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LARGE-SCALE TESTING OF A REPLACEABLE CONNECTION FOR CONCENTRICALLY BRACED FRAMES

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Abstract

With an increased focus on seismic resilience, there is an increasing desire among engineers and clients for structures that can be rapidly returned to occupancy following an earthquake while maintaining or reducing initial construction costs. One avenue towards this goal is to ensure that seismic damage occurs only within elements that can be easily removed and replaced following a damaging earthquake. For concentrically braced frames that use hollow structural sections, current design practice requires field welding of the slotted brace to the gusset plate. The expected behavior of this connection causes damage to the gusset plate when the brace buckles out-of-plane, which is expensive and time consuming to replace. The out-of-plane brace buckling caused by this connection can also damage surrounding walls and cladding. An alternative connection has recently been proposed that can be bolted into place and that is intended to confine seismic damage to easily replaceable components. The proposed connection is expected to result in reduced erection costs by avoiding site welding, and also to simplify repair following a major earthquake because the damaged brace could be replaced without cutting welds or field welding new components. Additionally, the new connection causes the brace to buckle in-plane during a seismic event, minimizing damage to the surrounding walls and cladding. This paper discusses the first large-scale testing of the proposed new connection, performed at McMaster University. The numerical results and visual observations of three brace tests are discussed. All three braces buckled in plane and had the same failure progression as other experimentally tested concentrically braced frame connections. Bolt slip was found to have very little effect on the overall force-deflection curves due to the brace compressive strength degrading below the slip load. The results indicate that the proposed new connection shows promise as an alternative for the performance-based design of concentrically braced frames.

Keywords: concentrically braced frames; replaceable bolted connections; experimental testing

1. Introduction

Concentrically braced frames (CBFs) are commonly used as steel lateral force resisting systems throughout North America, including in regions of high seismicity. CBFs have the high strength and stiffness that are needed for them to be serviceable under wind loads and smaller earthquakes. During rare large earthquakes, CBFs dissipate energy primarily through tensile yielding and nonlinear postbuckling behaviour of the braces. The inelastic deformation is intended to ensure life safety and collapse prevention during these extreme events. Hollow structural sections are commonly used as braces because their high compressive resistance results in a well-balanced response between paired braces.

Although the brace is the primary member in the design, the connections play a critical role in enabling the brace to dissipate seismic energy. To accommodate brace buckling, connections must be designed to allow multiple cycles of brace end rotation without fracture. Gusset plate connections typically do this using a linear or elliptical clearance rule, as shown in Fig.1 [1]. When using HSS braces, the brace is typically slotted and welded directly to the gusset plate, which requires site welding that can increase costs and complicate quality control. Furthermore, if the brace and gusset plate are damaged during a major earthquake, replacing them would require cutting out the gusset plate, welding a new plate on site and welding a new brace to the gusset on site. This would likely be an expensive and time consuming process, thus delaying the building's return to safe occupancy.

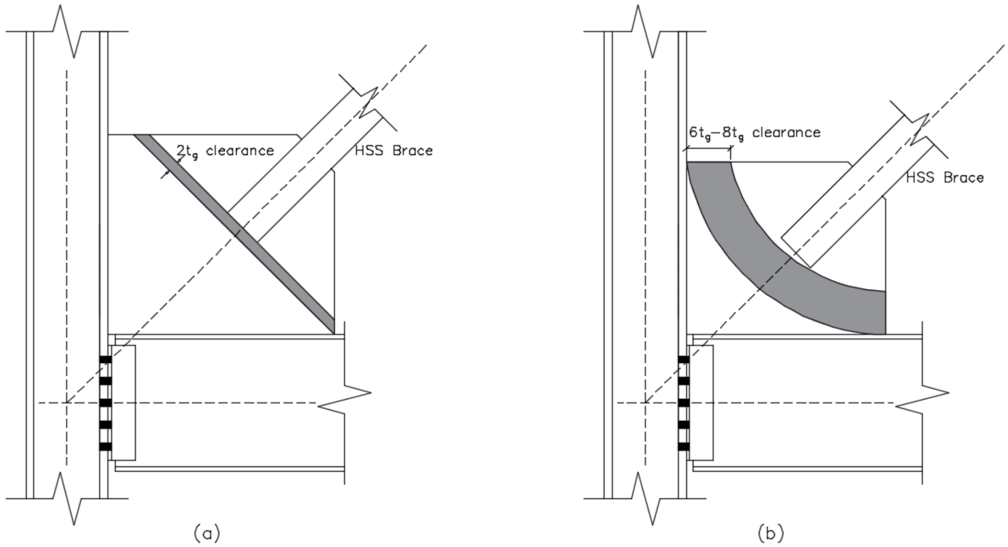


Fig. 1 – Typical CBF gusset plate designs: (a) Linear clearance rule; (b) Elliptical clearance rule

