Iranica Journal of Energy & Environment 4 {(3) Geo-hazards and Civil Engineering)}: 174-181, 2013
ISSN 2079-2115
IJEE an Official Peer Reviewed Journal of Babol Noshirvani University of Technology
DOI: 10.5829/idosi.ijee.2013.04.03.02

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Seismic Retrofitting of Steel Frames with Buckling Restrained Braces

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(Received: January 15, 2013; Accepted in Revised Form: April 18, 2013)

Abstract: Buckling-restrained braced frames (BRBFs) are used as primary lateral load resisting systems for buildings in high seismic areas. The main characteristics of buckling-restrained braces (BRBs) are enhanced energy dissipation potential, excellent ductility and nearly symmetrical hysteretic response in tension and compression. This paper presents an analytical study aimed to assess the feasibility of using BRBs as a retrofit scheme for existing steel frames. For that purpose, the seismic response of four two-dimensional frame models representative of typical steel frames was analyzed prior to and after including BRBs as a retrofit strategy. Comprehensive nonlinear static and time-history analysis were carried out for analyzing the frames. A set of seven code-compliant natural earthquake records was selected and employed to perform nonlinear time-history analysis. Frames were analyzed and designed based on 2800 Iranian Seismic Code. The evaluation was based on comparing seismic displacement demands such as target roof displacements, maximum displacements and inter-storey drifts. The results showed that the effectiveness of braced frames can vary significantly with ground motions, frame rises and retrofitting systems. It perceived that the seismic response of frames coincides well with the given design objectives.

Key words: Buckling-restrained brace · Steel frames · Retrofitting system · Nonlinear static analysis · Nonlinear dynamic analysis

INTRODUCTION

Braced systems exhibit high lateral stiffness and strength under moderate-to-large magnitude earthquakes. The most common structural configurations for lateral-resisting systems are ordinary concentric brace frames (OCBFs), which possess a lateral stiffness significantly higher than moment resisting frames [1]. Nevertheless, due to buckling of the compression members and material softening, the hysteretic behavior of OCBFs with steel braces is unreliable. Different retrofitting schemes may be used to upgrade the seismic performance of existing steel frames. Alternatively, buckling-restrained braces (BRBs) may be employed as diagonal braces in seismic retrofitting of steel frames. Tests of buckling-restrained braces (BRBs) have consistently demonstrated stable and robust behavior under cyclic loading [2, 3]. The cyclic behavior of steel braces subjected to reversed compressive and tensile force exhibits poor energy dissipation due to the buckling of the brace when the loading exceeds the buckling limit. The energy dissipation or damage prevention capacity of a steel frame can be greatly enhanced by employing buckling-restrained braces (BRBs) [4-5]. They usually consist of a steel core capable of undergoing significant inelastic deformation and a casing for restraining global and local buckling of the core element. Based on previous research [6-8], if BRBs are damaged, the rehabilitation after the earthquake is simple, since these elements are designed to be replaceable. The construction of BRB is quite simple because of it is made from widely available construction materials.

Although the practical implementation of buckling-restrained braces was originally focused on providing primary lateral resistance in new buildings; recently, these structural elements have been employed as a retrofit option for the existing buildings [9, 10]. A comprehensive study of damage controlled structures was performed by Wada *et al*. [11]; they have presented its potential to

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design new constructions and retrofit existing structures. Within this context, evaluating the feasibility of using BRBs as a retrofit scheme for existing steel frames is the primary objective of this paper.

Increasing the base shear demand might exceed the safe capacity of the foundations. In contrast, BRB can fully yield in compression as well as tension, a smaller cross section than conventional steel braces [12].

This paper evaluates the seismic structural performance of a typical steel framed building retrofitted with BRBs. Actually, the objective of present work is to evaluate and compare the rehabilitation results of some steel building using concentric bracing and buckling-restrained bracing. Behaviors of the original and retrofitted buildings were evaluated by conducting nonlinear static and time-history analysis. The results of comprehensive nonlinear (static and dynamic) analysis showed that the use of BRBs is more acceptable than concentric bracing. Applications for both low-rise and high-rise ordinary steel frames and the seismic retrofit of these frames showed good prospects of using BRBs [14].

