

Experimental study on a new type of buckling restrained braces wrapped by GFRP

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Abstract. This paper proposes a new type of brace, called the maintenance-free steel-composite buckling restrained brace (MFSC-BRB). The inner core of the proposed MFSC-BRB contains a steel plate in which a ribbed glass fiber reinforced polymer (GFRP) rectangular tube is used as a constraint unit. The whole core is encapsulated by the GFRP rectangular tube. Four different specimens were tested using the low cyclic loading test to investigate the failure mode, deformation capacity, and hysteretic behavior of MFSC-BRB. The results show that the structural form of the non-filling yield section can effectively constrain the supporting element of the inner core, and the support has stable bearing capacity and excellent energy dissipation capacity. Further, the expansion joint structure has good deformation ability under low cyclic loading. When the axial displacement is large, single wave section expansion joints perform better than double wave section expansion joints. The larger the constraint ratio of the restrained yield section, the better the energy consumption of the brace. Compared with the traditional BRB, the new BRB is more lightweight, corrosion resistant, and has good energy dissipation.

1. Introduction

Buckling restrained brace (BRB) is widely used in building structures with good results. However, it is rarely used in infrastructure high-rise steel tower structures. Utilizing BRB in high-rise steel tower structures can effectively control the displacement and internal force of the tower head and the tower body, and ensure a good damping effect. Further, applying BRB to the vibration damping design of bridge structures can provide a new way to solve the vibration damping problem of bridge structures under rare earthquakes.

In order to improve the energy-consumption ability of BRB and make it easier to manufacture, Zhang et al. [1] proposed a new type of buckling restraint brace composed of three round steel tubes with different diameters. Park et al. [2] used a square steel rod as the core member, a hollow steel tube as the restraining member, and steel bars as filler material for the gap between the core and the tube to manufacture and test six BRBs. Jia et al. [3] proposed a new type of light all-steel detachable fish-bone shaped core plate BRB, tested four different configurations of the specimen, compared it to the traditional BRB, and found that the new BRB had better seismic performance. Usami et al. [4] developed a buckling restrained rippled plate (BRRP) damper whose core member uses a 2D rippled plate instead of the 1D narrow plate of a conventional BRB. They found that fully designed BRRPs have better deformation than conventional BRBs. Seyed et al. [5] analyzed a set of BRBs without filler material using the finite element method to study the parameters of various spaces between core and restraint members. In order to improve the durability of BRB in corrosive environments, Wang et al. [6] applied aluminum alloy to buckling restraint brace and proposed an extruded aluminum alloy BRB. Zhang et al. [7] carried out quasi-static tests on six BRB specimens with aluminum alloy as the core.

In recent years, FRP has been widely used owing to its lightweight, high strength, and corrosion



resistance. For example, Dusicka et al. [8] proposed a new concept of BRB with FRP as a restraint mechanism, which reduced its weight by 50% compared with the traditional concrete-filled steel tube BRB. Dusicka et al. [9] developed a new ultra-lightweight BRB (ULWBRB). The stress unit of ULWBRB is aluminum alloy, with the outside wrapped using four pultrusion modeling GFRP rectangular tubes and transverse winding GFRP as the constraint unit. Zhou et al. [10] proposed a novel self-centering (SC) BRB with basalt fiber reinforced polymer (BFRP) composite tendons. Their results indicated that with increasing core thickness, the energy dissipation improves and residual deformation occurs when the core strength exceeds the initial prestress. Pan et al. [11] proposed a GFRP-steel BRB, and designed three full-scale specimens of GFRP-steel BRBs that they investigated using low cycle reciprocating tests. They obtained a hysteretic curve that is symmetric and full, revealing good energy dissipation performance, and no obvious degradation of stiffness and bearing capacity.

This paper proposes a new type of brace, called the maintenance-free steel-composite buckling restrained brace (MFSC-BRB), that utilizes a ribbed GFRP rectangular tube as the restraint mechanism and is formed using vacuum import technology. MFSC-BRB is lightweight, corrosion resistant, and maintenance-free. Further, the results of low cyclic loading tests conducted on four different scale specimens, focusing on their mechanical properties, failure modes, and energy dissipation capacity, are presented and analyzed.

