Effect of Design Loads in Buckling Restrained Braced Frames Performance

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ABSTRACT :

The concept of Buckling Restrained Braced Frames is relatively new and recently their use has increased in many countries. However, detailed design provisions for this type of bracing are currently under development. In this paper two approaches for designing of buckling restrained braced frames are considered. In first approach, the provision of Iranian Earthquake code, which used for designing of concentric braced frames, are considered for 4, 6, 8, 10, 12 and 14 stories building with chevron (V and Invert V) and split X configuration of buckling restrained braced frames. In the other approach a new load combination are considered for designing of these bracing types. Static cyclic and nonlinear dynamic analyses were performed for all frames.. The results in the term of story drifts, story shears, story shear versus drift hysteresis behavior and plastic hinges locations were compared. By comparing the response of these two series of frames, a better performance was observed for the new load combination for designing of buckling restrained braced frames.

KEYWORDS: Buckling Restrained Braced Frames, Static Cyclic Analysis, Nonlinear Dynamic Analysis.

1. INTRODUCTION

Steel moment-resisting frames are susceptible to large displacement during serve earthquake ground motion, and require special attention to limit damage and avoid problems associated with P-Δ effects. Therefore engineers have increasingly turned to concentrically braced steel frames for resisting earthquake loads, but damage to this braced frames in past earthquakes raises concerns about the ultimate deformation capacity of this class of structures.

Individual braces often possess only limited ductility capacity under cyclic loading. Braces hysteretic behavior is unsymmetric in tension and compression, and typically exhibit substantial strength deterioration when loaded monotonically in compression or cyclically.

Use of this braces in concentrically braced frames (CBFs) have long been known to be prone to many non-ductile modes of behavior when subjected to large ductility demands. Such modes include connection and member fracture, severe loss of strength, stiffness due to beam ductility resulting from unbalanced tension and compression strengths and unable to dissipate energy (AISC, 2002) have been observed in concentrically braced frames. It has also been noted that the lateral buckling of braces may substantial to damage and instability of structure.

Prompted to these concerns and faults of concentrically braced frames, seismic design needs to enhance the compressive capacity and symmetric hysteretic response of braces. Therefore considerable researches have also been done to improve the performance of individual braces and lead to introduce new generated of braces “Buckling-restrained braces”. These braces have an ultimate compressive strength as equal as tension strength.

An interesting design approach for buckling-restrained braced frames has been proposed by Wada (1992) in which the basic structural framework is designed to remain elastic during seismic response, and all of the seismic damage (yielding) occurs within the braces [1]. BRBFs are desirable for seismic design and rehabilitation for their superior ductile performance. This behavior in BRBFs allows for smaller beams in chevron bracing configurations, which are governed by the unbalanced vertical forces in the braces [2], because the tension and compression yield forces are usually within 6%–20% of each other [3]. BRBFs have been reported to have 50% of the steel weight of Special Moment- Resisting Frames (SMRFs) designed according to the UBC [4], while achieving maximum drifts of 50%–70% of those reached by SMRFs in static pushover analyses [5].

In this paper, the effect of design loads in the seismic performance of buckling restrained braced frames is investigated. Current design provisions do not contain specified load combination. For this purpose two approaches were selected for design of BRBFs. In the first approach, the provision of Iranian earthquake code which was recommended for designing of concentric braced frames, were used for designing of 4, 6, 8, 10, 12 and 14 stories building with chevron (V and Invert V) and split X configuration of buckling restrained bracing. The result of static cyclic and nonlinear dynamic analysis is used for proposed a new design load combination to achieve a better performance of buckling restrained braced frames. The result of analyses was compared in term of story drift, story shear versus drift hysteresis behavior and plastic hinges locations.

2. BUCKLING RESTRAINED BRACES

BRBs are made up of three principal components: a steel core coated in an “unbonding” substance, concrete, and an outer tube (Figure 1). The steel core plays the primary role of the brace by providing the necessary resistance to any applied axial forces. The core is encased in a concrete-filled sleeve that prohibits buckling under compression loads; this enables the brace to take advantage of the compressive strength of steel. Beyond the edges of the sleeve, the core extends and transitions into a configuration that allows for bolting to gusset plates (Figure 2) [5].

