Experimental Investigation of Miniature Buckling Restrained Braces for Use as Structural Fuses

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Abstract

This paper presents the design and experimental **investigation** of a miniature buckling-restrained brace (MBRB) which can act as a hysteretic damper to dissipate energy when subjected to inelastic axial deformations. The MBRB is similar to a buckling restrained brace (BRB) with a yielding steel core plate restrained from buckling by a grouted restraining tube. The MBRBs, however, are designed to have shorter lengths, smaller steel core dimensions, and smaller yield capacity as compared to a typical BRB. As a result, careful consideration is required for the detailing at the ends and the stability of the MBRB.

Small capacity BRBs can be useful in a range of applications as a primary energy dissipating structural fuse or supplementary axial hysteretic damper in seismic force resisting systems. The design, construction, and testing of six MBRB specimens with nominal axial yield forces between 30 kN and 95 kN is reported. Issues related to global stability of the MBRBs are discussed and a stability criterion to prevent global buckling was adopted to design the MBRB end connection pieces. The MBRBs exhibited cumulative plastic deformations between 181 and 400 times the yield deformation and cumulative plastic strain between 46% and 106%. Conclusions about the behavior and recommendations for the design of the MBRB are presented.

1. Introduction and background

Energy dissipating structural fuses have been developed for and implemented in seismic force resisting systems to dissipate energy and protect primary structural elements, thereby limiting structural repair costs and business downtime. Although there are numerous examples of such structural fuses in the literature, this section describes some past works on axially yielding energy dissipation devices due to its direct significance for the present research.

Buckling restrained braces (BRBs), first developed in Japan, are a widely used form of hysteretic energy dissipator that is implemented most often as diagonal bracing in buildings. A typical BRB consists of a core plate which yields when subjected to either elongation or shortening

deformations and a high strength outer casing filled with grout that provides lateral bracing to the core and thus prevents lower mode compression buckling of the core plate [1,2]. The typical buckling-restraining mechanism for a BRB consists of a hollow structural shape (HSS) member that is filled with mortar, concrete, or other **filler** material [3-8]. The cross-sectional shape of the inner steel core can vary (e.g. Jia et al. [9]), but typically the yielding segment of the core is a plate with rectangular section. To minimize friction between the core and restraining member, several kinds of debonding material [10,11] or air gap have been used [12-13]. The yield capacity of BRBs currently available is approximately 350-10000 kN.

There are several examples in the literature that highlight the potential applications for small capacity BRBs (e.g. 10-200 kN capacity) for energy dissipation and as sacrificial fuse elements to prevent damage to the primary structure. **Figure 1 summarizes some of the applications and needs for small capacity BRB energy dissipation elements (it is noted that the application shown in Figure 1a is described in Section 2).** Small capacity axial hysteretic energy dissipators have been used in self-centering moment connections [14] and post-tensioned cantilever bridge piers [15] as shown schematically in Figure 1c and 1d respectively. Small capacity hysteretic braces have also been used as knee braces in the seismic retrofit of reinforced concrete moment resisting frames (RCMRFs) [16] as shown schematically in Figure 1b and in simple frame structures to resist seismic loads [17,18]. In other instances, a commercially made small capacity buckling-restrained brace with 91 kN yield capacity was investigated as an option for ductile end cross frames in steel plate girder bridges to resist transverse earthquake loading [19] as shown in Figure 1e. Tsampras et al. [20] also used commercially-made small capacity BRBs with approximately 50 kN yield capacity as a horizontal deformable connection between the lateral force resisting system and the gravity load resisting system.

Research has been conducted on the development of replaceable energy dissipating elements with a design concept similar to the BRB. The majority of these designs used solid cylindrical bars such as Dywidag System International (DSI) threaded bars, reinforcing steel bars, or machined solid steel cylinders [14,15,18,21]. Hollow cylindrical tubes were most commonly used for restraining the steel core against buckling. Suita et al. [18] used a restraining **element** made of a steel tee section to confine the steel plate core against buckling. Mortar or epoxy was used as filler material in the space between the restraining element and the steel core and **several types of debonding agents were used** such as - Teflon®, rubber sheet, and grease lubrication. The end connection for these hysteretic energy dissipators were either pinned [19,20], bolted or fully fixed [14,15,18,21]. The rotational rigidity of the end connection zone however, varied depending on the expected rotations of the connecting elements (i.e. beams and columns).

Figure 1: Examples highlighting the need of small capacity BRB hysteretic dampers

This paper presents the background, design, fabrication details, experimental program, and testing results for a miniature BRB (MBRB). One of the challenges associated with small capacity BRBs is global buckling because the core can have very small bending moment capacity and the ends of the MBRB (i.e. the connection zone) can be relatively small as compared to typical BRBs. A global stability check from the literature is discussed and employed in the design process to discourage global instability. The detailing of the MBRB to allow shortening and elongation of the core without transferring significant axial force to the grout or restraining tube is described. Six MBRB specimens were subjected to a cyclic displacement protocol. The results are discussed with an emphasis on their hysteretic behavior and failure mechanism. Peak response quantities typically used to evaluate BRBs such as the compression strength adjustment factor, β , strain hardening adjustment factor, ω , cumulative inelastic axial deformation ratio, μ , and cumulative plastic strain, $\varepsilon_{cum,p}$, are investigated.

2. Intended Application for the MBRB

The MBRBs discussed in this paper were designed for implementation in a self-centering beam (SCB) as a replaceable energy dissipating element. The self-centering beam, shown schematically in Figure 1a, is a new seismic force resisting system that, like other self-centering

seismic systems can bring a building back to plumb after an earthquake, but also is a shop fabricated structural element that allows conventional field construction and reduces floor damage associated with differential movement between the self-centering system and gravity framing [22]. These systems are capable of resilient performance during large earthquakes, virtually eliminating residual drifts and concentrating all structural damage in the MBRB elements.

