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EXPERIMENTAL INVESTIGATION OF AN INNOVATIVE BEAM-TO-COLUMN CONNECTION UNDER CYCLIC LOADING.

Ahmed Mowafy[1], Ali Imanpour[2], Ying Hei Chui[3], Hossein Daneshvar [4]

ABSTRACT: The mechanical behaviour of steel is crucial in hybrid steel-timber systems, especially in areas prone to seismic activity. This paper presents a study of a novel semi-rigid connection that employs U-shaped steel plates as seismic fuses in a beam-to-column connection. The connection aims to introduce self-centring steel braced frames as lateral systems, combined with mass timber structures as a gravity load-resisting system, to enhance their structural performance against earthquakes. The fuses are designed to yield in axial compression or tension, with a bending combination that enables the connection to produce yielding at a specific moment level. The study focuses on the results obtained from cyclic fuse testing, connection testing, and comparing the connections to existing solutions to demonstrate their potential as a reliable and resilient option for mass timber buildings in seismic areas. The findings indicate that the developed connections provide reliable ductile behaviour, and timber elements can be protected from damage through the capacity protection provided by the fuses and their yielding mechanism.

KEYWORDS: Hybrid Structures, Mass Timber buildings, U-shaped plates, Semi-Rigid Connections, Seismic fuses, lateral load resisting systems (LLRS).

1 INTRODUCTION

Timber mass buildings face a unique design challenge due to the need for high-performance connections. In recent years, researchers have focused on improving the behaviour of these connections to enhance the seismic resilience of timber structures. One solution to this issue is to use a pure hinge connection for timber structures that can accommodate drift during seismic events, and steel frames can provide ductility to dissipate seismic energy [1]. Alternatively, the connection itself could dissipate the energy by introducing a steel component with reasonable ductile behaviour. Various types of connections that can dissipate seismic energy have been proposed, such as perforated plates [2], top and seat angle connections[3], wooden elements connected to steel stubs [4], Glulam post-to-beam connections reinforced by dowel-type fasteners [5], connections with three separate steel box sections [6], and prestressed timber beam-column connections[7]. Despite these solutions, the ideal type of connection for timber mass buildings would have replaceable sacrificial elements to reduce downtime and rehabilitation costs, as a lesson learned from the 2010-2011 Christchurch earthquake series [8]. One example is the proposed hybrid moment resisting frame connection with replaceable steel links [9]; however, there are few examples of these advanced replaceable-fuse connections.

This paper presents an innovative beam-to-column connection that uses replaceable U-shaped plates as a source of ductility during an earthquake. U-shaped plates were first introduced by Kelly et al. to provide energy dissipation between structural walls [10]. Incorporating U-shaped plates into the developed connection offers several advantages, including cost-effective fabrication, simple installation and replacement, as well as exceptional inelastic characteristics such as high energy dissipation capacity and fatigue performance [10,11]. The developed connection, shown in Figure 1, consists of two main parts: a pin mechanism located at the centre and replaceable U-shaped fuses situated above and below it.

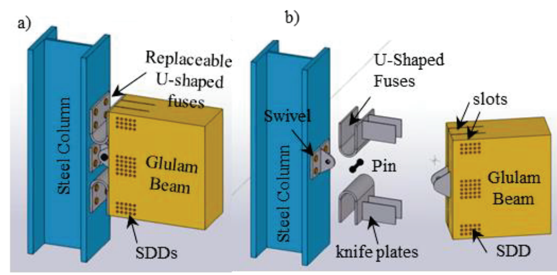

Figure 1: *Developed Beam-to-column Connection: a) Assembled connection b) Disassembled connection.*

All components are connected to the timber beam using two knife steel plates embedded in the timber and attached using self-drilling dowels (SDDs), which are widely used in these forms of connections due to their mechanical properties, including high tensile and shear strength, excellent corrosion resistance, and ductility, as well as their architecturally pleasing appearance. Then the components are connected to the steel column using regular high-strength bolts with ASTM A490 grade [13].

[1] Ahmed Mowafy, University of Alberta, Canada, mowafysa@ualberta.ca
[2] Ali Imanpour University of Alberta, Canada, imanpour@ualberta.ca
[3] Ying Hei Chui, University of Alberta, Canada, yhc@ualberta.ca
[4] Hossein Daneshvar, University of Alberta, Canada, Hossein.daneshvar@ualberta.ca

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The research aims to test the seismic performance of this innovative connection and compare it with other existing solutions to demonstrate its potential as a reliable and resilient option for timber mass buildings in seismic areas.