To prevent bonding between the concrete and steel core, an “un-bonding” material is applied to the steel; this enables the BRB axial forces to be restricted to the steel core. Due to the importance of this additional material, buckling-restrained braces are often referred to as “Unbonded braces”. An important design consideration for a BRB is the transition segment located between the steel core and core extension. The transition segment is designed to eliminate buckling by adding stiffeners to the core material; it is intended to be the only portion of the enclosed core that will exit the sleeve upon tensile deformation [5].

The principal advantage of BRBs is their ability to yield in compression as well as in tension (5). Because BRBs resist buckling, they exhibit a symmetric hysteretic behavior that is more stable than a typical buckling brace (Figure 3) [7]. Another advantage of BRBs is that yielding is confined to the steel core. By limiting yielding to the core, there is an increased control of performance [5].

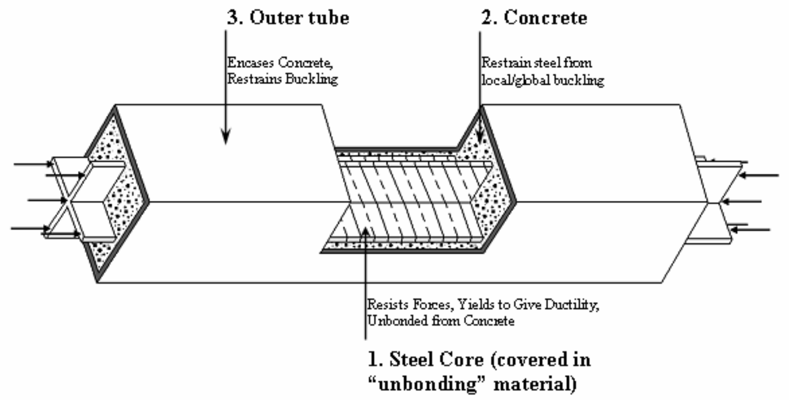


Figure 1. Principal BRB Components (with middle section cut away). [6]

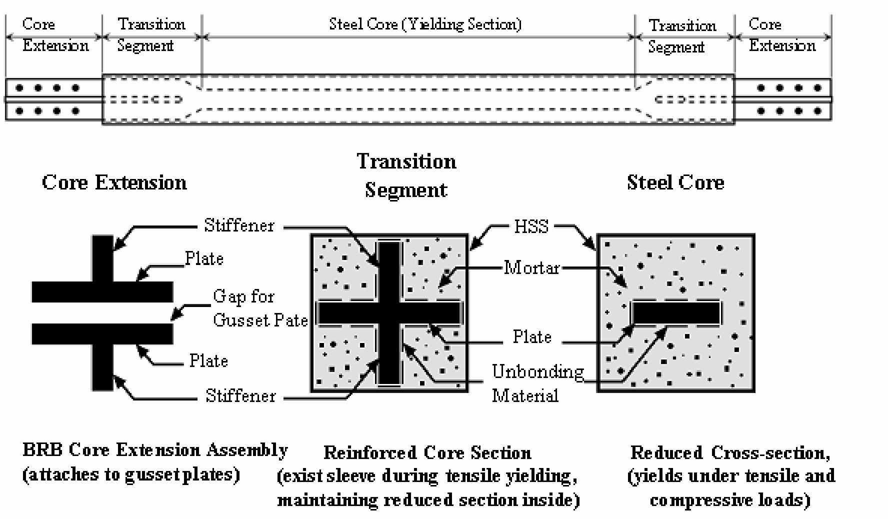


Figure 2. Cross-Section Diagrams for a BRB's Principal Segments. [6]

3. SEISMIC PERFORMANCE OF BRBS

Several analytical and experimental studies have been performed recently to determine the performance and behavior of BRBFs. Much of this research led to the formulation of the Provisions and future work will continue to develop an understanding of the behavior and consequently optimal design of BRBFs.

The 2005 AISC Seismic Provisions define buckling restrained braced frames (BRBF) and address design specifications pertaining to the design of these in Chapter 16 and Appendices R and T [2]. This is a new addition to the Provisions and is based on the provisions recommended by Sabelli (2004) [7]. They state that BRBFs ductility and energy dissipation is comparable to that of a special moment frame (SMF), while their stiffness is close to that of an Eccentrically Braced Frame (EBF). This is truly the optimization of behavior: high energy absorbing capability in a stiff (and thus damage resistant) system. This excellent behavior is reflected in the Provisions recommended Response Modification Factor (R), which is suggested, in the absence of code-specified factors, for BRBF to be 7 or 8, similar to those values specified for EBFs and SMFs. The Provisions require brace testing before utilization to qualify their behavior during a design earthquake under the performance requirements of the Provisions. Consistent with ASCE 2002 [8] and the 2003 NEHRP Recommended Provisions (FEMA, 2003) [9], a minimum 2 percent story drift is required for detailing.

