ANALYSIS OF UNIAXIAL AND SYSTEM PERFORMANCE TESTS OF BUCKLING-RESTRAINED BRACES WITH DIFFERENT DESIGNS

Kazım Burç Civelek

Faculty of Engineering, Department of Civil Engineering,
Akdeniz University, Antalya, Turkey
E-mail: burccivelek@akdeniz.edu.tr

Abstract
Structures should have adequate stiffness and strength to survive lateral forces caused by strong winds or earthquakes. Moment-resisting and braced frames are widely used for such purpose. Recent studies indicate that steel plates named steel cores provide higher axial load capacity compared to braces if covered with a buckling-restraining mechanism. Such braces are referred to as buckling-restrained braces (BRBs) and increase stiffness and strength against cyclic lateral forces when added into a structure. Unlike braces, BRBs exhibit stable hysteric characteristics under tension and compression demands. Moreover, they dissipate significant amount of the energy generated during earthquake and attenuate the effects of the building’s dynamic reactions. Studies indicate that systems involving BRBs are reliable for use in reinforcement of buildings against earthquakes and may provide alternative for the use of conventional braced frames.

This study analyzes uniaxial, sub-assemblage tests performed on BRBs and system performance tests performed on frames with BRBs.

Keywords: Buckling Restrained Brace, Seismic Reinforcement, Energy Dissipation, Cyclic Loading

1. INTRODUCTION
Braces are among popular structural members that have gained widespread use in structures in the recent years, which increase strength against earthquake and wind. It is known, in general, that braced frames carry horizontal loads economically affecting on buildings in proportion with their axial stiffness, thus providing adequate strength to the building. In addition, braced frames stiffen buildings and reduce displacement. Conventional buckling braces are used in the design of braced frames, which provide inelastic deformation and energy distribution. However, their limited energy distribution capacity, redundancy, early breakage seen in braces during cyclic loading and brittle fractures in cross joints appear to be the greatest problems related to braces (Akbaş, 2011). The root cause of these disadvantages is that braces have unequal tensile
and compressive capacities, suffer plastic deformation under tensile demands and buckle under compressive deformation, quickly losing their load-bearing capacity. As seen in Figure 1.a, braces are incapable of exhibiting a symmetric hysteric behavior under strong ground motion, due to the sudden drop in their load-bearing capacity which occurs in single-braced frame systems. Reciprocal braces are designed in concentrically braced (CB) frames in order to compensate for the asymmetric performance of singular braces, so that one brace is under tension while the other is under compression. Although hysteric characteristics are improved with the use of reciprocal braces, CB frames have limited energy distribution capacity, as seen in Figure 1.b.

On the other hand, buckling-restrained braces (BRBs), predecessor designs of which have appeared in Japan in the 1970s, exhibit nearly symmetric hysteric characteristics under tensile and compressive demands and provide higher energy dissipation capacity compared to conventional braces. This resulted in a rapid increase in the interest in and the usage of BRBs as of the 2000s. So far, researchers have analyzed BRB models of various different designs. However, the most widely-used BRB concept seen in Figure 2.a, was designed and manufactured in Japan in the early 1980s. A typical BRB comprises of a steel core (SC) member, a buckling-restraining mechanism (BRM) which can be of various types in order to prevent buckling of the steel core under axial stress forces, and an unconnected interface to eliminate unwanted interactions between the SC and the BRM. Figure 2.b demonstrates the hysteric characteristics of the BRB under the effect of cyclic axial deformation. As seen in the figure, local and global buckling of the SC is eliminated by the BRM, and a nearly identical tensile and compression yield is obtained. The abovementioned components of the BRB are explained in detail below.