2.1 Self-Centering Beam

The self-centering beam (SCB) body comprises of a typical W-section beam augmented by restoring force mechanism at its bottom flange made of two concentric tubes (inner and outer) precompressed by post-tensioning (PT) strands passing through the tubes. During earthquake loading, the concentric tubes move relative to each other, thereby forming a gap between the tubes and free-floating anchorage plates that slide over the connection region. The post-tensioning strands act to close this gap, bring the concentric tubes back into alignment, and thus force the SCB back to its original configuration after the earthquake ground motion ceases [23]. The MBRB, which is required to dissipate seismic energy and thereby limit peak drifts, is attached to the SCB in a way that exploits the relative motion between the inner and outer tube. To be effective in the self-centering beam, the MBRB must have a high deformation capacity and exhibit stable hysteretic behavior as the SCB is subjected to large story drift ratio. Another requirement for the MBRB detailing was replaceability (i.e. the MBRBs can be removed and replaced after large earthquakes).

2.2 MBRB Design Requirements for Use in the Self-Centering Beam

The MBRBs developed in this paper were subsequently used in large-scale testing of the self-centering beam [23]. Thus, several geometric and design requirements associated with the large-scale self-centering beam specimens were used as a guideline for the design of the miniature BRB test specimens described herein. The peak strain demand for the MBRB, ϵ_{demand} , was estimated using Eq. (1) assuming rigid body motion of all the adjoining parts. It is shown that MBRB strain demand depends on the expected peak story drift ratio, Δ_{story} , the depth of the SCB, d_{SCB} , as measured from the center of the top flange of the W-section to the centroid of the concentric tubes, and the length of the MBRB core plate, L_c .

$$\epsilon_{demand} = \frac{\Delta_{story} d_{SCB}}{L_c} \quad \text{Eq. (1)}$$

Based on the depth of the SCBs between $d_{SCB} = 432$ mm and $d_{SCB} = 622$ mm, and a target story drift ratio of 4% associated with the requirement for special moment resisting frame connections in AISC 341-10 [1], the length of the core could be selected. To explore the range of peak strain demands between 0.02 mm/mm and 0.04 mm/mm, two MBRB core lengths were selected as 610 mm and 914 mm.

The axial yield capacity of the MBRB was also selected to be applicable for use in the self-centering beam. The moment capacity of the SCB stems from a combination of the yield capacity of the MBRBs and the initial force in the post-tensioning strands. In the typical SCB configuration [23], four MBRBs are located on the sides of the SCB to keep their center of force concentric with the centerline of the tubes and post-tensioning force. The required yield force for a single MBRB was between 30 to 95 kN which is the range of capacity tested in the current study.

3. Miniature BRB Design and Detailing

The MBRB assembly is shown schematically in Figure 2. The MBRB core plates consisted of 9.5 mm thick ASTM A572 Grade 50 steel plates with wide ends that tapered down to a reduced width cross-section in the middle. High quality waterjet cutting (i.e. slowest speed option) was used to cut the core plate as shown in Figure 3. **This type of cutting results in a very smooth finish without heat affected edges.** The MBRB ends were 38 mm wide and had a 9.5 mm thick by 14.5 mm wide stiffener welded to one side. The ends were sufficiently large relative to the reduced section to concentrate all inelastic deformations to occur in the reduced middle section of the core plate.

Figure 2: Design of a typical MBRB

Figure 3: Waterjet cutting of the MBRB specimens

The restraining cylinder had an outside diameter and wall thickness equal to 51 mm and 3 mm, respectively and a nominal yield strength and nominal tensile strength of 496 MPa and 600 MPa respectively. A design parameter, insertion length, L_i , as shown in Figure 5, was used in conjunction with the core length to determine the length of the restraining tube. A lower bound for insertion length was based on the design recommendation of Takeuchi et al. [26] associated with global stability of a BRB wherein the insertion length should be at least twice the width of the core plate, W_c . The insertion length also has to be long enough to sustain the required peak elongation without allowing the tapered portion of the core to come out of the restraining tube. Since the core plate is not anchored to the restraining tube anywhere along its length, the ends are not constrained to pull out of the restraining tube an equal amount between the two sides. Based on these criteria and to examine the effect of insertion length, half of the specimens used L_i equal to 63.5 mm and the other half used L_i equal to 121 mm which were between five and ten times the width of the core plate.

The steps in MBRB fabrication are shown in Figure 4. First, 32 mm long pieces of Ethylene Vinyl foam were attached at both the ends of the tapered sections to allow shortening of the core plate without compressing the grout. The core plate was then covered with 0.8 mm thick adhesive backed Polytetrafluoroethylene (PTFE) sheet followed by a layer of 0.09 mm thick adhesive PTFE tape. PTFE tape was used to cover over the seams and edges of the PTFE sheet to prevent the grout from getting under the sheet. The PTFE sheet and tape act as a de-bonding layer between the Hydrocal® and the core plate enabling the core plate to slide relatively freely inside the restraining tube while also allowing (through compressibility of the tape / sheet layer) a small amount of transverse expansion of the core associated with Poisson's effect when the MBRB is subjected to compression.

The space between the restraining tube and the core plate was filled with Hydrocal® white gypsum cement. A 7-day compression test was conducted on three 50mm cubes from a typical Hydrocal® mix (i.e. not associated with any specific MBRB specimen) and the average compressive strength was found to be 31.5 MPa. This compressive strength was within 10% of the specified dry cured compressive strength of the product used (34.5 MPa). Hydrocal® was chosen over mortar or any other filler material because it is easy to pour and conforms to boundary contours without leaving gaps or voids.

