Response Sensitivity of Low-Rise Buildings to Coefficients of Variations of Random Semi-Active Isolation System Parameters under Near-Fault Earthquakes

S. Öncü-Davas and C. Alhan
Istanbul University, Civil Engineering Department, Istanbul, Turkey
Email: seda.oncu@istanbul.edu.tr, cenkalhan@istanbul.edu.tr

***Abstract*— Actual values of the mechanical parameters of isolation system elements of semi-active isolated buildings may deviate from their design values. Therefore, it is more realistic to evaluate their seismic performance via use of probabilistic analyses methods. While the mean values of random variables are used as nominal design values in a probabilistic model, their coefficients of variation (c.o.v.) represent the level of uncertainty. In the absence of adequate statistical observation for determining suitable c.o.v values of random semi-active isolation system parameters, it is worth evaluating the sensitivity of the seismic response to the aforementioned c.o.v values. Here, this issue is examined in the context of a low-rise benchmark semi-active isolated building under historical near-fault earthquakes. Cumulative distribution plots of peak base displacements and top floor accelerations are presented for different c.o.v values which shows that as the covariance values increase, the range of results expand depending on the earthquake data.**

***Index Terms*— Monte-Carlo simulation, coefficient of variation, semi-active isolation**

I. Introduction

The main objective of semi-active isolation [1, 2], which is among the structural control systems that have been developed as alternatives to the conventional earthquake resistant design method, is to both protect the structural integrity and the contents, devices, etc. from harmful effects of vibrations generated due to ground excitations. Thanks to such control systems, the excessive base displacements, which may occur if seismic isolated buildings are subjected to near-fault earthquakes [3,4], can be reduced effectively [5,6].

Although previous deterministic studies have shown that semi-active isolation systems are successful under near-fault earthquakes, actual values of the mechanical parameters of semi-active isolation system elements may deviate from their nominal design values due to various factors such as uncertainties in the material properties, dimensions, and production methods of the isolation elements, etc. which may affect overall structural response. Consequently, probabilistic analyses that take the aforementioned uncertainties into account should be preferred for evaluating the seismic performance of semi-active isolated buildings more realistically [7].

The first step of such a probabilistic evaluation is determining the probabilistic representation of the random mechanical parameters of the semi-active isolation system elements. The probability distributions of these random parameters are generated by utilizing the mean and the coefficient of variation (c.o.v) values [8]. While the mean values of the random variables are used as nominal design values in a probabilistic model of a semi-active isolation system, the c.o.v. represents the level of uncertainty. For most engineering system parameters, it is typically assumed that c.o.v. varies between 10% and 30% [8].

In fact, the c.o.v. used for the random parameters in a probabilistic evaluation should be based on statistical observation. Since there is inadequate statistical observation for determining suitable c.o.v values of random semi-active isolation system parameters, it is worth evaluating the sensitivity of the seismic response of semi-active isolated buildings to the aforementioned c.o.v values.

In this study, the sensitivity of the seismic response of a benchmark 3-story semi-active isolated building to the coefficient of variation values of random isolation system parameters is determined. For this purpose, Monte Carlo Simulations of the low-rise benchmark building are carried out under two historical near-fault earthquakes. The results are presented in the form of cumulative distribution plots of the peak values of base displacement and top floor acceleration for different c.o.v values.

II. Benchmark Low-Rise Semi-active Isolated Building

A 3-story semi-active isolated benchmark building model is used in this study. The superstructure is three dimensional shear building with a symmetrical plan that

Manuscript received December 4, 2017; revised August 8, 2018.

doi: 10.18178/ijscer.7.4.353-357

has four 5m bays in both directions [9]. The floor masses and the total floor stiffnesses are equal in each story providing a fixed-base superstructure period of 0.5 s. The modal damping ratio of the superstructure is 5% for all modes. The semi-active isolation system is formed by combining 8 semi-active devices placed in 4 plan corners (perpendicular to each other) connected in parallel with 25 rubber isolators placed under each column [7].

