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To cite this article: Wulong Chen and Guobiao Lou 2019 IOP Conf. Ser.: Earth Environ. Sci. 304 032027

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Research on Testing Methods of Inspection of Buckling-Restrained Braces

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Abstract. Testing methods of inspection of buckling-restrained braces is specified in many technical specifications, but the existing specifications do not clearly indicate the connection type used for the specimen. There are three main connection types of buckling-restrained braces applied in engineering. This paper has carried out a large number of tests, focusing on the influence of different connection types on the test results. For the welded joints specimen, typical test results of mechanical properties of buckling-restrained braces were obtained. For the bolted joints specimen, slippage is likely to occur during the test; for the pin joints specimen, misalignment is likely to occur during the test and they are not suitable for use. In order to ensure the normal operation of the test and the comparison of the test results, it is not necessary to simulate the connection types when the test of buckling-restrained braces is performed. No matter which connection type of the buckling-restrained braces is used in engineering, the unified connection type is recommended in the test. It is recommended to use the welded joints.

1. Introduction

The buckling-restrained braces consist of a core unit, a restraining unit, and an unbonded structural layer between the two units [1]. The buckling-restrained braces do not destabilize under pressure, can reach the yield state under tension and compression conditions, and has stable hysteretic energy-consuming characteristics during earthquake action[2]. Therefore, it is widely used as a seismic energy-consuming component in areas where earthquakes occur frequently. With the deepening of research on seismic dissipation and vibration isolation technology for construction projects, China's Ministry of Housing and Urban-Rural Development has also issued opinions on the promotion and application of seismic dissipation technology for building construction projects. The application of buckling-restrained braces has been rapidly developed in recent years.

In order to ensure the quality of the project, the buckling-restrained braces produced and supplied by professional manufacturers as professional products shall pass the test. China's technical requirements for performance requirements or testing methods for buckling-restrained braces are mainly as follows: JGJ297-2013 Technical specification for seismic energy dissipation of buildings, GB50011-2010 Code for seismic design of buildings, JG/T209-2012 Dampers for vibration energy dissipation of buildings, JGJ99-2015 Technical specification for steel structure of tall building, DG/TJ08-32-2008 Specification for steel structure design of tall buildings, Technical specification for the application of buckling-restrained braces(exposure draft).

In JGJ297-2013 Technical specification for seismic energy dissipation of buildings[3], the technical performance requirements for buckling-restrained braces are presented in Section 5.4. In
Section 8.2, a product inspection report shall be provided for the acceptance of the energy dissipation components. In GB50011-2010 Code for seismic design of buildings[4], the performance requirements and sampling test requirements for buckling-restrained braces are presented in the description of Article 8.1.6. In JG/T209-2012 Dampers for vibration energy dissipation of buildings[5], the appearance, material, and performance requirements of buckling-restrained braces are presented in Section 6.4. The testing methods are presented in Section 7.4, and the test rules are presented in Chapter 8. In JGJ99-2015 Technical specification for steel structure of tall building[1], the buckling-restrained braces are listed as the anti-lateral force component in Article 7.8.4, and the design of the lateral are specified in Appendix E. The test and acceptance requirements are presented in Section E.4. In DG/TJ08-32-2008 Specification for steel structure design of tall buildings[6], the design of the buckling-restrained braced frame becomes a separate chapter, and the test and acceptance requirements for buckling-restrained braces are presented in Section 11.6. In technical specification for the application of buckling-restrained braces(exposure draft)[7], performance testing requirements for buckling-restrained braces are presented in Chapter 6.

The above different technical standards have different requirements for the testing methods of buckling-restrained braces. There are still some details that are not clear in the specific implementation. The setting of connection nodes is an important aspect. Based on a large number of test cases, this paper selects representative results, summarizes the experience, and provides a reference for the improving of testing methods of buckling-restrained braces.

2. Main connection types of buckling-restrained braces

There are three main types of connection for buckling-restrained braces for engineering[2], including rigid joints (welded joints and bolted joints) and hinged joints (also known as pin joints), as shown in Figure 1.

![Fig.1 The connection types of buckling-restrained braces](image)

Wherein the welded connection is directly transmitted and the installation is simple; the pin connection is more complicated to install, but because it releases the rotation constraint, the force transmission is simple[11~13].