- SC is the component which carries the entire axial load applied to the BRB and exhibits yield strain characteristics under axial loads, thus enabling compensation of inelastic effects. Literature studies indicate that researchers utilize various SC designs (Figure 2.c). However, the most frequently-used SC designs are the one with a cruciform-shaped (+) transversal cross section, as seen in Figure 2.a, and the one with a cruciform-shaped (+) transversal cross section at the tip and a rectangular flat transversal cross section in the middle, as seen in Figure 3. As demonstrated in Figure 3, the SC is divided into 3 segments. These are the restrained yielding segment, restrained non-yielding segment and the unrestrained non-yielding segment. The restrained yielding segment is the segment inside the BRM, where axial loads are born during cyclic loading. As seen in Figure 3, the transversal cross section is increased in the middle section of this segment. The purpose of such cross section increase is to prevent relative motion of the BRM and the SC with respect to each other. The restrained non-yielding segment is the transition segment in the SC, which is surrounded by the BRM. The restrained non-yielding segment is the section providing connection of the BRB to the gusset plate. Connection of the BRB to the gusset plate may utilize a bolted connection, as seen in the A-A section in Figure 3, or a pinned or welded connection.

- The BRM provides lateral support to the SC, thereby preventing buckling of the SC. An overview of the literature studies indicates BRBs with various BRM designs. To that end, BRMs can be classified into two groups. The BRM design frequently used today is obtained by pouring concrete or mortar into steel square tubes. Here, the steel square tubes used in the BRM is dimensioned based on the global buckling probability of the BRB. However, this particular type of BRMs may pose concrete quality control issues during the manufacturing phase, as well as flexibility issues in the design details of both ends of the SC (Iwata et al, 2006). Another BRM design used to prevent buckling of SCs is the use of all-steel tubes. Such BRMs exhibit adequate hysteric characteristics under high stress (Iwata et al, 2000).
The unconnected interface is a thin layer of material or air gap between the SC and the BRM. The interface prevents shearing force transfer between the SC and the BRM during a cyclic motion of the BRB. Materials such as rubber, polyethylene, silicon grease or mastic tape were used in past studies and explained in detail. The unconnected interface additionally allows lateral expansion of the SC section. Under axial stress forces, the SC transversally expands in both directions with the Poisson effect. It would be sufficient that the unconnected interface is thick enough to allow such expansion.

A remarkable amount of studies have been conducted in the last 30 years in many countries for the purpose of improvement of BRBs, especially in Japan, USA and Taiwan. Such studies involved BRBs which have various designs but are essentially based on the same basic principles. Within such context, BRB-related studies first began with uniaxial experiments, and continued with sub-assemblage tests and the testing of frames containing BRBs.

![Figure 1. (a) Hysteric characteristics of a brace member (Engelhardt, 2007) (b) Cyclic characteristics of a CB frame (Wakabayashi et al, 1974)](image1)

![Figure 2. (a) BRB components (Brown et al, 2001) (b) Hysteric characteristics of a typical BRB (Christopulos, 2005) (c) Transversal cross sections of BRBs with different designs (Lai et al, 2004)](image2)
2. IMPROVEMENT OF BRB DESIGNS AND THE EXPERIMENTAL PROCESS

BRB designs are incorporated into specifications in many countries, notably in Japan. The AISC 341-05 Seismic Provisions for Structural Steel Buildings, published in the United States of America in 2005, includes design specifications for BRBs. Adjusted BRB strength ($P_{abs}$) according to AISC 341-05 is as follows:

$$P_{abs} = \beta \omega P_{yse} \quad \text{under compression}$$

$$P_{abs} = \omega P_{xse} \quad \text{under tension}$$

$$P_{xse} = F_{yse} A_{sc}$$

Where; $F_{yse}$: actual yield stress of the SC, as determined by coupon testing; $A_{sc}$: net area of the SC; $\beta$: compressive strength adjustment factor; $\omega$: strain-hardening adjustment factor.

Compression values $\beta$ and $\omega$, obtained as a result of the qualification testing provided in the FEMA 450 specification, are defined as follows.

