CYCLIC TESTING OF BUCKLING-RESTRAINED BRACES WITH REPLACEABLE STEEL ANGLES FUSES

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ABSTRACT

This research was focused on development and experimental validation of a new type of Buckling-Restrained Braces (BRBs) with replaceable steel angle fuses. The proposed BRB is envisioned to offer the ease of post-earthquake inspection of fuse damages, easy replacement of damaged fuses and re-use of the buckling restraining elements while maintaining the other favorable features of ordinary BRBs. To investigate seismic behavior of the proposed BRB, the proposed BRB specimens were tested. Test results show that the BRB can exhibit stable hysteretic behavior up to fairly high fuse strain levels. Failure modes of the specimens were found to be ruptures of the angle fuses as expected. The compression strength adjustment factors and the cumulative plastic deformations of the specimens satisfy the requirements specified by AISC 341-16. Moreover, this investigation showed that fuse replacement is convenient and prompt. Test results show that the specimens repaired through fuse replacements remained satisfactory.

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This research was focused on development and experimental validation of a new type of Buckling-Restrained Braces (BRBs) with replaceable steel angle fuses. The proposed BRB is envisioned to offer the ease of post-earthquake inspection of fuse damages, easy replacement of damaged fuses and re-use of the buckling restraining elements while maintaining the other favorable features of ordinary BRBs. To investigate seismic behavior of the proposed BRB, the proposed BRB specimens were tested. The test parameters varied in these specimens included fuse geometry and loading protocol. Test results show that the proposed BRB can exhibit stable hysteretic behavior up to fairly high fuse strain levels. Failure modes of the specimens were found to be ruptures of the angle fuses as expected. The compression strength adjustment factors and the cumulative plastic deformations of the specimens satisfy the requirements specified by AISC 341-16. Moreover, this investigation showed that fuse replacements remained satisfactory.

\textbf{Introduction}

Buckling-Restrained Braces (BRBs) which sustain yielding both in tension and in compression have been commonly adopted all over the world in new buildings and seismic retrofit of existing constructions (Brown \textit{et al.} 2001\cite{1}; Tremblay \textit{et al.} 2006 \cite{2}, Fahnestock \textit{et al.} 2007a \cite{3}; Fahnestock \textit{et al.} 2007b \cite{4}; Berman and Bruneau 2009 \cite{5}). Nevertheless, there are some limitations in the existing types of BRBs (i.e., these including mortar as the buckling restraining material and referred to herein as the ordinary BRBs) which impede the further widespread application of BRBFs in the design community. For example, detecting the damage caused by dissipating energy in the restrained yielding element of an ordinary BRB during the aftermath of a severe earthquake can be challenging and even destructive. Moreover, the buckling-restraining element of a well-designed ordinary BRB should remain elastic when damages develop in its restrained yielding segment. However, it is inconvenient to re-use the buckling-restraining elements of the ordinary BRBs, which does not help achieve the sustainable design objective. Besides, removal of the damaged BRB and installation of a new one can be onerous for many reasons such as the limited work space at the BRB ends.

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This paper proposed a new type of BRB which has the potential to overcome the above-mentioned limitations while keeping the favorable features of the ordinary BRBs and the steel-only BRBs. This research obtains test results from the cyclic testing of the proposed BRB specimens to form a basis to better understand the fundamental behavior of the BRB and help promote its applications in future building constructions. The following sections describe in detail the proposed BRB, experimental specimen design and fabrication, loading program, observations and test results.

Descriptions of the Proposed BRB

The proposed BRB is composed of the inner telescopic Buckling-Restraining Mechanism (BRM), the buckling-restrained angle fuses and the outer BRM. Figs. 1(a) to 1(f) schematically show the components in each assemblage and the process of assembling the proposed BRB. The following describes each assemblage in detail.

**Inner Telescopic BRM and Outer BRM**

As shown in Fig. 1(a), the inner telescopic BRM, which restrains the inward buckling deformation of the angle fuses, consists of two Steel Square Tubes (SSTs) connected through gusset plates. When assembled, the adapter needs to be plugged into the near ends of the SSTs. In addition, a rib is provided along the perimeter of the adapter to prevent the sliding of the adapter relative to the lower SST as shown in Fig. 1(a). Moreover, the gap between the two SSTs should be sufficiently large so that it remains open under the anticipated shortening deformation of the BRB. As shown Fig. 1(b), the outer BRM consists of four identical components connected via high-strength bolts along their edges. The bolted connections offer the ease of assembling (during fabrication) and disassembling (during the post-earthquake detection for fuse damages and replacement of the fuses). Note at each bolted connection that the restraining components being connected are separated by a washer to match the angle fuses with different thicknesses if needed.

