US-Taiwan Workshop on Smart Structural Technology for Seismic Hazard Mitigation
Taipei, Taiwan
October 12-14, 2006

Paper NO: 015

RECENT DEVELOPMENT IN PASSIVE SELF-CENTERING DAMPING DEVICE FOR CONCENTRICALLY BRACED FRAME SYSTEMS

Le-Wu Lu[1], Yunfeng Zhang[2], and Songye Zhu[3]

ABSTRACT

Presented in this paper are brief descriptions of a novel type of passive energy dissipation device termed self-centering friction damping brace (SDB) and its application to seismic hazard mitigation of steel concentrically braced framed buildings. The SDB uses superelastic Nitinol wire strands to enable its self-centering mechanism and enhanced energy dissipation capacity is achieved by friction effect over the sliding surfaces of SDB. Unlike conventional passive damping devices, SDB has the potential to minimize the permanent drifts of concentrically braced frames after strong earthquakes and withstand several moderate earthquakes without the need for repair or replacement. Nonlinear time history analysis which involves a 3-story steel framed building subjected to two suites of twenty earthquake ground motions was conducted and the analysis results are presented in this paper.

Keywords: Braced frame, Damping, Friction, Seismic response, Self-centering, Shape memory alloy

INTRODUCTION

Conventionally designed structural systems dissipate energy by connection yielding or damages developed in structural components during earthquakes. Such a seismic design strategy may not be desirable for high seismic regions because of costly repairs required after strong or even moderate earthquakes. After the 1994 Northridge earthquake, growing interests are given to a more logical seismic design approach which involves energy dissipation through supplemental damping system. Using this approach, the main structural system is designed to have little or no damage while the damping devices dissipate energy and can be replaced if damaged during an earthquake. Examples of such energy dissipation device are friction damper (Filiatrault and Cherry 1987), buckling-restrained brace (Uang et al. 2004), metallic yield damper (Tsai and Tsai 1995) and many other types of dampers.

Buckling-restrained braces (BRB), which have been developed to overcome the buckling problem of conventional braces in concentrically braced frames, are capable of yielding in both tension and compression (Sabelli et al. 2003; Uang et al. 2004). Buckling-restrained braced frames (BRBF) has been used extensively for seismic applications in Japan after the 1995 Kobe earthquake and is also gaining popularity in the United States after the 1994 Northridge earthquake. BRBFs are desirable for seismic design and rehabilitation for their superior ductile performance. Nonlinear dynamic analysis by Sabelli et al. (2003) has shown that the behavior of BRBFs is comparable and often better than that

[1] Professor Emeritus, ATLSS Research Center, Lehigh University, Bethlehem, PA, USA; E-mail: lwl0@lehigh.edu
[2] Assistant Professor, ATLSS Research Center, Lehigh University, Bethlehem, PA, USA; E-mail: yuz8@lehigh.edu
[3] Graduate Research Assistant, ATLSS Research Center, Lehigh University, Bethlehem, PA, USA, E-mail: soz2@lehigh.edu

of conventional concentrically braced frames and moment frames. However, several potential problems such as tendency of BRBs to yield even under frequent earthquakes and large residual drifts after strong earthquakes have been identified by a few researchers (Sabelli 2003; Kiggins and Uang 2004). Costly repair after moderate earthquakes might be necessary due to these problems. Recently, an alternative seismic resisting system with self-centering capability has been attracting considerable interests (e.g., Kurama et al. 1999; Lu et al. 2000; Ricles et al. 2001; Christopoulos et al. 2002). A flag-shaped hysteresis loop is typical of such self-centering systems. Self-centering systems have the ability to control damage and to reduce (or even eliminate) residual structural deformation, after strong earthquake events. It is worth noting that residual structural deformation is emphasized as a fundamental complementary parameter in the evaluation of structural (and non-structural) damage in the performance-based seismic design and assessment approach (Pampanin et al. 2003).

