Reliability Analysis of the Steel Moment-Resisting frame Equipped with Tuned Mass Damper under Earthquake Excitation

F. Nateghi-Alahi & K. Tarbali
International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran

15 WCEE
LISBOA 2012

SUMMARY:

In order to evaluate the efficiency of vibration-absorbing equipment in reducing the response of the building structures during earthquake, reliability analysis-based evaluation of a steel moment-resisting frame has been carried out. The structure has been equipped with tuned mass damper (TMD) in the top story, which is tuned to the first mode of vibration of the structure. In order to consider the uncertainty in the capacity and stiffness of the load-carrying elements, probabilistic model of the structure has been developed. Monte Carlo simulation has been used on the maximum inter-story drift ratio of each story to calculate the failure probability of the structure. The comparison between the response of the structure, with and without TMD, indicates that the effectiveness of the TMD is dependent on the frequency content of the seismic loading, rather than on the uncertainty in the dynamic characteristics of the structure.

Keywords: reliability analysis; TMD; steel structure; story drift; probability of failure;

1. INTRODUCTION

Seismic assessment of a structure requires accurate modelling of the parameters that have fundamental effect on the performance of the structure. Since the characteristics properties of a structure and the effect of the surrounding environment of the structure are not deterministic in nature, probabilistic evaluation is a proper approach to find the variability of the performance of the structure during the earthquake. The difference between the assumptions that are made in deterministic model and the actual response of the structure could root from inherited uncertainty in material properties, construction errors, loading uncertainty, and the faulty assumptions during the analysis. Advancements in computational capability have provided an opportunity to consider these uncertainties in analysis of the engineering structures and again more knowledge about the probabilistic behaviour of them (Wen, Ellingwood, Veneziano and Bracci, 2003).

In this paper, in order to investigate the effectiveness of the vibration-absorbing devices on the reliability of the steel moment-resisting frames under seismic loads, a tuned mass damper (TMD) has been installed on the top story of a 9-story building frame. The Monte Carlo simulation technique has been used to simulate the variability of the response of the structure with and without the TMD. Maximum inter-story drift of each story has been used as the characteristics response to evaluate the failure of each story of the structure. The uncertainty in the capacity and the stiffness of the structural elements are modeled through probabilistic fiber-discretized model. The variability in the seismic load has been considered by variability in the peak ground acceleration (PGA) of the selected records.

2. RELIABILITY ANALYSIS

The availability of the sophisticated computational tools provides the engineering society with the opportunity of estimating the performance of structures under uncertain environment. The capacity and stiffness of the load carrying elements and the effects of the surrounding environment (applied loads and boundary conditions) on the structure are not deterministic in reality. Therefore, in order to gain an accurate estimate on performance of the structure, the uncertainty inherited in these parameters should be accommodated in the analysis of the structural system. In this regard, accurate performance estimation of the structure should be carried out with respect to these uncertainties. In the context of the reliability analysis, failure probability of a structural system under randomness of its characteristic parameters and applied loads could be expressed mathematically in its simplest form as in Eqn. 2.1. (Ditlevsen and Madsen, 1996).

$$p_f = \int_{g(\mathbf{X}) \leq 0} f(\mathbf{X})\, d\mathbf{X} \tag{2.1}$$

Where, p_f is the probability of failure, X is the vector of considered random variables, $f(\mathrm{X})$ is the joint probability density function of the random variables, and $g(\mathrm{X})$ is the performance function which is used to define the state of the system. In structural reliability analysis, the performance function is defined in its simplest form as: *performance = threshold – response of the structure*. Threshold is a predefined constant value and the structure is considered safe if the response of the structure does not exceed this value. The limit in which the performance function is equal to zero ($g(\mathrm{X}) = 0$) is called limit state function (LSF). The LSF separates the space of the random variables into two domains: safe and failure domain.

