Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Performance of Perforated Plate Connections in Mass Timber Seismic Force Resisting Systems

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ABSTRACT

Ductile connections play a crucial role in enabling energy dissipation in mass-timber seismic force-resisting systems (SFRS). To achieve ductile connections at designated energy-dissipating locations of SFRS, conventional dowel-type fasteners, such as nails, bolts, steel dowels, and screws, are commonly employed. However, these fasteners come with certain limitations, such as unpredictable failure modes, limited capacity, as well as excessive damage to the timber components after a major seismic event. To address these drawbacks, this paper presents an experimental investigation on the use of perforated steel plates as a sacrificial seismic fuse for mass timber systems, including cross-laminated timber (CLT) shear walls and timber braced frames (TBF). The experimental work was conducted in four phases, with the initial phase (Phase Zero) comprising a feasibility study evaluating four types of connections in 21 tests to assess various fuse concepts (panel-to-panel, base shear, and hold-downs for the CLT shear wall system, as well as end brace connections for the TBF). Phase One focused on testing isolated perforated plates to investigate the effect of perforation configuration (30 tests) and the influence of the cyclic loading protocol (28 tests). Phases Two and Three evaluated full-scale end-brace specimens for TBF SFRS under cyclic loading. Six and twelve tests were performed in Phases Two and Three, respectively, with the main aim of improving the fuses' performance by shifting the failure mechanism from shear yielding to flexural or axial yielding. Among the key findings are: 1) the flexural yielding mechanism obtained with long-slotted perforations exhibited wide hysteresis loops with significant energy dissipation capacity, and 2) the perforated plate concept can achieve moderately ductile connections. These findings contribute to advancing the development of seismic-resistant mass timber systems by providing insights into using perforated steel plates as sacrificial fuses, which offer enhanced ductility, ultimate deformation, and energy dissipation capacity.

Keywords: Timber Braced Frame (TBF), Ductile Connections, Structural Fuse, Perforated Steel Plate Connections, Seismic Force Resisting System (SFRS).

INTRODUCTION

Sustainable structural systems such as cross-laminated timber (CLT) and mass timber braced frames (TBF) have been gaining attention for high-rise timber buildings worldwide. These systems are employed as Seismic Force Resisting Systems (SFRS) to resist seismic loads while reducing the environmental footprints of conventional structures. While tall timber buildings using these systems have been built mainly in non-seismic or low-seismic locations with regular wind loading, their application in high seismic or wind regions requires further research on the behaviour of the systems and their components with respect to the corresponding loading, particularly in the connections. Ductile connections are an indispensable structural component for energy dissipation in mass-timber SFRS. However, conventional dowel-type fasteners, such as nails, bolts, steel dowels, and screws, can achieve ductile connections at designated energy-dissipating locations of SFRS. Still, they have certain drawbacks, such as unpredictable failure modes, limited capacity and excessive damage to timber components after major seismic events.

This paper summarizes an extensive experimental study investigating the use of perforated steel plates as a sacrificial seismic fuse to enhance the structural resiliency of mass timber systems, including CLT shear walls and TBF. The central concept underlying the connection design is to impose all yielding on the steel plate elements to achieve reliable ductile behaviour while the dowel-type connection between the steel plate and mass timber member is capacity-protected. The approach assumes that the shear strength of the steel links, i.e., the clear distance between two adjacent perforations (see Figure 1), governs the load-carrying capacity of the fuse (as the sum of the individual link strengths, along the perforation zone length). The perforated plate fuse concept has been shown to be successful, as documented in previous studies in steel [1 - 6] and timber structures [7 - 10].