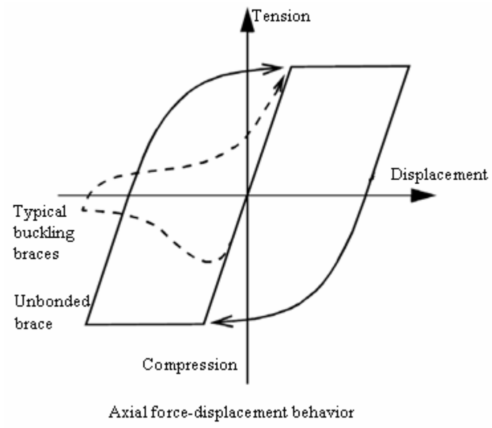


Figure 3. Buckling-Restrained Brace Hysteretic Behavior [7]

4. OBJECTIVE AND SCOPE

The exact design of any lateral resistance system is very important to have a desirable operation during the earthquake. Because there was not any recommendation on specified load combination for design of buckling restrained braces in current standard and codes, evaluating the effect of load combination in seismic performance of BRBFs is the objective of this paper.

5. BUILDING MODELS

To evaluate the seismic performance of buckling restrained braced frames 4, 6, 8, 10, 12 and 14 story building with the bay length of 6 m and three different bracing types (split X, chevron V and chevron-Inverted V Types) were selected. Figure 4 show the typical configuration of the models used. The story height of the models was considered as 3.2m. For member design subjected to earthquake, equivalent lateral static forces were applied on all the story levels. These forces were calculated following the provisions stated in Iranian Earthquake Code (Standard No. 2800) [10]. Base design acceleration 0.35g, soil type II, importance factor of structure 1 and response modification factors of 9.5 are assumed in calculation equivalent base shear. The dead and live loads of 6 and 2kN/m^2, respectively, were used for gravity load.

Allowable stress design method was used in accordance to part 10 of Iranian national code [11]. Buckling restrained braces were designed using two approaches or two load combination. In the first approach (AP1) the provision of Iranian seismic code in chapter 2 were considered in the design of buckling restrained braces. According to this section of provision, the BRBs were designed based on 1.5 times of earthquake load (factored). In the second approach (AP2) the BRBs were designed based on un factored earthquake load.

In both approach columns were designed for the following load combinations:

a) Axial compression according to: $P_{DL}+0.85P_{LL}+2.8P_E< P_{SC}=1.7F_aA$ (1)

b) Axial tension according to: $0.85P_{DL}+2.8P_E< P_{ST}=F_yA$ (2)

In which F_a is allowable compressive stress, F_y is the yield stress and A is area section of column.

P_{DL}, P_{LL}, P_E, are required axial strength on a column resulting from application of dead, live and earthquake load respectively and P_{SC}, P_{ST} are design tensile and compression strength of column respectively [10].

6. ANALYTICAL MODELING ASSUMPTIONS

The computational model of the structures was developed using the modeling capabilities of the software framework of OpenSees [12]. Only a single frame was modeled and analyzed for each frame configuration. Although the frames were not explicitly designed to be moment resisting, all beam to column connections are considered as pin-ended. Possible contributions of the floor slabs to the beam stiffness and strength were ignored.

Columns were modeled as having a pinned base. Braces were modeled as pin-ended members.
For the modeling of braces, nonlinear beam and columns element with the materials behavior of Steel01 was used. Considering idealized elasto plastic behavior of steel material, compressive and tensional yield stresses were considered equal to steel yield strength. Fiber cross section of the member was considered for the considering nonlinear behavior. The strain hardening of 2 percent was considered for the steel behavior in inelastic range of deformation.
For the modeling of beams and columns, nonlinear beam-column element was used. The used section for beams and columns is the fiber section. For the modeling of geometric nonlinearities the simplified P-Δ stiffness matrix is considered. For comparison the seismic performance of two series of BRB frames, static cyclic and nonlinear dynamic analyses were used. The results of analyses are presented as follow.

