Application of Monte-Carlo Simulation to Semi-Active Isolation Systems under Near-Fault Synthetic Earthquakes

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Abstract: Semi-active isolation systems can be effective in protecting structural integrity and vibration-sensitive contents concurrently. Due to external factors, the actual values of the mechanical properties of isolation elements used in semi-active isolated buildings may differ from their nominal design values. In order to determine the seismic behavior of semi-active isolated buildings more realistically, a probabilistic approach that takes such uncertainties into account is essential. Monte-Carlo Simulation technique is a suitable method to perform probabilistic investigation and conduct reliability analyses that take these uncertainties into account. In this study, it is explained how Monte-Carlo simulation method is applied to a typical semi-active isolated building. In order to make an illustration, the Monte-Carlo simulation of a 3-story benchmark semi-active isolated building is carried out under synthetic earthquakes with random characteristic parameters. For performing Monte-Carlo simulation, the previously modified version [Gavin, H., Alhan C., Oka, N., Fault Tolerance of Semiactive Seismic Isolation, 2003, *J Struct Eng*, 129:922-932] of 3DBASIS program [Nagarajaiah, S., Reinhorn, A.M., Constantinou, M.C., 3D-BASIS Nonlinear Dynamic Analysis of Three Dimensional Base Isolated Structures Part II", NCEER-910005, 1991, SUNY, Buffalo], which is able to conduct seismic analysis of semi-active isolated buildings, is further modified to perform recursive analyses with random variables under synthetic earthquakes. It is shown that the structural response parameters investigated attain values in wide range as opposed to single-valued deterministic results and the cumulative distribution function plots generated can effectively be used in determining probability of failures and thus reliability levels.

Key-Words: Monte-Carlo simulation, probabilistic dynamic analysis, semi-active isolated building, synthetic earthquakes

1 Introduction

It can be said that seismic isolation systems have two tasks: (1) maintaining structural integrity and (2) reducing floor accelerations thereby protecting the contents housed in the structure. Seismic isolation systems, which typically succeed in full-filling above-mentioned tasks under far-fault earthquakes, are being questioned for more than a decade because of the excessive base displacements which may occur in case of near-fault earthquakes. Keeping the base displacements under practical and economic limits in such cases is a major concern. Therefore, it has become necessary for isolation systems to adapt themselves to the external seismic loads of different nature, which they may be subjected during their lifetime, online. Consequently, different intelligent isolation system elements such as active and semi-active control devices, which can adapt to external loads, have been introduced recently in order to reduce damages that structures may suffer from earthquakes. Use of semi-active control systems are more reliable than active control systems because active control systems need much larger power requirements [1] and may also lead to stability problems [2]. With the use of semi-active control systems, base displacements and superstructure responses such as floor accelerations and story drift ratios can be reduced simultaneously [3].

On the other hand, due to aging, contamination, temperature, etc., the actual values of the mechanical properties of the isolation elements used in seismically isolated buildings may differ from their nominal design values [4]. Similarly, the actual values of the mechanical properties of the semi-active control devices/dampers may deviate from their nominal design values. And, in order to determine the seismic behavior of semi-active isolated buildings more realistically, a probabilistic approach that takes such uncertainties into account is essential. Monte-Carlo Simulation technique is a suitable method to perform probabilistic investigation and conduct reliability analyses that take these uncertainties into account. The Monte-Carlo simulation [5], a precise method for performing safety and reliability analyses, is based on recursive computer analyses and mathematical modeling that takes into account the uncertainties in random variables following certain probabilistic distributions. Various researchers (e.g. [6]-[8]) assessed the effect of variability in mechanical parameters of passive isolation system on the structural response. Monte-Carlo and reliability analysis of passive seismic isolation systems were conducted by [9] using a modified version of the 3DBASIS program when is able to conduct reliability analyses of passive seismic isolation systems. The results of such studies emphasize the importance of the variability of such parameters on the seismic response parameters of seismically isolated buildings. Although probabilistic seismic risk analysis of seismically isolated buildings has received interest in recent years, probabilistic research studies on semi-active isolated buildings in the literature are relatively scarce [10].

