Review of Application Research of BRBs in Seismic

Xiaoli Li [1, a]

[1]Institute of Road and Bridge Engineering, Dalian Maritime University, Dalian 116026, China

[a]6156156432@163.com

Keywords: Structural Seismic; Buckling Restrained Brace; Energy Consumption; Hysteretic Performance

Abstract: As a new type of energy dissipation component buckling — restrained brace overcomes traditional brace's drawbacks, such as compression buckling， inability to make full use of material's plastic hysteretic energy dissipation function when under pressure. Buckling — restrained brace also has the advantage of its simple working principle and high — efficiency energy dissipation function. It is a kind of very promising structure's energy dissipation component. This paper mainly introduces the research progress of buckling — restrained brace at home and abroad， focusing on BRB's working principle and composition， BRB subassembly and BRB system.

Introduction

Our country is earthquake-prone countries, since the founding of several earthquakes of highway bridges and culverts have serious damaging effects. How defense earthquakes, improve seismic capacity of highway bridges and culverts , has been thinking puzzle designer . In recent years, the development of anti- buckling support in seismic application matures and showed good seismic effect .

Buckling restrained brace(BRB)

BRBs were a new kind of energy-consuming elements common member and the metal support bar features a combination of damper. In Japan it was called unbonded Brace（for short UBB），In Taiwan it was called buckling restraint support. American scholars call Buckling-Restrained Braces（for short BRBs）， follow the US mainland China called it BRB.

BRB's structures

BRBs mainly consist of three parts[1]: core unit (main bear axial pulling force, pressure), constraints unit (constraint core unit , prevent its occurrence in whole or local buckling under pressure)and delaminating materials(prevent axis force suffered by core unit transmission to the constraint unit), as shown in the figure 1. Sections of several common core and constraints unit were as shown in the figure 2[2].

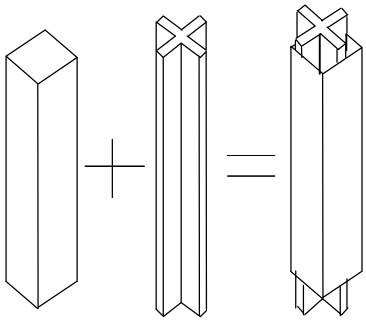

Fig. 1 Composition of buckling-restrained braces

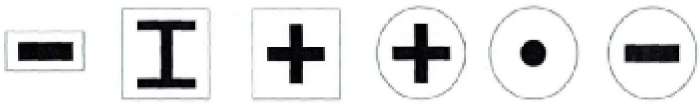

Fig. 2 Section type of inner core and constraint element

BRB's working principle

Under seismic action, BRB axial load borne by the kernel, the constraint unit provided to limit bending of the core necessary to prevent buckling its occurrence, so that the inner core in a state of tension and compression can achieve the yield, does not waste the design strength. The inner core prone to lateral expansion under axial pressure due to the Poisson effect, to prevent the hoop action, a certain distance should leave between the inner core and restraint unit. While the inner core is coated with a delaminating material constraints prevent the core unit and after contact with the constraining unit due to friction axial load [3]. In the small earthquakes, BRB can increase lateral stiffness of the structure under earthquake action, BRB act as a fuse structure, through "self-sacrifice" to protect against possible damage to the body structure, give full play to the consumption hysteresis. Compared to the general center support, BRB overcome its prone to buckling, causing the intensity of the shortcomings of waste. Superior hysteretic energy performance can meet the regulatory requirements. 1999, Clark P [4]compared hysteretic energy performance with BRB and center support through low cycle fatigue tests ,BRB hysteresis loop were symmetrical full and general center support quickly yield under pressure, curve was asymmetry under the action of tension and compression, as shown in the figure3. In addition, the eccentric support can limit support buckling by yield eccentric beams, But replacement eccentric girder segment was relatively complex and difficult to replace the BRB after the earthquake repair , therefore, the three supporting contrast showed that BRB best on carrying capacity and adaptability.