When the brace buckles during a major earthquake, typical gusset plate connections will cause buckling to occur out of plane. The out-of-plane displacement can be very large, with testing showing over 400 mm of displacement before brace fracture occurs [2]. This out-of-plane displacement can cause exterior cladding to fall off the building, endangering the lives of people evacuating the building and of other pedestrians. If the cladding is strong enough to restrict buckling, the expected behaviour of the system will change [3]. This could impact a number of design assumptions and cause the system to fail in a less desirable manner, such as gusset plate buckling due to the unexpectedly high compression force.

In order to address these issues, a new replaceable connection for concentrically braced frames is being developed. The intent of this connection is to meet the following three criteria:

1. The new connection design should be easy to install and easy to replace in the event of damage. To facilitate this, the connection should not require any field welding. If the brace is damaged in an earthquake, the damage should be confined to a region that can be unbolted and replaced as a unit.
2. It should allow the brace to buckle in-plane to minimize damage to the surrounding walls and cladding.
3. It should provide comparable seismic performance to the current design practice. This includes similar yield and failure progression and similar energy dissipation behaviour.

The purpose of this paper is to present the concept and first large-scale tests of the new connection design. The new design is explained and key design criteria are addressed with further details on concept development and finite element modelling available in [4]. The lab program and setup are presented, together with preliminary results. These results are then evaluated in order to draw conclusions about the expected performance of the connection. Plans for future testing and development of the new connection design are also discussed.

2. Proposed New Design

Fig.2 shows the new connection design that was proposed to address the issues identified above. In this design, a hinge plate is welded to a slotted HSS and is then bolted to support plates that have been welded to the beam flange in the fabrication shop. This connection would be relatively easy to install due to the simple single splice bolted connection. The support plates are intended to be sufficiently stiff that rotation is confined to the hinge plate, such that the damage would be contained to easily replaceable components. The rotated hinge plate ensures that the brace will buckle in-plane, minimizing damage to the surrounding walls and cladding.

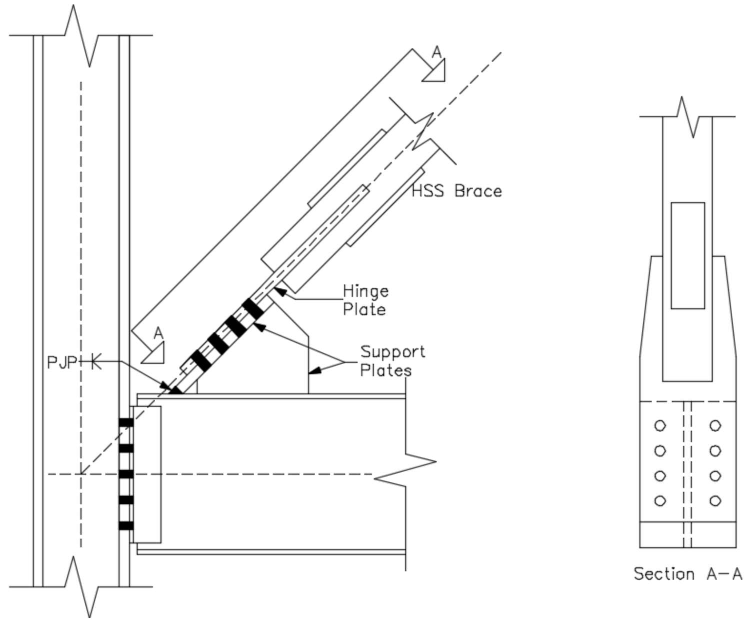


Fig. 2 – Proposed connection design

The proposed new connection has some key design criteria that differ from conventional connections. The first is that the hinge plate should be narrower than the connected beam flange width, so as to not interfere with surrounding elements. This requirement results in a thicker plate than typical gusset plates because the plate cannot generally utilize a full Whitmore width for resisting tensile loading. A thick plate is further required because of the eccentricity in the single sided connection. The connection must be designed for the combined compression and moment caused by this eccentricity so that failure does not occur in the connection before buckling occurs in the brace, as this would significantly reduce the compressive resistance of the system.