2 EXPERIMENTAL PROGRAM

Two testing programs, the Fuse-Testing (FT) and Connection Testing (CT) have been developed. The FT program (Figure 2) assesses the inelastic properties of the seismic fuses used in the connection, while the CT program (Figure 3) tests the capacity-protected items in the connection and determines the overall hysteresis response of the connection under cyclic loading. The testing setups, loading procedures, and specimens used for both programs are discussed in this section.

2.1 Fuse Test setup

The FT setup shown in Figure 2 examines two symmetric specimens to avoid introducing eccentric loading to testing machine. The setup includes two identical testing fixtures connected to the uniaxial machine via its grips. Two back-to-back angles are welded to an intermediate plate that is attached to the machine arm for each fixture. The load from the machine is distributed evenly to the fuse legs by distributing plates. The specimens are connected to the distribution plate and ultimately to the horizontal leg angle by four pre-tensioned high-strength steel bolts. Scissor Displacement, which is the relative vertical displacement between the two fuse legs, was measured using four Linear Variable Differential Transformers (LVDTs). The front face and the outside curved surface of the left specimen were monitored through non-contact strain field measurements utilizing Digital Image Correlation (DIC).

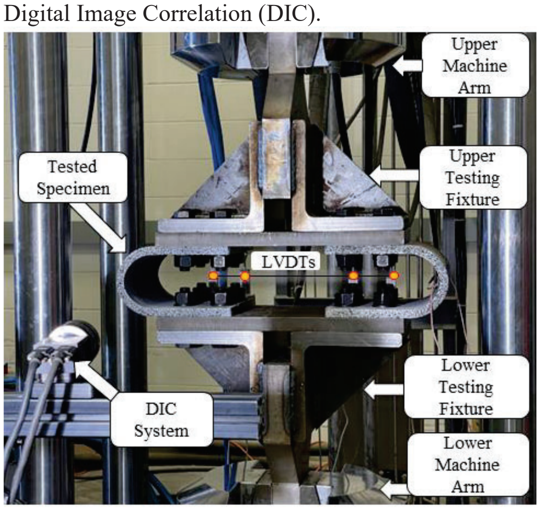

Figure 2: *Fuse-Testing Setup*

2.2 Connection Test setup

The connection testing was carried out at C-FER Technologies, Alberta, Canada, using a reaction wall made of reinforced concrete and a hydraulic actuator with a 300 kN maximum load capacity. A steel beam fastened to a reinforced concrete floor with steel anchors served as a representation of the column component. A load cell in the actuator was used to measure the load, and inclinometers, LVDTs, and potentiometers were installed to quantify connection, rotation, displacement, and lateral movement. DIC technology was used to assess the non-contact strain field.

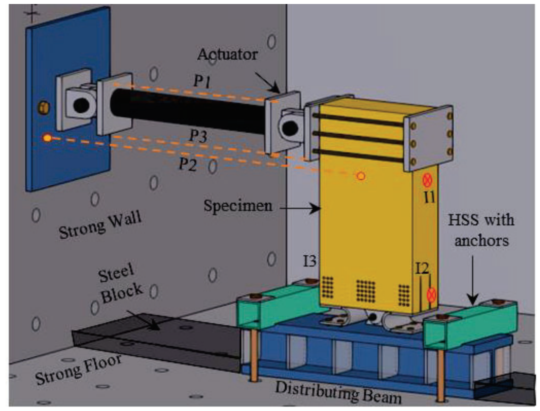

Figure 3: *Proposed Connection-Testing Setup*

2.3 Loading Procedure

Both sets of specimens were tested using the displacement control protocol recommended in FEMA 461 [14] as shown in Figure 4. This involved 26, where each pair of consecutive cycles shares the same amplitude, followed by a gradual increase in amplitude. This protocol was used to induce a 3% storey drift in a hybrid steel-timber structure. For the fuse testing, the cyclic displacement history consisted of 26 cycles to achieve a maximum displacement of 6 mm between the legs, followed by ten additional cycles to reach 20 mm. The maximum scissor displacement was limited to 20 mm to avoid bolt contact. Similarly, cyclic loading protocols were employed for connection testing, consisting of 26 cycles up to 54 mm displacement and ten additional cycles up to 140 mm or until failure. The maximum beam displacement was limited to 144 mm to avoid bolt contact and a 150 mm actuator stroke limit.

