

A New Type of Reduced Scale Buckling-Restrained Brace for Shaking Table Test

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Abstract: For applying into the reduced scale structure model with BRB test, a new type of reduced scale buckling-restrained brace (BRB) is present. This paper discusses the problems of manufacture and installation, and the new structure of BRB is designed for resolving these problems. For a frame with BRB structure model test whose length similarity ratio is 1/6, two reduced scale BRB specimens are produced. Through low cyclic loading tests, the seismic performance of the reduced scale BRB is validated, and the comparison between the reduced scale BRB and the full scale BRB is presented. The testing results conclude that basic seismic performance of reduced scale BRB is stable and good, but there is the higher asymmetrically mechanical property. Based on the testing process and testing termination, the improved design suggestions are given. The shaking table tests that is a RC frame with the improved reduced scale BRB are finished and its results show that the reduced scale BRBs have a good performance under a few earthquake wave cases.

Keywords: structure; BRB; scale model; shaking table test.

1. Introduction

Buckling-restrained brace (BRB) is a good metallic yielding damper for earthquake resistant systems [1~6]. Many seismic researches for BRB are done in China and abroad, including the pseudo-static test for full scale component [1, 2], the pseudo-static test for full scale frame-BRB and dynamic test for full scale frame-BRB [3~7]. However, the reduced scale model tests are less. Although whole structure and substructure model test are the trend of test research, considering the limit of equipment and budget, it is necessary to use reduced scale BRB in the structures model test. This also increases demand of reduced scale BRB.

The reduced scale BRB is different from the full scale BRB, and there are the following problems: (1) economic problem. The size of structure model test is usually large, which means many BRBs will be used. If a single BRB is well-produced and costly, the total cost must be increased. (2) encased components. The encased components of BRB usually are composed of steel tube filled with concrete or built-up steel components. Whether the encased components of reduced scale BRB can behavior the same performance as the full scale BRB is one of problems that need to be solved. It includes if encased components can restrain buckling deformation of steel core and if there is larger asymmetrically mechanical property which is mainly caused by friction between steel core and encased components. (3) weld problems of steel core. The area of steel core decreases by the square of the reduced scale proportion, so steel core area of reduced scale BRB is very small. Normal weld may damage the steel core, while advanced weld increases cost of production. (4) connection with the frame. There are usually two ways to connect with the frame: weld connection and bolt connection. The steel core can be easily damaged in welding process, while there is no applicable high-strength bolts in bolt connection.

2. The design of an all-steel BRB without welding

Our team designs a new type of all-steel BRB without welding. Its scale proportion is large, and the thickness of steel core is very thin. By structural design, the new type of BRB can avoid welding on its steel core.

2.1 Design demand of reduced scale BRB

The design prototypes of reduced scale BRB are from the practical engineering, and reduce its scale by the proportional relation based on the similarity theory. The length similarity ratio of substructure model test is 1/6. The elastic modulus similarity ratio of substructure frame is 1/2. Table 1 presents the design parameters of prototype BRB and reduced scale BRB.

Table 1 The design parameters of prototype BRB and reduced scale BRB

	Length of BRB /mm	Area of steel core /mm ²	Yielding force /kN	Yielding displacement /mm	stiffness s /kN/mm
Prototype BRB1	4700	2592	609	3.72	164
Reduced scale BRB1	780	36	8.5	0.62	13.6
Prototype BRB2	3930	2592	609	3.48	175
Reduced scale BRB2	655	36	8.5	0.58	14.6

2.2 Structural design

The Area of steel core is very small after reducing scale. A flat core plate whose dimension is 1.8mm x 20mm is selected for steel core. The flat core plate is cut from the hot rolled Q235 steel plate. Due to the processing technology and material characteristic of thin steel plate, its yielding stress usually is higher. Select the lowest rolled steel yielding stress for steel core, which is around 235 MPa. If the steel core of reduced BRB is welded together by several steel plates, the 1.8mm-thickness steel plate will be damaged. Therefore, the manufacturing process of steel core plate that includes working proportion, transition proportion and connection proportion should be cut from the whole steel plate.

