Experimental Study of an All-Steel Two-Segment Core Buckling Restrained Brace

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ABSTRACT

Buckling Restrained Braces (BRBs) have been exceedingly used for resisting seismic forces in framed structures because of their advantages of non-buckling and large energy absorption capacities. A type of fully steel brace has been designed in the present study that provides ease of construction and replacement of the core. The term multi-zone indicates that the part of the core undergoing plastic deformation is divided into two or more segments in order to provide a more uniform distribution of the plastic deformation. In other words, the core consists of two or more segments that can become plastic. The end parts of the core and shield are so designed as to eliminate the problems that have existed in the previous designs. The aim here is to produce a robust type of brace that can be constructed without strict building requirements, and the test results show that this has been achieved. Three ½ scale specimens were constructed for testing. These specimens were tested under quasi-static loading up to a target displacement. The results for all three specimens tested show that minimum values of parameters specified by the AISC Steel code (maximum compressive stress factor, $\beta = 1.3$, and minimum energy absorption factor $\eta = 200$) have been achieved and in all cases they exceeded the code requirements by a large margin (here: $\beta_{max} = 1.21$, $\eta_{min} = 1102$). In addition, each specimen was capable of carrying several additional cycles of loading (11 or more) at the end of the test. That is, they are more robust against fatigue than that specified by the said AISC code. Cyclic behavior of the specimens showed high energy absorption capabilities with strains of up to 4.6%. Based on the test results, it can be concluded that the multi-zone core BRB's with stiffened shield and restraining device tested here are suitable for use in new buildings as well as in retrofit of existing structures. The idea of using multi-zone cores not only allows for a better distribution of plastic region, but also enables us to stabilize the shield to the core at the middle zone, where no plastic deformation takes place. In this way, the stability of the shield is achieved by a simple mechanism without requiring elaborate details of a stopper.

Keywords:
Buckling restrained brace; Multi-zone core; Shield mechanism; Fatigue; Core length; Sliding stopper

1. Introduction

Structural ductility, i.e. the ability of a structure to absorb seismic energy without significant loss in strength, has been a major parameter in safe and economical design of structures for seismic loads. In structures, ductility may stem from various sources, but it mainly depends on materials and elements used in the design. The energy of severe ground motions is usually absorbed by inelastic deformations of specific elements that act as fuses dissipating the energy while other members are spared from energy absorption and damage [1]. Experience from past earthquakes as well as information obtained from testing specimens indicates that buckling of conventional braces is a non-ductile phenomenon with a major decline in strength and stiffness. In order to improve the low ductility of common braces, a new system called buckling restrained brace was introduced some thirty years ago in Japan. In this system, buckling of the core under compression is avoided by embedding the core in a confining system. The restraining shield has sufficient lateral stiffness to prevent the buckling of the core. In this system, unlike the conventional braces, all the core length can have an inelastic behavior under cyclic loading [2].

All the buckling restrained braces designed so far have been based on the same basic principle. However, over time, the shape of the core and the restraining mechanism for keeping the core from free motion have changed. Since the introduction of BRBs, three major types of buckling restrained braces have evolved. In all these types, the idea of taking advantage of yielding of the core in tension as well as in compression and under cyclic loading has been prominent. The first generation of buckling restrained braces introduced by Wakabayashi et al. [2] used panels or tubes filled with concrete as shield. The second generation used only tube shields that were filled with concrete with a rectangular core. The latter design has received more attention from researchers in recent years, e.g. Tremblay et al. [3]. The third generation consists of all steel BRBs in which the shield and the core are steel. The advantages of this type of BRB are its light weight, simplicity of use of a single material and reduced construction time [4]. Tremblay [5] has studied this type of brace, shown in Figure (1), with one piece yielding core. Numerical studies have also been conducted by Razavi et al. [6], shown in Figure (2), on a similar brace with two different segments; a compression-controlled segment with reduced hardness, and a rather rigid part to span the rest of the length of the brace. In this way, the length of the yielding part of the core is reduced in order to produce more uniform yielding. In case of short core segments, a problem arises due to low cycle fatigue that needs to be addressed. Another problem with all steel BRBs has been distortions in the end zones where a reduction of the shield section is effected in order to allow the movement of the connecting elements. This leads to a reduction in stiffness of the shield in the end zones causing distortion and local buckling in the core at those points (Figure 2).

