The effect of non-linear parameters on the modeling of multi-storey seismically isolated buildings

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SUMMARY:
Seismic isolation is used in relatively stiff buildings to reduce the transfer of seismic-induced loads on the superstructure by shifting their fundamental periods outside the dangerous for resonance range. Several base isolation systems have been proposed, the most common of which are the lead rubber bearings. Their force-displacement behavior is commonly approximated through bilinear inelastic or equivalent linearized models, although such isolators exhibit non-linear phenomena. In this paper, a more detailed non-linear inelastic model has been employed, the Bouc-Wen hysteresis model, in order to investigate the accuracy of the response quantities obtained by the commonly employed bilinear and equivalent linear elastic analysis procedures. A series of numerical simulations has been performed to obtain insights on the effect of non-linear parameters of the isolation system on the accuracy of the analysis of multi-storey seismically isolated buildings, and identify how that may be influenced by certain parameters and earthquake characteristics.

Keywords: Seismic isolation, non-linear effects, Bouc-Wen hysteresis model, bilinear and linearized models

1. INTRODUCTION

Seismic isolation is the most successful passive control methodology that can be used to prevent the disastrous consequences of severe earthquake excitations. The underlying idea is to uncouple the superstructure from strong seismic ground motions in order to reduce the induced seismic loads. This is typically achieved by shifting the fundamental period of a building outside the dangerous for resonance range incorporating flexibility, typically in the horizontal directions, through seismic isolators, which are often installed at the base of the building. By substantially decreasing the induced seismic loads, the interstory deflections and floor accelerations are significantly reduced, while damage of the structural and non-structural components can be avoided.

Among the most commonly used seismic isolation systems are the Lead Rubber Bearings (LRBs), which provide both high initial stiffness and hysteretic energy dissipation (Fig. 1.1). LRBs are essentially elastomeric bearings in which one or more lead cylinders are inserted in order to provide an additional hysteretic energy dissipation mechanism. The rubber ensures the necessary restoring force in order to avoid permanent relative displacements at the isolation level, while the presence of the lead plugs provide initial rigidity for minor horizontal loads, e.g. service loads, such as wind effects, prior to the yielding of the lead-plug.

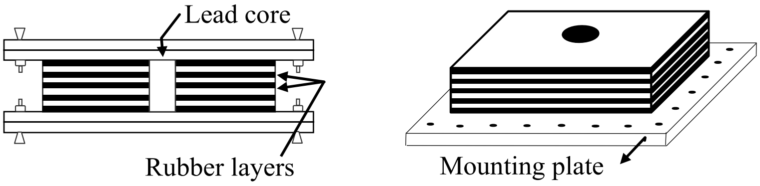

Figure 1.1: Lead Rubber Bearings.

A bilinear model is commonly employed in the literature to model the behaviour of LRBs (Robinson, 1982; Nagarajaiah et al, 1991). Early research efforts in evaluating the appropriateness of using equivalent linear elastic models can be traced back to the work of Iwan and Gates (1979) who compared the accuracy of nine different damping models for estimating the response of bilinear inelastic systems. Furthermore, several simplified equivalent linear models have been proposed by other researchers to represent the force-displacement behavior of isolators, applying mostly on seismically isolated bridges and single degree-of-freedom systems (e.g., Iwan, 1980; Hwang and Sheng 1993; Hwang and Sheng 1994; Hwang and Chiou, 1996; Jara and Casas, 2006). Limited research work has been carried out for buildings to investigate the influence of isolator characteristics on their seismic behavior and response (Matsagar and Jangid, 2004; Dicleli and Buddaram, 2007; Mavronicola and Komodromos, 2011).

Experimental results, however, indicate that the shear force-displacement relationship of seismic isolation systems, such as LRBs is characterized by high nonlinearities. It is natural to assume that accurate prediction of the seismic behavior of a base-isolated building depends on the accuracy of the mathematical model of the isolation bearings. According to results presented by Ramallo et al. (2002), the Bouc-Wen model provides accurate prediction to experimental data. Thus, further research is required to study the effect of LRB characteristics on the response of MDOF seismically isolated structures.

This research work focuses on the accuracy of the widely used bilinear model and the equivalent linear model proposed by AASHTO (1991). The main objective is to assess the validity of the bilinear and the corresponding equivalent linear models for describing the complex nonlinear hysteretic behavior of LRBs. To this end the seismic response quantities obtained from simplified analysis are compared with those computed using the more advanced Bouc-Wen model of hysteresis.