Nonlinear force-displacement behavior in the rubber isolator elements of seismic isolation system is defined as bi-linear with main parameters of (i) pre-yield stiffness, K_1, (ii) post-yield stiffness, K_2, (iii) yield force, F_y, (iv) yield displacement, D_y, and (v) characteristic force, Q. In this study, the nominal isolation period (rigid-body mode period) and the nominal total characteristic force ratio are assumed as T_0=4 s and Q/W=10%, respectively. Considering these values, the nominal total post-yield stiffness is calculated as K_2=3158 kN/m by using $T_0=2\pi(m_t/K_2)^{1/2}$ [10], where m_t=1280 t is the total mass of benchmark building. Assuming the nominal yield displacement D_y=20 mm, the corresponding nominal pre-yield stiffness value is calculated as K_1=65942 kN/m via use of relationship $K_1=Q/D_y+K_2$ [11]. Then, by using $\alpha=K_2/K_1$, the nominal post-yield to pre-yield stiffness ratio of the isolation system is obtained as α=0.048. Finally, the nominal total yield force is calculated as F_y=1318 kN with the help of $F_y= K_1D_y$. The nominal values of the post-yield to pre-yield stiffness and yield displacement would be the same for both the isolation system and each individual isolator. On the other hand, the nominal values of yield force, characteristic force, pre-yield stiffness, and post-yield stiffness per isolator are obtained by dividing their corresponding total values by the total number of isolators, i.e. 25.

The semi-active control device used in the isolation system is mainly a controllable Maxwell element [5] that comprises a controllable damper connected in series to a spring element. In this study, the control rule is assumed as a bang-bang pseudo-skyhook [12] given as $u=H(f_dV_a)$ where, u is the control signal, H(.) is the Heaviside step function, V_a is the absolute device velocity and f_d is the control force that depends on the velocity of the device ($\dot{z}_d$). If the multiplication of the control force and the absolute velocity of the device is equal to or less than zero, the device is set to off (u=0) position. If vice versa is true, then the device is set to on (u=1) position. Following $c_d(u)=c_{min}(1-u)+c_{max}u$, the controllable device damping would be equal to maximum damping (c_{max}) and minimum damping (c_{min}) for on and off positions, respectively [12].

III. Random Semi-active Isolation System Parameters

The uncertainty in the mechanical properties of the semi-active isolation system elements are taken into account by defining the post-yield stiffness to pre-yield stiffness ratio (α), the yield force (F_y), the yield displacement (D_y), the device stiffness (k_d), the maximum damping value (c_{max}), and the minimum damping value (c_{min}) as random variables. The nominal values of the selected random variables are α=0.048, F_y=52.8 kN, D_y=20 mm, k_d=1250 kN/m, c_{max}=150 kNs/m, and c_{min}=30 kNs/m. In this study, it is assumed that all of the aforesaid random semi-active isolation system parameters follow normal distribution. The shape of normal distribution depends on two parameters: mean, μ_x, and standard deviation, σ_x, values of the random variable Depending on these, a measure of dispersion of a probability distribution is defined as the coefficient of variation c.o.v.=σ_x/μ_x. In the context of this sensitivity study, the coefficients of variation (c.o.v.) for all random variables are taken as 10% and 20% for different sets of runs. The probability distribution of a random variable can be defined by the probability density function (PDF). The probability density function (PDF) plots of the above-mentioned random variables, generated for different covariance values (c.o.v=10% and 20%) in accordance with normal distribution, are presented in Fig. 1.

IV. Simulations and Results

Monte-Carlo simulations of the benchmark semi-active isolated low-rise building are carried out under two different historical near-fault earthquakes detailed in Table I. The records are retrieved from PEER Strong Ground Motion Databank [13]. In the context of the Monte-Carlo simulation, 3000 recursive bidirectional nonlinear time history analyses of the benchmark building are performed in software 3D-BASIS-SA-MC [7] for each record. The results obtained for the peak top floor accelerations (ptfa) and peak base displacements (pbd) are depicted for aforementioned covariance values (c.o.v=10% and 20%) in the form of cumulative distribution function (CDF) plots given in Fig. 2. Note that, cumulative distribution function (CDF) demonstrates the probability of a random variable taking a value less than or equal to a selected limit value.

Figures show that the structural response parameters (pfta, pbd) are somewhat influenced by the level of the uncertainty, represented by different c.o.v values in the semi-active isolation system elements. As seen, higher c.o.v. values result in a larger variance in the response results. As shown in Fig. 2 (a) -in case of Northridge Earthquake- while peak top floor accelerations obtained for c.o.v. of 10% vary between 1.66 m/s^2 to 1.92 m/s^2, this range becomes slightly larger for c.o.v. of 20% (i.e. 1.52 m/s^2 to 2.1 m/s^2). Similarly, the ranges of peak base displacements obtained from Monte-Carlo analysis for c.o.v. of 10% and 20% cases are (0.222 m to 0.231 m) and (0.219 m to 0.236 m), respectively (Fig. 2 (c)).