- $\beta$ is the ratio of the maximum axial stress force of the test specimens to their maximum tensile force, under deformations corresponding to 1.5 times the design story drift. In no case shall $\beta$ be taken as less than 1.0.
- $\omega$ is the ratio of the maximum tensile force of the test specimens to their nominal yield strength, under deformations corresponding to 1.5 times the design story drift.

The AISC/SEAOC specification, “Recommended Provisions for Buckling-Restrained Braced Frames”, mandate that the compression strength adjustment factor, $\beta$, be less than 1.3 for each displacement excursion greater than the yield displacement. According to the said specifications, $\beta$ must be between 1.0 and 1.3.

This section analyzes the existing tests in the literature, performed on BRBs on a uniaxial, sub-assemblage and system performance basis. The objective of uniaxial tests is to prove that conditions required for strength and inelastic deformations are fulfilled. In addition, it allows determination of maximum BRB forces for the design of adjacent members. The objective of sub-assemblage BRB testing is to understand whether or not the BRB design meets deformation and rotation demands. In addition, sub-assemblage tests reveal the hysteric characteristics of the BRB within the testing apparatus, like the uniaxial BRB tests.
System performance tests help determine the characteristics, deformation demands and overall system characteristics of the BRB systems and frame members.

2.1 Performance of Uniaxial Tests

(Wakabayashi et al, 1973) compressed a brace made of steel plates with a pair of precast concrete members and obtained a system referred to as sandwich. They formed a frictionless surface between the precast concrete members and the steel plates, and performed extraction experiments. They have exposed the member to cyclic loading tests in order to analyze the stiffness and strengths of the concrete panels. They have concluded that the steel plates changed shape uniformly, and their strength under compression is greater than their strength under tension. Moreover, they have conducted further studies in order to analyze the effects of the strength and stiffness of the precast concrete material on the reinforcements, and concluded that this system can be improved.

They referred to the studies by (Wada et al, 1990), (Kimura et al, 1976) and (Mochizuki et al, 1980), and reported as follows: “(Kimura et al, 1976) confirmed that stable hysteresis characteristics can be obtained with a conventional brace encased in a steel square tube, with the space left there between filled with mortar. But the deformation of the mortar is not enough to absorb a change in the cross-sectional area that occurs after the yielding of the brace. When the cross sectional restores to its original state, therefore, the yield stress on the compressive side increases more than on the tensile side. When such changes repeat, the end of the brace is repeatedly pulled outward, bringing about a localized buckling and a drop in yield stress in that region. (Mochizuki et al, 1980) made experiments on the inhibition of the buckling of diagonal bracing wrapped with reinforced concrete, with the concrete kept from adhering to the bracing by use of a shock-absorbing material. When subjected to repetitive loading, however, the concrete cracks to weaken its buckling preventing effect. Then, the brace reportedly becomes more susceptible to buckling.”

(Watanabe et al, 1988) encased the rectangular sectioned SC into the steel pipe, and then filled the remaining gaps with concrete. They applied vinyl/mastic tape along the surface of the SC in order to prevent axial loads to be transferred to the concrete by way of friction, and they used a 3-mm-thick foaming polystyrol along the thickness of the SC. In this study, they took into consideration the yield load of the SC against the elasto-plastic buckling analysis and buckling strength of the steel tube. They used five specimens in the experimental study. The ratio of the steel square tube Euler loads, Pe, of the specimens to the yield load, Py, of the SC were reported as 3.53, 1.39, 1.03, 0.72 and 0.55, respectively. They also reported that the segmental area of the steel square tube varied while the dimensions of the SC remained constant.

Following an analysis of the experiment results, they reported that no buckling occurred in specimens for which the steel square tube buckling strength exceeds the yield strength of the SC, including the compression segment, and a large amount of energy was absorbed, and the specimens exhibited stable hysteric characteristics. On the other hand, they determined, in specimens for which the buckling strength is less than the yield strength of the SC, that buckling occurred during compression loading, before the yield of the SC. Thus, they concluded that the SC should be encased in a steel square tube having an Euler load that is 1.5 times greater than its yield strength. They additionally reported that it was possible to determine the initial stiffness and yield strength of the BRB under compression and tension, and hysteric characteristics could be achieved even in cases of high deformation.