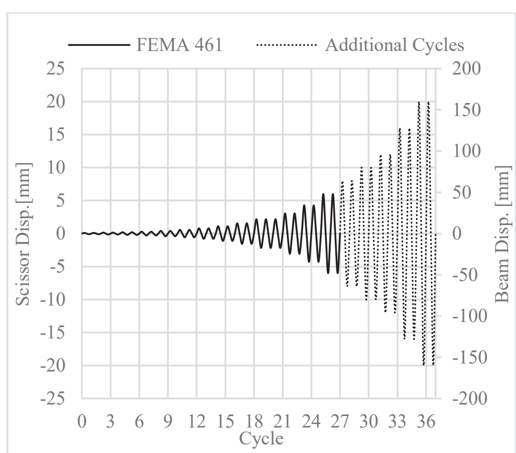

Figure 4: *Loading Protocol*

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2.4 Specimens

The U-shaped plates used as the test specimens for fuses were made of CSA G40.21 300W steel and came in four different thicknesses: 13 mm, 16 mm, 19 mm, and 22 mm for Specimens FT-S1, FT-S2, FT-S3, and FT-S4, respectively. The plates were shaped using a bespoke bender without any heat treatment. For the connection testing, four identical glulam beams with dimensions of 265x608x1150 mm were produced, each to be utilized for a different fuse thickness, as shown in Table 1. The only aspect of the beams that varied was the quantity of Self Drilling Dowels (SDD) employed at the top and bottom portions of each specimen. The predicted maximum shear force during cyclic loading was intended to be supported by the intermediate pin SDDs, with a total number of 25.

Table 1. *Connection Testing (CT) Specimens*

Specimen	Fuse thickness	SDD number per top or lower part
CT-S1	13 mm	20
CT-S2	16 mm	28
CT-S3	19 mm	40
CT-S4	22 mm	50

3 INSIGHT FOR THE TESTING PROGRAM RESULTS

This section describes the results of experimental testing and analysis of timber connections and fuses for seismic-resistant structures. The testing involved the use of fuse and connection specimens, and the results were analyzed based on deformation hysteresis curves, Von Misses strain measurements, and moment-rotation hysteresis responses. This section also includes a discussion of the behaviour of the fuses and connections in tension and compression and a comparison between the behaviour of the fuses in connection testing and fuse testing.

3.1 Fuse Testing

Figure 5 illustrates a deformation hysteresis curve for a chosen fuse specimen 3 (a 19-mm fuse). The fuses exhibited high ductility, enabling them to effectively dissipate seismic energy. Furthermore, the fuses were able to compress up to the expected yielding strength, and all specimens could move their scissor legs up to a maximum distance of 20 mm without fracture. However, the behaviour of the fuses in compression was not identical to that in tension due to the varying boundary conditions. Under tension, the fuse reached a maximum force of 250 kN, while under compression, it reached an even higher maximum force of 340 kN.

Figure 6 illustrates the Von Misses strain measurements at the front face of the fuse at maximum tension (Point a) and maximum compression (Point b). The scale range was set to show the strain values that go beyond yielding, enabling the detection of the plastic zones. During testing, a gap in tension was observed between the fuse leg that ends at the outer bolt edge and the horizontal plate of the testing fixture that applies the loads [Figure 6. a]. On the other hand, complete contact between the plate and the fuse leg occurred during compression [Figure 6. b]. The unloaded fuse seemed to yield at the same load level until full contact was achieved. At this point, the fuse started to accommodate more stiffness until the yielding zone occurred near the full contact edge. Overall, the results suggest that the behaviour of the fuses in compression was not the same as in tension due to various boundary conditions that affected the fuses in each situation. The findings have implications for understanding the behaviour of the fuses and their potential use in seismic-resistant structures.