DENG et al.[14] studied the connection methods of buckling-restrained braces and different structures. It can be seen that the welded connection has the fault tolerance of the installation dimensional deviation, and the bolted connection and the pin connection as the mechanical connection put forward higher requirements for the installation precision. For example, there is a contradiction in the pin connection: a small joint gap may cause alignment difficulties; in order to ensure alignment, the joint gap may become larger. The buckling-restrained braces described by DENG et al.[14], in the actual installation, in order to cooperate with the high-precision pin connection, the deviation correction was performed by means of post-welding of the gusset plate.

3. Testing methods of buckling-restrained braces

3.1 Test device
The hysteresis performance test of buckling-restrained braces is carried out by four 10000kN jacks, and the test is carried out in a horizontal position. The test device is shown in Figure 2. The specimen is connected with the test frame mounting base and the loading head by high-strength bolts.

3.2 Test protocol
Loading is controlled by displacement control, the loading speed is 0.1mm/s, and it is stretched and compressed 3 times in the deformation of 1/300, 1/200, 1/150, 1/100 brace's length, then 30 times in the deformation of 1/150 brace's length. The specific loading protocol is shown in Figure 3.

Record the displacement and load of the actuator, the data of each displacement gage and the test phenomenon during the test;

When all loading is completed or specimen is damaged, the test is terminated. If one of the following conditions occurs, the specimen is fractured:

- The specimen is broken;
- Excessive out-of-plane displacement (displacement recorded by displacement sensors D15 and D16 is greater than 50 mm);
- In the third cycle of the last stage deformation, the bearing capacity decreased to 85% of the maximum bearing capacity.

![Fig.2 Schematic of BRB test device](image)

![Fig.3 Diaphragm of loading method(L is the brace’s length)](image)

3.3 Test measurements

3.3.1 Loading force
The loading force is measured by the pressure sensor of the test loading system.

3.3.2 Displacement
Install displacement gages at the position shown in Figure 4 for a total of 18. See Table 1 for specific locations and measurements.
Fig. 4 Schematic of displacement gage arrangement

| No. | Name   | Position                                      | Measurement contents                                      |
|-----|--------|-----------------------------------------------|----------------------------------------------------------|
| 1   | D1, D2, D3, D4 | Between the ends of the buckling-restrained braces | Total deformation of buckling-restrained braces |
| 2   | D5, D6, D7, D8 | Left side of the core unit and restraining unit | Relative displacement of the left end of the core unit and restraining unit |
| 3   | D9, D10, D11, D12 | Right side of the core unit and restraining unit | Relative displacement of the right end of the core unit and restraining unit |
| 4   | D13, D14 | Left end of restraining unit | Out-of-plane displacement of the restraining unit |
| 5   | D15, D16 | Right end of restraining unit | Out-of-plane displacement of the restraining unit |
| 6   | D17, D18 | Central restraining unit | Out-of-plane displacement of the restraining unit |

4. Analysis of test results and related problems

Up to now, the test device described in Section 3.1 has completed hundreds of tests. More than 90% of the specimens are welded, and the rest are bolted and pinned. In the actual test, most of the welded specimens obtained the expected and uniform test results, as shown in Figure 5, however, some problems were found in the specimens connected by bolts and pins.

4.1 Typical test results

In a typical experiment, the general criteria for judging are summarized in two aspects:

(1) Conventional performance: The buckling-restrained braces are tested by the deformation of 1/300, 1/200, 1/150, 1/100 brace's length and repeated 3 times in sequence. The hysteresis curve should be stable, full and repeatable, and the incremental stiffness is positive. The bearing capacity of the third cycle of the last stage deformation is not less than 85% of the maximum bearing capacity,
and the maximum bearing capacity is not higher than 1.1 times the design value of the ultimate bearing capacity.

![Fig.6 Time history curve of out-of-plane displacement](image)

Fig. 6 Time history curve of out-of-plane displacement

(2) Fatigue performance: The buckling-restrained braces are tested according to the 1/150 brace's length and the deformation is repeated 30 times. The bearing capacity attenuation should not exceed 15% and no damage occurs.

Further analysis found that the out-of-plane displacement is usually small (as shown in Figure 6), which does not exceed 5 mm (in this case the length of the brace is 3600 mm).

4.2 Problems found in bolted connection specimen

In order to simulate the actual working conditions, the bolted connection was retained in the test. The details and test photos are shown in Figure 7. During the loading process, a sharp metal impact sound is emitted, and the displacement gage is shaken, which seriously affects the normal progress of the test. The hysteresis curve is shown in Figure 8.

