Performance-Based Criteria for Buckling-Restrained Braces Replacement After Severe Earthquakes

A. Deylami & M.A. Mahdavipour
Amirkabir University of Technology (Tehran Polytechnic), Iran

SUMMARY:
Buckling-Restrained Braced Frames (BRBFs) are known as favorable lateral resistant systems that have good behaviors in cyclic seismic loads. Whereas these frames have enough elastic stiffness in low earthquake events, they can fulfill Codes drift control conditions. On the other hand in severe earthquake they dissipate big amount of energy in plastic deformations without instability. However, BRBs have low post-yielded stiffness that makes large residual drifts in structures. These residual drifts can affect the performance level of structures for future earthquake events and owners must follow a repair plan to initial performance level of structure back. In this study a performance-based procedure has been presented to replace deformed BRBs after moderate and severe earthquakes. For performance evaluation, Energy Balance Concept has been used. Three earthquakes with different intensities have been applied as first earthquake to make residual drifts and then with some assumptions adjusted model of structure has been built.

Keywords: BRBF, Energy balance, residual drift, performance criteria

1. INTRODUCTION

Today Buckling-Restrained Brace Frames (BRBFs) are known as a favorable lateral system for resisting against earthquake loads that are used in new structures and for existent structures rehabilitation too (Kiggins, 2006). BRBFs in comparison with Conventional Bracing Frames (CBF), are capable of dissipating energy in both compression and tension forces without any local or global instability. The expected cyclic behavior of a typical BRB element is shown in Fig. 1.1(Mahmoudi, 2010). Different kinds of BRBs have been investigated in many of papers and the result has been that BRBs are like fuses for structures (El-Bahey, 2011). As for low earthquakes (serviceability hazard level) structures have enough lateral stiffness to control drifts and for severe earthquakes (Design hazard level) structures have favorable nonlinear behavior that can dissipate big amount of energy.

As opposed all good properties, BRBs have an unfavourable, low post-yielded stiffness behavior (see Fig. 1.1). Therefore large residual drifts will occur in the structure (Kiggins, 2006). A research that has been done by Sabelli et al. is showing that these residual drifts can be 40%-60% of maximum structure's drifts(Kiggins, 2006). These residual drifts can affect the performance of structures. So in such structures after earthquake, owners need to have a repair and replacement plan for deformed elements to return structures into initial performance.

On the other hand nowadays in addition to conventional design procedures, many of structures are designed by Performance-Based Design (PBD) approach. In PBD approach a hazard level and a performance level are defined and then structure is checked for selected performance point (Naeim, 2001). Now there is a question that after an intermediate and severe earthquake for returning structure into initial performance point, which BRBs must be replaced? Certainly replacement of all BRBs is not economical.

So in this research a method is studied to replace deformed BRBs and return to initial performance of structure based on energy balance concept. In this method residual drifts of structure are used as inputs and then a procedure is followed for BRBs replacement and finally structure is repaired without replacing all of them.