For the full scale BRB, the I-section steel core should be welded with the rib plates on out-plane of steel core and on outside of encased component. However, the core plate is too thin to weld this rib plate which restrains the out-plane buckling of the core plate. In this paper, the reduced scale BRB increase thickness of connection proportion plate to enhance the ability to restrain the out-plane buckling of the core plate. The additional steel plate-A and the steel core plate are bounded together by the steel glue whose shear strength can achieve 20 MPa. Which is indicated as Fig.1. At the working proportion, the additional steel plate-B is used to complement the thickness difference between the working proportion and the connection proportion whose thickness includes the core plate and additional plate-A. The additional steel plate-B is free without fixing with other components, and there is proper gap between the additional plate-A and the additional plate-B for compression of the steel core. Which is indicated as Fig.2 and Fig.3. The encased components are composed by angle-steels. Fig.4 and Fig.5 show that the combined angle-steel and the plate are bounded together by bolts.



Fig.1 The core plate glues with additional plate **Fig.2 Reserved gap for compressing of steel core**

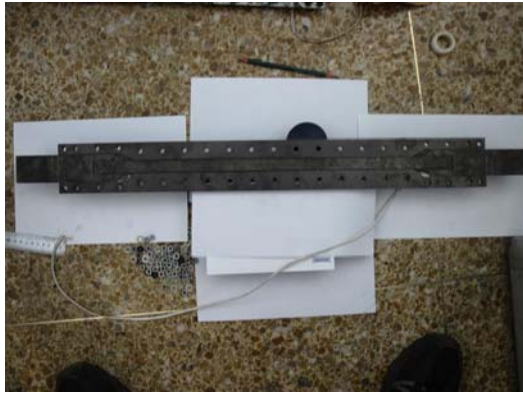


Fig.3 The overall inside of reduced scale BRB



Fig.4 Completed product

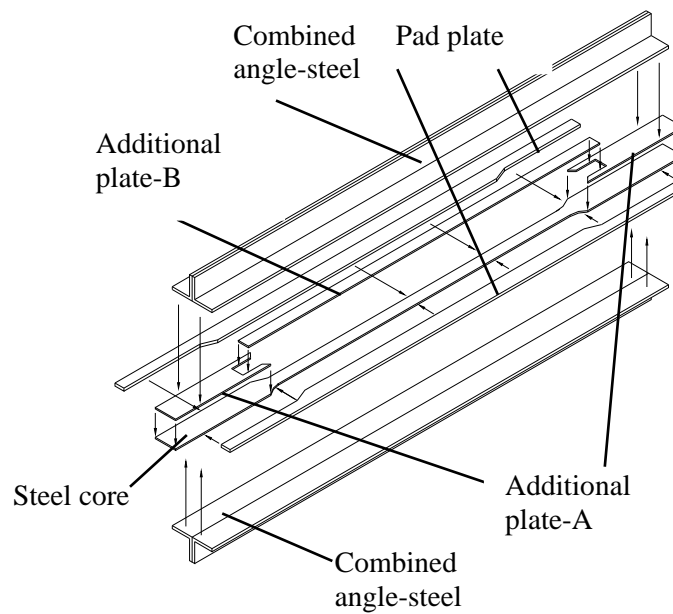


Fig.5 Structure and assembly of reduced scale BRB

3. The test under low cyclic loading

The test is finished in mechanics laboratory of college of materials science and engineering, Beijing University of Technology, and the testing equipment is the MTS 810 material testing machine of MTS Systems Corporation. The testing equipment is as Fig.6. The MTS connect BRB by self-locking clamping end-plate of BRB. There are two testing specimens, BRB1 and BRB2, to test their seismic performance, and the design parameters are shown in Table 1.



Fig.6 Testing specimen and MTS testing equipment

The testing specimens are tested under repeated cyclic multi-stage loading. Every loading stage is controlled by axial displacement that corresponds to the ratios of yielding displacement D_{by} . The control displacements are shown in Table 2 and Fig.7.

Table 2 Loading scheme of BRB1

	Ratio of yielding displacement	Control displacement	Number
1	1 D_{by}	± 0.62	1
2	2 D_{by}	± 1.2	2
3	4 D_{by}	± 2.5	2
4	6 D_{by}	± 3.7	2
5	8 D_{by}	± 5.0	2
6	10 D_{by}	± 6.2	2
7	12 D_{by}	± 7.4	2
8	15 D_{by}	± 9.3	2
9	18 D_{by}	± 11.2	2
10	20 D_{by}	± 12.4	2