Description of Selected Frames: Five-, 7-, 17- and 20-story buildings consisting CBF and BRBF buildings were designed to meet seismic code criteria. The buildings were analyzed to evaluate the seismic retrofitting effects with buckling restrained braces. To distinguish type of frames, they are labeled with abbreviated names. For example, OCBF5 model is a 5 story ordinary concentric braced frame, 1BRBF5 model is a 5 story buckling-restrained braced frame, which braces are designed with the same section area as designed for OCBF5 model and 2BRBF5 model is a 5 story buckling-restrained braced frame, which braces are designed based on their capacity (The brace section area of 2BRBF models are smaller than OCBF and 1BRBF models). The same abbreviated names are used for 7-, 17- and 20-story frames.

The elevation view of all systems is shown in Fig. 1. A Rayleigh damping model was used with 5% critical damping ratios for the first two modes according to common practice for code designed steel structures [6]. Nonlinear static and dynamic analyses were carried out using the computer program SAP2000 version 14.1.0 [13].

Buckling-Restrained Braces: Since many of the potential performance difficulties associated with conventional concentric braced frames rise from the difference between the tensile and compression capacity of the brace and the degradation of brace capacity under compressive and cyclic loading, considerable research has been devoted which exhibit more ideal elastoplastic behavior. One means of achieving this ideal behavior in compression is an external mechanism. A number of approaches to accomplish this target have been suggested including enclosing a ductile metal (usually steel) core (rectangular or cruciform plates, circular rods, etc.) in a continuous concrete filled steel tube, within a continuous steel tube, a steel tube with intermittent stiffening fins and so on. The central yielding core can deform longitudinally independent from the mechanism that restrains lateral and local buckling. Since lateral and local buckling behavior modes are restrained, large inelastic capacities are attainable. Theoretically, based on methods have been developed to design the restraining media [15, 16]. Provisions have been developed in draft form literature [17] for design, specification and testing of buckling-restrained braces to help insure braces meet performance expectations.

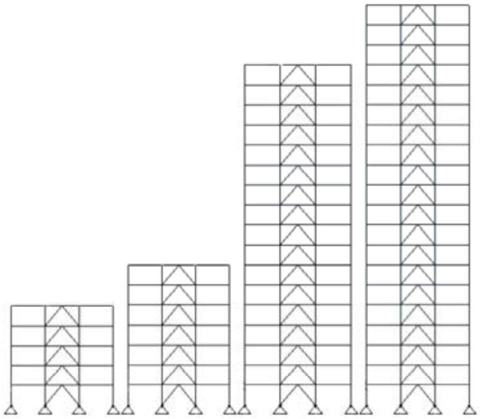

Fig. 1: Frame elevations of low-rise (5-, 7- story) and high-rise (17-, 20- story) steel Frames

Design of BRB: BRB is designed based on the details described by Wada *et al.* [18] and Clark *et al.* [19]. It is expected to withstand significant inelastic deformations when subjected to the forces resulted from the earthquake. The steel core should be designed to resist the entire axial load in the brace. The yield axial load, P_y, can be computed by the following equation:

$$P_y = F_y A_{sc} \tag{1}$$

where F_y is the actual yield stress and A_{sc} is net area of steel core. The buckling of steel core will be restrained by grout mortar in the steel casing. The buckling strength of combination between grout mortar and steel casing, P_c, can be computed by the following equation:

$$P_c = \frac{\pi^2 EI_{cs}}{(kL)^2} \tag{2}$$

where kL is an effective length and P_c is the rigidity of the steel casing. The buckling strength of the casing must be greater than P_y to prohibit the buckling of BRB. It should be noted that the thickness of unbounded material needs to be sufficient large to allow the expansion of yielding core in compression. The transition section must be designed properly to ensure that inelastic deformation limited within steel core and elastic deformation occurs in other segments. It can be achieved by enlarging the section and welding the stiffeners in perpendicular direction. The longitudinal gap between the stiffen plates and filled mortar has to be provided to accommodate the movement of yielding core.

Non-Linear Static Procedure (NSP): As the name suggests this procedure is essentially a static analysis, in which the static loads are applied in an incremental fashion until the ultimate state of the structure is attained. The non-linear designation comes from the fact that the various components/elements are modeled using a non-linear mathematical model.