**Buckling-Restrained Angle Fuses**

Each proposed BRB includes four buckling-restrained angle fuses. As shown in Fig. 1(c), each angle fuse consists of the following types of segments: the restrained yielding segment (which has the reduced area), the restrained nonyielding segment (which extends from a restrained yielding segment but with an enlarged area and is restrained by the inner and outer BRMs), the nonyielding connection segment (which is locally restrained by a buckling-restraining tee and bolted to the SST of the inner BRM). Adopting an interior restrained nonyielding segment in the fuse to cover the gap between the two SSTs helps reduce the fuse stress amplitude and damage concentration over this region, preventing occurrence of the unexpected fuse ruptures. In addition to the interior restrained nonyielding segment, each angle also has two exterior restrained nonyielding segments. Further, small angle brackets holding the outer BRM are welded to the lower nonyielding connection segments of the angle fuses, for avoidance of excessive sliding of the outer BRM relative to the angle fuses.
Figure 1. Illustration of the proposed BRB: (a) components in the inner telescopic BRM; (b) components in the outer BRM; (c) angle fuses; (d) assembled inner telescopic BRM; (e) angle fuses and inner BRM; (f) the proposed BRB after fabrication; (g) inner BRM of Specimen B0; (h) angle fuses of Specimen B0; and (i) angle fuses and inner BRM of Specimen B0.

Specimen Design and Fabrication

This research team developed and tested several specimens to experimentally investigate behavior of the proposed BRBs. The following describes four of the tested specimens in detail due to the limitation of paper length. Information about the other specimens can be found in Qu et al. 2017 [6].

Figs. 2 and 3 present the geometries of the components in the inner and outer BRMs, respectively. Moreover, it is noteworthy that each component of the outer BRM was cold-folded from a flat plate element. Geometries of the angle fuses varied in Specimens B0 to B3. Table 1 summarizes the key geometrical parameters defined in Fig. 4. It is recognized that the cross-section profile and geometries of standard angles do not meet the requirements of the angle fuses. Alternatively, all angle fuses were cold-folded from the flat plates processed using the laser-cutting machine (see Fig. 4). Note that a nominal gap of 1 mm was intentionally left between the
outer face of each angle fuse and the inner and outer BRMs to accommodate the debonding layers in the specimens. When thickness of the angle fuse changes, the gaps for the debonding layers can be achieved through adjusting the thickness of the washers used between adjacent components of the outer BRM (see Fig. 3(c)).

Figure 2. Inner telescopic BRM: (a) geometries of the SSTs; and (b) geometries of the adapter (unit: mm).

Figure 3. Design of the outer BRM (unit: mm).

Figure 4. Design parameters of angle fuses.

It is noteworthy that Specimen B0 was the same as Specimen B1 except that Specimen B0 did
not include the debonding agent of silicon grease, the male-male adapter and the buckling-restraining tees and that the angle fuses of Specimen B0 did not include the interior restrained nonyielding segments over the gap between the SSTs (see Figs. 1(g) to 1(i)). Specimen B0 was tested as a pilot specimen at the early stage of this investigation to form a basis for improving the design of Specimens B1 to B3 and design of Specimen B0 may be used in seismic retrofit of brace members under less severe seismic demands.

Table 1. Summary of the specimens.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>( L_y = L_{y1} + L_{y2} ) (mm)</th>
<th>( L_{ny1} ) (^a) (mm)</th>
<th>( L_{ny2} ) (mm)</th>
<th>( r ) (mm)</th>
<th>( t ) (mm)</th>
<th>B (mm)</th>
<th>b (mm)</th>
<th>Unbonding agent (^b)</th>
<th>Fuse steel</th>
<th>Weight of each fuse (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0</td>
<td>1100</td>
<td>650</td>
<td>0</td>
<td>30</td>
<td>5.4</td>
<td>75</td>
<td>45</td>
<td>NA</td>
<td>Q235</td>
<td>12.07</td>
</tr>
<tr>
<td>B1</td>
<td>890</td>
<td>650</td>
<td>210</td>
<td>30</td>
<td>5.7</td>
<td>75</td>
<td>45</td>
<td>SG</td>
<td>Q235</td>
<td>13.14</td>
</tr>
<tr>
<td>B2</td>
<td>890</td>
<td>650</td>
<td>210</td>
<td>30</td>
<td>5.7</td>
<td>75</td>
<td>45</td>
<td>SG</td>
<td>Q235</td>
<td>13.14</td>
</tr>
<tr>
<td>B3</td>
<td>850</td>
<td>650</td>
<td>230</td>
<td>40</td>
<td>5.7</td>
<td>75</td>
<td>35</td>
<td>SG</td>
<td>Q235</td>
<td>12.24</td>
</tr>
</tbody>
</table>

\(^a\) \( L_{ny1} = L_{ny3}; \) and  
\(^b\) NA=Not Applied; SG = Silicon Grease.