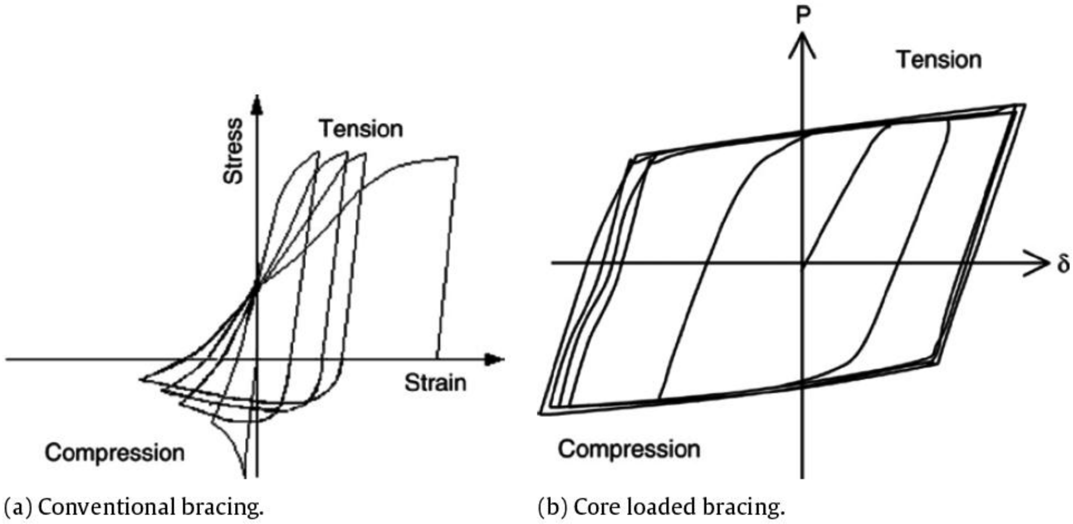


Figure 1.1. Difference in energy dissipation between conventional braces and BRBs under cyclic loading.(Mahmoudi, 2010)

2. ENERGY BALANCE CONCEPT IN PERFORMANCE EVALUATION

Energy balance concept has been used by different researchers for Performance-Based Design. There are some contexts about using Energy balance concept in BRBFs systems (Kim, 2004). Energy balance concept is based on the assumption that, energy needs for pushing inelastic structure monotonically to target displacement equals to maximum input energy from the earthquake in corresponding elastic system. This input energy can be calculated by using elastic pseudo velocity spectrum (Leelataviwat, 2008). The energy balance equation is given by:

$$E_e + E_p = \gamma.\left(\frac{1}{2}M.S_v^2\right) = \frac{1}{2}\gamma.M.\left(\frac{T}{2\pi}S_a.g\right)^2 \tag{2.1}$$

Where E_e and E_p are elastic and plastic energy computed from pushover analysis. M is effective mass of structure and T is structure's fundamental period. Also S_v and S_a are pseudo velocity and pseudo acceleration that can be calculated from elastic spectrums that have been defined in specification such as FEMA publications (FEMA, 2000). γ is energy modification factor that has been presented by Lee and Goel for making relevance between inelastic and corresponding elastic systems based on ductility of structure (Fig.2.1). Lee and Goel have shown that γ is a function of structure ductility factor μ_s and yield reduction factor R_μ that is given by (Lee, 2001):

$$\gamma = \frac{2\mu_s - 1}{R_\mu} \tag{2.2}$$

Whereas, in accordance with Eqn. 2.2 the relation between R_μ-μ_s-T for calculating energy modification factor γ is needed, so Newmark and Hall equations can be used. These equations are shown in Fig. 2.1 for different ductility factors μ_s (Liao, 2010).

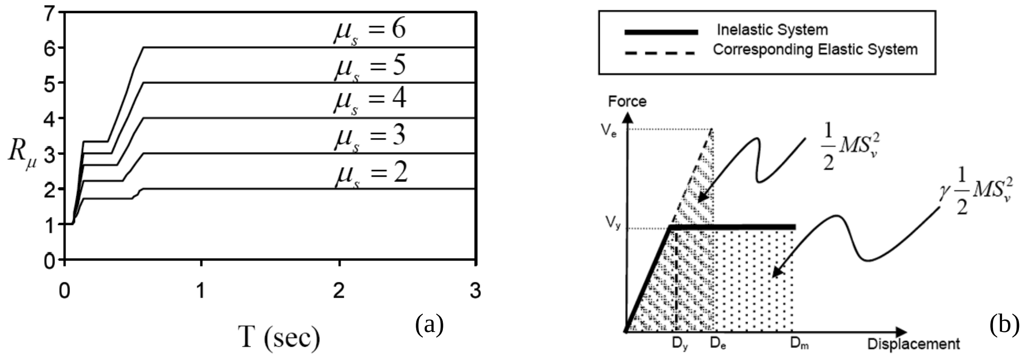


Figure 2.1. (a) Plot of Newmark and Hall's Equations (Liao, 2010). (b) Modified Energy Balance Concept (Liao, 2010).

