Review of Research and Application of Reinforced Concrete Structures Strengthened by Braces

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Abstract. Many of RC frame structures are urgently needed to be strengthened and maintained due to the increase of service life, the change of use function, and the impact of natural disasters. This paper reviews the research status of strengthening RC structures with braces; introduces the features and connection forms of joints connecting with braces; summarizes the engineering application of buckling-restrained braces, pointing out that buckling-restrained brace is an effective means to strengthen the RC frame structures with more reliable performance and broad application prospect.

1. Introduction

Many of RC structures had such serious problems as cracking and slumping due to the impact of aging and earthquake, causing great harm to people's lives and properties. Some existing structures cannot meet the requirement of seismic fortification intensity need for seismic reinforcement in accordance with Code for Seismic Design of Buildings [1]. China has issued Design Code for Strengthening Concrete Structure [2], summarizing many strengthening techniques, such as increasing section method, encasing steel, prestressed strengthening, bonding steel and carbon fiber polymer, introducing the requirements of design and construction and calculation of sections. Particularly, strengthening structures by adding braces has prominent advantages. Common steel brace not only can improve stiffness of structures, but weaken ductility of structures less because of its good ductility performance. Buckling-restrained brace can yield instead of buckling in tension and compression with better seismic performance, stronger energy-dissipated capacity in rare earthquake and more stable mechanical performance comparing with common brace.

2. Characteristics of strengthening structures by adding braces

Strengthening by adding braces is a common method to improve the bearing capacity of structures and reduce deformation of structures. Concentric braces, eccentric braces, buckling-restrained braces are classified. Reference [3-5] introduced the features of common steel braces in detail. Based on stiffness and bearing capacity, concentric braces were adopted with high lateral stiffness, however, buckling occurred after compression in the earthquake, resulting in a sharp decline in stiffness and bearing capacity. Based on energy dissipation, eccentric braces were produced with an important segment called the link beam. Energy from earthquake can be dissipated by inelastic deformation of the link beam. Reference [6] and [7] summarized and introduced detailedly different sections and composition of BRBs. Based on bearing capacity and energy dissipation, buckling-restrained braces were produced with better energy-dissipated capacity, composing of inner core, outer constraints and unbonded material. Under the strong earthquake, the inner core bore axial loads to dissipate seismic energy; the
outer constraints brought lateral restraint to the inner core, preventing from buckling; the unbonded material guaranteed the inner core to bear axial force.

3. Connection forms of joints connecting with additional braces

3.1 For new reinforced concrete frame structures
Firstly, the bolt sleeve is embedded in the beam-column, the anchor plate is fixed on the beam-column by bolts, and the adjacent anchor plate weld together, the gusset plate of brace is welded with the anchor plate as Figure 1.

![Screw connection](image1.png) ![Anchor bolt connection](image2.png)

**Figure 1.** Screw connection  **Figure 2.** Anchor bolt connection

![Encase steel hoop outside](image3.png) ![Embed steel frame inside](image4.png)

**Figure 3.** Encase steel hoop outside  **Figure 4.** Embed steel frame inside

3.2 For existing reinforced concrete structures
The anchor plate is fixed on the surface of the beam-column by anchor bolts, the anchor plate is welded vertically and horizontally, and the gusset plate is welded with the anchor plate as Figure 2. Surface of beam-column is polished and cleaned, then steel plate is bonded on the surface in epoxy resin, the gusset plate is welded with the steel plate as Figure 3. The steel frame is embedded in the reinforced concrete frame, and the gusset plate is welded with the steel frame. How to fix the steel frame? first reserving stud holes in the beam-column, then arranging studs on the steel frame and positioning accurately, finally pouring cement mortar between the steel frame and concrete frame as Figure 4.

4. Study on the performance of strengthening structures with braces

4.1 Common steel braces
Gonzalez [8], through the comparative study on the seismic performance of RC frame strengthened with Y-shaped steel braces and shear walls, showed that strengthening RC frame with Y-shaped steel braces was more economical and effective to improve the stiffness and ductility. Ghobarah [9],
through the comparative study on the seismic performance of three-layer RC frames strengthened with Y-shaped eccentric steel brace and concentric steel brace, showed that eccentric bracing frame exhibited lower deformation and damage, the main damage was in the part of the link beam, dissipating energy by inelastic deformation; The frame inverted concentric steel brace damaged more. Man Xu [10], through elastic-plastic dynamic response analysis of failed middle and side column of five commonly concentrically braced steel frames, showed that the stiffness of structures was greatly improved, but the ultimate bearing capacity of structures was not improved obviously; V-typed, inverted V-typed and X-typed braces effectively reduced the displacement of the failure point; strengthening effect of the forward-brace for middle column was better than that of side column; the influence of backward-brace was approximate. Baocheng Zhao [11] made low cyclic loading test of RC frame strengthened with Y-shaped eccentric steel brace with different connection forms between the link beam and RC-frame beam. U-steel hoop was encased on the beam to protect the connection point. Another form was just to anchor a 20mm-thick steel plate under the beam, showing that steel brace contributed to improve the lateral stiffness of structures and dissipate energy; the connection joint with U-steel hoop was more effective without damage, failure of structure was led by the failure of the link beam; the joint anchoring a steel plate damaged, leading to the failure of structure. Surong Fan [12] made low cyclic loading test of RC frames strengthened by encasing steel brace and embedding steel frame brace, showing that steel brace contributed to improve the stiffness and aseismic shear capacity of structures and reduce the story drifts, the beam-column joints were not damaged. In contrast, steel frame had better strengthening effect, working performance and stronger energy dissipation capacity.

