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PROOF-OF-CONCEPT AND EXPERIMENTAL QUALIFICATION FOR A REPAIRABLE BUCKLING-RESTRAINED BRACE (BRB)

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Abstract. *Reinforced concrete buildings designed and built before enacting modern seismic codes are considered seismically vulnerable, particularly when subjected to strong ground motions. These buildings require retrofitting to increase building strength, stiffness, and energy dissipation. Among the practical retrofitting methods is Buckling Restrained Braces (BRBs). An experimental investigation was carried out on a new type of BRB of circular steel core bar. The core is protected against buckling using a steel/mortar composite sleeve and novel end pieces that provide continuous restraint against buckling. The BRB core unit sample is stainless steel, with all threaded cross-sections. The BRB specimen underwent uniaxial cyclic loading following the AISC 341 qualification testing protocol. The experimental results showed that the BRB system successfully passed the qualification testing protocol by attaining the required cumulative displacements. In addition, The successful tests showed a stable hysteretic response in the tension and compression phase of loading and a significant ductility of* $\mu=4$.

1. INTRODUCTION

In an earthquake, structures are subjected to seismic load resulting in lateral deformations. Traditionally these lateral deformations are controlled by lateral supporting systems or braces for the existing buildings. The common practice in the construction industry is to design and build structures with moment resisting frames that typically can experience high lateral deformations in the occurrence of an earthquake. The lateral deformation can damage the structural and nonstructural members, which may affect the structure's integrity [1], [2].

Conventionally the existing buildings vulnerable to seismic loads are braced. These braced frames are standalone steel section that works under tension and compression. The governing failure mode in braces is buckling under compressive forces depending on the corresponding slenderness ratio. In addition, the conventional steel brace frames (CSBFs) exhibit an asymmetrical tension-compression behavior (hysteresis) under cyclic loading with signs of load capacity degradation under compression [1]–[3].

An alternative for the CSBFs is the emerging steel braces restrained from buckling under compression called Buckling Restrained Braces (BRBs). BRBs have exhibited more energy dissipation capacity and have an almost symmetric and stable hysteresis behavior with around 30% higher compression capacity than tension capacity [4]-[7]. In contrast to the CSBFs, BRBs are fabricated from two main components: yielding inner unit (core), outer restraining tube (jacketing case), and a third component, the end connection for fitting the BRB in the building. The core comes in cross-section shapes such as rectangular or circular. The core is usually made of three segments; end parts (none restrained), non-yielding zone (restrained), and yielding zone (restrained). Compared to CSBFs, the core in BRB is jacketed with a concrete-encased steel pipe to prevent global buckling failure when loaded under compressive forces. Thus, the BRB will exhibit a similar compression behavior to tension [8], [9]. Several researchers have studied BRB's design and applications in the literature [10]–[14]. For example, Yooprasertchai and Warnitchai [15] conducted a study to investigate the BRB application in a low-rise reinforced concrete building. The tested BRB had a rectangular steel core and a mortar-filled outer case. The BRB was subjected to a quasi-static cyclic loading in the test setup, diagonally. In another study, Takeuchi et al. [16] proposed a simple method for predicting the energy absorption

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capacity of BRBs under random force amplitudes. Many recent studies investigated various methods to enhance the seismic behavior of RC structures. Specifically, alternate construction materials, such as BRBs replacing conventional braces, FRP bars replacing standard steel reinforcement, etc. This led to substantial enhancements to numerous aspects of structural behavior, as described in [18]-[39]. Moreover, cost benefits were reported for several seismic applications [40]-[52].

This paper aims to propose and test an innovative BRB by performing the qualification test per the AISC 341 requirement. One unique difference of the proposed BRB with the existing BRB in literature is the absence of internal longitudinal gaps along the bar length, typical in all other BRBs. This gap is provided in conventional BRB systems at the ends of the non-yielding zone to facilitate the shortening of the core under compression. The proposed BRB is design facilitates the core shortening under compression while being restrained continuously along its length without any gap at the mentioned location. Innovative end units were employed to allow the interior core steel bar to extend and contract while maintaining continuous lateral restraint against buckling.

2. EXPERIMENTAL PROGRAM

According to qualification standards AISC 341 [52] provision test protocol, the BRB was tested under uniaxial cyclic loadings. In practice, the tested BRB is 1/3 of an actual size BRB to facilitate the testing inside the available structural laboratory.

