ON THE LINEARIZATION OF THE SEISMIC BEHAVIOR OF SEISMIC ISOLATION SYSTEMS

E. Mavronicola[1], P. Polycarpou[2], L. Papaloizou[3], M.C. Phocas[4], P. Komodromos[5]

[1] *M.Sc. Student, Dept. Civil and Environmental Engineering, University of Cyprus, Cyprus*
[2,3] *PhD Candidates, Dept. Civil and Environmental Engineering, University of Cyprus, Cyprus*
[4] *Assistant Professor, Dept. of Architecture, University of Cyprus, Cyprus*
[5] *Lecturer, Dept. Civil and Environmental Engineering, University of Cyprus, Cyprus*
Email: ce03me1@ucy.ac.cy

ABSTRACT:

Seismic isolation is used in relatively stiff buildings to reduce their induced seismic loads, by shifting their fundamental periods outside the dangerous for resonance range. Seismic isolation systems exhibit non-linear inelastic behavior, which can be sufficiently well represented by a bilinear model. However, simplified linear elastic analysis is often used, at least at the preliminary design and analysis phases of seismically isolated buildings. Therefore, it is very important to investigate the appropriateness of using linearized models by comparing their computed responses with those of the more accurate bilinear models. In particular, this research work investigates whether linearized models are suitable for the analysis of seismically isolated buildings, considering the maximum relative displacements at the isolation level, the peak interstory deflections and the absolute floor accelerations. A number of numerical simulations and parametric studies have been performed, using specially-developed software, to obtain an insight on the suitability of using equivalent linear elastic models to simulate seismically isolated buildings, and identify how that is affected by certain structural parameters and earthquake characteristics.

KEYWORDS: Seismic-isolation, bilinear behavior, linearized model, effective stiffness and damping.

1. INTRODUCTION

Seismic isolation, is increasingly used, the last couple of decades, in order to minimize the earthquake induced loads in low- to medium-rise buildings and to mitigate structural and non-structural damage (Naeim & Kelly, 1999; Komodromos, 2000). Seismic isolation is usually implemented by incorporating flexible isolators, typically at the base of a building, in order to shift its fundamental period outside of the dangerous for resonance range. Avoiding resonance, reduces significantly the floor accelerations and the inertia forces that are developed, which minimizes damage of sensitive equipment that may be housed in the building. The inelastic interstory deflections are substantially reduced due to the almost rigid-body motion of the superstructure. Large deformations are confined at the isolators, which are capable to experience such cycles of inelastic deformations. Additional damping, provided usually within the isolation system, reduces the expected relative displacements at the isolation level. Nevertheless, a wide seismic gap must be provided, as a clearance around the building, to facilitate the expected large relative displacements and limit the possibility of poundings with the adjacent moat wall or with neighboring buildings during severe earthquakes (Komodromos et al., 2007).

Although, most seismic isolation systems, such as the lead rubber bearings, exhibit nonlinear, essentially bilinear, inelastic behavior, equivalent linear elastic models are often used in order to simplify the design and analysis of seismically isolated buildings. The linearization of the bilinear behavior of isolation systems is based on the definition of equivalent, or effective, characteristics, such as the effective stiffness and the effective viscous damping ratio. The comparison of linear elastic and bilinear inelastic models for seismic isolators has been studied by other researchers in the past (Hwang & Sheng, 1993; Hwang 1996; Hwang & Chiou, 1996; Dicleli & Buddaram, 2006; Dicleli & Buddaram, 2007a). However, that research has mainly focused on bridge applications, while very limited research work has been carried out for multistory buildings. Matsagar and

Jangid (2004) analyzed the influence of isolator characteristics on the seismic response of base-isolated structures modeled as multi-degree of freedom (MDOF) systems. That research work suggested that equivalent linear elastic models underestimate the superstructure accelerations and overestimate design displacements, showing that the response of base-isolated buildings is significantly influenced by the shape and parameters of the bilinear hysteresis loop of the isolator. Dicleli and Buddaram (2007b) also examined the accuracy of equivalent linear analysis, considering single-degree of freedom (SDOF) systems, and concluded that the equivalent linear elastic models underpredict design displacements. Their parametric analyses showed that the equivalent linear elastic analysis produces more reasonable estimates of the bilinear responses for ground motions with larger intensities relative to the characteristic strength of the isolator.

In this study, we examine further whether linearized models are suitable for the analysis of seismically isolated buildings, using MDOF systems, and how certain structural parameters and earthquake characteristics influence the suitability of such linearizations. In particular, the seismic response quantities obtained by equivalent linear elastic analysis procedures for multistory buildings are compared with the corresponding response quantities obtained from bilinear analyses. The maximum displacements at the isolation level, the maximum interstory deflections and the maximum floor accelerations, are selected as the most important response measures.

2. MODELLING OF SEISMICALLY ISOLATED BUILDINGS

2.1. Modeling of the seismically isolated superstructure

While past research studies are limited mostly to bridges and SDOF systems, in the present research work we examine multistory seismically isolated buildings modeled to have shear-beam behavior with one lateral degree-of-freedom at each floor (Figure 1.a), and with the isolation system installed at the base of the building. The superstructure is assumed to remain within the linear elastic range during the earthquake excitation, which is a single horizontal component of ground motion.