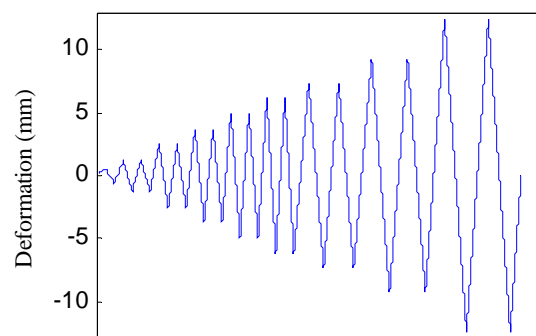


Fig.7 Time history of displacement loading

3.1 Process and results of test

At beginning of test, the performance of BRB is stable. The displacement-force hysteretic curve is smooth and plump, and there is no slip and sudden change of stiffness. Due to lack of locating clip, the encased components gradually slide to the end of BRB. The encased components of BRB1 slip upward, and that of BRB2 slips downward. Under 15 D_{by} loading level, the buckling instability happens at the exposed part of two BRB specimens which is between the encased components and connection of testing equipment. The test is terminated, and the buckling of BRB end is as Fig.8.

The hysteretic curves of two testing specimens are present in Fig.9 and Fig.10. It can be observed that the asymmetry of hysteretic curve between tension and compression is obvious. Asymmetrically mechanical

property is a common hysteretic characteristic. Its main cause is friction between steel core and encased components asymmetrical property). The asymmetric strength coefficient is the ratio of the maximum force in compression to that in tension under the same deformation level, and it can reflect the degree of asymmetrically mechanical properties. The asymmetric strength coefficient of a well-designed BRB should be lower than 1.3 [8]. Table 3 shows that the asymmetric strength coefficients under different loading level. It is obvious that the asymmetric strength coefficients of specimens are abnormal. The serious asymmetrically mechanical property shows that there are problems about the structure of reduced scale BRB.



Fig.8 The buckling instability of testing specimen

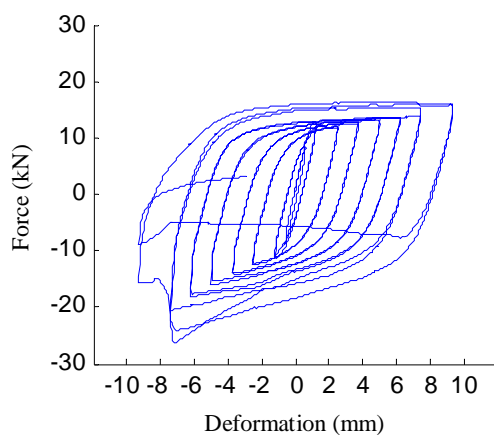


Fig.9 Hysteretic curve of BRB1

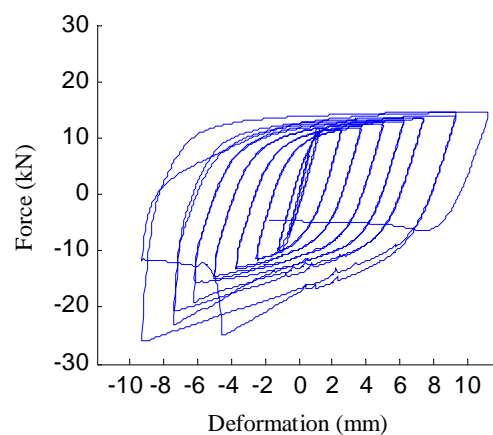


Fig.10 Hysteretic curve of BRB2

Table 3 Asymmetric strength coefficient under indifferent loading level

	4 Dby	6 Dby	8 Dby	10 Dby	12 Dby	15 Dby
BRB1	1.05	1.11	1.20	1.32	1.70	>1.5*
BRB2	1.01	1.10	1.18	1.46	1.71	1.78

* At this loading level, the control displacement is not achieved.

3.2 Comparison with the full scale BRB

This section presents comparison between the reduced scale BRB and the full scale BRB. The full scale BRB that is as compared specimen selects test number BRAB-C-1.4K-5 in Ref.9 [9], and its basic design parameters is presented in Table 4. The yielding displacement of the compared BRB is close to that of the prototype BRB, the yielding force of the compared BRB is close to 2 times of that of the prototype BRB. After normalization of hysteretic curve whose horizontal axis is divided by its yielding displacement and vertical axis is divided by its yielding force, the initial stiffness of the compared BRB is close to that of the prototype. Fig.11 shows the normalization comparison of hysteretic curve between the reduced scale BRB and the full scale BRB.

Through the comparing the hysteretic curves between the reduced scale BRB and the full scale BRB from Fig.12, the shape and plump degree of hysteretic curves are close and the asymmetrically mechanical property of reduced scale BRB is more severe and abnormal. Fig.11 also shows that the basic skeleton curves of three

BRBs are close, so equivalent stiffness of reduced scale BRB under different deformation is close to that of the full scale BRB.

