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# CYCLIC TESTS OF INTERLOCKING CROSS LAMINATED TIMBER SHEAR WALLS

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**ABSTRACT:** Cyclic tests of interlocking cross laminated timber shear walls were conducted to determine hysteretic behavior under lateral load and the effect of anchorage on wall strength. Four 3.05-m tall by 2.44-m long by 288-mm wide shear wall specimens were constructed. Two types of let-in braces (rectangular and dovetailed) and two types of distributed anchor configurations (conventional and a withdrawal type connection) were examined. Shear walls without end anchorage (hold-downs) were compared to shear walls with 14-gauge and 12-gauge strap hold-downs. All specimens successfully resisted cyclic loading up to approximately 2.5% story drift without significant degradation in strength and stiffness. Walls with withdrawal type distributed anchorage increase the lateral strength compared to walls with the conventional configuration of distributed anchorage. The test results showed that hold-down straps increased the wall lateral strength by a factor of two compared to shear walls with only conventionally distributed anchorage.

**KEYWORDS:** Mass timber, seismic resistance, shear walls

## 1 INTRODUCTION

Many timber structures typically use high-grade building materials and often involve products that emit volatile organic compounds. The grade of dimensional lumber mainly depends on the slope of grain (fiber alignment relative to the edges of the member) and the size and number of knots (pieces of wood branches that intersect the cross section of the member) [1]. High-grade dimensional lumber has a low slope of grain, and few knots. Light frame construction in the United States often uses Grade No. 2 lumber. This grade of lumber has a low slope of grain and may contain moderate sized knots. In contrast, low-grade lumber has a higher of slope of grain and may contain larger knots. Lumber from trees killed by the Mountain Pine Beetle is an important example of low-grade lumber because it is plentiful in the United States. In Colorado alone, it has been estimated that nearly half of the forest areas have been infested [2]. If left standing, beetle killed trees pose a hazard for wildfires, but if employed as a building material, the wood has the potential to be a low-cost building material. As a result, there has been interest in utilizing beetle kill wood in mass timber systems, such as cross laminated timber, because the cost of the material can be much lower than high-grade materials.

Similar to other engineered wood products, the most common type of cross laminated timber relies on adhesives to bind the layers of wood. Commonly used adhesives include urea-formaldehyde, for interior use wood products, and phenol-formaldehyde, for exterior use wood products. Formaldehyde is a volatile organic compound that is emitted into the surrounding environment. In a building, the concentration of formaldehyde in the environment is increased when the air is refreshed low rates. In the United States, the Department of Housing and Urban Development sets limits on the amount of formaldehyde that may be emitted by building materials. Although formaldehyde emissions from wood products made with urea-formaldehyde or phenol-formaldehyde adhesives are less than the Department's limits, long-term exposure to volatile organic compounds may contribute to building occupants becoming sick proportional to the time spent inside the structure, without any specific illness or cause [3,4], a condition called "sick building syndrome" [5].

Interlocking cross laminated timber is a relatively new type of prefabricated mass timber panel structural system that has the potential to employ low-grade wood without volatile organic compounds [2]. Figure 1 shows an interlocking cross laminated timber structure under construction.

*Figure 1: Interlocking cross laminated timber structure under construction.*

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Similar to conventional cross laminated timber, interlocking cross laminated timber is a panel that consists of orthogonal layers (plies) of wood. But unlike conventional cross laminated timber, interlocking cross laminated timber is assembled without adhesives. The plies in a panel can be interlocked using various methods [6]. One of these methods is to create a diagonal "let-in" brace within the panel.

Interlocking cross laminated timber was developed to be fabricated using low-grade wood material [7]. The orthogonal orientation of the plies minimizes the overall effect of the slope of grain on the strength. Thus, interlocking cross laminated timber systems can be sourced from local standing dead timber material, such as beetle-kill trees, and it can decrease the concentrations of pollutants in buildings.

Similar to conventional shear walls, interlocking cross laminated timber shear walls use distributed anchorage to resist sliding, and end anchorage to resist rocking. Figure 2 shows the distributed and end anchorage in a shear wall. The conventional type of distributed anchorage uses small-diameter self-tapping screws to fasten the wall to a wood sole plate that is bolted to the concrete foundation. For wide-segment shear walls with lower lateral demands, strap hold-downs are often used. Strap hold-downs are embedded in the foundation before the concrete hardens, and then later fastened to the face of the shear wall. For narrow segment shear walls, like the one shown in Figure 2, a larger-capacity hold-down is required.