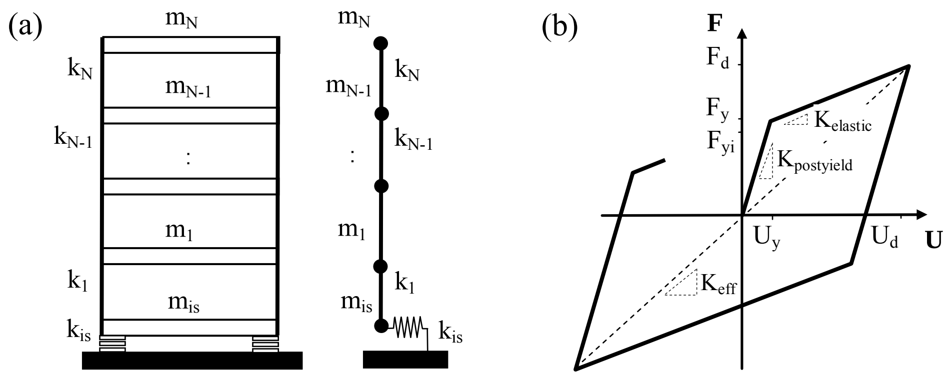

Figure 1: (a) Model of an N-story seismically isolated structure, (b) bilinear hysteretic model of the isolator.

2.2. Modeling of the isolation system

Among the most commonly used seismic isolation systems are the elastomeric bearings with one or more lead plugs, which provide both high initial stiffness and hysteretic energy dissipation. Although the behavior of these isolators is essentially bilinear inelastic (Figure 1.b), equivalent linear elastic models are often used to simplify the design and analysis of such systems, avoiding costly nonlinear inelastic analyses. The equivalent linear elastic model is based on effective properties, i.e effective stiffness and effective viscous damping ratio, that are defined for the seismic isolation system so as to approximate its nonlinear inelastic seismic responses.

In the bilinear force-deformation behavior of the isolation system, as illustrated in Figure 1.b, F_{yi} is the characteristic strength, $K_{elastic}$ is the elastic stiffness, $K_{postyield}$ is the postyield stiffness, F_y and U_y , the yield force and displacement, respectively, while U_d is the design displacement of the isolator corresponding to the maximum force, F_d. The effective stiffness, K_{eff}, of the isolation system is defined by the slope of the force-displacement curve at the maximum displacement, U_d , through Eqn 2.1.

$$K_{eff} = \frac{F_d}{U_d} = \frac{F_{yi}}{U_d} + K_{postyield} \tag{2.1}$$

The effective viscous damping ratio, ξ_{eff}, of the isolator is specified so as to represent the hysteretic energy dissipation due the actual nonlinear inelastic behavior. Usually, the effective viscous damping ratio is defined based on the area that is enclosed by the hysteresis loop of Figure 2.b, through Eqn 2.2.

$$\xi_{eff} = \frac{4\,F_{yi}\left(U_d - U_y\right)}{2\pi\,K_{eff}\,U_d{}^2} \tag{2.2}$$

2.2.1. Equivalent Linear Analysis Procedure

In this research work a special iteration procedure is used, after the initial estimation of the equivalent linear elastic properties of the isolators, in terms of the effective stiffness, K_{eff} and viscous damping ratio, ξ_{eff}, seeking to improve the initial estimates for the characteristics of the equivalent linear elastic model. In particular, estimations of the effective stiffness and viscous damping ratio, considering a corresponding SDOF system and a design spectrum, are used as initial values for the MDOF system. Then, for each ground excitation, the design displacement, U_d, is calculated, through linear elastic analysis, and new, improved effective stiffness and damping ratio are obtained. If the difference between the new and the previous estimations of the effective stiffness is sufficiently small, the iterations terminate. Otherwise, the new estimation of equivalent characteristics is used for the next round of iterations. Eventually, after some iterations and linear analyses, the effective stiffness and damping ratio are determined more precisely, for the particular seismic excitation.

3. SIMULATIONS - PARAMETRIC STUDIES

Based on the described assumptions, a software application has been specifically developed in order to efficiently perform large numbers of dynamic simulations of seismically isolated buildings using both linear and bilinear models. An Object-Oriented Programming (OOP) approach and the Java programming language have been utilized to design and implement a flexible and extendable software application with effective visualization capabilities that is used in the numerical simulations and parametric analyses. Using the developed software, a large number of simulations of seismically isolated buildings have been conducted under harmonic excitations and a range of earthquake excitations to assess the influence of ground motion characteristics and isolator properties on the suitability of the linearized models.

