International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol.2, Issue.1, pp-134-140 ISSN: 2249-6645

Seismic Performance Enhancement Methodology for Framed Structures using Supplemental Damping

K. Sathish Kumar[1], R. Sundararajan[2], C. Antony Jeyasehar [3], T. Radha Krishnan[4] & K. Muthumani [5]

[1] (Senior Principal Scientist, ASTaR Laboratory, CSIR-Structural Engineering Research Centre, Taramani, Chennai, India)
[2] (Professor, Department of Structural Engineering, Government College of Technology, Coimbatore, India)
[3] (Professor, Department of Civil and Structural Engineering, Annamalai University, Annamalai Nagar, India)
[4] (M.E., Student, Department of Structural Engineering, Government College of Technology, Coimbatore, India)
[5] (Chief Scientist, ASTaR Laboratory, CSIR-Structural Engineering Research Centre, Taramani, Chennai, India)

Abstract

Supplemental damping through passive energy dissipation (PED) devices is often used for enhancing the seismic performance of a seismically deficient structure to reduce the seismic response under earthquake loading. Such PED devices are normally incorporated within the frame structure between adjacent floors through different bracing schemes like diagonal and chevron, so that they efficiently enhance the overall energy dissipation ability of the seismically deficient frame structure in the loading direction. These PED devices function based on the large and stable energy dissipation obtained using energy dissipation mechanisms like visco-elastic and elasto-plastic. This paper presents a methodology based on the direct displacement based design (DBD) for designing PED devices for providing supplemental damping to enhance the energy dissipation ability of multi-storey frames subjected to earthquake loading.

Keywords - Seismic performance enhancement, seismic retrofitting, displacement based design, supplemental damping, passive energy dissipation device

1. INTRODUCTION

Recent damaging earthquakes provided powerful reminders of how vulnerable we all are to the forces of nature. Even in an advanced industrial nation, our built environment is still quite susceptible to natural disasters. Consequently, one of the principal current challenges in structural engineering concerns the development of innovative design concepts to better protect structures, along with their occupants and contents, from the damaging effects of destructive environmental forces due to earthquakes. The traditional approach to seismic design has been based on providing a combination of strength and ductility to resist the imposed loads. For major earthquakes, the structural design engineer relies upon the inherent ductility of structure to prevent catastrophic failure, while accepting a certain level of damage. In this traditional seismic design, acceptable performance of a structure during an earthquake is based on the lateral force resisting framed system being able to absorb and dissipate energy in a stable manner for a large number of cycles. Energy dissipation occurs in specially detailed ductile plastic hinge regions of beams and column bases which also form part of the gravity load carrying system. Plastic hinges are regions of concentrated damage to the gravity frame which often is irreparable. Nevertheless, this design approach is acceptable because of economic considerations provided, of course, that structural collapse is prevented and life safety is ensured. Sometimes, situations exist in which this traditional seismic design approach is not applicable. When a structure must remain functional after an earthquake, as the case of lifeline structures, the conventional seismic design approach is inappropriate. For such cases, the structure may be designed with sufficient strength so that inelastic action is either prevented or is minimal; an approach that is very costly. Moreover, in such structures, special precautions need to be taken in safeguarding against damage or failure of important secondary systems which are needed for continuing serviceability. But this draw back can be mitigated, and perhaps eliminated, if the earthquake-induced energy is dissipated in supplemental damping devices placed in parallel with the gravity load resisting system. The new approach for improving seismic performance and damage control is that of passive energy dissipation (PED) systems. This strategy is attractive for two primary reasons:

1. Damage due to the gravity load resisting system is substantially reduced, leading to major reduction in post earthquake repair costs.
2. Earthquake damaged PED devices can be easily replaced without the need to shore the gravity framing.