Figure 4: General fabrication process for the MBRBs

4. Cyclic Testing of MBRB

This section describes the cyclic testing program including the matrix of test specimens, test setup and displacement protocol. The matrix of test specimens showing the varying design parameters is presented in Table 1. The nomenclature for each specimen based on their design parameters is also shown in Table 1. A set of six MBRBs were tested as a part of this testing program. The important design parameters that were varied included: width of the core plate, W_c , aspect ratio of the core plate (ratio of the plate thickness to the plate width, W_c / t_c), length of the

core plate, L_c and insertion length L_i . See Figure 5 for a graphical representation of these variables. The test matrix has been divided into two sets of specimens. The first set consists of test specimens with core plate length of 610 mm whereas the second set includes specimens with core plate length of 914 mm. As shown in Figure 5, the core plate length refers to the active length of the core that has a reduced width.

Table 1: Test Matrix and specimen nomenclature

SPECIMEN NOMENCLATURE	Specimen ID	Core plate width, W_c , mm	Core plate area, A_c mm^2	Aspect ratio, (W_c / t_c)	Expected Yield force, P_y kN	Core plate length, L_c , mm	Insertion length, L_i mm
<div>Core plate width, mm</div> <div>Core plate length, mm</div> <div>Specimen letter</div> <div>MBRB-610-11.6a</div>	MBRB-610-7.1	7.1	67.5	0.75	30.4	610	63.5
	MBRB-610-11.6a	11.6	110	1.22	49.5		
	MBRB-610-11.6b	11.6	110	1.22	49.5		
	MBRB-914-11.9	11.9	113	1.25	49.4	914	121
	MBRB-914-17.8	17.8	169	1.87	73.9		
	MBRB-914-22.9	22.9	218	2.41	95.3

Figure 5: A schematic representation of the two sets of MBRB test specimens

The core plate thickness was kept constant (9.5 mm) for all the specimens while the plate width was varied to produce a range of MBRB yield capacities. The yield capacity of the element, P_y , as given in Table 1 is based on the measured yield stress of the core plate material equal to 450

MPa and 437 MPa for MBRB-610 and MBRB 914 specimens respectively (coupon tests described in the following paragraph). As described in the previous section, the core plate reduced section area was selected to produce the required yield capacities associated with energy dissipation elements in related self-centering beam specimens [23]. The range of the MBRB yield capacities tested was 30 kN-95 kN. The aspect ratio was also varied to investigate if the onset of core buckling is sensitive to this parameter. The core length was varied to investigate maximum deformation capacity and cumulative deformation capacity of the MBRB. The insertion length was varied in the test matrix to investigate if it has an influence on the global stability of the miniature BRB.

Tension coupon testing of the MBRB core plate material was conducted prior to the cyclic testing to determine the material properties. Tension coupons cut from the 9.5 mm thick A572 Grade 50 steel plates used in the fabrication of both the sets of MBRB specimens (610 mm and 914 mm core length specimens) were tested in accordance with ASTM E8 [24]. A total of five dogbone-shaped tension coupons were tested from the miniature BRB core plate material: three from material used in MBRB-610 series and two from the MBRB-914 series. The reduced section length and width of the tension coupon was 229 mm and 38 mm, respectively. The specimens were cut using the same waterjet cutting machine used for the BRB core plates. A stress-strain plot for one representative coupon from both groups is shown in Figure 6(a) and (b) and the average material properties are listed in Table 2.

Figure 6: Engineering Stress- strain plots from one of the tension coupon tests for core material from (a) MBRB-610 series (b) MBRB-914 series

Table 2: Material properties of the two batches of 9.5 mm thick steel plates (Values given are average for a group of tension coupons)

Steel material	Number of specimens tested	Young's modulus (GPa)	Yield stress (MPa)	Ultimate strength (MPa)	Maximum elongation %
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MBRB-610 series	3	197	450	581	24%
MBRB-914 series	2	204	437	544	26%

The MBRB test setup is shown in Figure 7. Load was applied using an MTS Servo-Hydraulic 240 kN capacity actuator with a maximum stroke of 150 mm. The miniature BRB ends were welded to built-up WT sections which were bolted to the actuator end plate on the live end and a reaction block on the dead end. The actuator was laterally braced to prevent any out-of-plane movement during cyclic loading.

The wire potentiometer labeled as WP-1 in Figure 7 was oriented along the length of the MBRB specimen and was used to record axial deformation of the MBRB. Two more wire potentiometers (labeled as WP-2 and WP-3) were used to measure the movement of the ends of the core relative to the restraining tube. The actuator's load cell was used to measure applied force and the actuator's internal linear variable differential transformer (LVDT) was also recorded.

Figure 7: Miniature BRB cyclic test setup

The displacement protocol used for the cyclic testing of the miniature BRBs was adapted from the cyclic loading sequence for beam-to-column connections outlined in AISC 341-10 (AISC 2010). As discussed in the previous section, the peak elongation/shortening of the MBRB core plate in each cycle was computed based on the deformation that the miniature BRBs were expected to experience when implemented in a SCB of a given depth, d_{SCB} . The peak story drifts at each displacement level in the large-scale test displacement protocol was used to calculate the associated expected deformation in the miniature BRB, δ_{MBRB} using Eq. (1).

From Eq. (1), it is clear that a deeper SCB will result in larger levels of MBRB deformation. Therefore, to test the MBRBs under more severe loading conditions, the displacement protocol was based on the deeper of the two SCBs tested, $d_{SCB} = 622$ mm [23]. The elongation associated with 4% target story drift from the AISC 341-10 loading sequence was 24.88 mm, and the rest of the cyclic displacement protocol was scaled accordingly as shown in Figure 8. The loading rate for the test was set at 38 mm/min.

Figure 8: Displacement protocol for MBRB cyclic test

5. Global stability of MBRBs

Past studies have indicated that BRB global flexural buckling, often associated with flexibility or failure of the connection region, may occur before core yielding. In MBRB design, therefore, it is essential to design the end connections to discourage plastic hinge formation prior to core plate yielding. This section presents the stability criteria used to design the MBRB end connection regions to prevent global buckling of the MBRB prior to core plate yielding.