Since interlocking cross laminated timber is relatively new, the structural strength and behavior of interlocking cross laminated shear walls is not yet fully understood. In the first study of the system [7], full-scale specimens of 2.44-m tall by 2.44-m long 340 mm wide five-layer interlocking cross laminated timber shear walls made with beetle killed wood were subjected to a monotonically applied lateral load in the plane of the wall. The lateral monotonic strength of the shear wall was 170 kN, approximately twice the unit shear strength of a comparable conventional shear wall.

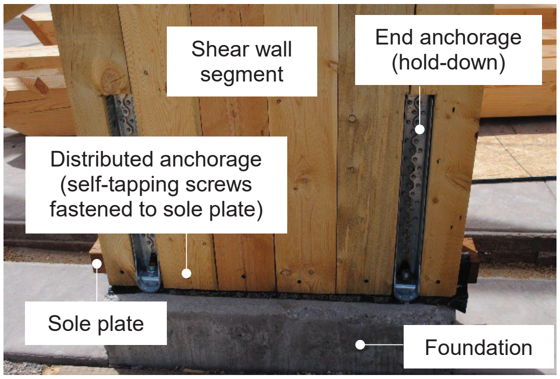

***Figure 2:*** *Distributed and end anchorage in an interlocking cross laminated timber shear wall.*

In a subsequent study [8], 2.44-m tall by 2.44-m long 216 mm wide three-layer interlocking cross laminated timber shear wall specimens made with beetle killed wood were subjected to monotonic in-plane lateral load, and then, in a separate test, the wall was subjected to a monotonic load applied to the face of the wall. The in-plane lateral monotonic strength of the shear wall was 148 kN. Internal crushing of the dovetailed members in the layers of the wall led to ductile in-plane and out-of-plane behavior. In another study [6], 2.44-m tall by 2.44-m long 349 mm wide shear wall specimens using five vertically oriented layers of beetle killed wood were subjected to a monotonically applied in-plane lateral load. The average lateral monotonic strength was 147 kN for shear walls with dovetailed horizontal braces, and 246 kN for shear walls with horizontal and diagonal dovetailed braces.

The focus of the previous studies was on the monotonic lateral strength of the wall. Cyclic strength and behavior of interlocking cross laminated timber shear walls was not investigated. In the authors opinion, this is a significant gap in knowledge because cyclic strength and behavior are important in order to better understand how the shear walls will respond to seismic demands in an earthquake. Furthermore, in the previous studies the shear walls were secured directly to the test frame. No attempt was made to determine the effect on the lateral behavior of distributed and end anchorages that are used in the field. This is also a significant gap in knowledge because lateral behavior of a shear wall is known to be dependent upon anchorage.

In this study, four full-scale interlocking cross laminated timber shear wall specimens were constructed and tested under a cyclic loading sequence to determine hysteretic behavior under lateral load and to determine the effect of anchorage. Two types of let-in brace cross sections (rectangular and dovetailed) were used in this study. Distributed anchorage using medium-diameter self-tapping screws fastened to the wide face of the sole plate was compared to the typical configuration (small-diameter self-tapping screws fastened to the narrow edge of the sole plate). The effect of end anchorage was examined by testing two specimens without hold-downs, and two specimens with strap hold-downs.

## 2 METHODOLOGY

The shear wall specimens were 3.05-m tall by 2.44-m long by 288-mm wide. The specimens were manufactured by Euclid Timber Frames (https://euclidtf.com/), located in Heber City, Utah, using computer numerical control (CNC) milling machinery. Figure 3 shows a drawing of the shear wall. The wall used 102-mm thick Kiln-dried Douglas fir vertical interior plies, exterior tongue and grove (T&G) plies, and horizontal let-in braces. Specimens 1 and 2 used standard rectangular ("R") cross-section let-in braces (Figure 4a), and Specimens 3 and 4 used dovetailed ("D") braces (Figure 4b). The exterior T&G plies extended below the bottom of the wall to accommodate a rectangular wood sole plate.

