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Preface

These proceedings contain the papers presented at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation—joined a few years later by the Hong Kong Institute of Steel Construction.

These proceedings bring together most recent findings in numerical, theoretical and experimental research, as well as its practical implementation in design practice in the areas of Assembled Structure, Bridge, Cold-formed Steel, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue, Fire, High-Strength Steel, Impact and Protection, Intelligent Construction, New Material, Seismic Resistance, Stability, Stainless Steel, Structure Systems, Testing & Monitoring. The papers presented in these proceedings come from a wide range of countries/regions and will be a great reference source.

Specially, the subject matter has been categorized under the broad heading of:

**Volume I:** Keynotes Lectures, Assembled Structure, Bridge, Cold-Formed, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue


Each of the papers was subjected to stringent review by a panel of experts in the respective area. This peer review began with an assessment of the submitted abstracts and following this, authors were invited to submit their full manuscripts. Each manuscript was then carefully reviewed by relevant experts, and their recommendations on accepting, rejecting or modifying the submissions were strictly adhered to, before inclusion in the conference proceedings.
TEST ON RESILIENCE CAPACITY OF SELF-CENTERING BUCKLING RESTRAINED BRACE WITH DISC SPRINGS

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Abstract: The properly constructed buckling restrained braces (BRBs) usually have good ductility and energy dissipation capacity and therefore can be used in braced steel frames. However, large residual plastic deformation of the BRBs deteriorates their resilience capacity and hence results in large residual deformation of the buckling restrained braced steel frames (BRBFs) under large drifts. To reduce the residual deformation of BRB while keeping good ductility and energy dissipation capacity, a new self-centering buckling restrained brace (SCBRB), letting both BRB part and self-centering part work in parallel, is proposed. The self-centering capacity of SCBRB is provided by a combination of pre-compressed disc springs, which provides restoring forces and facilitates reduction of the residual deformation of the BRB. The BRB is composed of a core steel plate brace, a restraining member formed by the circular steel tube filled with mortar, and debonding materials between them. By quasi-static tests, one self-centering buckling restrained brace specimen (SCBRB) and one pure BRB specimen were tested to mainly examine the constructional details and hysteretic behavior of SCBRB. The material and configuration details of core steel plate brace in both the SCBRB and the pure BRB are the same for comparison. The test results show that, compared with the pure BRB which still exhibits large residual deformation, the SCBRB presents a flag-shape hysteretic performance and its residual deformation decreases significantly. The hysteretic curves of both the SCBRB and the pure BRB are stable before tension fracture of plate brace due to low cyclic fatigue, and the other components remained intact.

Keywords: Buckling restrained brace; Self-centering brace; Disc spring; Resilience capacity; Hysteretic behavior; Residual deformation

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1 INTRODUCTION

Although steel frames with buckling restrained braces (BRBFs) have good aseismic performance due to good ductility and energy dissipation capacity of buckling restrained braces (BRBs), promoting popular application of BRBs [1,2,3,4], remarkable plastic deformation of BRBs leads to large residual deformation of structures which would deteriorate the use function of buildings employing BRBs after large story drifts under severe earthquake action. A study has revealed that the cost to repair a building will exceed that to rebuild it when the inter-story residual drift after an earthquake is larger than 0.5% [5]. The seismic response of the BRBFs also revealed that inter-story residual drift was prone to be far larger than 0.5% under strong earthquakes [4,6,7,8,9]. For example, the tests of BRBFs [7] showed that residual story drifts
would exceed 0.5% when story drifts exceeded 1.0%. When the story drifts were about 2%, which is the drift limit of steel structures under strong earthquake excitations stipulated by the Code for Seismic Design of Buildings [10], the residual drifts were approximately 1.2%–1.5%, which are far larger than 0.5%.