In order to use the energy concept for performance evaluation purposes, the right hand side of Eqn. 2.1 can be viewed as energy demand for the given hazard, E_d, and the left hand side as energy capacity of the given structure, E_c. Both these quantities vary with displacement. The value of the desired maximum Target displacement can be obtained by either solving the work-energy equation analytically, or graphically by constructing the two energy curves as a function of the Target displacement and determining their point of intersection (Liao, 2010). The graphical method is preferred over the analytical one because the two energy plots present a good visual picture of the capacity and demand as a function of the target displacement. Fig. 2.2 is showing the main procedure of energy balance concept that was explained before (Liao, 2010). For a structure in accordance with spectrum acceleration in the fundamental period, there is a corresponding pseudo acceleration S_a. on the other hand energy modification factor γ is a function of R_μ and μ_s that these parameters can be related with Newmark and Hall equations. Finally γ is related to Target displacement u_t. The capacity energy curve can be calculated by selecting an appropriate lateral load pattern and pushing the structure (Liao, 2010).

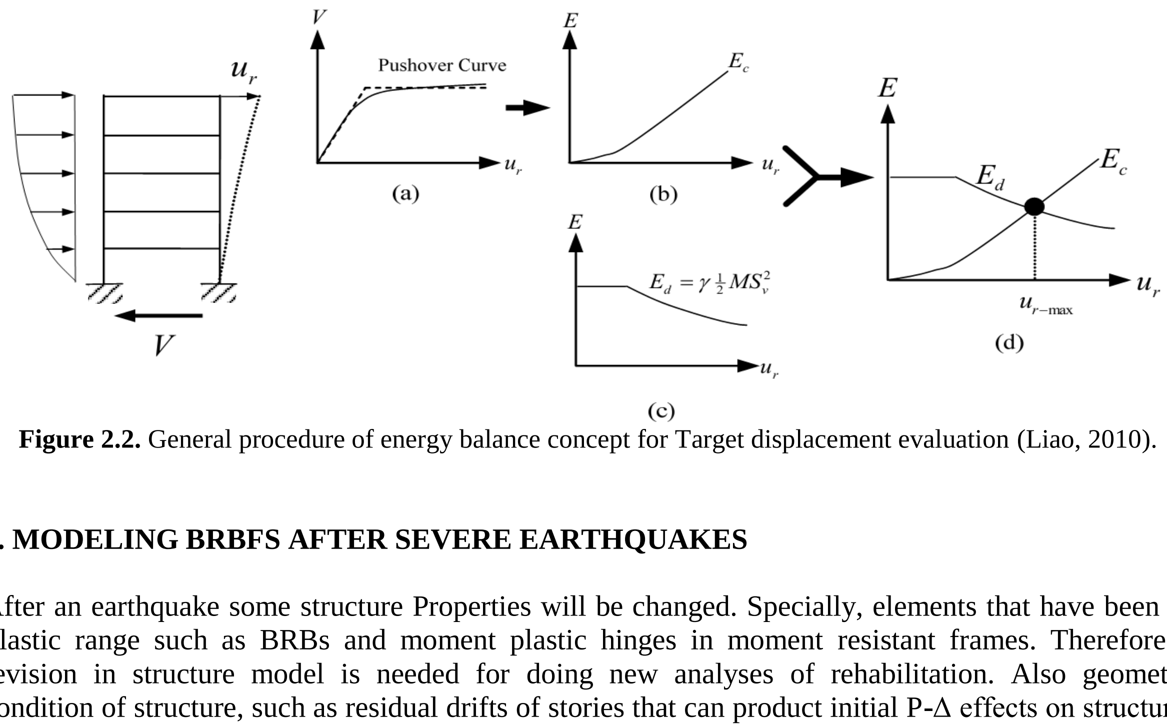


Figure 2.2. General procedure of energy balance concept for Target displacement evaluation (Liao, 2010).

