DEVELOPMENT OF A NOVEL REPLACEABLE CONNECTION FOR SEISMICALLY DESIGNED STEEL CONCENTRICALLY BRACED FRAMES

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ABSTRACT

There is increasing demand, from both engineers and their clients, for structures that can be rapidly returned to occupancy following an earthquake, while also maintaining or reducing initial costs. One possible way towards this goal is to ensure that seismic damage occurs only within elements that can be removed and replaced following a damaging earthquake. For concentrically braced frames that use hollow structural sections, the current design practice requires field welding of the brace to the gusset in a way that causes the brace to buckle out-of-plane. In the event of a damaging earthquake, the out-of-plane brace buckling may damage both the gusset plate and any adjacent exterior cladding. The plate cannot be easily replaced, resulting in expensive and time-consuming repairs, and the damaged cladding could endanger the lives of people evacuating the building and of other pedestrians. This paper discusses the development of an alternative connection that can be bolted into place and that confines damage to replaceable components. The proposed connection is expected to result in reduced erection costs and be easier to repair following a major earthquake. Moreover, the new connection causes buckling to occur in plane, preventing dangerous damage to the cladding. Potential challenges in the design of such a connection are discussed and evaluated, and a finite element model that was created to confirm the performance of the proposed connection is also introduced. Finally, future areas of research and development of the connection are identified.

Keywords: Earthquake Engineering, Concentrically Braced Frames, Replaceable Bolted Connections

1. INTRODUCTION

Steel concentrically braced frames (CBFs) are a commonly used lateral force resisting system in moderate and high seismic areas in North America. CBFs have the high strength and stiffness needed to be serviceable under wind loads and smaller earthquakes. During larger, infrequent earthquakes, CBFs dissipate energy primarily through nonlinear tensile yielding and postbuckling behaviour of the braces. The inelastic deformation is meant to provide life safety and collapse prevention during these major events. Hollow structural sections are commonly used as braces due to their high compressive resistance that 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 allowing the brace to dissipate the seismic energy. To accommodate brace buckling, connections must be either designed to allow for brace end rotation or designed as fully restrained. In practice, gusset plate connections typically allow brace end rotation using a linear or, more recently, an elliptical clearance rule that allows the brace to buckle out of plane, as shown in Figure 1 (Lehman et al. 2008). When using HSS braces, the brace is typically slotted and welded directly to the gusset plate. This requires welding on site, which can increase costs and complicate quality control. Additionally, if the brace and gusset plate are damaged during a major seismic event, replacing the brace and gusset would require cutting out the gusset plate, welding a new plate on site and welding a new brace to the gusset on site. These processes would be expensive and time consuming, delaying the building’s return to safe occupancy.
Figure 1: Typical CBF gusset plate designs: (a) Linear clearance rule; (b) Elliptical clearance rule

When the brace buckles during a major earthquake, the typical gusset plate connection 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 (Tsai et al. 2013). 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 (Sen et al. 2013). 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.

Some research has been done on creating connections that are easily replaceable or that will reliably ensure that buckling occurs in plane, but little work has been done on providing a solution that would reliably solve both problems (Kotulka 2007, Sen et al. 2013). This paper discusses the development of an alternative connection that can address these issues. The objectives of the proposed new design are presented and several design iterations are investigated. The proposed new design is explained with a focus on its benefits and the unique criteria that must be addressed when designing the new connection. A preliminary finite element model was created and is introduced. Future areas of research and next steps are also discussed.

2. OBJECTIVES OF PROPOSED NEW DESIGN

To find a solution to the issues presented, a clear set of objectives needed to be created. Each iteration of the design needed to meet these objectives. The objectives of the proposed new design were as follows:

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.
3. DESIGN ITERATIONS

In order to meet the proposed objectives, several different connection designs and details were created and evaluated. Initial designs focused on modifying a knife plate design that has been investigated in previous studies (Tsai et al. 2013). When using a knife plate, most of the yielding and rotation that would otherwise occur in the gusset plate occurs in the knife plate instead. Typically, the knife plate is slotted and welded directly to the gusset plate. Figure 2(a) shows an example of a typical knife plate connection.