Material Properties

Q235 steel which has a nominal yield strength of 235 MPa was used for the components of the BRB. Coupon tests were conducted for the materials used in the angle fuses. For Specimen B0, values of yield strength, \( F_y \), ultimate strength, \( F_u \), and the strain associated with \( F_u \) (denoted as \( \varepsilon \) ) of the fuse materials were 284MPa, 438MPa and 0.182, and for Specimen B1 to B3, the values are 316MPa, 470MPa and 0.182, respectively.

Loading Scheme

Displacement-controlled loading schemes were employed in all tests. Assuming that the axial deformation concentrates in the yield region (Wu et al. 2014 [7]), the nominal strain, \( \varepsilon_{nom} \), can be calculated by using the nominal axial deformation divided by the total length of the two restrained yielding segments in each angle fuse (i.e., \( L_y \), see Table 1). Fig. 5 illustrates the loading protocol for each specimen. Notably, the loading sequence, number of cycles at each loading level, and the peak strain amplitudes were determined based on recent tests of ordinary BRBs (Wu et al. 2014 [7]; Lin et al. 2016 [8]). Each test was concluded once a significant in-cycle strength degradation was observed. The axial forces were measured by a load cell connected to the actuator. The actual axial deformation of the fuses, \( \delta_A \), was measured by the displacement transducers installed at the ends of the fuses.

![Figure 5. Loading protocol.](image-url)
Test Results

Each specimen was tested as planned. This section reports the noteworthy observations and failure modes of the specimens followed by interpretation of the recorded test data.

General Behavior and Failure Mode

Specimen B0 did not exhibit the global buckling behavior; it exhibited the stable hysteretic behavior but only up to the nominal fuse strain of 2.2%. In the first tension excursion of the loading cycle with the peak nominal fuse strain of 3.3%, the specimen exhibited an in-cycle strength degradation. Consequently, the axial resistances of the specimen at the peak strains of this cycle significantly reduced, resulting in conclusion of the test. After the test, the research team removed the outer BRM from the specimen to better examine the fuse angles. It was found that three out of the four angle fuses of Specimen B0 ruptured. The ruptures concentrated over the middle portion of each fuse which essentially covered the gap between the two SSTs of the inner BRM. Due to the absence of the adapter, the inward buckling deformations of the angle fuses were not restrained, resulting in strain concentration under the compressive loading excursions and consequently leading to fuse ruptures over this region. Based on the failure mode of Specimen B0, the adapter was introduced as a part of the inner BRM to limit the fuse inward buckling deformation and hence reduce the fuse strain concentrations in the following specimens. Moreover, an interior restrained nonyielding segment (which had the same cross-section area as the exterior restrained nonyielding segments, see Fig. 1(c)) was also introduced over the adapter region in the following specimens. The enlarged cross-section area of the interior restrained nonyielding segment was intended to reduce the normal stress amplitude and hence help avoid concentrated fuse damage over the adapter region.

With the design improvements based on the observations from Specimen B0, Specimens B1 to B3 were fabricated and tested. All these specimens exhibited similar stable hysteretic behaviors during the tests. Specimens B1 to B3 all sustained a considerable number of loading cycles with fairly high levels of fuse strains. None of the specimens developed the global buckling failure. Failures of these specimens are characterized by the strength degradation in the tension excursion of the last loading cycle. The inner and outer BRMs did not develop any visible damages as expected and they were re-used throughout the entire experimental program. Fig. 6 shows the process of replacing the damaged angle fuses by new ones during the break between two consecutive tests. Note that the weight of each fuse is listed in Table 1. It took a team of three student assistants (with limited hands-on construction experiences) about 2.5 hours on average to repair the damaged specimens. Based on the visual inspections on the angle fuses removed from Specimens B1 and B3, all the angle fuses were found to develop the high-mode buckling deformations although amplitudes of the buckling deformations were small due to the presence of the inner and outer BRMs. The paint flakes off from the angle fuses suggest that the high-mode buckling deformations of the angles caused frictions between the angle fuses and the BRMs. One angle fuse ruptured in each specimen. All the ruptures occurred in the restrained yielding segments of the angle fuses as expected, suggesting that adding the interior restrained nonyielding segment effectively avoided the fuse ruptures occurred in Specimen B0. Table 2 summaries the maximum resistance, the fuse strain associated with the maximum resistance, and the maximum fuse strain.
Figure 6. Replacement of angle fuses: (a) removing the instrumentation facility from the damaged specimen; (b) the damaged specimen after removal of the outer BRM; (c) the damaged specimen after removal of damaged angle fuses; (d) the repaired specimen after installation of the new angle fuses; and (e) the repaired specimen after installation of the outer BRM.