2.1 Fabrication and assembling

The BRB is manufactured from two distinct main parts: a Hollow Structural Steel (HSS) mild steel buckling restraining pipes filled with grout and a stainless-steel (SS) core bar (Figure 1), and an innovative third part called end units (Figure 2). The reason for favoring stainless steel for core bar over mild steel is its remarkable elongation properties from the tensile coupon tests and test results reported in the literature. Thus it will enhance the ductility and energy dissipation properties of BRB. Novel end units will facilitate the push-pull loading of the core without force transmission to the BRB's buckling restraining pipe.

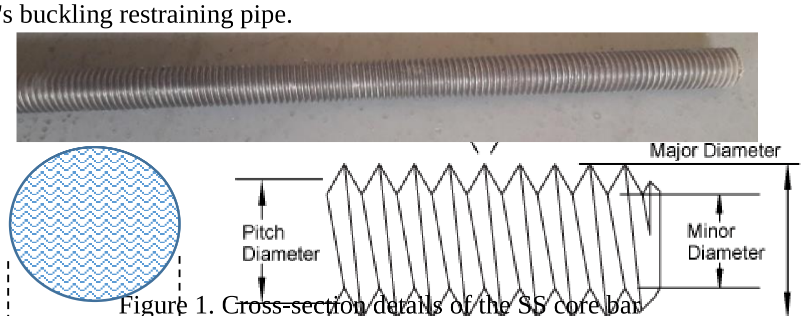

Figure 1. Cross-section details of the SS core bar

The restraining part is made of one external HSS pipe (88.9 mm outer diameter, 4 mm thickness, and 1115 mm length), one internal HSS pipe is inserted into the external pipe with a steel ring (17 mm outer diameter, 2 mm thickness, and 805 mm length). The gap between the external and internal pipes is filled with grout (with a compressive strength of 60 MPa) to save in material usage and also reduce the total weight of BRB. A total of 1 mm (0.5 mm around the core bar) longitudinal gap was left between the core bar and internal pipe to accommodate the lateral deformation of the core bar and prevent the restraining unit from resisting applied axial load.

The SS core bar had a 12 mm diameter, a yield strength of 585 MPa, a yield strain of 0.0032%, and an elongation of 25%. The reason for selecting a fully threaded bar was to overcome the possible cross-sectional area reduction at the location of fitting hinges. Because in the case of a smooth bar, the end parts need to be threaded for inserting fixing nuts to assemble the BRB, resulting in less cross-sectional area than the intact smooth (unthreaded) yielding zone in the middle region. The core bar yielding length is 660 mm, while 330 mm is the transition zone on each end, totaling the bar length to 1320 mm, whereas part of the length is kept for the insertion of the end units.

A novel end unit made of mild steel was used at both ends of the BRB to eliminate any possibility of core bar buckling (Figure 2). During bar axial elongation and shortening, the two end fingers will move relative to each other. The fingers, end connection hinges, and the internal pipe were used to couple the core bar with the restraining unit while allowing the core bar to extend or contract during loading and provide continuous restraint to the core bar throughout its length. An external gap of 40 mm was kept at each side between the external steel pipe and the steel hinge plates. This gap was designed to accommodate the BRB steel core bar's expected lateral deformation in the qualification testing while having no contact between the external steel pipe and the steel plate at either side of the BRB sample. Heavy-duty steel bolts were used to fasten the BRB parts and fix the BRB to hinge joints fixed at either side of the test setup (actuator and base support). These hinges provide zero moment forces to the BRB steel core bars. The total length of BRB with end connection hinges was 1650 mm. Figure 3 shows all parts of the BRB before assembly.