For an adequate seismic retrofitting system evaluation, the proper selection of the load pattern is imperative. These patterns should bound approximately the likely distribution of inertia forces in a design earthquake; thus, requiring to incorporate, in some cases, higher mode effects into the selected lateral load pattern.

As no single load distribution can identify the variation of the local demands expected in a design earthquake, the use of at least two load patterns is recommended. In this paper, three lateral load patterns (Triangular, Uniform and Modal lateral load pattern) are used in the non-linear static procedure.

Target Roof Displacements: Pushover curves show the relationship between the base shear force and the roof displacement. For summary, the pushover diagrams are not shown in this paper but the target roof displacements are listed in Table 1. The lateral force distribution of pushover procedure in this study is taken as a three-phase load pattern.

As it is observed, the target roof displacements noticeably increases when the building height increases.

Capacity Curves of Steel Frames for Lateral Load Pattern: The nonlinear models were used to evaluate the retrofitting systems for the steel frames. The lateral loads are applied in profiles and should represent approximately the distribution of the inertial forces during the seismic event. It can be easily understood that due to the changing stiffness and the different mode effects during the seismic event, the force distribution cannot be clearly distinguished. Figs. 2, 3 and 4 represent the capacity curve, base shear *vs.* control roof displacement (top displacement), using uniform, triangular and modal lateral load patterns. These curves are given important properties of the structures, such as the initial stiffness, the maximum strength and yield global displacement. From these figures it can be seen that the uniform load pattern produced smaller shear for same displacements. The response is sensitive to the load pattern adopted. The differences between the triangular and the modal capacity curves are minimum as the first mode is very close to a triangular distribution. In all cases, it is apparent that retrofitting with buckling restrained braces leads to better results. Especially for 2BRBFs (buckling-restrained braced frame, which braces are designed based on their capacity) it can be seen that retrofitting with BRBs increases flexibility and target displacement which lead to more energy dissipation of earthquakes. Furthermore, in 1BRBF models which braces are designed with the same section as designed for OCBF models, more initial stiffness and maximum strength for retrofitting with BRBs were achieved, but these retrofitting systems decreased the flexibility of structures.

Table 1: Target roof displacements for assumed frames (cm)

	Lateral load pattern		
Frame model	Triangular	Uniform	Mode 1
OCBF5	7.36	6.04	7.65
1BRBF5	7.61	7.28	8.03
2BRBF5	12.02	9.91	12.37
OCBF7	11.07	9.14	11.52
1BRBF7	11.42	9.29	11.91
2BRBF7	16.17	13.07	16.87
OCBF17	41.93	38.74	42.23
1BRBF17	39.86	37.25	40.52
2BRBF17	37.93	34.23	38.72
OCBF20	47.21	43.94	48.13
1BRBF20	45.98	42.41	46.77
2BRBF20	50.02	47.19	51.12

Non-Linear Time-History Analysis (NLTHA): Nonlinear time-history analysis was conducted to assess the retrofitting of existing structures with BRBs when subjected to scaled ground motion records. Scale factors for the 7 selected ground motion records were calculated.

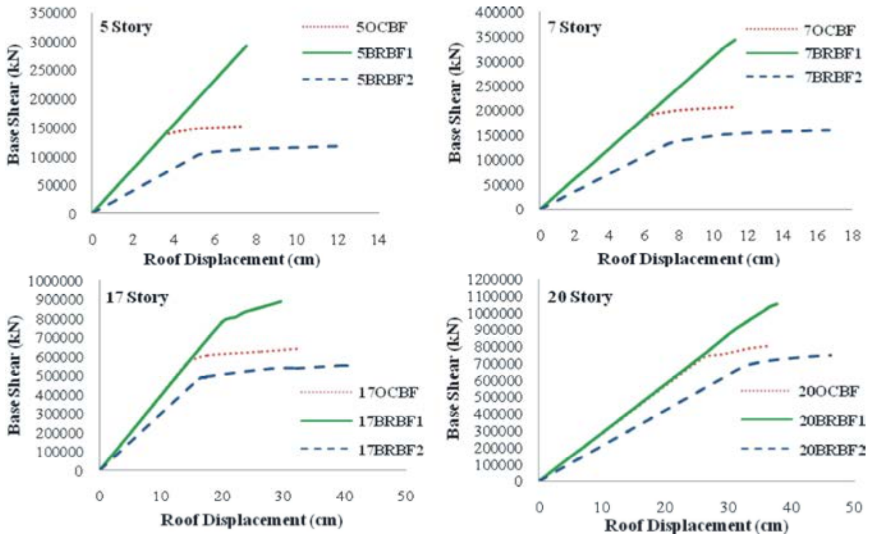

Fig. 2: Capacity curves of 5-, 7-, 17- and 20-story frames for triangular lateral load pattern