In this study, it is explained how Monte-Carlo simulation method is applied to a typical semi-active isolated building. In order to make an illustration, the Monte-Carlo simulation of a 3-story benchmark semi-active isolated building is carried out under synthetic earthquakes with random characteristic parameters. For performing Monte-Carlo simulation, the previously modified version -named here as 3DBASIS-SA- [11] of 3DBASIS program [12], which is able to conduct bi-directional seismic analysis of three-dimensional semi-active isolated buildings, is further modified in this study to perform recursive analyses with random variables under synthetic earthquakes, and named as 3DBASIS-SA-MC [13].

2 Structural Model

In this study, a 3-story semi-active isolated benchmark building model, whose plan view is shown in Fig.1, is used. The model consists of two parts as the superstructure and the semi-active isolation system. The superstructure is modeled as a 3-dimensional shear building. The floor masses are considered to be equal and to be concentrated at the center of gravities of the floors. The floor stiffnesses are chosen to be equal and are adjusted to provide a fundamental fixed-base superstructure period of 0.34 s. The modal damping ratios are assumed to be constant and 5% for all modes. The isolation system consists of a total of 25 rubber isolators under each column and 8 semi-active control devices are placed perpendicularly at each corner of the isolation system. As shown in Fig. 2, the rubber isolators are modeled to represent bi-linear hysteretic behavior [12]. The main relationships between the main mechanical parameters of the rubber isolators, i.e the nominal characteristic force (Q), the nominal yield force (F_y), the nominal yield displacement (D_y), the nominal pre-yield stiffness (K_1), and the nominal post-yield stiffness (K_2), are given in Table 1 and are also depicted in Fig. 2. The nominal rigid-body isolation period of the benchmark building (T_0) is obtained depending on the total weight of building (W) and the total post-yield stiffness (K_{2t}) of the isolation system (Eq. 1).

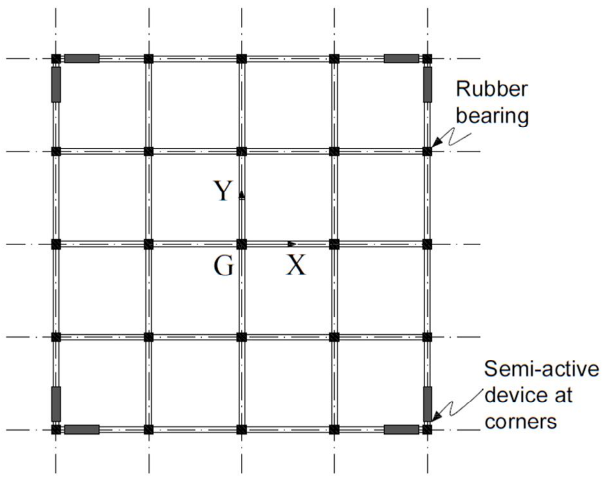

Figure 1. Plan view of benchmark 3-story semi-active isolated building.

Table 1. Main relationships between the main mechanical parameters of the isolation system elements

	Mechanical parameter	Formulation	Equation	References
Rubber isolator	Nominal isolation period	$T_0 = 2\pi\sqrt{W / gK_{2t}}$	(1)	[14]
	Characteristic force	$Q = (K_1 - K_2)D_y$	(2)	
	Yield force	$F_y = K_1 D_y$	(3)	[15]
	Post-yield stiffness to pre-yield stiffness ratio	$\alpha = K_2 / K_1$	(4)	
Semi-active control device	Control signal	$u = H(f_d \cdot V_a)$	(5)	
	Controllable device damping	$c_d(u) = c_{min}(1-u) + c_{max}u$	(6)	[11]
	Control force	$\dot{f}_d = -\frac{k_d}{c_d(u)} f_d + k_d \dot{z}_d$	(7)	

The total weight of the prototype 3-story model is (W) 12557 kN. In Eq. (1), g is the gravitational acceleration. Thus, the nominal total post-yield stiffness (K_{2t}) can be obtained for the assumed isolation system period of 4 s. The nominal post-yield stiffness (K_2) for per isolator is then obtained by dividing the nominal total post-yield stiffness (K_{2t}) by the total number of isolators. Here, the nominal yield displacement (D_y) is assumed as 20 mm and the nominal total characteristic force ratio (Q_t/W) is taken as 10% representing design values of typical seismic isolation systems. Once Q_t is obtained based on 10% Q_t/W ratio, the nominal characteristic force (Q) for each isolator can be calculated by dividing the total characteristic force ratio by the total number of isolators. Then, the nominal pre-yield stiffness (K_1) can be obtained via Eq. (2) while the nominal yield force (F_y) and the post-yield stiffness to pre-yield stiffness ratio (α) are calculated from Eqs. (3) and (4), respectively.