To reduce the residual deformation of BRBs, some researches had conducted to form self-centering buckling-restrained brace (SCBRB), in which a BRB member work in parallel with a self-centering member including pre-tensioned bars formed by shape memory alloy (SMA) or by high strength steel or composite materials. When two ends of each commonly used steel strand are anchored, the elastic deformation of steel stands is so limited that the axial deformation capacity of the brace is significantly reduced. To enlarge axial elastic deformation capacity of self-centering member, three tubes together with steel stands were employed in the tests [11,12] to double the axial deformations and dual tubes together with composite tendons made of basalt fiber-reinforced polymer were used in the test [13]. The residual deformations of SCBRB employing SMA bars were found to be approximately half of the corresponding peak deformations under large drifts [14]. Besides, steel disc spring is also a better choice as both strength and deformation capacity can be reached by flexibly adjusting the dimension and stacking configuration of disc springs [15].

In this study, an assembled SCBRB was proposed by employing a new SC part, which consists of steel bars, pre-compressed disc springs and stud bolts, to flexibly meet the demand of both axial strength and axial deformation capacity. To examine the effects of constructional details on the hysteretic behavior of SCBRB, one SCBRB specimen was prepared and tested within the drifts of 4%. In addition, one pure BRB specimen, which has the same configuration as the BRB part in the SCBRB specimen, was tested to make a direct comparison.

2 CONSTRUCTIONAL DETAILS AND PREPARATION OF TESTS

2.1 Construction of self-centering buckling restrained brace

The SCBRB (Figure 1) includes three parts: a buckling restrained brace (BRB), a self-centering system (SC) and end connections. Each end connection, each push/pull bar or each push block is formed by welding several components together.

Four perforated steel angles in each end connection were used to connect with each end of BRB part by eight 10.9 grade high-strength M12 bolts and one perforated circular plate with thickness of 20 mm in each end connection was used to connect with each end of SC part by 10.9 grade twelve high-strength M20 bolts. During fabrication, firstly the buckling restrained brace is placed inside the tubes of the self-centering system. Then, both are connected to the end connection to let BRB part and SC part work in parallel in the SCBRB.

As shown in Figures 1 and 2, the SC part composes of a lower push-pull bar denoted as “LPPB”, an upper push-pull bar denoted as “UPPB”, and a pre-compressed disc spring system, which is a self-balance system built by placing two push blocks denoted as “PB” at both ends of pre-compressed disc springs and by applying compression on disc springs by twelve pre-tension rods. The pre-tension rods are designed with two functions. All rods are used to provide the balancing force for counteracting the pre-compressed force applied on disc springs. Half of them are used to connect with a lower push-pull bar and the remaining half are used to connect with the upper push-pull block. The working mechanism of SC part is shown in Figure 2.

Based on the GB/T 1972-2005 [16] and the availability of disc spring provided by the manufacturer, the disc springs used for the SC have 200 mm outer diameter, 104 mm inner diameter, and 13.05 mm thickness with support surface type. To satisfy the load and deformation requirement, the series stack modes is selected and arranged with 30 disc springs.
The BRB is mainly composed of an inner steel plate brace, restraining member and debonding material (Figure 3). The restraining member is formed by mortar filled in steel tube. Mortar is used to fill the space between the inner plate brace and outer steel tube. Since the limitation of the diameter of the disc spring using in compression disc spring system and the required maximum design of restraining capacity with larger yielding width of plate brace in BRB, the mortar filled in steel tube would have an advantage over other encasing members. The inner plate brace which is purposely used to dissipate energy through plastic deformation is coated with plastic tape (using as debonding material). The soft rubber is used for contraction (or expansion) allowance of the inner plate brace in the direction perpendicular to the length of the brace. The width ($b$) and the thickness ($t$) of yielding segment of core plate brace is 45.0mm and 10.1mm, respectively.

The Chinese Q235-B steel was used for most components in the specimens. The BRB’s core is hot-rolled Q235-B flat steel plate. By coupon tensile tests, the acquired actual steel properties for the core brace are as follows. The yield stress and ultimate stress are 289.11 MPa and 432.56 MPa, respectively, and Poisson’s ratio and Young’s modulus $E$ are 0.28 and 1.85×10^5 MPa, respectively. Moreover, the steel material used for disc springs is 60Si2MnA, and yield stress
and ultimate stress provided by the manufacturer are 1477 MPa and 1647 MPa, respectively. The average compressive strength of the mortar is 54.49 MPa.

Figure 3: Configuration of buckling restrained brace.