The support plates of the connection must confine rotation to the hinge plate, not only to ensure that the damage is contained to easily replaceable components, but also to ensure that the connection does not create an undesirable buckling mechanism. Due to the configuration of the connection within a braced bay, the hinge plates at either end of the brace will rotate in different ways; Fig.3 shows the difference in rotation at either end of the brace. It is important that an appropriate hinge clearance length is chosen that will allow the rotations in Fig.3 without causing the undesirable buckling mechanisms or early fracture of the hinge plates.

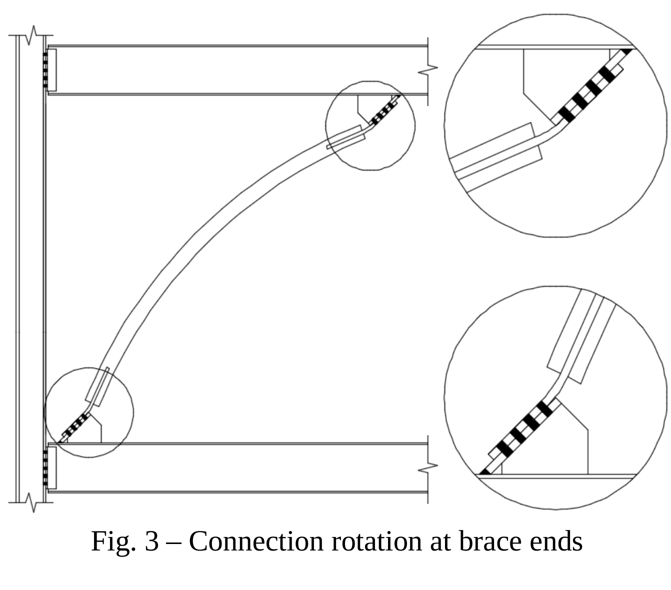


Fig. 3 – Connection rotation at brace ends

3. Laboratory Program and Setup

This section describes the first tests within a laboratory program that was developed to test the ability of the proposed connection to provide the desired benefits while also maintaining the performance of a conventional connection. The key issues that the experimental tests were designed to assess were whether a brace with the new connection would exhibit a similar yield and failure progression as what has been reported in the literature for conventional brace connection designs, in addition to providing comparable energy dissipation and ductility.

The test was designed to test the region of a braced bay highlighted in Fig.4. As shown in Fig.5, the brace was rotated 45 degrees and tested vertically between connections that were designed to simulate the end connections. The triangular boxes used at either end of the brace were designed to behave elastically during testing so that they could be used for multiple brace tests. The test frame applies reversed cyclic axial displacements.

