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On the response of base-isolated buildings using bilinear models for LRBs subjected to pulse-like ground motions: sharp vs. smooth behaviour

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Abstract. Seismic isolation has been established as an effective earthquake-resistant design method and the lead rubber bearings (LRBs) are among the most commonly used seismic isolation systems. In the scientific literature, a sharp bilinear model is often used for capturing the hysteretic behaviour of the LRBs in the analysis of seismically isolated structures, although the actual behaviour of the LRBs can be more accurately represented utilizing smoothed plasticity, as captured by the Bouc-Wen model. Discrepancies between these two models are quantified in terms of the computed peak relative displacements at the isolation level, as well as the peak inter-storey deflections and the absolute top-floor accelerations, for the case of base-isolated buildings modelled as multi degree-of-freedom systems. Numerical simulations under pulse-like ground motions have been performed to assess the effect of non-linear parameters of the seismic isolation system and characteristics of both the superstructure and the earthquake excitation, on the accuracy of the computed peak structural responses. Through parametric analyses, this paper assesses potential inaccuracies of the computed peak seismic response when the sharp bilinear model is employed for modelling the LRBs instead of the more accurate and smoother Bouc-Wen model.

Keywords: seismic isolation; base-isolation; lead rubber bearings; bilinear model; Bouc-Wen model

1. Introduction

Seismic isolation can be used to prevent the disastrous consequences of severe earthquake excitations, usually by shifting the fundamental eigenperiods of relatively stiff buildings outside the dangerous for resonance range, in order to reduce the induced seismic loads. The elongation of the fundamental eigenperiod of a building is achieved by incorporating flexibility, in the form of seismic isolators that are, typically, installed at the base of the building. The superstructure of a seismically isolated building is oscillating as an almost rigid body, while the inter-storey deflections and the absolute floor accelerations can be substantially decreased so that potential damage of structural and non-structural components, as well as contents of the building, can be avoided (Skinner *et al*. 1993, Naeim and Kelly 1999, Komodromos 2000, Higashino and Okamoto 2006). Lateral deformations are confined at the seismic isolation level, where seismic isolators are

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specifically designed to be capable of accommodating cycles of large strains. Therefore, an energy dissipation mechanism must be provided at the isolation level and a sufficiently wide clearance must be ensured around a seismically isolated building in order to avoid potential structural pounding with the surrounding moat wall or adjacent structures during severe earthquakes (Polycarpou and Komodromos 2010, Mahmoud and Jankowski 2010, Polycarpou and Komodromos 2011, Masroor and Mosqueda 2012).

Among the most commonly used seismic isolators are the Lead Rubber Bearings (LRBs), Fig. 1(a), which are constructed of alternating layers of rubber pads and steel plates bonded together, where one or more lead plugs are vertically inserted in order to provide a high initial stiffness and an additional hysteretic energy dissipation mechanism. The elastomeric rubber ensures the necessary restoring force to prevent permanent relative displacements at the isolation level, while the lead plug dissipates energy hysteretically during severe earthquakes, as it is forced by the steel plates to deform inelastically in shear after exceeding its yield stress (Komodromos 2000). Numerous hysteretic models of various complexities have been proposed for the behaviour of LRBs (Nagarajaiah *et al.* 1991, Kikuchi and Aiken 1997, Fenves *et al.* 1998, Abe *et al.* 2004). These include bilinear hysteretic responses that have been widely used in general-purpose structural dynamics programs, as well as formulations suitable to represent the overall isolator behavior that require calibration on the basis of experimental data. Recent publications attempt to incorporate the deteriorating hysteretic behaviour exhibited by LRB's due to the heating of the lead core (Kalpakidis *et al.* 2010) into an improved model, which has been employed in research studies (Ozdemir 2014). Temperature effects on the LRB constitutive responses are not considered in this paper as its main focus is to quantify any discrepancies that might arise between the usage of the sharp and the smooth inelastic models.

