Research Status and Application of Buckling Restrained Brace Technology

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Abstract. For the past four decades, researchers have worked upon and developed a bracing system called the buckling restrained brace (BRB) for frame braced structures. This system counteracts compression from buckling during strong earthquakes. The system has the advantages of a common brace and damper, providing lateral stiffness to the structure under frequent earthquakes. Seismic energy can be dissipated by the steel core yield, under both rarely expected and moderate earthquakes. This paper is devoted to the concept of BRB, its components, characteristics, and its current deficiencies. It also discusses the current limitations and estimates the developing trend of this technique. It has a certain reference value for in-depth studies on BRB system.

Keywords: Buckling restrained brace; Energy dissipation; Earthquake; Hysteretic behaviors; Earthquake resistant design.

1. Introduction
With the development of economy, there is a constant increase in the number of high-rise buildings. During an earthquake or lateral wind load, controlling the excessive deformation becomes a critical task. Energy dissipation braces can make the structure have higher lateral stiffness to limit the lateral displacement. It mainly includes the following three forms as illustrated in Figure 1, (a) Eccentric energy dissipation brace, (b) Energy dissipation brace, and (c) Energy dissipation frame brace [1]. But during the occurrence of major earthquakes, these three types of braces will yield, both in compression and/or tension. Especially compression yield, that is non-conducive to passive energy dissipation. In recent years, it was deeply studied in Japan, America and other countries, particularly after the Northridge earthquake in 1994 and Kobe earthquake in 1995. In China, the research on BRB has gradually become perfect, identifying it to be a typical design idea of absorbing and dissipating the input energy of the earthquake. Under severe earthquake loading, the specially designed energy dissipating member is allowed to enter into the plastic state to absorb the energy input into the structure without causing any damage to the main structure, keeping it functional. These energy dissipation components are made of materials with high plastic deformation capacity, which can also be easily replaced. As a new technology for shock absorption and earthquake resistance, the BRB is used in large public buildings, which has improved the earthquake resistant capability significantly [2].
Figure 1. Three forms of energy dissipation braces.

In 1973, Wakabayashi put forth the idea of internal steel plate brace, which was tested with epoxy resin, silica gel, polyethylene, and other bonding materials. The results showed that a combination of epoxy resin coated with silica gel gave the best performance [3]. In 1976, Kimura first carried out the research on composite restrained buckling brace of concrete filled structural tubes, and concluded that, with the ratio of Euler buckling load to core yield load greater than 1.9, the peripheral components of the brace will not lose its stability [4]. In 1992, Inoue proposed the use of prefabricated reinforced concrete slab as the peripheral restraint member that was more suitable for industrial production with controlled precision [5]. In 2005, Cai kequan developed the double steel plate core buckling brace that solved the problem of a long connection section being prone to buckling [6]. In 2008, Cheng Guangyu summarized and discussed the design method of buckling proof brace and suggested that the stirrup configuration should be strengthened at both ends of the encased reinforced concrete [7]. In 2010, Gao Xiangyu proposed a combined hot-rolled steel angle buckling brace, that had a simple structure, strong energy consumption capacity and good ductility [8]. In 2015, Guo Yanlin studied the peripheral restraint mechanism and stiffness values of the double moment tube assembly buckling brace, which were verified by the experiment [9]. In 2016 Ma Hua proposed a new type of buckling brace with limit function. The results showed that the limit buckling restrained brace (LBRB) member with reasonable structure has good energy dissipation capacity and can provide additional stiffness in case of large deformation [10].

This paper summarizes the developments in BRBs since they were invented. The developing trends are also pointed out to look for the new approaches to design BRB, and to provide a reference for structural seismic design.