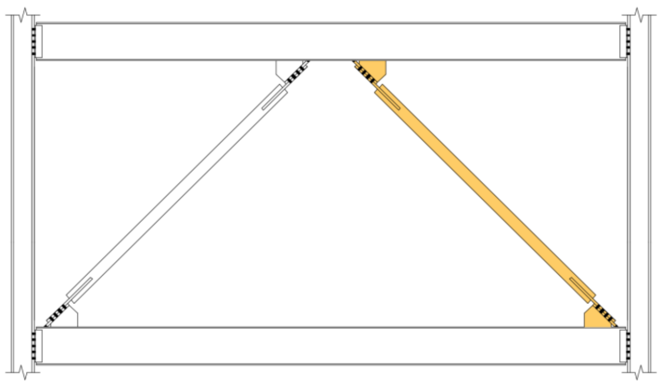


Fig. 4 – Testing region

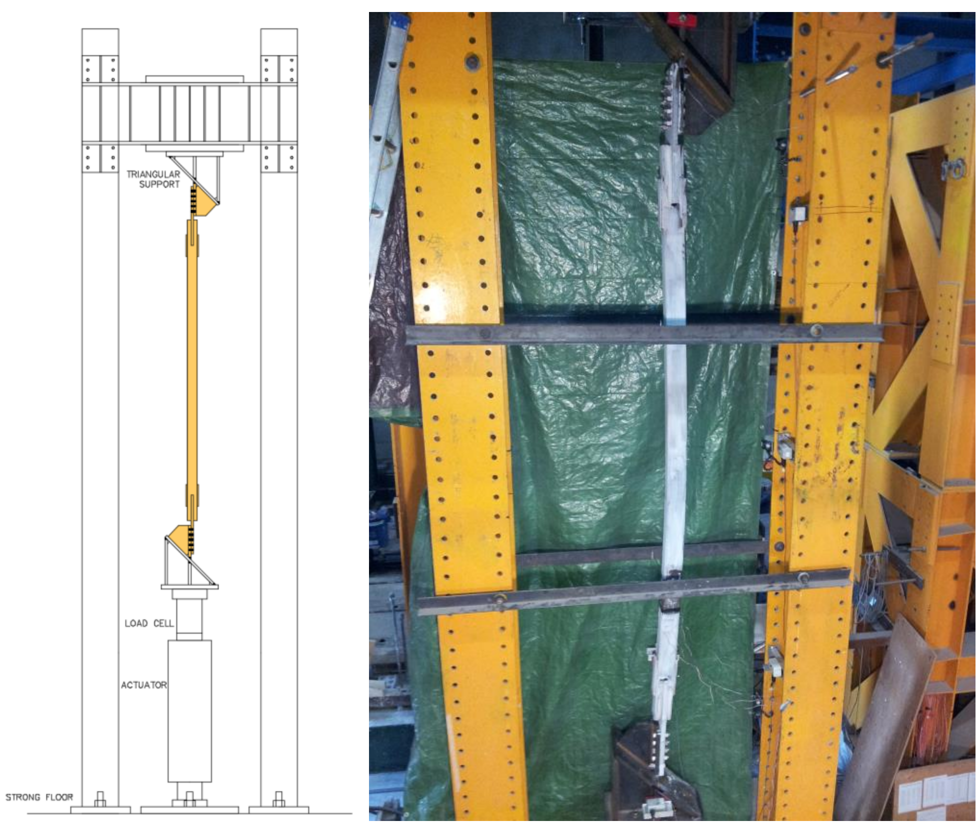


Figure 5 – Test frame

3.1 Loading Protocol and Instrumentation

Loading was applied to the specimens axially by an actuator that was secured to the strong floor. The loading was applied cyclically and quasi-statically following the ATC-24 testing protocol [5]. Fig.6 shows the typical deformation history that is applied in increments of yield drift, Δ_y, defined as the displacement at which first buckling occurs. If the brace did not fracture after the end of the protocol, then paired cycles at +1 Δ_y of the previous displacement were performed until failure. The applied load was measured by a load cell connected to the actuator. Axial displacements and deflections along the brace length were measured using string potentiometers, while strain gauges were used on the brace and connections to identify how the stresses were distributed.

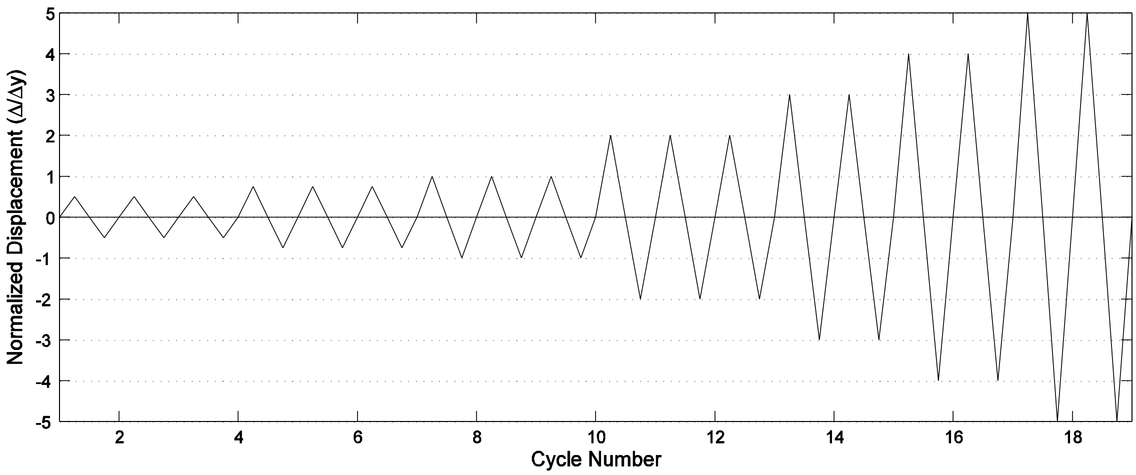


Figure 6 – Load protocol

3.2 Tested Specimens

In this phase of testing, three different specimens were tested with variations in section size and hinge plate clearance distance. All braces tested were G40.21 350W Class C square hollow structural sections. The hinge plates were made with 350W steel and the bolts used were ¾" A325. Fig.7 and Table 1 summarize the dimensions and differences between each sample tested.