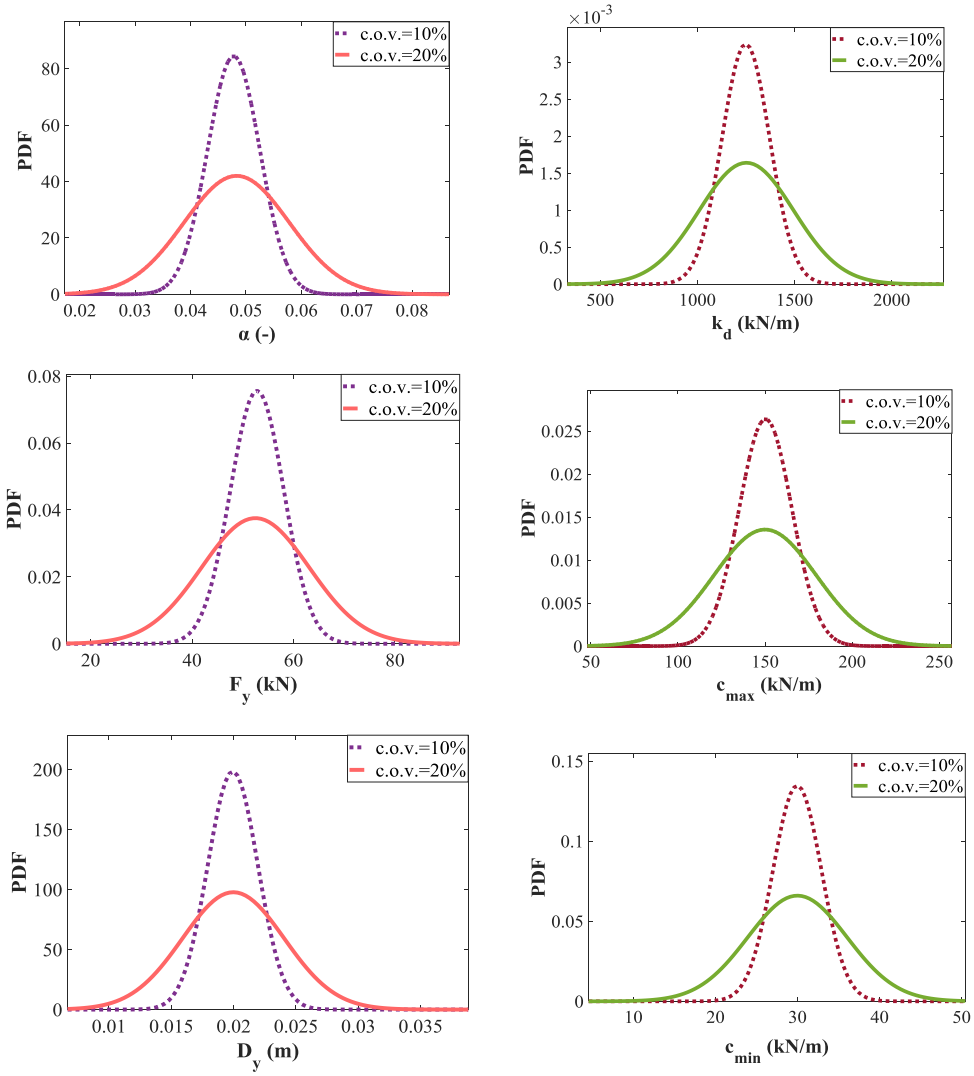

Figure 1. Probability distribution function (PDF) plots of the random variables of the semi-active isolation system.

Likewise, it is observed from Fig. 2(b) that under Darfield Earthquake, the ranges of peak top floor accelerations for c.o.v. of 10% vary between 1.48 m/s^2 and 1.65 m/s^2 and increase to the range of 1.4m/s^2 and 1.87 m/s^2 for c.o.v. of 20%. Similarly, the ranges of peak base displacements obtained from Monte-Carlo analysis for c.o.v. of 10% and 20% cases are (0.171 m to 0.202 m), and (0.156 m to 0.229 m), respectively (Fig. 2 (d)).

V. Conclusions

In this study, the sensitivity of the seismic response of a benchmark 3-story semi-active isolated building to the coefficient of variation values of random semi-active isolation system parameters is determined. For this purpose, Monte Carlo Simulations of the benchmark building with 3000 recursive bidirectional nonlinear time history analyses are carried out under two historical near-fault earthquakes using software 3D-BASIS-SA-MC [7]. The results are presented in the form of cumulative distribution plots of the peak values of base displacement and top floor acceleration for c.o.v values of 10% and 20%.