Previous experimental results indicate that the shear force-displacement relationship of the LRBs is highly nonlinear and hysteretic, which can be well represented by the Bouc-Wen model, as shown with a solid line in Fig. 1(b). In particular, the nonlinear model of Bouc (1967), as extended by Wen (1976) and Park *et al.* (1986), is able to capture the hysteretic behaviour and the restoring force of the LRBs and is commonly employed in the literature (Nagarajaiah *et al.* 1991, Makris and Black 2004, Varnava and Komodromos 2013). Nagarajaiah and Xiaohong (2000) demonstrated that this model provides accurate results in close comparison to experimental data. In particular, the Bouc-Wen model provides an analytical relation for the smooth hysteretic behaviour and the restoring force of the seismic isolation system, F_b, which can be expressed as a combination of the elastic and plastic force components:

$$F_b = \alpha \frac{F_y}{u_y} u_b + (1-\alpha)\, F_y\, z \tag{1}$$

where u_y is the displacement corresponding to the yield force F_y; u_b represents the relative displacement at the isolation level; α is the ratio of the post-yield to the pre-yield elastic stiffness and z is a dimensionless hysteretic parameter, with the possible range of z being $|z| \leq 1$, which follows a first-order differential equation with zero initial conditions. The internal variable z, which controls the hysteretic behaviour, should satisfy the differential equation:

$$\dot{z} = \frac{1}{u_y}\left\{A\, \dot{u}_b - \gamma |\dot{u}_b|\, z|z|^{n-1} - \beta\, \dot{u}_b\, |z|^n\right\} \tag{2}$$

where A, β, γ, and n are dimensionless quantities controlling the scale and shape of the hysteresis loop. More precisely, parameters β and γ define the shape of the hysteretic loop (regarding

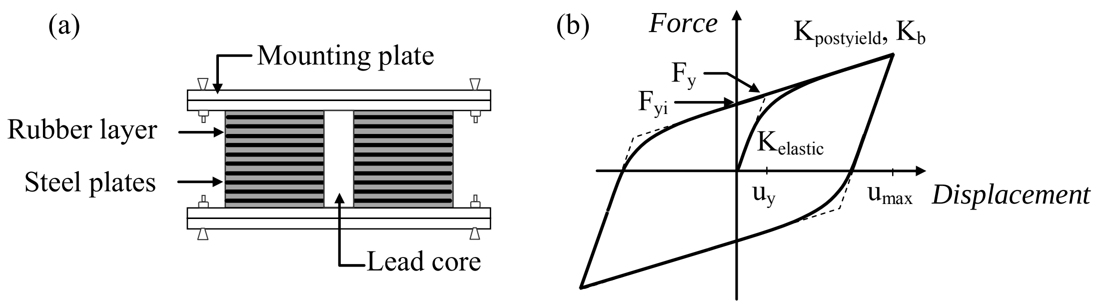

Fig. 1 (a) Cross-section, and (b) force-displacement behaviour of an LRB

softening or hardening), parameter A controls the restoring force amplitude and the tangent stiffness, while n defines the smoothness of the transition from an elastic to an inelastic range in the force-deformation relationship. As $n \rightarrow \infty$ the hysteresis model is reduced to the bilinear case.

By adjusting the above parameters, one can construct a variety of restoring forces, such as hardening or softening, narrow or wide-band systems (Sain *et al.* 1997). It should be mentioned that when $\beta=\gamma=0$ the relationship between the restoring force and the displacement is linear, while the interaction curve between the forces in the two directions is circular when the conditions A=1 and $\beta+\gamma= 1$ are satisfied (Constantinou *et al.* 1990, Fenves *et al.* 1998). When typical parameters for the LRBs, A=1 and $\beta=\gamma=0.5$, are used, Eq. (2) simplifies to:

$$\dot{z}(t) = \frac{K_{el}}{F_y} \begin{cases} \dot{u}(t)\left[1-\left|z(t)\right|^n\right] & \text{if } \dot{u}(t)\cdot z > 0 \\ \dot{u}(t) & \text{otherwise} \end{cases} \tag{3}$$

Several research studies for seismic isolation devices, such as the LRBs, suggested that a bilinear approximation of the shear force-deformation relationship might be adequate (Robinson 1982, Skinner et *al.* 1993, Kikuchi and Aiken 1997, Makris and Vassiliou 2011, Mavronicola and Komodromos 2011, Kampas and Makris 2012, Vassiliou *et al.* 2013). Following the AASHTO Guide Specifications for Seismic Isolation Design, an LRB can be modelled by a sharp bilinear inelastic model, which is characterized by the yielding of the lead core after a critical shear force is exceeded, as shown with a dashed line in Fig. 1(b). Prior to the yielding of the lead core, the LRB has an initial stiffness $K_{elastic}$, which is much higher than the post-yield stiffness $K_{postyield}$ that corresponds solely to the stiffness of the rubber.