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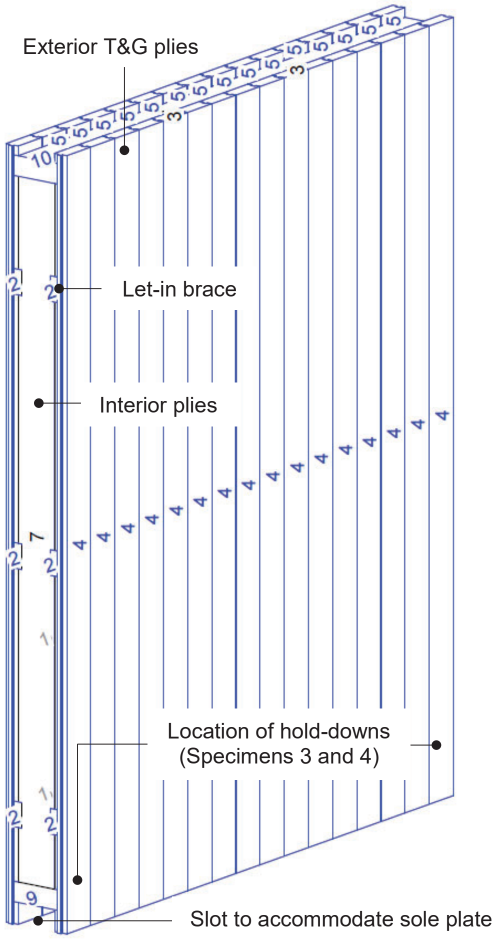

*__Figure 3:__ Drawing of shear wall specimen.*

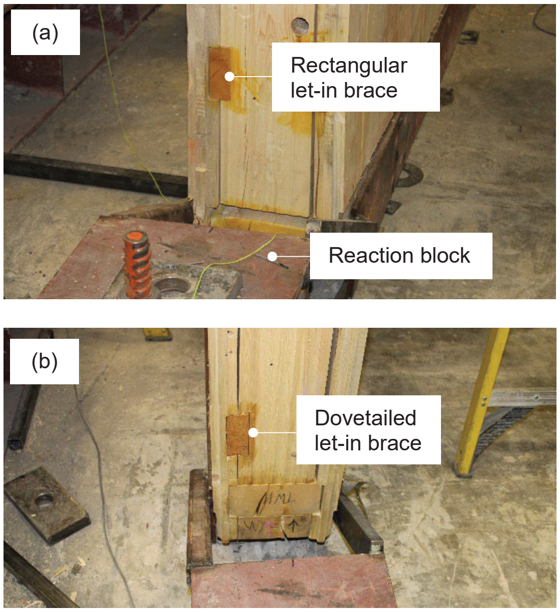

*__Figure 4:__ Let-in braces: (a) rectangular, and (b) dovetail.*

Two types of distributed anchorage were used. For Specimen 1, the distributed anchorage consisted of two rows of 10-mm diameter by 215-mm long TCC self-tapping screws spaced every 76.2 mm. The face of the sole plate was fastened to the web of a steel beam below the wall. The screws passed through the sole plate and into the end grain of the interior plies of the shear wall. In this paper, this anchorage is referred to as type “W”. For Specimens 2, 3, and 4, the distributed anchorage consisted of 4.8-mm diameter by 178-mm long OLYLOG self-tapping screws spaced every 203 mm. The screws were fastened through the exterior T&G plies of the shear wall to the narrow edge of the sole plate on both sides of the sole plate. Figure 5 shows the distributed anchorage. This type of distributed anchorage was intended to be representative current construction practices. In this paper, it is termed type “C”.

Figure 6 shows the test setup. The top of the shear wall specimen was fastened to the web of a steel beam using 10-mm diameter by 215-mm long TCC self-tapping screws spaced every 76.2 mm. The beam was pin-connected to a spreader beam above. The pin allowed the wall to move vertically (rock). The spreader beam was connected to the end of a hydraulic actuator, and the actuator was mounted to a steel frame. Out-of-plane movement of the shear wall specimen was restrained by a surrounding steel framework. For Specimens 2, 3, and 4, the sole plate was fastened to the web of a steel beam below using 15.9-mm diameter anchor bolts spaced every 914 mm. The steel beam was secured to steel reaction blocks at each end (see Figure 3).