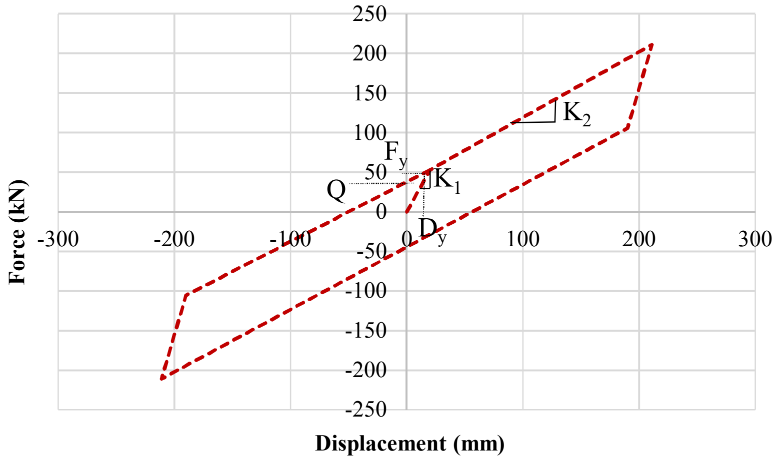

Figure 2. Bi-linear hysteretic behavior of each isolator.

The other main component of the isolation system is the semi-active control device, which is essentially a controllable Maxwell element and the details of its model is given by Gavin et al. [11]. The control rule utilized in the operation of the semi-active device is modeled using the bang-bang pseudo-skyhook control rule [16] that depends on the control signal, u, which is given in Eq. (5) where, H(.) is the Heaviside step function, f_d is the control force and V_a is the absolute device velocity. The control rule mimics optimal damping by switching the dampers on and off. If $f_d.V_a \leq 0$, the control rule decides to minimize the damping of the semi-active device and sets u = 0. Otherwise, the control signal, u, is set to 1; thus, the damping is maximized. As shown in Eq. (6), the controllable device damping $c_d(u)$ is dependent on the control signal, u, where, c_{max} and c_{min} are the maximum and the minimum damping values, respectively. The control force of the Maxwell element (f_d) is calculated by Eq. (7), where k_d is the device stiffness, and $\dot{z}_d$ is the relative velocity of the device. The over-dot symbol stands for time derivative.

3 Synthetic Earthquakes

In the recorded historical near-fault earthquakes within approximately10 km from the fault line, long-period and large-amplitude velocity pulses are commonly observed. Use of historical records in parametric studies conducted for systematic investigations may be difficult since such records are scarce and can't be uniformly classified with respect to the earthquake magnitude, fault-distance, pulse period, etc. Thus, various analytical pulse models have been proposed by researchers ([17]-[19]) for use in such studies. Monte-Carlo simulations aiming systematic probabilistic investigations also require the use of such synthetic earthquake records. In this study, Agrawal and He (2002) pulse model is used and the ground acceleration record formulation obtained based on this model is given in Eq. (8) where ζ_p is the decaying sinusoid damping factor, s is the initial amplitude of the velocity pulse, $\omega_p=2\pi/T_p$ is the frequency of the sinusoid, T_p is the pulse period, and t is the time (sec).

$$a(t) = se^{-\zeta_p\omega_p t}[-\zeta_p\omega_p \sin\omega_p\sqrt{(1-\zeta_p{}^2)}t + \omega_p\sqrt{(1-\zeta_p{}^2)}\cos\omega_p\sqrt{(1-\zeta_p{}^2)}t] \tag{8}$$

Following the methodology presented by Dicleli and Buddaram [20], the functions proposed by Somerville [21] are used to determine the maximum pulse velocity, υ_p, and the pulse period, T_p to be inserted in Eq. (8). Here, M_w is the earthquake magnitude and r is the closest distance to the fault.