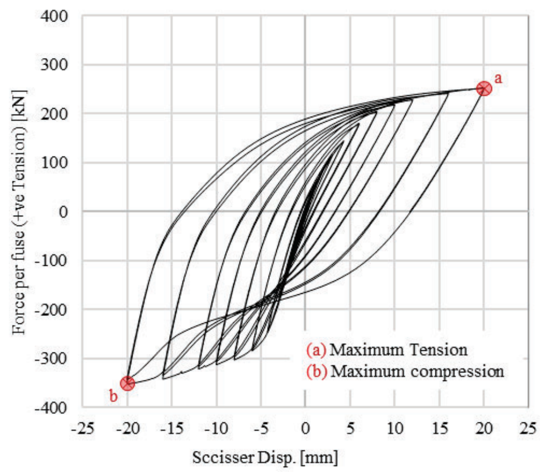

Figure 5: *Fuse Testing* **-** *Sample hysteresis response: FT- S3*

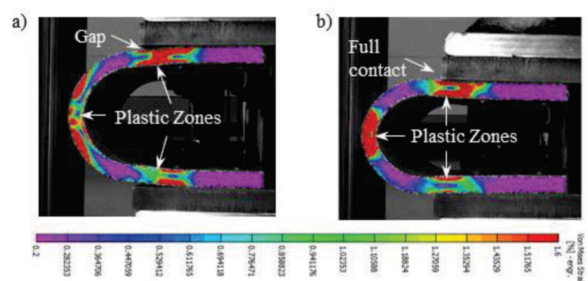

Figure 6: *Fuse Testing – Von Misses Strain measures for Specimen FT-S3: a) Maximum Tension (Point a); b) Maximum Compression (Point b).*

3.2 Connection Testing

In Figure 7, the moment-rotation hysteresis response of the CT-S3 specimen is shown, demonstrating high ductility, good energy dissipation, and no strength degradation in the connections. The overall connection stiffness did not reduce nor exhibit pinching, which suggests that even better ductility could have been achieved if the beam had undergone higher displacement during testing. All specimens followed a consistent pattern and were able to reach the maximum rotation level

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without global failure. No significant out-of-plane deformations were captured. The ultimate moment for CT-S1, CT-S2, CT-S3, and CT-S4 specimens as 32, 48, 72, and 92 kN, respectively.

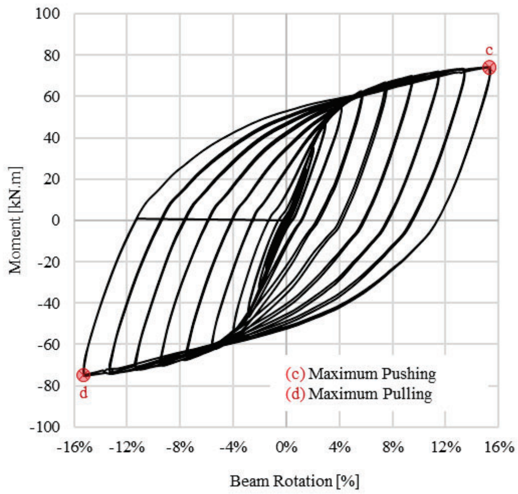

Figure 7: *Connection Testing – Sample hysteresis response: CT- S3*

Figure 8.and Figure 8.b showcase the CT-S3 specimen at maximum pushing (Point c) and pulling (Point d) during testing, respectively. As demonstrated, no splitting cracks emerged in the glulam beam specimens during testing. In Figure 9, the DIC strain measurements at the front view of both fuses in tension and compression utilized in the connection at maximum pushing (Point c) are presented. The plastic zones, in this case, were more concentrated at the mid-bent of the fuse rather than the legs.

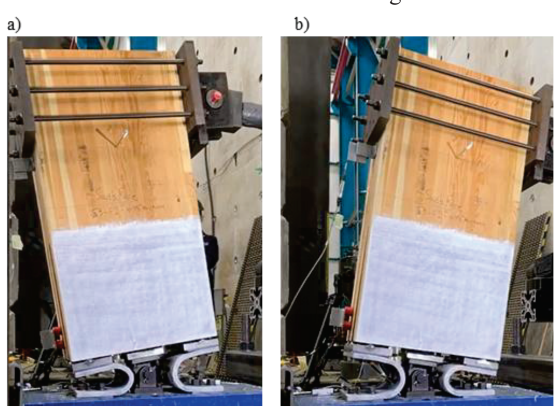

Figure 8: *Connection Testing – Specimen CT-S3 deformations: a) maximum rotation at pushing (Point c); b) maximum rotation at pulling (Point d).*