A typical 3-story and a typical 5-story seismically isolated building are used in the parametric studies with a *240 tons* lumped mass at each floor and a *180 tons* for the roof mass. Each story has a horizontal stiffness of *340 MN/m*. An additional mass of *240 tons* is assumed to be lumped at the isolation level, while the characteristics of the isolation system were selected so that the fundamental period of the isolated building is about three times the fundamental period of the superstructure when fixed supported (*0.349 sec* and *0.560 sec*, for the 3- and 5-story buildings, respectively). The bilinear properties of the isolation system for the 3-story building were selected as follows: $K_{elastic} = 245000\,kN/m$, $K_{postyield} = 24500\,kN/m$ and for the 5-story building were taken as follows: $K_{elastic} = 90000\,kN/m$, $K_{postyield} = 9000\,kN/m$, $F_y = 0.10 \cdot W_{tot}$, where W_{tot} is the total weight of the building considering *0.5 g* design ground acceleration. A viscous damping ratio equal to *2 %* was assumed for the superstructure as well as for the bilinear isolation system, while energy is dissipated hysteretically at the isolators due to inelastic deformations.

3.1. Evaluation using harmonic excitations

In order to consider the effect of the excitation frequency on the suitability of the linearized model, a set of harmonic ground motions is used. Specifically, the response of multistory base isolated buildings is investigated under harmonic ground motions with excitation periods, T_g, ranging between *0.3 sec* and *1.0 sec*, which correspond to peak ground acceleration (*PGA*) to peak ground velocity (*PGV*), *PGA/PGV*, ratios between *6.28* and *20.94 sec*$^{-1}$. The harmonic ground excitations are scaled to have *PGAs* between *0.2 g* and *0.6 g*.

The computed values of the equivalent viscous damping ratios, ξ_{eff}, according to Eqn 2.2, are shown is Figure 2.a for a range of excitation periods and values of *PGA*. Figure 2.b shows the maximum ratio of the relative displacements at the isolation level using bilinear inelastic to those using linear elastic modeling for the 3- and 5-story buildings, with the effective viscous damping ratio computed by Eqn 2.2. The influence of the intensity and the frequency-content of the ground motion to the value of the effective viscous damping ratio, ξ_{eff} and to the accuracy of the computed relative displacements at the isolation level using the linear elastic model is significant. In general, the ratios of the displacements using the equivalent linear elastic model to the corresponding displacements using the bilinear model tend to decrease with the increase of T_g. In particular, for the 3-story building the results indicate that the displacements at the isolation level are overestimated, by the linear elastic analysis, for harmonic ground excitations with higher frequency content ($PGA/PGV>10$).

In practice, a constant effective damping ratio, equal to about *15 %*, is often assumed and used, independently of the intensity and characteristics of the excitation. In order to examine the validity of such assumption, a comparison of the displacements at the isolation level, using the linear model with constant viscous damping ratio, is also considered. Figure 2.c displays the $U_{bilinear}/U_{linear}$ ratios in terms of the excitation period of the harmonic ground excitations for various PGAs. As expected, comparing this figure with Figure 2.b shows that when the effective damping ratio ξ_{eff}, calculated by Eqn 2.2 is larger than *15 %*, displacements at the isolation level, using the equivalent linear model with constant effective damping compared to the displacements computed when the effective viscous damping ratio according to Eqn 2.2, are overestimated, while the opposite occurs, when the effective damping ratio that is calculated by Eqn 2.2 is smaller than *15 %*. Evaluating the deviation of the $U_{bilinear}/U_{linear}$ ratio for the desired value of *1.0*, for the 3- and 5-story building, respectively, it is interesting to note that the linearized model may provide more accurate results, when a constant effective viscous damping ratio is used, than when the effective viscous damping ratio is computed by Eqn 2.2.