Previous studies have examined the influence of the bilinear modelling of the LRBs' behaviour and the characteristics of the ground motion on the response of seismically isolated bridges (Huang *et al.* 2000, Hameed *et al.* 2008). While preliminary results of the LRBs' characteristics effect on the response of multi-degree of freedom (MDOF) structures have been presented (Jangid 2007, Matsagar and Jangid 2008, Providakis 2008), a systematic in-depth investigation on the accuracy of such an approximation is still missing and would be valuable for both research and practical purposes. The comparison presented by Bessasson (1992), considering a single degree-of-freedom model, suggested that the bilinear and the Bouc-Wen hysteresis models provide identical results if the controlling parameters for the two models are properly adjusted. However, according to the work of Ramallo *et al.* (2002), the bilinear model causes overestimation of the acceleration levels in base-isolated structures.

Considering that the sharp bilinear model is still in use in the scientific literature, this paper aims in showing the pitfalls that may arise from its usage. The investigation is performed using a software application that has been specifically developed to efficiently and effectively perform large numbers of dynamic simulations and parametric analyses of base-isolated buildings using both the sharp bilinear and the smooth Bouc-Wen models. Specifically, this paper provides (i) the comparison of the response of base-isolated buildings using the aforesaid nonlinear hysteresis models under pulse-like ground motions, and (ii) the assessment of the effect of certain structural parameters and earthquake characteristics on the discrepancies between the usage of the sharp and the smooth bilinear inelastic models.

2. Modelling and simulation details

2.1 Software development

In order to effectively perform the necessary numerical simulations for the fulfilment of the aims of this investigation, an extendable software application has been developed, using an object-oriented programming approach and the Java programming language. The specially developed software application enables the efficient performance of dynamic simulations and provides visualization capabilities that can be utilized to effectively monitor the performed numerical simulations and parametric analyses. The software application uses an algorithm that combines the solution of the equations of motion, using the unconditionally stable Newmark's method, and the solution of the differential equation governing the behaviour of the Bouc-Wen for the LRBs, based on the implicit Runge-Kutta method with a fixed time-step. Validation of the developed software has been carried out using SAP2000 with very good agreement of the computed results. However, conducting a simulation with SAP2000, or any other general-purpose structural analysis program, requires about 2−3 orders of magnitude more time than what is required to conduct the corresponding analysis with the software specifically developed for this purpose. This significant efficiency of the developed software allows the performance of large numbers of numerical simulations and parametric analyses, within a realistic time span.

2.2 Structural model

In this study, the responses of a 3- and a 5-storey base-isolated building are investigated. For simplicity, the analyses of the simulated structures are performed in two dimensions, while the superstructure of the seismically isolated building is modelled as a shear-type structure mounted on LRBs with one lateral degree-of-freedom at each floor and the masses lumped at the floor levels. It is assumed that the superstructure remains linear elastic during the induced earthquake excitations, which is justified by the rationale of using seismic isolation as an earthquake resistant design approach. The seismically isolated MDOF system is subjected to horizontal components of pulse-like excitations. Two typical base-isolated buildings with 340 tons lumped mass at each floor level and a roof mass of 250 tons have been selected and used in the analysis. An additional mass of 340 tons is assumed to be lumped at the seismic isolation level. Each storey has a horizontal stiffness of 600 MN/m whereas a viscous damping ratio equal to 2.0 % is assumed for the superstructure. It is noted that the energy dissipation of the seismic isolation system is restricted to the hysteretic damping that is taken into account explicitly by the nonlinear force-displacement behaviour. These assumptions are reasonable considering the purposes of this investigation.