2. MODELING OF THE ISOLATION SYSTEM

2.1. The Hysteresis Bouc-Wen Model

The nonlinear hysteresis model of Bouc (1967), as extended by Wen and Park et al. (1986) is able to represent a large class of hysteretic behavior. According to the Bouc-Wen model, which gives an analytical description of a smooth hysteretic behavior, the restoring force, F_{nl}, can be expressed in relation to the base displacement, u_b, as a combination of an elastic and plastic force and can be expressed as

$$F_{nl} = \alpha \frac{F_y}{u_y} u_b + (1-\alpha) F_y z \tag{2.1}$$

where u_y is the yield displacement corresponding to the yield force F_y, α is the stiffness hardening ratio of the isolator and z is a dimensionless hysteretic parameter. The range of z is $|z| \le 1$, which follows a first-order differential equation with zero initial condition:

$$\dot{z} = \frac{1}{u_y} \left\{ A \dot{u}_b - \gamma |\dot{u}_b| z |z|^{n-1} - \beta \dot{u}_b |z|^n \right\} \tag{2.2}$$

where A, β, γ, n are dimensionless quantities controlling the scale and shape of the hysteresis loop. More specifically, parameters β and γ define the shape of the hysteretic loop (softening or hardening), parameter A controls the restoring force amplitude and tangent stiffness, n defines the smoothness of the transition from elastic to inelastic regime in the force-deformation relationship. It should be noted that for $n \to \infty$ the hysteresis model is reduced to the bilinear case.

It therefore becomes apparent that by adjusting the dimensionless parameters, one can construct a variety of restoring forces, such as hardening or softening, narrow or wide-band systems (Wen, 1976). It should be mentioned that when $\beta=\gamma=0.0$ the relation between the restoring force and displacement is linear, while the case $\beta=\gamma=0.5$ can be used as a model for an elastoplastic system with smooth transition. Constantinou et al. (1990) have shown that the interaction curve between the forces in the two directions is circular only when this condition is satisfied. When the commonly selected parameters for lead rubber bearings ($A=1$, $\beta=\gamma=0.5$) are chosen the above equations reduce into

$$\dot{z}=\frac{K_{elastic}}{F_y}\cdot\begin{cases}\dot{u}_b\left[1-|z|^n\right] & \text{if } \dot{u}_b\cdot z>0\\ \dot{u}_b & \text{otherwise}\end{cases} \tag{2.3}$$

2.2. The Simplified Bilinear and Equivalent Linear Models

The behavior of a lead rubber bearing can be well repesented as a bilinear hysteretic element. In that case the bilinear behavior is justified by the yielding of the lead core after a certain shear force. In particular, prior to the yielding of the lead core, the isolation system has an initial stiffness $K_{elastic}$, which is much higher than the post-yield stiffness $K_{post\text{-}yield}$ that corresponds solely to the stiffness of the rubber (Fig. 2.1b).

At a preliminary design stage, it is common practice to approximate the nonlinear behavior with a simplified equivalent linear damping and stiffness in order to avoid a complex and time-consuming nonlinear analysis. As per the most commonly used specifications for the dynamic analysis of a seismically isolated structure, those published by the American Association of State Highway Transportation Officials (AASHTO), the equivalent linearization of nonlinear isolation systems is based on the determination of equivalent, or effective, characteristics, specifically the effective stiffness and the effective viscous damping ratio, in order to represent both the deformation forces and the energy dissipation during earthquake excitations.

In particular, 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 Equation (2.4), as shown in Fig. 2.1c.

$$K_{eff}=\frac{F_d}{u_d}=\frac{F_{yi}}{u_d}+K_{post\text{-}yield} \tag{2.4}$$

The effective viscous damping ratio, ξ_{eff}, of the isolator is specified so as to represent the hysteretic energy dissipated due to the bilinear inelastic behavior. It is commonly defined based on the area that is enclosed by the hysteresis loop at the design displacement, through Equation (2.5).

$$\xi_{eff}=\frac{4F_{yi}\left(u_d\text{-}u_y\right)}{2\pi K_{eff}\,u_d^2} \tag{2.5}$$