2. Basic Structure of MFSC-BRB

The basic structure of MFSC-BRB is shown in figure 1. The supporting element of the inner core contains a type of steel plate, a ribbed GFRP rectangular tube is used as a constraint unit, and this constraint unit is covered by a polyurethane foam strip to cover the glass fiber. The cloth introduction resin is cured to form a GFRP rib, as shown by the A-A cross-section in figure 1. The whole specimen is encapsulated by the GFRP rectangular tube, and the GFRP of the restrained yielding segment is in direct contact with the inner core through the ribs, thereby playing a restraining role on the force-receiving element of the inner core. The support ends with the expansion joint structure. The expansion joint has a smaller axial stiffness and can be designed according to the stiffness of the inner core. The steel core and the external GFRP rectangular tube are stressed as a whole when BRB operates, but the axial rigidity of the expansion joint is smaller than that of the inner core, and the axial force is distributed to a small part of the external GFRP rectangular tube. The axial tension supported by BRB can be regarded as being fully supported by the inner core. In order to prevent MFSC-BRB from sliding relatively between the constraint unit and the inner core during transportation, installation, and operation, a stopper is set at the middle of the inner core. Further, to eliminate friction between the inner steel core and the GFRP constraint unit and to ensure that the inner steel core can freely extend and retract during operation, the entire area of the steel core restrained by MFSC-BRB is coated with silica gel as an unbonded material.

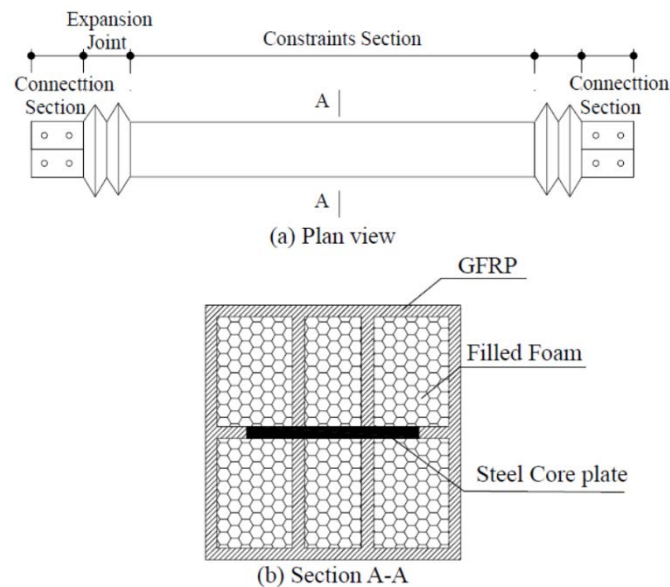


Figure 1. Configuration of the specimen

3. Design and Manufacture

Based on the actual cross-bracing geometry at the bottom of a high-voltage power transmission tower, four BRB specimens were designed and fabricated using a 1:3 scale model, as shown in figure 2. The inner core employs a shaped steel plate, in order to prevent relative movement between the constraint unit and the inner core, and a stopper is situated in the middle of the steel plate. Ribbed GFRP rectangular tubes serve as the constraint unit. The GFRP of the restrained yielding segment is in direct contact with the inner core through the ribs, playing a restraining role on the inner core. The GFRP expansion joints are set at both ends of the BRB specimen to ensure that the axial force of the specimen is mainly borne by the inner core when the specimen operates. The expansion joints are divided into two forms: single wave section and double wave section. The major parameters of the specimens are shown in Table 1.