Friction damped braced (FDB) frames have been studied by Pall and Marsh (1982), Filiatrault and Cherry (1987), and Aiken et al. (1988). Their results show that properly designed FDB frame can outperform traditional moment frames and cross-braced moment resisting frames. The addition of friction dampers results in significant reduction in inter-story drifts and internal forces. Nims et al. (1993) developed a passive friction-based energy dissipation device termed Energy Dissipating Restraint (EDR), which has a self-centering capability. The EDR would be installed in a building as a part of the bracing system which resists seismically induced lateral forces. Special metals such as superelastic shape memory alloys (SMA) possess the self-centering hysteretic behavior. This paper presents a novel bracing element termed self-centering friction damping brace (SDB) which has a self-centering capability and enhanced energy dissipation capacity through friction. A novel type of concentrically braced frame systems can be established with the use of SDB, which offers a potential solution to the potential problems associated with BRB frames.

DEVICE MECHANICS AND TEST RESULTS

The mechanical configuration of SDB is shown in Fig. 1. Like BRB, SDB would be typically installed in a concentrically braced frame building as part of the bracing system which resists lateral seismic loads. The SDB is comprised of two steel parts that can slide past each other. Superelastic Nitinol wire strands are attached to the two parts using special anchors. In order to increase the friction force over the sliding surface for enhanced energy dissipation, a pre-specified amount of normal force can be applied using the bolts, as shown in Fig. 1.

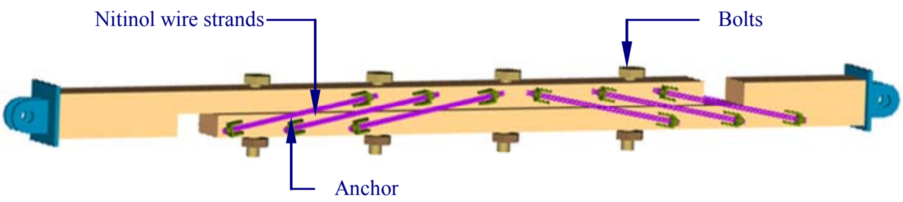

Figure 1. Schematics of the mechanical configuration of SDB

Fig. 2-(a) shows the typical hysteretic behavior of superelastic Nitinol wire strands which contribute to the self-centering capability of SDB. This unique hysteresis is a result of stress-induced phase transformation from austenite to martensite and reverse transformation upon unloading (Grasser and Cozzarelli, 1992). This important characteristic is called superelasticity or pseudoelasticity, which involves certain energy dissipation with zero residual strain upon unloading. Fig. 2-(b) shows the friction force induced hysteresis. By properly adjusting the ratio between the 'yield' strength of Nitinol wire strands and the friction forces, the final combined hysteresis loop exhibits a nearly self-centering behavior, as shown in Fig. 2-(c).

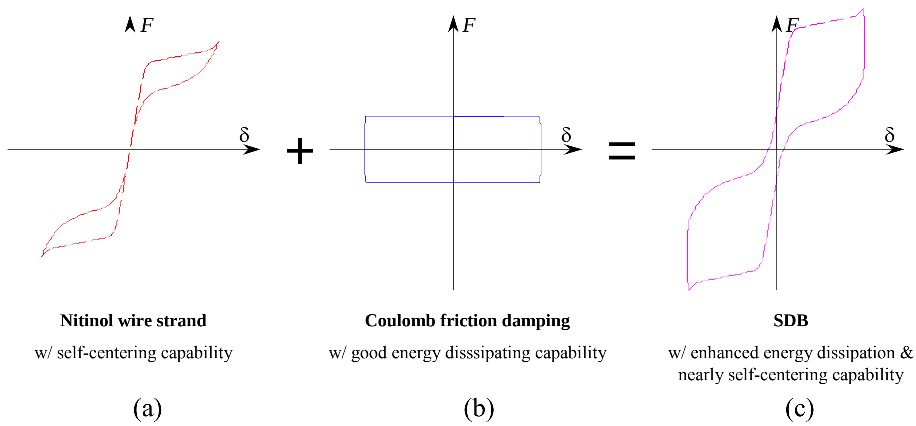

Figure 2. Illustration of the self-centering and energy dissipation mechanism of SDB