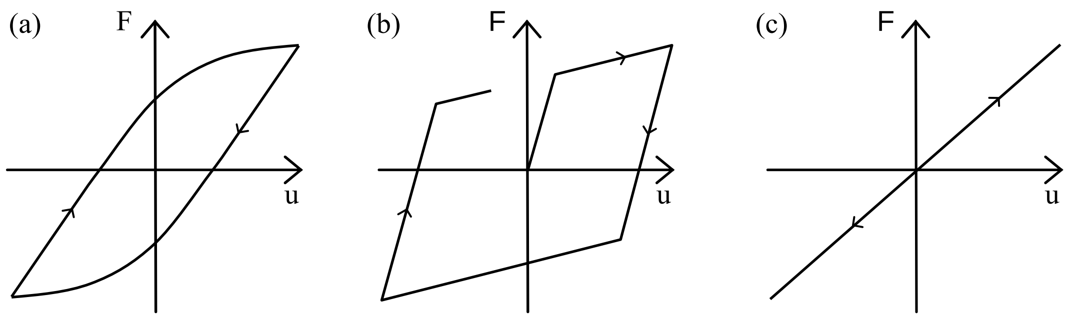

Figure 2.1: Typical force-displacement characteristics for the (a) Bouc-Wen, (b) bilinear and (c) linear models.

3. COMPARATIVE STUDIES

A software application has been specifically developed in order to efficiently perform large numbers of dynamic simulations of seismically isolated buildings using Bouc-Wen hysteresis model, as well as with the corresponding bilinear and equivalent linear models. An object-oriented programming approach and the Java programming language have been utilized to design and implement a flexible and extendable software application with effective visualization capabilities that can be used in relevant numerical simulations and parametric analyses.

The algorithm developed involves the solution of equations of motion using the unconditionally stable Newmark's method and the solution of the differential equation governing the behavior of the Bouc-Wen isolation elements using the implicit Runge-Kutta method. Comparison with results obtained using the general purpose program SAP2000 are conducted for verification of the developed algorithm.

3.1 Analysis Assumptions

In the current research work, the superstructure is modeled as a shear type structure mounted on seismic isolation systems with one lateral degree-of-freedom at each floor and the masses lumped at the floor levels, assuming that the superstructure remain linear elastic during earthquake excitations. Additionally, the system is subjected to single horizontal component of the earthquake ground motion, while the effects of soil–structure interaction are not taken into consideration.

A typical 6-story seismically isolated building is used in the parametric studies with a 250 tons lumped mass at each floor and a 200 tons for the roof mass. Each story has a horizontal stiffness of 320MN/m. An additional mass of 250 tons is assumed to be lumped at the isolation level. A viscous damping ratio equal to 2.0 % was assumed for the superstructure and the isolation system, while energy is dissipated hysteretically at the isolators due to inelastic deformations.

In order to evaluate the appropriateness of the bilinear and the corresponding linearized elastic models, a set of earthquake excitations is used (Table 1), after appropriately been scaled to have specific values of peak ground acceleration (PGA) according to the parametric analyses performed.

Table 1: Earthquake records that were used in the simulations.

Earthquake	Mw	Station	PGA [g]
Kobe, Japan 1995	6.9	JMA Station, Comp 0	0.82
Northridge, USA 1994	6.7	24514 Sylmar - Olive View Med FF	0.60
Northridge, USA 1994	6.4	74 Sylmar - Converter Station	0.90
San Fernando, USA 1971	6.4	Pacoima Dam, Comp 164	1.17
Chi-Chi, Taiwan 1999	7.6	CHY080	0.96

3.2 Evaluation of Response Quantities

The seismic response of the selected multi-storey seismically isolated building is investigated, while the maximum relative displacements at the isolation level, the maximum interstory deflections and the peak absolute floor accelerations are selected as the most important response measures. The accuracy of the dynamic response obtained by the bilinear model and the corresponding equivalent linear elastic model, respectively, are quantified by the magnitude of the error with respect to the corresponding response provided when the Bouc-Wen behavior of the isolation system is used in the simulations. Positive sign of the percentage error indicates overestimation of the response in comparison with the more accurate Bouc-Wen results, while negative signs indicate underestimation of the actual response.

3.3 Evaluation of the Bilinear and the Corresponding Equivalent Linear Elastic Models

3.3.1. Effect of post-yield to elastic stiffness ratio on the accuracy of simplified models

The degree of the non-linearity of bilinear systems can be expressed as the stiffness hardening ratio, α, which is the ratio of the post-yield to the elastic stiffness. A high degree of non-linearity may excite higher modes and cause higher absolute floor accelerations. A comparison of the response quantities of the 6-story seismically isolated buildings is performed for the Bouc-Wen, the bilinear and the equivalent linear models with the stiffness hardening ratio, α, varied between 0.05 and 0.20 while the post-yield stiffness was set equal to 8,500 KN/m, and the F_{yi} / W_{tot} was kept constant equal to 5.0%.

