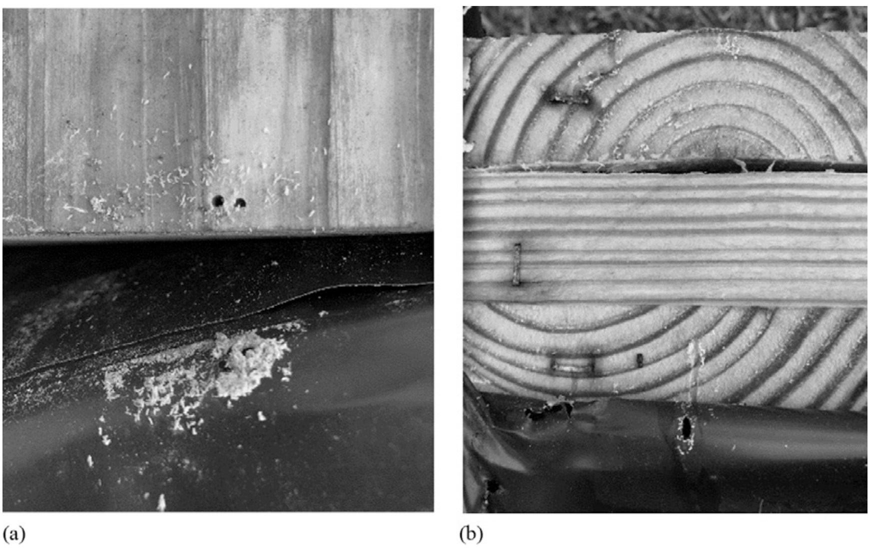
As mentioned in Cross Laminated Timber Manufacture section, the bottom edge of both Obex11 and Termimesh panels were wrapped with the barriers and then sealed with aluminum flashing. Even though termites were present under the panels, no termite damage or mud tubes were seen on any of the specimens in the Obex11 group. It appeared that the blend of essential oils and plastic sheeting of the Obex11 prevented the termites from climbing across or puncturing the barrier. In previous lab studies, it was seen that termites were not able to chew through amorphous polyamide plastic material, such as pipes and bars, but were able to deteriorate the low-density polyethylene plastic sheets. However, it should be noted that these tubes and bars were thicker and harder (1 and 6 mm) (Tsunoda et al 2010) compared with Obex11, which resisted termites despite its small thickness (0.16 mm).

Furthermore, the use of insecticides in plastic membranes was found to be effective against termites in previous research (Gay and Wetherly 1969). Recently, weather resistive barriers like Pango wrap that offers termite protection through the integration of copper compounds are also available commercially in the United States. But there remain uncertainties about their in-use serviceability as not enough field studies are reported. The same holds true for Obex11 even though the presence of essential oils were able to keep the termites away from the CLT despite their exposure to the weather of coastal Mississippi. Termite repelling membranes similar to Obex11, can be a more ecofriendly solution against termites compared with soil insecticides and membranes that use toxic chemicals. The essential oils present in Obex11 are plant-based, which further lowers the use and manufacture of toxic chemicals, contributing to sustainable construction. Since this field test was only 34-wk long, the durability and serviceability of Obex11 for more prolonged exposure times still needs further research. Nevertheless, the use of physical barriers blended with essential oils/nonpoisonous chemicals seems to be a promising solution against termites compared with the use of paints, water-repellants, films, or coatings of polyurea, which can deteriorate over time (Konkler et al 2019).

Beetle Damage

An unanticipated phenomenon in this field test was the presence of ambrosia beetles in the CLT specimens and their ability to chew through the Obex11 membrane. Even though the chemicals and plastic membrane of the Obex11 successfully repelled termites and kept them off the exposed faces of CLT, the Obex11 failed to deter these wood-boring beetles. The three collected adult beetles were identified as *Ambrosiodmus minor* (Stebbing). These beetles have heavily sclerotized mouthparts that chewed through both the membrane and wood to create round-shaped entry holes that led to bored trails within the wood (Fig 7[a]) or sandwiched between the wood and the panel base, which was wrapped first with the membrane and an outer band of aluminum flashing (Fig 6[b]). Sawdust from bored trails was also often observed accumulating between the membrane and the wood near the soil line (Fig 7[a]). In addition, a few CLT specimens in the Obex11 group showed delamination (Fig 7[b]) due to swelling from moisture trapped by the membrane. This moisture accumulated due to rainfall and higher humidity inside the air cavity.

Averages of NH_{beetle} were 1.9, 1.7, and 0.8 for control, Obex11, and Termimesh with no significant difference among totals for treatment groups (Fig 8[a]), although a difference was apparent when hole position was taken into account.



(a) (b)

Figure 7. Damage seen in a typical Obex11 specimen showing (a) two beetle puncture holes through the membrane (accumulating sawdust below) and into the face of the CLT near the soil line, and (b) one beetle puncture through the membrane, a bored trail along the CLT base, and laminate separation caused by swelling from trapped moisture.