Since calculating the integral in Eqn. 2.1. is not feasible for most of real-world structural systems (Haukaas and Der Kiureghian, 2004), simulation techniques such as Monte Carlo simulation (MCS) could be used to find the solution for structural reliability problems. The idea of using simulation techniques to solve the reliability analysis problems comes from the fact that any given integral could be solved by generating the sufficient amount of random samples (Ditlevsen and Madsen, 1996)

The simulation techniques are highly efficient methods to compute the reliability of complex engineering structures. The efficacy of the simulation method is not dependant on the number of the considered random variables (RVs) in the simulation. Also the statistical correlation between the RVs or the type of the distribution of each RV has no influence on the accuracy or the efficiency of the simulation methods such as Monte Carlo simulation. However, in order to maintain an acceptable accuracy, these methods involve obtaining hundreds of samples for the desired responses of the structure, (Ditlevsen and Madsen, 1996; Nowak and Collins, 2000; Baecher and Christian, 2003). One of the pitfalls of the simulation techniques is that the number of the simulations is dependent on the failure probability itself. The number of the simulation required to maintain the accuracy of the obtained failure probability could be found by Eqn. 2.2., (Soong and Grigoriu, 1993; Nowak and Collins, 2000):

$$N = \frac{1 - p_f}{\mathrm{C.O.V}^2[p_f].(p_f)} \tag{2.2}$$

Where $\mathrm{C.O.V}\ [p_f]$ is the coefficient of variation of the failure probability (p_f), which indicates the accuracy of the MCS results. Based on Eqn. 2.2., in order to calculate a small failure probability large number of samples are required. Since the designed building structures are supposed to enter the nonlinear phase and dissipate the applied excitation of the earthquake by plastic deformation, in order to calculate the failure probability of a structure in near-to-collapse state, rational number of samples could practically help the analyst to have a prior idea about the failure probability. Based on Eqn. 2.2., for probability of failure equal to 28%, 1000 simulations would result in 5% accuracy and for the failure probability greater than 28%, higher accuracy will be secured.

3. TUNED MASS DAMPER

In order to investigate the effectiveness of the vibration-absorbing devices on reliability of steel moment-resisting frames under seismic loads, a tuned mass damper (TMD) has been installed on the top story of a 9-story building frame. TMD is composed of a mass, a spring, and a viscous damper, which is added to the primary structure to absorb the energy of the applied excitation. It may cause reduction in the damage of the structural elements and improve the performance of the structure. TMD was first suggested by Frahm in 1919 to reduce the vibration of a ship (Den Hartog, 1956). Den Hartog (1956) first introduced the optimum characteristics of the TMD to reduce the response of a single degree of freedom system (Den Hartog, 1956). Most of the work that has been done on TMD is dedicated to investigating the effectiveness of the TMD in reducing the response of the structures under wind or seismic loading, and determining the optimum parameters of it (for example: Kaynia, Veneziano, and Biggs, 1981; Warburton, 1982; Sadek, Mohraz, Taylor and Chung, 1997; Rana, Soong, 1998; Soto-Brito and Ruiz, 1999; Lukkunaprasit and Wanitkorkul, 2001; Mohebbi and Joghataie, 2011; De Angelis, Perno and Reggio, 2012; to name a few).

In this paper, the characteristic parameters of TMD (mass, damping and stiffness) have been calculated based on the method proposed by Sadek et al. (Sadek, Mohraz, Taylor and Chung, 1997). The TMD has been tuned to the fundamental mode of the structure. Since in engineering practice the parameters of the TMD are calculated based on the deterministic characteristics of the primary structure, the parameters of the implemented TMD has been assumed to be invariant. Since the different realizations of the considered random variable will cause uncertainty in the vibration characteristics of the structure, the effectiveness of the TMD in reducing the response of the structure could not be assured (Der Kiureghian and Dakessian, 1998; Gupta and Manohar, 2004).

4. NUMERICAL ANALYSIS

4.1. Probabilistic Modelling of the Structure

Here, the effect of using TMD on failure probability of a 9-story steel moment-resisting frame denoted as SAC-9 building has been investigated. This building has been designed according to the 1994 UBC seismic design code specifications for Los Angeles, California region. Detailed characteristics of the SAC-9 building can be found in Gupta and Krawinkler (1999). The 2-D moment-resisting frame of this building used in numerical analyses, is presented in Figure 4.1.

By assigning a material with random characteristics to the fiber sections of the elements, probabilistic capacity and stiffness of the structural elements has been incorporated into the finite element model. Modulus of the elasticity and the yield stress of the constructional steel have been taken as the probabilistic characteristics of the steel. Also the uncertainty in the seismic mass of the stories and the damping ratio of the first and third modes of vibration (to assign rayleigh damping) are considered in creating the probabilistic model of the structure. The probabilistic parameters considered in reliability analysis of the structure, along with their mean value, coefficient of variation (COV), standard deviation (SD) and distribution type are shown in Table 4.1. The OpenSees finite element platform (McKenna, Fenves and Scott, 2003) has been used to perform the nonlinear time history analysis of the structure.