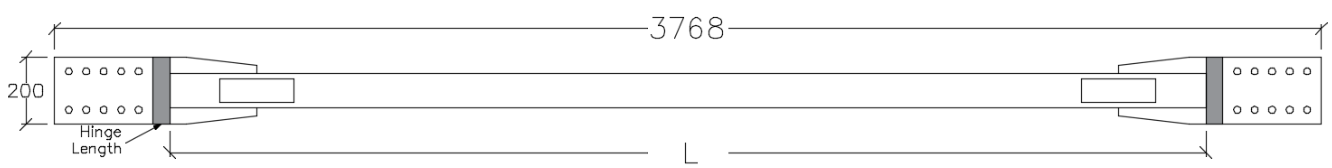


Figure 7 – Specimen diagram (units in mm)

Table 1 – Specimen Information

Specimen Number	Brace Shape	Total Specimen Length (mm)	Brace Length, L (mm)	Hinge Plate Thickness, t (mm)	Hinge Length (mm)	Material Yield Strength (MPa)
1	HSS 89x89x6.4	3768	3200	19	2t = 38	459
2	HSS 102x102x6.4	3768	3097	25	2t = 50	444
3	HSS 102x102x6.4	3768	3082	25	3t = 75	444

4. Results

The measured force deflection curves from the cyclic loading can be found in Fig.8. The normalized displacements used in the force-deflection curves are taken from just outside the support plates at either end of the brace. This location was chosen as it includes the deflections caused by plate rotation and bolt slip that would most closely reflect the response of the brace unit in a full frame. Geometrically, the resulting peak compressive and tension displacements are roughly equivalent to storey drifts of -2.8% to +2.4% drift for test specimen 1, and storey drifts of -2.1% to +1.6% drift for test specimens 2 and 3. This is within the range of values commonly found in previous experimental studies using a conventional CBF connection [6] [7].

The peak buckling loads for each test specimen were found to be 451kN, 605kN, and 590kN respectively. Using the flexural buckling equations found in CSA standard S16-14 [8], assuming a Class C section and substituting the real yield stress of the steel and the total brace length and the L, experimental effective length factors (K) of 0.8, 0.77 and 0.79 are found for the three specimens. Predicted and experimental buckling data are summarized in Table 2.