Takeuchi et al. [25] suggested two stability requirements for BRBs which take into account the effects of moment transfer capacity at the restraining tube ends on rotational stiffness of the end connection zone. The end connection zone refers to the section of the MBRB from the restraining tube end to the end connection fixture as shown in Figure 9. The stability criteria for the end connections given by Takeuchi et al. [25] are presented in Eqs. 2 and 3. The first criterion, given by Eq. (2), ensures that the expected failure axial force of the MBRB **assuming that the built-up WT end connection pieces stay elastic**, N_{lim1} is greater than the maximum axial strength of the MBRB core plate at the reduced section after hardening, N_{cu} . The second criterion calculates the expected failure load, N_{lim2} assuming the formation of plastic hinges in the built-up WT end connection pieces. The stability condition for this collapse mode is expressed in Eq. (3). For the cyclic testing of the MBRB specimens, the built-up WT end connection pieces were proportioned in such a way that **second stability criterion, as given by Eq. (3)**, never governed (i.e. considerably stronger than the first criterion).

Figure 9: Notations used in the calculations related to end stability

$$N_{lim1} = \frac{\frac{M_p^r - M_o^r}{a_r} + N_{cr}^r}{\frac{M_p^r - M_o^r}{a_r N_{cr}^B} + 1} > N_{cu} \quad \text{Eq. (2)}$$

$$N_{lim2} = \frac{\frac{[(1-2\xi)M_p^c + M_p^r - 2M_o^r]/a_r}{\frac{[(1-2\xi)M_p^c + M_p^r - 2M_o^r]}{a_r N_{cr}^B} + 1}}{a_r N_{cr}^B} > N_{cu} \quad \text{Eq. (3)}$$

$$N_{cu} = A_c \sigma_{cu} \quad \text{Eq. (4)}$$

Where the following variables are defined here and discussed further in subsequent paragraphs:

M_p^r = Plastic bending capacity of the neck zone

M_o^r = Secondary moment associated with out of plane drifts
(taken as zero for MBRB specimens)

a_r = effective initial imperfection

N_{cr}^r = Elasto-plastic buckling strength of the restraining tube

N_{cr}^B = Elastic buckling strength of the MBRB

ξ = Ratio of connection zone length to total length (see Figure 9)

M_p^c = Plastic bending capacity of connection
(e.g. built-up WT section for this configuration)

A_c = Measured core plate reduced cross section

σ_{cu} = Measured ultimate tensile stress of core plate material

The capacity to transfer moment at the restraining tube end, M_p^r is estimated using the equation proposed by Matsui et al. [26] wherein M_p^r is the minimum of the plastic bending capacity of the T-section neck zone, M_p^{r-neck} , and plastic bending capacity of the restraining tube at the end of the core plate plastic zone, M_p^{r-rest} . The neck zone and plastic zone of the MBRB are shown in Figure 9. For MBRB designs with small insertion lengths, L_i , plastic hinge formation at the ends of the reduced section of the core plate may result in the failure of the restraining tube. In such a case, the capacity to transfer moment at restraining tube end will be limited by the plastic moment capacity of the restraining tube at the plastic zone ends of the core plate, M_p^{r-rest} . For designs with sufficiently long insertion lengths, the plastic hinge occurs at the T-section neck zone of the core plate. Takeuchi et al. [25] concluded that for BRBs with insertion length greater than twice the core plate width, the M_p^r is governed by the plastic moment capacity at the neck zone section, M_p^{r-neck} . For the MBRB specimens, the insertion length ranged between five and ten times the core plate width, and thus the plastic capacity of the neck zone, M_p^r was calculated by Eq. (5). The resulting values are given in Table 4.

$$M_p^r = M_p^{r-neck} = Z_{cp}\sigma_{cy} \quad \text{Eq. (5)}$$

where,

Z_{cp} = Plastic section modulus at T-section neck zone = 4752 mm³ for MBRB specimens

σ_{cy} = Measured yield stress of core plate material (see Table 2)

The secondary moment associated with the out-of-plane drifts observed in BRBs, M_o^r , is taken as zero for the MBRB specimens since there is no lateral displacement at the ends during the testing program or in the SCB configuration. For other configurations where the ends of the MBRB can move laterally relative to one another, see Takeuchi et al. [25].

The effective initial imperfection, a_r , can be caused by a combination of factors as given in Eq. (6). The initial imperfection in the MBRB core plate was assumed as $L_c/500 = 1.8$ mm. The eccentricity of the axial force, e , is due to the offset between the centroid of the core plate and the center of the applied load. Since the axial load was transferred to the MBRB specimens at the weld between the built-up WT section and MBRB ends, the eccentricity, e , was taken as half of the core plate thickness = 4.8 mm. The clearance between the restraining tube and the core plate and was assumed as negligible ($s_r=0$).

$$a_r = a + e + s_r + \frac{2s_r}{L_{in}}\xi L_o = 1.8 + 4.8 + 0 + 0 = 7 \text{ mm} \quad \text{Eq. (6)}$$

To calculate the elasto-plastic buckling strength of the restraining tube, N_{cr}^r , or the global elastic buckling strength of the MBRB, N_{cr}^B , first, the rotational stiffness of the end connections must be evaluated. As shown in Figure 9, the MBRB end connection consists of a built-up WT section with a web thickness of 12.7 mm and stem length, of 76 mm. The rotational stiffness of the WT section is given by Eq. (7). The web has a weak axis moment of inertia, $I_{conn}=21679 \text{ mm}^4$, cantilever length, $L_w = 76 \text{ mm}$, and assuming a nominal modulus of elasticity, $E=200 \text{ GPa}$, results in a rotational stiffness, $K_{Rg} = 285 \cdot E \text{ kN} - \text{mm/rad}$. This calculation assumes that components of the test setup beyond the WT are rotationally rigid.