Fig. 3.1 presents the relative errors of the maximum relative displacements at the isolation level of the 6-story structure obtained by the bilinear and the equivalent linear model proposed by AASHTO, for a PGA equal to 0.4 and 0.8 g, respectively, with respect to the corresponding responses from the more accurate hysteretic Bouc-Wen model. According to the computed responses (left column of Fig. 3.1), the error of the peak displacement at the isolation level considering the bilinear model varies within -5.0 to 5.0%. while for larger PGA the error appears to be further suppressed. Furthermore, the stiffness hardening ratio does not considerably influence the relative errors of the equivalent linear model which seems to be influenced mostly by the characteristics of the earthquake excitations.

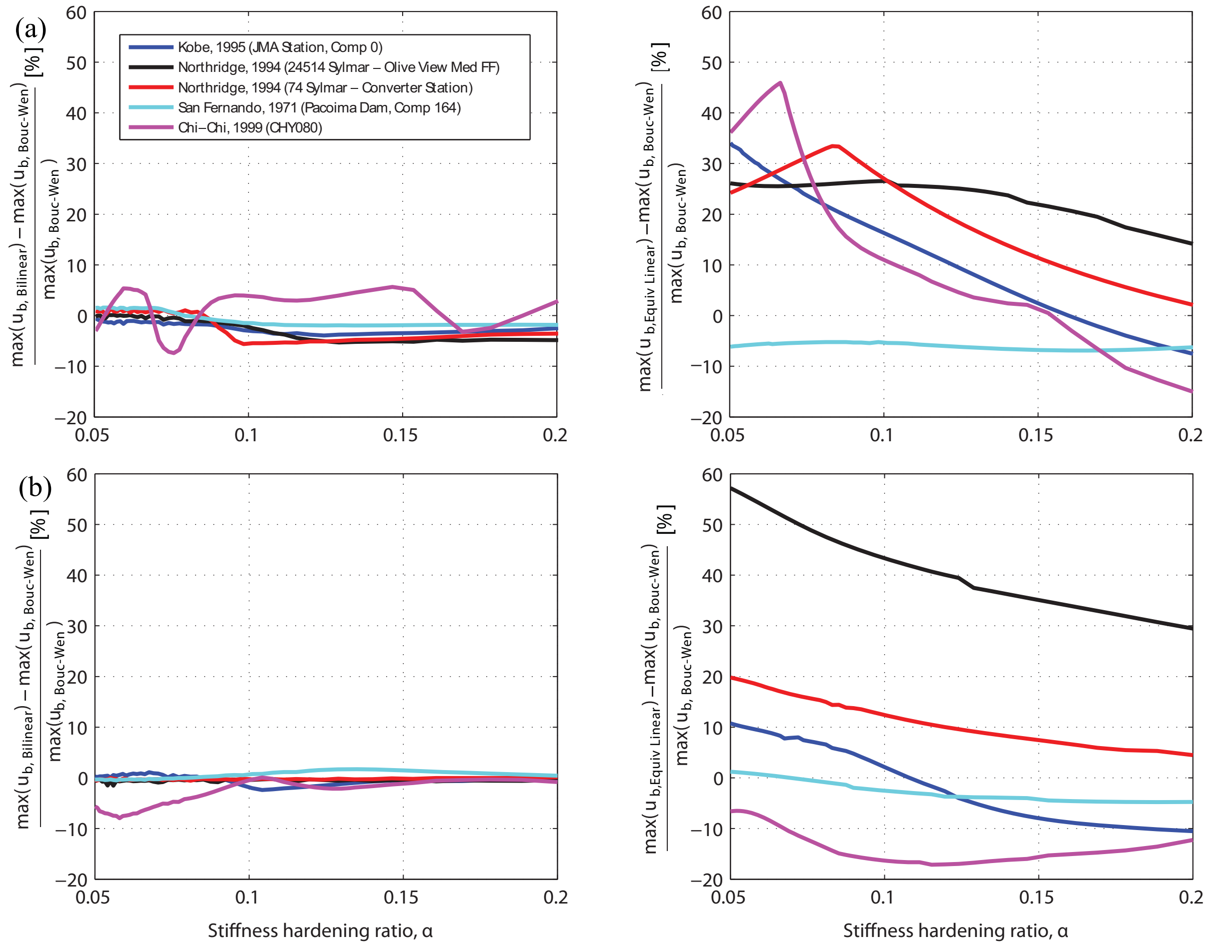

Figure 3.1. Relative errors of the maximum relative displacements at the isolation level considering the proposed bilinear and the corresponding equivalent linear model, varying α, under the selected earthquake excitations, scaled to a (a) PGA =0.4g and (b) PGA = 0.8g.