$$\log_{10}(\upsilon_p) = -1.0 + 0.5M_w - 0.5\log_{10}(r) \tag{9}$$

$$\log_{10}(T_p) = -2.5 + 0.425M_w \tag{10}$$

4 Application of Monte-Carlo Simulation

4.1 Random Variables

In order to determine the seismic behavior of semi-active isolated buildings more realistically, a probabilistic approach that takes such uncertainties into account is essential. In this study, among the mechanical properties of the rubber isolators, the post-yield to pre-yield stiffness ratio (α), the yield displacement (D_y), and the yield force (F_y) are considered as random variables. Similarly, the characteristic mechanical parameters of the semi-active control device, i.e the device stiffness (k_d), the maximum damping (c_{max}), and the minimum damping (c_{min}) are also considered as random parameters. The probabilistic distribution type, the coefficient of variation (c.o.v.) and the mean (nominal) values of the selected random variables are given in Table 3.

Table 3. Information on the random variables of the semi-active isolation system

Random variable	Distribution type	Mean value	c.o.v.
α	normal	0.048	10%
F_y	normal	52.8 kN	10%
D_y	normal	0.02 m	10%
k_d	normal	1250 kN/m	10%
c_{max}	normal	150 kNs/m	10%
c_{min}	normal	30 kNs/m	10%

In addition to the uncertainties in the mechanical parameters of the semi-active isolation system elements, the uncertainties in the synthetic earthquake parameters are also taken into account. Accordingly, the decaying sinusoid damping factor (ζ_p), the pulse period (T_p) and the maximum pulse velocity (υ_p) of the synthetic earthquake parameters are considered as random variables. The information on the probability distributions, the mean values and the shape parameters/coefficient of variations is presented in Table 4. For a random variable following Weibull distribution, k_x is the shape parameter that changes the variance of the random variable. In this study, as a representative near-fault earthquake record, the earthquake magnitude (M_w) and the closest distance to the fault (r) are selected as 6.5 and 3 km, respectively and the nominal maximum pulse velocity (υ_p) and the nominal pulse period (T_p) given in Table 4 are calculated by using Eqs. (9) and (10). The random values for the above-mentioned variables are produced by MATLAB [22] for the selected number of simulations (nrand) which are then input to 3DBASIS-SA-MC.

Table 4. Information on random variables of the synthetic earthquake

Random variable	Distribution type	Mean value	c.o.v./k_x
ζ_p	normal	20%	15%
T_P	Weibull	1.83 s	7
υ_p	Weibull	102 cm/s	5

To illustrate the randomness in the synthetic earthquake records generated here, sample acceleration time histories with nominal and 10% deviated cases are given in Fig. 3 in a comparative fashion. This figure shows the curve corresponding to the nominal case determined by the nominal values of the decaying sinusoid damping factor (ζ_p), the pulse period (T_p) and the pulse velocity (υ_p), and also the curves corresponding to deviated cases where each aforementioned parameter deviates by ±10%.

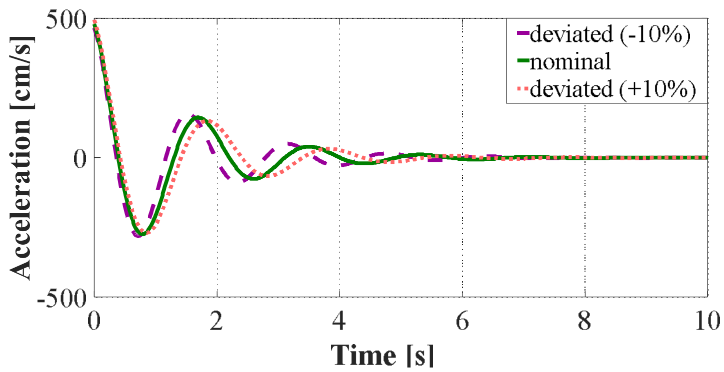

Fig. 3. Simulation of acceleration time-histories of random synthetic earthquakes.