$$K_{Rg} = \frac{EI_{conn}}{L_w} \quad \text{Eq. (7)}$$

The elasto-plastic buckling strength with pinned conditions at the restraining tube ends, N_{cr}^r , was obtained by substituting the equivalent slenderness ratio, λ_r , given by Eq. (8), into the column curve given in AISC *Steel Construction Manual* as shown in Eq. (9) to find the critical buckling stress, σ_{cr} . The values of λ_r and σ_{cr} is tabulated in Table 3. The buckling strength of the connection zone, N_{cr}^r , can then be obtained as given in Eq. (10) and the resulting values are tabulated in Table 4.

$$\lambda_r = \frac{2\xi L_o}{i_c} \sqrt{\frac{\xi K_{Rg} + 24/\pi^2}{(1-2\xi) \xi K_{Rg}}} \quad \text{Eq. (8)}$$

$$\sigma_{cr} = \begin{cases} \left\{ 0.658 \frac{\sigma_{cy}}{\sigma_e} \right\} \sigma_{cy} & \left(\text{for } \lambda_r \leq 4.71 \sqrt{\frac{E}{\sigma_{cy}}} \right) \\ 0.877 \sigma_e & \left(\text{for } \lambda_r \geq 4.71 \sqrt{\frac{E}{\sigma_{cy}}} \right) \end{cases} \quad \text{Eq. (9)}$$

$$N_{cr}^r = \sigma_{cr} * A_{T-sec} \quad \text{Eq. (10)}$$

where,

ξL_o = Length of the connection zone (see Figure 9) = 216 mm for MBRB-914 series specimens and 158 mm for MBRB-610 series specimens

i_c = Radius of gyration of connection zone, $i_c = \sqrt{\gamma_J I_B / A_{T-sec}} = 6.33$ for MBRB specimens

$\gamma_J I_B$ = Moment of inertia of the T-section at neck zone (formulated here as a constant, γ_J , multiplied by the moment of inertia of the restraining tube, I_B , but could also be calculated directly) = 19980 mm⁴ for MBRB specimens

A_{T-sec} = Area of the T-section at neck zone = 499 mm² for all the MBRB specimens

ξK_{Rg} = Normalized rotational stiffness for the built-up WT section (see Table 3),
 $\xi K_{Rg} = K_{Rg} \xi L_o / (\gamma_f E I_B)$
 σ_{cy} = Yield stress of core plate material (assuming that neck and core are same material)
 σ_e = Euler buckling stress given by $\sigma_e = \pi^2 E / \lambda_r^2$ (see Table 3)

The global elastic buckling strength of the MBRB considering the rotational stiffness of the end connections, N_{cr}^B , is calculated using Eq. (11).

$$N_{cr}^B = \frac{4\pi^2 E I_B}{L_o^2} \frac{{}_L K_{Rg}^2 + 10 {}_L K_{Rg} + 16}{{}_L K_{Rg}^2 + 14 {}_L K_{Rg} + 64} \quad \text{Eq. (11)}$$

where,

I_B = Moment of inertia of the restraining tube = 133000 mm⁴ for MBRB specimens
 L_o = Total length of the MBRB specimen (see Table 3)
 ${}_L K_{Rg}$ = Rotational stiffness for the built-up WT section normalized by total length, ${}_L K_{Rg} = K_{Rg} L_o / (E I_B)$ (see Table 3)

Both stability checks were performed for all specimens tested and the results are presented in Table 4. The first stability criterion (enforcing the maximum axial strength of the MBRB core plate at the reduced section after hardening to be less than N_{lim1}) was satisfied for all specimens, ensuring that the core plate will yield before the MBRB experiences global buckling due to plastic hinge formation at the connection zone. Table 4 also shows that the capacity associated with the second stability criterion, N_{lim2} , was 40% and 110% larger than that for the first stability criterion, N_{lim1} , for the MBRB 914 and MBRB 610 series MBRBs, respectively.

It was also observed that the buckling capacities are much less sensitive to the core dimension (variations within the MBRB 914 and 610 sets) as compared to the length of the specimen (primary difference between the MBRB 914 and 610 sets). Since MBRBs with shorter connection zone length ξL_o and total length L_o resulted in larger expected failure axial force, N_{lim1} for the MBRB-610 series specimens it is clear that shorter connection zone length and total length is desirable to promote stable MBRB behavior. However, the smaller the axial strength of the MBRB core plate, the less likely it is to undergo global buckling prior to core plate yielding (i.e. less likely that N_{cu} is less than either limit).

Table 3: End stability check related parameters for MBRB specimens

Specimen ID	A_c (mm ²)	L_o (mm)	ξL_o (mm)	ξK_{Rg}	LK_{Rg}	λ_r	σ_e (MPa)	σ_{cr} (MPa)
MBRB -610-7.1	67.5	902	158	1.93	2.25	93	224	194
MBRB -610-11.6 (a&b)	110	902	158	1.93	2.25	93	224	194
MBRB -914-11.9	113	1435	216	3.08	3.08	109	168	148
MBRB -914-17.8	169	1435	216	3.08	3.08	109	168	148
MBRB-914-22.9	218	1435	216	3.08	3.08	109	168	148

Table 4: End stability check for MBRB specimens

Specimen ID	N_{cr}^B (kN)	N_{cr}^r (kN)	M_p^r (kN-mm)	N_{cu} (kN)	N_{lim1} (kN)	N_{lim2} (kN)	Check ($N_{lim1} > N_{cu}$ & $N_{lim2} > N_{cu}$)
MBRB -610-7.1	550	97	2138	39	259	548	OK
MBRB -610-11.6 (a&b)	550	97	2138	64	259	550	OK
MBRB -914-11.9	242	74	2076.6	61	166	232	OK
MBRB -914-17.8	242	74	2076.6	92	166	231	OK
MBRB-914-22.9	242	74	2076.6	119	166	230	OK

6. Miniature BRB Test Results

This section presents the cyclic testing results of six MBRB specimens. The discussion of test results includes hysteretic behavior of the MBRBs, initiation of local buckling in the core plate, and failure modes. The MBRB cyclic behavior was also quantitatively evaluated and peak quantities were calculated for each specimen.