*__Figure 5:__ Distributed anchorage (Specimens 2, 3 and 4).*

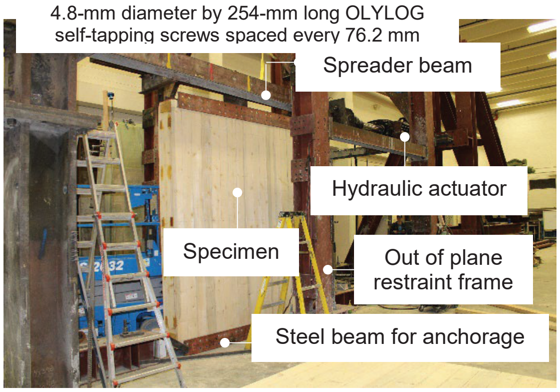

*__Figure 6:__ Test setup.*

Specimens 1 and 2 were installed without hold-downs. Specimen 3 used a 14-gauge LSTHD8 strap hold-down at each end, and Specimen 4 used a 12-gauge STHD14 strap. The upper portion of the strap was fastened to the face of the shear wall according to manufacturer's instructions [9]. The lower portion of the strap is ordinarily embedded in concrete. For testing purposes, this portion was removed and the cut end of the strap was welded directly to the flange of the steel beam, as shown in Figure 7.

The shear wall specimen was subjected to a quasi-static cyclic loading sequence to determine lateral strength, ductility, and cyclic degradation of strength and stiffness. Figure 8 shows the loading sequence. The displacement-controlled loading sequence consisted of an initial two cycles at 1.67% target story drift, followed by two cycles at increments of 1.67% target story drift, continued until failure. The load rate was 50.8 mm/min.

The shear wall specimens were instrumented with string potentiometers (SPs) to measure in-plane and out-of-plane movement of the wall. Figure 9 shows the location of the instrumentation. The actuator internally measured its own displacement and force. The wall displacement was calculated by subtracting the sole plate movement from the displacement at the top of the wall.

***Figure 7:*** *End anchorage placement (Specimens 3 and 4).*

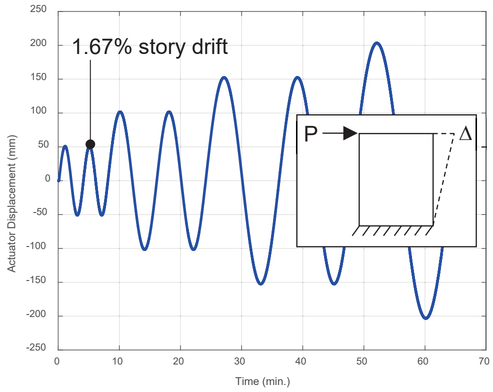

***Figure 8:*** *Cyclic loading sequence.*

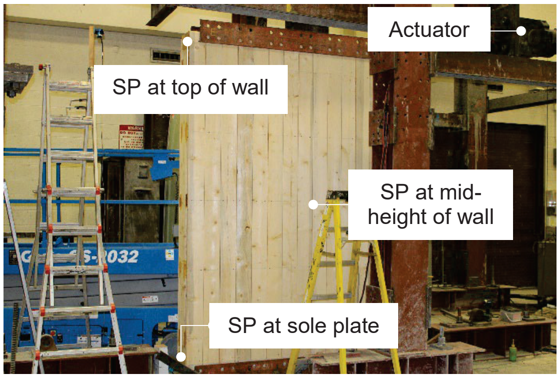

***Figure 9:*** *Instrumentation.*

## 3 RESULTS

The lateral load versus wall displacement response of Specimen 1 is shown in Figure 10. No substantial damage was observed during the first cycles at 1.21% story drift. During the second cycle at 2.79% drift, vertical cracks initiated at the end of the shear wall. As loading increased, the bottom of the wall withdrew from the TCC self-tapping screws in the sole plate, as shown in Figures 11 and 12. The ultimate load achieved was 97.5 kN. Finally, at 4.39% drift, the sole plate failed in tension perpendicular to grain due to cross-grain bending.