3. MODELING BRBFS AFTER SEVERE EARTHQUAKES

After an earthquake some structure Properties will be changed. Specially, elements that have been in Plastic range such as BRBs and moment plastic hinges in moment resistant frames. Therefore a revision in structure model is needed for doing new analyses of rehabilitation. Also geometry condition of structure, such as residual drifts of stories that can product initial P-Δ effects on structure, will be changed. Existence of residual plastic deformation in a brace can decrease deformation capacity of it. This reduction is shown in fig. 3.1. So for adjusting structure conditions below items must be considered.

- Adjusting Plastic Hinges for modelling structures after earthquake.
- Simulating deformed structures for considering global second order effects (P-Δ).

For the first item it is enough to change definition of plastic hinges based on residual deformations (see fig.3.1) and for the last item inclined leaning column can be used. This inclined column with small stiffness is added to structure with rigid links such as that is shown in fig. 3.1.

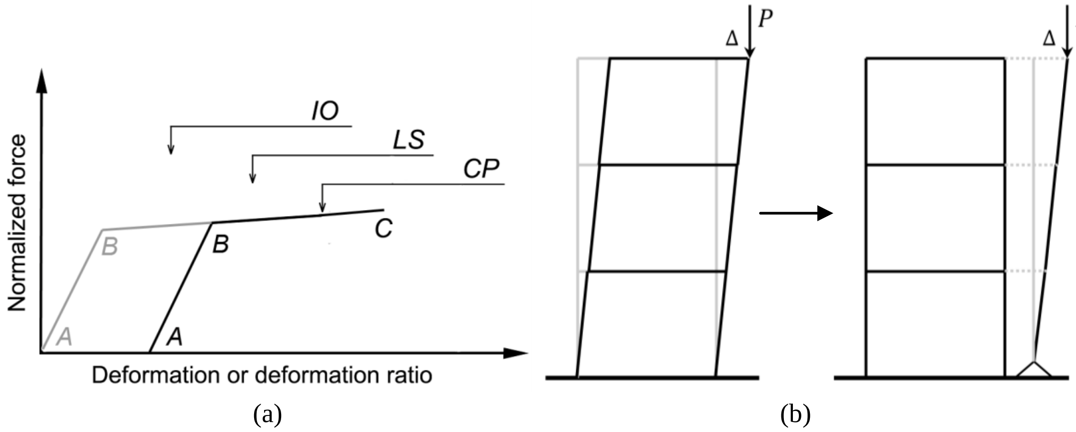


Figure 3.1. (a) Changing in Plastic hinge after an earthquake. (b) Inclined leaning column for considering initial P-Δ effects

Based on some steps a procedure can be defined for Performance-Based replacement of BRBs after earthquakes.
Step1: Adjust plastic hinges and add inclined leaning column for residual deformations and initial P-Δ effects.
Step2: evaluate performance of Adjusted Structure by using energy balance concept
Step3: Replace plastic hinges that performance criteria are exceeded.
Step4: return to Step2 and continue until all hinges fulfill performance criteria.