Nitinol alloys have an inherent self-centering capability, high ductility and very long fatigue life compared to other SMA materials. For example, the maximum recoverable strain of superelastic Nitinol wires can reach up to 8%. The test conducted by the writers shows that Nitinol wires with a diameter of 0.58 mm can sustain over two thousands load cycles under 8% strains cycles. These superior properties of superelastic Nitinol wires form the physical basis on which SDBs can self-center and can be reused for several strong earthquakes without performance deterioration. The reusability of SDB is very appealing in the sense that it can enhance the robustness of structural system performance during strong aftershocks following a significant earthquake event, thus eliminating the need for unnecessary evacuation or inspection after strong earthquakes.

Figure 3. External view of scaled SDB specimen in an MTS test machine

To validate the concept of SDB, cyclic testing of scaled SDB specimens was conducted. Fig. 3 shows one the scaled SDB specimens under test, which has a length of 2.3 feet. Each wire strand was comprised of ten loops of superleastic Nitinol wires with a diameter of 0.58 mm. The length of the Nitinol wire strands was 254 mm (10 inch). The cyclic test was carried out at room temperature on an MTS servohydraulic test machine and the loading frequency is 2 Hz. Figs. 4-(a) to (c) show the measured hysteretic loops of the SDB specimens with different levels of friction force. The friction force was measured using the same loading protocol for the MTS test machine after removing the Nitinol wires. For the tests corresponding to Figs. 4-(a) and 4-(c), no bolts were used to apply the normal force and lubricant oil was added to the sliding surfaces in SDB in order to minimize the friction force. With increasing level of friction force, the SDB specimens exhibit a hysteresis loop with enhanced energy dissipation capacity (see Figs. 4-(b) and 4-(c)).

It is also seen in Figs. 4-(a) to (c) that the behavior of SDB is almost symmetrical under tension and compression, which is another advantage of SDB derived from its unique mechanical configuration in contrast to directly using SMA bars as bracing members in a concentrically braced frame structure. The unique configuration of SDB enables the direct transfer of applied load to the Nitinol wire strands in tension.