(Wada et al, 1990) subjected BRB specimens to fatigue testing, in addition to the (Watanabe et al, 1988) study, and shed light on the analysis and design equations of BRBs. In addition, they studied the BRB frame systems used in the Shinkawa building in Japan. Thereby, they revealed the parameters of the BRB frame systems. They reported that the SC could become wavy in the gap together with the coating material even if the concrete has sufficient stiffness, however, such wavy deformation had no effect on the hysteric
characteristics of the BRB. They concluded that the wavy deformation caused on the SC by the moment of flexion had no effect on the buckling resistance and yield strength of the steel square tube. 

(Clark et al, 1999) built and tested prototypes for the BRBs to be used in the UC Davis Planet & Environmental Sciences building at the University of California. The objective of the study was to determine the characteristics of full-scale BRBs under cyclic loads of increasing width. Within such scope, they tested 3 full-scale BRBs. The SC length of all BRBs were approximately 14.75 ft., but their cross-sectional areas were 4.5 in$^2$, 6.0 in$^2$ and 8.0 in$^2$, and their yield strengths were 270 kips, 360 kips and 470 kips, respectively. Moreover, two of the specimens featured SCs with rectangular cross-sections while the third specimen had a SC with a cruciform-shaped (+) cross section. They obtained the loading protocol used in the testing phase (SAC, 1997) from the testing program.

They determined, as a result of an experimental study, that the maximum BRB force under compression is slightly greater than that under tension, and reported that all BRB specimens exhibited stable hysteric characteristics in the cyclic loading tests. In conclusion, they reported that all three BRBs exhibited predictable characteristics, high strength and high level of energy dissipation in the tests they were exposed to.

(Lai et al, 2004) conducted a study at the National Taiwan University (NTU), for the purpose of analyzing the effects of two different BRB parameters on the hysteric characteristics of BRBs. For the purpose of examining the effects of various isolation materials used in the unconnected interface, they performed uniaxial tests on 6 BRBs in order to obtain detailed information regarding 10 types of connections between BRBs and gusset plates. They examined more than 50 uniaxial BRB experiments previously conducted at NTU, as well as double-cored BRBs (Figure 5), constructed within such scope. In the study, the goal of constructing double-cored BRBs was specified as decreasing the BRB connection length and the number of bolts between the BRB and the gusset plates. The standard loading protocol used in the cyclic tests was obtained from (SAC, 1997).

The testing apparatus and the double-cored BRB are presented in Figure 5. It was concluded that double-cored BRBs and those the BRMs of which are obtained by pouring concrete into double steel square tubes exhibited stable strength under intensive inelastic cyclic axial stress. It was also concluded that the connection length was reduced, with a single set of bolts at the tip of each BRB being sufficient. They additionally reported, following an analysis of the results, that the use of a 2-mm-thick silicon rubber strip provided the minimum axial load difference.

(Black et al, 2004) designed two BRBs for the Kaiser Santa Clara Medical Center building, in addition to the (Clark et al, 1999) study, and conducted uniaxial testing for these two specimens. The BRBs used in this study are referred to in the literature as Unbonded Braces, the design of which is shown in Figure 2.a. They reported, upon analysis of the experiment results, that both BRBs exhibited stable hysteric characteristics throughout the cyclic tests, and the yield occurred in the members had a uniform distribution. In conclusion, they reported that the BRBs performed quite well under standard loading protocols, with the SC’s plastic deformation buckling being the most critical stability issue.