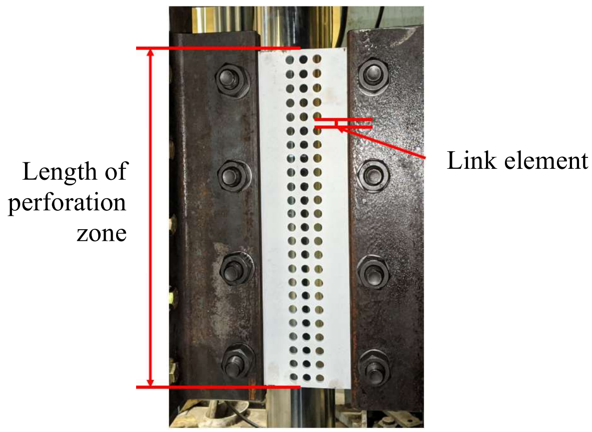


Figure 1: Perforated plat fuse concept and link element definition

EXPERIMENTAL PROGRAM

Phase Zero (Feasibility Phase)

The feasibility phase (called Phase 0 herein) was conducted in two sub-phases, each with distinct objectives. Phase 0A involved the feasibility evaluation of three types of connections intended for three locations in an SFRS. These include panel-to-panel connection and hold-down for CLT shear wall system, which control the rocking mechanism in the shear wall, and end brace connections for the TBF, which dissipate energy through truss action. Figure 2 shows these three connection specimens under test. Twenty one monotonic and cyclic tests were performed in Phase 0A. Phase 0B, investigated base shear connections in CLT shear walls, which controls the sliding mechanism in shear walls. Two types of base shear connections were studied, one with conventional solid angle brackets (BSC) and the other with perforated angle brackets (PBSC), and their performances were compared. Three PBSCs were tested, one in monotonic and two in cyclic loading, while three conventional BSC using self-tapping screws (STS) were also considered for comparison, as shown in Figure 3. Ancillary material properties tests were performed to verify the predictability of the PBSC connection responses.

The results of Phase 0A show that the fuses had reasonable ductility and the ability to dissipate energy. Significant ultimate strength and deformations were observed in monotonic tests. Although the specimens' strength, ultimate deformation, and energy dissipation capability were reduced under cyclic loading (as can be seen in Figure 4(a)), the ductility of the connections was higher than the suggested values for moderately ductile connections. The test results confirmed the scalability and predictability of the yield and ultimate strengths of the perforated steel plates, allowing connections to be reliably designed to fail in a ductile manner under monotonic loading. Furthermore, it is shown that perforated fuses in combination with capacity-protected dowel-type fasteners, e.g., tight-fit pins and self-tapping screws (STS), provide a resilient solution that could be replaced with ease after a major seismic event.

For phase 0B, as intended in design, the PBSC and BSC exhibited inelastic behaviour through plastic deformations in the fasteners and perforated zone, respectively. For the BSC, the STSs yielded in double hinge mode. This caused cracks and wood crushing in the outer plies of CLT only, despite penetrating three layers. For the PBSC, in addition to the yielding of the perforated zone, out-of-plane deformation of the outstanding and supporting legs was observed.

This out-of-plane deformation contributed to the general ductility of the connection but might have accelerated the failure of the perforated zones. Regarding ductility, PBSC provided 3 to 5 times greater ductility than BSC. These ductility values suggest that the perforated plate concept could achieve moderately ductile connections in timber construction. Moreover, the ductility of the PBSC was substantially reduced under cyclic loading compared with that under monotonic loading, as seen in Figure 4(b). In contrast, ductility remained largely unchanged for BSC. Under cyclic loading, the BSC achieved a similar displacement level at peak load as under monotonic loading without significant capacity degradation. In contrast, the PBSC only reached about 50% of the corresponding monotonic displacement. The models proposed to calculate the ultimate load and displacement of the PBSC under shear load were found to produce results that were close to the corresponding values measured from tests. Regarding resiliency, the PBSC is preferable to the BSC due to limited damage to CLT panels and replaceability after a major incident.