The much more pronounced elative errors of the maximum relative displacements at the isolation level considering the proposed linearized model, as illustrated in the right column of Fig. 3.1 for a PGA equal to 0.4 and 0.8g, are also mostly influenced by the characteristics of the earthquake excitation. In general, the proposed linearized model overestimates the relative displacements at the isolation level, compared to the more accurate Bouc-Wen hysteresis model. It is also worth noting that the errors tend to decrease with the increase of the stiffness hardening ratio. It can also be observed that the scattering of the errors is more significant for higher PGAs. In particular, for a 0.8g PGA the error of the maximum relative displacements at the isolation level varies between -20 to +65 % (Fig. 3.1b), while for a 0.4g PGA it varies between -15 and +45 % (Fig. 3.1a). The magnitude of the errors is very critical, since the estimation of the required gap that must be ensured around a seismically isolated building should be based on the most severe credible earthquake that is expected, so as to avoid pounding with adjacent structures during strong earthquakes.

Fig. 3.2a presents the relative errors of the maximum interstory deflections of the 6-story seismically isolated building obtained by the proposed bilinear and the corresponding linearized model (right column), respectively, for a PGA equal to 0.4g, as compared to the responses obtained by the more accurate Bouc-Wen model. In general, the maximum relative displacements at the isolation level obtained by the bilinear model (Fig. 3.2a, left column) are overestimated, up to about +18%. Additionally, Fig. 3.2a shows that the stiffness hardening ratio does not considerably influence the relative errors of the maximum interstory deflections obtained by the equivalent linear model, which seems to be dependent mostly be the earthquake characteristics. Moreover, for this particular set of excitations the deviation appears to stabilize for stiffness ratios greater than 0.15.