(Young et al, 2009) conducted a study, analyzing the load resistance capacity of BRBs comprised of H-shaped SCs and outer steel square tubes not filled with concrete, with uniaxial tests. Within the scope of the study, they divided the SC into two main parts (Figure 6). They defined the first part as the constrained part, which is located in the center of the SC and encased in a steel square tube, and the other part as the unconstrained part containing the required connections of the SC. The study included uniaxial tests of a total of 7 BRBs. The differences between the BRBs are the thickness of the outer steel square tube and the length of the unconstrained part. In this context, they did not use a steel square tube for the first BRB specimen, while setting the steel square tube thickness in the other specimens as 3, 4 and 5 mm. The length of the
unconstrained part was set as 200 mm and 300 mm. Moreover, the SC unconstrained part of the last 4 specimens were supported by welding of steel plates. The test apparatus used in the study is shown in Figure 6. In this study, they analyzed the effects of design parameters on the maximum strength and energy dissipation capacities of BRBs. They determined, from the outcome of the experiments, that correct design increased the maximum strength of a BRB by 290%, and calculated a cumulative ductility ratio of 330. In conclusion, they reported that stable characteristics could be obtained in the BRBs of such design if the unconstrained part of the SC is appropriately supported and the thickness of the steel tube is sufficient, and buckling could thereby be effectively prevented.

(Wu et al, 2012) conducted cyclic tests for three new-generation, all-steel BRBs. Unlike conventional BRBs, the ones used in this study had BRMs comprising of two identical steel buckling-preventing members. As seen in Figure 7, they used separator brackets that are slightly thicker than the SC, in order to provide a gap between the SC and the BRM. They reported that this BRM design allowed a visual inspection to be sufficient in the determination of deteriorations of the SC following exposure of BRBs to excessive earthquake loads. They additionally reported that, in the case of damage to the BRBs due to earthquake loads, the design allowed easy removal of the BRM and reinstallation of the same after replacement of the SC.

The study incorporated SCs of various cross sections. They manufactured the SC and the separator brackets from CNS SN490B steel with a yield strength of 340 MPa. At the center of the SC, they welded two stopper pins of 10 mm diameter and 15 mm length onto the SC surface. They reported the purpose of the said pins as ensuring that the SC and the BRM moves in a parallel direction. In the experimental study, they manufactured the two buckling-restricting members from A36 steel of 25 mm thickness, and clamped them using S10T high-strength bolts of 20 mm diameter. They left a gap of 1 mm between the SC surface and the BRM, and a gap of 2 mm between the edge of the SC and the BRB. They concluded that the design of easily-inspectable and easily-installable/removable new-generation BRBs are quite effective. They were able to observe the high-shaped buckling reactions of the SC throughout the test, without having to disassemble the BRM. In conclusion, they reported that the recommended BRM was in reusable condition and different SC cross section dimensions could be used in order to improve the hysteretic reactions of the BRB. They additionally reported that all BRB specimens exhibited favorable energy dissipation capacities, and the ratio between compressive and tensile strength peaks were less than 1.22 for all BRB specimens. They confirmed that generation of friction force between the SC and the BRM is greatly reduced in new-generation BRBs. The outcomes of the tests revealed that an increase in the applied axial compressive stress resulted in a decrease in the wavelength of the high-shaped buckling. In addition, they reported that the wavelength would not increase in cases where the last applied compressive stress is less than the preceding one.

Figure 5. Testing apparatus, double-cored BRB and its hysteric characteristics (Lai et al, 2004)
2.2 Performance of Sub-assemblage Tests

(Newell et al, 2006) conducted sub-assemblage tests at the California University, Seismic Response Modification Device testing facility for 4 full-scale BRBs, using a shake table. Of the BRBs manufactured within the scope of the study, it was reported that specimens 1 and 2 had a rectangular SC while specimens 3 and 4 had a cruciform-shaped (+) SC (Figure 8). SCs of all specimens were made of A36 steel having a yield strength of 36 ksi, and the steel tubes used in the BRM was made of A500 Grade B steel. The testing apparatus is shown in Figure 8. On the testing apparatus, one end of the BRBs were fixed to the reaction wall, while the other ends were fixed to a shake table which can apply axial and diagonal displacement loads. In the cyclic tests, the BRBs were exposed to Standard Loading Protocol (AISC 341-05, FEMA 450), High Amplitude Loading Protocol and Low-Cycle Fatigue Protocol test.