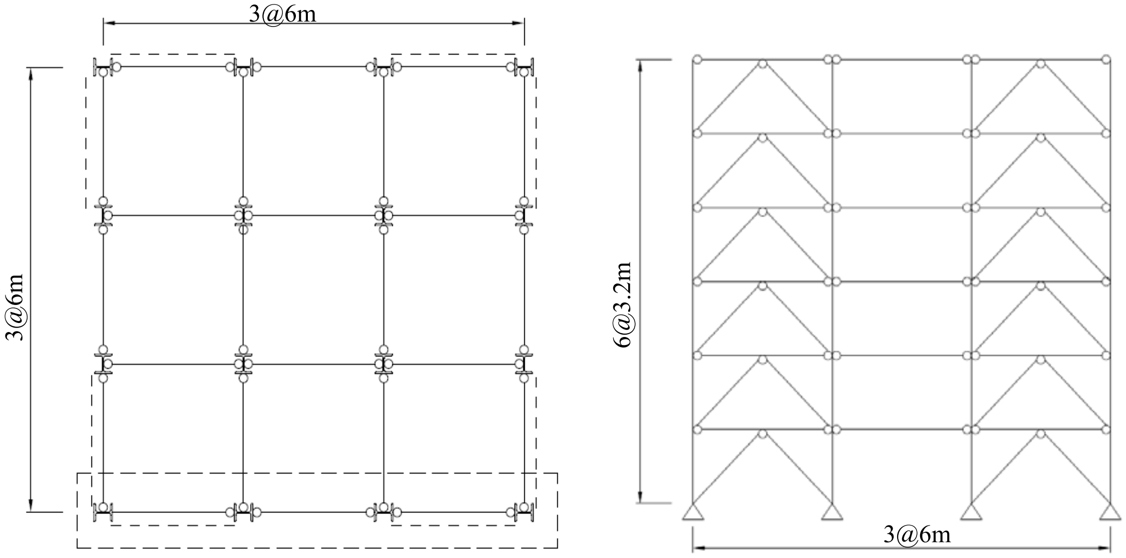


Figure 4. Configuration of model structures (a) Plan (b) Invert chevron brace

7. BEHAVIOR UNDER CYCLIC LOADING

A first step in assessing the behavior of BRBFs was to apply the standard cyclic load protocol that simulating the behavior under earthquake. The used protocol was that suggested by OSHPD (Office of Statewide Health, Planning and Development) [13]. The static cyclic nonlinear analysis was developed up to drift 3.5 percent. The results for the two approaches were presented in figures 5 and 6.
Static cyclic analysis shows that in first series of BRBs (AP1), most column buckling starts after some steps, but this behavior was not observed for second series of BRBs (AP2). By comparison of roof displacement versus base shear (hystersys loops) of two systems, it could be concluded that the second series of BRBs can absorb more energy during strong ground motion.

8. BEHAVIOR UNDER NONLINEAR DYNAMIC ANALYSIS

For nonlinear dynamic analysis, the models were analyzed using suites of ground motions. These suites consist of 3 ground acceleration records adjusted so that their mean response spectrum matches with Standard No. 2800 design spectrum. For this study, the earthquake suites corresponding to Elcentro, Tabas and Kobe were selected for seismic hazard levels corresponding to a 10% probability of exccedence in a 50 year period. The story drift demand, expressed in terms of the story drift angle, is the best measure of performance at the story level. Story drift demands are evaluated for the sets of ground motions discussed previously. Figure 7 compares story drifts for both serried of BRBs.
Maximum story drift in AP2 models were greater than AP1 that means that BRBs which were design for 100 percent of lateral loads have ability to damp more energy of earthquake in nonlinear range of deformation.

However the drift demand in both sets of BRBs is less than the values allowed by the Iranian Earthquake code [10].