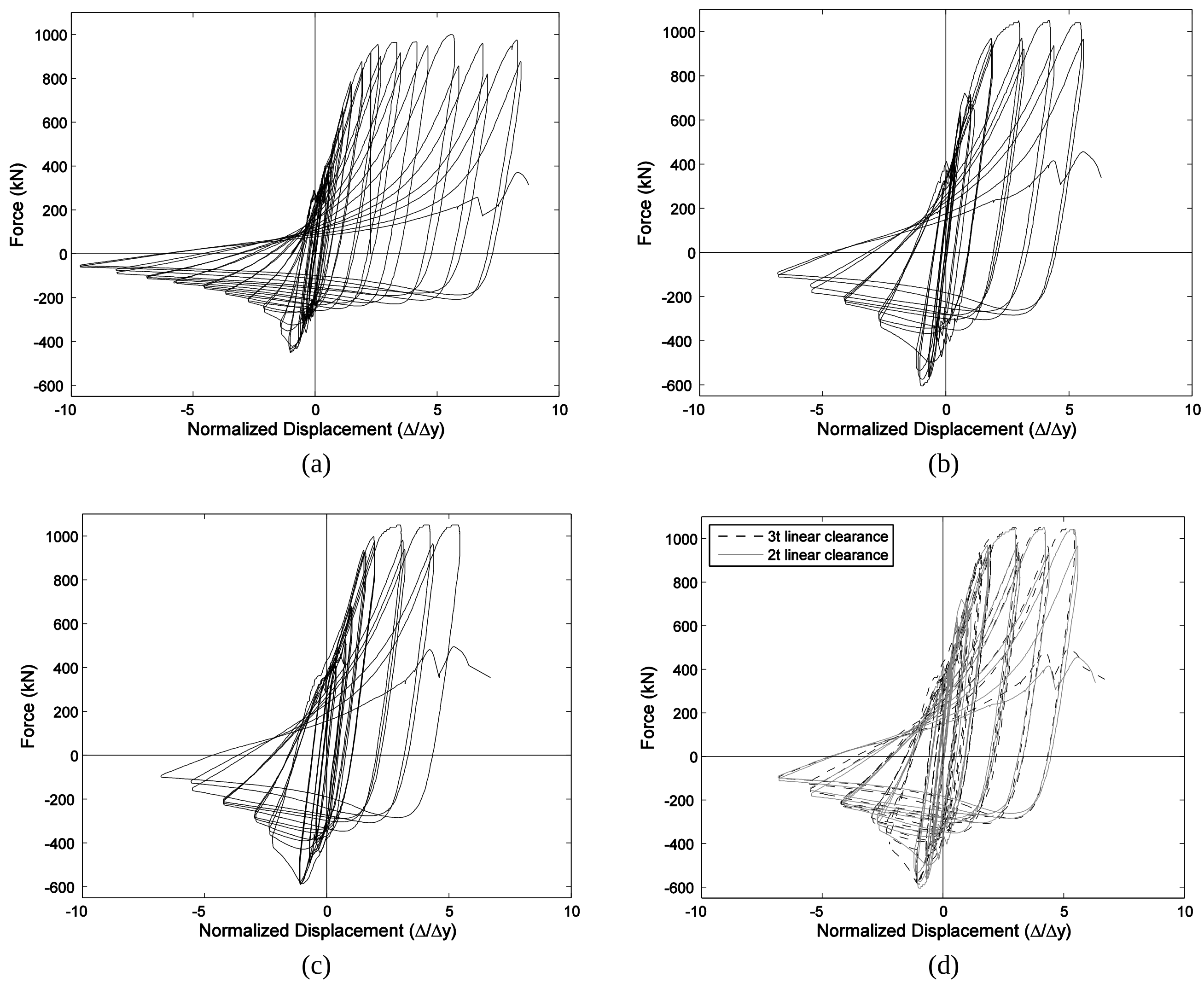


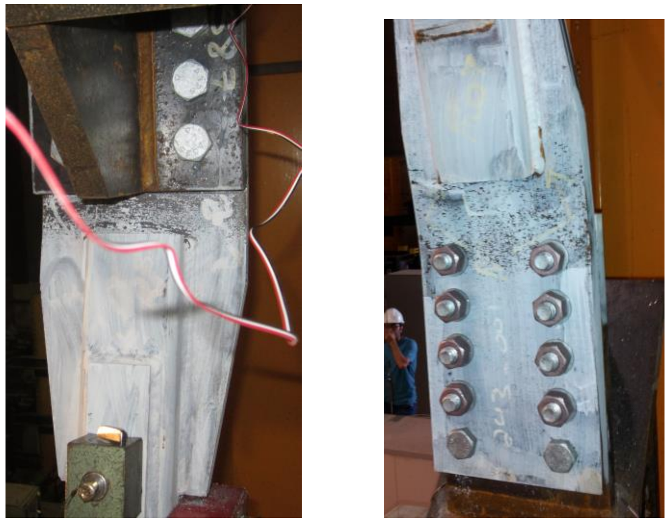
Fig. 8 – Cyclic force-deflection curves: (a) Test specimen 1; (b) Test specimen 2; (c) Test specimen 3; (d) Test specimens 2 (2t clearance) and 3 (3t clearance)

Table 2 – Predicted and experimental buckling data

Specimen Number	Predicted Effective Length Factor, K	Experimental Effective Length Factor, K	Predicted Buckling Load (kN)	Experimental Buckling Load (kN)
1	0.81	0.8	439	451
2	0.77	0.77	604	605
3	0.77	0.79	604	590