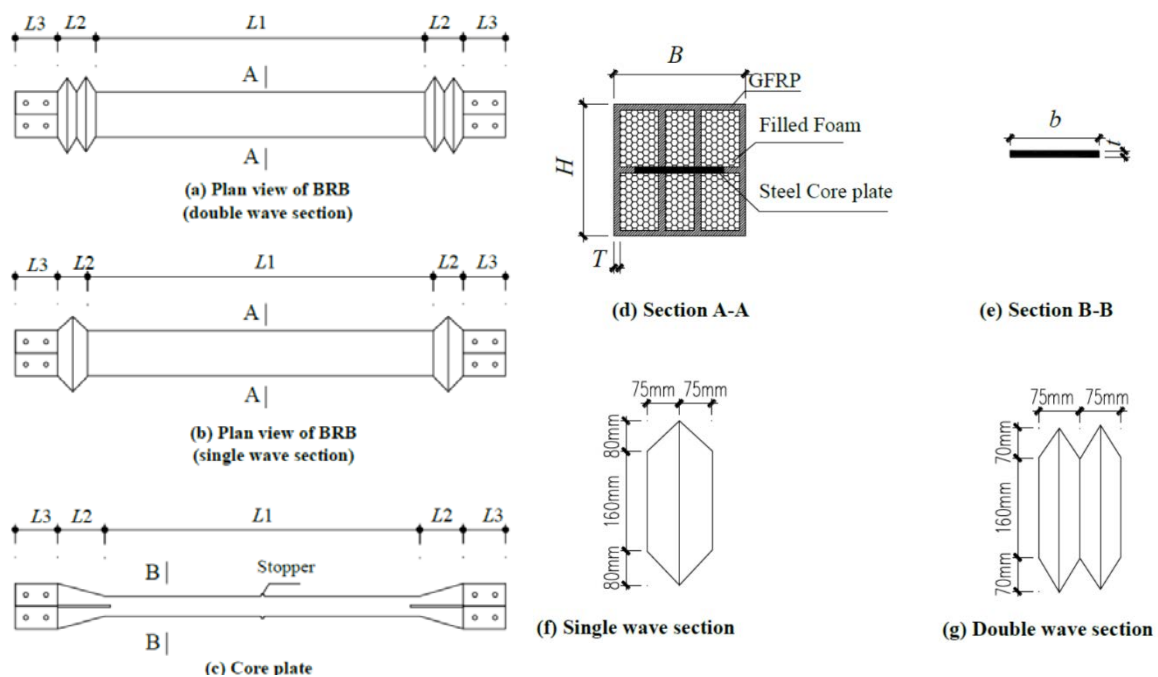


Figure 2. Details and dimensions of the specimens

Table 1. Major parameters of the specimens

Specimens	$B \times t$ (mm \times mm)	L1 (mm)	L2 (mm)	L3 (mm)	$B \times H \times T$ (mm \times mm \times mm)	Wave section
S1	50×6	1400	150	150	$160 \times 160 \times 6$	double
S2	50×6	1400	150	150	$160 \times 160 \times 4.8$	single
S3	60×6	1400	150	150	$160 \times 160 \times 6$	single
S4	60×6	1400	150	150	$160 \times 160 \times 4.8$	single

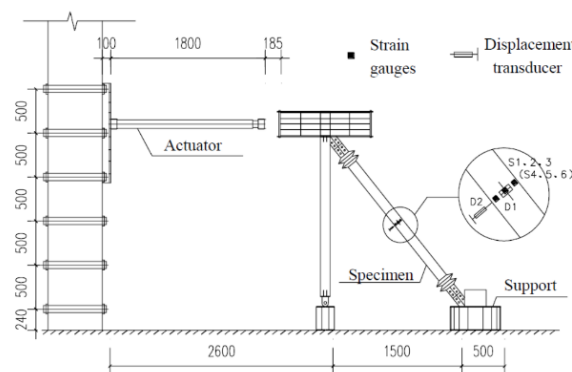
The molded specimen is shown in figure3. The completed specimens are lightweight and can be easily lifted by a single person.

**Figure 3.** Molded specimen

4. Test Program

4.1. Test Setup

A 250kN electro-hydraulic servo actuator was loaded in the test, and the test data were collected automatically by the computer data acquisition system. The loading setup is shown in figure4.

**Figure 4.** Loading setup

The cyclic quasi-static test was used in the test. The load was divided into three stages: (1) Preloading test. The preloading was controlled by a load of 20kN (1 circle) or 40kN (1 circle). The main purpose of the preloading test was to determine whether the instrument was operating normally and to ensure that the parts of the test were in good contact. (2) Standard loading test. Standard loading test reference to the relevant code in the buckling restraint brace test requirements. A standard loading

scheme based on the multiples of the yield displacement D_y was therefore designed. The loading protocol is shown in figure 5. The strain amplitude of each cycle increased from $1 D_y$ to $12 D_y$ with the increment D_y and two times per stage. (3) Extra cyclic loading test. The extra cyclic loading test was based on the standard loading test on the basis of two D_y and two times per stage until failure.