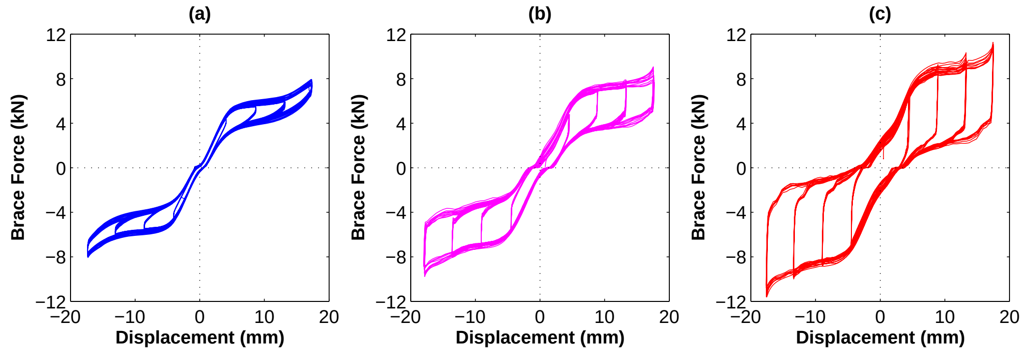

Figure 4. Test results of SDB specimens

COMPARATIVE SEISMIC ANALYSIS OF SDB AND BRB FRAMES

In this study, the 3-story frame structure (model 3vb2) developed by Sabelli et al. (2001, 2003) for a study on BRB frames is selected as the prototype structure for nonlinear dynamic analysis. This 3-story building is designed to be located in downtown Los Angeles with site class D (firm soil). The design of this building follows the FEMA building design criteria, in which a response of modification factor (R) of 8 is employed. Figure 5 shows the typical hysteretic behaviors of a single brace in the 3rd story of the prototype building structures for BRB, SDB and SDB-NF, respectively. Nonlinear time history analysis was carried out using the computer program DRAIN-2DX (Prakash et al. 1993). The time history analysis employs the suites of earthquake ground motions developed previously by Somerville et al. (1997) for use in the FEMA project on steel moment-resisting frames. In this study, the earthquake suites corresponding to downtown Los Angeles, California, were selected for seismic hazard levels corresponding to a 50% and 10% probability of exccedence in a 50 year period, each of which contains 20 records designated as LA01 - LA20 and LA41 - LA60, respectively. These twenty records were derived from fault-parallel and fault-normal orientations of ten earthquake records with adjustment in amplitude and frequency domain. It is worth noting that other researchers also used the same suites of earthquake ground motions in their previous research on BRB frames (e.g., Sabelli 2003; Kiggins and Uang 2004).

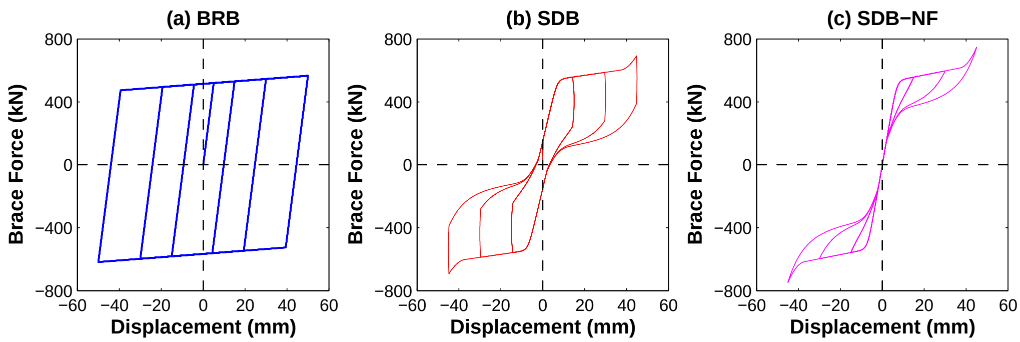

Figure 5. Typical hysteretic behavior of single brace in 3rd story: (a) BRB; (b) SDB; (c) SDB-NF

In the nonlinear time history analysis, only one single braced bay was modeled and analyzed. Thus the seismic mass of each floor was calculated by dividing the total seismic floor masses by the number of braced bays in each principal direction (i.e., ¼ of the total dead load for the 3-story building). All beam-column connections except for those at the roof were modeled as being fixed by considering the effect of attached gusset plates while the ends of all braces were assumed as frictionless pins. Rigid floor diaphragm is assumed for this 3-story building and thus all nodes at the same floor are constrained together in the horizontal direction of the input ground motion. In order to approximately account for the stiffness contribution from all other columns in the unbraced frame, a column running the full height was added to the model. The moment of inertia of this column is equal to 1033 in^4 and its plastic modulus, $Z = 290\ in^3$, which is the same as that in Sabelli (2003). Global P-Δ effect was also considered in the analysis.

Element type 1 in DRAIN-2DX, i.e. the inelastic truss bar element, was used to simulate the hysteretic behavior of BRB. In order to simulate the hysteretic behaviors of SDBs, one new element in DRAIN-2DX was developed in this study, which uses a modified Wilde model (Zhang and Zhu 2006) to describe the superelastic behavior of Nitinol wire strands and consider the friction over the sliding surface of SDB. The parameters of the modified Wilde model are calibrated with the dynamic test data from Nitinol wires of a 0.58 mm diameter. The loading frequency of the cyclic tension test is 2 Hz with 6% strain amplitude, which is believed to be close to the seismic response of the prototype structure.