4.2 Recursive Analyses

General flow chart of 3DBASIS-SA-MC program composed in this study, which is capable of performing Monte-Carlo simulation, is given in Fig. 4. The input file that contains random values following certain probability distributions consistent with the natures of the random variables is generated externally in MATLAB [22]. The random values of the random variables used in this study are produced as much as the required number of simulations (nrand). Also, synthetic earthquake records characterized by random variables given in Table 4 are generated as much as the required number of simulations (nrand) within 3DBASIS-SA-MC which makes use of 3DBASIS-SA which is a previously modified (by [11]) version of 3DBASIS [12] program. For conducting Monte-Carlo simulation, 3DBASIS-SA is run recursively in an automatic fashion in order to realize each simulation within 3DBASIS-SA-MC.

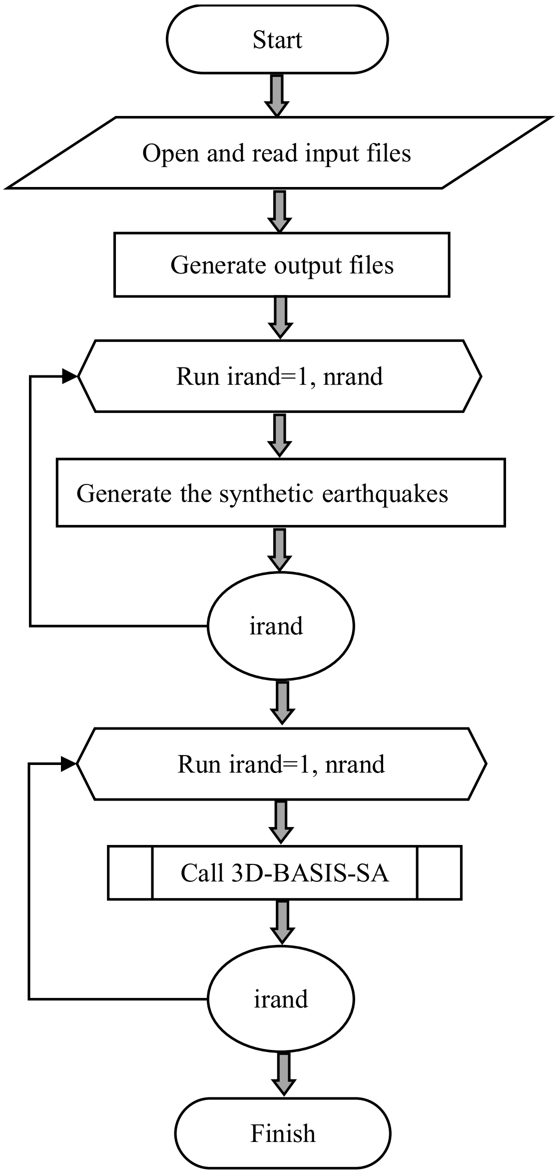

Fig. 4. General flow chart of 3DBASIS-SA-MC program

4.3 Simulation and Results

A sample Monte-Carlo simulation of the 3-story benchmark semi-active isolated building is carried out for nrand=3000 simulations using 3DBASIS-SA-MC program. The building is subjected to synthetic near-fault earthquakes with a moment magnitude of 6.5 and a closest distance to the fault of 3 km. For conducting nrand=3000 simulations, random parameters of semi-active isolation system (α, F_y, D_y, k_d, c_{max} and c_{min}) and synthetic earthquake model (ζ_p, T_p and υ_p) are generated with 3000 different random values following certain probabilistic distributions (see Tables 3 and 4). The results are presented in the form of cumulative distribution functions (CDF) (Fig. 5). CDF plots can be used to determine the reliabilities of the investigated buildings as they provide information on the probability of exceedances corresponding to any selected limit state value. CDF plots in this study are constructed in terms of peak top floor acceleration (pfta) and peak base displacement (pbd) response parameters (Fig 5).