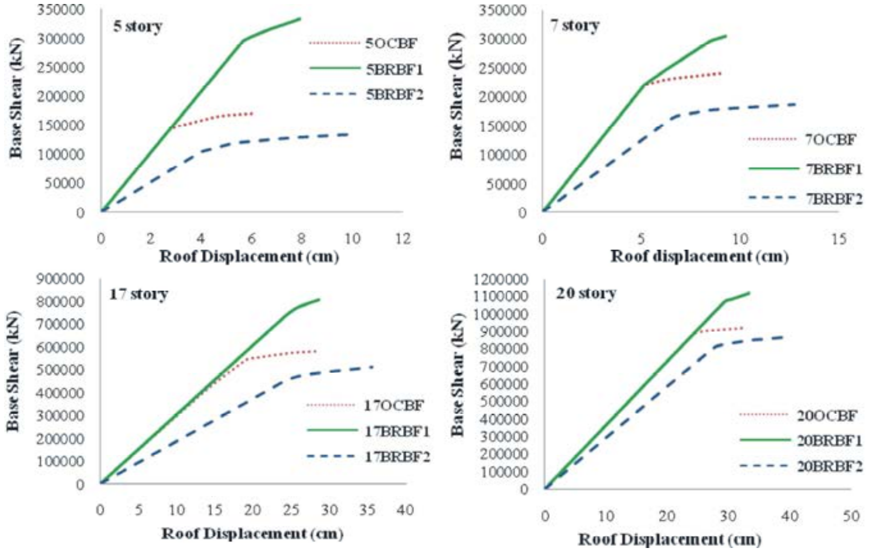

Fig. 3: Capacity curves of 5-, 7-, 17- and 20-story frames for uniform lateral load pattern

Then, the elastic response spectra for the records matched the target spectra, which were defined by SEI/ASCE7-05 [20], at the first natural period, T_1, of the structural system.

Earthquake Ground Motions: One set of seven ground motions was considered in this study. The selection of ground motions from the PEER Center strong motion database [21] was based on three fundamental parameters including site class, source distance and magnitude. These are the parameters that are known to have the strongest influence on ground motion characteristics [22]. Although recent research [23] has demonstrated the influence of epsilon on nonlinear structural response, it was not considered in this research. Ground motions associated with site class C, as defined in SEI/ASCE 7-05 [20], a source distance greater than 15km were chosen. Table 2 summarizes the 7 ground motion records that were used in this work. In this study, the energy dissipation capacity and earthquake response of steel structures retrofitted with BRB were investigated. Parametric study was performed for two important design parameters including cross sectional area and the yield strength of BRBs. Based on the results of parametric study, a straightforward design procedure to achieve a target displacement was developed in the framework of capacity spectrum method.

