Review of Research Progress on Buckling Restrained Braces

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Abstract: Buckling restrained brace is a type of non-bonded energy dissipation support. The center of buckling restrained brace (BRB) is a core material made of low yield point steel, which allows large plastic deformation under axial force to consume the seismic energy. Based on a large number of related experiments and researches done by previous researchers, this paper reviews the latest progress of the research on buckling restrained braces at home and abroad.

1. Introduction

The buckling restrained brace (BRB) is an effective seismic resistance, which can absorb more energy during earthquake than the normal steel braces as their buckling can be restrained. The typical structure of a BRB generally consists of three parts: core restraint members for energy consumption, peripheral restraint members, and non-adhesive layer, as shown in Figure 1. Energy is mainly dissipated through the plastic deformation of core members under earthquakes. Peripheral restraint members are members that are placed around the core members to prevent them from buckling during compression. At the same time, in order to prevent the buckling of the braces under the compressive stress after the external restraint members participate in the axial load, the transmission of the longitudinal force between the core member and the restraint member must be isolated. Therefore, an adhesive layer is used. The core members remain elastic under wind or small earthquakes, which can effectively improve the lateral stiffness of the structure. Under moderate and large earthquakes, the structure yields before it enters the state of plastic energy dissipation and dissipates the earthquake energy to protect the main structure. Compared with the traditional braces, the BRBs can reach the maximum energy assumption ability of steel by restraining the buckling of the braces.

![Figure 1 Composition of a common buckling restraint brace](image_url)

2. Earlier Researches of Buckling Constrained Support

Indian engineer Shuhaibar added an outer tube to the ordinary axially loaded members to restrain its deformation, which is an early prototype of BRB. Since then, many researches and developments on BRBs have been made. In 1976, Kimura et al. [1] proposed a modern-type BRB, which laid the foundation for the research of BRB theoretically and experimentally. The structural design and construction technology of BRB have been further studied by Professor Clark et al. [2]. The joint committee of SEAOC and AISC formulated the "Recommended Provisions for BRB" in 2001 and then...
included these regulations into AISC (Seismic Provisions for Structural Steel Buildings) in 2005.

Guo et al. [3,4] carried out numerical simulation on the stability of BRBs, and analyzed various parameters which may influence the performance of BRBs theoretically. A simplified seismic calculation method and practical design methods for buckling-restrained braced frames were then proposed. New types of assembled BRBs were developed using existing steel sections, as shown in Figure 2.

![Assembled Buckling Restrained Brace](image)

Wu et al. [5,6] conducted experiments on BRB to explore the influence of the assembly. Two new types of BRBs, self-centering BRB and combined concrete-filled steel tube BRB. The seismic performance of the buckling-restrained braced frames was also studied.

Li et al. [7,8] developed two types of BRBs, TJ1 and TJ2, which are the first BRB productions developed by China and have been used in many large projects. The hysteretic performance and elastoplastic stiffness equations of the two types of BRBs were studied. The seismic performance of the buckling-restrained braced structure was studied by conducting shaking table tests, and the bearing capacity, stiffness and joint design criteria of the buckling-restrained braced structure were proposed based on the test results.

Zhao [9] developed a full-angle steel BRB to avoid the problem of traditional BRB with welded cross-shaped core. Its seismic performance and the impact of end rotation on the stability of the extension region of inner core and on the overall stability were studied by experiments. The concept of bending moment amplification factor were proposed, and the in-plane stability design method was given, which further standardizes and simplifies the design method of BRB.

3. The latest research progress of BRB

3.1 Perforated steel plates buckling-restrained brace

Due to many advantages of steel plate assembled BRBs, such as stable in performance and easy to process, more and more studies have been conducted on them. In order to solve the existing problems of local buckling of end connection segments and random failures locations of core unit in plate BRBs, and to optimize the structures of plate BRBs, Zhou et al. [10] proposed the concept of perforated steel plates buckling-restrained brace (PBRB). Studies of the impact of PBRB energy absorption performance and the related influencing parameters were carried out [11-13]. The results proved that PBRB has many advantages such as clear energy consumption mechanism, relatively fixed failure location, good energy consumption capacity, stable hysteresis performance and good fatigue resistance, which effectively improved the seismic performance of the traditional plate BRB.