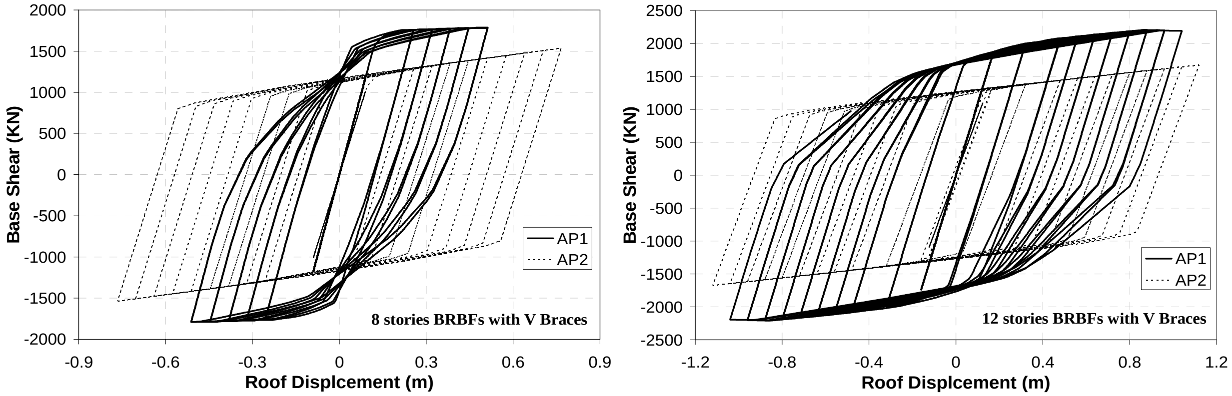


Figure 5. Recorded base shear versus roof displacement for 8 and 12 story BRBFs that have V braces.

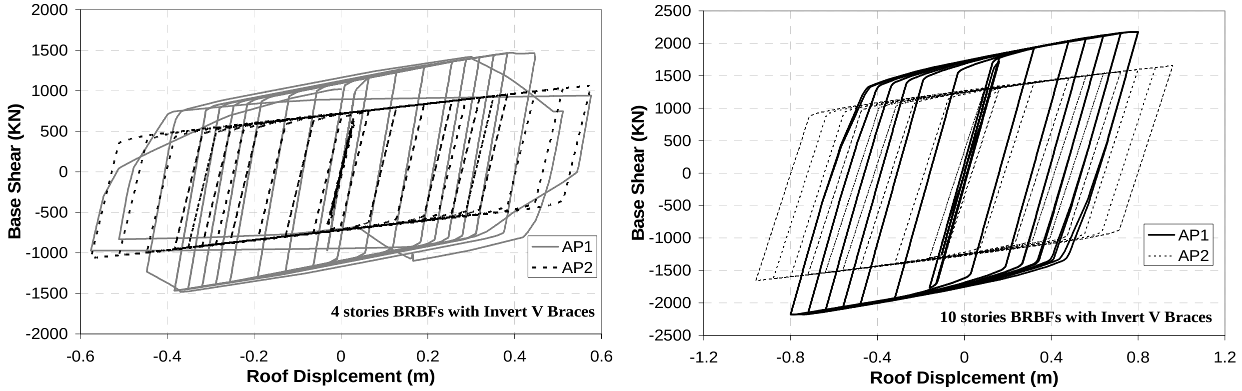
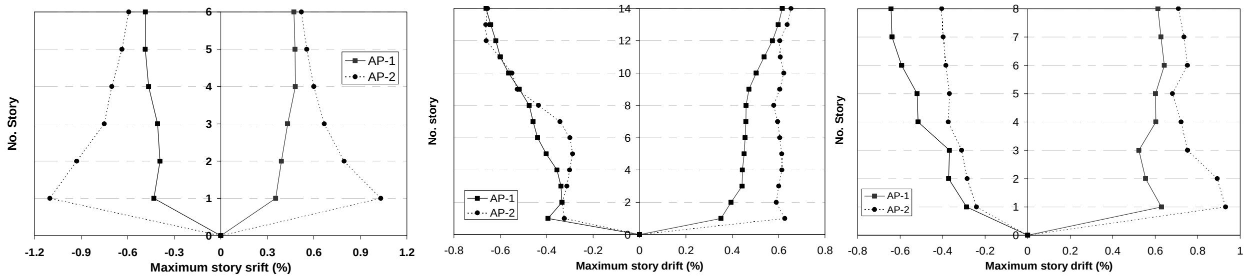