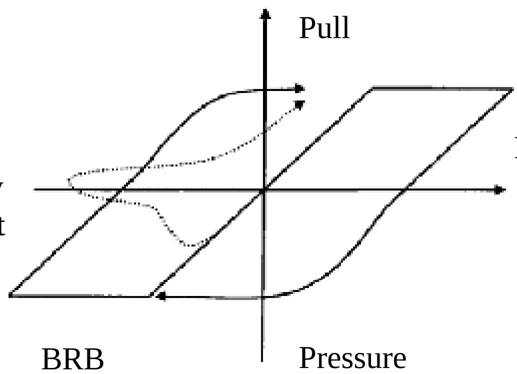

Fig. 3 Comparison of hysteretic behavior buckling-restrained braces and central braces

Foreign research status of BRB

Yoshino et al. [5] were first on the BRB carried out research, have they will be coated with an adhesive material disposed steel reinforced concrete wall panels. Two groups of specimens (A left 15mm gap between the steel plate and wall , a group without leaving gaps)were low cyclic loading test and showed that , energy dissipation capacity of shear specimen with gap was strong.
Wakabayashi et al. [6,7] would pack in prestressed concrete steel plates and carry out a series of tests:(1) explore the effects of different materials unbounded on members, the test results showed the performance of epoxy resin component silicone outsourcing were best;(2) 21 members compression tests conducted, the analysis showed that if we would not adopt measures to strengthen the concrete slab, that deformation out-plane of the support would promote earlier breakage of concrete slab edge under load.(3) The steel plate was attached to the hinge frame respectively in the form of diagonal and V form, support was clamped using of precast concrete panels， a scale model of the overall ratio of 1/5， steel plate produced uniform deformation, compressive strength greater than the tensile strength of the support under large deformation.(4)cyclic loading of two spans of two layers framework(containing diagonal bracing and V-shaped support respectively) was conducted, the compressive strength greater than the tensile strength of a single support under large deformation. When the support symmetric appeared on each floor, the reaction was also symmetric.
Kimura et al. [8,9] got on the first test to support of steel pipe constraint unit, filled with mortar. Although no adhesive material and the gap were not between the mortar and the inner core unit, but mortar played the role of prevent buckling of the core unit . They produced four full-scale specimens, slip of core relative to the mortar had been under cyclic loading of two specimens. The results from the test showed when Euler yield load limit of constraint unit and inner core was greater than 1.9, and core unit buckling should not occur, and the overall hysteretic performance was good.
Fujimoto et al. [10] got on experimental research on specimens ,which was the square steel tube filled mortar, maintaining the core dimensions unchanged, inspected variation of the mechanical behavior of the whole specimen by changing the size of the pipe.
Watanabe et al. [11] studied steel inner core specimens wrapped by steel pipe filled concrete and tested impact of constraints ratio（the ratio with elastic buckling strength of peripheral constraint unit and yield strength of inner core unit）variety on specimens hysteretic energy，analysis showed hysteretic performance stabilized only when the constraint ratio was greater than 1，and support could not unstable failure when the constraint ratio was greater than 1.5.
Indian scholars Sridhara [12,13] proposed a new type with a set pressure bar device， it was similar to the BRB， the working principle was multi-stage bending of pressure bar enhancing the overall carrying capacity of the specimen. As long as the bending stress after bending was less than the yield

strength of the outer sleeve, specimens can remain pressure. So the inner core support can greatly improve carrying capacity much larger than their yield strength.
Tada [14] proposed a new concept of a interpolation constraints steel pipe support in contrasted with the coat constraint unit. Results were showed that interpolation constraints could effectively limit the coat steel pipe buckling under pressure and hysteresis performance was well.
Iwata [15] compared test results of the BRB with four sections. Due to the lack of filling mortar and concrete constraints, in core unit of the second and fourth specimen happened local buckling occurs soon under low peripheral circulation load, overall performance instantly dropped. The first specimen was most superior performance, mortar crush and side stiffening plate fracture appeared after 14 cycles of load. The third specimen consisted of peripheral component constraint unit with two channels connecting by the high-strength bolts, its performance was after the first specimen.
Koetaka [16] carried out full-scale tests of BRB by four steel pipe as constraint unit. Core unit of this specimen was no difference with common BRB. Four pieces of pipe connected as a single entity by conjugation, 2-3mm gap was between core unit and steel pipe considering eccentric load and connection rigid impact. A safety factor a of sectional composition by formula for bending bar when overall bending buckling does not occur.