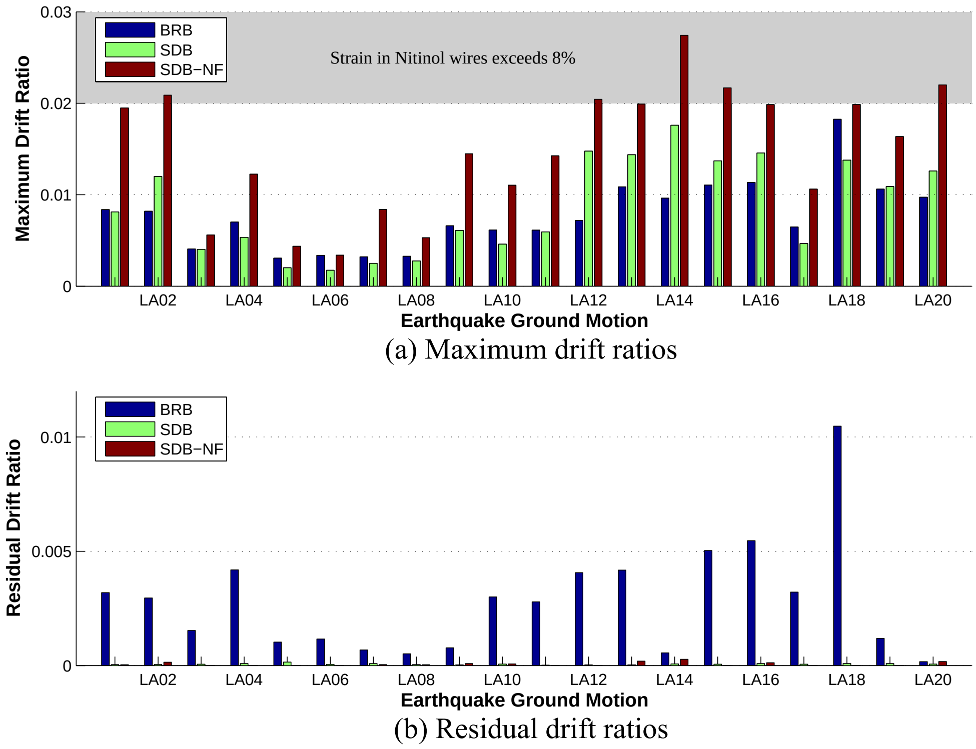

Figure 6. Maximum and residual drift ratios for 3-story buildings

Results and Discussion

Figs. 6 to 7 show the results of a comparative study of the seismic behaviors of BRB and SDB frames under the DBE suite of earthquake ground motions, i.e. with 10% of probability of exceedence in 50 years. Figs. 6-(a) and 6-(b) show the maximum drift ratios and residual drift ratios for the BRB and SDB frames subjected to the DBE suite of earthquake ground motions. SDB-NF represents the case in which SDB braces without friction were used. For the SDB-NF, energy is dissipated only through the hysteretic damping of Nitinol wires which give reduced energy dissipation compared with normal

SDB. The mean values of the maximum drift ratios of BRB, SDB and SDB-NF frames are 0.77%, 0.86% and 1.49% respectively, while the mean residual drift ratios are 0.28% for the BRB frame and almost zero for both the SDB-NF and SDB frames. The large value for the maximum story drift associated with the SDB-NF frame can be explained by the fact that the stiffness and energy dissipation capacity of SDB-NF are smaller than those of corresponding BRB in this study. However, with the increase of energy dissipation and initial stiffness by utilizing the friction effect, SDB frames can achieve a control performance comparable to the BRB frame in terms of peak story drift. More interesting to note is that even with much greater peak drift ratios, SDB-NF frames still have far smaller residual drifts than the BRB frame. This significant reduction of residual drifts in both SDB-NF and SDB frames manifests the benefit due to the unique self-centering characteristic of this new bracing element.