For a knife plate design to meet all the objectives of the proposed new design, the weld connecting the knife plate to the gusset plate must be replaced with a bolted connection. Figure 2(b) shows a design that was considered. This connection consists of the typical knife plate design but with 4 angles bolted around the gusset and knife plate to replace the knife plate to gusset plate weld.

This connection would meet the stated design objectives but has a number of associated concerns. The primary issue is the poor force transfer that would occur between the knife plate and the gusset plate. The angles have very little room to develop the high tensile forces that would need to be transferred between the gusset and the knife plate. This could result in significant rotation and warping of the angles, which is problematic under the cyclic loading an earthquake would impose on the connection.

The next iteration of design investigated using an end plate connection attached to a hinge plate to bolt the connection directly to the beam or column. Two examples of this are found in Figure 3. The connections for these braces would be assembled and welded together before being sent to site and would be bolted to the beam or column as a unit. This connection would meet the proposed goals and would be relatively easy to install and replace on site. The primary issues with this iteration of the design were geometric. First, if connected directly to the column as in Figure 3(a), there is very little possibility that the workpoint of the brace would pass through the desired location at the intersection between the beam and column centrelines. This eccentricity would induce a large moment in the column, which could require expensive stiffeners or a significantly larger column (Gross and Cheok 1988). There is also a concern that the high eccentricity could cause irreparable damage to the column under the large cyclic loading cause by a major earthquake. Second, the bolts nearest to the hinge plate could be very difficult to install.
If connected directly to the beam as shown in Figure 3(b), workpoint eccentricity can usually be avoided. However, in order to prevent this eccentricity, the connection end would usually need to be very close to the beam edge. This proximity to the beam edge could create problems for the design of the beam-column connection. The beam-column connection would need to be more robust to accommodate the increased shear from connecting the brace directly to the beam, and this would create interference problems between it and the bolts and stiffeners required for the brace connection. There would also be a concern that the large tension force on the bolts in the beam flange would require excessive stiffeners or welded plates to increase the flange thickness.

4. PROPOSED CONNECTION DESIGN

Working in consultation with industry experts, a solution was proposed that would meet all of the design objectives while limiting the negative effects of the previous proposals. The final proposal combines a knife plate design with a support that is attached directly to the beam, as shown in Figure 4. For 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.
In addition to meeting all of the design objectives, this design provides other benefits. The proposed design would be very easy to install due to the simple single splice bolted connection. Hinging is unlikely to occur outside the brace and hinge plate due to the stiffness of the support, meaning that in all but the most catastrophic earthquakes, the only damaged components would be those that are easily replaceable. Since the hinge plate would be welded to the brace in the shop, there would be the option of slotting both the hinge plate and the brace, as suggested by Martinez-Saucedo et al. (2008) and shown in Figure 5. This would eliminate the need for the costly cover plates that are typically required on slotted HSS braces to prevent net section fracture. A potential issue with the proposed connection is the eccentricity due to the single sided splice connection. Eccentricities are typically avoided because they can increase the deformation demand on the connection, leading to earlier fracture (Gross and Cheok 1988).

Figure 5: Slotting of brace and hinge plate: (a) Only the brace is slotted; (b) Brace and plate are slotted
There are two main design criteria that need to be considered for this connection that are not present in a typical gusset plate connection. The most significant design criterion is the selection of the hinge plate thickness to allow buckling to occur in the brace before failure in the connection. A thicker plate allows for higher initial buckling capacity by providing greater end rotation restraint, but it also tends to concentrate more damage in the brace during cyclic loading, reducing the total drift capacity of the system (Roeder et al. 2011). Determining the correct balance of strength and ductility will be essential for optimizing the performance of the proposed connection. The calculation of the connection capacity is also challenging because of the unique configuration of the eccentric splice plate. Most equations for determining the ultimate capacity of a single-sided splice are unable to adequately account for one plate being significantly stiffer than the other (Fang et al. 2015, Davaran et al. 2015, Packer et al. 2010). Another special design criterion is the sizing of the support plates to provide the required strength and stiffness in an efficient manner.