2. Basic Principle of BRB

The principle for a BRB structure is quite similar to other forms of bracing. During an earthquake, the axial force of the supporting structure is borne by the core steel plate and completely absorbs the energy under axial tension and pressure. In order to avoid its buckling under compression (yield can be achieved both in tension and in compression), the core steel plate is placed in a steel tube filled with concrete and separated by very narrow air layer of unbonded material. The purpose is to reduce or eliminate the axial force on the core steel plate that is not transmitted to the concrete or the outer steel pipe. Figure 2 is the schematic diagram of BRB that mainly consists of the following five parts: Restrained yield section, restrained non yield section, unconstrained non yield section, unbonded expandable material, buckling restraint mechanism [2]. As depicted in Figure 3, the core plate is connected with other components and bears the entire load. The buckling of the core plate is restrained by the outer sleeve and the filling material. Under both tension as well as compression loading, the bearing capacity of the load is equivalent. This kind of brace can yield without bending in tension and compression, and it has more stable mechanical properties than the conventional bracing system. A properly designed BRB not only has a high stiffness, but also good hysteretic energy dissipation capacity of steel. Therefore, unbonded braces have the functions of both concentric diagonal braces and hysteretic energy dissipation elements, along with good seismic application value [11]. As Figure 4 illustrates, BRB has been employed in two arrangements: (a) in the seven-storey office building of Tokyo "I. K. building" and (b) in another steel frame structure with a total height of 180 m and a plane size of 50 m×50 m.
Buckling energy dissipation braces do not participate in energy dissipation (neither yield) under frequent earthquake action. In general, BRB technology is suitable for all kinds of buildings. For a structure with higher, softer, and larger deformation or higher seismic fortification intensity, its energy dissipation and damping effect is more significant. Therefore, BRB is particularly suitable for long-period frame structure system in high earthquake intensity area. It can also be applied to the seismic reinforcement of existing buildings and repair of earthquake damaged structures for the improvement of its performance.
3. Development and Application of BRB

Japan is a pioneer in the study of BRBs, with the largest variety and number of these braces. A group of Japanese scholars had successfully developed the earliest wall plate BRBs. As of 2004, more than 300 buildings have been supported by BRBs in Japan. It is also the country with the largest number of manufacturers with patented design in the world. After Northridge earthquake in 1994, the United States began to carry out corresponding design research and large-scale tests on the BRBs system. Simultaneously, the advantages of this support system in comparison with other support systems were analyzed by theoretical calculation. In 2000, the Plant and Environmental Science Building of University of California Davis was completed using 132 BRBs as the lateral force members of the structure, which became the first structure in the United States to use BRBs. Till date, more than 30 structures have been built or are under construction with BRBs in the United States, with a large number of them in its pacific region [12].

In recent years, many buildings have been built in Taiwan with this system, such as the gymnasium at the Taiwan University of culture and the Beijing Weisheng and Beijing Yintai Center buildings, which are under construction in the mainland. The steel structure project of Western electromechanical technology business center adopts the non bonding brace of Nippon Steel Co., Ltd. The Shanghai World Expo also uses the TII type constraint brace developed jointly by Shanghai Lanke Company and Tongji University. Compared with the United States, Japan, and other countries, the research and application of BRB in China started late and is still in its infancy. However, in mainland China, the BRB system has been used in nearly one thousand buildings, and good economic benefits have been achieved. Currently, there are different kinds of steel core types and styles that can be chosen. Based on recent usage, the most common types are highlighted in Figure 5: outer steel pipes are either square or round; the core section is I-shaped, plus shaped, 工-shaped, etc. These are commonly used as sections of BRBs. Figure 5 (d) shows a core plate wrapped in precast concrete spliced with two bolts. The core in Figures (e) - (h) is restrained by the section steel. The statistics of research in recent years are detailed in Table 1.