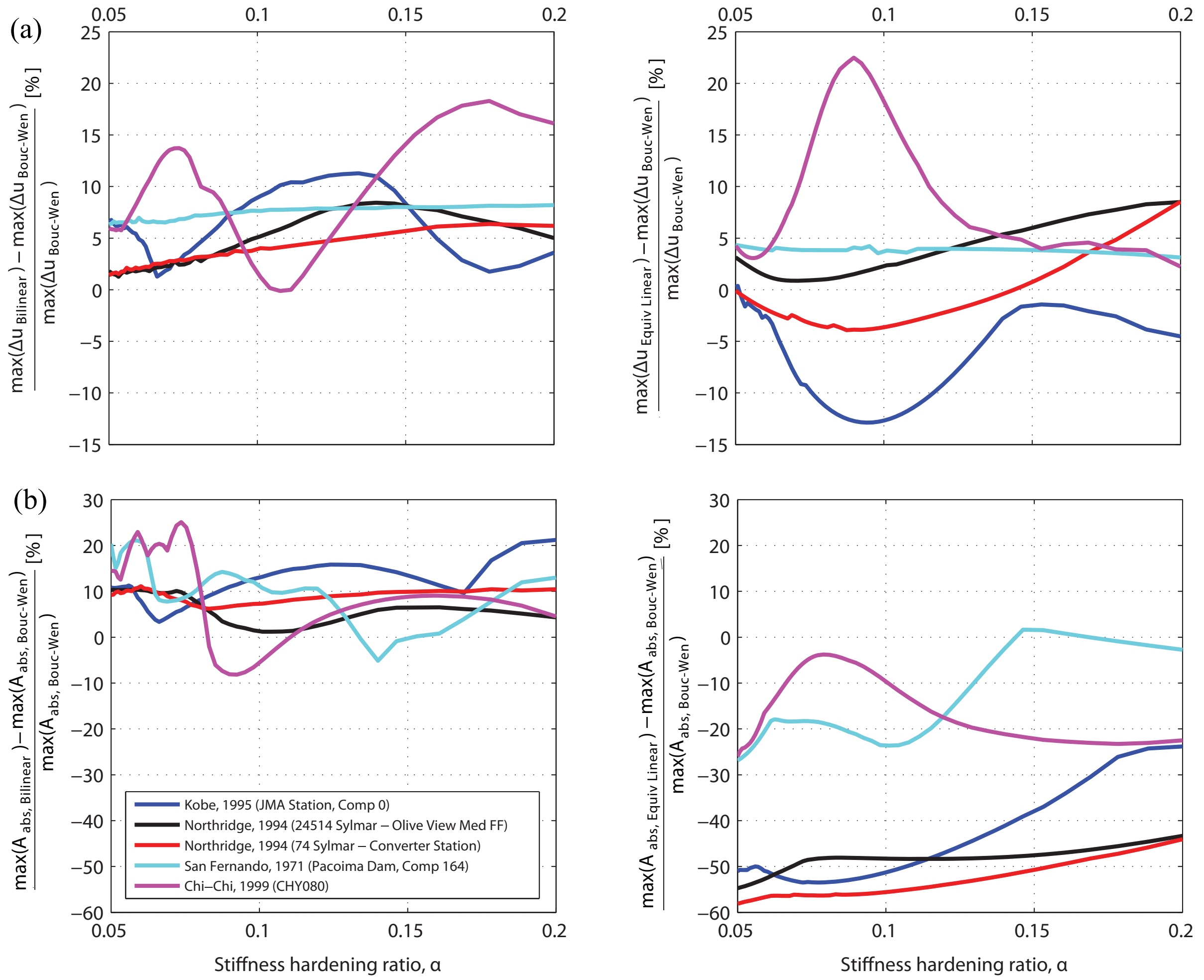

Figure 3.2. Relative errors of (a) the maximum interstory deflections, (b) the peak absolute floor accelerations considering the proposed bilinear and the corresponding equivalent linear model, varying α, under the selected earthquake excitations, scaled to a PGA =0.4g.

The relative errors of the peak absolute floor accelerations obtained by the proposed bilinear and the corresponding linearized model, respectively, as illustrated in Fig. 3.2 for a PGA equal to 0.4 g, are also mostly influenced by the characteristics of the earthquake excitation. In general, the bilinear model overestimates the peak absolute floor accelerations of the seismically isolated structure up to +25%. In contrast, to the tendency of the bilinear model to overestimate the responses as compared to the Bouc-Wen analysis, the equivalent linear model consistently underestimates the peak floor accelerations with recorder deviations up to -60%.

3.3.1. Effect of F_{yi}/W_{tot} ratio on the accuracy of simplified models

The second parameter considered in this study is the characteristic strength, F_{yi} normalized by the weight acting on the isolator, W_{tot}. Therefore, a set of simulations has been conducted varying the ratio between 2.0 to 8.0%, while the hardening stiffness hardening ratio was kept equal to 10. Note that at each simulation, the elastic and post–yield stiffness were selected so that the fundamental period of the isolated building is about three times the fundamental period of the superstructure when fixed supported, considering 0.5g as the design ground acceleration.