BRB's domestic research status

Kequan Cai et al. [17-19] proposed a double steel pipe（double-T core or double plate with double pipe）and groove fit BRB， theoretical and experimental research of related specimens were studied. Pull differential pressure value calculation method， effective engagement details and design method of BRB and frame, and theory of groove fit and thin type BRB reduced the cost effectively were putted forward. Test conclusions of V type double steel double pipe showed, core support tensile strain will be greater than the compressive strain of adjacent support when the frame occurred the maximum lateral displacement angle, so adjacent support will be balanced in tension and compression stress situation. In addition, different delamination material impact on the performance of the structure was researched, it showed sticky rubber as delamination material support could get optimal energy performance.
For limited damping of studies Guoqiang Li et al. [20-23] proposed elasto-plastic displacement theory formulas and node connection design criteria containing BRB frame structure, theoretical value and average value of time-history analysis under dozens of earthquake waves by numerical simulation were compared, the results were high accuracy. The lateral stiffness calculation method frame structure of semi-rigid connection with BRB was derived. The mechanical properties of the anchor node configuration and other details were made a theoretical analysis.
Harbin Institute of Technology's Yaochun Zhang and Yukun Ding[24,25] got on numerical simulation to shear walls containing BRB herringbone, general support and special central support. Analysis showed a good vertical force was provided to the fulcrum of support beams before support instability, shear effect to the fulcrum was generated after instability of the center support center and special support , BRB generated vertical force to fulcrum closed to zero and now the largest plastic deformation was cumulative. Li Yan [26] proposed an improved design program to BRB containing a font and a cross-two of the inner core by static cyclic test, proving its energy damping effect and good low cycle fatigue properties through the sub-structure pseudo-dynamic test, further comparative analysis accuracy simulating the BRB by the bilinear and Bouc-Wen model , the results showed that analysis error of bilinear model according to the energy equivalent principle was smaller than the other two models. Jun Tian [27] derived critical load formula of steel BRB and buckling loads formula of inner core and width-thickness ratio formula by theoretical analysis, the initial moments came a greater impact on performance than the initial torque of specimen in the analysis of the various initial defects, and carrying energy of a cross-shaped inner core was stronger font inner core using ANSYS finite element results by preliminary simulation. On the basis of Jun Tian Ning Ma [28]

further researched on the BRB with anti-cross-shaped inner core outer side of the steel pipe and entity tests carried out, proved its good hysteretic properties. And the width-thickness ratio limit of two inner core and the outer tube stiffness were deduced considering the various nonlinear, the influence of other parameters on the performance was explored. Ming Ming Jia[29]gave that the constraints ratio preventing overall instability of BRB should be greater than 25, and the distance between the inner core and the outer casing should be included between 5% -10% of the core thickness. In order to solve the suffered moment of core unconstrained segment Lin Sun [30] presented a cross section of the I-shaped form of the new BRB, and variable cross-section of the inner core using curved transition was recommended.

Tsinghua University's Yanlin Guo, Jianbin Liu et al [31, 32] for solving eigenvalues and nonlinear proposed structure demand for BRB, examined impact on performance of constraints stiffness , core width-thickness ratio ,initial defect , layout and other factors through the history analysis, in addition, also proposed the best lateral stiffness scope of BRB frame and relationship of interlayer displacement angle and lateral stiffness , the design critical point value was calculated.

Xiaodong Li in Lanzhou University of Technology [33] deduced overall stability capacity formula of multi-point support and continuous support through theoretical researches, contrast six groups test results showed that BRB with arc cross-shaped flange inner core and double-steel tube type had energy consumption significantly, BRB damping effect on steel arch structure and cylindrical latticed shell was also studied at the same time.