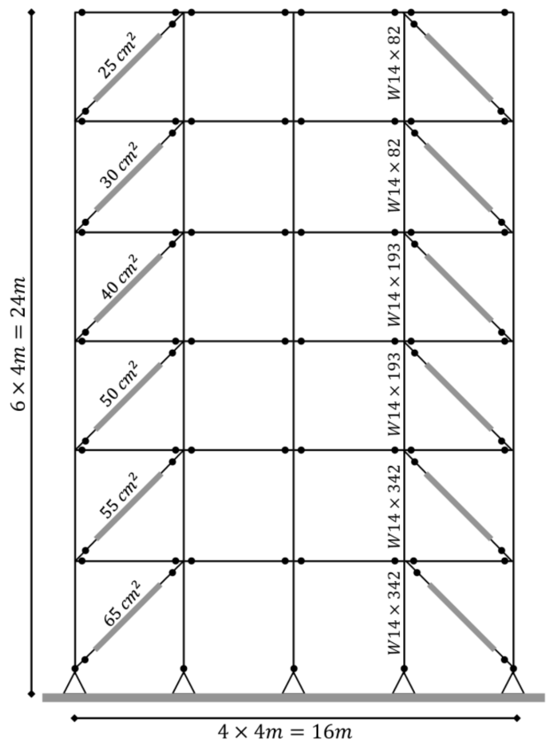
4. CASE STUDY OF 6 STORIES BRBF

For evaluating the expressed method, a six story frame was studied. The Geometry of this frame is shown in fig. 4.1. this frame has been designed for Basic Safety Objective (BSO) in accordance FEMA 356 (FEMA, 2000) and structure is constructed in a site in San Francisco included D category of soil and response acceleration parameter at short-periods equals S_s=1.541 also spectral response acceleration parameter at one-second is S_1=0.887. BSE-1 spectrum (10%/50 years Probability of exceedance) for this site accordance FEMA 356 is shown in fig. 5.1. As an earthquake one ground motion (Imperial Valley) is selected and scaled in three intensities included BSE-1, 0.8 times of BSE-1 and 0.6 times of BSE-1.

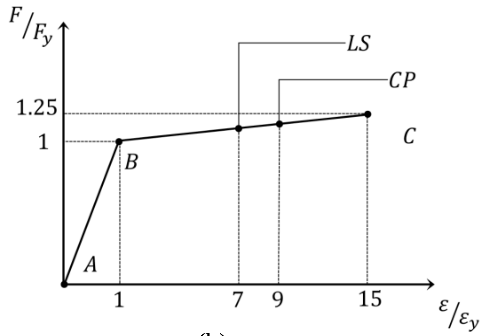
From time history analyses deformed shape of structure has been obtained. The residual displacement of each story for these 3 intensities has been listed in fig. 4.1. These values are measurable in real structures after earthquakes.

In order to make computer models OPENSEES software has been used to structure nonlinear analyses. For modelling of BRB Truss elements and for columns Nonlinear Beam-Column Elements with fiber section have been used. All connections have been assumed to be ideal pin connection. For nonlinear behavior of elements nonlinear material Steel01 has been used that is a bilinear behavior of steel (see fig. 4.1)(Mazzoni, 2005). For BRB elements steel with yield strength F_y=290 MPa and for rest of structure's elements steel with yield strength F_y=345 MPa has been used. For geometry nonlinearity, P-Δ effects are considered and P-δ effects are ignored. All stories have a rigid diaphragm in horizontal

DOF. For each of 3 assumed earthquake one adjusted structure has been built based on residual deformations of structure. Capacity curves of these models are shown in fig. 4.2. a little shifting has occurred in capacity curves for initial P-Δ effects under gravity loads. Based on energy balance concept, target displacements (u_t) of roofs have been obtained. Then structure performance for these target displacements has been checked. In some case braces exceed performance criteria and therefore, they must be replaced. Energy balance method results and point of first exceeded brace of structure are shown in figure 4.3. End of each curve is status that deformation of one brace exceeds from $15\Delta_y$.