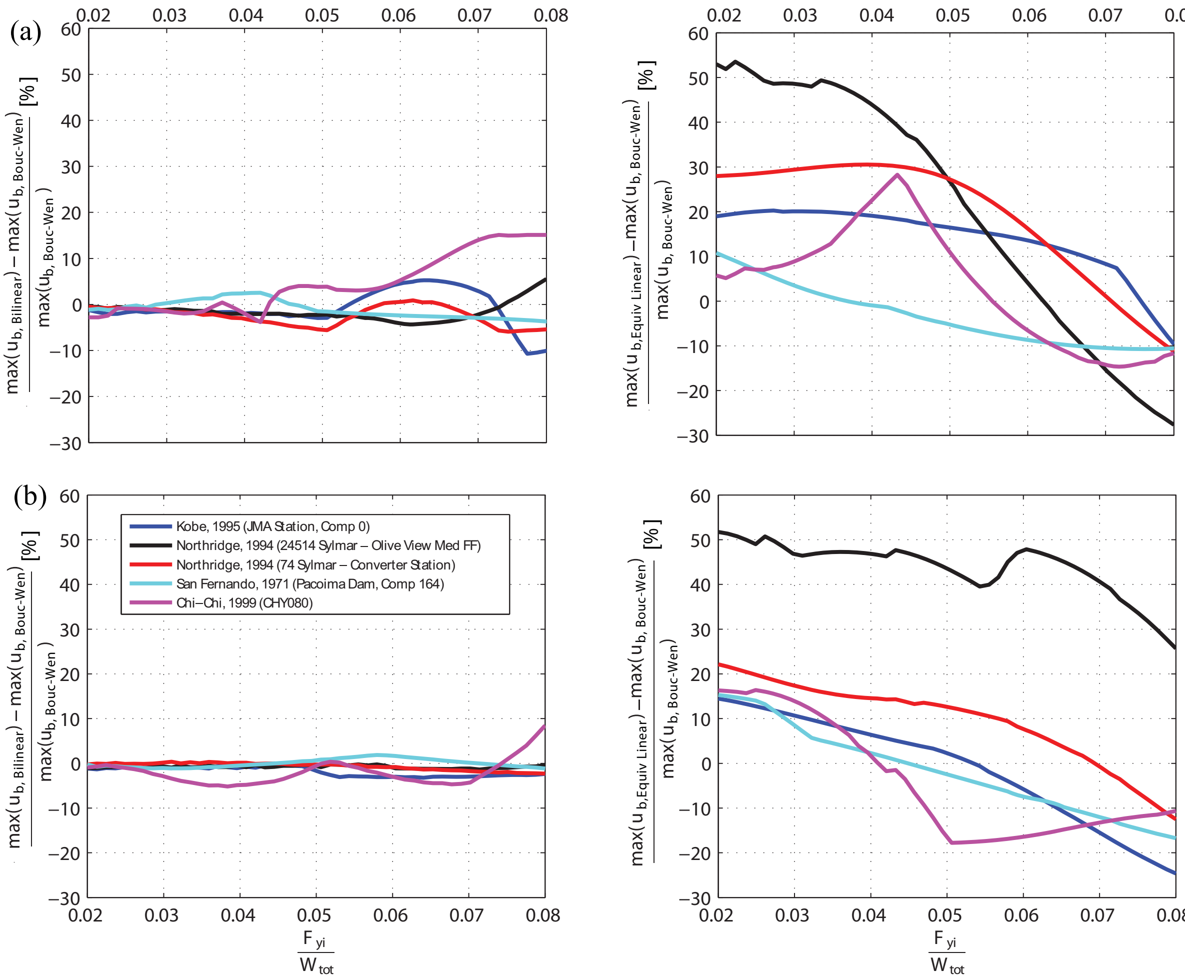

Figure 3.3. Relative errors of the maximum relative displacements at the isolation level considering the proposed bilinear and the corresponding equivalent linear model, varying F_{yi}/W_{tot} ratio, under the selected earthquake excitations, scaled to a (a) PGA =0.4g and (b) PGA = 0.8g.

Fig. 3.3 presents the relative errors of the maximum displacements at the isolation level obtained by the bilinear and the equivalent linear model proposed by AASHTO, for a PGA equal to 0.4 and 0.8g, respectively, with respect to the corresponding responses from the more accurate hysteretic Bouc-Wen model, as a function of the varying the F_{yi}/W_{tot} ratio. According to the computer responses, the discrepancy of error of the peak displacement at the isolation level considering the bilinear model (left column) is significantly lower compared to the error of the responses obtained using the equivalent linear model proposed by AASHTO (right column).

The error of the maximum relative displacements at the isolation level obtained by the bilinear model tends to increase for higher F_{yi}/W_{tot} ratios. The results indicate that the maximum relative displacements at the isolation level obtained by the equivalent linear model are primarily affected by the excitation characteristics. Furthermore, for small F_{yi}/W_{tot} ratios the response is in general overestimated, while as the F_{yi}/W_{tot} ratio increases the tendency is for the error to reduce. In fact, for most earthquake excitations negative errors (underestimation) are reported for large F_{yi}/W_{tot} ratios with magnitudes reaching values down to -30%.