As a result of the tests, it was reported that all BRB specimens exhibited highly favorable performance. No deformation was observed in the SCs of specimens 1, 2 and 4 during the tests. A crack was seen in the SC of specimen 3, at the initial stress corresponding to $4.3\Delta_{\text{hm}}$ deformation amount of the High Amplitude Loading Protocol. They reported that the bolted end connections of the BRBs were suitable for end rotations exceeding 0.031 radians. As a result of the study, it was concluded that the hysteric characteristics of the BRBs were highly stable, the energy dissipation capacities were quite high, and the BRB specimens were able to withstand cumulative axial deformations much greater than the $200\Delta_{\text{by}}$ deformation value required by the AISC specification. The sub-assemblage tests revealed that all BRB specimens fulfilled all acceptance criteria specified in the FEMA 450 specification, as well as those specified in Appendix T10 of the AISC 341-05 specification.

(Tremblay et al, 2006) conducted a study where 6 full-scale BRBs were built, where the BRMs of two BRBs were constructed by pouring concrete into steel tubes, and the BRMs of four BRBs were all-steel. They
Additionally constructed 1 conventional brace with a hollow structural cross-section for comparison purposes, and applied tests to all specimens on the sub-assembleage testing apparatus. Within such context, two SCs with restrained non-yielding segments of different lengths and two different BRMs were analyzed (Figure 9). This study was conducted at the Ecole Polytechnique of Montreal, with the objectives reported as follows; (i) analyze the in-plane flexural demand of BRB members under realistic loads and the effects of such bending moments on the BRB performance, (ii) reduce the length of the restrained non-yielding segment in the SC in order to improve BRB performance, and (iii) develop new-generation BRBs with all-steel BRMs.

It was reported that the difference between the BRBs constructed by pouring concrete into steel tubes were the lengths of the SC plastic segments. Polyethylene foam of 3 mm thickness was placed alongside the SC on both sides, and the SC was wrapped in 4 layers of 0.2 mm polyethylene film. BRBs made of all-steel members had BRMs containing two ASTM A500 HSS 127*127*4.8 steel tubes, which were welded to guide plates of 10 mm*270 mm dimensions. Shim plates and filler plates were used alongside the restrained yielding segment of the SC.

As a result of the study, it was reported that the BRB specimens constructed by pouring concrete into steel tubes exhibited satisfactory performance under the quasi-static cyclic test protocol. In BRBs comprised of all-steel members, as the yield capacity of the SC is exceeded, a significant amount of axial force caused strain-hardening and cracking of the SC. These BRB systems performed well in the static and dynamic loading indices, but it was noted that the gap between the SC and the BRM should be kept minimum. It was additionally reported that the conventional brace member also performed well, but it had a very limited energy dissipation capacity compared to BRBs constructed by pouring concrete into steel tubes.