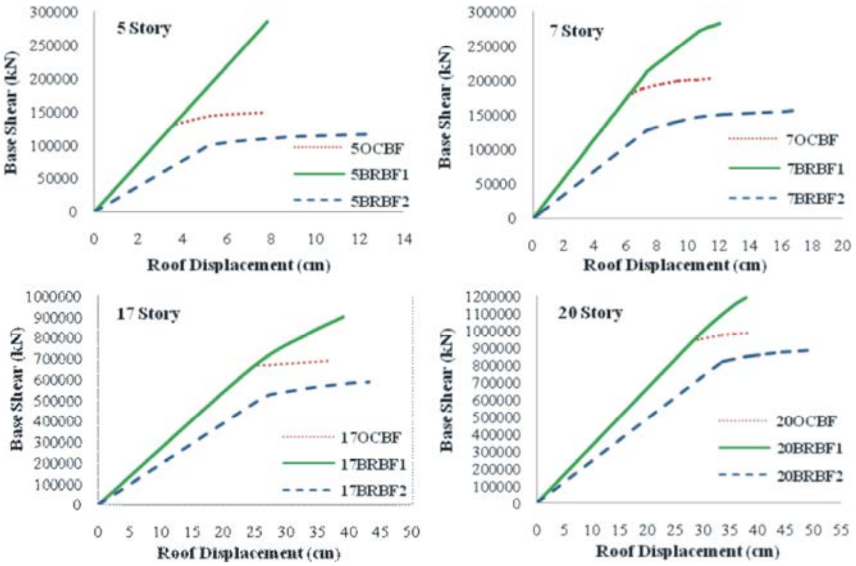

Fig. 4: Capacity curves of 5-, 7-, 17-, and 20-story frames for modal lateral load pattern

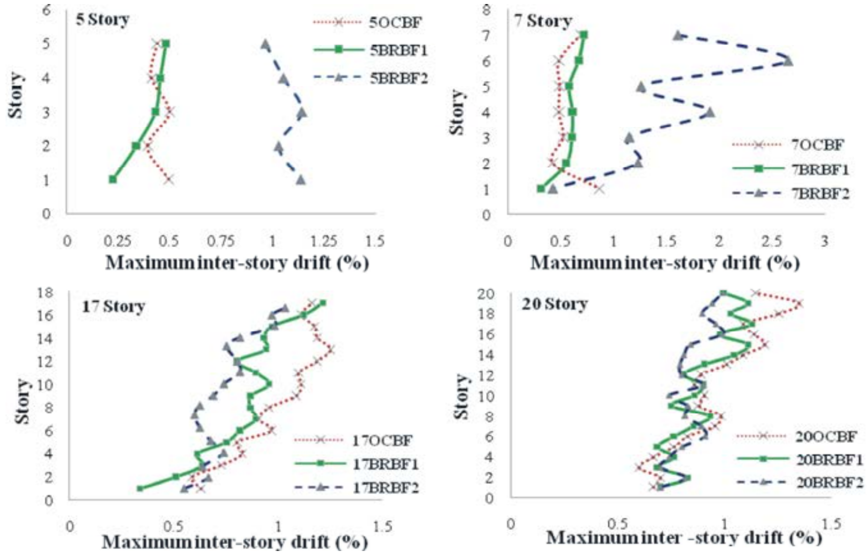

Fig. 5: Maximum inter-story drifts of 5-, 7-, 17- and 20-story frames obtained from time-history analysis

Maximum Inter-Story Drift Ratio: Fig. 5 illustrates the maximum inter-story drift ratio of the OCBF, 1BRBF and 2BRBF (retrofitted systems) models computed from time-history analysis corresponding to the average ground motions. Generally, the maximum inter-story drift ratio that occurs at any level during the earthquake for low-rise frames in the 2BRBF models is the largest drift ratio. But in high-rise frames, 2BRBF models have the smallest inter-story drift. Thus, using 2BRBF models as retrofitting systems to prevent extensive deformation especially for high-rise frames is preferred. Generally larger inter-story drifts occur at the top of frames than the bottom. The use of buckling restrained braces in 1BRBF models tends to distribute the drifts more uniformly along the height of the frames as shown in Fig. 5. Brace ductility for the buckling-restrained braced frames generally vary in the same manner as inter-story drift. Also, the inter-story drifts for the 17- and 20-story frames are similar; in addition the mean ductility demands for these two high-rise structures are similar as well.

Maximum Displacements: Fig. 6 provides the average time-history response of the maximum story displacements for the OCBF, 1BRBF and 2BRBF (retrofitted systems) models subjected to seven earthquakes. It can be observed that the maximum story