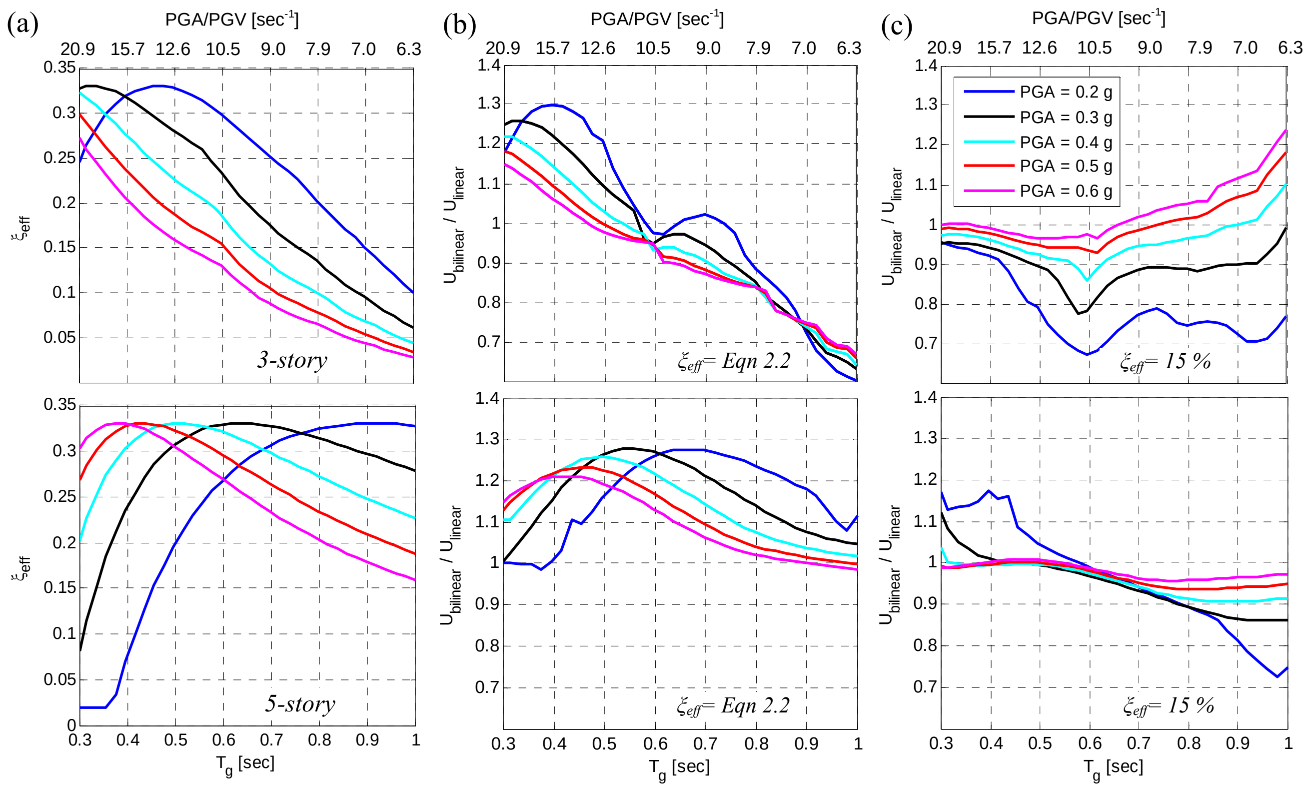

Figure 2: (a) Effective damping according to Eqn 2.2, (b, c) Maximum isolation displacement ratio with ξ_{eff} calculated from to Eqn 2.2 or set to a constant *15 %* value, respectively.

3.2. Evaluation using ground motion excitations

Next, a set of earthquake excitations (Table 1), are used, after appropriately scaled to have specific values of PGA according to the parametric analyses that are held.

Table 1: Earthquake records used in the analyses.

	Earthquake	Station	PGA [m/sec^2]	PGV [m/sec]	PGA/PGV [sec^{-1}]
	El Centro, 1940	Imperial Valley, Comp 180	3.41	0.381	8.950
	Kobe, 1995	JMA Station, Comp 0	8.05	0.813	9.902
	Northridge, 1994	Olive View	5.93	0.774	7.662
	Northridge, 1994	Converter Station	8.80	1.022	8.611
	San Fernando, 1971	Pacoima Dam, Comp 164	11.48	1.146	10.018
	Kocaeli, 1999	Duzce-Meteoroloji Mudurlugu West	3.54	0.540	6.556

3.2.1 Effect of $K_{elastic}/K_{postyield}$ ratio of the seismic isolation system

A comparison of the response quantities of the 3- and 5-story base isolated buildings is done for the bilinear and the equivalent linear models with the $K_{elastic}/K_{postyield}$ ratio varying between *5* and *15*. The ratios of the relative displacements at the isolation level, $U_{bilinear}/U_{linear}$, maximum interstory displacements, $\Delta u_{bilinear}/\Delta u_{linear}$ and maximum absolute floor accelerations, $A_{abs,bilinear}/A_{abs,bilinear}$ for both models are presented in Figure 3 and 4, for the different levels of *PGA*, *0.5 g* and *1.0 g*, respectively. It is observed that the ratio $K_{elastic}/K_{postyield}$ does not, in general, considerably influence the ratio of the maximum displacement at the isolation level, $U_{bilinear}/U_{linear}$, which seems to be affected mostly by characteristics and intensity of the excitation. The scattering of the ratio $U_{bilinear}/U_{linear}$ of the computed displacements using the bilinear models to those of the equivalent linear elastic models, ranges between *30 %* and *50 %*.