![Fig.7 Test photo](image)

Fig. 7 Test photo

(a) total view  (b) bolted joints

The reasons for the problem are analyzed as follows: The friction type high-strength bolts slipped during the test loading, and the oil pressure in the jack was released at the moment of slipping, and then the oil pressure in the jack was raised at the moment when the bolt was stopped, so that the burr in the hysteresis curve was generated. Due to the slippage of the joints, the displacement gage mounted on both ends of the buckling-restrained braces is caused, and the reaction appears to be offset on the abscissa of the hysteresis curve.

After analyzing the hysteresis curve, it can be found that the mechanical properties of the buckling-restrained braces in this case are consistent with the requirement that the hysteresis curve should be stable, full, repeatable, and the incremental stiffness is positive. However, the test did not work properly due to the influence of slippage at the joints.

In the end constraint, the bolted connection is similar to the welded connection and can be considered as a fixed end. In order to ensure the normal operation of the test and to exclude the influence of other factors on the mechanical properties of the buckling-restrained braces as much as possible, obtain the laterally comparable test results. In practice, it is recommended to use a welded
joints specimen for testing.

4.3 Problems found in pin connection specimen

In order to simulate the actual working conditions, the pin joints were retained in the test. The details and test photos are shown in Figure 9. The hysteresis curve is shown in Fig. 10. It can be seen that the bearing capacity under compression is significantly higher than that under tension at the same strain rate, and the compressive peak bearing capacity in the three loading cycles under the same strain rate is slowing down, and it shows smooth convergence in the fatigue performance test.

The out-of-plane displacement is shown in Figure 11. It can be seen that in this case, the position of the buckling-restrained braces at the zero position (the position when the external force is zero) changes, and in the fatigue performance test (the strain rate is 1/150), the overall offset is about 6.5mm with respect to the original position. The initial stress state of the first loading step is the tensile force, and the initial deflection of the mid-span position is reduced by about 1 mm, which is consistent with the typical test results of Section 4.1, then the specimen was compressed, and gradually, the specimen connected by the pin was misaligned.

The reason or mechanism remains to be further studied. Obviously, the test results of the specimen connected by welding and the specimen connected by the pin are not directly comparable, and the specimen connected by the pin increases the degree of freedom at least in the direction of rotation about the pin shaft.

4.4 Analysis of the essentials of technical specifications

In the technical specifications described in Chapter 1, technical specification for the application of buckling-restrained braces(exposure draft) proposed that the test of buckling-restrained braces should include component test and substructure test. The provisions of the article indicate that the component test for the buckling-restrained braces is to ensure that the buckling-restrained braces can meet the requirements of strength and elastoplastic deformation, and determine the ultimate bearing capacity of the braces, and verify whether the actual performance parameters are consistent with the design performance parameters; the substructure test is to test whether the gusset plate, the core unit
overhanging section and the outer restraining unit break under the condition of satisfying the axial and rotational deformation requirements.

Undoubtedly, the testing methods for the mechanical properties of buckling-restrained braces specified in Section 7.4 of the product standard "JG/T209-2012 Dampers for vibration energy dissipation of buildings" belong to the category of component testing. The mechanical properties in the range of the length of the core unit are tested. The core unit consists of the working section, the transition section and the connection section. However, it does not include the joints. The testing methods proposed by other standards, such as GB50011-2010 Code for seismic design of buildings, JGJ99-2015 Technical specification for steel structure of tall building, DG/TJ08-32-2008 Specification for steel structure design of tall buildings, are also within the scope of component testing.

How the core unit is connected to the testing machine during the test, none of the above technical standards has clearly defined. The testing methods in Chapter 3 are also within the scope of component testing. Therefore, it is not necessary to consider how the buckling-restrained braces connect to the main structure in the project. It is recommended to use welded joints (rigidly connected end plates) for product inspection to ensure the success rate of the test.

5. Conclusions
(1) The specimens connected by bolts may slip, and the specimens connected by the pins may be misaligned. These two connection types are not suitable for the test of mechanical properties of the buckling-restrained braces.

(2) The component testing of the buckling-restrained braces does not need to consider the connection type in the engineering. In order to obtain the laterally comparable test results, it is recommended to uniformly use the welded joints specimen and indicate the connection type in the test report.
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