4.2 Buckling-restrained brace 
Mahrenholtz [13] made quasi-static test of RC frame strengthened with BRB, and introduced the design method of anchor connection, showing that the inter-story displacement angle of the frame was within 3%, and the mechanical properties of the brace and the joints were stable. Corte [14] made a of field test of a two-storey RC frame strengthened with buckling-restrained brace, showing that BRB occurred overall buckling, and the inter-story displacement angle of the frame was within 3%. Yooprasertchai [15], carried on quasi-static tests on RC columns connected with buckling restrained braces, showing that although BRB can greatly improve the lateral stiffness and strength of columns, but the overlap of steel bars has been seriously damaged. Hui Wu [16] carried on the experiment on seismic performance of three-storey RC frame strengthened with buckling-restrained brace, showing that the seismic performance of structure was improved remarkably, and the earthquake energy was mainly dissipated by BRB. Hui Wu [17] made a study on the seismic performance of replacing buckling-restrained brace. First a three-storey RC frame was strengthened by BRB, imposing loads until BRB yielded; then replaced the failed BRB, showing that BRB greatly contributed to improve the bearing capacity of structure and energy dissipation capacity. After the replacement of BRB, the structure regained good seismic performance. Bingzheng Cao [18], carried on the low cyclic test of two-layer RC frame strengthened with BRB, showing that the bearing capacity of structure was improved, but the adjacent beam-column connecting with BRB damaged, leading to the failure of main frame and decline of deformation capacity of frame. It was suggested that adjacent beam-column should be strengthened first.

5. The advantages of buckling-restrained brace
The lateral stiffness and bearing capacity of RC frames can be improved by common steel braces. However, it is easy to produce instability and buckle under the rare earthquake, so the seismic performance of steel braces is much poorer as Figure 5. BRB can not only effectively solve such problems as buckling in compression to ensure the stable seismic performance, but as a energy dissipation damper, it can effectively dissipate seismic energy to avoid the occurrence of serious damage of the main body of structures as Figure 6.
6. Engineering application of buckling restrained braces

The building of crop and environment science in California University was the first use of buckling-restrained braces; 14-storey dormitory building in California University was strengthened by BRB [19]. The federal building creating in 1960s in Salt Lake City was retrofitted by 344 BRBs [20]. The project won the Utah annual outstanding engineering award in 2002.

A lot of researches on buckling restrained braces had been done in Taiwan. Cathay International Building in Taichung, a steel structure building, suffered the "9.21" earthquake in the construction process. After the earthquake, the seismic grade of the area was modified to improve. So 80 pure steel were adopted to strengthen the case as [21]. Yangming Culture University Gymnasium in Taipei was a elliptic structure. In order to improve the seismic performance of the structure, the diagonal part was provided with 96 buckling-restrained braces [21].

Hiroshima branch building of Takenake Corporation was built in 1971 as the RC frame structure. In order to meet the seismic fortification criterion of the new seismic code in Japan, the buckling restrained brace made of low yield point steel was used to retrofit. A total of 32 BRBs were designed to the four corners of each layer from the 2nd to 9th layer without effects on the appearance and lighting of the building [6].

Shanghai Earthquake Prevention and Disaster Reduction Center. The seismic fortification intensity was 8 degrees. If shear walls were adopted to strengthen, shear walls cracked and even failed and stiffness degradation was serious. After the comprehensive consideration, buckling-restrained braces system was used to provide the lateral stiffness and dissipate seismic energy under the rare earthquake [22]. Shanghai Expo Center used TJ-typed buckling-restrained braces developed by Professor Guoqiang Li from Tongji University and his team. In addition, Shanxi library, Shanghai Sanlin Sports Center Gymnasium, Shanghai Shenhong Office Building, Oriental Sports Center and Shanghai Hengfeng Middle School adopted TJ-typed BRB [23].