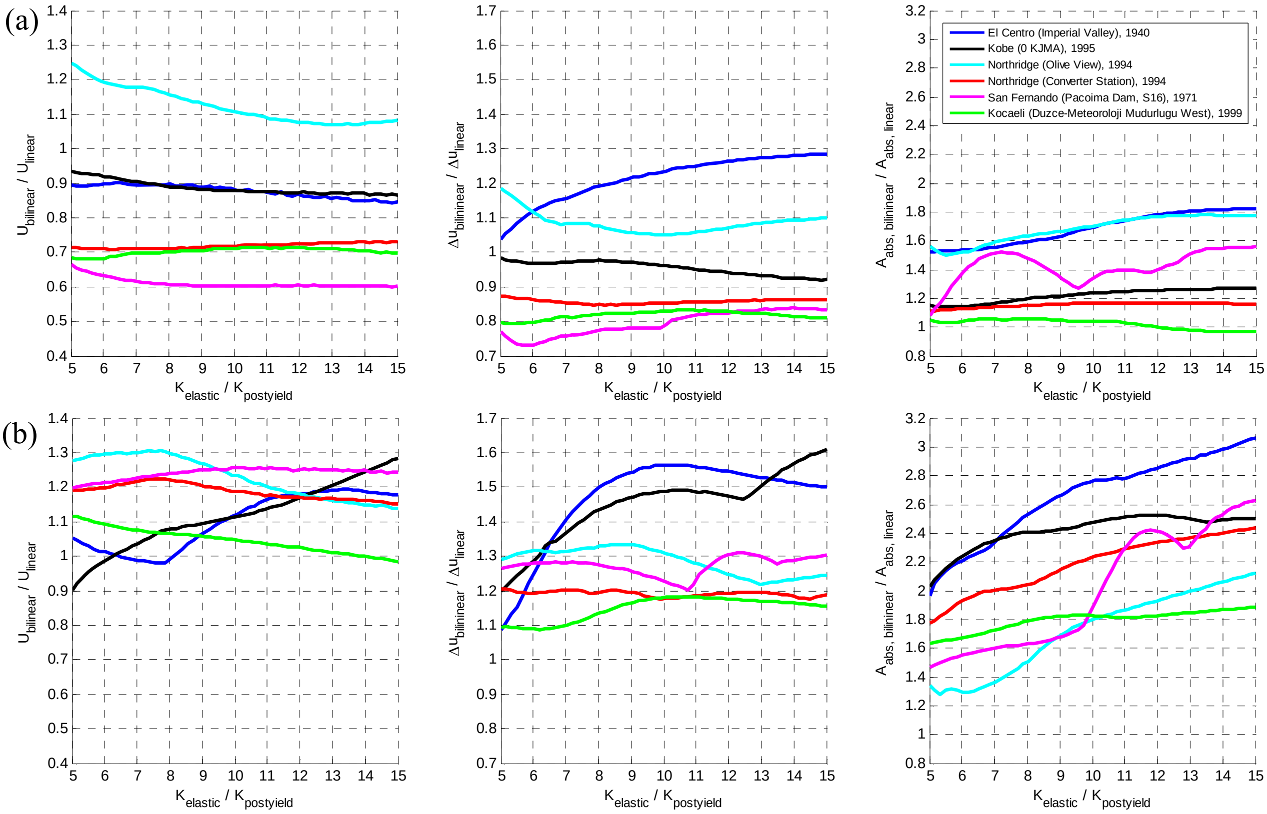

Figure 3: Ratio of the equivalent linear elastic analyses results to those of the bilinear inelastic analyses for varying ratio $K_{elastic}/K_{postyield}$ under *PGA = 0.5 g*: (a) 3-story and (b) 5-story building.

The discrepancy between the displacements at the isolation level computed with the bilinear model and those computed with the linearized model are reduced with the increase of the intensity of the earthquake. The computed maximum relative displacements at the isolation level using the equivalent linear model are closer to those computed by the bilinear model for *PGA* equal to *1.0 g* (Figure 4), than those for PGA equal to *0.5 g* (Figure 3). This finding may be important since the estimation of the required seismic gap that must be ensured around a seismically isolated building should be based on the maximum credible earthquake that is expected in the specific region, so as to avoid the possibility of poundings during severe earthquakes.

According to the results (Figures 3 and 4) the $K_{elastic}/K_{postyield}$ ratio does not significantly influence the maximum relative displacements ratio, $\Delta u_{bilinear}/\Delta u_{linear}$, which is also affected mostly by the characteristics and intensity of the earthquake excitation. The ratios of the maximum absolute floor accelerations obtained from bilinear inelastic analyses to those obtained from equivalent linear analyses, $A_{abs,bilinear}/A_{abs,linear}$, are also more influenced by the earthquake excitation, rather than the characteristics of the isolation system. Specifically, the results indicate that the peak absolute floor accelerations are, in general, underestimated, up to *3* times, accordingly to absolute accelerations that are calculated using the more accurate bilinear model. Finally, the analyses results obtained using equivalent linear model for PGA equal to *1.0 g* are, again, relative more precise than the corresponding results obtained for *PGA* equal to *0.5 g*.