(Yooprasertchai et al, 2008) conducted a study investigating applicability of BRBs to low-rise buildings with reinforced concrete frames. The primary objective of the study was reported as improving the energy dissipation capacity of the building by reducing the inelastic deformation demands of non-ductile structural elements (e.g. columns). In the first phase of the study, they constructed BRBs comprising of a rectangular SC encased in a mortar-filled steel tube, a simple yet effective design, and applied a series of quasi-static cyclic loading tests. However, the first two BRBs performed very poorly due to unexpected defects. With the correction of such defects, the 3rd BRB exhibited favorable yield characteristics under tensile and compressive conditions. In the second phase of the study, the well-performing BRB was diagonally mounted on a sub-assembleage testing apparatus containing a reinforced concrete column and exposed to quasi-static loads. The details of the sub-assembleage testing apparatus are shown in Figure 10. The results of the first BRB specimen revealed that the yield did not fully occur and the expanding segment of the SC was not sufficiently inside the BRM. During the testing of the 2nd BRB, it was observed that the concrete in the BRM slipped inside the steel tube and the BRM went out of sight at the top end of the BRB. In response, plates were welded on the SC of the 3rd BRB, in order to prevent slipping of the BRM. Thereby, the 3rd BRB was constructed, which exhibited stable characteristics under cyclic loads and uniform yield characteristics under tensile and stress forces. In the second phase of the study, quite stable cyclic rings were observed in the BRB sample diagonally mounted on the reinforced concrete column, at drift levels from narrow to wide, without any signs of deterioration. However, deterioration began in the entire system at 2.5% drift of the column. With the introduction of the BRB into the system, improvement was observed in strength and stiffness as well as an increase in the amount of energy dissipation. Test results suggest that the use of systems with BRBs is an alternative method for the reinforcement of non-ductile reinforced concrete structures.
2.3 System Performance of Frames with BRBs
(Fahnestock et al, 2003) conducted a study at the Lehigh University, ATLSS Center, analytically and experimentally examining seismic characteristics of frames having concrete-filled steel tube-shaped columns and structural steel sectioned beams. The objective of the study was reported as examination of the seismic performance of such frames, determination of their design parameters and establishment of an analytic model.

The design parameters for the BRB frame was taken from the IBC 2000 and AISC/SEOC specifications. The tested BRB was of 3/5 scale, with a four-story, single-bay. The DRAIN-2DX analysis software was used in the study for the prototype frame model, also including material and geometric nonlinearity. In the study, earthquake records were dimensioned in two distinct seismic input levels, namely the Design-Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE). The target level for design-basis
earthquake was set as the Life Safety (LS) performance level, while the target level for earthquake where maximum is considered was set as the Collapse Prevention (CP) performance level. As a result of the study, it was reported that the frame with BRBs exceedingly fulfilled the criteria defined for the seismic input levels, and the BRBs exhibited sufficient ductility capacity. It was reported that the roof and story drifts were at an acceptable level, and the frame was reparable and at an economical level following the DBE. Similarly, it was reported that the performance of the frame with BRB which was exposed to MCE-level seismic motion was much better compared to its CP performance, approaching the LS level. It was noted that much higher maximum ductility demands could be achieved without any cracking in the SC. In conclusion, the analytical and experimental studies conducted on the frame with BRBs yielded exceedingly successful results for the improvement of the resistance of the building against earthquakes.

(Mahin et al, 2004) conducted a study at the California-Berkeley University, involving a series of tests for three full-scale frames with BRBs. The objectives of the study were reported as follows; (i) analyze the effects of BRB end rotations occurring due to lateral deformations of the frame on the characteristics of the entire BRB, (ii) compare the hysteric characteristics of the BRB in the frame with the hysteric characteristics observed in the uniaxial tests, and (iii) determine the performance of the connection between the BRB and the gusset plate in expected building drifts.

As seen in Figure 11, the frame used in the test program is one-story, single-bay. Within such scope, three different frame tests were performed in two distinct BRB configurations. The first frame (No. 1) had a chevron type BRB configuration, while the second (No. 2) and third (No. 3) frames had diagonal BRB configuration. The same column-beam components were used for all configurations. However, the cross sections and yield segments of the SCs of the BRBs were varied. Two distinct BRBs with different cross sections were designed and analyzed. In the BRB system with Chevron configuration, one of the BRBs had a SC with rectangular cross section, while the other had a SC with cruciform-shaped (+) cross section. On the other hand, in the BRB system with diagonal configuration, No. 2 had a SC with rectangular cross section, while No. 3 had a SC with cruciform-shaped (+) cross section.