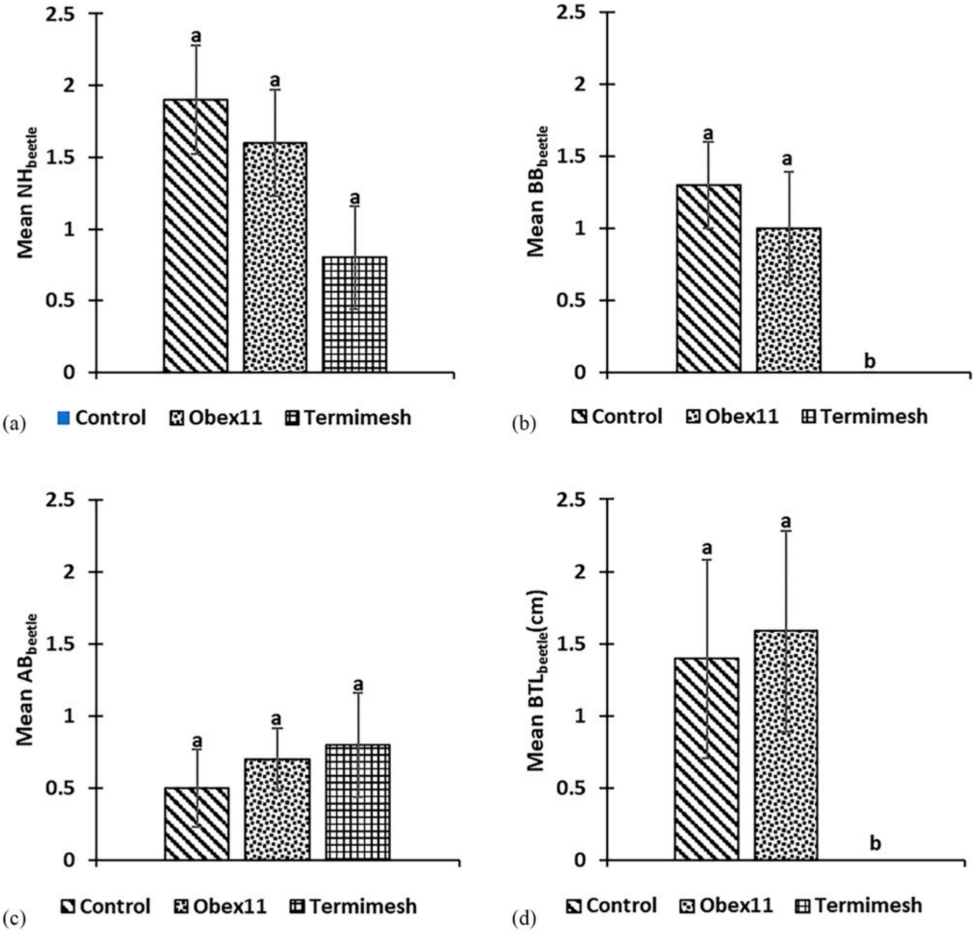


Figure 8. Mean beetle (a) NH (b) BB (c) AB and (d) BTL. Different lowercase letters within a plot indicate significant differences among treatments. Bars represent ± SE.

Control and Obex11 groups had significantly higher BB_{beetle} averages (1.3 and 1.0 holes, respectively) near the bottom edge or below the barrier height compared with 0 holes for Termimesh (Fig 8[b]). Number of holes above the barrier height (AB_{beetle}), however, was not significantly different among the three treatments (0.5, 0.7, and 0.8 for control, Obex11, and Termimesh, respectively) (Fig 8[c]). Thus, these wood-boring beetles could not chew through or otherwise penetrate the Termimesh wherever it covered the wood, but neither Termimesh nor Obex11 protected the wood above the barrier. Nearly all beetle holes were no more than 75 mm above the barrier, suggesting that there is a requisite minimum wood MC for attack by *A. minor,* as there is for subterranean termites and decay fungi (Nakayama et al 2005; Wang et al 2018). The significant difference in beetle hole positions below the barrier also explains the differences in bore trail length, which were only visible at the base of the CLT panels. The averages of BTL_{beetle} were 1.4, 1.6, and 0 cm for control, Obex 11, and Termimesh, respectively, with Termimesh significantly less than either control or Obex11 (Fig 8[d]).

Research has shown that certain species of beetles (eg Japanese beetles) are attracted by essential oils, such as citronella oil, camphor oil, coffee, and grapefruit oil (Youssef et al 2009). Manuka, phoebe, and cubeb oil lures have been used to attract redbay ambrosia beetles (Kendra et al 2018). We speculate that one or more of the nine essential oils (cedar oil, cinnamon oil, citronella oil, eugenol, geraniol, lemon grass oil, geranium oil, mint oil, and peppermint oil, each at 0.01%) present in the Obex11 acted as a beetle attractant. Field tests with baited sticky traps containing the essential oils present in Obex11 could be an interesting future research project to identify specific beetle attractant(s). The bright yellow color of the Obex11 may have also served as a visual cue, but since it was covered by the wall envelope, it seems unlikely that color was involved. Further research will need to be done to ascertain the correlation between Obex11 and beetle activity.