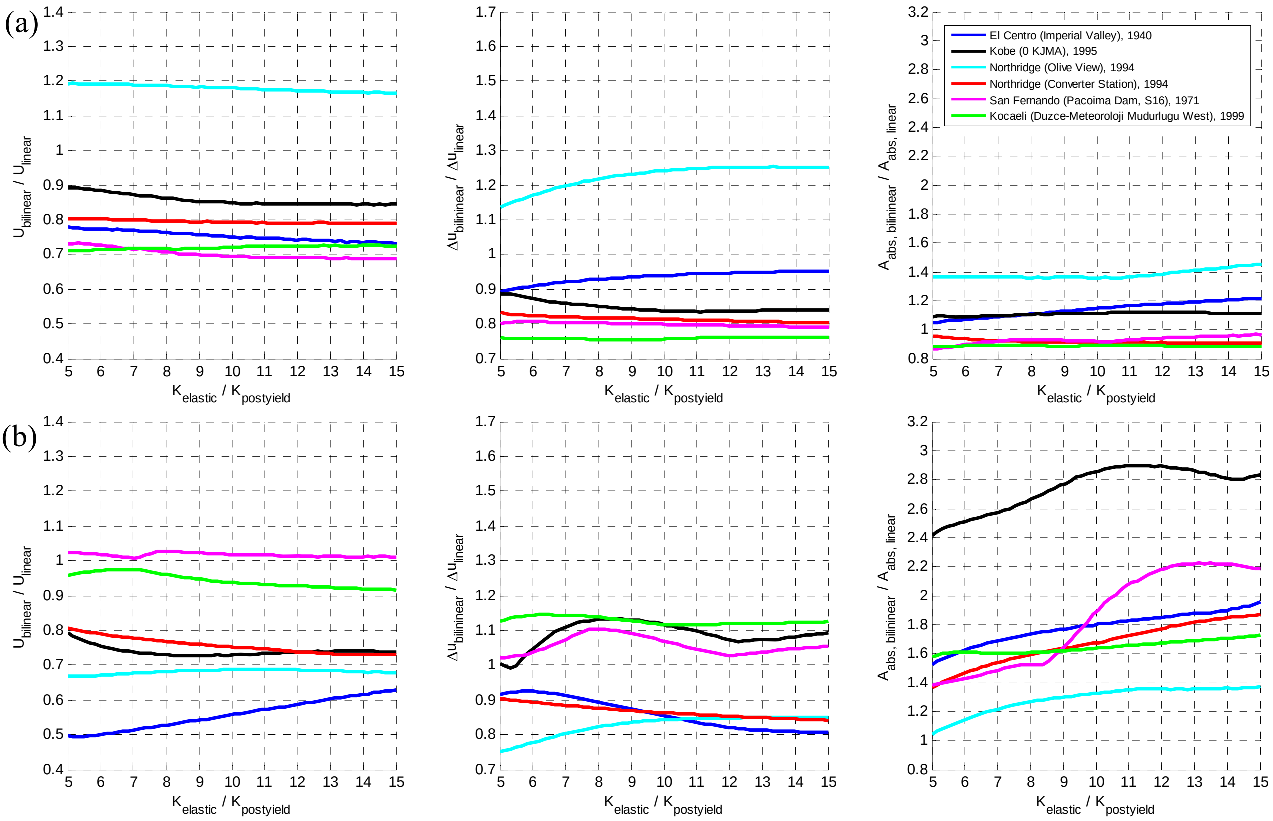

Figure 4: Ratio of the equivalent linear elastic analyses results to those of the bilinear inelastic analyses for varying ratio $K_{elastic}/K_{postyield}$ under $PGA = 1.0\,g$: (a) 3-story and (b) 5-story building.

3.2.2 Effect of F_{yi}/W_{tot} ratio of the seismic isolation system

A seismic isolation system maintains its initial, elastic, stiffness up to a fraction of the building's total weight without exceeding the yield force level of the isolators. The shear force that can be transferred by the initial, high, stiffness of the seismic isolation system is about *10 %* of the total weight of the structure. Another set of simulations has been conducted in order to examine the effect of the yield force of the isolation system as a fraction of the total weight of the structure, varying the F_{yi}/W_{tot} ratio between *5 %* and *15 %*. Figures 5 and 6 present the results of this parametric analysis, for *PGA* equal to *0.5 g* and *1.0 g*, respectively, for all 6 earthquake excitations, while the $K_{elastic}/K_{postyield}$ ratio was kept equal to *10*.