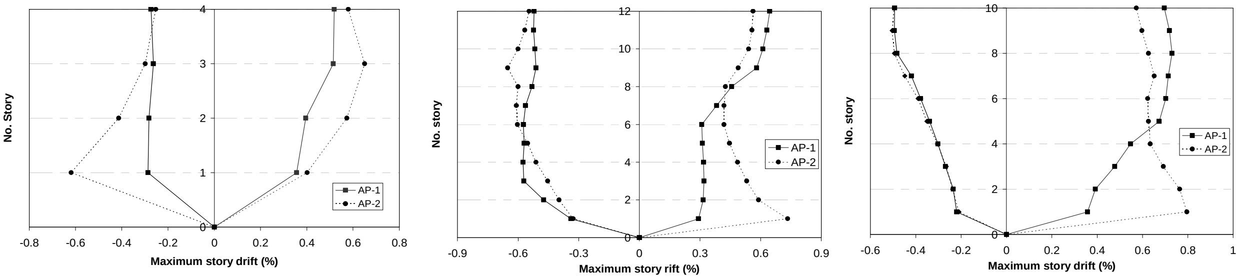
Figure 6. Recorded base shear versus roof displacement for 4 and 10 story BRBFs that have invert V braces.



6 story with V braces under Kobe G.M.

14 story with V braces under Elcentro G.M.

8 story with X braces under Tabas G.M.

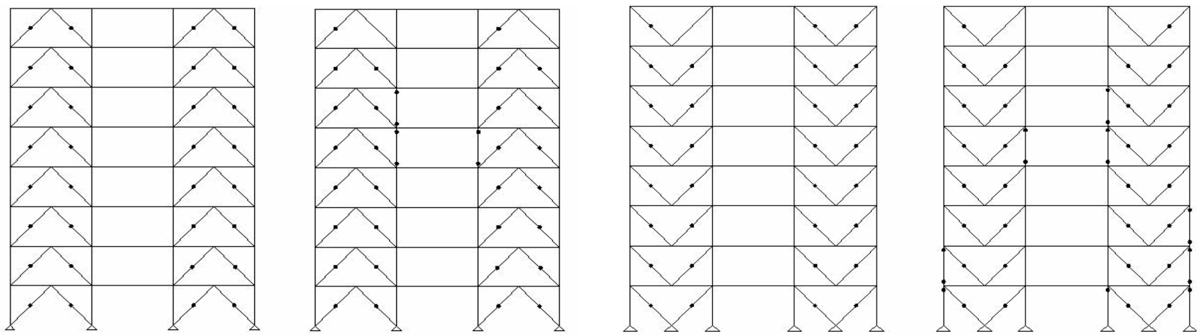


4 story with X braces under Elcentro G.M.

12 story with invert V braces under Tabas G.M.

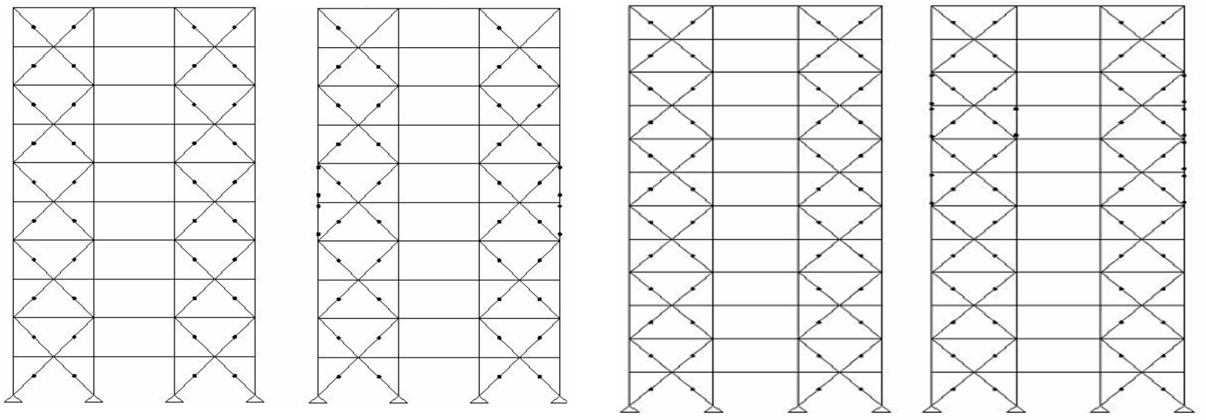
10 story with invert V braces under Kobe G.M.

Figure 7. Maximum story drift of BRBFs



AP2 AP1 AP2 AP1

BRBFs under Elcentro G.M. BRBFs under Kobe G.M.



AP2 AP1 AP2 AP1

BRBFs under Tabas G.M. BRBFs under Elcentro G.M.