Alternate seismic performance enhancement strategies [1] have been developed which incorporate earthquake protective systems in the structure. In these systems, mechanical devices are incorporated into the frame of the structure to dissipate energy throughout the height of the structure. The means by which energy is dissipated is either yielding of mild steel, sliding friction, motion of a piston or a plate within a viscous fluid, orifice action of fluid or visco-elastic action in polymeric materials. In addition to increasing the energy dissipation capacity per unit drift of a structure, some energy dissipation systems also increase the strength and stiffness. Such systems include the following types of energy dissipation mechanisms: yielding, extrusion, friction, viscous and visco-elastic action.

2. MECHANISM OF SUPPLEMENTAL DAMPING

Fig. 1(a) and Fig. 1(b) show the pushover curves of a linearly elastic frame and yielding frame which is essentially a plot of base shear vs. top floor displacement. Similarly, the corresponding force displacement hysteretic loops depict linear behavior and limited ability to absorb energy.

Consider the case when energy-dissipating devices are added to the frame, it is assumed that the connection details of the devices are such that neither inelastic action nor damage occurs in the frame at the points of attachment during seismic excitation. It is also assumed that the design of the energy dissipation system is such that it functions properly and dissipates energy throughout the height of the frame. The ability of the frame to dissipate energy is substantially increased as demonstrated in the force-displacement hysteretic loops of the frame. Accordingly, the frame undergoes considerably reduced amplitude of vibration in comparison to the frame without the energy dissipation system under the same earthquake motion. While the energy dissipation system can achieve a considerable reduction in the displacement response, it can also achieve a reduction in the total force exerted on the structure. In general, reduction in force will not be as much as reduction in displacement which is due to the increased strength or increased stiffness provided by the energy dissipation system. Comparable reductions in displacement and force can be achieved with systems that do not increase the strength or stiffness of the structure to which they are attached.

3. MODELING OF PED DEVICES

For analysis of structures with PED devices, various mathematical modeling techniques have been developed. Various models with increased complexity are reviewed in Reinhorn et al., (1995) [2] for PED devices of viscous type. Constantinou and Symans (1993) [3] showed that the Maxwell model is adequate to capture the frequency dependence of the viscous PED device. It is also shown that, below a cut off frequency of approximately 4 Hz, the model can be further simplified into a purely viscous dashpot model. It is stated in FEMA-273 [4] and FEMA-274 [5] that the damping force of a viscous PED device can be modeled to be proportional to the velocity with a constant exponent ranging between 0.2 and 2.0. In preliminary analysis and design stages, the velocity exponent of 1.0 is recommended for simplicity. In this study, based on those references, the behavior of viscous PED device is modeled by a linear dashpot.

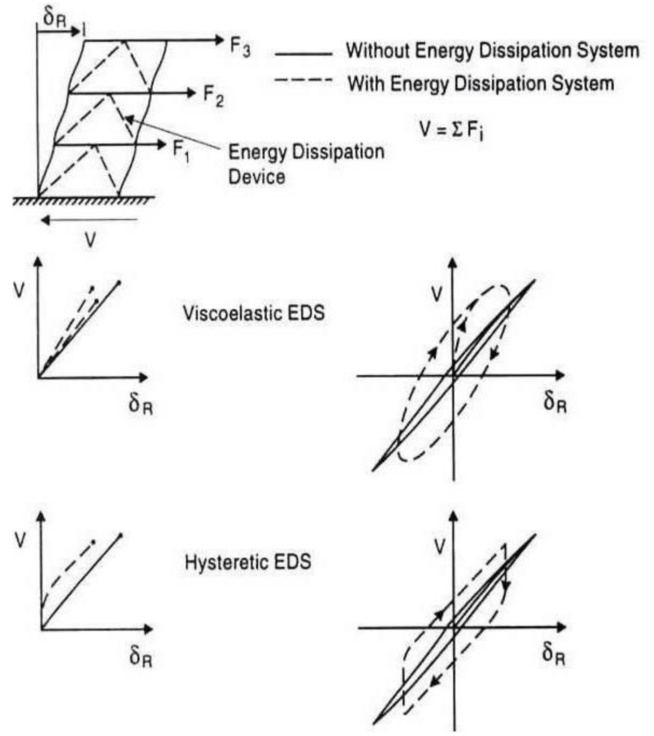

Fig.1 (a) Pushover curves and force-displacement hysteretic curves of an elastic structure without and with passive energy dissipation devices