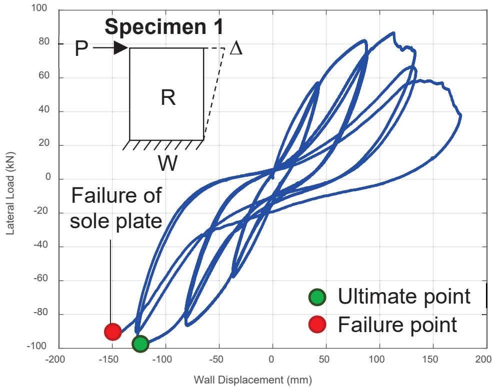

***Figure 10:*** *Specimen 1: load versus displacement response.*

***Figure 11:*** *Specimen 1: wall withdrawal from sole plate.*

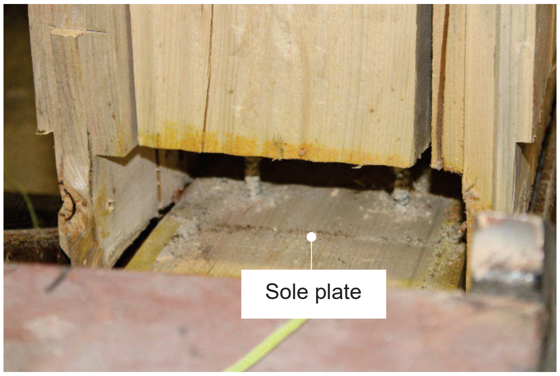

***Figure 12:*** *Specimen 1: wall withdrawal from sole plate.*

Figure 13 shows the response of Specimen 2. As in the previous test, no substantial damage was observed during the first cycles. However, during subsequent cycles, the OLYLOG self-tapping screws tore through the exterior T&G plies, as shown in Figure 14. The ultimate load achieved was 32.8 kN. After completing the third set of cycles, the sole plate failed due to cross-grain bending.

Figure 15 shows the response of Specimen 3. The initial response was similar to the previous tests. As loading progressed, the hold-down straps buckled in compression.

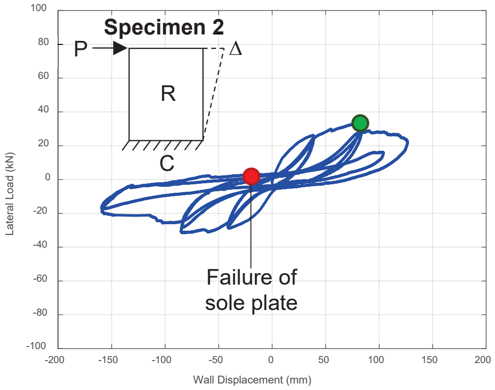

***Figure 13:*** *Specimen 2: load versus displacement response.*

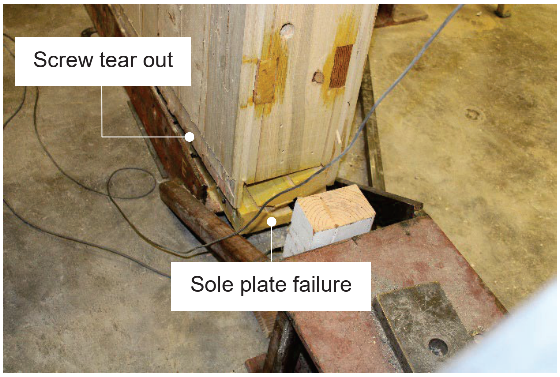

***Figure 14:*** *Specimen 2: screw tear out and sole plate failure.*

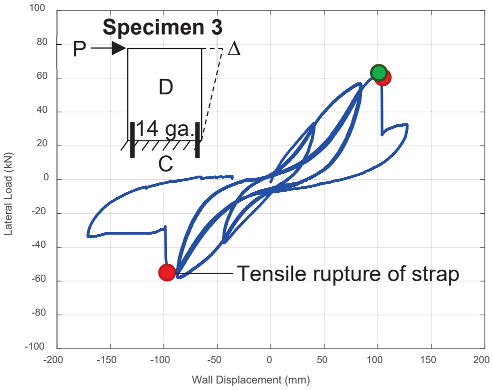

***Figure 15:*** *Specimen 3: load versus displacement response.*

Figure 16a shows the buckled strap. At 3.34% drift, an ultimate load of 62.2 kN was achieved, and one of the straps ruptured in tension (Figure 16b). The loading continued in the reverse direction and the other strap ruptured at 3.23% drift. Finally, the sole plate failed due to cross-grain bending.

Figure 17 shows the response of Specimen 4. The response was similar to the previous test: the straps buckled in compression, then both straps ruptured in tension, and eventually the sole plate failed. The ultimate load achieved was 32.8 kN.at 4.36% drift.