Force- deformation behavior of the MBRB specimens is presented in Figure 10. The deformation of the MBRB as measured by wire potentiometer WP-1 (refer Figure 7), has been normalized to the core plate length to get an effective strain. This effective strain is approximately equal to the average axial strain in the core plate assuming that the connection regions are relatively rigid compared to the core plate. The MBRB force has been normalized to **the yield strength based on measured yield stress and measured area of each** specimen as given in Table 1.

Figure 10: Force-deformation behavior of MBRB test specimens

Figure 10 shows that the specimens consistently experienced peak cycle forces at or above the expected yield strength, suggesting that the axial force capacity of the MBRB is predictable. All specimens exhibited full and stable hysteretic behavior up to failure in the MBRB core plate. No end connection failure or global instability was observed in any of the test specimens, suggesting

that the stability criteria used in the design of the MBRB end connections successfully prevented buckling. Peak axial tension forces and compression forces reached as high as approximately 1.25 and 1.5 times the expected yield force, respectively. Larger forces in compression are due to increased friction forces between the core and the surrounding restraining apparatus resulting from Poisson's effect. The amount of hardening in tension and compression will be analyzed later in this section.

The specimens experienced a considerable number of inelastic loading cycles before exhibiting a loss of axial capacity. For all specimens, strength degradation occurred during the compression excursion one to two cycles before the tension excursion associated with core fracture. This strength degradation is identified in Figure 10 as likely due to grout crushing. Although there was no external visible damage on the MBRB, based on subsequent analysis of the failed specimens presented later in this section, it was concluded that this degradation in compressive strength likely occurred as the grout started to crush in a localized region adjacent to some of the core plate local buckles. As a result, the amplitude of those local buckles increased and fracture ensued. This type of hysteretic behavior is similar to that observed by Iwata et al. [29] in all-steel BRBs wherein the restraining mechanism failed allowing larger amplitude local buckles in the core plate.

The peak strains at which strength degradation initiated appeared to be related to the core plate aspect ratio (width to thickness, W_c / t_c). For example, specimens MBRB-610-7.1, MBRB-610-11.6(a or b), and MBRB-914-22.9 with aspect ratios of 1:0.75, 1:1.22, and 1:2.41, respectively, experienced strength degradation during cycles with effective core plate strains of 0.02 mm/mm, 0.03 mm/mm and 0.036 mm/mm, respectively. Specimen MBRB-914-17.8 with the second largest aspect ratio of 1:1.87 sustained the largest strain cycles at 0.04 mm/mm.

The strain hardening adjustment factor, ω , is calculated based on Eq. (12) and gives an indication of the magnitude of material strain hardening. The maximum value of the factor for any cycle beyond first significant yield of the MBRB core plate is reported in Table 5 as the maximum strain hardening adjustment factor. This is consistent with the way references such as AISC 341-10 [1] require reporting of the peak value during a test rather than an average for BRBs.

$$\omega = \frac{T_{max}}{P_y} \quad \text{Eq. (12)}$$

where,

T_{max} = Maximum tension force measured during each cycle

P_y = Axial yield force of the MBRB specimen based on measured yield area

It is shown in Table 5 that the set of test specimens had an average maximum strain hardening adjustment factor, ω , of 1.22 and largest value of 1.26 for specimen MBRB-914-22.9. This

magnitude if similar to values reported for buckling restrained braces and as expected does not show large variation because it is related to material behavior. Although the MBRB-610 series and MBRB-914 series of specimens used different plate material, the properties were similar (see Table 2) with ratio of ultimate stress to yield stress of 1.29 and 1.24, respectively.

The compression strength adjustment factor, β , is calculated using Eq. (13) as the ratio of the peak compressive force to the peak tension force in each cycle. Similar to the strain hardening adjustment factor, the maximum value of the factor for any cycle beyond first significant yield of the MBRB core plate is taken as the maximum compression strength adjustment factor and is reported in Table 5.

$$\beta = \frac{C_{max}}{T_{max}} \quad \text{Eq. (13)}$$

where,

C_{max} = Maximum compression force measured during each cycle

The MBRB specimens produced maximum values of the compression strength adjustment factor between 1.07 and 1.28. Unlike the strain hardening adjustment factor which is related to a material property, the compression strength adjustment factor is related more to the detailing and construction of the MBRB. Increased compression forces related to friction between the core and the restraining mechanism is sensitive to the space provided to allow Poisson's expansion of the core. AISC 341-10 [1] includes an acceptance criterion for BRBs wherein the measured maximum compression strength adjustment factor shall not exceed 1.3. It is shown in Table 5, that all the MBRB specimens satisfy this criterion and therefore, it is concluded that sufficient space for core expansion was provided by the MBRB detailing described previously.

Based on the measured values of strain hardening adjustment factor and compression strength adjustment factor, a conservative estimate (using the largest values of both) for the peak forces that could be produced by the MBRB would be approximately 1.6 times the yield force as calculated based on expected yield stress. This is consistent with the peak forces shown in Figure 10 and gives designers an estimate of the largest forces that can be produced by the MBRB for use in the design of surrounding structural elements.

Since the MBRBs have been designed as sacrificial fuse elements to prevent damage to the primary structure, the deformation capacity of these elements is an important benchmark of their performance. In this paper, the measured deformation capacity of the MBRB was quantified with three parameters given in Table 5. A normalized cumulative inelastic axial deformation, μ , was calculated as given by Eq. (14). The peak core strain was calculated as the peak MBRB deformation divided the core length. The cumulative plastic strain of the core plate, $\varepsilon_{cum,p}$, was calculated by taking twice the plastic strain accumulated in each half cycle, ε_{ph} and summing it

up for a given displacement amplitude level, as given in Eq. (17) and Eq. (18) [27]. All the resulting values are provided in Table 5.

$$\mu = \sum_{i=1}^{nc} \left(\left[\frac{(\delta_i^+ + \delta_i^-)}{\delta_y} - 2 \right] > 0 \right) \quad \text{Eq. (14)}$$

where,

nc = Number of cycles

δ_i^+ = Maximum tensile deformation and δ_i^- the maximum compressive deformation in the core plate for the i^{th} cycle.