Another challenge of a buckling restrained brace is its stopper system. A steel stopper pin is usually placed at one or two points in the middle of the flat face of the core. As shown in Figure (3), when the restraining is done by welding of the core, premature failure of the latter occurs. Figure (3) also shows that the same problem can exist at the edges of the end stiffeners. In the latter case, an improvement can be made by using the so called Toe-Finished segments to avoid stress concentrations [7].

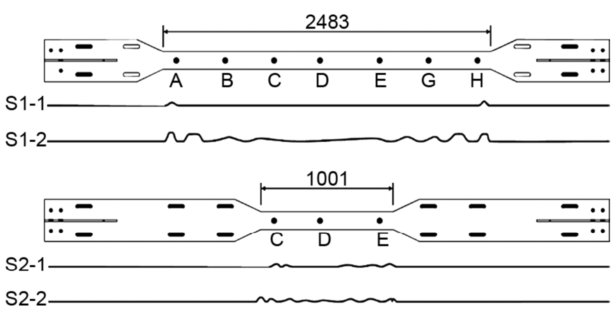


Figure 1. Residual deformation in the core of specimens tested by Tremblay [5].

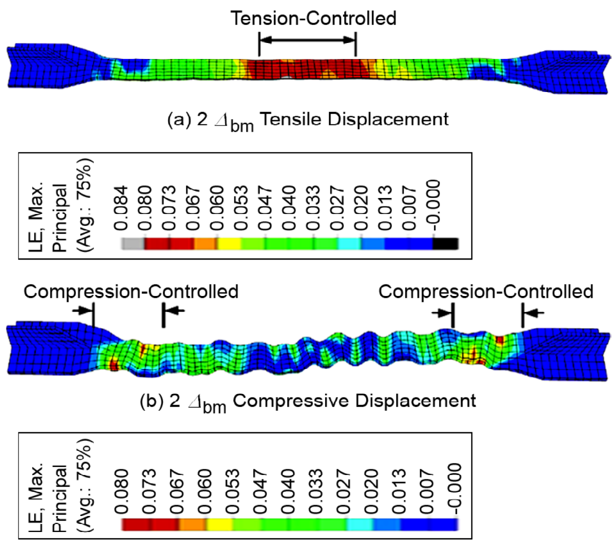


Figure 2. Principal tensile and compressive strains of the core under maximum displacement [6].

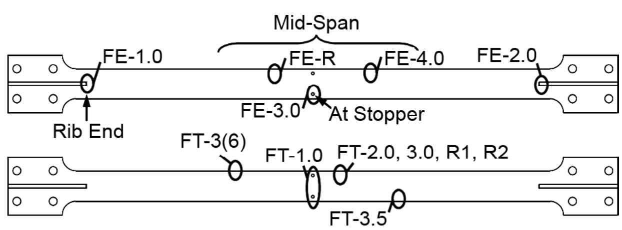


Figure 3. Failure mode of specimens due to stress concentration [7].

In this study, an attempt has been made to alleviate the above-mentioned problems. The stability of the shield is achieved by attaching it to the core at one section only in order to avoid oblong bolt holes, and yet no strain is introduced in the shield. The results also show that a good degree of success is achieved in dealing with the end distortions. In addition, the multi zone core used for the brace allows the plastic deformations to be spread throughout the length of the core. There was a worry that the short lengths of the zones cause a reduction in the fatigue capacity of the brace. However, all the specimens tested showed a fatigue capacity much beyond that required by the AISC code.