2.3 Nonlinear hysteretic model of isolators

The simplified force-displacement behavior of the LRBs can be characterized by three parameters, namely: (i) the characteristic strength, F_{yi} (ii) the post-yield stiffness, $K_{postyield}$, and (iii) the yield displacement, u_y. In particular, the characteristic strength is defined as the force that is required to yield the lead core, and its ratio to the weight acting on the isolator, F_{yi}/W_{tot}, is one of the parameters considered in this study. The flexibility of the isolator is quantified through the post-yield stiffness of the system and is generally designed in such a way so as to provide a specific value for the isolation period (Matsagar and Jangid 2008), T_b, which approximates the post-yield fundamental eigenperiod of the base-isolated building and is expressed as:

$$T_b = 2\pi\sqrt{\frac{m_{tot}}{K_{postyield}}} \tag{4}$$

where m_{tot} is the total mass of the base-isolated structure. The third parameter evaluated in this study is the yield displacement of the isolation bearings, which typically ranges between 10 to 25mm, or more. In order to assess the effect of isolator characteristics on the potential inaccuracies of the peak response incorporated through the use of the sharp bilinear model for the LRBs, a significant number of LRBs with varying characteristics are considered. The selection of the specific ranges of the aforementioned parameters included in this study is selected based on previous research studies that investigated the optimum design parameters for LRBs (Park and Otsuka 1999, Jangid 2007, Matsagar and Jangid 2008).

2.4 Pulse-like ground motions

Previous research studies have shown that seismic ground motions characterized by intense velocities place extreme demands on structures (Makris and Black 2003, Mavroeidis *et al.* 2004). A collection of 50 accelerograms of a distinct pulse-type, which correspond to historic records from 18 different seismic events, have been selected from the Pacific Earthquake Engineering Research (PEER) Center database (Beta Version). The identification and characterization of records with pulse-like velocities is based on the work of Baker (2007), who utilized wavelet

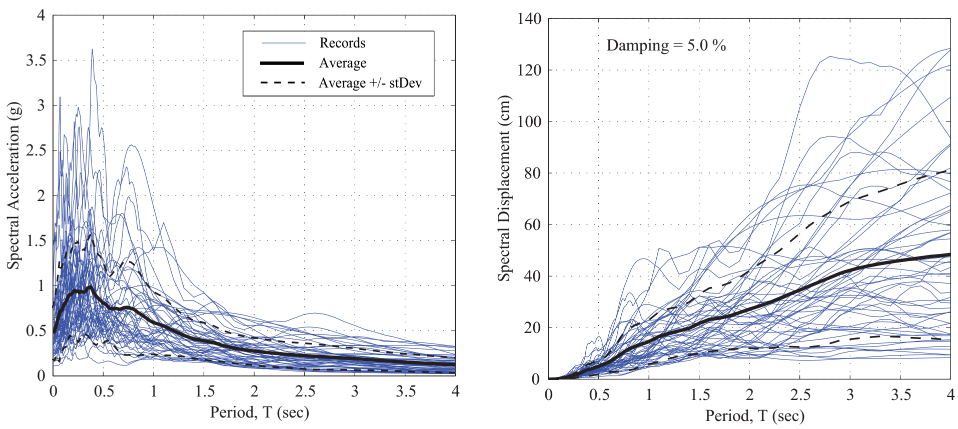

Fig. 2 Response spectra and average response spectra for the selected pulse-like ground motions

transforms. In the present study, further criteria have been imposed for the selection of the 50 ground motions: (a) magnitude of the earthquake $M_w \geq 6.0$; and (b) closest distance to the fault rupture $R_{rup} < 15$ km. The selected ground motions have been recorded during the action of the following earthquakes:

1. San Fernando 09/02/1971 (1 Station: Pacoima Dam−upper left abut).
2. Imperial Valley 15/10/1979 (10 Stations: Aeropuerto Mexicali, Agrarias, Brawley Airport, El Centro Array #10, El Centro Array #11, El Centro Array #4, El Centro Array #5, El Centro Array #8, El Centro Differential Array, Holtville Post Office).
3. Irpinia, Italy 23/11/1980 (1 Station: Sturno).
4. Morgan Hill 24/04/1984 (2 Stations: Coyote Lake Dam−southwest abut, Gilroy Array #6).
5. Nahanni, Canada 23/12/1985 (1 Station: Site 2).
6. Palm Springs 08/07/1986 (1 Station: North Palm Springs).
7. Loma Prieta 18/10/1989 (7 Stations: Gilroy – Gavilan Coll., Gilroy Array 1, Gilroy Array 2, Gilroy Array 3, LGPC, Saratoga−Aloha Ave, Saratoga–W Valley Coll).
8. Erzican, Turkey 13/03/1992 (1 Station: Erzincan).
9. Cape Mendocino 25/04/1992 (2 Stations: Cape Mendocino, Petrolia).
10. Landers 28/06/1992 (1 Station: Lucerne).
11. Northridge 17/01/1994 (6 Stations: Jensen Filter Plant Generator, LA Dam, Newhall–West Pico Canyon Rd., Pacoima Dam–downstr, Sylmar Converter Station, Sylmar–Converter Station East).
12. Kobe, Japan 16/01/1995 (2 Stations: KJMA, Takarazuka).
13. Kocaeli, Turkey 17/08/1999 (1 Station: Yarimca).
14. Chi–Chi, Taiwan 20/09/1999 (9 Stations: CHY035, CHY101, TCU049, TCU054, TCU076, TCU082, TCU101, TCU104, TCU136).
15. Duzce, Turkey 12/11/1999 (2 Stations: Bolu, Duzce).
16. Denali, Alaska 03/11/2002 (1 Station: TAPS Pump Station 10).
17. Chi-Chi, Taiwan-03 20/09/1999 (1 Station: TCU076).
18. Chi-Chi, Taiwan-06 25/09/1999 (1 Station: TCU080).

The acceleration and displacement response spectra of the selected ground motions records, which correspond to a viscous damping ratio of 5.0 %, are shown in Fig. 2. The solid black lines in these figures provide the mean values for all selected excitations, whereas dashed black lines represent the mean plus/minus one standard deviation of the 5.0 % damped response spectra.

3. Parametric analyses

In the current parametric study, dynamic time-history analyses are conducted for the previously described 3- and 5-storey base-isolated buildings under the selected set of pulse-like excitations. The seismic isolation system has been designed so that the fundamental eigenperiods of the seismically isolated 3- and 5-storey buildings take values that are sufficiently longer than the fundamental eigenperiods of the corresponding fixed-supported buildings (0.31 and 0.50 seconds, respectively). For all performed dynamic analyses, values 1.0, 0.5, 0.5 and 2 are adopted for the Bouc-Wen models' parameters A, β, γ and n respectively. These values are proposed by Nagarajaiah and Xiaohong (2000), Shrimali and Jangid (2002), Jin *et al.* (2008) in relevant studies, and they are in good accordance with experimental data (Fenves *et al.* 1998). The time interval for solving the equations of motion has been set to 2E−05 seconds.

The peak relative displacements at the isolation level, the peak inter-storey deflections of all floors and the peak absolute top-floor accelerations are selected as the most important response measures, since they can be directly correlated to the potential damage of a building and its content. In order to quantify the discrepancies of the response, while using the two models, the ratio of the peak response of the structure utilizing the sharp bilinear (BL) model to the corresponding peak response considering the smooth Bouc-Wen (BW) model is computed. The response ratio is an index of the accuracy of the sharp bilinear model for the LRBs. Thus, values less than 1.0 indicate underestimation of the peak response, whereas values greater than 1.0 denote overestimation of the peak response values, compared to the response obtained while employing the Bouc-Wen model. A statistical analysis of the response ratio for the selected 50 pulse-like ground motions is performed.

3.1 Comparison of the response for sharp and smooth bilinear models

In order to distinguish the differences in the response of the 3-storey base-isolated building, while using the sharp bilinear and the smooth Bouc-Wen models, indicative curves of the force-displacement nonlinear behaviour for the LRBs and the corresponding time-histories of the relative displacements at the isolation level (i.e. base drifts), under the Loma Prieta earthquake, as recorded at the Saratoga-Aloha Ave Station: Comp FN, are plotted in Fig. 3. The responses are shown for both nonlinear models, for an isolation period T_b = 2.0 sec, a yield displacement of u_y=1.0 cm, and for 3 different values of the normalized characteristic strength F_{yi}/W_{tot}.