Torsion effect of previous studies for BRB was less attention, Yuanyuan Zhang[34] in Hebei University of Engineering simulated irregular structure containing BRB by ETABS , She founded arrangement of BRB in irregular structural was more far distant from stiffness center modal response spectrum, nonlinear time history analysis, effect of reducing torsional displacement ratio and the upgrading torsional stiffness was obviously.

Research Status of BRB in bridge seismic

BRB was mainly used in the buildings field and less in bridge structure application.

Samer El-Bahey et al. [35] carried out a 2/3 scale quasi-static experiment by two groups of double-column pier(erecting shearing steel plate and BRB for support), it showed hysteretic energy effect of two groups specimens was good, and piers could maintain the elasticity. Lyle P.Carden et al [36]researched steel girder bridge model supported steel plate between the two main beams through the erection of BRB by a shaking table test to explore the hinged and rigid connection performance with support end portion, the results showed that despite the slip but joint type bending was better. When against two times El-Centro wave, bridge model base shear was only 69% of the elastic base ,meanwhile relative displacement to the previous results made by X-general support to was low. O.C.Celik et al. [37] simulated model of two bridges(transverse and longitudinal two group BRBs were erected between steel beam and concrete slab end closed to the abutment at the bridge) against bidirectional earthquakes performance . Tsutomu Usami et al [38] simulated steel arch bridge (as shown in the figure 4) by ABAQUES, to enhance the seismic performance the portion of the side column section member and a member rib were replaced by BRB, whole structure lateral vibration period grown because adding BRB by nonlinear time history analysis, the maximum axial force suffered side legs and strain of key parts significantly reduced compared with previous models ,and BRB hysteresis effect was obvious.

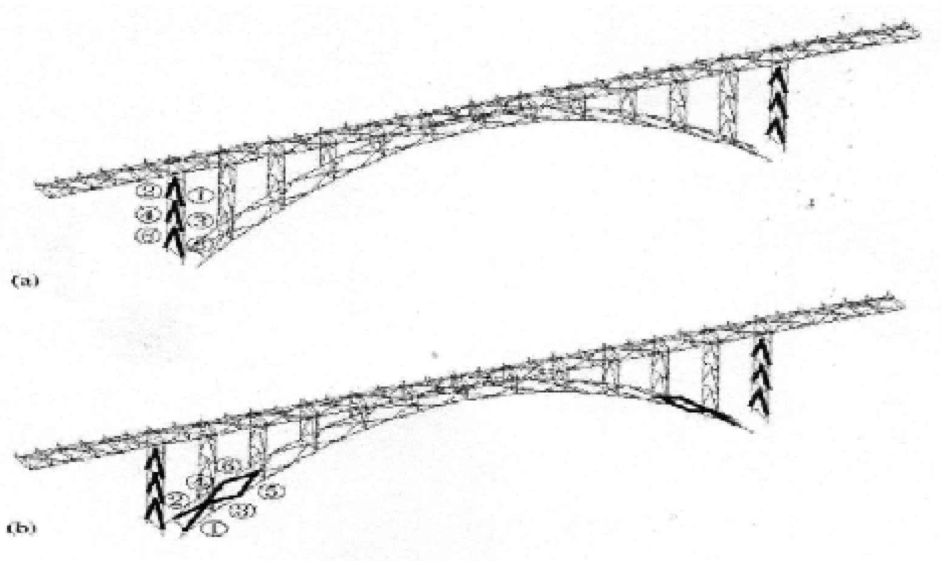

Fig.4 Steel arch bridge model

Domestic and foreign engineering applications

Seismic energy dissipation advantages gradually of BRB were known scientists and architects by theoretical and experimental study of the long-term. After the 1994 Northridge earthquake, the BRB gradually began use to in new construction and reinforcement projects in United States. After the 1995 Kobe earthquake BRB was widely used in Japan, at present, applied BRB in more than 300 buildings, involving various fields of the construction industry, It became the country,there most using BRB. After the 1999 Chi-Chi earthquake in Taiwan, the use of BRB was began to pay attention. Mainland began using BRB late, BRB mainly used in new construction as well as construction reinforced.

