TESTING OF BUCKLING – RESTRAINED BRACES WITH REPLACEABLE FUSES

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Abstract: This research was focused on a new type of Buckling-Restrained Braces (BRBs) with replaceable steel angle fuses. The proposed BRB is composed of the inner telescopic Buckling-Restraining Mechanism (BRM), the buckling-restrained angle fuses and the outer BRM. The proposed BRB offers the ease of post-earthquake examination on fuse damages, the convenient and prompt replacement of damaged fuses and the re-use of the buckling restraining elements. To investigate seismic behavior of the proposed BRB, four brace specimens were tested. The test parameters varied in these specimens included fuse design, debonding material, 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 were found to satisfy the requirements specified by AISC 341-16. Moreover, the authors demonstrated that the specimens repaired through fuse replacements remained satisfactory in the following tests.

Keywords: Cyclic test; Replaceable structural fuse; Buckling-restrained brace; Energy dissipation

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1 INTRODUCTION

Buckling-Restrained Braces (BRBs) gain increasing popularity in new buildings and retrofit of existing constructions due to the advantage of yielding in both tension and compression without buckling [1-5]. Nevertheless, there are some limitations impeding the widespread acceptance of the existing types of BRBs. For example, dissipating hysteretic energy and excessive deformation would lead to the restrained yielding element of an ordinary BRB damaged and even fractured during an earthquake event, possibly compromising adequacy of the BRB for the subsequent earthquakes. It can be challenging and even destructive to detect the damage in the restrained yielding element of an ordinary BRB or replace the ruptured BRB with a new one after a severe earthquake due to the limited work space at the BRB ends and so on. Besides, 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.
This research proposed a new type of BRB, which has the potential to overcome the above-mentioned limitations while maintaining the favorable features of the ordinary BRBs. To investigate seismic behavior of the proposed BRB, four BRB specimens were tested under cyclic axial loading. The test results obtained from this investigation form a basis to better understand the fundamental behavior of the proposed BRB and help promote its applications in future building constructions. The following sections describe in detail the proposed BRB, experimental specimen design and fabrication, test setup, loading program, observations, test results and discussions on the influences of the design parameters.

2 DESCRIPTIONS OF THE PROPOSED BRB

The proposed BRB includes three key assemblages: the inner telescopic Buckling-Restraining Mechanism (BRM), the buckling-restrained angle fuses and the outer BRM. In addition, the debonding agents can be introduced along the buckling-restrained angle fuses to reduce the friction forces between the buckling-restrained angle fuses and the outer/inner BRMs. Figures 1(a) to 1(f) schematically show the components in each assemblage and the process of assembling the proposed BRB. The following describes in detail each assemblage.

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.

2.1 Inner telescopic BRM

Figure 1(a) shows the components of the inner telescopic BRM including two Steel Square Tubes (SSTs) connected through a male-male adapter. The inner telescopic BRM is designed to restrain the inward buckling deformations of the angle fuses. To prevent the sliding of the adapter relative to the lower SST, a rib is provided along the perimeter of the adapter. In general, the inner telescopic BRM alone should have negligible contributions to the axial stiffness and the resistance of the BRB under the axial deformations.
2.2 Outer BRM

As shown in Figure 1(b), the outer BRM consists of four identical components bolted via high-strength bolts along their edges, which offers the ease of assembling and disassembling. The outer BRM is expected to remain fully elastic when the BRB is subjected to the axial loading and can be re-used in the subsequent earthquakes. Note at each bolted connection that the restraining components being connected are separated by a washer to allow installation of the angle fuses with different thicknesses if needed.

2.3 Buckling-restrained angle fuses

The proposed BRB includes four buckling-restrained angle fuses. As shown in Figure 1(c), each angle fuse consists of the following types of segments: the restrained yielding segment (which has the reduced area and is designed to yield and dissipate hysteretic energy); the restrained non-yielding segment (which extends from a restrained yielding segment but with an enlarged area and is restrained by the inner and outer BRMs); the non-yielding connection segment (which is locally restrained by a buckling-restraining tee and bolted to the SST of the inner BRM). Long-rod high-strength bolts are used to connect the angle fuses to the SSTs. Each long-rod high-strength bolt in turn penetrates the buckling-restraining tee, one leg of an angle fuse, the SST, one leg of another angle fuse, and the buckling-restraining tee on the other side of the SST. Further, small angle brackets holding the outer BRM are welded to the lower non-yielding connection segments of the angle fuses, for avoidance of excessive sliding of the outer BRM relative to the angle fuses.

3 SPECIMEN DESIGN AND FABRICATION

It was perceived that the proposed BRB could keep all the favorable features of the ordinary BRBs while offering the extra benefits in damage detection, fuse replacement and re-use of the buckling-restraining elements. However, no testing data have been reported to confirm whether the proposed BRB would behave as expected. This research team developed and tested four specimens to experimentally investigate the behavior of the proposed BRB. The following describes in detail the specimens.