2. Design and Construction of Test Specimens

In order to have a robust brace, it should not only be able to satisfy the pertinent code requirements, but also provide a reserve of capacity. With this idea in mind, a series of specimens were designed, constructed and tested at the IIEES Structural Laboratory. The length of the specimens was chosen by considering a typical building frame (Figure 4). After subtracting the approximate dimensions of the beams, columns and gusset plates at both ends of the brace, the length of the prototype was established. The length of the ½ scale experimental specimens was then found to be 1.5 m by the laws of similitude. This allowed the specimens to be tested in a universal machine avoiding additional devices needed for tests in a loading frame. The values of minimum and maximum story drifts are specified by the AISC code [8] to be one and two percent, respectively, that is, design drifts in common buildings are usually between these two

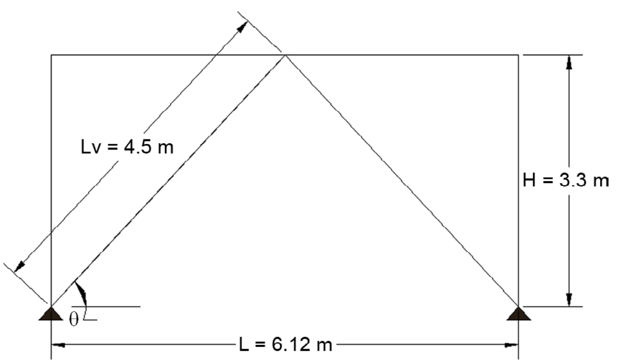


Figure 4. Braced span with buckling restrained brace in the prototype.

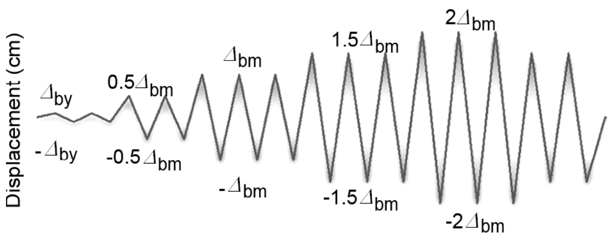


Figure 5. Loading protocol of experimental specimens.

values. Here, a value of 1.34% was used due to the displacement limit of the universal machine. The loading protocol used (Figure 5), is that specified by the AISC code. The tests were carried out under quasi-static loading and were continued up to a target displacement.

2.1 Design of the Core

With force and displacement demands of 11 tons and 1.5 cm calculated for the test specimens, the cross section of the specimen core was determined from the following relationships in AISC code. The compression force coefficient is calculated by Equation (1) and the length of the yielding part of the core (L_y) was determined by the limiting Equation (2), suggested by Tsi et al. [9].

$$\beta = (1 + 2\varepsilon)^2 \leq 1.3 \tag{1}$$

$$L_y \geq L_{\min} = \frac{2\lambda^{|c|}\Delta_{bm}}{\varepsilon_0}, \quad \lambda = \sum_{i=1}^{i=k} n_i\left(\gamma_i\right)^{\left|\frac{1}{c}\right|} \tag{2}$$

Equation (1) gives the compression strength factor, β, in terms of the average strain (ε) of the core. Equation (2) provides the minimum length needed to avoid low cycle fatigue. Δ_{bm} is axial deformation and γ_i the coefficient of Δ_{bm} in the load protocol of the AISC10-7 Code. Parameters ε_0 and c are determined from constant-cycle fatigue tests. λ is a constant related to the number of loading cycles (n_i) with a range ($\gamma_i\ \Delta_{bm}$). Value of λ can be calculated from a relationship suggested by Nakamura et al. [10].