3.2 Buckling restraint braces with multiple casing

Buckling restraint support with multiple casing was invented by Takino [14]. Steel pipes were used as the core member and the restraint unit. The low yield point steel was used for the core energy consumption section to ensure the BRB yielding at early stage of the seismic. In contrast, steel with higher capacity were used for the casing and the connection to provide greater lateral stiffness and ensure that the casing part would not entering the yield stage too early under bending. This design was propose to solve the problem of local buckling of the core member, and to ensure that the connection parts remain elastic after the yield of the core member, so as to ensure the normal operation of the buckling-restrained braced frames in the structure.

Yin [15] added a contact ring on the steel pipe inner core, as shown in Figure 3, to improve the lateral stiffness of the core member of double sleeve BRB. One-way and reciprocating axial loading tests were
conducted for five different types double sleeve BRBs proposed. The energy dissipation capacity and ductility of these BRBs were compared and studied. The results show that the energy dissipation performance of this type of support is good, and its restoring force model could be fitted with a three-fold line model or a double-fold line model.

Zhang et al. [16] proposed a BRB in the form of a triple steel pipe with slotted holes in the core tube. The influence of factors such as the number of slots and the size of the slots on the hysteretic behavior of the support were studied through low-cycle reciprocating tests and FEM analysis. The results show that the opening could effectively control the deformation position of the inner core, and better energy dissipation effect of the BRB would be achieved with an opening ratio of 0.2.

Wang et al. [17] developed a Bamboo-Shape Buckling Restrained Brace, as shown in Figure 4. The behavior of this BRB were experimentally studied. The test results show that it has good energy dissipation ability, and that the low-cycle fatigue performance of this Bamboo-Shape BRB will be affected by the length of its energy consumption section. It is also found that the rotation of the support end will affect the stability of the test specimen and the longer slub element, the less end rotations, and therefore better stability.

Xiao [18] simplified the model of multiple steel pipe BRBs to a rod model using the symmetry principle, and derived a design formula according to the classic mechanics and edge yield criteria. The formula proposed provide guidance and reference for the design of such BRBs.

3.3 Steel bar buckling restrained braces

Wu [19] proposed a steel bar buckling restrained braces (SBBRB) by combining the advantages of different BRBs. The steel bar of SBRBR is embedded in the steel tube sleeve, and it can withstand both the tension and the compression.

SBBRB includes the core steel bar component and the external restraint component. The core steel component includes the middle yielding region, the transition region and the elastic region at both ends. High-strength concrete grouting is filled into the core member and the outer member. The outer restraint member restrains the buckling of the core member, and it is not designed to bear the axial forces. There is a proper gap between the core steel rod and the outer restraint member to provide space for the lateral deformation of the core steel rod after yielding. Besides, rubber, silicone, latex, etc. were used to isolate the core member with mortar or concrete, making the core steel rod and the filling material can move separately.

3.4 Buckling restraint braces with replaceable elements

Liu [20] proposed a buckling restraint braces with replaceable energy dissipating angle steel elements, which is supported by a freely retractable inner restraining member, as shown in Figure 5. The angle steel element is shown in Figure 6 and the restraining member, composed of three parts, is shown in Figure 7. This structure is convenient for post-earthquake damage detection, replacement of energy-consuming components, and recycling of restraining members.
3.5 BRBs with H-section steel

Compared with the I-shaped BRB, the section for the restrained parts of the H-shaped steel BRB is relatively smaller, and the stability of the H-shaped steel BRB is better. Compared with the cross-shaped BRB, the H-shaped steel BRB is easier to produce with less welding engaged in the production, and the processing quality is more stable.

Kim et al. [21] performed cyclic tests on three H-shaped steel BRBs. One H-shaped steel BRB, of which the square steel tubes was filled with concrete, effectively restrained the local buckling of the flanges and webs of the H-shaped core components.

Shang [22] proposed two types of H-shaped steel BRBs, web weakened H-shaped steel BRB and end strengthened H-shaped steel BRB. The hysteretic performance was studied by experiments and finite element analysis.