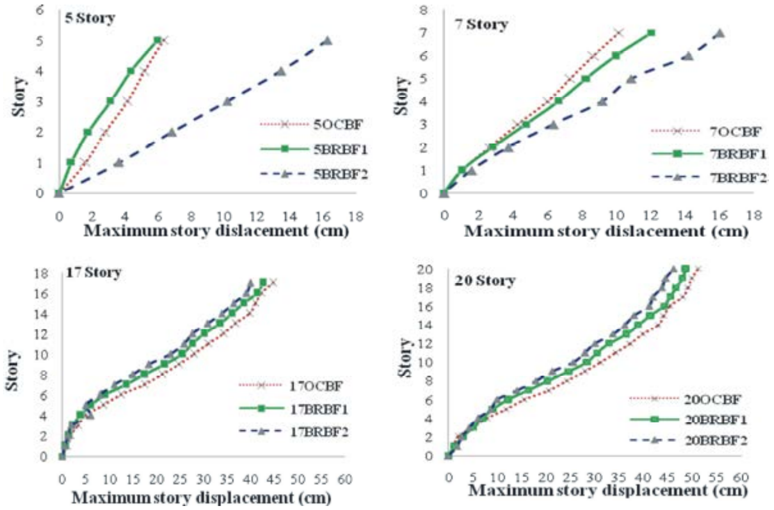

Fig. 6: Maximum story displacements of 5-, 7-, 17- and 20-story frames obtained from time-history analysis

Table 2: Characteristics of considered earthquake motions

No	Year	Earthquake	Earthquake magnitude	Station	PGA (g)
1	1980	Victoria	6.33	Chihuahaua	0.15
2	1980	Trinidad	7.2	Rio Del Overpass	0.0614
3	1989	Loma Prieta	7	Halles Valley	0.134
4	1979	Imperial Valley	6.53	Coachella Canal	0.115
5	1994	Northridge	6.69	La-Faring RD	0.231
6	1979	Coyote Lake	5.74	Halles Valley	0.0391
7	1984	Morgan Hill	6.19	Apeel 1E Hayward	0.0406

displacement curves are close to linear lines. According to the analysis results, the maximum story displacements and the maximum inter-story drifts of the low-rise frames (5- and 7-story frames) generally match with the target displacements on the conservative side. However, the results of the high-rise frames (17- and 20-story frames) turned out to be somewhat conservative. Therefore, based on the analysis results it can be concluded that the seismic design procedure based on the energy balance concept can safely be applied to low-rise structures with BRB. For high-rise structures the procedure may result in too conservative design.

CONCLUSIONS

An analytical study aimed at evaluating the feasibility of using buckling-restrained braces as a retrofit scheme in existing multi-bay multi-story steel frames is presented. The following conclusions are obtained from NSP estimates of seismic demands and the corresponding values determined by NLTHA for 5-, 7-, 17- and 20-story models which were designed to meet seismic code criteria:

- Buckling-restrained braces showed good results that represent an attractive option for the retrofitting of steel buildings.
- The use of buckling-restrained braces to retrofit existing high-rise steel frames not only represents an advantage in terms of well control of the maximum inter-story drift demand, but results in fairly uniform distribution along height of permanent drift.
- Because of their large maximum and cumulative plastic deformation capacities, it has been suggested that dual systems composed of steel frames and buckling-restrained braces can and should undergo significant nonlinear behavior during severe ground motion. A dual system composed of a flexible gravitational system and buckling-restrained braces can outperform, particularly in terms of structural efficiency, similar systems in which the steel frames are assigned a larger role in terms of seismic resistance. A key element within this context is the need to carefully control the maximum inter-story drift in such a way as to achieve a serviceable gravitational system.

- The uniform load pattern seems to indicate conservative results regarding the base shear evaluation but they may be misleading in some cases.
- A limitation of the nonlinear time-history analysis is its sensitivity to the characteristics of the input motions, thus selection of representative acceleration time-histories is fundamental. This result obtained from diagrams of seven earthquakes which are not plotted in this paper. They showed some differences in inter-story drifts and story displacements for various earthquakes.
- The buckling-restrained braces reduced the drift demands and story displacements. It can be observed that the retrofitted high-rise steel frames exhibit a more uniform distribution of inter-story drift index demand. In spite of the reduction in inter-story drift demands in high-rise steel frames, it should be noted that the buckling-restrained braces in low-rise steel frames increased the inter-story drifts.