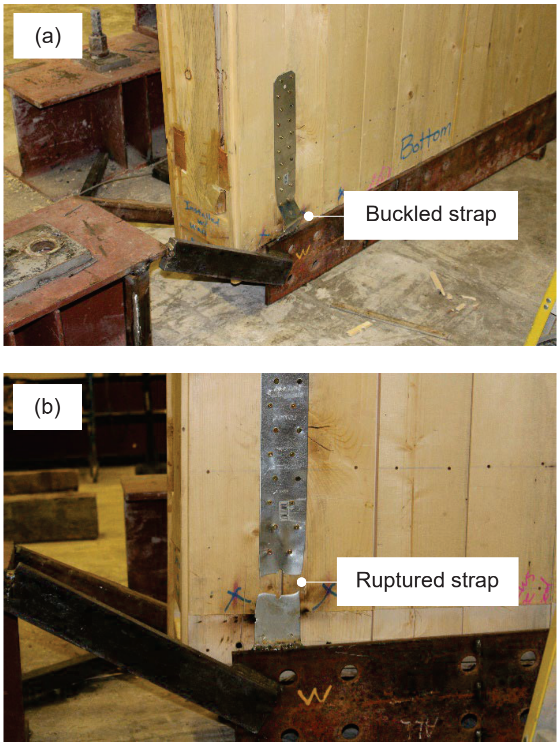

***Figure 16:*** *Specimen 3: (a) buckled strap, and (b) ruptured strap.*

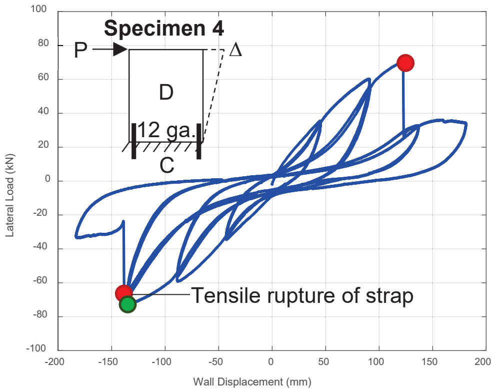

***Figure 17:*** *Specimen 4: load versus displacement response.*

The test results are summarized in Table 1. All specimens successfully resisted cyclic loading up to at least 2.5% story drift without significant degradation in strength and stiffness.

The results indicated that rectangular versus dovetailed let-in bracing did not have a significant effect on the wall response. In contrast, distributed anchorage had a considerable effect. If hold-down straps were not installed, the ultimate strength of the wall with small-diameter self-tapping screws fastened to the narrow edge of the sole plate (Type C distributed anchorage) was a third of the strength compared to medium-diameter self-tapping screws fastened to the wide face of the sole plate (Type W distributed anchorage). The difference in lateral behavior can be attributed to the combined shear and uplift demands that are imposed on the self-tapping screws fastened to the narrow edge of the sole plate when end anchorage is not present to take the uplift loading.

The test results show that hold-down straps successfully resisted the uplift loads until the straps buckled and ruptured after repeated cycles. When the straps failed, the uplift load was transferred to the screws. For both types of distributed anchorage, the drift attained at the ultimate load was approximately 3%. The strength of the wall with Type C distributed anchorage increased by a factor of two if hold-down straps were installed, and the drift attained at ultimate load increased to over 4% drift.

***Table 1:*** *Results of cyclic tests*

| Spec. | Anchorage | | Strength | |
|---|---|---|---|---|
| No. | Dist. | End. | $P_u$ (kN) | $\Delta_u$ (%) |
| 1 | W | -- | 97.5 | 3.20 |
| 2 | C | -- | 32.8 | 2.66 |
| 3 | C | 14 ga. | 62.2 | 3.34 |
| 4 | C | 12 ga. | 72.1 | 4.36 |

Although the results show that distributed anchorage fastened to the face of the sole plate effectively resisted uplift, this type of distributed anchorage configuration would require connecting the sole plate to the shear wall prior to connecting the sole plate to the foundation, which is not the normal construction sequence. Normally, the sole plate is fastened to the foundation wall first and the shear wall is installed later. Therefore, additional research is needed to determine the construction viability of using self-tapping screws fastened to the wide face of the sole plate as a means to anchor the base of the shear wall.

# 4 CONCLUSIONS

Four 3.05-m tall by 2.44-m long by 288-mm wide interlocking cross laminated timber shear wall specimens were tested under cyclic loads. The test results indicated that the distributed anchorage and the end anchorage have a significant effect on the load deformation response of the shear wall. The type of let-in brace was not significant based on the two cross sections examined. The results show that end anchorage was vital to resist the uplift demands at the base of the shear wall. The conventional configuration for distributed anchorage, using small-diameter self-tapping screws fastened to the narrow edge of the sole plate, led to a shear wall strength that was a third of the strength compared to fastening medium-diameter self-tapping screws to the wide face of the sole plate. However, it is recognized that fastening to the wide face may be challenging to accomplish in the field. In summary, the results suggest that interlocking cross laminated timber shear walls may be a viable lateral system in seismic areas provided sufficient distributed and end anchorages are provided.

# ACKNOWLEDGEMENT

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