Conclusions

Theory, experimental research related to its scientific computing will also become a hot seismic research with continuous development of BRB in the structure seismic, but there will be some new problems to be solved. BRB in research and application has just started in bridge seismic, therefore, exploring the meaning of their development in the field of bridge seismic is significant.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No.51178222) and the Fundamental Research Funds for the Central Universities(Grant No. 3132015093).

References

[1]Kequan Cai,Junwei Lai.The principle and application of BRB[C]. First National Symposium on Earthquake Disaster Mitigation Project,Beijing,2004. (In Chinese)

[2]Jiawei Sun,Shoufeng Jiang.System research status and its application in engineering[J]. Journal of Heilongjiang Science and Technology Information, 2008,8: 237-238. (In Chinese)

[3]Yanlin Guo,Jianbin Liu et al..Structure energy dissipation and BRB[J].Journal of Building Structure, 2005,35(8):18-23. (In Chinese)

[4]Clark P, Aiken I, Kasai K, et al. Design procedures for buildings incorporating hysteretic damping devices[C]. Proceedings 68th Annual Convention. 1999: 355-371.

[5]Yoshino T, Karino Y. Experimental study on shear wall with braces: Part 2[C]. Summaries of Technical Papers of Annual Meeting of the Architectural Institute of Japan. Structural Engineering Section. 1971,11.

[6]Wakabayashi M, Nakamura T, Katagihara A, et al. Experimental Study on the Elastoplastic Behavior of Braces Enclosed by Precast Concrete Panels under Horizontal Cyclic Loading: Parts 1 & 2[C], Summaries of Technical Papers of Annual Meeting, 1973: 1041-1044.

[7]Wakabayashi M, Nakamura T, Katagihara A,et al. Experimental Study on the Elastoplastic Behavior of Braces Enclosed by Precast Concrete Panels under Horizontal Cyclic Loading:Parts 1 & 2[C]. Summaries of Technical Papers of Annual Meeting, 1973: 121-128.

[8]Kimura K, Yoshioka K, Takcda T, et al. Tests on Braces Encased by Mortal In-Filled Steel Tubes[C].Summaries of technical papers of annual meeting. Architectural Institute of Japan, 1976: 1041-1042.

[9]Takeda T,Kimura K.Experimental Study on Precast Concrete Shear Wall: Part 6[C].Summaries of technical papers of annual meeting. Architectural of Institute of Japan, 1979:1677-1678.

[10]Fujimoto M, Wada A, Sacki E,et al. A study on the unbonded brace encased in buckling-restraining concrete and steel tube[J]. Journal of Structural and Construction Engineering, AIJ, 1988, 34: 249-258.

[11]Watanabe A, Hitomi Y, Saeki E, et al. Properties of brace encased in buckling-restraining concrete and steel tube[C]. Proceedings of Ninth World Conference on Earthquake Engineering. 1988, 4: 719-724.

[12]Sridhara B N. Sleeved column-as a basic compression member[C]. Proc. 4th International Conference on Steel Structures & Space Frames. 1990: 181-188.

[13]Prasad B. Experimental Investigation of Sleeved Column[C]. Proceedings of the 33rd Structural Dynamics and Materials Conference, American Institute of Aeronautics and Astronautics. Dallas, 1992.

[14]Tada M. Horizontally Loading Test of the Steel Frame Braced with Double-Tube Members[J]. Annual Technical Papers of Steel Structures, (1): 203-208.

[15]Iwata M, Kato T, Wada A. Buckling-restrained braces as hysteretic dampers[J]. Behaviour of Steel Structures in Seismic Areas, STESSA, 2000, 2000: 33-38.

[16]Koetaka Y, Narihara H, Tsujita O. Experimental Study on Buckling-Restrained Braces[C]. Proceedings of Sixth Pacific Structural Steel Conference. Beijing,China, 2001: 15-17.