An alternative form of the proposed connection design has splice plates that eliminate the connection eccentricity, as shown in Figure 6. This may improve the connection performance under repeated cyclic loading. Although the eccentricity is prevented, this connection also has an increased risk of achieving a sway buckling mode where both the hinge plates and the splice plates bend, resulting in a brace that does not buckle, as seen in Figure 7. If that occurred, the deformation would be confined to the connection, which is very undesirable.

Figure 6: Concentric Variation of Proposed Connection

Figure 7: Sway Buckling Mode of Concentric Connection
5. PRELIMINARY FINITE ELEMENT MODELLING OF PROPOSED DESIGN

5.1 Model description

In order to assess the viability of the proposed design, a finite element (FE) model was created using the general nonlinear analysis package ABAQUS (Dassault Systemes 2011). The model was created to simulate the behaviour of a future physical experiment and included the full brace, support plates, hinge plates and bolts, as seen in Figure 8. The braces modelled ranged from HSS 89x89x6.4 to HSS 102x102x6.4 with lengths around 3m. The beams were not modelled and were assumed to provide rigid support to the support plates. The compressive load was applied as a uniform displacement at one support plate. Movement of the support plate ends along the axes perpendicular to the path of loading were prevented and the rotation degrees of freedom were fixed. An initial geometric imperfection was introduced into the model in proportion to the first buckling mode of the brace. This imperfection was scaled to a midspan deflection of 0.1% of the brace length. Two analysis steps were used in the model. The first step was a buckling analysis that was used for creating the imperfection. The second step was a nonlinear Riks arc-length analysis that was used to determine the critical buckling load and to observe the yielding behaviour at various compression strains.

The brace was modelled using 4-noded quadrilateral shell elements, while the support plates, hinge plates and bolts were modelled using 8-noded brick elements. Contact surfaces were modelled using hard contact behaviour with no penetration in the normal direction. Friction was modelled using the penalty method with a coefficient of friction of 0.2. Tie connections were used to simulate the fillet welds between the brace and the knife plate. The material model was simulated using an isotropic hardening model with Von Mises yield criterion. The region of a typical braced bay that was modelled is highlighted in Figure 8.

![Figure 8: Modelled Region of a Typical Braced Bay](image)

The modelling approach and selection of elements was based on two previous FE studies that validated models from companion physical experiments. Modelling of the brace was based on a study of concentric tubular braces subjected to seismic loading (Haddad 2015). The modelling of the hinge and support plates was based on a study of the compressive strength of single sided splice connections (Fang et al. 2015). In the future, full validation of the model for the proposed connection will be completed using the results of the planned physical experiment.

5.2 Modelling Results

The results of the model were used to confirm that the system would exhibit the desired failure behaviour and to estimate the critical buckling load. The stress distribution at critical buckling load is shown in Figure 9. The connection retains its strength and does not yield before the brace buckles. Figure 10 shows the stress distribution at an axial displacement of 1% of the brace length, approximately 5 times the yield strain. Significant yielding is observed in the hinge zone and the middle of the brace. This yielding does not spread to the support plates, meaning that any damage due to yielding is expected to remain confined to the easily replaceable components.
To estimate the peak compression load of the full system ($P_u, full\ assemblage$), the material yield and ultimate stresses were selected based on the material data sheets for the future physical experiment ($F_{y, brace} = 444$ MPa, $F_{u, brace} = 500$ MPa, $F_{y, plate} = 375$ MPa, $F_{u, plate} = 464$ MPa). The loads were calculated for a 3082 mm 102x102x6.4 HSS section with varying hinge plate dimensions. The theoretical buckling load of the brace ($P_{cr, brace}$) was found using the same yield strength as the model and assuming a Class H section due to the model not incorporating residual stresses. An estimated value of $K$ for the theoretical buckling load was based on the relative moment resistances of the brace and the hinge plate, as shown in Figure 11 (Takeuchi and Matsui 2015). This theoretical buckling load was compared to a FE model that only included the brace and hinge plate, and that was loaded concentrically. Good agreement was found between the theoretical and FE results, as shown in Table 1. The ultimate compressive resistance of the eccentric splice connection was calculated using Equation 1, which is adapted from the procedure outlined in AISC Design Guide 24 for the compressive strength of single sided shear splice connections for HSS members (Packer et al. 2010). In this equation, $P_a$ is the axial strength of the connection, $P_t$ is the compressive resistance of the thinner splice plate with an effective length of 1.2 times the length of the connection, $M_u$ is the ultimate moment, which is taken as half of $P_a$ times the connection eccentricity, and $M_t$ is the plastic flexural capacity of the thinner plate.
\[ \frac{P_u}{P_f} + \frac{8}{9} \left( \frac{M_u}{M_r} \right) = 1 \]