δ_y = Axial deformation associated with the yield of the MBRB core plate and was calculated using Eqs. (15) and (16) and reported in Table 5.

$$\delta_y = \frac{A_c \sigma_{cy}}{K_e} \quad \text{Eq. (15)}$$

$$K_e = \frac{1}{\frac{1}{K_c} + \frac{2}{K_{T-sec}} + \frac{2}{K_{WT-axial}} + \frac{2}{K_{WT-bending}}} \quad \text{Eq. (16)}$$

where,

K_c = Elastic stiffness of the reduced section of the MBRB

K_{T-sec} = Elastic stiffness of the neck zone of the MBRB specimen

$K_{WT-axial}$ = Axial stiffness of the built-up WT-section

$K_{WT-bending}$ = Bending stiffness of the built-up WT section

It is noted that the elastic stiffness of the reduced section of the core plate, K_c , contributed to an average of 85% of the effective flexibility of the whole MBRB system including the end connection pieces.

$$\varepsilon_{cum,p} = \sum_{k=1}^M 2N_k \varepsilon_{ph,k} \quad \text{Eq. (17)}$$

$$\varepsilon_{ph} = (\varepsilon_{T,peak} - \varepsilon_{C,peak}) - \left(\frac{\sigma_{T,peak} - \sigma_{C,peak}}{E} \right) \quad \text{Eq. (18)}$$

where,

N = Number of cycles per displacement amplitude level

M = Number of displacement amplitude levels

$\sigma_{T,peak}$ and $\sigma_{C,peak}$ = Peak stresses in tension and compression for a displacement amplitude level calculated by dividing the MBRB axial force by the measured core plate cross-sectional area.

$\varepsilon_{T,peak}$ and $\varepsilon_{C,peak}$ = Peak strains in tension and compression for a displacement amplitude level, calculated by dividing the MBRB axial deformation by the core plate length.

Table 5: Summary of test results

Specimens	Aspect ratio (W_c/t_c)	Yield Force, P_y (kN)	Max ω	Max β	δ_y , (mm)	μ , (δ_y)	Peak core strain (%)	Cum. Plastic strain, $\varepsilon_{cum,p}$ (%)
MBRB-610-7.1	0.75	30	1.21	1.07	1.54	223	3.0%	56%
MBRB-610-11.6a	1.22	50	1.21	1.22	1.63	285	4.0%	79%
MBRB-610-11.6b	1.22	50	1.18	1.07	1.63	225	3.0%	66%
MBRB-914-11.9	1.25	49	1.24	1.18	2.26	181	2.8%	46%
MBRB-914-17.8	1.87	74	1.22	1.28	2.41	400	4.5%	106%
MBRB-914-22.9	2.41	95	1.26	1.21	2.54	267	3.8%	78%

As shown in Table 5, the two specimens with the largest aspect ratios, Specimens MBRB-914-22.9 with $W_c/t_c = 2.41$ and MBRB 914-17.8 with $W_c/t_c = 1.87$, produced two of the largest cumulative inelastic deformation capacities equal to $\mu = 267 \delta_y$ and $\mu = 400 \delta_y$, respectively. Conversely, the two specimens that produced the smallest cumulative inelastic deformation capacities, $\mu = 181 \delta_y$ and $\mu = 223 \delta_y$, had low aspect ratios: Specimens MBRB-914-11.9 with $W_c/t_c = 1.25$ and MBRB 610-7.1 with $W_c/t_c = 0.75$, respectively. Based on these observations, it appears that there is a link between the aspect ratio of the core and the cumulative inelastic deformation capacity of the MBRBs.

There may also be a relationship between core length and cumulative deformation capacity. Specimen MBRB-914-11.9, which produced the smallest cumulative deformation capacity, $\mu = 181 \delta_y$, had a similar aspect ratio as MBRB-610-11.6a and MBRB-610-11.6b but longer core length ($L_c = 914$ mm vs. $L_c = 610$ mm). The longer MBRB-914-11.9 resulted in only 64% and 80% of the cumulative inelastic deformation of Specimens MBRB-610-11.6a and MBRB-610-11.6b, respectively. The same trend can be observed in the cumulative plastic strain which was $\varepsilon_{cum,p} = 46\%$ for the longer MBRB-914-11.9 as compared to $\varepsilon_{cum,p} = 79\%$ and $\varepsilon_{cum,p} = 66\%$ for the shorter MBRB-610-11.6a and MBRB-610-11.6b, respectively.

It was found that all the specimens except MBRB-914-11.9 satisfied the AISC 314-10 [1] requirement for BRB qualification that they achieve a cumulative inelastic axial deformation of 200 times the yield deformation. That suggests that the tested configurations possess substantial ductility, similar to conventional BRBs. The values reported in Table 5 for cumulative inelastic deformation capacity, peak core strain, and cumulative plastic strain, could be useful for designers implementing the MBRB in a seismic system.

In terms of variability, it was observed that MBRB-610-11.6a and MBRB-610-11.6b specimens, which had identical designs, produced slightly different behavior. MBRB-610-11.6b experienced strength degradation during an earlier cycle (1st cycle of 3% strain) as compared to MBRB-610-11.6a which reached 4% peak strain (two cycles later in the displacement protocol)

before it fractured. The cumulative inelastic axial deformation, μ , for MBRB-610-11.6a was 27% larger than MBRB-610-11.6b. Two possible sources of differences were identified that may explain this type of variability in the behavior of nominally identical MBRB specimens. First, the buckling of the MBRB is expected to be sensitive to the initial imperfections in the core plate. It was observed that the welding of the wing plates at the connection regions causes some bending of the reduced section of the core plate due to differential cooling rates. The magnitude of this initial imperfection was observed to vary. Second, the compressive strength of the grout may vary depending on factors such as water content, air moisture content and temperature.