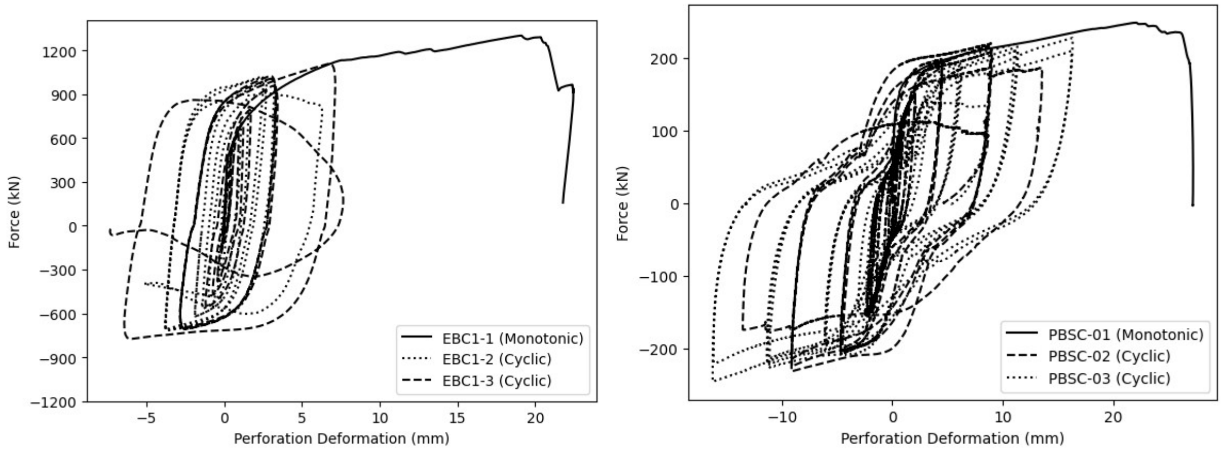
Hence, based on the results of the Feasibility Phase, it was noted that despite the excellent performance of the fuse type in monotonic loading, premature fatigue-type failure of the fuses in shear yielding under cyclic loading was a shortcoming [11 & 12]. This finding led to the need for subsequent phases.

(a) (b) (c)

Figure 2: Images of the experimental program: phase 0A (a) hold-down (HD) (b) panel-to-panel (PPC) (c) end brace connection (EBC)

(a) (b)

Figure 3: Images of the experimental program: phase 0B (a) PBSC, (b) STS base shear connections

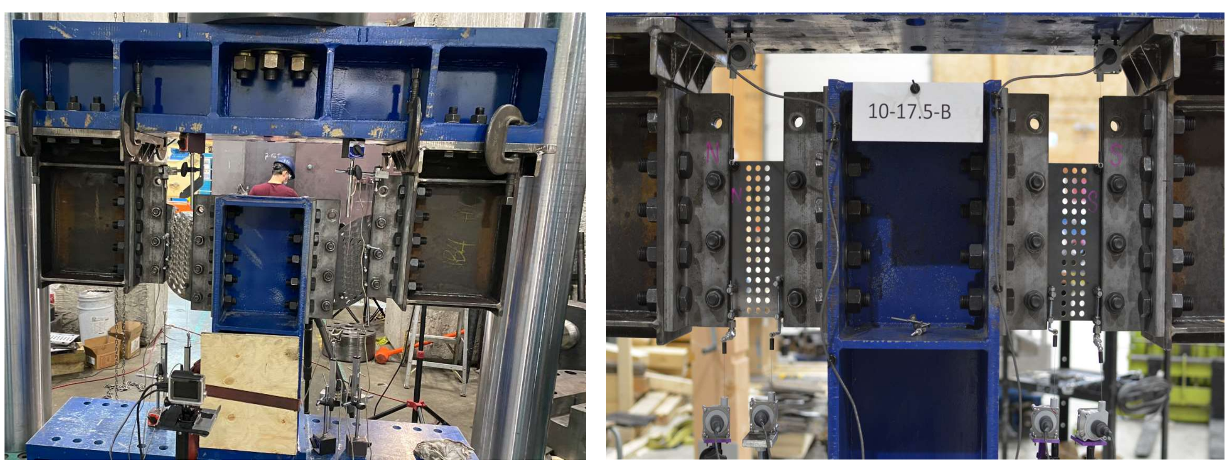


(a) (b)