4.2. TMD Parameters

As mentioned before the characteristic parameters of TMD have been calculated based on the method proposed by Sadek et al. (Sadek, Mohraz, Taylor and Chung, 1997). In this method, for a given mass ratio (Eqn. 4.1); which is defined as the ratio of the TMD mass to mass of a story of the structure; the vibration frequency and the damping ratio of the TMD are calculated (Eqn. 4.2 and Eqn. 4.3):

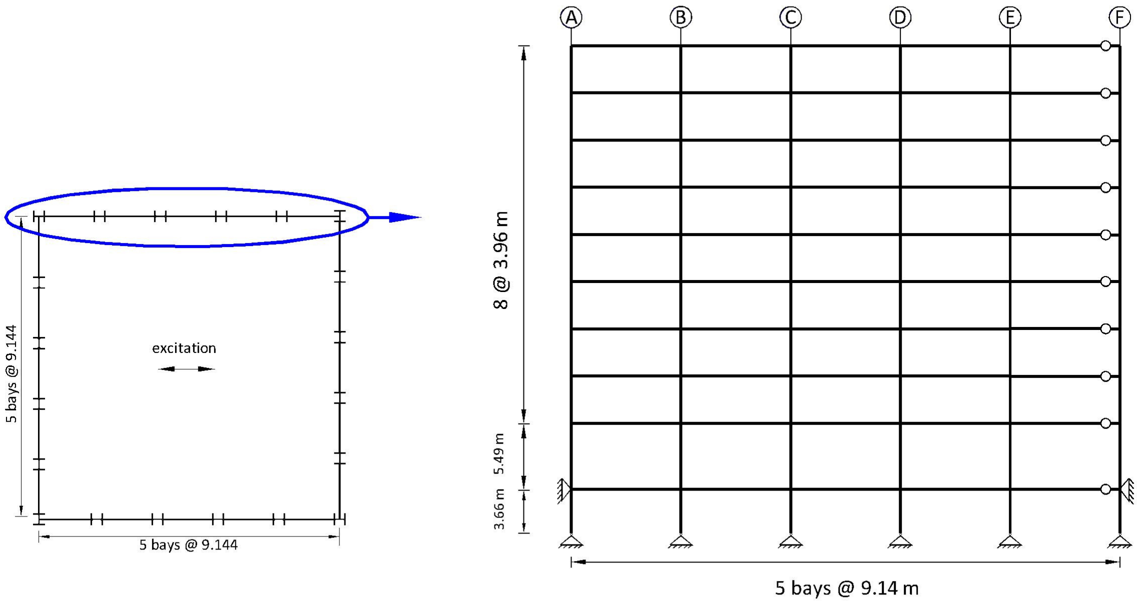


Figure 4.1. Moment-resisting frame of the SAC-9 building

$$\mu = \frac{m}{\phi_1^{\mathrm{T}}\,[\mathrm{M}]\,\phi_1} \tag{4.1}$$

$$f = \frac{1}{1+\mu\Phi}\left[1-\beta\sqrt{\frac{\mu\Phi}{1+\mu\Phi}}\right] \tag{4.2}$$

$$\xi = \Phi\left[\frac{\beta}{1+\mu}+\sqrt{\frac{\mu}{1+\mu}}\right] \tag{4.3}$$

where μ is the mass ratio, m is the mass of the TMD, [M] is the mass matrix of the structure, ϕ_1 is the fundamental mode shape of the primary structure, Φ is the component of the first mode shape vector in the TMD installed degree of freedom, β is the damping ratio of the structure, f the vibration frequency of the TMD, and ξ is the damping ratio of the TMD. The stiffness of the TMD spring and the viscous damping parameter of the dashpot is calculated through Eqn. 4.4 to Eqn. 4.6.

$$f = \omega_{TMD} \,/\, \omega_1 \tag{4.4}$$

$$k = m\,\omega_{TMD}^2 \tag{4.5}$$

$$c = 2\xi m\,\omega_{TMD} \tag{4.6}$$

Where ω_1 is the circular frequency of first mode, ω_{TMD} is the circular frequency of the TMD, c is the viscous damping parameter of TMD, and k is the stiffness of the TMD spring.