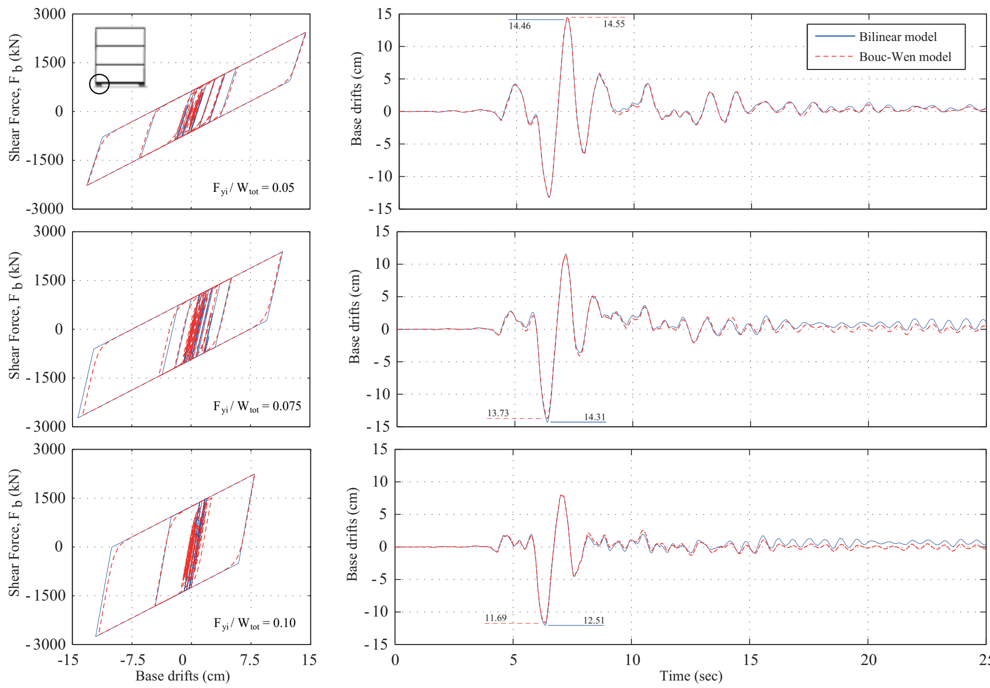

Fig. 3 Comparison of the force-deformation behavior for both bilinear models and time-variation of base drifts for the 3-storey structure under the Loma Prieta earthquake (T_b=2.0 sec, u_y=1.0 cm)

The peak relative displacements at the isolation level tend to decrease with the increase of the normalized characteristic strength of the isolation system. In general, the computed responses using either of the two models are very similar with only minor discrepancies. The computed responses for the specific earthquake excitation indicate that the base drifts are affected by the characteristics of the seismic isolation system, and can be slightly either underestimated or overestimated, through the usage of the sharp bilinear model for the LRBs. The magnitude and the occurring time of the base drifts are influenced by the response that precedes the peak, which may justify the variation of the response ratio.

In Fig. 4, time-histories of the absolute top-floor acceleration for the 3-storey building are plotted for both sharp and smooth nonlinear models. In general, the peak top-floor accelerations increase consistently and significantly with the increase of the normalized characteristic strength of the isolation system, and the peak responses computed with the sharp bilinear model are higher than those computed with the more accurate smooth model. Based on the corresponding FFT amplitude spectra shown in the right column of Fig. 4, it is observed that for both bilinear hysteretic models there is a contribution from a wide range of frequencies to the top-floor accelerations. However, contributions from higher frequencies seem to be more pronounced for the sharp bilinear model. Higher modes of the superstructure are excited for a sharp-cornered hysteretic model, such as the bilinear model, compared to the smoother Bouc-Wen model with the more gradual change of the stiffness upon yielding of the seismic isolation system.