3.3 Comparison between Fuse behaviour in Fuse testing and connection testing

On analyzing the behaviour of fuses in connection testing (Figure 10.a) and fuse testing (Figure 10.b) under compression, a significant difference was observed. In connection testing, the fuse leg is allowed to rotate, while in fuse testing, it is fixed. Consequently, the plastic zones in connection testing (Figure 10.c) are more prominently concentrated at the mid-bent of the fuse than at the contact points of the fuse leg end. On the other hand, in fuse testing (Figure 6), the legs are more actively engaged due to the testing fixture forcing the legs to remain straight.

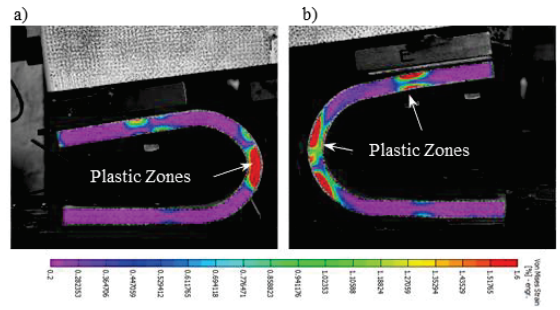

Figure 9: *DIC Von Misses Strain measures at maximum pushing (point c): a) Compressive Fuse; b) Tensile Fuse.*

This difference arises because the connection rotation matches the deformed shape of the fuse if it is compressed freely in the perpendicular direction to its legs. However, in fuse testing, the legs are constrained, and thus the deformation pattern is different. Moreover, the gap that was observed during tension in the connection testing fuses did not completely close during compression due to the residual deformations introduced in the fuse leg during tension. Therefore, the inelastic properties of the tensile fuse dominate the overall hysteresis performance of the connection, and a symmetric hysteresis response can be easily developed, which is not the case in fuse testing.

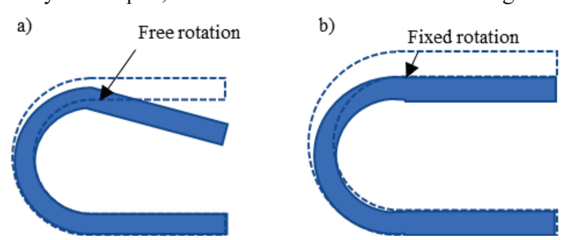

Figure 10: *Deformed shapes of fuses: a) Connection Testing; b) Fuse Testing.*

In conclusion, the testing results demonstrate the importance of considering the effects of connection rotation and leg deformation when evaluating timber connection performance. The observed ability of the fuse leg to rotate freely during connection testing resulted in a distinct deformation pattern and a concentrated plastic zone at the mid-bend of the fuse. This, combined with the inelastic properties of the tensile fuse, facilitated the development of a symmetric hysteresis response. However, using the results of fuse testing to ensure the capacity design of the connection remains valid is a more conservative approach. These findings have significant implications for the design and evaluation of timber connections, potentially leading to the development of more efficient and reliable structural systems.

4 Connection Evaluation

The connection evaluation is done by comparing its characteristics to some of the existing solutions. These characteristics include ductility factor, μ, ultimate moment, M_u and failure mode. Table 2 shows the tests used in this comparison along with the beam cross-section and the failure mode shown in each one.

Table 2. *Comparison test results with previous connection tests*

Connection	Beam Cross Section	Failure mode
Developed connection (2023)	608×265	Ductile U-shape yielding
Dong et al (2021) [15]	450×315	Ductile Dowel Yielding
Karagiannis et al.(2017) [16]	280×140	a bolt-row shear failure
He et al.(2017) [17]	260×130	Wood Splitting
He and Liu(2015) [5]	300×200	Ductile rod yielding
Lam et al.(2010) [18]	304×130	Splitting

Figure 11 provides a visual representation of the relationship between two critical factors in connection design. The chart is divided into several zones, each representing a different type of connection performance based on the compromise between ductility and ultimate moment. The horizontal axis represents ductility, a measure of how much a material can deform before fracturing. The vertical axis represents the strength ratio, which is the ultimate moment divided by the yielding moment of a connection used to measure the connections' ability to resist external loads and stresses without failing. The chart is divided into several regions or zones, each representing a different type of connection performance. The zone in the upper right corner represents the ideal connection design, characterized by high ductility and high ultimate moment. Other zones represent various levels of compromise between ductility and strength ratio, such as connections with lower ductility but a higher strength ratio or vice versa. The chart provides a valuable tool for engineers and designers to optimize connection design based on their specific needs and constraints.