The equivalent viscous damping ratio is an important parameter in the structure analysis and design, and it can reflect energy dissipation of BRB and considers the nonlinear effect in the response spectrum method. The formula for calculating the equivalent viscous damping ratio is as Eq.1.

$$\zeta_{eq} = \frac{1}{2\pi} \frac{W_c}{W_s} \tag{1}$$

Where, W_c is the positive half a circle area of hysteretic curve in tension, while it is the negative half circle area of hysteretic curve in compression. W_s is the total strain energy of specimen under target displacement.

Fig.12 presents the comparison of the equivalent viscous damping among two testing specimens and the full scale BRB. The comparison shows that the tendency of each level equivalent viscous damping in the tensile direction is close, while that in the compressed direction is different because of the severe asymmetrically mechanical property.

Table 4. The basic design parameters of the full scale BRB BRAB-C-1.4-5

	Overall length /mm	Area of steel core /mm ²	Yielding force /kN	Yielding displacement /mm	Stiffness /kN/mm
BRAB-C-1.4K-5	5000	5957	1400	3.68	164

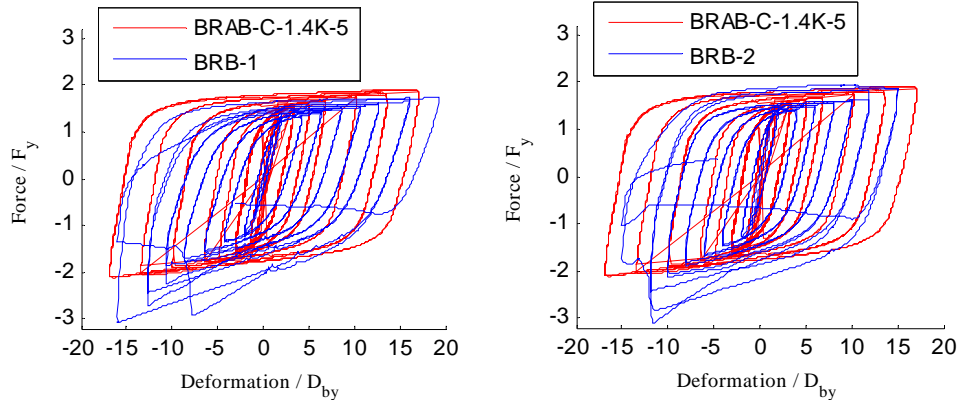


Fig.11 Normalization comparison of hysteretic curve between the reduced scale BRB and the full scale BRB

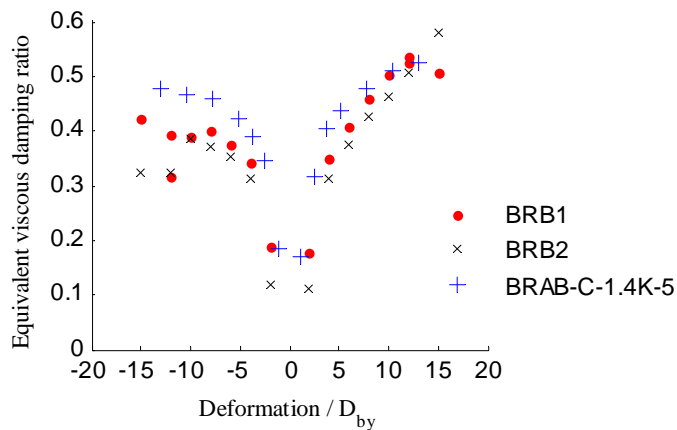


Fig.12 Comparison of equivalent viscous damping ratio

3.3 Improve design of reduced scale BRB

There are two reasons of early invalidation after analysis. One is the bending capacity of exposed part is low, and another is the compression axial force is larger because of the large asymmetrically mechanical property.

Therefore, there are two ways to improve the structure of reduced scale BRB. To increase the bending capacity of exposed part, the thickness of additional plate-A need to be increased, or the additional plate-A is set on the both two sides of steel core. For decreasing the asymmetrically mechanical property, the gap between

steel core and encased components or smearing the lubricant inside the reduced scale BRB needs to be set. For avoiding the mechanical jam, the right angles of additional plate-B should be polished.

4. The shaking table test of applying the reduced scale BRB

The improved reduced scale BRB are applied in a shaking table test that is RC frames model with BRB. The test specimen is as Fig.13.