In order to determine the effect of the core length on the fatigue capacity, three identical specimens with different lengths of the core yielding segments were tested. One had the minimum core length given by Equation (2), which was found to be 64 cm. The other two specimens had greater core lengths. To achieve more uniform plastic regions the yielding part of the core was divided into two segments

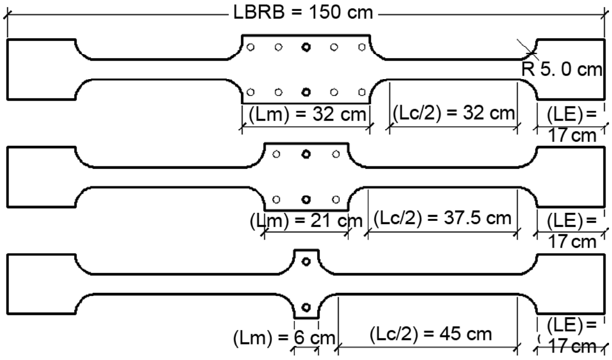


Figure 6. Core geometry of the experimental specimens.

(Figure 6). The different core lengths were then determined by using a segment of increased width, with length L_m at the mid-length of the core. With this geometry of the core, the brace could span the available space without requiring additional pieces.

2.2. Design of Restrains

A set of restraining elements and end stiffeners had to be provided in order to prevent free movement of the shield over the core. In designing both of these elements stiffness as well as strength criteria have been considered. The restraining elements were designed to satisfy the following relations [11]:

$$\frac{p_e^R}{p_y} \geq \left(1 + \frac{\frac{\pi^2 E}{2\sigma_y} \cdot \frac{a+g}{L}}{\frac{L}{D}} \right) = \gamma \tag{3}$$

$$\frac{p_e^R}{p_y} \geq 1.5 \tag{4}$$

where p_e^R and p_y are the Euler buckling load of the shield and the yielding load of the core. a is the initial deflection of the mid-length of the brace, g is the gap between the core and the shield, L and D are the length and height of the shield, respectively. E is the modulus of elasticity and D the yield load of the shield.

That is, the buckling capacity would be greater than 1.5 times of the core yielding load and more than β times the loading capacity. The value of γ is a function of the original tolerance and slenderness of the restrained element. The details shown in Figure (7) provide the required end stiffness of the core while keeping the weight of the brace reasonably low.

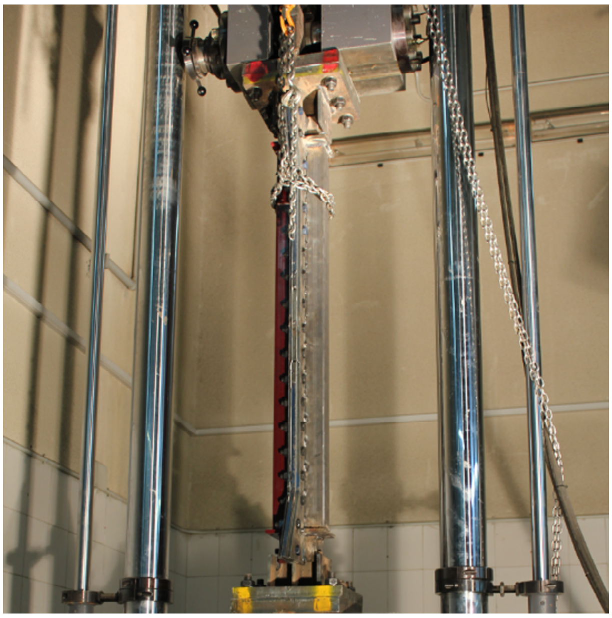
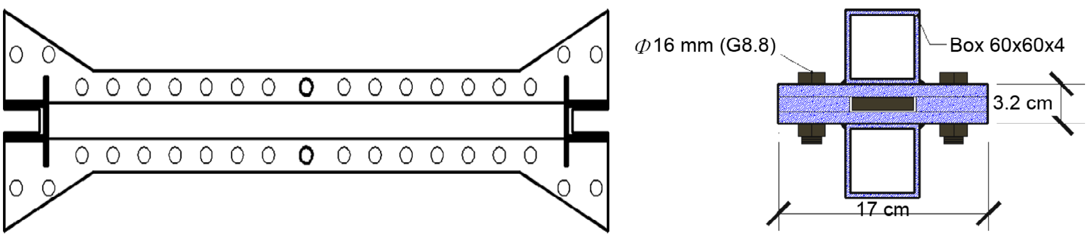


Figure 8. Testing of specimen by uniaxial machine.