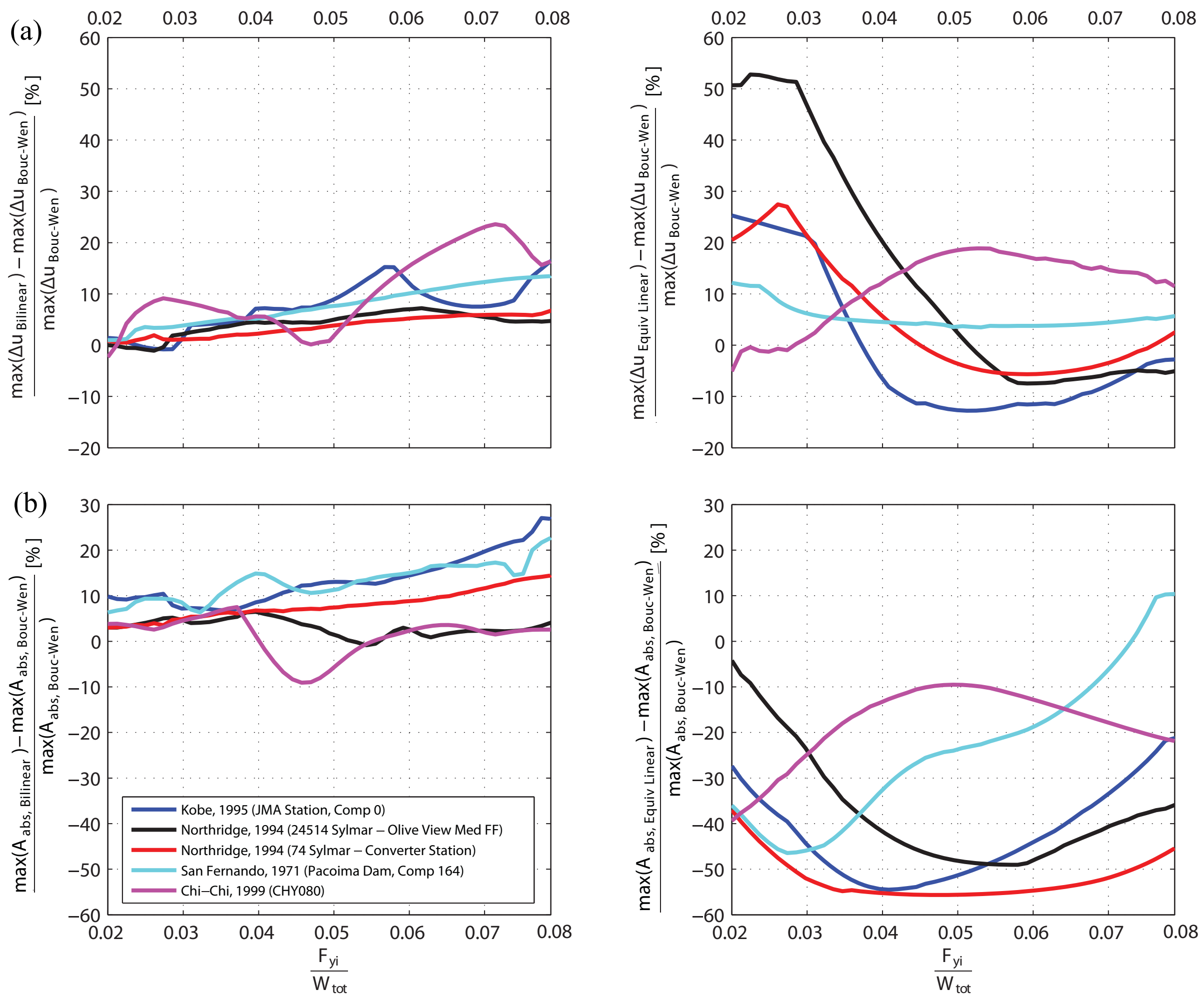

Figure 3.4. Relative errors of (a) the maximum interstory deflections, (b) the peak absolute floor accelerations considering the proposed bilinear and the corresponding equivalent linear model, varying F_{yi}/W_{tot} ratio, under the selected earthquake excitations, scaled to a PGA =0.4g.

Fig. 3.4a and 3.4b present the relative errors of the simplified models in comparison to the Bouc-Wen for the maximum interstory deflections and the peak absolute floor accelerations respectively. The earthquake excitations for these simulations have been scale to a PGA of 0.4g. In general, the response quantities obtained by the bilinear model (left column) are overestimated. Additionally, the results indicate that as F_{yi}/W_{tot} ratio increases the bilinear response tends to be more conservative, with errors reaching values up to approximately +25%.

Fig. 3.4a (right column) shows that the difference between the maximum interstory deflections using the equivalent linear elastic model proposed by AASHTO and the more realistic Bouc-Wen model depends both on the excitation characteristics and the F_{yi}/W_{tot} ratio. Moreover, the relative errors of the peak absolute floor acceleration obtained by the corresponding linearized model, as illustrated in Fig. 3.4b (right column), are very scattered without any specific tendency. The response values are also mostly influenced by the characteristics of the earthquake excitation and they are, in general, underestimated with deviations reaching -60%, in contrast to the mostly overestimated peak absolute floor accelerations obtained using the bilinear model.

4. CONCLUDING REMARKS

This research work has assessed the discrepancies of the computed responses of interest of multi-storey seismically isolated buildings while using the commonly employed bilinear inelastic and the equivalent linear elastic analysis procedures instead of a more accurate nonlinear model, such as the Bouc-Wen model. By performing a number of parametric analyses, using a 6-story seismically isolated building, the effect of non-linear parameters of the isolation system on the accuracy of the structural response has been investigated. In general, the errors depend on all parameters that have been considered, specifically the earthquake excitation characteristics, the hardening stiffness ratio and the ratio of the characteristic strength to the building's total weight. The discrepancies of the computed responses between the more accurate Bouc-Wen model and the linearized approach proposed by AASHTO are much more substantial than those while using the bilinear inelastic model. Thus, a bilinear inelastic analysis seems to be more appropriate to use, for the design and analysis of seismically isolated buildings, than a linearized model.

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