Table 4.1. Characteristics of the considered random variables

Parameter	Mean	COV (%)	SD	Distribution Type
Yield Stress in Columns	3620.4 *kgf/cm^2*	15%	543.1×10^4	Lognormal
Yield Stress in Beams	2606.1 *kgf/cm^2*	15%	309.9×10^4	Lognormal
Modulus of Elasticity	2.1×10^{10} *kgf/cm^2*	3%	63×10^7	Lognormal
PGA	Record PGA m/sec^2	30%	$0.3\times$ Record PGA	Lognormal
Story Seismic mass	50410 *kgf-sec^2/m*	20%	10082	Lognormal
Damping Ratio	4%	25%	1%	Lognormal

In order to investigate the effect of the different mass ratios of the TMD on failure probability of the structure, three different TMD parameters with 5%, 30%, and 60% mass ratios, denoted as TMD1, TMD3, and TMD5 are calculated. These parameters are presented in Table. 4.2

Table 4.2. Parameters of the installed TMDs

	Spring Stiffness kgf/m	Damping Coefficient $kgf-sec/m$	Mass TMD $kgf-sec^2/m$	Mass Ratio
TMD1	20059	2516	2725	5%
TMD3	108999	27964	16350	30%
TMD5	194695	69679	32700	60%

4.3. Record Selection

In order to study the effect of the frequency content of the selected records on effectiveness of the TMD in reducing the seismic response of the structure, two records with different frequency contents are selected. Based on the study conducted by Rathje et al., mean period of a record could be used as a characteristics parameter to distinguish the frequency content of the record (Rathje, Abrahamson and Bray, 1998). Mean period is the representative of the dominant periods of the record and is calculated based on the Fourier amplitude of the records, as presented in Eqn. 4.7:

$$T_m = \frac{\sum_i C_i^2 \times \frac{1}{f_i}}{\sum_i C_i^2} \quad \text{for} \quad 0.25\text{Hz} \le f_i \le 20\text{Hz} \tag{4.7}$$

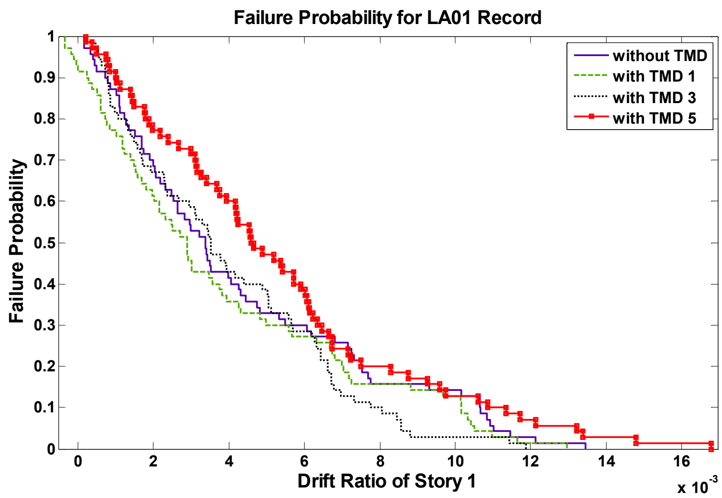
Where C_i is the coefficient of the Fourier amplitude in frequency f_i. The characteristics of the selected records are presented in Table. 4.3. The mean period of the LA01 (Imperial Valley) record is higher than 0.60 and the mean period of the Chichi record is lower than 0.35. The PGA of these records has be randomly created in each simulation of the reliability analysis, based on the characteristics presented in Table 4.1.

Table 4.3. Characteristics of the selected records

Earthquake	Year	M	Station	Closest distance to fault(km)	PGA (g)	PGV (cm/s)	Tm (sec)	Site Condition	
								CWB	USGS
LA01 (Imperial Valley)	1940	6.9	--	10	0.46	452	0.64	--	--
Chichi	1999	7.6	TCU071	4.94	0.655	69.4	0.33	--	C

4.4. Results of the Numerical Analysis

The Monte Carlo simulation technique has been used to obtain the failure probability of each story of the structure. For the primary structure and for each of the structures with a specific TMD, 1000 random samples are created around the mean value of the considered random variables (Table 4.1). Nonlinear time history analysis of the primary structures and the 3 structures with different TMDs are conducted and the results are obtained for each of the selected records. As a limited representative for the obtained results, failure probability of the first and ninth stories of the structure is presented in Figure 4.2 and Figure 4.3.