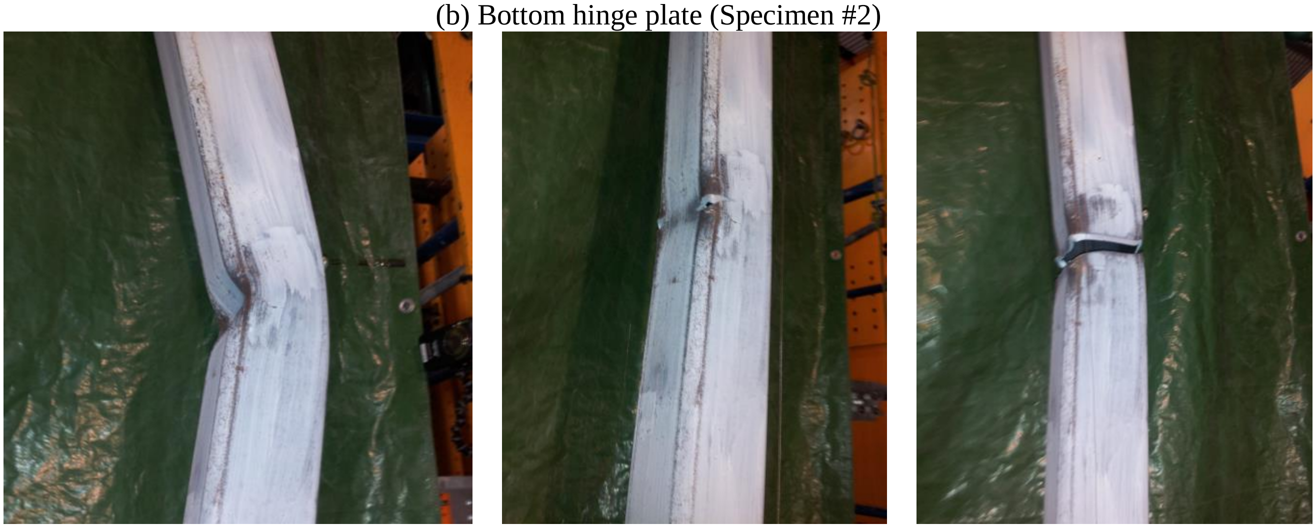
All three tests experienced yielding and failure in the intended regions. The brace yielded in tension and buckled in compression with no undesirable buckling mode. Fig.9 shows the rotation of the hinge plates that occurs as the brace end buckles. Yielding in the top hinge plate was confined to the region between the brace end and the bottom of the support plate, as seen in Fig.10(a). Yielding in the bottom plate was spread over a larger area, with the largest yielding occurring along the centerline of the first row of bolts, as seen in Fig.10(b). No tears or major damage occurred in the hinge plates or the hinge to brace welds. Due to the thickness of the hinge plate, the bolt holes had no identifiable ovalization. All three tests failed due to fracture of the brace in the midspan. In all three tests, the brace experienced significant local buckling in the compression cycle and then tore in the following tension cycle, as seen in Fig.11. This is consistent with the brace failure sequence that is observed with more conventional connections [6].

Fig. 9 – Rotation in the hinge plates under peak compressive displacement (Specimen #2)



(a) (b)

Fig. 10 – Rotation in the hinge plates under peak compressive displacement: (a) Top hinge plate (Specimen #1); (b) Bottom hinge plate (Specimen #2)



(a) (b) (c)

Fig. 11 – Brace failure progression (Specimen #2): (a) Significant local buckling; (b) Tensile tears form; (c) Complete fracture

5. Discussion

As mentioned previously, the drift ranges of all three specimens were within the normal range for experimentally tested CBFs. However, test specimen 1 reached significantly higher drift values than the other two specimens. Local buckling occurred in the midspan of the brace much earlier for specimens 2 and 3 leading to the earlier fracture. The likely cause of the difference in drift range is the difference in the width to thickness ratios of specimen 1 ($b/t = 10.9$) and specimens 2 and 3 ($b/t = 12.9$). Although specimens 2 and 3 marginally passed the AISC criteria for a highly ductile member based on their nominal yield strength ($b/t < 13.1$), they do not pass the criteria when their true yield strength is considered ($b/t < 11.6$) [9].

The peak buckling forces were higher than what would be calculated assuming an effective buckling length (KL) equal to the brace length. This is due to the thick hinge plates providing significant rotational restraint to the brace ends. Estimated values of KL using the relative moment resistances of the brace and hinge plates, as seen in Fig.12, accurately predict the effective buckling lengths that were found during the experiment, as seen in Table 2 [10].

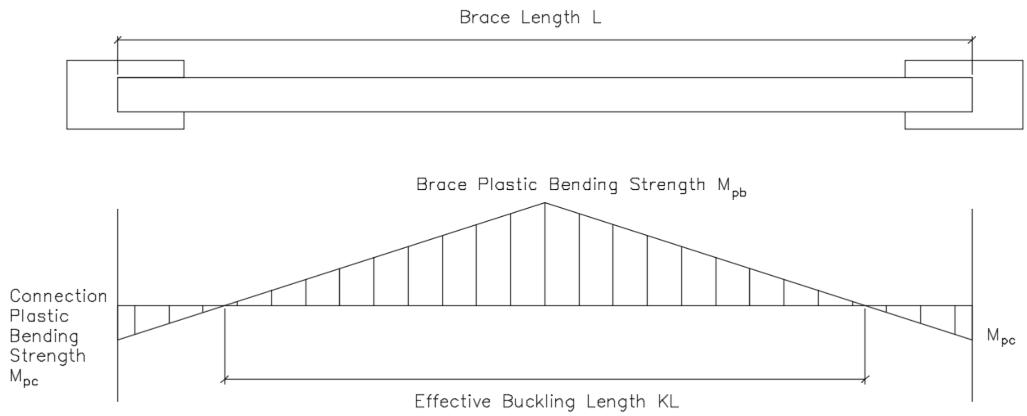


Fig. 12 – Determination of effective buckling length factor K

Although the hinge plates did rotate and yield, there appeared to be significant ductility capacity remaining in the plates after brace fracture. Based on visual inspections of damage, it appears that the plates could have sustained many more nonlinear cycles had the brace not fractured, especially for specimens 2 and 3. This meant that the brace ultimate strength and ductility dominated the system behavior, and is likely why there was almost no difference in performance between specimens 2 and 3 as seen in Fig.8(d). This suggests that all tested hinge plates were conservatively designed to achieve the required performance of the brace under compression.