Figure 8. Location of plastic hinges in BRBFs

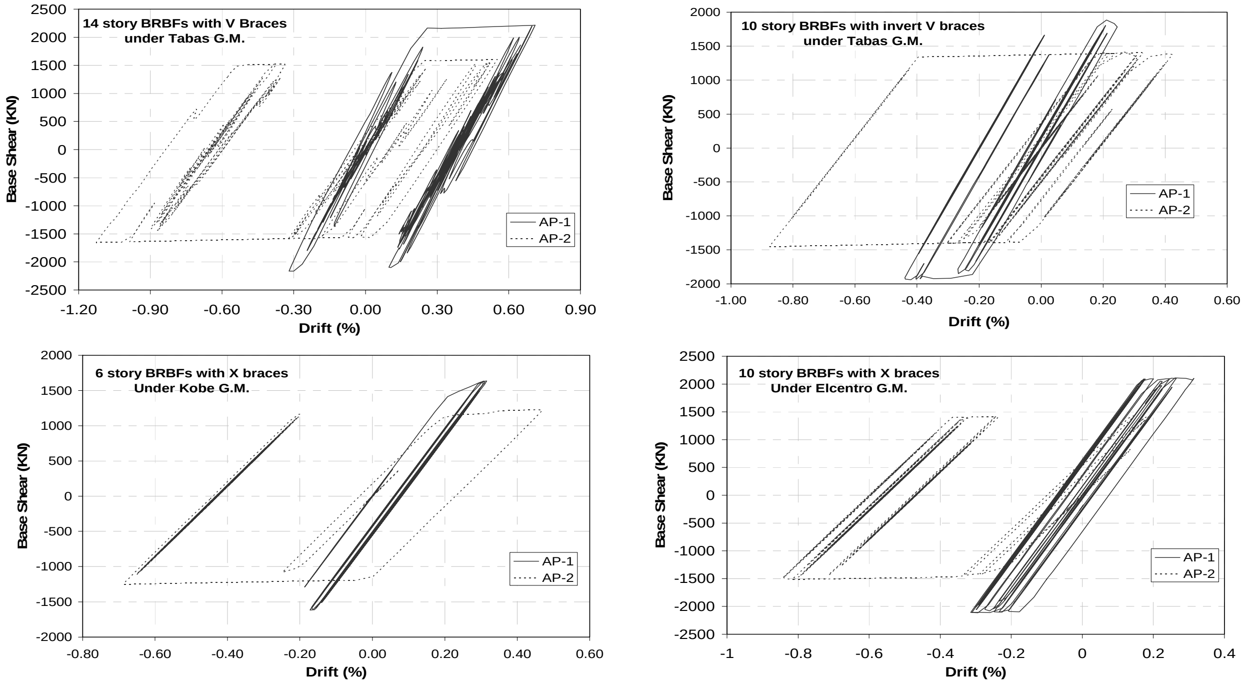


Figure 9. Base shear versus first story drift for BRBFs

Figure 8 shows the location of plastic zones (plastic hinges) in frames. In nonlinear dynamic analysis, plasticity was formed in some columns of AP1 models at most configuration of buckling restrained bracing type, while this behavior was not observed in columns of AP2 models.

The hysteretic behavior of the frames is evaluated for the sets of ground motions discussed previously. Figure 9 compares the hysteretic behavior of the first story (story shear versus story drift). Compared to AP1, more energy absorbsion can be observed for AP2 and this system provides a better behavior in the nonlinear range of deformations.

9. CONCLUSION

This study presents the effect of load combination used during design stage of BRBs in the performance of buckling restrained braces frames. For this purpose two design approaches were considered. Then static cyclic analysis and nonlinear dynamic analyses were performed for 4, 6, 8, 10, 12 and 14 stories building with chevron (V and Invert V) and split X buckling restrained bracing configurations. The results of analysis shows that the buckling restrained braced frames which were designed based on 1.5 times of earthquake load (provision of Iranian seismic code for CBFs) have low energy absorption compared to the second set of BRBs. Meanwhile, plastic hinges are formed in bracing columns of first series. Nonlinear dynamic analysis shows that all columns of proposed approach (braces design for 100 percent of earthquake load) remain in elastic range of deformations. Taking into account cyclic and nonlinear dynamic analysis performed for both systems, it can be concluded that BRBs were designed based on 100 percent of earthquake loads exhibits superior behavior and a better performance when it is compared with the BRBs designed with a load factor of 1.5.

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