It is shown that as the covariance values increase (from 10% to 20%) the range of results of the structural response parameters in terms of peak top floor accelerations and peak base displacements expand. However, it is seen that the significancy of this influence, i.e the sensitivity of the seismic response of the benchmark semi-active isolated building to c.o.v heavily depends on the earthquake record. Therefore, more cases under different earthquakes should be investigated as part of the future work.

TABLE I. Information about Historical Near-Fault Earthquakes

Earthquake	Date	M_w	Station	Component	PGA (g)	PGV (cm/s)
Northridge	1994	6.7	LA Dam	LDM064	0.42	74.8
Darfield	2010	7.0	LINC	LINCN23E	0.46	108.6

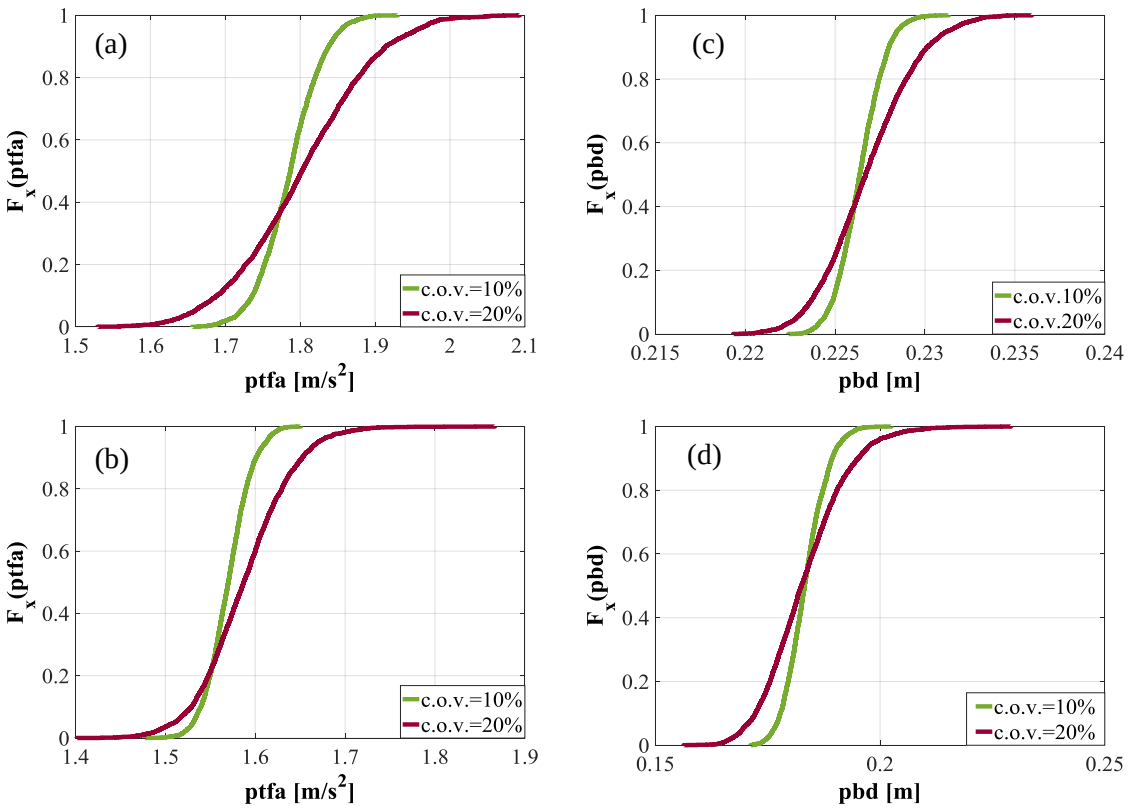

Figure 2. Cumulative distribution function plots: peak top floor acceleration (a) under Northridge Earthquake (b) under Darfield Earthquake and peak base displacement (c) under Northridge Earthquake (d) under Darfield Earthquake.

REFERENCES

[1] F. Casciati, J. Rodellar, and U. Yildirim, "Active and semi-active control of structures - theory and applications: A review of recent advances," *J. Intell. Mater. Syst. Struct.*, vol. 23, pp. 1181-1195, 2012.

[2] B. F. Spencer Jr and S. Nagarajaiah, "State of the art of structural control," *Journal of Structural Engineering*, vol. 129, pp. 845-856, 2003.

[3] P. K. Malhotra, "Response of building to near-field pulse-like ground motions," *Earthquake Engineering and Structural Dynamics*, vol. 28, pp. 1309-1326, 1999.