Fig. 7 shows the distribution of the ensemble average of the maximum and residual drift ratios along the height of the 3-story prototype building with either BRBs or SDBs. The ensemble average was calculated based on the twenty earthquake ground motion records in either the DBE suite or the frequent earthquake suite. Figs. 7-(a) and 7-(b) show the statistical results under the design basis earthquakes and frequent earthquakes (i.e. with 50% of probability of exceedence in 50 years) respectively. It is seen that the peak story drifts of the SDB frame were close to that of the BRB frame under both the design basis earthquakes and frequent earthquakes. The SDB frames have minimal residual story drifts under both design basis earthquakes and frequent earthquakes, while for the BRB frame, non-trivial residual story drifts occurred under both earthquake suites. The ensemble average of the residual drift ratios of the BRB frames are about 30% of the peak story drift ratio under both earthquake suites. Even under the frequent earthquakes, the peak strains of the BRBs exceeded its yield strain under fifteen ground motions out of a total of twenty records. This observation confirms the findings by other researchers (e.g., Uang et al. 2004) that BRB tends to yield even under frequent earthquakes.

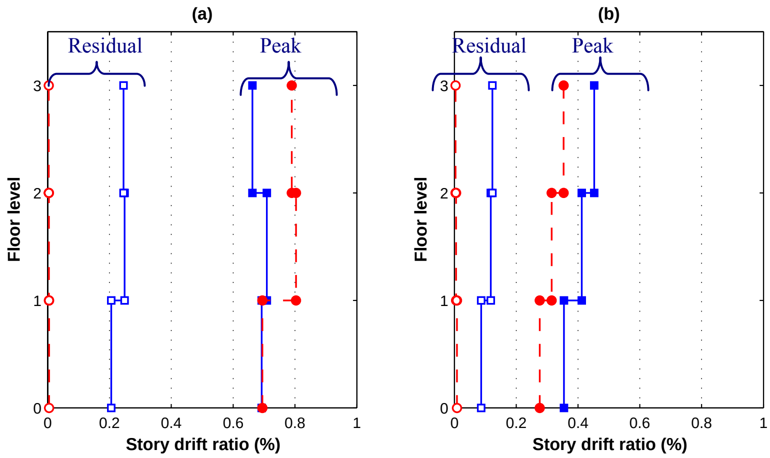

Figure 7. Ensemble average of the peak and residual story drift ratios of the 3-story prototype building: (a) under design basis earthquakes with 10% probability of exceedence in 50 years; (b) under frequent earthquakes with 50% probability of exceedence in 50 years (legend: square = BRB frame, circle = SDB frame)

CONCLUSIONS

The seismic behavior of a novel concentrically braced structural frame system with self-centering capability is presented in this paper. An innovative type of bracing element termed self-centering friction damping brace (SDB) is proposed in this paper, which will be installed to concentrically braced frame buildings as part of the bracing system. The SDBs thus resist the lateral seismic loads in such concentrically braced frame buildings. The mechanical configuration of SDB is described in this paper. In SDB, superelastic Nitinol wire strands are used as core component to provide the self-centering capability while friction damping is utilized for enhanced energy dissipation. By adjusting the ratio between the 'yield' strength of superelastic Nitinol wires and friction force in SDB, hysteresis loops with nearly self-centering behavior can be obtained for SDB. A proof-of-concept test on scaled SDB specimens was carried out in this study and experimental results validate the anticipated hysteretic behavior of SDB. Due to the unique behavior of superelastic Nitinol wires, SDB can be designed to withstand several design basis earthquakes without the need for replacement or repair.

A comparative study of the seismic responses of 3-story nonlinear frames with buckling-restrained braces (BRBs) and SDBs was carried out by using the computer program DRAIN-2DX. Two suites of earthquake ground motions each containing 20 earthquake records were used for frequent and design basis earthquakes respectively. The nonlinear time history analysis result shows that compared with BRB frames, SDB frames have significantly reduced residual story drifts while still capable of achieving a control effect comparable to the BRBs in terms of peak story drifts and acceleration responses. The analysis results also demonstrate the enhanced performance of SDB owing to its friction damping. This study also confirms the findings by other researchers that BRB tends to yield even under frequent earthquakes, which might require costly repair. SDB has the potential to realize damage free structural frame systems under frequent and design basis earthquakes.