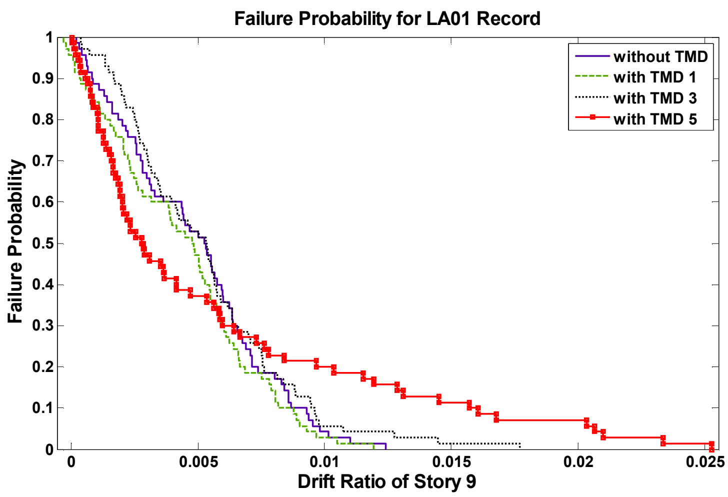
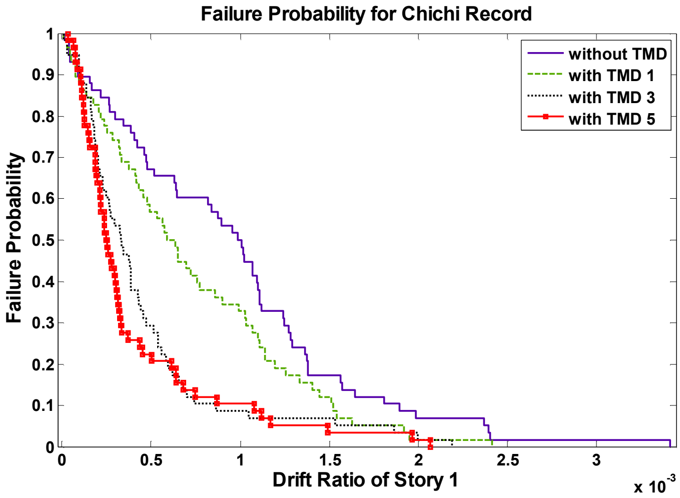


Figure 4.2. Failure probability of the SAC-9 building under LA01 (Imperial Valley) record



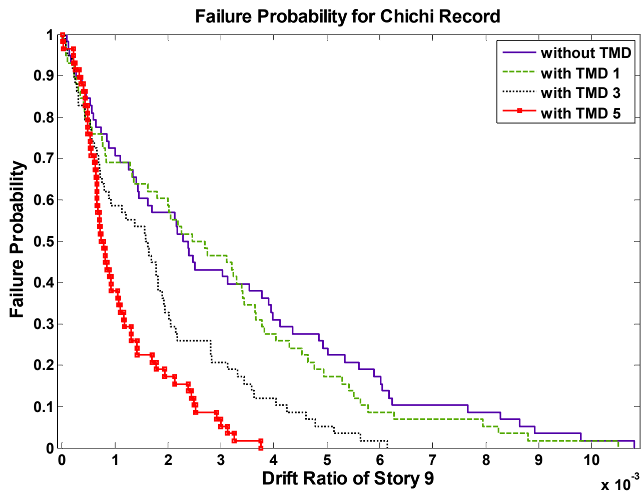


Figure 4.3. Failure probability of the SAC-9 building under Chichi record

Since the drift in each story of the structure could be a proper representative for the amount of the seismic damage, inter-story drift values of each story has been used to obtain the corresponding failure probability, and to observe the positive or negative effect of the TMD on seismic performance of the structure. The results indicate that for the record with lower mean period, TMD is positively effective in reducing the failure probability of the structure. Although for the records with higher mean period the TMD could be destructive for lower stories of the structure, and could only have positive effect in lower thresholds of failure in higher stories of the structure. Increasing the mass ratio of the TMD for the record with higher mean period results in higher failure probability.