Fig.13 Specimen of shaking table test with reduced scale BRB

After 18 earthquake wave cases, which include 6 levels of acceleration for 3 earthquake waves, and 3 sine wave cases, the results of tests show that the reduced scale BRBs have a good performance in a few earthquake wave cases. In shaking table test model, the RC frame installs 12 reduced scale BRBs. Only one BRB break in its steel core after all of cases. The hysteretic curves of partial shaking table cases are shown in Fig.14. Among these cases, 0.175g corresponds to the frequent earthquake intensity, 0.525g corresponds to the fortification intensity and 1.0g corresponds to the rare intensity. Fig.14 can show the BRB is same as the design performance that includes BRBs can keep linear in frequent intensity, BRBs begin to yield in fortification intensity and BRBs keep a good ductility in rare intensity.

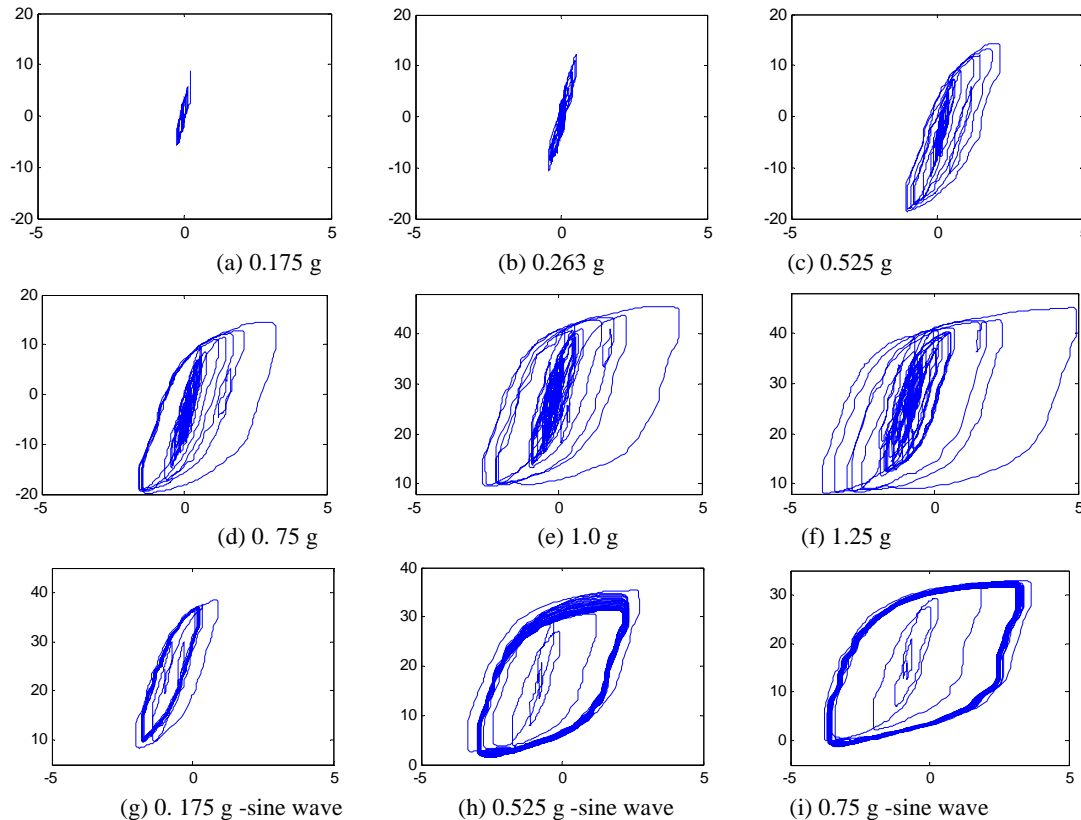


Fig.14 Hysteretic curves of BRB under El-centro wave and sine wave

5. Conclusions

1) There are demand and problems to produce the reduced scale BRB for applying the reduced scale structure model into the BRB test. Based on the problems of manufacturing process and installation, a new type of reduced scale BRB is presented.

2) The low cyclic loading tests for two specimens are finished. The testing results conclude that basic seismic performance of reduced scale BRB is stable and good, but there is a higher asymmetrically mechanical property.

3) Through the test and comparison with the full scale BRB, the improved structure design for the reduced scale BRB is given.

4) The shaking table tests that is a RC frame with the improved reduced scale BRB are finished and its results show that the reduced scale BRBs have a good performance in a few earthquake wave cases.

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