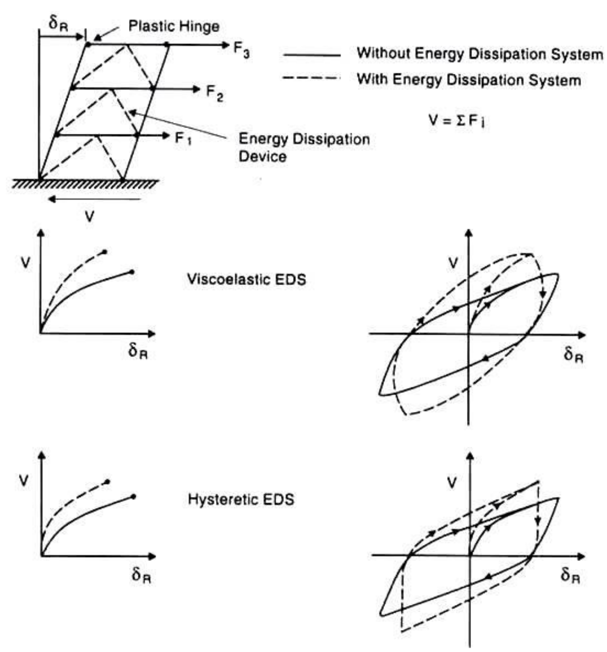

Fig.1 (b) Pushover curves and force-displacement hysteretic curves of a yielding structure having proper plastic hinge formation, without and with passive energy dissipation devices

A typical visco-elastic PED device consists of thin layers of visco-elastic material bonded between steel plates. In practice, the dynamic behavior of visco-elastic PED device is generally represented by a spring and a dashpot connected in parallel [6]. For the linear spring-dashpot representation of the visco-elastic PED device, the stiffness K_d and the damping coefficient C_d are obtained as follows:

$$K_d = \frac{G'(\omega)A}{t}$$
$$C_d = \frac{G''(\omega)A}{\omega t} \qquad (1)$$

Where, $G'(\omega)$ and $G''(\omega)$ are the storage shear modulus and loss shear modulus respectively; A and t are total shear area and the thickness of the material respectively; and ω is forcing frequency for which the fundamental natural frequency of the structure is generally utilized in time domain analysis. With this spring-damper idealization, the dynamic system matrices of the structure with added visco-elastic PED devices can be constructed by superposing the damper properties to the stiffness and damping matrices of the structure. Fig. 2 represents the mathematical models of viscous and visco-elastic PED devices employed in this study.