(a)



(b)

Residual stories displacement (m)			
Level	BSE-1	0.8 BSE-1	0.6 BSE-1
Story 1	0.035	0.017	0.005
Story 2	0.066	0.033	0.011
Story 3	0.095	0.051	0.021
Story 4	0.123	0.066	0.028
Story 5	0.149	0.080	0.035
Story 6	0.159	0.083	0.036

(c)

Figure 4.1. (a) Configuration of six stories BRBF model. (b) Nonlinear Steel01 material in OPENSEES (c) Residual displacement for each earthquake

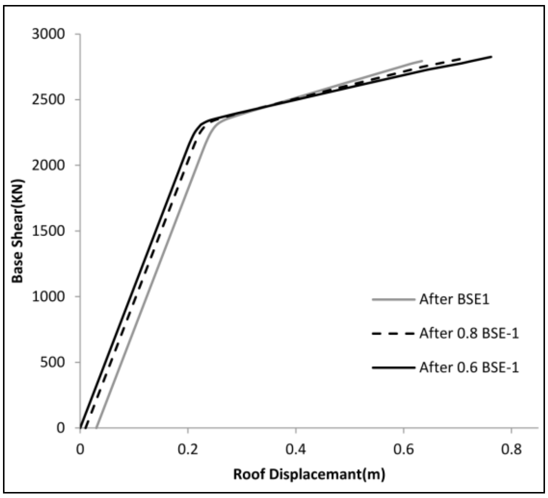


Figure 4.2. Capacity Curves after 3 assumed earthquakes

Results are showing that after a BSE-1 earthquake, BRBs of 5 first stories must be replaced. As well as after a 0.8 BSE-1 earthquake, BRBs of 2 first stories must be replaced but after a 0.6 BSE-1 earthquake, all BRBs have satisfied performance criteria.

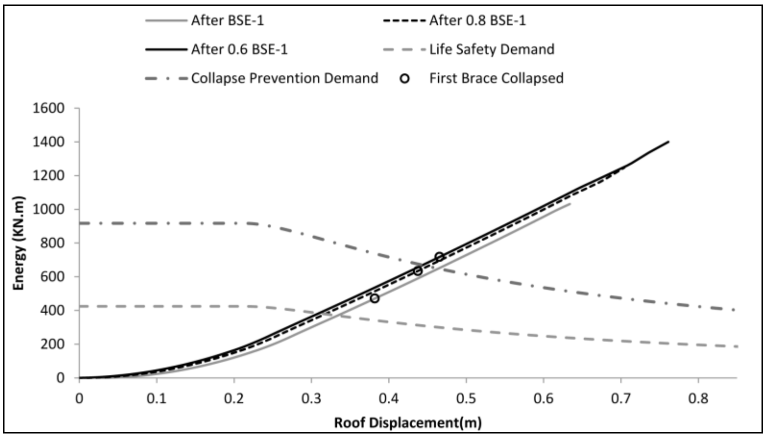
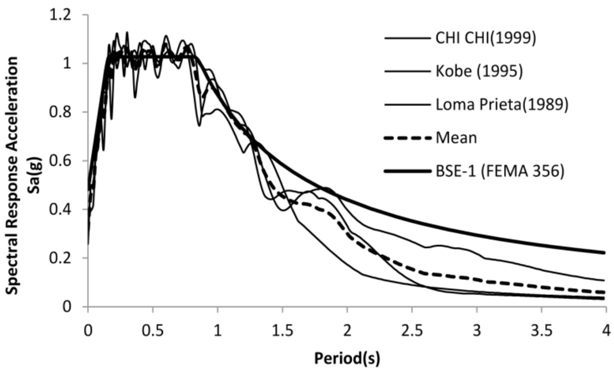


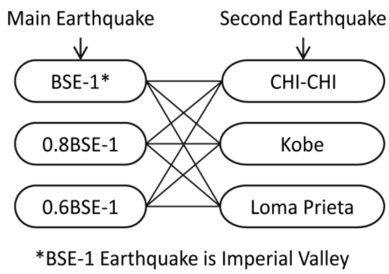
Figure 4.3. Performance evaluation of three adjusted structures.