REFERENCES

1. Yun, S.Y., R.O. Hamburger, C.A. Cornell and D.A. Foutch, 2002. Seismic performance evaluation for steel moment frames. Journal of Structural Engineering, 128(4): 534-545.
2. Black, C.J., N. Makris and I.D. Aiken, 2002. Component testing, seismic evaluation and characterization of BRBs. J. Struct. Eng., 130(6): 880-894.
3. Merritt, S., C.M. Uang. and G. Benzoni, 2003. Subassemblage testing of star seismic BRBs. Structural systems research project report No. TR-2003/04. San Diego: University of California.
4. Kim, J. and H. Choi, 2004. Behavior and design of structures with buckling-restrained braces. Engineering Structures, 26(6): 693-706.
5. Fahnestock, L.A., R. Sause. and J.M. Ricles, 2007. Experimental evaluation of a large-scale buckling-restrained braced frame. J. Struct. Eng., 133(9): 1205-1214.
6. Sabelli, R., S. Mahin. and C. Chang, 2003. Seismic demands on steel braced frame buildings with buckling- restrained braces. EngStruct, 25: 655-666.
7. Aiken, I., *et al*., 2002. Large-scale testing of buckling restrained braced frames. In: Proceedings, Japan passive control symposium. Japan: Tokyo Institute of Technology, pp: 35-44.
8. Fahnestock, L.A., R. Sause. and J.M. Ricles, 2007. Seismic response and performance of buckling-restrained braced frames. J. Struct. Eng., 133(9): 1195-204.
9. Ash, C. and S. Bartoletti, 2009. Seismic rehabilitation of an existing braced frame hospital building by direct replacement with buckling-restrained braces. In: Proceedings of the ATC & SEI 2009 conference on improving the seismic performance of existing buildings and other structures, Paper 68.
10. Choi, H. and J. Kim, 2009. Evaluation of seismic energy demand and its application on design of buckling- restrained braced frames. Structural Engineering and Mechanics, 31(1): 193-112.
11. Wada, A., Y.H. Huang and M. Iwata, 2000. Passive damping technology for buildings in Japan. Progress in Structural Engineering and Materials, pp: 335-350.
12. Xie, W., 0000. State of the art of buckling-restrained braces in Asia. Journal of Constructional Steel Research, 61(6): 727-748.
13. SAP2000 Version 14.1.0, Integrated Software for Structural Analysis & Design, CSI,Computers & Structures, Inc., Structural and Earthquake Engineering Software, Berkeley, California, USA.
14. Kim, J. and Y. Seo, 2004. Seismic design of low-rise steel frames with buckling-restrained braces. Engineering Structures, 26(5): 543-551.
15. Yoshida, K., *et al*., 1999. Stiffness requirement of reinforced unbounded brace cover. Journal of Structural and Construction Engineering (Trans. of AIJ), 521: 141-147 (in Japanese).
16. Yoshida, K., I. Mitani and N. Ando, 2000. Shear force of reinforced unbounded brace cover at its end, Composite and Hybrid Structures: Proceedings of the Sixth ASCCS International Conference on Steel-Concrete Composite Structures, Dept. of Civil Engineering, University of Southern California, Los Angeles, CA, 1: 371-376.
17. SEAOC (Structural Engineers Association of California), 2001. Draft provisions for buckling-restrained braced frames, Sacramento, CA.
18. Wada, A., A. Watanabe, Y. Hitomi, E. Saeki and M. Fujimoto, 1988. Properties of Brace Encased in Buckling-Restraining Concrete and Steel Tube. Proc. 9th World Conference on Earthquake Engineering, Tokyo-Kyoto, Japan, 4: 719-724.
19. Clark, P., L. Aiken, K. Kasai, E. Ko and I. Kimura, 1999. Design Procedures for Buildings Incorporating Hysteretic Damping Devices. Proceedings, 68th Annual Convention, Santa Barbara, California SEAOC.

20. ASCE, 2005. Minimum design loads for buildings and other structures. ASCE/SEI 7-05.
21. PEER strong motion database (peer.berkeley.edu/smcat). 2000. Berkeley: Pacific Earthquake Engineering Research Center, University of California.
22. Bozorgnia, Y. and V.V. Bertero, 2004. Earthquake engineering: from engineering seismology to performance-based engineering. CRC Press.
23. Baker, J.W. and C.A. Cornell, 2005. A vector-valued ground motion intensity measure consisting of spectral acceleration and epsilon. Earthquake Engineering & Structural Dynamics, 34: 1193-1217.