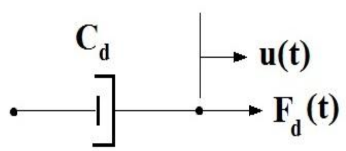

Fig. 2(a) Mathematical model representing viscous PED device

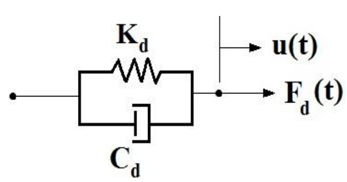

Fig. 2(b) Mathematical model representing visco-elastic PED device

4. PERFORMANCE EVALUATION USING DISPLACEMENT SPECTRUM AND CAPACITY CURVE

The direct displacement based design (DBD), which focuses on displacement as the key design parameter, is considered to be an effective method for implementing performance based seismic design utilizing deformation capacity and ductile detailing standards. In the present study, the general procedure of the DBD documented in the SEAOC Blue Book [7] is applied in reverse order for evaluation of seismic performance of an existing structure. In principle, the proposed analysis procedures are similar to the capacity spectrum method [5],[8],[9] in that performance point is determined as a location where the displacements demand of the earthquake becomes equal to the plastic deformation capacity of the structure. The difference is on the use of displacement spectrum instead of the so called acceleration displacement response spectrum (ADRS). Therefore, the extra work required for transforming the capacity and demand curves to ADRS format can be avoided. Although this may not be a significant improvement, it has the advantage of maintaining consistence with the proposed design procedure for supplemental dampers. Two nonlinear static analysis procedures, the step by step and the graphical procedure, which correspond to the nonlinear static procedures A and B of ATC-40 [8] respectively, are proposed for seismic performance evaluation of structures (without PED devices). The two procedures are summarized as in the following sub-sections:

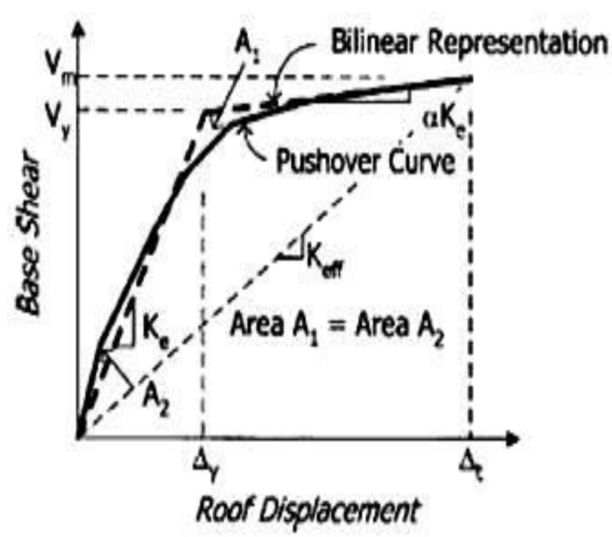

Fig. 3 Bilinear representation of a capacity (pushover) curve

4.1 Step by step procedure

1. Obtain base shear versus roof storey displacement capacity curve for the frame structure from pushover analysis.
2. Approximate the capacity curve by bilinear lines based on equal energy concept (area A_1 = area A_2), and determine the quantities such as effective elastic stiffness K_e, elastic natural period T_e, base shear at yield V_y, yield displacement Δ_y and post-yield stiffness ratio α (Fig.3).

3. Transform the roof storey displacement coordinate into pseudo-displacement coordinate S_d using the following relation:

$$S_d = \frac{\Delta_R}{\Gamma \phi_R} \tag{2}$$

Where, Δ_R is the roof displacement and Γ and ϕ_R is the modal participation factor and the roof storey component of the fundamental mode respectively. This process corresponds to the transformation of the structure into an equivalent single degree of freedom (SDOF) structure.

4. Assume the first trial value for the maximum displacement S_{dm} of the equivalent structure, and determine the ductility factor $\mu = S_{dm}/S_{dy}$. The equivalent damping ratio ξ_{eq} can be obtained as:

$$\xi_{eq} = \frac{2(\mu-1)(1-\alpha)}{\pi\mu(1+\alpha\mu-\alpha)} \tag{3}$$

Then, the effective damping for the structure can be obtained as the sum of the equivalent damping and the inherent damping of the structure:

$$\xi_{eff} = \xi_{eq} + \xi_i \tag{4}$$

Where, ξ_i is the inherent damping for which 5% of critical damping is generally utilized. Also, the effective period T_{eff} corresponding to the maximum displacement can be obtained as:

$$T_{eff} = T_e \sqrt{\frac{\mu}{1+\alpha\mu-\alpha}} \tag{5}$$

Where, T_e is the fundamental period of the structure.