3.6 Two-level yielding BRB

Although the buckling restraint support is widely used in engineering, there are also shortcomings: in order to avoid low-cycle fatigue failure, the buckling restraint support is designed to remain elastic under small earthquake and cannot absorb energy.

To solve the problem, a new type of the buckling restraint braces were proposed by Sun et al. [23], in which conventional BRB and the metal tube damper were combined. The metal sleeve damper consists of two parts: the inner core plate and the outer steel tube with the energy dissipation steel strips, which are connected by plug welding and fillet welding, as shown in Figure 8. The yield bearing capacity of the steel strips is lower than the stability bearing capacity of both inner I-beam and outer seamless steel tube. Therefore, under frequent earthquakes, the metal tube damper yields to dissipate energy and the buckling restrained core remains elastic. While under large earthquakes, the buckling restrained core plate is the key energy dissipation part. Hysteretic loading tests were carried out on the proposed two-level-yielding BRBs to determine their mechanical property. The results show that the dissipation capacity of specimens was good. The behavior of frames with such BRBs under different earthquakes were also numerically studied.

Hu [24] proposed a type of BRB which have better performance for energy consumption and stiffness adjustment, as shown in Figure 9. The traditional BRBs have many disadvantages such as the core material yield threshold is not easy to control and the sudden change in stiffness of the BRB, which may impact the overall behavior of the structure. The working mechanism is shown in Figure 10. The inner and outer core members allow the BRB to achieve different levels of energy consumption.
3.7 Self-centering buckling restraint braces
Pre-tensioned self-centering buckling-restrained brace (SC-BRB) has good energy consumption and self-reset performance, which can effectively improve the post-seismic repairability of the structure. For existing SC-BRB structures, the pretension bar may still yield or even break under a large earthquake, thereby affecting the repairability and safety of the structure. At the same time, when the pretension bar fails to meet the structural deformation requirements or the adjacent bending frame yield, it will cause residual deformation for a certain structure. As the current performance-based design method of SC-BRB frames only considers the maximum deformation and does not include residual deformation, it is difficult to ensure the repairability of such SC-BRB structure after an earthquake.

Xie [25] analyzed the existing problems for the traditional pre-stretch SC-BRB by tests, as shown in Figure 11, such as the limit deformation ability and relatively smaller tested initial stiffness compared with the theoretical value. The influence of the casing length error on the initial stiffness of the brace were studied. To solve the problem, improvements were made on the traditional SC-BRB to form a new type of pre-tensioned SC-BRB. The improvements on the configuration include rubber sandwiched end plates (to improve the controllability of the initial stiffness of the support), Friction safety device and tandem SC-BRB (increased their deformation capacity).

The working mechanism and mechanical behavior of the new type of SC-BRB were analyzed, and the design method for this SC-BRB were proposed.

3.8 Hybrid shape memory alloy and buckling restraint support system
This hybrid self-resetting anti-seismic structure is equipped with both EDDs and self-resetting devices. The self-resetting anti-seismic design can be realized by integrating post-tensioned prestressed tendons (beams) or shape memory alloy (SMA) smart materials with traditional seismic structures. Zhang et al. [26] set NiTi SMA at the intersection of ordinary steel supports and beams. The SMA damper is used to reduce or eliminate the residual deformation of the structure after earthquakes to achieve the self-resetting of the structure. Li [27] proposed a hybrid shape memory alloy (SMA) and buckling restrained brace (BRB) system. In this hybrid self-resetting device, BRB is used to consume the earthquake energy, while SMA provides a self-resetting function. SC-BRB can reduce the residual displacement of the structure by more than 50%. The hybrid self-resetting device has good engineering application prospects in long-span structures and high-intensity seismic fortification zone.

4. Conclusions
This paper mainly introduces the research progress and application of buckling restrained braces in recent years. Some key issues in the design of different types of buckling restrained braces are discussed. The researches show that the seismic performance of different types of BRBs are good, and they are designed to satisfy the need of different practical scenarios. Developing new buckling restraint braces with better seismic performance and less cost remains an important issue.
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