After the testing was completed, the core plate was removed from the grouted restraining tube. As shown in Figure 11, the core plate buckled in a higher-order mode along the weak axis of the MBRB core plate. The amplitude of the buckles was quite small relative to the core thickness over most of the core length. However, near the ends, one or two local buckles were found to have increased amplitude that implies the surrounding grout was crushed at these locations. All of the MBRB specimens experienced fracture at one of the larger amplitude local buckles such as shown in Figure 12 and Figure 13. In some cases, such as Specimen MBRB-914-22.9 shown in Figure 13, the local buckle of the core became large enough to cause a section of the restraining tube to deform outward and ultimately fracture in a punching shear mode. The specimen shown in Figure 13 has the largest core and thus the largest axial yield force. Specimens with smallest cores did not experience failure of the restraining tube. Specimen MBRB-610-7.1 had a core width smaller than the thickness, and as expected, experienced buckling in the plane of the core plate.

Figure 11: Buckling of MBRB core plate in higher-order mode

Figure 13: Failure mode MBRB-914-22.9 (a) Core plate buckling in the weak axis (b) magnified view of the fracture core end (c) fracture in the restraining tube where the core plate buckled

7. Design Recommendations based on experimental results

The design of the MBRB can be tuned to produce the desired deformation capacity and strength. For a given axial force demand, the yield strength of the MBRB can be adjusted by selecting the core plate width, thickness, and yield stress. Special attention should be paid to selecting the aspect ratio. For MBRBs with core lengths such as the tested specimens with $L_c=610$ mm, the aspect ratios of $W_c / t_c = 0.75$ to 1.22 produced 3% peak strain and adequate cumulative inelastic deformation capacity to pass AISC 341-10 BRB qualification [1]. For the longer MBRBs such as the tested specimens with $L_c=914$ mm, aspect ratios between $W_c / t_c = 1.87$ to 2.41 were capable of sustaining large peak strains, cumulative plastic strain, and cumulative inelastic deformation. Conversely, the $L_c=914$ mm specimen with the lower aspect ratio of $W_c / t_c = 1.25$ was unable to pass BRB qualification and thus may not be desirable. Since the failure mode was

similar to the other specimens (e.g. Figure 11), and because MBRB-914-22.9 had similar cumulative strain as MBRB-610-11.6, it is concluded that larger aspect ratios may be required for the longer core lengths to achieve the same amount of cumulative deformation capacity.

Based on the experimental results, larger aspect ratios are expected to produce more cumulative deformation capacity. However, comparing cumulative deformation capacity of specimens MBRB-914-17.8 and MBRB-914-22.9, it was observed that increasing the aspect ratio beyond a certain limit may not improve the performance of the MBRB any further. Investigating a similar issue, Iwata et al. [28] conducted a series of tests on BRBs with varying thickness to width aspect ratio of the BRB core plate. The study, which varied the aspect ratio from $W_c/t_c = 4$ to 11, concluded that BRB designs with smaller aspect ratios performed better and sustained higher levels of deformation before failure. Based on that study, it may be desirable to keep the MBRB core aspect ratio from exceeding $W_c/t_c = 4$.

To provide sufficient deformation capacity, the length of the core plate reduced section can be adjusted. Except for Specimen MBRB-914-11.9 which has a geometry not recommended above, all MBRB specimens achieved a minimum of 3% peak core strain and a cumulative plastic strain of 56%. These values of strain capacity and cumulative plastic strain capacity may be useful in designing the length of the core plate for specific applications with defined strain demands.

It is also important to provide sufficient insertion length, L_i of the core plate inside the restraining cylinder. Although none of the MBRB specimens tested experienced global buckling failure or instability of the connection region, previous testing and design recommendations identify insertion length as an important parameter [25]. The insertion length for the tested specimens was between five and ten times the width of the core plate.

8. Summary and conclusions

A small capacity buckling restrained brace was designed, fabricated and tested. The miniature buckling restrained brace (MBRB) has a steel core plate that deforms axially while a restraining tube filled with grout prevents the core plate from buckling in compression. An experimental program was conducted on six MBRB specimens with varying core plate width (7.1 mm to 22.9 mm), core plate length (610 mm and 914 mm) and insertion length while keeping the core plate thickness constant (9.5mm).

In the design of the end connection pieces, the possibility of global instability in the MBRBs due to end connection failure was explored and two stability criteria from the literature were used to prevent premature failure due to global buckling of the MBRB. It was shown that the stability criteria used to ensure stable behavior of MBRB, depends not only on the design parameters of the MBRB such as the core plate cross-section, neck zone cross-section, restraining tube design, and insertion length, but also on the characteristics of the pieces connected to the MBRB such as connection zone length and rotational stiffness of the end connection.

Both 610 mm and 914 mm long specimens were capable of sustaining average peak strains (before failure) of about 3.5%. MBRB-610 and MBRB-914 series specimens sustained an average cumulative inelastic deformation of 244 and 282 times the axial deformation associated with core plate yield respectively. In terms of cumulative plastic strain, MBRB-610 and MBRB-914 specimens underwent an average of 67% and 77% strain respectively before failure. In general, all the MBRB specimens showed slight strength degradation as the grout crushed locally followed by core plate fracture in the same or subsequent loading cycle. Five out of six specimens were also shown to satisfy the acceptance criteria set by AISC 341-10 for BRB designs in terms of cumulative axial deformation, μ and the compression strength adjustment factor, β .

Design recommendations were developed based on the tested configurations. It was found that the core plate aspect ratio (ratio of core width to thickness) has an influence on the cumulative deformation capacity of the MBRB. Values for the aspect ratio were suggested based on MBRB specimens that produced large cumulative inelastic deformations that satisfied BRB qualification criteria in AISC 341-10.

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