5. Construct the displacement response spectrum for design earthquake using the effective damping obtained in the previous step, and read from the spectrum the next trial value for the maximum displacement S_{dm} corresponding to the effective period T_{eff}.
6. Repeat the process from step 4 using the maximum displacement computed in the above step. Once the maximum displacement S_{dm} converges, then convert it into the maximum roof displacement using equation 2.
7. Carry out pushover analysis until the roof displacement reaches the maximum value computed above to estimate the maximum inter-storey drifts.

4.2 Graphical procedure

1. Steps 1 & 2: The same as those of the step by step procedure.
2. Step 3: Draw displacement response spectra with various damping ratios.
3. Step 4: For a series of ductility ratios, obtain maximum displacements ($S_{dm} = \mu \cdot S_{dy}$), effective periods $T_{eff}(\mu)$ [Eq.5] and effective damping ratios (ξ_{eff}) [equations.3 and 4].
4. Step 5: Find out the point at which the effective damping ratio corresponding to a ductility ratio, obtain in step 4, is equal to the equivalent damping ratio of a displacement spectrum crossing the point [$T_{eff}(\mu)$, $S_{dm}(\mu)$].
5. Step 6: Convert the maximum displacement computed in the above step into the maximum roof displacement, and carry out pushover analysis until the roof displacement reaches the maximum value computed above to estimate the maximum inter-storey drifts.

5. DESIGN PROCEDURE FOR PED DEVICES

If the maximum storey drift of a structure subjected to a code-specified earthquake load exceeds the desired performance level, the structure needs to be retrofitted. Among the various methods for seismic retrofit, this study focuses on increasing damping to decrease earthquake induced structural responses. To this end, a procedure for estimating the amount of supplemental damping required to satisfy the given performance objective is proposed. The basic idea is to compute the required damping from the difference between the total effective damping needed to meet the target displacement and the equivalent damping provided by the structure at the target displacement.

5.1 Required damping to meet target displacement

The damping ratio of the displacement response spectrum that intersects the point of the target displacement S_{dt} on the displacement ordinate (vertical axis) and the effective period T_{eff} on the period ordinate (horizontal axis) corresponds to the total effective damping ξ_{eff} for the structure to retain to meet the performance objective. For structure with supplemental dampers, the total effective damping is composed of the three components: inherent viscous damping ξ_i, equivalent damping of the structure contributed from inelastic deformation of the structural members ξ_{eq} and the damping required to be added by the PED devices ξ_d. The equivalent damping of the structure is obtained from the following equations [4]:

$$\xi_{eq} = \frac{1}{4\pi}\frac{E_{DS}}{E_S} = \frac{V_y S_{dt} - S_{dy} V_t}{\pi V_t S_{dt}} \tag{6a}$$

for Viscous PED device

$$\xi_{eq} = \frac{V_{yd} S_{dt} - S_{dy} V_{td}}{\pi V_{td} S_{dt}} \tag{6b}$$

for Visco-elastic PED devices

Where, $V_{yd} = V_y + K_d S_{dy}$, $V_{td} = V_t + K_d S_{dt}$ and E_s and E_{DS} are the stored potential energy in the structure and the energy dissipated by hysteretic behavior of the structural members in the retrofitted structure respectively. Tsopelas et al., (1997) [10] provides the contribution of the added damping to the total effective damping as $(\xi_d.\ T_{eff})/T_e$, where ξ_d is the supplemental damping ratio. Then the required supplemental damping can be computed from the following equation:

$$\xi_d = (\xi_{eff} - \xi_{eq} - \xi_i)\frac{T_e}{T_{eff}} \tag{7}$$

Where, the total effective damping and the equivalent damping can be obtained from the displacement response spectrum and from equation 6 respectively.