7. Conclusion

Strengthening RC frames by braces has better properties than other strengthening techniques. Particularly, buckling-restrained brace has such outstanding features and superiority as yielding without buckling in tension and compression, more stable mechanical performance, stronger energy dissipation capacity. However, this technology has been patented in many foreign countries without opening to the public, limiting the development and promotion of the technology. So we should enhance the research to enact technical specification for design and construction in accordance with the reality of our country. It should be noted that braces will have an impact on the internal force distribution of the beam-column joints connected with braces, which need to be strengthened to meet bearing capacity. The joints connected braces with the main structure are the weak link in the whole system. How to ensure the connecting joints are not damaged is needed solving and noticing in current design and construction.

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9. References

[1] GB50011 2010 Code for Seismic Design of Buildings (Beijing: China Building Industry Press)
[2] GB50367 2013 Code for Design of Reinforced Concrete Structures (Beijing: China Building Industry Press)
[3] Tremblay R 2002 Inelastic seismic response of steel bracing members J Constr. Steel Res. 58 pp 665-701
[4] Edoardo M and Nakashima M 2006 Seismic performance and new design procedure for chevron-braced frames J Earthq. Eng. & Struct. Dyn. 35 pp 433-52
[5] Jianbin L 2005 Study on design theory of buckling restrained brace and buckling restrained braced steel frame D Tsinghua Univ.
[6] Yun Z 2007 Designing and application for buckling-restrained brace frame (Beijing: China Building Industry Press) p 212
[7] Yanlin G Jingzhong T and Peng Z 2016 Research progress of buckling restrained braces: types, design methods and applications J Eng. Mech. 33 pp 1-14
[8] Gonzalez S 2007 Retrofitting of RC structures on gravity columns using Y-inverted steel bracing D Puerto Rico: University of Puerto Rico, Mayaguez
[9] Ghobarah A and Elfiath H 2001 Rehabilitation of reinforced concrete frame using eccentric steel bracing J Eng. Struct. 23 pp 745-55
[10] Man X Shan G and Libin Z 2013 Progressive collapse dynamic analysis of concentrically braced steel frames J Chin. Civ. Eng. Journal 46 pp 329-38
[11] Baocheng Z Anlin Y and Sicheng J 2013 Experimental investigation of Y-eccentrically steel braced RC frames energy-dissipation J Earthq. Eng. & Eng. Vibr. 33 pp 47-53
[12] Surong F 2002 Experimental research on seismic retrofitting of reinforced concrete frame D Nanjing Univ. Techn.
[13] Mahrenholtz C Lin P and Wu A 2015 Retrofit of reinforced concrete frames with buckling-restrained braces J Earthq. Eng. & Struct. Dynam. 44 pp 59-78
[14] Corte G D’Aniello M and Landolfo R 2014 Field testing of all-steel buckling- restrained braces applied to a damaged reinforced concrete building J Struct. Eng. 141 D4014004-11
[15] Yooprasertchai E and Warnitchai P 2008 Seismic retrofitting of low-rise nonductile reinforced concrete building by buckling-restrained braces Proc. the 14th World Conf. on Earthq. Eng. (Beijing: China)
[16] Hui W Guowei Z and Jian Z 2013 Seismic performance of existing RC frame structures reinforced with buckling-restrained braces J Chin. Civ. Eng. Journ. 46 pp 37-46
[17] Hui W Yanxia Z and Guowei Z 2013 Experimental study on seismic performance of replaceable buckling-restrained braces in reinforced concrete frame J Chin. Civ. Eng. Journ. 46 pp 29-36
[18] Bingzheng C Chunming Z and Hao Zhen H 2012 Experiment study on seismic behavior of RC frames strengthened by buckling-restrained braces J Earthq. Resist. Eng. and Retr. 34 pp 1-7
[19] Parry B Aiken D and Jafarzadeh F 2001 Seismic retrofit of Wallance F. Bennett Federal Building J Mod. Steel Constr. 1-6
[20] Sabelli R Mahin S and Chang C 2003 Seismic demands on steel braced frame building with buckling-restrained braces J Eng. Struct. 25 pp 655-66
[21] Keh-Chyuan T and Junwei L 2004 Principle and application of buckling-restrained braces The 1st Nat. Symp. on Earthq. Prev. and Dis. Red. Eng. (Beijing: China) p 31
[22] Lu Z Weihua Z and Rui H 2011 Application of buckling restrained brace in Shanghai Seismological Bureau Building J Build. Struct. 41 pp 125-30
[23] Guoqiang L Feifei S and Hai G 2009 Engineering application of TJ-type buckling restrained brace J Build. Struct. 39 pp 607-10