3. Test Results

Figure (8) shows a specimen constructed and ready to be tested in the universal machine. The results of the tests for specimens with three different lengths of the yielding part of the core are shown in Table (1). In addition to the values of displacements, the maximum average strains as well as the values of β, calculated by Equation (1), and those obtained from the experiments are shown in Table (1).



(a) Restraining Bolts (b) Front View of Restrains

Figure 7. Rrestraints of the experimental specimens.

Table 1. Results of the experiments compared with the theoretical values.

Specimen	Total Length of Yielding Core (cm)	Displacement at Yielding (cm)	Maximum Strain (%)	β Calculated	β (From Test)	η
First	90	0.135	3.35	1.14	1.21 , 1.18	1240
Second	75	0.11	4.02	1.17	1.19 , 1.16	1414
Third	64	0.096	4.69	1.2	1.19 , 1.17	1102

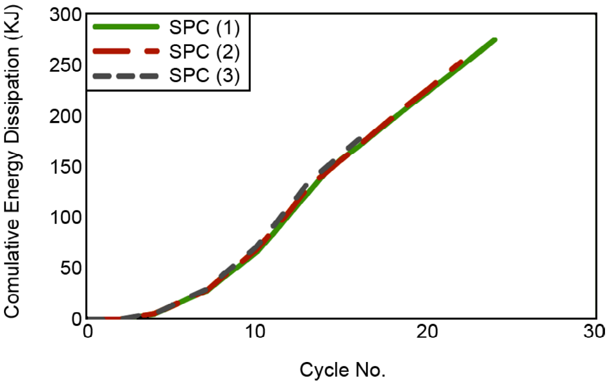


Figure 9. Comparison of the cumulative energy absorbed by different specimens.