As a result of the study, it was concluded that all three frames performed quite well as a seismic lateral system. It was reported that the BRBs performed very well in the tests, providing high energy dissipation capacity and added to the ductility of the frame. No visible differences were reported between BRBs with chevron and diagonal configurations, having different SC cross sections. However, it was noted that cracks occurred on the gusset plate in Test No. 2, and buckling occurred at the free edges of the gusset plate (Figure 11). On the other hand, the connection members suffered much more severe deformation in Test No. 3. The entire flange below the main beam cracked from the beam towards the column. It was reported that the crack caused loss of buckling stability in the beam-gusset plate segment, and the BRB severely shifted outside the plane (Figure 11). It was emphasized that additional research is needed on the gusset plates located in the column-beam joint.

(Tsai et al, 2008) performed Pesudodynamic tests for 3-story, 3-bay frames with BRBs constructed using steel tube columns filled with concrete. The study was conducted in 2 phases. In the 1st phase, a different type of BRB was used on each story of the frame. The BRB types were reported as all-steel BRBs, single-cored BRBs and double-cored BRBs, respectively. In the second phase, double-cored all-steel BRBs were used in the 1st story, while concrete-filled double-cored BRBs were used in the 2nd and 3rd stories. The seismic motions for the Pesudodynamic tests performed within the scope of the study were selected and adapted from the 1999 Chi-Chi and 1989 Loma Prita earthquakes and the levels from the said earthquakes which represent three seismic zones.
No stiffeners was used in the connection prior to the 1st phase testing. However, due to the buckling occurred on the gusset plates in the 1st phase, stiffeners of 12 mm thickness were added to the gusset plates of all three stories. As a result, Pesudo dynamic tests were successfully completed without any deterioration in the gusset plate or the BRBs.

As a result of the study, it was concluded that adding stiffeners to gusset plates was a very effective method for preventing gusset plates from buckling and shifting from their axes. It was reported that all BRBs exhibited full hysteric response and absorbed high amount of energy. It was observed that the cumulative plastic deformation of the BRBs placed in the frame was less than that calculated in the uniaxial tests. It was reported that the end rotation of the BRBs was quite high, and such demands varied between 30% and 96% of the story displacement demands.

Figure 11. Testing apparatus and buckling occurred in the gusset plates (Mahin et al, 2004)

Figure 12. Testing apparatus and addition of stiffeners to the gusset plates (Tsai et al, 2008)

1. CONCLUSIONS

As seen in the literature studies, BRBs improve stiffness and strength of buildings with their almost equal compressive and tensile capacities, ductility characteristics and high energy dissipation capacities. However, such advantages can only be achieved through the design of the right BRBs and connection members. Certain parameters should be taken into consideration in order to enable BRBs to exhibit stable and steady characteristics under cyclic loading. Such parameters include, for instance, the thickness of the gap or isolation material used in the unconnected interface, prevention of the relative motion of the SC and the BRM with respect to each other, and the BRM providing sufficient stability to the SC. BRBs also performed well in the frame tests, providing high energy dissipation capacity and ductility to the frame. In addition, a significant reduction was achieved in the story displacement rations with the addition of the system with BRBs, and the deformation of the frame members was limited. However, as stated above, the connection members underwent deformation and buckling under excessive story displacements, which resulted in end
rotations in the BRBs. This reveals the necessity to concentrate more on the design of connection members in future studies. Furthermore, there are many studies in the literature on the reinforcement of steel structures with BRB systems, while the number of studies on the reinforcement of concrete structures with BRB systems is very limited. The researchers are expected to concentrate more on this subject in future studies.

REFERENCES


AISC-SEAOC; 2003 - Recommended Provisions for Buckling Restrained Braced Frames. American Institute of Steel Construction. California, USA.


SAC; 1997 - Protocol for fabrication, inspection, testing and documentation of beam column connection tests and other experimental specimens. SAC Joint Venture, USA.