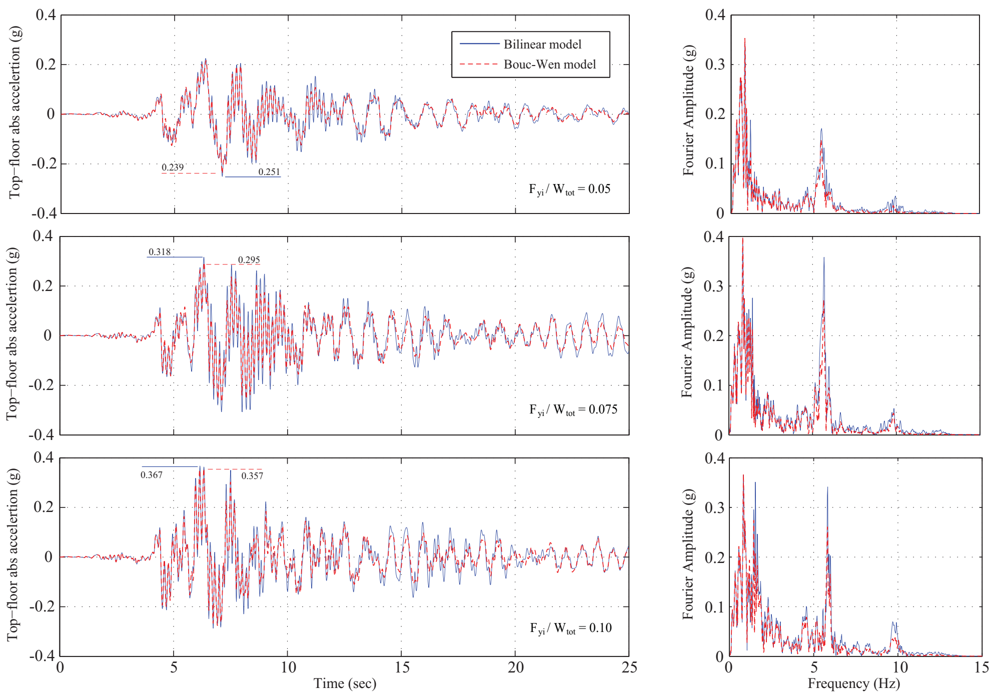

Fig 4 Comparison of the time histories and the corresponding FFT spectra of the top-floor acceleration of the 3-storey base-isolated structure under the Loma Prieta earthquake ($T_b = 2.0$ sec, $u_y = 1.0$ cm)

3.2 Effect of the yield-displacement of the isolators

A series of parametric studies has been performed with respect to the nonlinear properties of the LRBs, which cover the range of typical seismic isolation systems that are used in practice. For all considered cases, a nonlinear time-history analysis has been performed for the simulated MDOF base-isolated buildings, considering both the sharp and the smooth bilinear models, under all 50 selected pulse-like ground excitations. In order to understand the influence of the nonlinear hysteretic loop shape on the peak responses of the base-isolated buildings, the variation of the peak response ratio for the 3-storey structure is plotted against the yield displacement of the isolators (Fig. 5). The peak response ratios are provided for three values of the normalized characteristic strength (i.e. F_{yi}/W_{tot} = 0.05, 0.075 and 0.10). The value of the isolation period has been kept constant at T_b = 2.0 sec.

Regarding the discrepancies of the computed peak relative displacements at the isolation level $u_{isol\,level}^{max,BL} / u_{isol\,level}^{max,BW}$, no specific pattern can be observed, as the response can be either underestimated