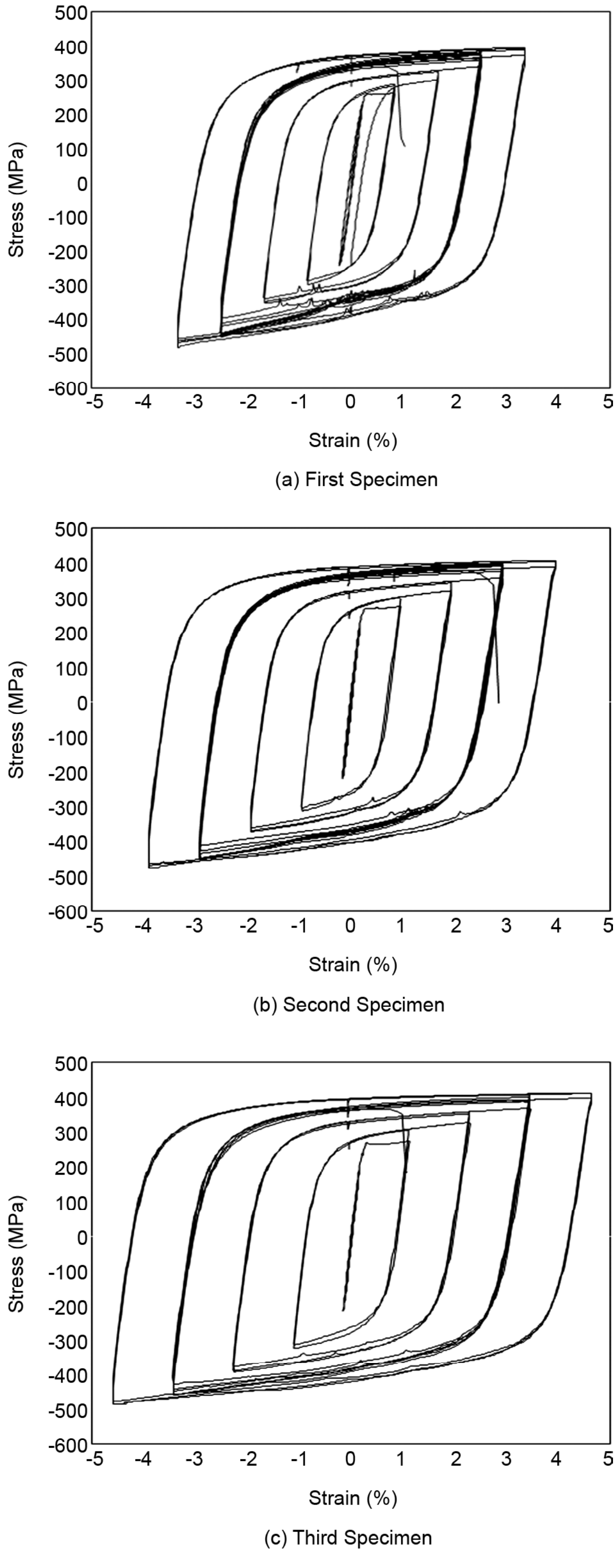


Figure 10. Hysteresis curves of tested specimens under quasi - static cyclic loading.

The results show that theoretical and experimental values of compressive strength factor (β) are almost the same for larger load values. The values of the factor η are found to be greater than 200, the required value by the AISC code. In order to judge the potential of energy absorption of each specimen more accurately, cumulative energy per cycle was calculated and plotted for each specimen (Figure 9).

It can be concluded from Figure (9) that by increasing the length of the yielding segment of the core from the minimum value of Equation (2) to the maximum value, the absorbed energy will increase by 1.5 times. This is in contrast to some previous research results [12] in which the maximum energy absorption had been for specimens with minimum core lengths. It should be noted that the amount of energy absorption shown in Figure (9) is for 1/2 scale models. For prototypes, the amount of energy will be eight times larger. Thus, the proposed brace has a good reserve of capacity for absorbing earthquake energy.

Figure (10) shows the cyclic behavior of three tested specimens. As can be seen, the hysteresis curve for each specimen has a sustainable and symmetric behavior in tension as well as compression and indicated the capacity of the brace for absorbing a good amount of energy. The fact that all the specimens tested show capacities beyond that required by the AISC acceptance criteria is an indication that the designed brace can be used in actual applications. In more recent years, other aspects of steel buckling reinforced braces have been studied by various authors [13-17].

4. Conclusions

All the specimens tested in this study, in addition to satisfying the acceptance criteria of the AISC code, had a good reserve of capacity for absorbing earthquake energy. That is the capacity of all the specimens was five or more times the minimum value specified by AISC code. The results can be summarized as follows:

- The theoretical Equations (1) and (2) for determining the minimum required length in order to avoid low cycle fatigue, and the compression strength adjustment factor for this type of brace seem to provide adequate results. The fatigue cycles endured by all the specimens were several cycles more than that required by the AISC code. The compression strength adjustment factors (β) were in all cases less than 1.21, and less than the maximum value of 1.3 specified by the AISC code.
- The simple restraining element used at the mid-length of the core for preventing slip of the shield worked well without the need for a special tightening device or additional elements for non-slip restraints. Thus, by a simple tightening of the restraining bolts, the stability of the shield was achieved.
- The multi-zone design of the core allows the yielding to be somewhat uniform throughout the core while allowing the brace to cover the span of the frame.
- The satisfactory results of all the specimens tested give the assurance of robustness of the design and its readiness for use in practice. In terms of numbers for the prototype, the axial load was 44 tons and the displacement 3 cm. In view of the scale of the test (1/2) for the test model, the axial force and displacement were 11 tons and 1.5 cm, respectively.

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