Figure 4: Sample load versus perforation deformation curves: (a) phase 0A: EBC (b) phase 0b: PBSC

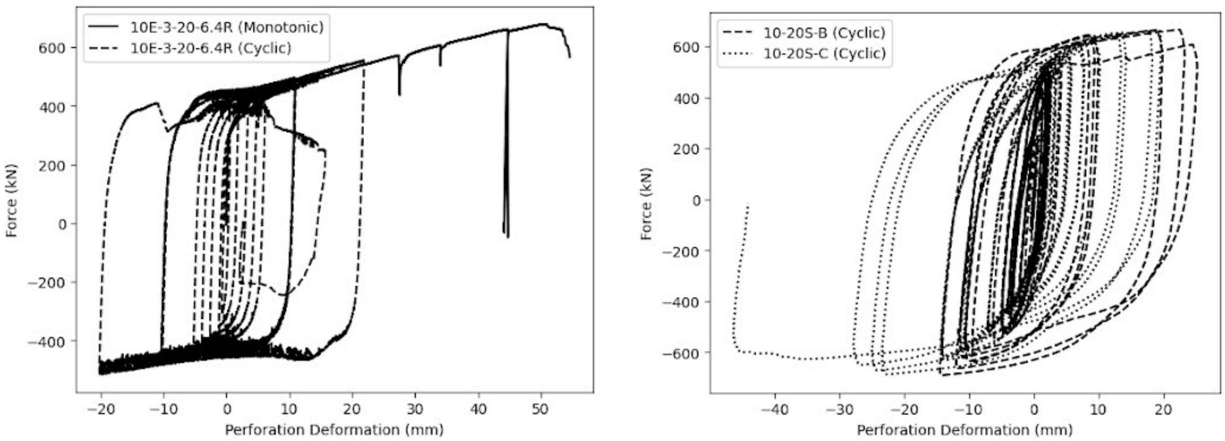
Phase One

In this phase, we investigated the factors contributing to the limited ultimate deformation under cyclic loading, focusing solely on the steel plate fuse. Phase 1 was divided into two sub-phases. Phase 1A examined the effect of different parameters, such as the number of perforation rows, link element (clear distance between two adjacent perforations) size, perforation size, shapes, and patterns, on the monotonic and cyclic behaviour of perforated fuses, with 30 tests performed. In Phase 1B, the cyclic loading protocol's influence on the fuses' performance was investigated by performing 28 additional tests. The Phase 1 specimens and test setup are shown in Figure 5. Phase 1A results revealed that several configurations exhibited improved performance in cyclic loadings, such as the ellipse shape that combined shear yielding with flexural yielding (See the hysteresis loops of an ellipse-shaped fuse in Figure 6(a)). Based on Phase 1B results, we inferred that ASTM E2126 [13] Method C might be a better option at the fuse scale than method B, see Figure 6(b). Further research is ongoing to investigate the effect of loading protocol on the performance of perforated plate fuses.



(a) (b)

Figure 5: Images of the experimental program: plate tests (a) phase 1A, (b) phase 1B



(a) (b)

Figure 6: Sample total load versus perforation deformation curves: plate tests (a) phase 1A, (b) phase 1B