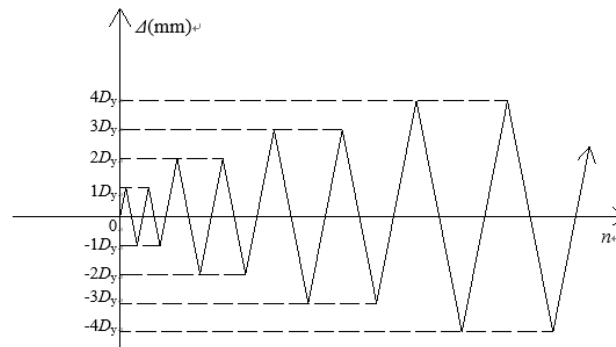


Figure 5. Loading protocol

4.2. Test Phenomenon

The failure mode of specimen S1 was removal of the expansion joint at the corners and valleys. The failure mode of specimens S2 and S3 was expansion joint compression failure. The failure mode of specimen S4 was GFRP crack. The typical failure mode of each specimen is shown in figure 6. Compared with S1, the single-joint specimens, S2, S3, and S4 exhibited better deformability in the standard loading stage and also better integrity. When the axial displacement was large, the bearing capacity of the single-joint specimens was more obvious. The failure of the expansion joint with double joint structure was mainly concentrated at the corner and the trough of the wave joint, because the stress concentration at the corner of the expansion joint and the trough easily resulted in damage. This is also related to the expansion joint manufacturing process. When the specimens were wrapped in glass fiber cloth, the fiber cloths at the junction and the drape were discontinuous, resulting in a weak link. When the tension and compression displacement was large, rupture first occurred.

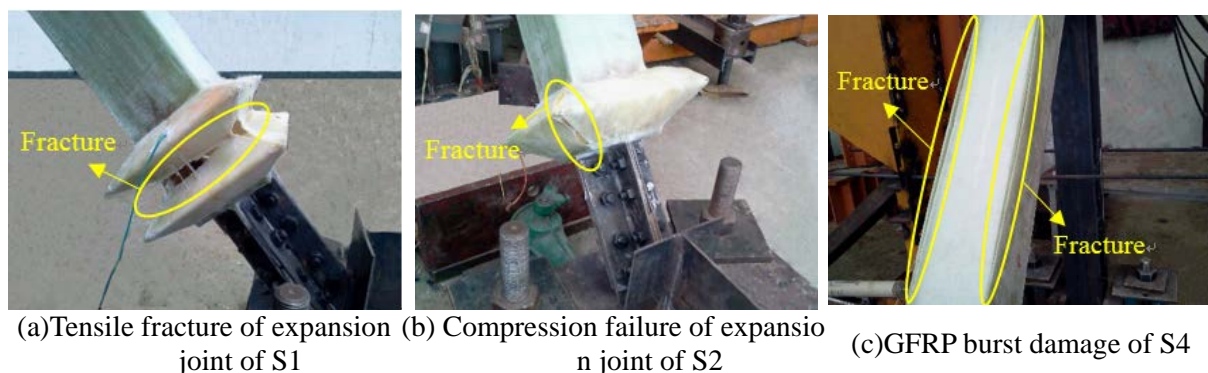


Figure 6. Typical failure patterns of the specimens

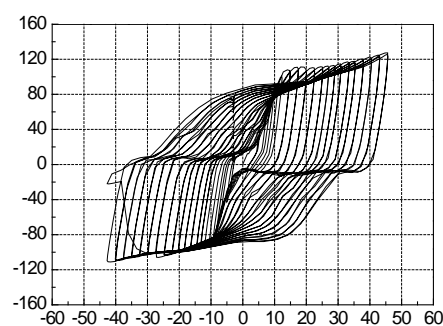
4.3. Hysteresis Curves

It can be seen from figure 7 that the hysteresis curves of S1–S4 have an obvious pinch phenomenon at the initial stage of loading, which is caused by the bolt connection of the test device. With increasing loading displacement, the plastic deformation of the core steel increases, the influence of bolt slippage on the hysteresis curve decreases, and the curve shows increasing fullness. The area of the hysteresis curve envelope of S1–S4 also increases with increasing displacement.