Ambrosia beetles are an invasive species that were first detected in 2011 in Florida and have been slowly expanding their range from the Atlantic coast of northeastern Florida to the Gulf coast of Mississippi (Schiefer 2018). In this study, beetles were detected using Lindgren funnel traps hung on bald cypress that used 50/50 mixture of 70% ethanol and ethylene glycol as attractant (Schiefer 2018). Our experiment, on the other hand, demonstrates that the beetles have become established enough in the area to appreciably infest closed CLT walls made up of SYP lumber that was in contact with the soil and had increased MC. Another serious concern, aside from the bore hole and trail damage to the wood, is that *A. minor* carries a white-rot fungus, *Flavodon subulatus,* which it introduces into the wood it infests. This beetle-associated, white-rot fungus is aggressive and has been shown to cause significant weight loss of wood at rates faster than that of other naturally occurring wood decay fungi (Kasson et al 2016). This was further complicated by the fact that Obex11, being a plastic membrane, was holding moisture and causing swelling-induced delamination of the CLT laminates. Both factors would favor invasion and growth of decay fungi capable of compromising the mechanical strength of the CLT panels (Neupane 2021). In addition, the beetle-chewed holes in the plastic membrane barrier are large enough to compromise membrane integrity by providing entry points for termites to access to the underlying wood. Thus, the conditions that can prevent a multifront attack by beetle, fungi, and termite on CLT certainly warrants future investigation, especially in coastal regions of southeastern United States, where *A. minor* and *Reticulitermes* species overlap range and where fungal decay hazards are high.

CONCLUSIONS

The effectiveness of using Obex11 and Termimesh as barriers for subterranean termites (*Reticulitermes* spp.) were evaluated in a short-term (34 wk) field test in coastal Mississippi, where environmental moisture was allowed to penetrate CLT panels faced with a simple wall envelope system. Barriers were wrapped around the base of the CLT and extended 150 mm up the CLT faces. Like most wall envelope systems, a thin air cavity separated the wall envelope from the CLT. In this study, the use of such a cavity seems to promote insect activity by creating a favorable shaded humid space in CLT proximity. Because of the large size of the CLT and proportionately less overall damage, visual ratings along with termite counts and mud tube lengths were measured to compare treatment groups. An unexpected result was damage caused by an invasive wood-boring ambrosia beetle (*A. minor*), which has been expanding its range in southeast USA. Beetle attack was evaluated by number of bored holes, hole position, and trail lengths.

Data showed that Obex 11 protected the CLT against termite damage in all 10 panels but failed to protect the panels against attack by wood-boring beetles (*A. minor*). It is possible that one or more of the essential oils used as termite repellents acted as a beetle attractant. Although termite damage had not yet occurred in the Obex11 treatment, the beetle-chewed holes clearly compromised the integrity of the membrane and were large enough to give termites and other organisms access to the underlying wood. Moreover, other researchers have found that *A. minor* inoculates wood with an aggressive white-rot decay fungus

(*F. subulatus*), which under favorable conditions of temperature and moisture, would cause more structural damage to the wood than the beetle itself. The Obex11 treatment also trapped enough moisture to cause CLT delamination. Separation of the laminates reduces mechanical strength properties of engineered mass timber and provides more entry points for wood destroying organisms.

Data for Termimesh showed protection in 9 out of 10 replicates, but in the 10th replicate, termites were able to circumvent the barrier by constructing a long mud tube that crossed above the 150 mm high barrier and continued to the top of the panel (450 mm from the soil line), where damage was found. In addition, beetle damage never occurred where the Termimesh actually covered the wood. Neither termite nor beetle could physically chew or otherwise penetrate the stainless-steel mesh due to its hardness and restrictive mesh size. However, a 150 mm barrier height was not adequate to provide 100% protection above the barrier against either termite or beetle as long as wood moisture was conducive to insect attack.

This field test of physical barriers has shown that it is possible to protect CLT walls from termites if suitable material and installation method are chosen. However, further in situ research is needed to ensure that compound(s) that are successful at repelling one wood attacking species do not in fact attract another. Durability, moisture, and barrier height are some of the areas that can be further researched to investigate the effectiveness of using physical barriers in a CLT wall envelope system. Barriers that are flexible, permeable, self-adhering, and have insect repellency can be an effective solution against wood-degrading pests. These findings can further lead researchers and CLT manufacturers to seek innovations on integrating physical barriers to CLT panels during the manufacturing process, thus reducing the installation complications and cost during mass timber buildings construction.

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