The ductility factor(μ) plays a crucial role in determining the behaviour of a structural element under seismic loading conditions. As per the EN12512 [19] guidelines, μ is calculated using Equation (1):

$$\boldsymbol{\mu = \theta_u/\theta_y} \quad (1)$$

Where θ_u represents the rotation at ultimate moment capacity, and θ_y is the rotation at yielding. Based on the value of μ, the structural element is categorized as brittle (μ ≤ 2), low ductility (2 < μ ≤ 4), moderate ductility (4 < μ ≤ 6), or high ductility (μ > 6), according to Smith et al.'s categorization of Timber connections [20]. This classification helps in selecting the appropriate connection design for seismic-resistant structures based on the desired ductility and ultimate moment capacity. the ductility factor is calculated based on the average of tested specimens. In cases where there are multiple groups, the average of the strongest group is considered. For determining the ultimate moment capacity, the average value of tested specimen is used, except for the cases with no replicates, where the most robust specimen represents each study, as is the case for our developed connection.

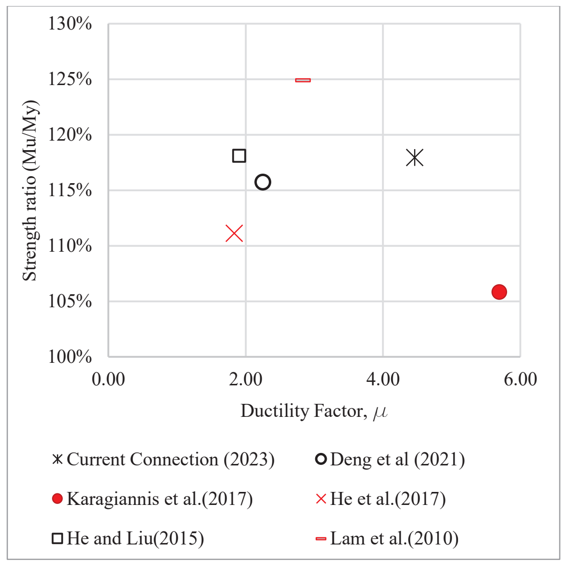

Figure 11: *Optimization chart used in the comparison between the developed connection and samples from existing solutions.*

The chart (Figure 11) clearly indicates that the developed connection is located in a favourable position. It exhibits higher ductility than the connection with the highest strength ratio presented by Lam et al. (2010) [18] and a higher strength ratio than the connection with the highest ductility factor introduced by Karagiannis et al. (2017) [16]. It is noteworthy that all the connections with a red colour legend in the chart have a brittle failure mode, such as plug shear, splitting, or bolt-row shear failure. Thus, by excluding these connections that failed in a brittle manner from the chart, the developed connection would be an ideal solution. Moreover, the developed connection offers a unique advantage in that it is the only one among the represented solutions that feature easy-to-replace fuses. This feature sets it apart from other connections and makes it a superior choice for multiple applications.

5 SUMMARY AND CONCLUSIONS

This study describes the experimental program developed to evaluate the cyclic response of a steel timber beam-to-column connection for seismic-resistant design. The testing program includes fuse testing and connection testing, which are used to determine the inelastic

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mechanisms of seismic fuses and the connection. The results of the experimental testing are presented, including overall connection response, von Misses strain demands, and moment-rotation hysteresis responses. The fuses demonstrated a high capacity for dissipating seismic energy, and the connections were capable of resisting significant cyclic demands (in the order of 8% drift ratio) without brittle failure. The proposed connections demonstrated a comparative performance in terms of overstrength and deformation capacities in comparison with similar timber connections developed in the past. Overall, the experimental program provides valuable insight into the cyclic behaviour of U-shaped fuses implemented into beam to column connections of timber structures in tension and compression and provides a basis for future research in this field.

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