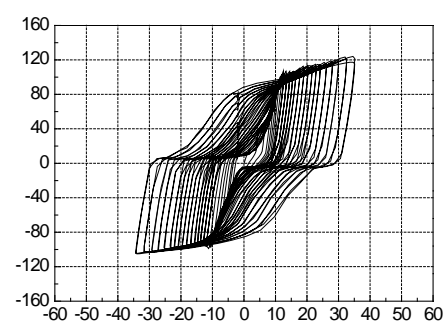
Under the same level of displacement, the specimen under test is slightly higher than the tension load. The reasons for this phenomenon are as follows: (1) The inner core has a transverse expansion

owing to pressure, which produces extrusion of non-bonded silica gel and GFRP, and produces frictional resistance when relative slip occurs. (2) When the specimen is under compression, the transverse expansion of the inner core is limited by the restraining mechanism of GFRP, such that the inner core is under three-direction stress, resulting in the compression on the specimen at the same level being slightly higher than the tension load. The compressive strength ratio is defined as the ratio of the compressive bearing capacity to tensile strength under tensile and compressive displacement of the same grade, and the tensile strength ratio of the buckling restrained brace is between 1.1 and 1.4. The maximum tensile strength ratio is 1.23 in figure 7, which is within the normal range of results.

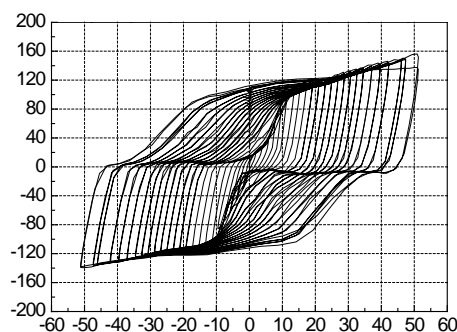
It can be seen from the hysteresis curve of the specimen that the hysteresis energy dissipation performance of S1 is better than that of S2, and the energy dissipation performance of S3 is better than that of S4, which indicates that the larger the restraint ratio of the GFRP restraint yield section, the better the energy dissipation capacity of the specimen.



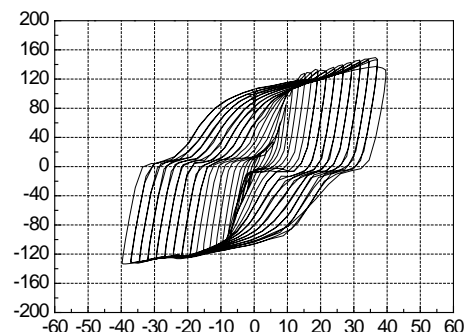
(a) Hysteresis curve of specimen S1



(d) Hysteresis curve of specimen S2



(b) Hysteresis curve of specimen S3



(e) Hysteresis curve of specimen S4

Figure 7. Hysteresis curves of the specimens

5. Conclusions

This paper proposed a new type of maintenance-free steel-composite buckling restraint brace. In the proposed brace, the composite material is used as the restraining member. The inner core is wrapped by the composite material through the expansion joint structure. The brace is lightweight and corrosion resistant. Further, its energy dissipation and fracture morphology under cyclic loading were validated. The major conclusions obtained in this study are as follows:

- Based on the vacuum forming process, the preparation process of the new brace was designed, and four specimens were processed and tested focusing on energy dissipation and failure of the bracing under the action of low cycle repeated loading.

- MFSC-BRB solves the problems of large deadweight and easy corrosion besetting traditional BRB. The brace vacuum forming process uses a one-time overall molding, and the entire support is a GFRP sealed package. In contrast to other new types of brace structures, it can achieve a full maintenance-free life-cycle. In addition, MFSC-BRB has advantages such as good design ability, easy molding, and flexible design that can be based on need.
- The strength of the support during loading is not significantly degraded, and the area of the hysteresis curve envelope increases with increasing displacement. This indicates that the new type of maintenance-free steel-composite buckling restraint brace has good energy dissipation capacity and stable bearing capacity.

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