In the monotonic tests, failure was initiated at one link element and then progressively distributed to other link elements. In the cyclic tests, the nature of the rupture was sudden and happened in a group. Hence, increasing the edge link sizes may postpone the failure under monotonic loading but provide a slight improvement under cyclic loading in terms of increasing the ultimate deformation. In specimens with 10 mm or wider link elements, the assumption of a pure shear failure mechanism may not be valid; tensile field action plays a role in the failure mechanism. Besides, while the extent of out-of-plane deformation in the monotonic specimens can be ignored, such deformation in some specimens (e.g., those with a staggered pattern) tested under cyclic loading was significant. These two phenomena are considered in developing models for predicting the peak strength and deformation of this type of fuse, which is currently underway. Under monotonic loading, increasing the number of rows of perforations beyond three improved the performance, in terms of ultimate deformations, of the fuse. However, it did not lead to any improvement under cyclic loading. The specimen with the ellipse perforation had the largest cyclic peak deformation, while the smallest was associated with specimens with a staggered pattern. These specimens possess the largest and smallest monotonic peak deformations as well. The staggered specimens are among the stiffest types of connections investigated in the linear zone. The values of the over-strength factor are between 1.1 and 1.2, suggesting moderate post-yield strength potential. While the performance of the specimens was significantly beyond the CSA O86-19 commentary requirement [14], in the monotonic tests, the specimens' strength, ultimate deformation, and energy dissipation capability were reduced under cyclic loading, as shown in Figure 6(a). Accordingly, the connection can still be classified as at least moderately ductile, as the lowest ductility ratio reached was 5.4, and the highest was 74.5. The ultimate deformation achieved in cyclic loads was about 43% to 50% of the corresponding monotonic deformations caused by premature low-cycle fatigue-type steel rupture at the fuses. As a result, within the scope of the configuration considered in this phase, the reduced ultimate deformation under cyclic loading remains a technical challenge that needs to be addressed if this type of seismic fuse is to be installed in timber-based SFRS, despite the promising potential of some of the patterns, e.g., ellipse [15]. Based on the test observations and obtained results, it is recommended that the effects of the cyclic testing protocol on load-deformation hysteresis response and mode of failure, particularly fatigue-type rupture, be further investigated. In addition, there was evidence to suggest that a yielding mechanism other than shear yielding, e.g., yielding in flexural or tension/compression action, can reduce the propensity of the steel material to low-cycle fatigue-related rupture. This is an important finding that was investigated in Phases 2 and 3.