The results of the FE model \( P_{u,full\ assemblage} \) are compared to the theoretical calculations in Table 1. The hinge plate thickness of 25 mm was chosen because, according Equation 1, it was capable of reaching the critical buckling load of the brace with a K value of 1, the value typically assumed for a CBF. The FE model demonstrated that it could reach this load and brace buckling was the governing failure mode. The FE model and Equation 1 also agreed well for the thinnest plate considered, with connection failure occurring near the predicted value. The FE model and Equation 1 do not agree well for the intermediate plate thicknesses, with the variation of \( P_{u,full\ assemblage} \) being more proportional to the brace buckling strength than the connection strength. This inconsistency between the predicted strength and the actual strength remains true for other methods of calculating the connection strength (Fang et al. 2015, Davaran et al. 2015).

<table>
<thead>
<tr>
<th>Hinge Plate Thickness</th>
<th>K</th>
<th>( P_{cr,brace\ (Theory)} )</th>
<th>( P_{cr,brace\ (FE)} )</th>
<th>( P_{u,connection\ (Eq. 1)} )</th>
<th>( P_{u,full\ assemblage\ (FE)} )</th>
<th>Failure Mode</th>
</tr>
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<tr>
<td>25</td>
<td>0.75</td>
<td>850</td>
<td>864</td>
<td>673</td>
<td>640</td>
<td>Brace Buckling</td>
</tr>
<tr>
<td>22</td>
<td>0.8</td>
<td>805</td>
<td>810</td>
<td>567</td>
<td>608</td>
<td>Brace Buckling</td>
</tr>
<tr>
<td>19</td>
<td>0.84</td>
<td>767</td>
<td>776</td>
<td>464</td>
<td>585</td>
<td>Brace Buckling</td>
</tr>
<tr>
<td>16</td>
<td>0.88</td>
<td>730</td>
<td>740</td>
<td>364</td>
<td>345</td>
<td>Connection Failure</td>
</tr>
<tr>
<td>~</td>
<td>1</td>
<td>620</td>
<td>627</td>
<td>~</td>
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These results are typical of what was found for the eight specimens that are to be tested, and they suggest that the connection will achieve the desired failure hierarchy, but that improved guidance for determining the connection strength will be necessary.

6. CONCLUSIONS AND NEXT STEPS

This paper documents the development of a novel replaceable connection for the seismic design of concentrically braced frames. The objectives of the proposed new design were listed and some early design iterations were discussed and evaluated. The proposed new design was presented and the results of a preliminary finite element model were analyzed. The proposed new connection is expected to be easy to install, easy to replace if damaged, and to cause the brace to buckle in plane, thereby avoiding damage to exterior cladding. The FE model verified that the connection confines yielding to the easily replaceable components. Thus, the connection shows promise as an alternative for the seismic design of concentrically braced frames.
The next steps for this project involve performing a physical experiment to better understand the new connection’s behaviour and to validate a robust FE model. The results from the physical experiment and the FE model will be used to develop improved equations to predict the behaviour of the new connection, and these equations will be incorporated into guidelines for the practical design of the new connection. Future work will investigate how this connection would affect the seismic performance of a full structure, how to best incorporate this connection into different braced frame designs such as full bay bracing or X-bracing, and how to design the beams and columns of the structure in conjunction with the proposed brace connection design.

REFERENCES