![Figure 4. Two layouts of BRB [1].](image)

![Figure 5. Section forms of BRB [2].](image)
### Table 1. Details of Specimens.

| Time  | Author          | Research Content                                                                 | Conclusion                                                                 |
|-------|-----------------|----------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| 1973  | Wakabayashi     | Epoxy resin, silica gel and polyethylene were used as bonding materials for testing. | Epoxy resin coated with silica gel has the best performance.              |
| 1976  | Kimura          | It was the first study that carried out the research on CFST composite restrained BRB. | If the ratio of Euler buckling load to core yield load is greater than 1.9, the overall buckling failure of the brace does successfully avoided. |
| 1988  | Fujimoto        | For steel casting, the stiffness and strength design criteria were obtained by filling mortar between steel core and casing. | It improves the hysteretic performance for braces with large constraint ratio. |
| 1993  | Inoue           | The precast reinforced concrete slab was used as the peripheral restraint element. | It is more suitable for industrial production due to its controllable precision. |
| 2000  | Koetaka         | Buckling-restrained energy dissipation braces with four steel tubes as restraint elements. | The safety factor of section composition without global bending is obtained. |
| 2005  | Cai Kequan      | A BRB with double steel plate core was proposed. | It solves the problem of buckling in case of long connecting section. |
| 2006  | Li yan          | The static reciprocating test of buckling restrained steel brace with I-shaped core encased in a steel tube was carried out. | It exhibits improved hysteretic characteristics and energy dissipation. |
| 2008  | Cheng Guangyu   | The design method for a BRB was summarized. | It is suggested that stirrups should be strengthened at both ends of the encased reinforced concrete. |
| 2009  | Li Guoqiang     | A series of low cycle reciprocating cycle load tests were carried out on TJ type BRBs. | The test results indicate that TJ BRB has superior hysteretic characteristics and energy dissipation performance. |
| 2010  | Chou            | The core components, in addition to the upper and lower parts were made of steel plates, and the spacing was adjusted by cushion blocks. | The proposed design increases the accuracy of the gap size between the kernel and the peripheral constraints. |
| 2011  | Gao Xiangyu     | The BRB made of combined hot rolled angle steel was proposed. | It has the advantages of simple structure, increase energy consumption, and improved ductility. |
| 2013  | Guo Yanlin      | External restraint ratio of the support and the bolt design between the external restraint members were put forward. | It ensures the global and local stability of the external constraint components. |
| 2014  | Qu              | A novel BRB frame system was proposed. | It significantly reduces the adverse effects of gusset plate on the surrounding beam column connection. |
| 2015  | Guo Yanlin      | A new type of double rectangular tube fabricated BRB was proposed. | The rationality of the external restraint mechanism was verified by experiments. |
| 2016  | Ma Hua          | A novel BRB with displacement stopper was proposed. | It exhibits superior energy-dissipation ability and provides an additional stiffness under larger deformation. |
| 2017  | Wang Chunlin    | A new type of bamboo BRB is proposed | This design displayed stable hysteretic performance. |
| 2019  | Zhonggenquan    | BRBs under two directional horizontal earthquakes are studied. | Increasing the out-of-plane stiffness of the fabricated BRB reduces the out-of-plane deformation. |
4. The Problems of BRB and its Future Development

Although the concept of BRB system is simple and clear, its design and construction process is complicated because of its convoluted working mechanism, and hence is not the most popular among engineering designers. Therefore, it is necessary to bring in practical design methods.

(1) In recent years, due to the diversified requirements of engineering construction for BRB, its application scope is expanding. BRB show the trend of light weight and high bearing capacity.

(2) In recent years, the progress of experimental methods, numerical simulation, and theoretical analysis methods have provided convenient conditions for studying the failure mechanisms to achieve optimal designs of BRBs. Simultaneously, the development of section forms and structural measures of BRBs with different application ranges promoted the rapid development of buckling-restrained braces.

(3) The new type of BRB has been gradually expanded from one-dimensional space to two-dimensional, or even three-dimensional space. As a result, it has a wider application prospect. Moreover, it also promotes rapid advancements in the field of structural energy dissipation and vibration reduction.

(4) It is difficult to machine the conventional integral BRB system to control the gap between the peripheral concrete and the core steel members leading to a high processing cost. However, the assembling type BRB system can effectively overcome the above problems. Throughout the development of this system, we have seen that it has gradually emerged from the conventional integral restraint type to the assembling type.

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