Hysteretic Curves

Fig. 7 presents the axial resistance versus the fuse strain curves of all the tested specimens. As shown, Specimens B1 to B3 exhibit stable hysteretic curves and none of these specimens exhibits in-cycle strength degradation prior to the last loading cycle. The repeatable favorable hysteretic behavior of these specimens is similar to that of the ordinary BRBs. Specimen B0 appeared less robust compared with the other specimens; nevertheless, it replicates the stable hysteretic responses of ordinary BRBs prior to the last loading cycle.

Figure 7. Hysteretic curves of the tested specimens.
Cumulative Damage Tolerance and Compression Strength Adjustment Factor

To compare the cumulative damage tolerance, the Cumulative Plastic Deformations (CPDs) defined by AISC 341-16 (AISC 2016 [9]) were calculated for all specimens. The CPD results are reported in Table 2. As listed, all specimens except Specimen B0 achieved CPDs larger than 200, meeting the CPD requirement per AISC 341-16 (AISC 2016 [9]). Among all the tested specimens, Specimen B1 gained the highest CPD of 1220.

Table 2. Summary of the specimens.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Maximum resistance (kN)</th>
<th>εA corresponding to maximum resistance (%)</th>
<th>Maximum εA (%)</th>
<th>CPD</th>
<th>Maximum β</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sup&gt;a&lt;/sup&gt;</td>
<td>C&lt;sup&gt;b&lt;/sup&gt;</td>
<td>T&lt;sup&gt;a&lt;/sup&gt;</td>
<td>C&lt;sup&gt;b&lt;/sup&gt;</td>
<td>T&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>B0</td>
<td>695</td>
<td>809</td>
<td>2.11</td>
<td>1.68</td>
<td>3.25</td>
</tr>
<tr>
<td>B1</td>
<td>768</td>
<td>943</td>
<td>3.39</td>
<td>3.13</td>
<td>3.31</td>
</tr>
<tr>
<td>B2</td>
<td>784</td>
<td>987</td>
<td>4.39</td>
<td>3.70</td>
<td>4.48</td>
</tr>
<tr>
<td>B3</td>
<td>608</td>
<td>762</td>
<td>3.70</td>
<td>3.63</td>
<td>3.71</td>
</tr>
</tbody>
</table>

*<sup>a</sup> T = tension; and <sup>b</sup> C = compression.

Fig. 8 show the values of the compression strength adjustment factor β. As shown, β is lower than 1.3 in all specimens under the considered fuse strain ductility ranges. Note that AISC 341-16 (AISC 2016 [9]) requires an upper bound of 1.3 for β. Therefore, the test results suggest that the differences in tension and compression resistances of the tested specimens are acceptable. Moreover, it is found that the varies from 1.0 to 1.2 up to the fuse strain ductility of 16 in the tested specimens. This range is similar to that of some ordinary types of BRBs (Wu et al. 2014 [7]; Lin et al. 2016 [8]).

Figure 8. Evaluation of the β factor.

Conclusions

Based on the test results obtained, the following significant conclusions were drawn:

• Hysteretic behavior of the proposed BRB is similar to those of the ordinary BRBs. The compression strength adjustment factor, β, and the CPD satisfy the requirements specified by
AISC 341-16 (AISC 2016 [9]). In practice, the proposed BRB can be used as surrogates to the ordinary BRBs if the proposed BRB can be properly designed to allow the structure inter-story drift associated with the ultimate BRB fuse strain to be higher than the expected inter-story drift.

- Although seismic performance of Specimen B0 was not as favorable as the other specimens, it replicated the stable hysteretic behavior of the ordinary BRBs up to the moderate fuse strain levels. Future research opportunities exist to address applicability of the design of Specimen B0 in seismic retrofit of the braces in OCBFs.
- The test results demonstrated that the inner and outer BRMs can be re-used and that replacement of the angle fuses is convenient and prompt. The repaired specimens remained as satisfactory as expected.

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