2.2 Preparation of tests

The upper and lower end plates in the end connections (Figure 1) were used to connect a specimen with upper and lower beam of the test rig (Figure 4) through 12.9 grade M20 high-strength bolts. Cyclic horizontal loading, controlled by applying horizontal increasing displacements, was applied on the upper beam of test rig. The actuator adopts 100-ton electro-hydraulic servo actuator and lateral supports of test rig are given by two strong steel columns. Both the horizontal force $P$ applied by the actuator and the relative horizontal displacement $\Delta$ of the upper and lower ends of the specimen were recorded.

Four specimens were tested. Except for the SCBRB specimen (Figure 1), when the BRB part was removed from SCBRB, the specimen is referred to as SC specimen. When the disc springs, two PBs and twelve pull rods in SC part were removed from SCBRB, the specimen is referred to as BRB specimen, in which the upper and lower push-pull bars were still employed to provide the BRB part with the potential lateral restraint. When the BRB part was further removed from BRB specimen, the specimen is referred to as S specimen, in which only LPPB and UPPB were kept to investigate the interaction of steel tubes between LPPB and UPPB.

During testing, the amplitude of horizontal loading displacements $\pm 0.35\text{mm}, \pm 0.71\text{mm}, \pm 1.06\text{mm}, \pm 1.41\text{mm}, \pm 1.77\text{mm}, \pm 2.12\text{mm}, \pm 2.47\text{mm}$, and $\pm 2.83\text{mm}$ were applied firstly with only one cycle under each loading. For the SCBRB and BRB, the two cycles of each loading with a displacement increment of 2.8mm, which is approximately equal to the yielding displacement of BRB part according to the dimension (Figure 3) and actual material properties of plate brace (Table 1) were then continuously applied, the displacement amplitudes are $\pm 5.7\text{mm}, \pm 8.5\text{mm}, \ldots$ $\pm 31.2\text{mm}$ (corresponding to 2% drift level of the specimen with height of 1560mm), $\ldots$ $\pm 62.4\text{mm}$ (corresponding to 4% drift level) until failure of specimen occurred. For the SC, the loading amplitude is the same as the above specimens and only one cycle under each loading was used. It should be noted that the positive displacement indicated that the specimen is being pulled (Figures 4 and 5). Hysteretic curves formed by horizontal load $P$ and horizontal displacement $\Delta$ are shown in Figure 5.
3 TEST RESULTS

3.1 Hysteretic behavior

According to the constructional details above, all specimens contain the lower push-pull bar and the upper push-pull bar. The hysteretic curves of the SC, SCBRB and BRB in Figure 5 affected by the interaction between the control tube of lower push-pull bar and the outer tube of upper push-pull bar, and this interaction improves horizontal bearing capacity through friction and bending moment resistance from the tubes (Figures 1 and 4), which is verified by the hysteretic curves of the specimen S (Figure 5).

The SC shows good flag-shape curve with a certain amount of energy dissipation and the energy dissipation in tension is slightly larger than that in compression, which would be due to the asymmetric response from the interaction of the push-pull bars. Besides contributing to the bearing capacity through the interaction of the push-pull bars, the interaction also contributes to the energy dissipation of the system through friction action between the outer tube and the control tube when they have relative axial movements.

The hysteretic curves of the SCBRB present a very stable flag-shape performance before tension failure of plate brace. The response of SCBRB after tension failure of plate brace is on the whole similar to the response of SC except that compression forces under larger amplitude displacements sharply increased due to two broken segments of plate brace contacted again. Since the BRB specimen contains the push-pull bars which are purposely assembled to ensure the global buckling of the brace, it should be noted that the hysteretic curves of the BRB (Figure 5) are not a pure buckling restrained brace. Therefore, the bearing capacity of the BRB is affected by the interaction of the push-pull bars also. Despite those effects, the BRB still shows a full and stable curve. After the tension failure of the plate brace, the almost linear increase of bearing capacity in the curves of the BRB, when the BRB was continuously loaded, indicates the presence of impacts from the interaction of the push-pull bars (Figure 5), which is on the whole similar to the curves from the S test.