Figure 2: Inner telescopic BRM: (a) geometries of the SSTs; and (b) geometries of the adapter (unit: mm).
Due to the sustainable nature of the proposed BRB, the inner and outer BRMs were re-used in all specimens. Figures 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.

![Diagram of the outer BRM](image)

(a) Side view  
(b) Cross-section  
(c) After assembled

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

The test parameters varied in Specimens B1 to B4 included geometries of the angle fuses and debonding agent. Table 1 summarizes the key geometrical parameters of each specimen. Figure 4 illustrates definitions of the geometrical parameters. All angle fuses were cold-folded from the flat plates processed using the laser-cutting machine (see Figure 4). A group of six long-rod high-strength bolts were used to connect each end of the angle fuse to the SST (three bolts on each leg of the angle, see Figure 4). Additionally, Specimen B2 adopted polyethylene as the debonding agent while the other Specimens adopted silicone grease as the debonding agent. 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 the adjacent components of the outer BRM (see Figure 3c).

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>$L_y = \frac{L_y1 + L_y2}{2}$ (mm)</th>
<th>$L_{ny1}$</th>
<th>$L_{ny2}$</th>
<th>$r$ (mm)</th>
<th>$t_a$ (mm)</th>
<th>$B$ (mm)</th>
<th>$b$ (mm)</th>
<th>Unbonding agent</th>
<th>Weight of each fuse (kg)</th>
</tr>
</thead>
<tbody>
<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>13.14</td>
</tr>
<tr>
<td>B2</td>
<td>650</td>
<td>210</td>
<td>30</td>
<td>5.7</td>
<td>75</td>
<td>45</td>
<td></td>
<td>P</td>
<td>13.14</td>
</tr>
<tr>
<td>B3</td>
<td>850</td>
<td>230</td>
<td>40</td>
<td>5.7</td>
<td>75</td>
<td>35</td>
<td></td>
<td>SG</td>
<td>12.24</td>
</tr>
</tbody>
</table>

$a \quad L_{ny1} = L_{ny3}$; and  
b $SG = $ Silicon Grease; and $P = $ Polyethylene.
4 MATERIAL PROPERTIES

Q235 steel which has a nominal yield strength of 235 MPa was used for all components of the BRB. Coupon tests were conducted for the materials used in the angle fuses. For Specimens B1 to B4, the yield strength, $F_y$, ultimate strength, $F_u$, and the strain associated with $F_u$ (denoted as $\varepsilon_u$) of the fuse materials were 316MPa, 470MPa and 0.182, respectively.

5 TEST SETUP LOADING SCHEME AND INSTRUMENTATION

The same test setup was adopted for all specimens. Figure 5 schematically shows the test setup. The cyclic axial loads were applied along the longitudinal direction of each specimen. The length of the specimens (measured from end to end as shown in Figure 5) was kept constant at 4.17m.

Displacement-controlled loading schemes were employed in all tests. The displacements applied by the actuator were intended to impose specific strains on the angle fuses. Assuming that the axial deformation concentrates in the restrained yielding segment [6], 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). Figure 6 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 [6,7]. The tensile strain was applied first in all tests. 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 angle fuses, \( \delta_A \), was measured by the displacement transducers installed at the ends of the angle fuses. The fuse strain \( \varepsilon \) was calculated based on \( \delta_A \).

![Figure 6: Loading protocol.](image)

### 6 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.

#### 6.1 General behavior and failure mode

Although Specimens B1 to B4 had different test parameters (including the differences in fuse geometry, debonding material and loading scheme), all these specimens exhibited similar stable hysteretic behaviors and sustained a considerable number of loading cycles with fairly high levels of fuse strains during the tests. 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. Figure 7 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 to B4, 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. Each specimen had one ruptured angle fuse. Figure 8 illustrates the rupture location along each fractured angle fuse. As shown, all the ruptures occurred in the restrained yielding segments of the angle fuses as expected.
6.2 Hysteretic curves

As shown in Figure 9, it presents the axial resistance versus the fuse strain curves of all the tested specimens. As shown, all the specimens 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. Figure 9 also shows the strain ductility, \( \mu \varepsilon \), observed from the specimens, where \( \mu \varepsilon \) is defined as the ratio of the fuse strain, \( \varepsilon \), to the fuse yield strain, \( \varepsilon_y \) (which can be calculated based on the yield strength, \( F_y \)). The ductility of many ordinary BRBs range from 15 to 25 [8-12]. Table 2 summarizes the maximum resistance, the fuse strain associated with the maximum resistance, and the maximum fuse strain.
Figure 9: Hysteretic curves of the tested specimens.