5.2 Storey-wise distribution of PED devices

In multi-storey frame structures, the supplemental damping computed in the equivalent SDOF system using equation 7 should be distributed throughout the stories of the original structure in such a way that the damping ratio for the fundamental mode becomes the required supplemental damping ξ_d. For this purpose, the expression for equivalent damping (equation 6) is used again except that the energy dissipated by the PED device E_{DV} is used in the numerator instead of E_{DS}

$$\xi_{eq} = \frac{1}{4\pi}\frac{E_{DV}}{E_S} \tag{8}$$

If the PED devices are placed as diagonal members with the inclination θ, then, the energy dissipated by the PED devices can be expressed as follows [4]:

$$E_{DV} = \frac{2\pi^2}{T_{eff.d}} \sum_{i=1}^{N} C_{di} \cos^2\theta_i (\Delta_i - \Delta_{i-1})^2 \tag{9}$$

Where, $T_{eff.d}$ is the secant period of the retrofitted structure; C_{di} and Δ_i are the damping coefficient and the maximum lateral displacement of the i^{th} storey respectively, and N is the number of storey. The potential energy stored in the multi-storey structure can be expressed as follows:

$$E_S = \frac{2\pi^2}{T_{eff.d}} \sum_{i=1}^{N} m_i \Delta_i^2 \tag{10}$$

$$T_{eff.d} = 2\pi \sqrt{\frac{M^* S_{dt}}{V_y(1+\alpha\mu-\alpha)}} \tag{11a}$$

for Viscous PED devices

$$T_{eff.d} = 2\pi \sqrt{\frac{M^* S_{dt}}{V_y(1+\alpha\mu-\alpha) + K_d S_{dt}}} \tag{11b}$$

for Visco-elastic PED devices

Where, M^* is the effective modal mass and m_i is the mass of the i^{th} storey. By substituting equation 9 and 10 into equation 8, the damping ratio contributed from the PED devices can be expressed as:

$$\xi_d = \frac{1}{4\pi}\frac{T_{eff.d}\sum_{i=1}^{N} C_{di}\cos^2\theta_i(\Delta_i - \Delta_{i-1})^2}{\sum_{i-1}^{N} m_i \Delta_i^2} \tag{12}$$

In equation 12, the left hand side of the equation ξ_d is obtained from equation 7 in the equivalent SDOF system. For viscous device, the damping coefficient of the damper device in the i^{th} storey C_{di} can be determined in equation 12, whereas for visco-elastic device, both C_{di} and K_{di} are the variables that should be determined. This can be done by using the relation $K_d = (G'/G'')\omega.C_d$ obtained from equation 1. The simplest case is to assume that the PED devices in all storeys have the same capacity, and the damping coefficient in this case can be obtained from equation 12 as:

$$C_d = \frac{1}{4\pi}\frac{4\pi\xi_d \sum_{i=1}^{N} m_i \Delta^2{}_i}{T_{eff,d}\sum_{i=1}^{N}\cos^2\theta_i(\Delta_i - \Delta_{i-1})^2} \tag{13}$$

In this stage, however, the maximum storey displacements, except for the top-storey displacement given as performance limit state, are known. Therefore, the configuration for lateral storey drifts Δ_i needs to be assumed in equations 12 and 13. A simple case is to assume that the maximum storey drifts are proportional to the fundamental mode shape or to the pushover curve. The storey-wise distribution pattern for the PED devices also needs to be assumed. For viscous dampers, the design process ends here. However, for PED devices with stiffness such as visco-elastic or hysteretic dampers, iteration is required, because the added PED devices increase system stiffness. In that case, the capacity curve of the system needs to be redrawn considering added PED devices, and the process is repeated until convergence.

6. DESIGN PROCEDURE FOR PED DEVICE SCHEME

The proposed procedure to design supplemental dampers for performance based seismic retrofit of existing structures can be summarized in the following steps:

1. Carry out eigen value analysis of the structure to obtain natural periods and mode shapes. Using the mode shapes, perform pushover analysis to obtain top storey versus base shear curve, and transform the pushover curve into a capacity curve using equation 2. Idealize the curve into a bilinear shape, and read the yield displacement S_{dy}.