3.2 Failure phenomenon

After the test, the SC specimen has no damage and deformation, and the system is all intact and can be reused. The SCBRB specimen has no obvious damage and deformation except for the broken plate brace of BRB part (Figure 6) due to low cycle fatigue. The BRB part was taken out from the self-centering system and the broken plate brace was observed after cutting the steel tube and breaking the mortar (Figure 6). Because of the relatively uniform gap between the inner plate brace and the restraining member due to the good casting of mortar and gluing of debonding material, the broken plate brace of BRB part kept flexural buckling deformations.
with multiple waves about strong axis of the encased plate brace (Figure 6), indicating that the mortar filled in steel tube can provide the encased plate brace with sufficient lateral restraint, effectively preventing the appearance of the overall instability during the axial compression. Therefore, the encased plate brace can enter the post-yielding state, the bearing capacity of steel is fully utilized, and the plate brace underwent cumulative cyclic plastic deformation and finally entered the fatigue fracture. Except for the broken plate brace, other components of SCBRB remain intact. Similarly, the tension fracture of plate brace occurred finally in the BRB due to low cycle fatigue (Figure 5). It should be noted that, the mortar filled in steel tube used as the restraining member in both SCBRB and BRB remain intact. Thus, in the future, assembled constructional details of restraining member can be employed further to reuse the restraining member and to facilitate the inspection and replacement of plate brace.

![Figure 5: Hysteretic curves of the specimens.](image)

![Figure 6: Residual deformations of encased steel brace after testing.](image)

### 3.3 Residual deformation

The residual deformation is a key parameter to understand the re-centering capacity of a specimen. Based on the hysteretic curves of the SCBRB and BRB shown in Figure 5, the residual deformations, which are the deformations when the loads of each specimen were decreased to zero, are taken from the first cycle under each corresponding loading displacement.
Therefore, the relationship of horizontal residual deformation and horizontal loading displacement is acquired, shown in Figure 7.

As mentioned by McCormick et al. [5], when the lateral residual story drift exceeds 0.5%, the repairing cost of the structure will be higher than the combined cost of demolition and reconstruction. Therefore, 0.5% lateral (horizontal) residual drift is used as the base value for comparison. At 2% drift level, the lateral residual deformation of the BRB, which includes the push-pull block interaction, reaches up to about 1.75% which is larger than the desired limit value of 0.5%. For the SCBRB, the lateral residual deformation of the brace is slightly over 0.5% when the drift level reaches 2%. It should be noted that the BRB and SCBRB contain nearly the same designed structural and mechanical properties of BRB part. Figure 7 suggests that the design of the BRB part with the addition of the self-centering system to generate the SCBRB can greatly reduce the residual story drift.

![Figure 7: Residual deformations of the specimens SCBRB and BRB.](image)

4 CONCLUSION

Four specimens, including the SCBRB, the SC, the BRB and the S in which the upper and lower push-pull bars of SC part were kept only, were assembled for horizontal cyclic loading tests. The conclusions and recommendations are as follows.

1) The complete assembling of the self-centering system to create a self-centering brace is reliable. The SC specimen showed stable performance with flag-shaped hysteretic curves, indicating good self-centering behavior. The hysteretic curves of SC exhibited certain energy dissipation, which would be mainly from the friction and bending actions between the upper and lower push-pull bars in the SC part, which provides additional energy dissipation and horizontal resistance, reflected by the hysteretic curves of the S.

2) The precasted buckling restrained brace with mortar filled in circular steel tube, which is referred to as BRB part and can be placed inside the self-centering system in the SCBRB, works well. The hysteretic curves of the BRB indicate a full shape with good energy dissipation, together with large residual deformations under large loading drifts. In order to reuse the restraining member and to facilitate inspection and replacement of plate brace, further assembled configurations of restraining member can be investigated.

3) The hysteretic curves of the proposed SCBRB specimen, letting the composite BRB part and the SC part with disc springs work in parallel, are stable before tension fracture of plate brace due to low cyclic fatigue, showing good ductility and energy dissipation capacity, and the residual deformation of SCBRB specimen is greatly reduced compared with the BRB. Except for eventual tension fracture of plate brace, the other components in the SCBRB remained intact. Therefore, the assembled configurations are convenient to replace the BRB part and to reuse the intact components.
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REFERENCES


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