[17]Zhiyu Wei,Anjie Wu,Kequan Cai et al..Research of groove fit BRB seismic performance and optimization delamination effect[C]. Eighth National Conference on Earthquake Engineering, Chongqing, 2010. (In Chinese)

[18]Baojun Lin,Anjie Wu,Kequan Cai et al..The frame test real size of BRB with 3 floors [C] . Eighth National Conference on Earthquake Engineering(Ⅱ), Chongqing, 2010. (In Chinese)

[19]Kequan Cai ,Yanzhi Huang,Chongxing Weng.Seismic behavior and application of twin-tube BRB [J]. Journal of Progress in Steel Building Structures, 2005,7(3): 1-8. (In Chinese)

[20]Baolin Hu,Wenjuan Yao,Guoqiang Li.The simplified calculation method of inelastic displacement of frame structure with BRB under rare earthquake loads [J] . Journal of Vibration and Shock ,2011,30(2): 144-148. (In Chinese)

[21]Guoqiang Li ,Xiaokang Guo.The connecting node design principles of BRB based on the reliability theory[J]. Journal of Building Structure, 2010,40(3): 65-67. (In Chinese)

[22]Guoqiang Li ,Dazhu Hu,Feifei Sun et al..The elastoplastic seismic displacements simplify computing of semi-rigid connection frame with BRB [J]. Journal of Earthquake Engineering and Engineering Vibration,2009，29(4): 33-40. (In Chinese)
[23]Guoqiang Li , Xiaokang Guo , Feifei Sun et al..Experimental study on mechanical properties of concrete anchor node of support buckling restraint [J].Journal of Building Structures,2012,33(3): 89-95. (In Chinese)
[24]Yaochun Zhang,Yukun Ding.Seismic performance analysis of steel frame with BRB general and special center braced[J]. Journal of Progress in Steel Building Structures,2009,11(5): 8-15. (In Chinese)
[25]Yukun Ding,Yaochun Zhang. The seismic beams discussion joining herringbone BRB[J]. Journal of Industrial Buildings,2009, 39(10):114-119. (In Chinese)
[26]Yan Li.Seismic performance and substructure test method of BRB [D].Harbin: Harbin Institute of Technology,2007. (In Chinese)
[27]Jun Tian.Steel BRB seismic performance [D].Harbin: Harbin Institute of Technology,2007. (In Chinese)
[28]Ning Ma.BRB steel and steel frame structure on seismic behavior and design method [D].Harbin: Harbin Institute of Technology,2010. (In Chinese)
[29]Mingming Jia,Sumei Zhang,Dagang Lv.Stability and ductility performance analysis of BRB[J]. Journal of Building Structures, 2009 (supplement): 76-81. (In Chinese)
[30]Lin Sun.Seismic performance experimental study on concrete filled steel tubular columns composite frame structure with BRB [D].Harbin: Harbin Institute of Technology,2011. (In Chinese)
[31]Jianbin Liu.Design theory research of BRB and steel frame and with BRB[D].Beijing:Tsinghua University，2005. (In Chinese)
[32]Ying Zhao,Yanlin Guo.Design method research of BRB framework [J]. Journal of Building structure,2010,40(1): 41-45. (In Chinese)
[33]Xiaodong Li.Research on dynamic performance of buckling restrained braces and its application in the steel arch structure[D].Lanzhou: Lanzhou University of Technology,2008. (In Chinese)
[34]Yuanyuan Zhang.Damping control research of BRB in irregular structure[D].Handan: Hebei University of Engineering,2011. (In Chinese)
[35]Samer El-Bahey, Michel Bruneau. Bridge Piers with Structural Fuses and Bi-Steel Columns. I : Experimental Testing[J]. Jounal of Bridge Engineering, 2012: 25-35.
[36]Carden L P, Itani A M, Buckle I G. Seismic performance of steel girder bridges with ductile cross frames using buckling-restrained braces[J], Journal of structural engineering, 2006,132(3): 338-345.
[37]Celik O C, Bruneau M. Seismic behavior of bidirectional-resistant ductile end diaphragms with buckling restrained braces in straight steel bridges[J]. Engineering Structures, 2009,31(2):380-393.
[38]Usami T, Lu Z, Ge H. A seismic upgrading method for steel arch bridges using buckling-restrained braces[J]. Earthquake engineering & structural dynamics, 2005, 34(4-5):471-496.