5. COMPARE BRBS REPLACEMENT WITH NONLINEAR DYNAMIC ANALYSIS

For evaluating expressed method results, consecutive nonlinear dynamic analysis (CNDA) is used. At first a main earthquake (BSE-1, 0.8 BSE-1 or 0.6 BSE-1) and then a series of 3 second earthquakes are applied to structure. The second earthquakes are scaled in BSE-1 spectrum and are shown in fig. 5.1. The result of CNDA and the method presented in this article are tabled in table 5.1. In accordance with table 5.1 the method presented is conservative and number of stories that BRBS must be replaced is more than CNDA.



(a)



(b)

Figure 5.1. (a) Three records scaled in BSE-1 Spectrum as second earthquakes. (b) Consecutive Nonlinear Dynamic Analysis.

Main Earthquake	Second Earthquake	Max. number of replaced stories	
		CNDA	Presented method
BSE-1	CHI CHI(1999)	3	5
	Kobe (1995)		
	Loma Prieta(1989)		
0.8 BSE-1	CHI CHI(1999)	1	2
	Kobe (1995)		
	Loma Prieta(1989)		
0.6 BSE-1	CHI CHI(1999)	0	0
	Kobe (1995)		
	Loma Prieta(1989)		

Table 5.1. Compare number of stories that must be replaced in CNDA and presented method.

Although CNDA is more accurate but it is impossible to find a ground motion record that can produce exact deformations such as deformations that have been occurred in real structure but in this article has been used for making damaged structure for evaluating presented method.

4. CONCLUSION

In this paper a simple Performance-Based procedure for replacement BRBs after earthquakes was presented. In this method, residual displacements of stories are as input data and accordingly, an adjusted model of structure is built included adjusted hinges and global initial P-Δ effects. Then by using energy balance concept structure performance is evaluated and BRBs that exceeded performance criteria will be replaced. Results are showing that this method is a conservative one. Since after earthquake there is not any special information about structure conditions some simplified assumptions are necessary. In addition some side effects such as fatigue capacity and imperfections are neglected. Case study is showing that after an earthquake in BSE-1 hazard level about 80% of BRBs must be replaced that this is showing the importance of rehabilitation after such earthquakes. This rate for the structure after 0.8 BSE-1 is about 30% of BRBs. But in lower intensity of earthquake such as 0.6 BSE-1 this structure does not need any BRB replacement for achieving desired performance.

REFERENCES

El-Bahey, S., Bruneau, M. (2011). Buckling restrained braces as structural fuses for the seismic retrofit of reinforced concrete bridge bents. *Engineering Structures,* **22,** 1052-1061.

FEMA (2000). Prestandard and commentary for the seismic rehabilitation of buildings. Federal Emergency Management Agency,Washington D.C.

Kiggins, S., Uang, C.M. (2006). Reducing residual drift on buckling-restrained braced frames as a dual system. *Engineering Structures,* **28,** 1525-1532.

Kim, J., Choi, H. (2004). Energy-based seismic design of strucures with buckling-restrained braces. *Steel and Composite Structurs,* **4,** 437-452.

Lee, S.S., Goel, S.C. (2001). Performance-Based Design of Steel Moment Frames Using Target Drift and Yield Mechanism. Dept. of Civil and Envr. Eng. University of Michigan.

Leelataviwat, S., Saewon, W., Goel, S.C. (2008). An energy based method for seismic evaluation of structures. *14th World Confrance on Earthquak Engineering.* China.

Liao, W., C. (2010). *Performance-based plastic design of earthquake resistant reinforced concrete moment frames.* Doctor of Philosophy, University of Michigan.

Mahmoudi, M., Zaree, M. (2010). Evaluating response modification factors of concentrically braced steel frames. *Journal of Constructional Steel Research,* **66,** 1196-1204.

Mazzoni, S., Mckenna, F., Fenves, G.L. (2005). OpenSees Command Language Manual.

Naeim, F., Bhatia, H., Lobo, R.M. (2001). Performance Based Seismic Engineering. *In:* Naeim, F. (ed.) *The Seismic Design Handbook.* 2nd Edition ed.: Kluwer Academic Publishers.