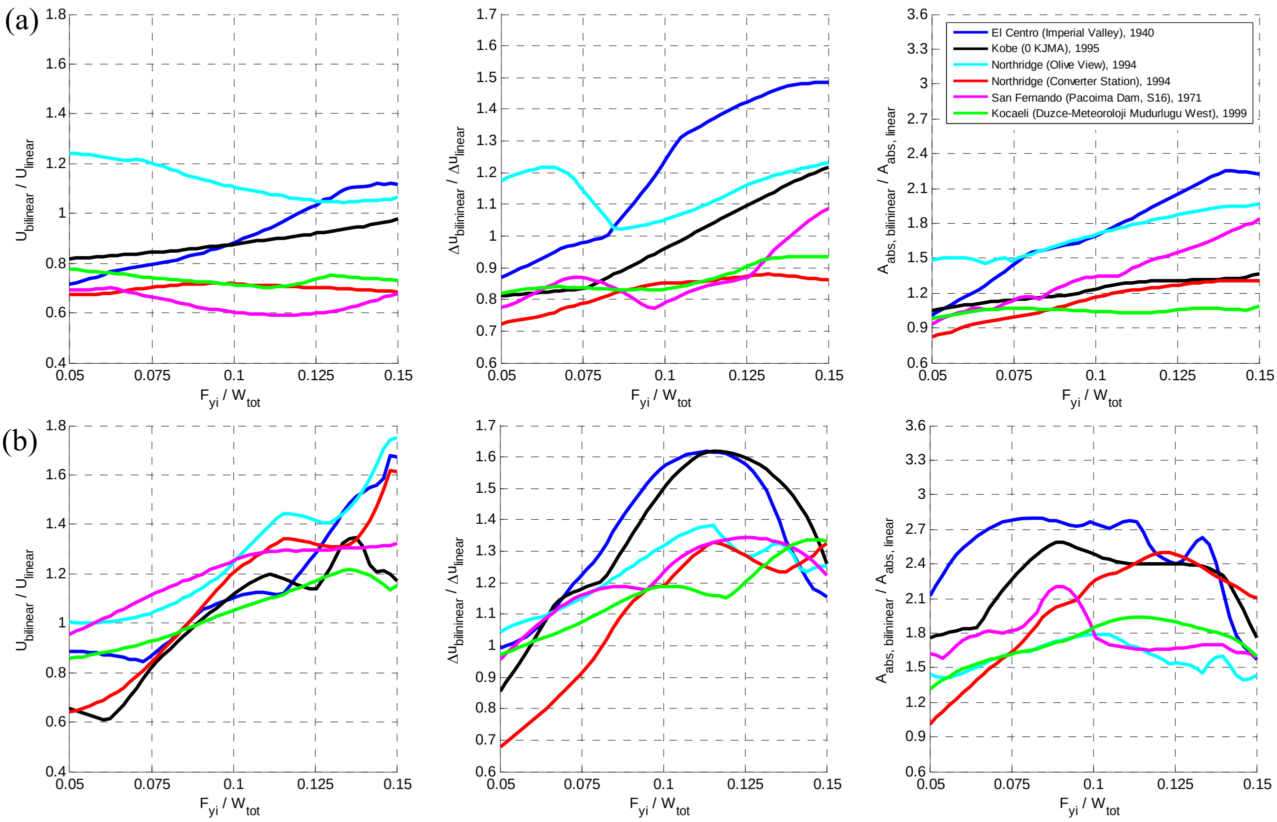

Figure 5: Ratio of the equivalent linear elastic analyses results to those of the bilinear inelastic analyses for varying ratio F_{yi}/W_{tot} under $PGA = 0.5\ g$: (a) 3-story and (b) 5-story building.