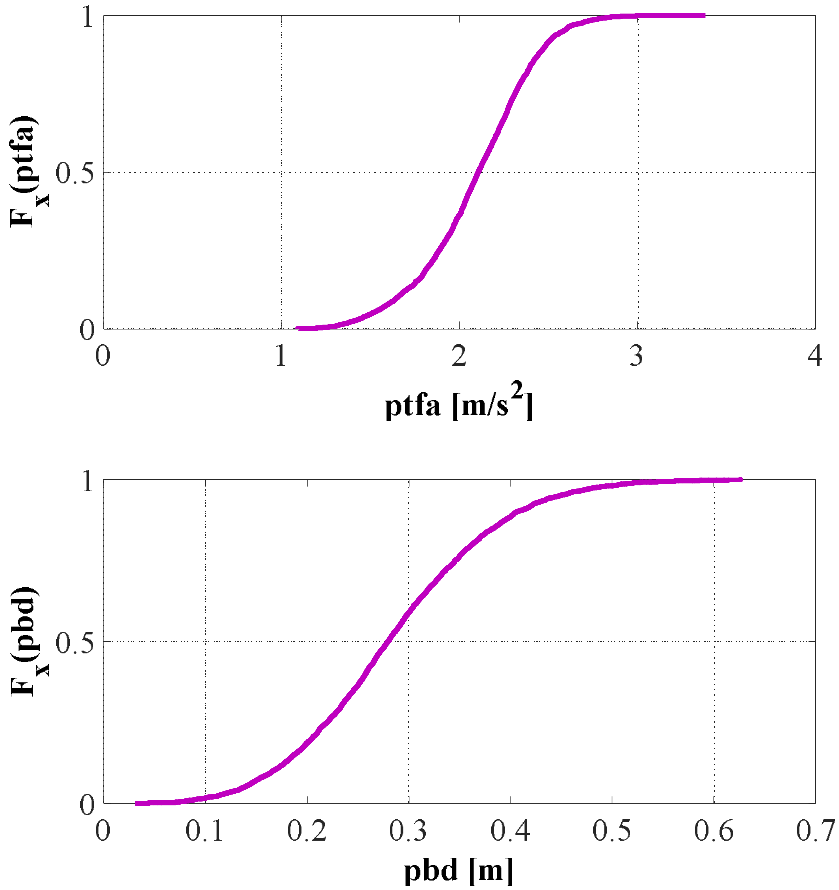

Figure 5. CDF plots of peak top floor acceleration (pfta) and peak base displacement (pbd)

When CDF plots are examined, it is clearly observed that the results appear in a wide range as opposed to single-valued counterpart deterministic results that would be obtained using nominal values given in Tables 3 and 4. Compared to the deterministic peak base displacement value of 28 cm, the probabilistic values of peak base displacements obtained from Monte-Carlo analysis vary between 3 cm and 63 cm. Compared to the deterministic peak acceleration value of 2.1 m/s^2, the probabilistic values of peak top floor accelerations obtained from Monte-Carlo analysis vary between 1.1 m/s^2 and 3.4 m/s^2. These plots can effectively be used to determine probability of failures. For example, 50% and 95% of peak top floor accelerations are below about 2.1 m/s^2 and 2.6 m/s^2, respectively. That is, the probability of peak top floor acceleration exceeding 2.1 m/s^2 and 2.6 m/s^2 is 50% and 5%, respectively. Similarly, the probability of peak base displacement exceeding 28 cm and 45 cm is 50% and 5%, respectively.

5 Conclusions

In this study, it is explained how Monte-Carlo simulation method is applied to a typical semi-active isolated building by making use of a 3-story benchmark structure with random isolation system characteristic parameters under synthetic earthquakes also with random characteristic parameters. For performing Monte-Carlo simulation, the previously modified version [11] of 3DBASIS program [12], which is able to conduct seismic analysis of semi-active isolated buildings, is further modified to perform recursive analyses with random variables under synthetic earthquakes. As the output of the Monte-Carlo analysis, cumulative distribution plots are constructed which depicted that the seismic response parameters of the semi-active isolated benchmark building attain values in a wide range as opposed to single-valued deterministic results. In addition, it is demonstrated how these cumulative distribution function plots can effectively be used in determining probability of failures and thus reliability levels. It is thus shown that via this probabilistic approach, the seismic behavior of semi-active isolated buildings can be determined more realistically.

In an ongoing study conducted by the authors of this study, CDF plots for a wide range of different M_w and r values are generated via Monte-Carlo analysis described here in order to assess the reliability levels of semi-active isolated buildings subjected to different practical and economical limits of peak base displacements and peak top floor accelerations under near-fault earthquakes.

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