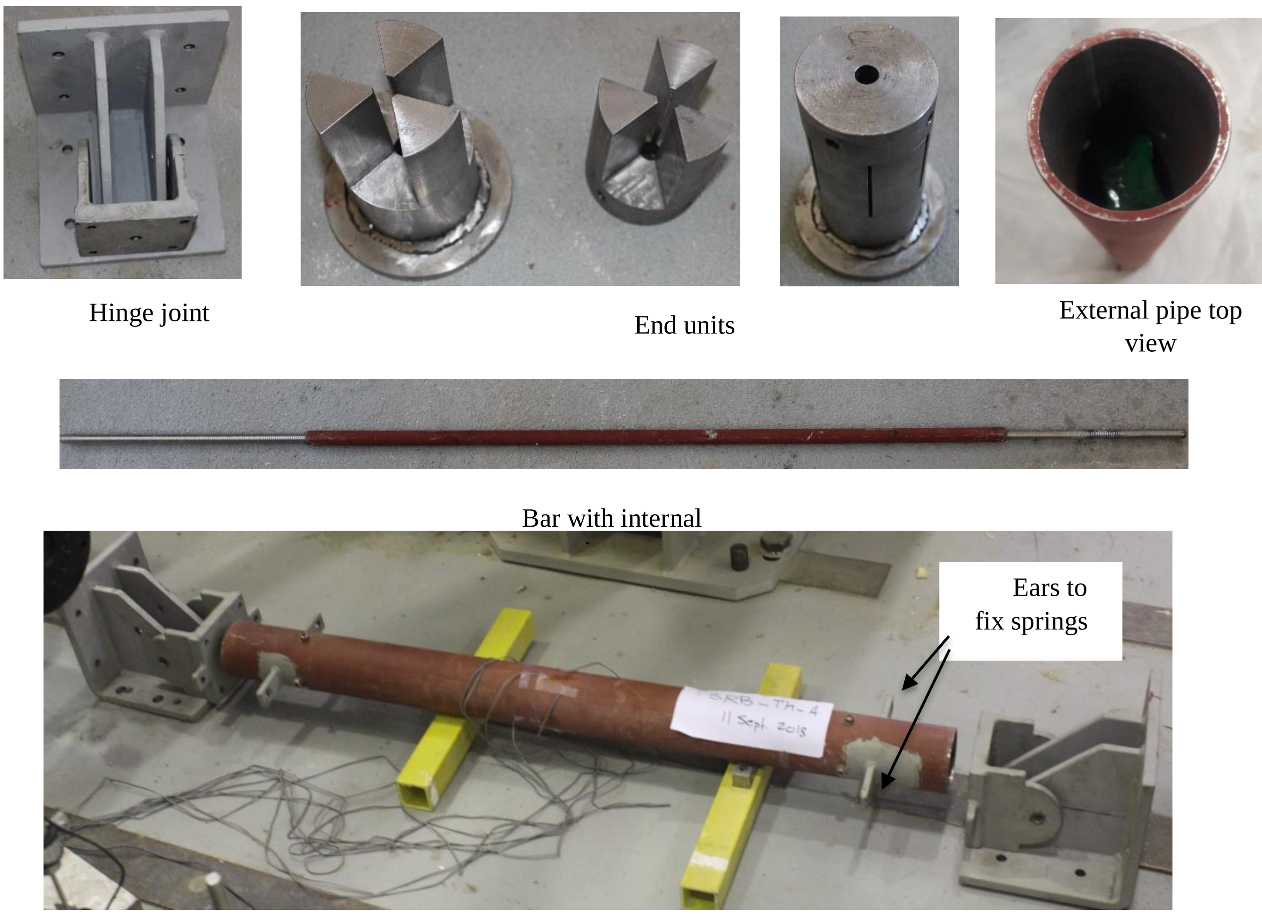

Figure 2. Actual photo of the hinge joint, end units, and restraining unit

To assemble the BRB, the core bar was first inserted through the built-in internal pipe surrounded by the grout-filled external pipe, followed by the insertion of the internal and external parts of the end unit. Holes were drilled on the external pipe at two ends to bolt the inner fingers (Figure 3). The external end unit was inserted afterward and bolted to the end connection steel plate called hinges before placing the BRB in the test setup. Two springs of high stiffness were used to keep the restraining end units in position during testing (horizontally or inclined) and to maintain a 40 mm gap at both ends of the BRB (between the two end units on each side of the BRB). The springs were fixed on both BRB ends between the welded plates to external pipe so-called ears (as shown in Figure 2). Steel nuts were used inside and outside the connection hinges steel plates to activate the core bar under tension and compression load cycles.