An additional point to discuss is the slipping of the bolts in tension and compression. The bolts were pretensioned but the connection was not designed to prevent slip before yielding due to the large number of bolts that this would require. This meant that bolt slippage occurred during the first few cycles before and after first yield. However, after the brace compressive strength deteriorated below the slip load, significant bolt slip no longer occurred because the brace had fully slipped in tension and the brace always buckled before reaching the slip load in compression. The influence of bolt slip is almost imperceptible in the full force deflection curves in Fig. 9, but it is noticeable in the force-deflection curve at low amplitudes, as seen in Fig.13.

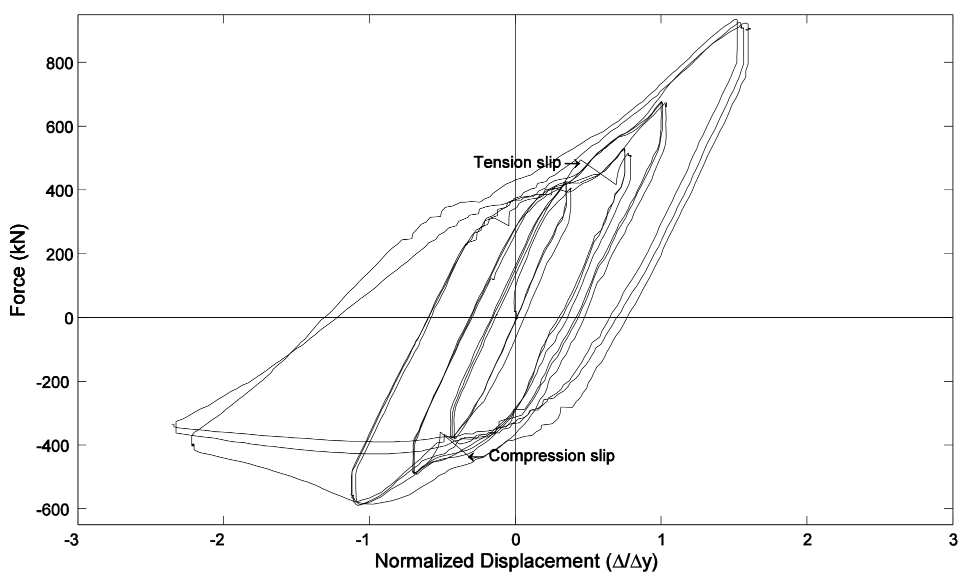


Fig.13 – Bolt slip at low displacements (Specimen #3)

6. Conclusions and Future Work

The experimental program presented here was the first large-scale testing of a new replaceable connection for concentrically braced frames. This study focused on the global performance of a brace and connection under quasi-static axial loading. The study tested two different brace sizes and two different hinge plate linear clearances. The study indicates that:

- The new connection design ensures that brace buckling occurs in-plane at that damage is confined to an easily replaceable assembly.
- The new connection provides comparable brace performance to conventional connections.
- Assuming that the effective buckling length is equal to the brace length underestimates the actual buckling load. This is due to the thick hinge plates providing more rotational stiffness than a typical gusset plate. Instead, the effective buckling length should be determined by using the relative plastic moment capacities of the brace and hinge plate.
- Changing the hinge plate linear clearance length from 2t to 3t had little impact on the system performance for the brace size and plate thickness that was tested. However, more tests would be required to determine an optimal clearance rule.
- Bolt slip had very little effect on the force-deflection curves, except at lower displacement amplitudes before significant energy dissipation occurs. This is because the bolts do not slip in either direction after the brace compressive strength has degraded to less than the slip load.
- The new connection shows promise as an alternative for the performance-based design of concentrically braced frames.

More research is required to continue developing the proposed new connection. Continued experimental testing using the existing laboratory setup will help to answer questions about ideal hinge plate thickness and linear clearance rules. Large scale testing of complete braced bays is also needed to evaluate the overall system-level behavior of a frame with the proposed connection detail.

7. Acknowledgements

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