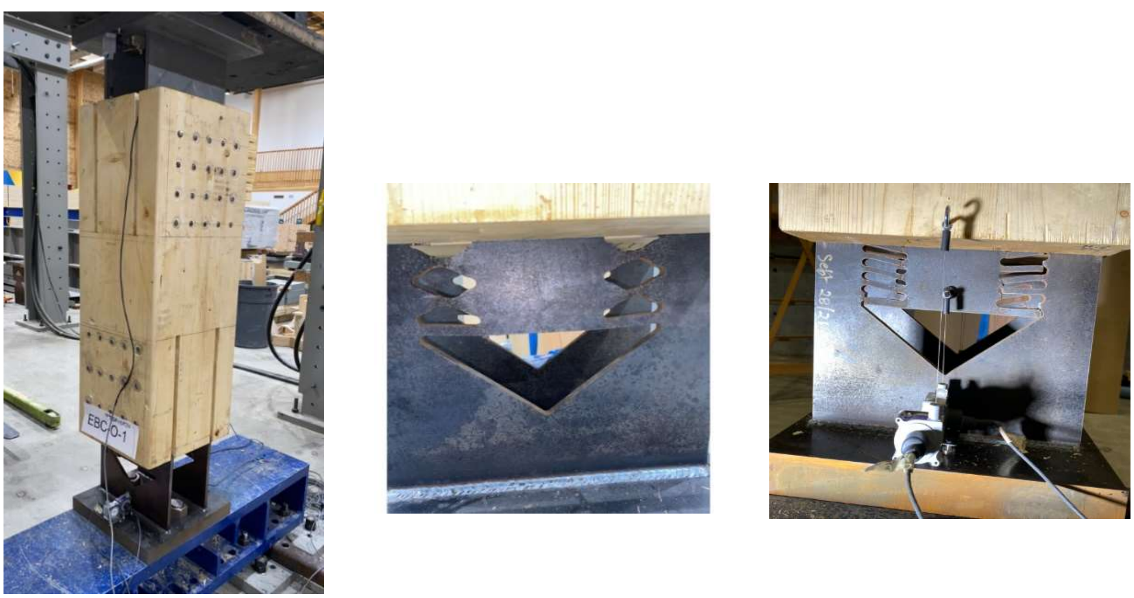
Phases Two and Three

Phase 2 and Phase 3 were performed using the same specimen setup, as shown in Figures 7 and 8, respectively. Six specimens were designed for Phase 2 as full-scale end-brace specimens for TBF and tested under cyclic loading according to ASTM E2126 Method C. Three different arrangements and two levels of capacity protection were considered, and ellipse-shaped fuse end specimens showed better cyclic performance, as shown in Figure 9(a).

Phase 3 was initiated to investigate the potential improvement in the ultimate displacement of the fuse concept by altering the yielding mechanism from shear yielding to flexural yielding or axial yielding. A total of 12 end-brace specimen tests were carried out in accordance with ASTM E2126 Method C. Figure 8 shows an example. The results indicate that using long-slotted perforations to achieve flexural yielding produces wide hysteresis loops with significant energy dissipation capacity, as demonstrated in Figure 9(b). The obtained results for the long oval pattern were promising in satisfying the ultimate displacement requirement, making the fuse concept a strong candidate for achieving moderately ductile connections. Moreover, the evaluated perforated plate patterns provided resilient solutions that could be replaced after yielding failure, as shown in Figure 10 [16].

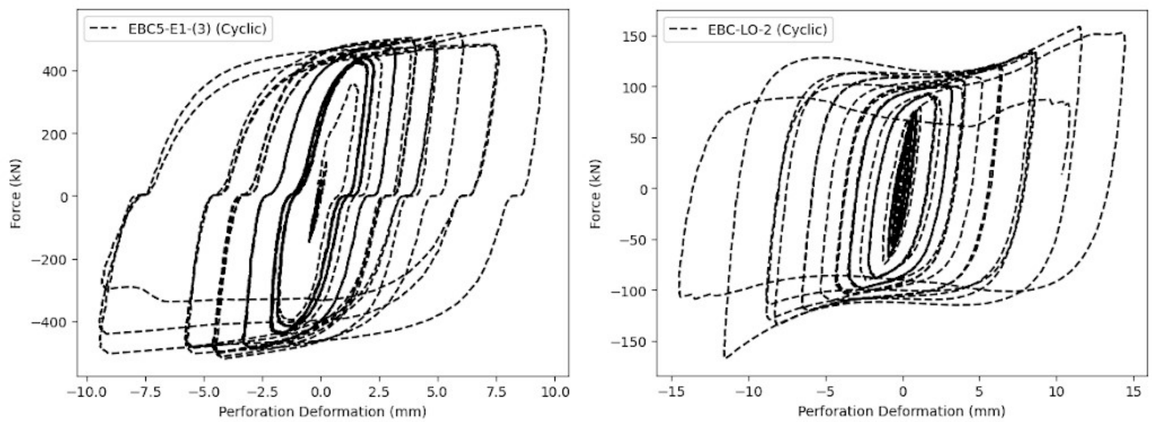
(a) (b)

Figure 7: Images of the experimental program: phase 2 (a) test setup (b) sample specimen: ellipse