ACKNOWLEDGEMENTS

Travel grant received from NSF to attend the US-Taiwan Workshop on Smart Structural Technology for Seismic Hazard Mitigation is gratefully appreciated. The authors are also grateful to the Pennsylvania Infrastructure Technology Alliance and Lehigh University for providing additional financial support for this research. However, the findings, opinions and conclusions expressed in this paper are solely those of the writers and do not necessarily reflect the views of the sponsors.

REFERENCES

Aiken, I.D., Kelly, J.M. and Pall, A.S. (1988) "Seismic response of a nine-story steel frame with friction damped cross-bracing," *Report No. UCB/EERC-88/17*, University of California, Berkeley, CA.

Christopoulos, C., Filiatrault, A., and Folz, B. (2002) "Seismic response of self-centering hysteretic SDOF systems," *Earthquake Engineering and Structural Dynamics*, **31**, 1131–1150.

Filiatrault, A. and Cherry, S. (1987) "Performance evaluation of friction damped braced frames under simulated earthquake loads," *Earthquake Spectra*, 3(1), 57-78.

Kiggins, S. and Uang, C.M. (2004) "Reducing residual drifts in BRBF systems," Proc. of 73rd SEAOC Annual Convention, Sacramento, CA, 481-492.

Kurama, Y., Sause, R., Pessiki, S. and Lu, L.-W. (1999) "Lateral load behavior and seismic design of unbonded post-tensioned precast concrete walls," *ACI Structural Journal*, **96**(4), 622–632.

Lu, L.-W., Sause, R., Ricles, J.M., and Pessiki, S.P. (2001). "High Performance, Cost Effective Structural Systems for Seismic-Resistant Buildings." Earthquake Engineering Frontiers in the New Millennium, Proceedings, U.S.-China Millennium Symposium on Earthquake Engineering, pp. 367-370.

Nims, D.K., Ritcher, P.J., and Bachman, R.E. (1993). "The use of the energy dissipating restraint for seismic hazard mitigation," Earthquake Spectra, **9**(3): 467-489.

Pall, A.S. and Marsh, C. (1982) "Response of friction damped braced frames," *J. Struct. Div., ASCE*, **108**(ST6), 1313-1323.

Pampanin, S., Christopoulos, C. and Priestley M.J.N. (2003) "Performance-based seismic response of frame structures including residual deformations, Part II: multidegree-of-freedom systems," Journal of Earthquake Engineering, **7**(1): 119–147

Prakash, V., Powell, G.H., and Campbell, S. (1993). "DRAIN-2DX: Base Program and User Guide," *Report No. UCB/SES-93/17*, University of California, Berkeley, CA.

Ricles, J.M., Sause, R., Garlock, M.M., and Zhao, C. (2001) "Post-tensioned seismic-resistant connections for steel frames," *Journal of Structural Engineering*, **127**(2): 113-121.

Sabelli, R. (2001) “Research on improving the design and analysis of earthquake-resistant steel-braced frames,” The 2000 NEHRP Professional Fellowship Report, EERI, Oakland, CA.

Sabelli, R., Mahin, S.A., and Chang, C., (2003) “Seismic demands on steel-braced buildings with buckling-restrained braces,” *Engineering Structures*, **25**, 655-666.

Sommerville, P., et al. (1997) “Development of ground motion time histories for Phase 2 of the FEAM/SAC steel project,” *SAC Background document SAC/BD-91/04*, SAC joint venture, Sacramento, California.

Tsai, C.S., and Tsai, K.C. (1995) “TPEA device as seismic damper for high-rise buildings,” ASCE Journal of Engineering Mechanics, **121**(10): 1075-1081.

Uang, C.M., Nakashima, M., and Tsai, K.C., (2004) “Research and application of buckling-restrained braced frames,” *International Journal of Steel Structures*, **4**, 301-313.

Wilde, K., Gardoni, P., and Fujino, Y. (2000). “Base isolation system with shape memory alloy device for elevated highway bridges,” *Eng. Struct*., **22**(3), 222-229.

Zhang, Y. and Zhu, S. (2006) “Seismic response control of building structures with superelastic shape memory alloy wire Damper,” *ASCE Journal of Engineering Mechanics*, in review.