5. CONCLUSION

In this study, reliability analysis of a steel moment-resisting frame equipped with tuned mass dampers (TMDs) is investigated. The efficiency of the TMD in reducing the response of a 9-story building structures during earthquake has been observed through probabilistic modeling of the structural system and the applied loads. Monte Carlo simulation has been used on the maximum inter-story drift ratio of each story to calculate the failure probability of the structure. The comparison between the response of the structure, with and without TMD, indicates that the effectiveness of the TMD is dependent on the frequency content of the seismic loading, rather than on the uncertainty in the dynamic characteristics of the structure. For the record with lower mean period, TMD is positively effective in reducing the failure probability of the structure. Although for the records with higher mean period the TMD could be destructive for lower stories of the structure, and could only have positive effect on lower thresholds of failure in higher stories of the structure. Increasing the mass ratio of the TMD for the record with higher mean period results in higher failure probability.

REFERENCES

Nowak A.S, Collins K.R (2000). Reliability of Structures, Mc Graw Hill,

Baecher G. B., Christian J. T. (2003). Reliability and Statistics in Geotechnical Engineering. Wiley, Chichester, New York, NY.

De Angelis M., Perno S., Reggio A. (2012). Dynamic response and optimal design of structures with large mass ratio TMD. *Earthquake Engineering and Structural Dynamics* **41:1**,41-60

Den Hartog J.P, (1956). Mechanical Vibrations. 4th edn, McGraw-Hill, New York.

Der Kiureghian A, Dakessian T., (1998). Multiple design points in first and second-order reliability. *Structural Safety* **20:1**,37–49.

Ditlevsen, O. and Madsen, H. O. (1996). Structural Reliability Methods. Wiley, Chichester, New York, NY.

Gupta A, Krawinkler H. Seismic demands for performance evaluation of steel moment resisting frame structures (SAC Task 5.4.3). Report no. 132. Palo Alto, CA: John A. Blume Earthquake Engineering Center, Stanford University. 1999

Gupta S, Manohar CS. (2004). An improved response surface method for the determination of failure probability and importance measures, *Structural Safety* **26:2**,123-139.

Haukaas, T., Der Kiureghian, A. (2004). Finite element reliability and sensitivity methods for performance-based engineering. Report PEER 2003/14, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Kaynia N.M., Veneziano D., Biggs J.M, (1981). Seismic Effectiveness of Tuned Mass Dampers, *Journal of Structural Division* **107:8**, 1465-1484.

Lukkunaprasit P., Wanitkorkul A., (2001). Inelastic buildings with tuned mass dampers under moderate ground motions from distant earthquakes, *Earthquake Engineering and Structural Dynamics* 30, 537-51

McKenna, F., Fenves, G. L., and Scott, M. H. (2003). Open system for earthquake engineering simulation, Pacific Earthquake Engineering Research Center, Univ. of California, Berkeley, Calif. http://opensees.berkeley.edu/

Mohebbi M., Joghataie A. (2011). Designing optimal tuned mass dampers for nonlinear frames by distributed genetic algorithms, The Structural Design of Tall and Special Building **21:1**,57-76

Rana R, Soong TT, (1998). Parametric study and simplified design of tuned mass dampers. *Engineering Structures* **20:3**,193-204.

Rathje EM, Abrahamson NA, Bray JD., (1998). Simplified frequency content estimates of earthquake ground motions, *Journal of Geotechnical and Geoenvironmental Engineering* **124:2**:150–159.

Sadek F., Mohraz B., Taylor A.W., Chung R. M., (1997). A method of estimating the parameters of tuned mass dampers for seismic application. *Earthquake Engineering and Structural Dynamics* **26:6**,617-635

Soong, T.T., Grigoriu, T., (1993). Random Vibration of Mechanical and Structural System, Englewood Cliffs, NJ: Prentice Hall.

Soto-Brito R., Ruiz S.E., (1999). Influence of ground motion intensity on the effectiveness of tuned mass dampers, *Earthquake Engineering and Structural Dynamics* **28:11**,1255-1271.

Warburton GB., (1982). Optimum absorber parameters for various combinations of response and excitation parameters, *Earthquake Engineering and Structural Dynamics* **10:3,** 381-401.

Wen Y. K., Ellingwood B. R., Veneziano D., Bracci J (2003). Uncertainty Modeling in Earthquake Engineering, MAE Center Project FD-2 Report February 12, 2003.

Wong SM, Hobbs RE., Onof C. (2005). An adaptive response surface method for reliability analysis of structures with multiple loading sequences. Structural Safety 27:4,287–308.