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Figure 3. Assembling Process of the BRB

2.2 Experimental testing

The BRB specimen was tested under uniaxial tension-compression load cycles using a hydraulic actuator with a displacement capacity of ± 75 mm (150 mm) and a load capacity of ±100 kN. The specimen was installed using the hinge joints (Figure 2) between two rigid fixed supports where one end had the actuator connected to apply the axial load while the other end acted as a rigid wall. Figure 4 shows the BRB ready for the test with instrumentation deployed. The instrumentation added were two Linear Variable Displacement Transducers (LVDTs), one vertical and one horizontal, to measure the possible out-of-plane deformation of the external pipe. Additional two LVDTs were placed on both ends of the test setup to monitor the displacements of supports if it happens during testing. In addition, a video recording camera was included in the test setup to observe the behavior of the BRB while testing.

The value of axial deformation quantity at the first significant yield of the test specimen is labeled Δ_{by}. The total axial deformation of the tested BRB are multiples of this term (Δ_{by}). The aforementioned axial deformation is used to control the AISC 341 provision test protocol [52]. For the threaded stainless steel (SS) core bar of the tested BRB, the value of yield deformation Δ_{by} (i.e., ΔL_e) was calculated from the mechanical properties to be 4 mm.

The BRB was tested in a displacement control mode under cyclic loading as per the AISC 341 provision (Table C-T6-1) [52], where the brace axial deformation corresponds to the design story drift was set to be four times the yield deformation, Δ_{by}, and that the design story drift is larger than the minimum 2 percent. As per AISC 341 [52], the BRB

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should resist a cumulative deformation of not less than 200 Δ_{by} before failure. The loading rate was constant at 0.25mm/sec for the test duration. Further details of The test protocols are given in Table 4.

Top view Side view

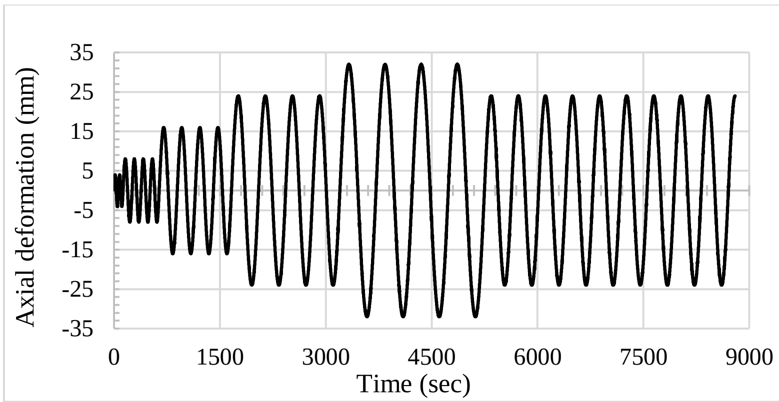
Figure 4. Instrumentation of BRB within the testing facility

Table 1: Test protocol for the threaded bar

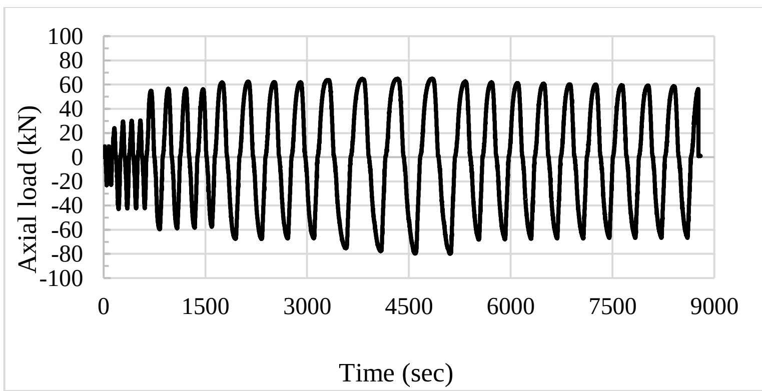
Amplitude	# of cycles	Accumulative # of cycles	Deformation	Axial deformation (mm)	Inelastic deformation	Accumulative inelastic deformation
1	2	2	1 Δ_{by}	4	0 Δ_{by}	0 Δ_{by}
2	4	6	2 Δ_{by}	8	8 Δ_{by}	8 Δ_{by}
3	4	10	4 Δ_{by}	16	24 Δ_{by}	32 Δ_{by}
4	4	14	6 Δ_{by}	24	40 Δ_{by}	72 Δ_{by}
5	4	18	8 Δ_{by}	32	56 Δ_{by}	128 Δ_{by}
6	8	26	6 Δ_{by}	24	80 Δ_{by}	208 Δ_{by}
7	2	28	6 Δ_{by}	24	20 Δ_{by}	228 Δ_{by}