Table 2: Summary of the specimens.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Maximum resistance (kN)</th>
<th>$\varepsilon$ corresponding to maximum resistance (%)</th>
<th>Maximum $\varepsilon$ (%)</th>
<th>CPD</th>
<th>Maximum $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>768</td>
<td>943</td>
<td>3.39</td>
<td>3.13</td>
<td>1220</td>
</tr>
<tr>
<td>B2</td>
<td>774</td>
<td>874</td>
<td>3.25</td>
<td>3.37</td>
<td>1166</td>
</tr>
<tr>
<td>B3</td>
<td>784</td>
<td>987</td>
<td>4.39</td>
<td>3.70</td>
<td>1100</td>
</tr>
<tr>
<td>B4</td>
<td>608</td>
<td>762</td>
<td>3.70</td>
<td>3.63</td>
<td>1053</td>
</tr>
</tbody>
</table>

$^a$ T = tension; and $^b$ C = compression.

6.3 Hysteretic energy dissipation and cumulative damage tolerance

Based on the hysteretic curves shown in Figure 9, the total hysteretic energy absorbed in each specimen, $E_h$, can be quantified. To compare the hysteretic energy absorbed in each unit volume of the material over the restrained yielding elements of the fuses and also to exclude the influence of fuse material strength on the magnitude of the energy dissipated, the normalized hysteretic energy dissipation ($E_h/F_yA_rL_y$) was calculated for each specimen, where $F_y$ represents the yield strength of fuse material; $A_r$ represents the cross-section area of the restrained yielding segments of the four fuses in the specimen; and $L_y$ represents the total length of the two restrained yielding segments of an angle fuse in the specimen (see Table 1). Figure 10 presents the normalized hysteretic energy dissipation of each of the tested specimens. The maximum fuse strains experienced by Specimens B1 to B4 are comparable. The four specimens achieve a similar level of normalized hysteretic energy absorption on the order of 0.60.
To compare the pinching degree of the hysteresis loops, the shape factor of hysteresis loops, $\chi$, was calculated for each loading cycle of each specimen. Figure 11(a) schematically shows the definition of $\chi$. As illustrated, a system with less pinching hysteresis loops should have a larger $\chi$ value. Figure 11(b) compares the evolution of $\chi$ as the cumulative hysteretic energy absorbed in the brace progressively increases. For better comparisons, the cumulative hysteretic energy was normalized by the total energy absorbed in the figure (with the normalized cumulative hysteretic energy of 1.0 representing the failure of a specimen). Moreover, $\chi$ is higher than 2.0 as the normalized cumulative energy dissipation increases beyond 0.1.

![Figure 11: Definition and evaluation of the $\chi$ factor.](image)

To compare the cumulative damage tolerance, the Cumulative Plastic Deformations (CPDs) defined by AISC 341-16 (AISC 2016) were calculated for all specimens. The CPD results are reported in Table 2. As listed, all specimens achieved CPDs larger than 200 [13], meeting the CPD requirement per AISC 341-16 (AISC 2016). Among all the tested specimens, Specimen B1 gained the highest CPD of 1220.

### 6.4 Compression strength adjustment factor

By definition, $\beta$ represents the ratio of the maximum compression resistance to the maximum tension resistance of the BRB in a specific loading cycle. Figure 12 shows the $\beta$ values of the tested specimens. As shown, $\beta$ is lower than 1.3 in all specimens under the considered fuse strain ductility ranges. Note that AISC 341-16 (AISC 2016) requires an upper bound of
1.3 for $\beta$[13]. Therefore, the test results suggest that the differences in tension and compression resistances of the tested specimens are acceptable.

6.5 Selection of debonding materials

In this investigation, Specimens B1 and B2 had the same fuse design. The two specimens were tested using the same loading protocol (see Figure 6). The only parameter varied in Specimens B1 and B2 is the debonding material. As listed in Table 1, Specimens B1 and B2 adopted silicone grease and polyethylene as their debonding materials, respectively. The test results presented in the prior section reveal that there are no noticeable response differences observed in these two specimens, suggesting that both materials can be alternatively used in the proposed BRB. However, cutting polyethylene mat and applying the polyethylene mat to the proposed BRB are onerous. Therefore, it is recommended to use silicone grease in the proposed BRB in future implementations. Note that comparison of the durability of silicone grease and polyethylene is beyond the scope of this research.

![Figure 12: Evaluation of the $\beta$ factor.](image)

7 SUMMARY AND CONCLUSIONS

This research experimentally addressed the seismic behavior of a new type of BRB with replaceable steel angle fuses. The experimental program included the tests of four specimens under cyclic loading. 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, $\beta$, and the CPD satisfy the requirements specified by AISC 341-16 (AISC 2016). 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.

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.

The polyethylene mat and silicone grease can be both used as the debonding agent in the proposed BRB; however the silicone grease is more preferable due to its ease of implementation.
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REFERENCES