[4] S. Öncü, "Effect of pulse periods on the performance of seismically isolated buildings," M.S. thesis, Institute of Science, Istanbul University, 2011 [in Turkish].

[5] H. Gavin, C. Alhan, and N. Oka, "Fault tolerance of semiactive seismic isolation," *J Struct Eng-ASCE*, vol. 129, pp. 922-932, 2003.

[6] C. Alhan, H. P. Gavin, and U. Aldemir, "Optimal control: Basis for performance comparison of passive and semiactive isolation systems," *J Eng Mech-ASCE*, vol. 132, pp. 705-713, 2006.

[7] S. Öncü-Davas, "Probabilistic behavior of buildings with semi-active seismic isolation systems under earthquake loads," Istanbul University, Ph.D. disseration (unpublished).

[8] A. Haldar, S. Mahadevan, *Probability, Reliability and Statistical Methods in Engineering Design*, John Willey & Sons, 2000.

[9] C. Alhan and M. Sürmeli, "Necessity and adequacy of near-source factors for not-so-tall fixed-base buildings," *Earthquake Engineering and Engineering Vibration*, vol. 14, pp. 13-26, 2015.

[10] V. A. Matsagar and R. S. Jangid, "Influence of isolator characteristics on the response of base-isolated structures," *Eng Struct*, vol. 26, pp. 1735-1749, 2004.

[11] F. Naeim and J.M. Kelly, *Design of Seismic Isolated Structures: From Theory To Practice*, Wiley, New York, 93–121, 1999.

[12] D. Karnopp, M. Crosby, and R. Harwood, "Vibration control using semi-active force generators," *Journal of Engineering for Industry*, vol. 96, pp. 619-626, 1974.

[13] Berkeley. [Online]. Available: https://ngawest2.berkeley.edu/, Peer Strong Motion Data [Time accessed: 10 September 2017]

S. Öncü-Davas has completed her BS and MS degrees in Civil Engineering at Istanbul University in 2009 and 2011, respectively. In 2011, Öncü-Davas has started working as a research assistant in structural engineering division and has also served as a teaching assistant for courses such as statics, dynamics, structural analysis, structural mechanics, structural dynamics, and earthquake engineering at Istanbul University where she is currently a PhD candidate. Her major field of study is structural and earthquake engineering. She has given oral presentations about seismically isolated structures at national and international conferences held in Turkey, Greece, Portugal, Italy and Spain. She has published in and also act as a reviewer for Engineering Structures journal. She has also co-authored two book chapters.

C. Alhan has earned his BS, MS, and PhD degrees in civil engineering at Middle East Technical University (Turkey), Bogazici University (Turkey), and Duke University (USA) in 1996, 1999, and 2003, respectively. He worked as a research assistant at Bogazici and Duke Universities in 1997–2000 and 2000–2003, respectively. During his stay at Duke, he worked as a researcher in a National Science Foundation funded research project. He became a Faculty Member at

Istanbul University in 2006 where he currently works as a Professor in Civil Engineering Department. He works in structural and earthquake engineering area and his research interests include probabilistic structural dynamics, seismic isolation, semi-active control, irregular structures, strengthening, and engineering education. He teaches Courses in structural and earthquake engineering including Statics, Strength, Structural Mechanics, Structural Analysis, Earthquake Engineering, Seismic Isolation, and Structural Dynamics. He has given oral presentations at conferences and seminars worldwide such as those in Boston, Alaska, Edmonton, Michigan, Vienna, Istanbul, Singapore, Sydney, Delft, Barcelona, and Reykjavik. Prof. Dr. Cenk Alhan has published in important technical journals including Journal of Structural Engineering, Journal of Engineering Mechanics, Smart Materials and Structures, Engineering Structures, Engineering Optimization, Mechanical Systems and Signal Processing, Earthquake Engineering and Engineering Vibration, Smart Structures and Systems, and Bulletin of Earthquake Engineering for which he has received more than a hundred citations. He also acts as a Reviewer for various SCI journals. He is a member of Earthquake Engineering Research Institute and American Society of Civil Engineers. He worked as a working team member in the European Civil Engineering Education and Training Thematic Network in Romania and Spain. Dr. Alhan has also gained extensive industrial experience by working as a Senior Structural Design Engineer at Laurene & Rickher, P.C. in Raleigh, NC, USA in 2003–2006 where he has been involved in earthquake resistant design of steel, concrete, and wooden structures. Additionally, he has been working as a Structural Consultant for high-rise building projects in Istanbul and Izmir, Turkey.