2. Decide a desired target roof displacement, and transform it into the target value in the equivalent SDOF system S_{dt}. Obtain ductility ratio $\mu S_{dt}/S_{dy}$, the effective period T_{eff} (equation 5) and the equivalent damping ξ_{eq} (equation 6) at the target displacement.

3. Find out the effective damping ratio corresponding to the displacement response spectrum that crosses the point of the target displacement and the effective period. This corresponds to the total demand on damping imposed by the earthquake. It would be more convenient to start the procedure with response spectra with various damping ratios.

4. Compute the required damping for supplemental dampers from equation 7.

5. The required damping is distributed throughout the storeys using Equation 12. The size of PED device in each storey is designed based on the required damping allocated to the storey.

6. For structures retrofitted with visco-elastic PED devices, carry out eigen value analysis and redraw the capacity curve of the structure using the newly obtained mode shape, and repeat step 1 until convergence.

7. Check whether the structural members, especially columns, can resist the additional axial and shear forces imposed by PED devices.

7. SUMMARY AND CONCLUSIONS

The general procedure of the direct displacement based design (DBD) documented in the SEAOC Blue Book is applied in reverse order for evaluating the seismic performance of an existing structure. Based on which a methodology is presented for designing PED devices of viscous and visco-elastic types for providing supplemental damping to enhance the energy dissipation ability of multi-storey frames subjected to earthquake loading.

ACKNOWLEDGEMENT

The authors wish to express their deep appreciation to Director, CSIR-SERC, Chennai, for the support and encouragement provided in carrying out the above research work and for the kind permission to publish the paper in the International Journal of Modern Engineering and Research.

REFERENCES

[1] J.M. Kelly, R.I. Skinner, and A.J Heine, Mechanism of Energy Absorption in Special Devices for Use in Earthquake Resistant Structures, *Bull, N.Z., Soc. Earthquake Engineering, 5(3)*, 1972, 63-88.

[2] A.M. Reinhorn, C. Lie, and M.C. Constantinou, *Experimental and Analytical Investigation of Seismic Retrofit of Structures with Supplemental Damping, Part I: Fluid Viscous Damping Devices* (Technical Report, NCEER-95-0001.National Center for Earthquake Engineering Research, Buffalo, New York, 1995).

[3] M.C Constantinou, and M.D. Syman, Experimental Study of Seismic Response of Buildings with Supplemental Fluid Dampers, *Struct. Des. Tall Buildings, 2(2)*, 1993, 93-132.

[4] Federal Emergency Management Agency (FEMA), *NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA-27* (prepared by the Applied Technology Council for the Building Seismic Safety Council, Washington, D.C.,1997a).

[5] Federal Emergency Management Agency (FEMA), *NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings, FEMA-274* (prepared by the Applied Technology Council for the Building Seismic Safety Council, Washington, D.C. 1997b).

[6] T.T. Soong, and G.F. Dargus, *Passive Energy Dissipation Systems in Structural Engineering* (Wiley, New York, 1997).

[7] Structural Engineers Association of California (SEAOC), *Recommended Lateral Force Requirements and Commentary* (Appendix I, Sacramento, California, 1999).

[8] Applied Technology Council (ATC), *Seismic Evaluation and Retrofit of Concrete Buildings*, (ATC-40, Redwood City, California, 1996).

[9] S.A. Freeman, Development and Use of Capacity Spectrum Method, *Proceedings of 6th National Conference on Earthquake Engineering*, Seatle, 1998.

[10] P. Tsopelas, M.C. Constantinou, C.A. Kircher, and A.S. Whittaker, *Evaluation of Simplified Method of Analysis for Yielding Structures* (Technical Report: NCEER-97-0012, National Center for Earthquake Engineering Research, State University of New York at Buffalo, Buffalo, New York. 1997).