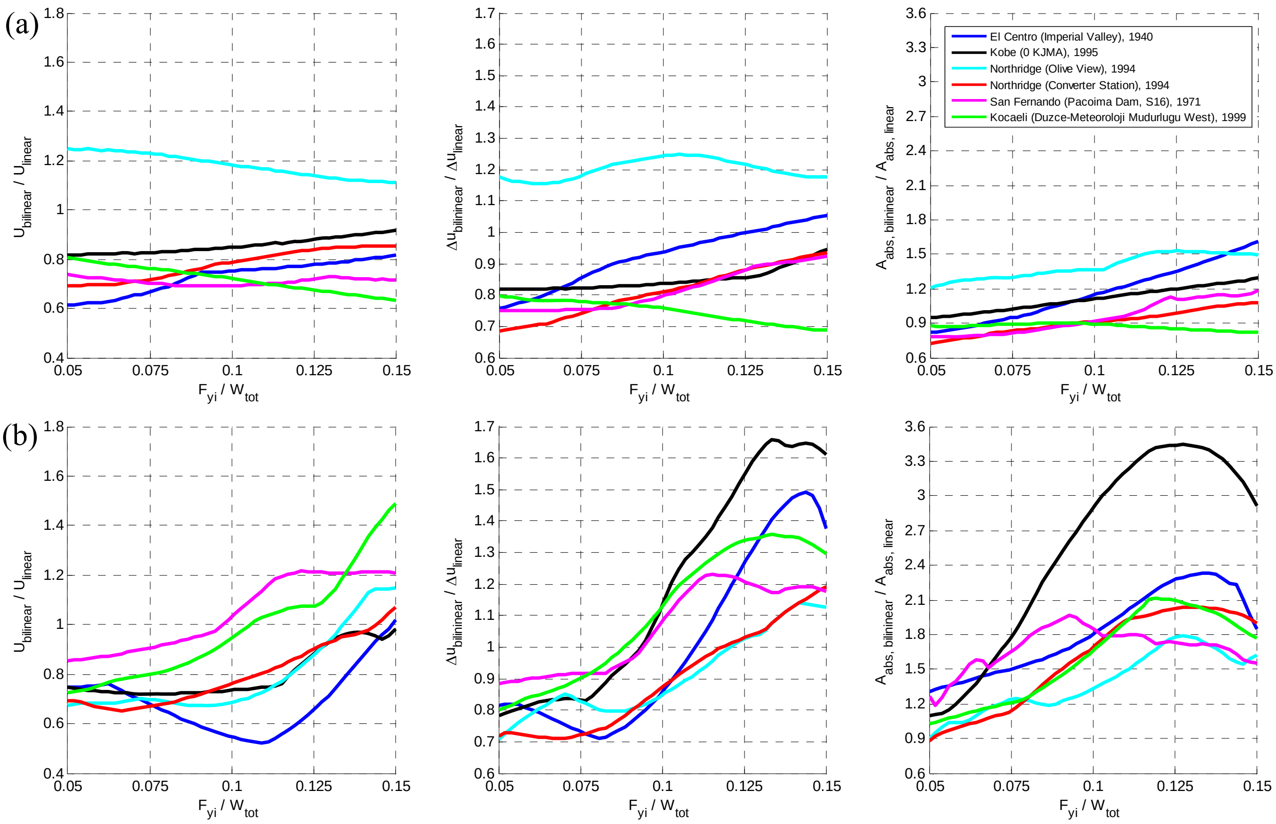

Figure 6: Ratio of the equivalent linear elastic analyses results to those of the bilinear inelastic analyses for varying ratio F_{yi}/W_{tot} under $PGA = 1.0\ g$: (a) 3-story and (b) 5-story building.

For the 3-story building, it is observed that the F_{yi}/W_{tot} ratio does not, in general, influence the ratio of the maximum displacements at the isolation level, $U_{bilinear}/U_{linear}$. The characteristics and the intensity of the seismic excitation appear again to influence significantly the $U_{bilinear}/U_{linear}$ ratio, which is relatively constant and with dispersion, that reaches *20-40 %.* Although, the maximum relative displacements ratio and the maximum absolute floor accelerations obtained from bilinear inelastic analyses to those obtained from equivalent linear elastic analyses, , $\Delta u_{bilinear}/\Delta u_{linear}$ and $A_{abs,bilinear}/A_{abs,linear}$, respectively, are influenced by the F_{yi}/W_{tot} ratio and tend to be underestimated with the increase of that ratio. The simulation results presented in Figures 5.b and 6.b, for the 5-story building, reveal that there is a considerable dispersion of the $U_{bilinear}/U_{linear}$ ratios for the range of F_{yi}/W_{tot} ratio that is examined. Furthermore, the results indicate that the response quantities are, in general, underestimated with the increase of the F_{yi}/W_{tot} ratio.

4. CONCLUSIONS

This research work aims to investigate the suitability of using linearized elastic models for the analysis of seismically isolated multistory buildings by comparing their computed responses with those computed with the more accurate bilinear inelastic models for the isolation system. Performing a number of parametric studies, using a 3- and a 5-story seismically isolated building, the effects of the earthquake characteristics and the isolation system properties are assessed. The results indicate that the estimation of the effective viscous damping ratio influences considerably the analysis. The formula that is usually used to estimate the effective viscous damping ratio may not provide appropriate values for the linearized elastic analysis. The parametric studies show that the excitation characteristics and intensity influence greatly the precision of the results and should be taken into account. Furthermore, the characteristics of the isolation system, in particular the $K_{elastic}/K_{postyield}$ do not seem to affect considerably the accuracy of the computed ratio of the maximum displacements at the isolation level, $U_{bilinear}/U_{linear}$. Also, the results show that the response quantities tend to be underestimated with the increase of the F_{yi}/W_{tot} ratio. Finally, the significant discrepancies between the results obtained by the bilinear inelastic analysis and those when a simplified linear elastic analysis is used, suggest that either better linearized models should be devised, or the more accurate bilinear inelastic analysis should be used.

REFERENCES

Dicleli, M. and Buddaram, S. (2006). Improved Effective Damping Equation for Equivalent Linear Analysis of Seismic-Isolated Bridges, *Earthquake Spectra*, **22:1**, pp. 29-46.

Dicleli, M. and Buddaram, S. (2007a). Equivalent linear analysis of seismic-isolated bridges subjected to near-fault ground motions with forward rupture directivity effect, *Engineering Structures*, **29**, pp. 21-32.

Dicleli, M. and Buddaram, S. (2007b). Comprehensive evaluation of equivalent linear analysis method for seismic-isolated structures represented by sdof systems, *Engineering Structures*, **29**, pp. 1653-1663.

Hwang, J.S. and Sheng, L.H. (1993). Effective stiffness and equivalent damping of base-isolated bridges, *Journal of Structural Engineering*, **119:10**, pp. 3094–3101.

Hwang, J.S. (1996). Evaluation of equivalent linear analysis methods of bridge isolation, *Journal of Structural Engineering*, **122:8**, pp. 972–976.

Hwang, J.S. and Chiou J.M. (1996). An equivalent linear model of lead-rubber seismic isolation bearings, *Engineering Structures*, **18:7**, pp. 528-536.

Komodromos, P. (2000). Seismic Isolation for Earthquake Resistant Structures, WIT Press, Southampton, UK.

Komodromos, P., Polycarpou, P., Papaloizou, L. and Phocas, M.C. (2007). Response of Seismically Isolated Buildings Considering Poundings, *Earthquake Engineering and Structural Dynamics*, **36**, pp. 1605-1622.

Matsagar, V.A. and Jangid, R.S. (2004). Influence of isolator characteristics on the response of base-isolated structures, *Engineering Structures*, **26**, pp. 1735-1749.

Naeim, F. and Kelly, J.M. (1999). Design of Seismic Isolated Structures, John Wiley & Sons: Wellington, New Zealand.