3. DISCUSSIONS OF RESULTS

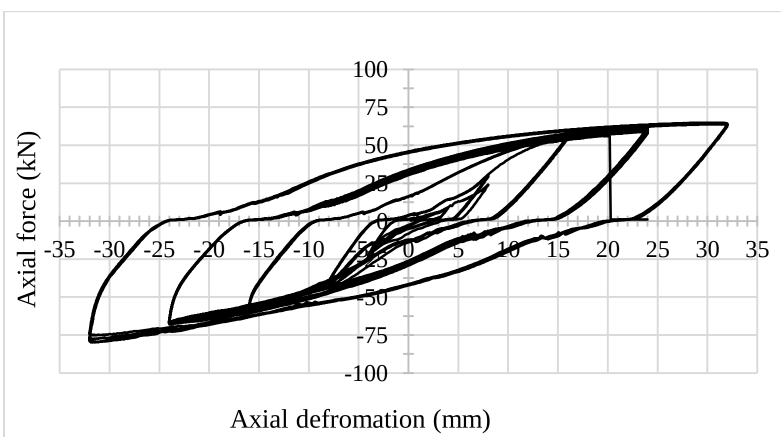
The loading cycles applied to the BRB as per the test protocol, and the resulted hysteresis response are shown in Figure 5. Figure 5a represents the axial deformation of the BRB, while Figure 5b shows the load both vs. time during the testing protocol. The BRB withstands a maximum axial load capacity of 65 kN in tension and 80 kN in the compression cycles, at an axial deformation of ± 32 mm with a ductility ratio of 4. The yielding deformation was 8 mm, and the yielding load was 32 kN, while in the push cycle, the yielding deformation was 8 mm, and the yielding load was 41 kN. The yielding and ultimate forces are higher on the push side (compression on the bar), which is an agreement to the literature [4],[5].



(a)



(b)



(c)

Figure 5. Hysteresis relationships for the BRB specimen.

The tested BRB completed the AISC qualification test. It surpassed the AISC set limit of having a cumulative deformation not less than 200 Δ_{by}. The proposed BRB could survive 27 push-pull cycles before failing in the 28th cycle. The BRB failed after resisting an accumulative inelastic deformation of 218 $\Delta_{by.}$ The BRB also exhibited a stable and repeatable hysteric characteristic under tension and compression (Figure 5c). Eventually, it failed in the pull cycle under tension, as can be noticed from the drop in the hysteresis. The energy dissipation is calculated by finding the cumulative area under the hysteresis curves divided by the corresponding number of cycles to get an average value per cycle. The tested BRB dissipated an energy amount of 12412 kN.mm.

Figure 6 – Photo of the BRB core bar upon failure

The BRB was dismantled to examine the core bar's location and type of failure. Figure 6 shows the tested BRB with typical buckling waves in one end and fractures in the other end. The fracture location of the core bar coincided with the location of the end unit.

4. CONCLUDING REMARKS

An experimental investigation was carried out on a new type of buckling restrained brace, BRB, as a seismic retrofit strategy. The BRB has a ductile inner steel core bar embedded in two steel tubes filled with mortar. Novel end units, called fingers, were used to provide full longitudinal restraint while the BRB core bar undergoes longitudinal tension and compression deformation. The BRB cross-sectional steel core bar is stainless steel of all threaded types to avoid any reduction in the cross-sectional area when securing the bars to steel hinges at either side of the bar. These hinges provide free induced moments on the BRB and could be connected, in practice, to column beam joints. The new type BRB is reusable after an earthquake event and could be replaced for only the inner core bar while other parts are utilized as restraining elements. The BRB tested according to the AISC 341 qualification testing protocol. The hysteretic response results showed stable behavior in the tension and compression cycles and a ductility ratio of $\mu=4$. In addition, the BRB accumulated inelastic deformation of 218 $\Delta_{by,}$ which is beyond the acceptable limit of the testing protocol.

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