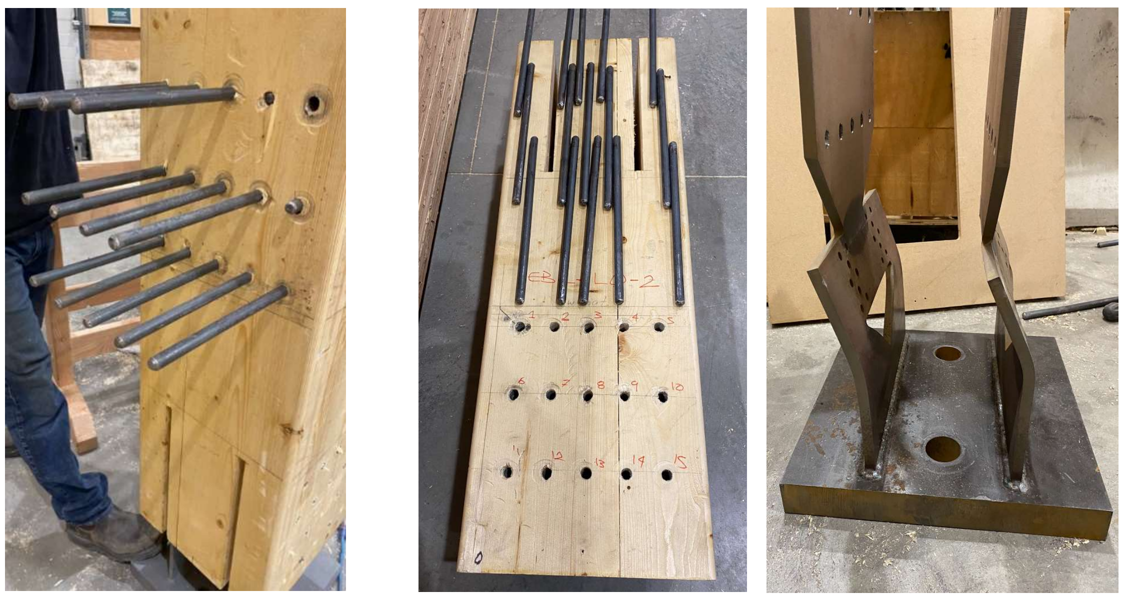
(a) (b)

Figure 8: Images of the experimental program: phase 3 (a) test setup (b) sample specimens: diamond shaped and long slotted.



(a) (b)

Figure 9: Sample total load versus perforation deformation curves: plate tests (a) phase 2 (b) phase 3



(a) (b) (c)

Figure 10: Resiliency in terms of replaceability (Sample specimen from Phase 3)

CONCLUSIONS

This paper summarizes an extensive experimental study on using perforated steel plates as a dissipating energy device, also called a seismic fuse, to enhance the structural performance of timber systems during extreme loading events. The study evaluated the strength, stiffness, ductility, over-strength, and failure mechanisms of the perforated plate in BSC, PPC and HD in CLT shear walls and EBC in TBF. The experimental work was conducted in four phases, including a feasibility study (Phase Zero), an experimental parametric study and loading protocol investigation at fuse scale (Phase One), loading protocol and pattern assessment with full-scale EBC testing (Phase Two), and perforated plate yielding evaluation (Phase Three). In general, the reduced ultimate deformation under cyclic loading remains a technical challenge that needs to be addressed for most of the patterns investigated. The findings suggest that long oval perforations provided the best ductility, energy dissipation, and ultimate deformation performance. The study recommends exploring other yielding mechanisms, such as axial or flexural yielding, to enhance the performance of the fuse under cyclic loading. The evaluated perforated plate patterns provide resilient solutions that could be replaced after failure. Ongoing investigations involve the numerical study of perforated plate fuses, further validation, and evaluation of developed analytical tools for design use, and system performance evaluation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Industrial Research Chair program as well as the Natural Resources Canada (NRCan) through the Green Construction through Wood (GCWood) program. The donation of test materials by Western Archrib and Structurlam is gratefully acknowledged. The support from the technicians from I.F. Morrison Structures Laboratory, C-FER Technologies, and the Wood Innovation Research Laboratory is greatly appreciated. John Spencer and Brian Qi assisted with the testing and data visualization, respectively. Their contributions are acknowledged.

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