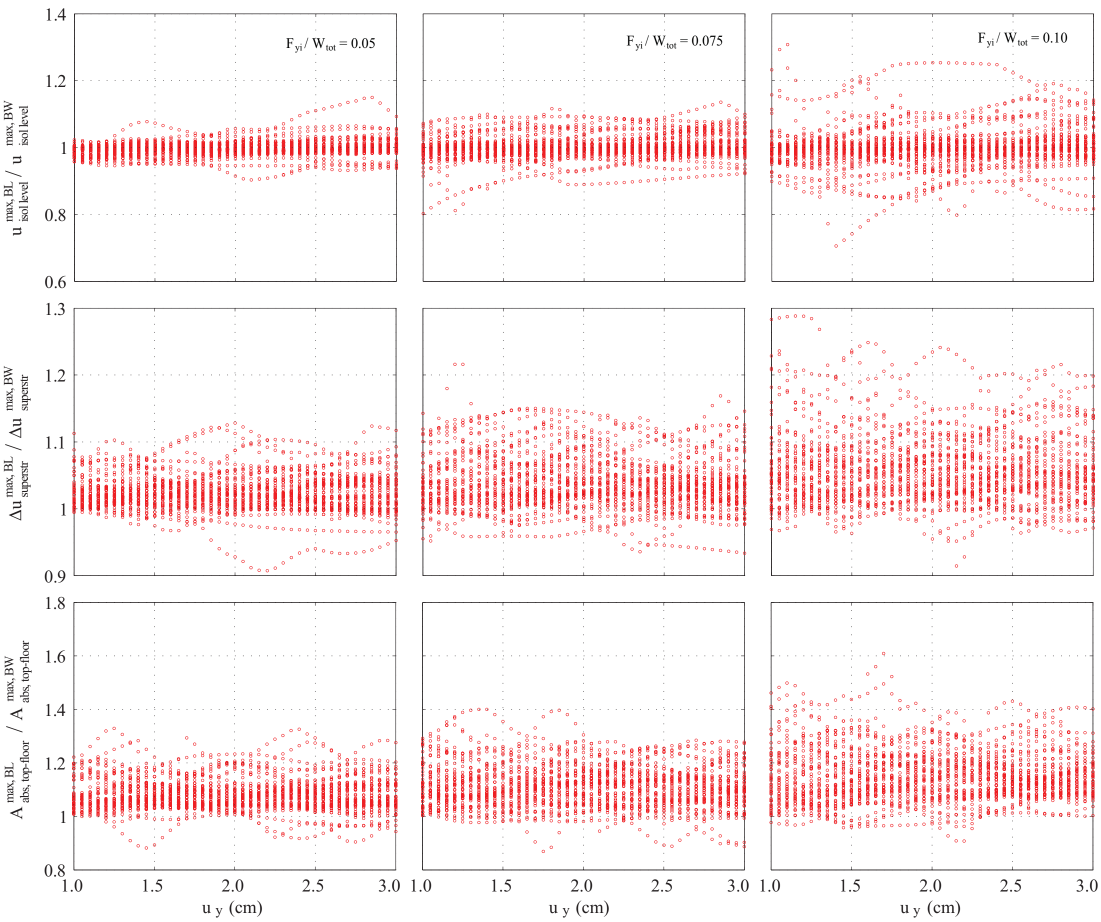

Fig. 5 Effect of the yield displacement of the isolators on the peak response ratios of the 3-storey base-isolated building for three different values of F_{yi}/W_{tot} = 0.05, 0.075 and 0.10 and T_b = 2.0 sec

or overestimated when the bilinear, instead of the Bouc Wen, inelastic model is used for the base isolation system. The discrepancies seem to increase with the F_{yi}/W_{tot} ratio. Given that an accurate estimation of the required clearance must be provided around a seismically isolated building in order to avoid any structural pounding during strong earthquakes, it is very important to note that, from a safety point of view, the underestimation of the peak relative displacements when the sharp bilinear model is used, should be taken into account using an appropriate safety factor.

On the other hand, the peak response ratios of the superstructure for the peak inter-storey drifts among all floors $\Delta u_{superstr}^{max,BL} / \Delta u_{superstr}^{max,BW}$ and the peak absolute top-floor accelerations $A_{abs,top-floor}^{max,BL} / A_{abs,top-floor}^{max,BW}$ are, in general, kept at values higher than 1.0, indicating overestimation of the computed peak response when the bilinear model is used for the LRBs. Furthermore, it is observed that as the normalized characteristic strength of the seismic isolation system increases, the deviation of the peak response ratio is more pronounced. This finding indicates that the response ratio is influenced by the characteristics of both the earthquake excitation and the seismic isolation system, and therefore, it would be useful to be investigated in a statistical manner, as discussed in subsequent paragraphs.

The various examined cases in this parametric study are presented in Table 1. A total of 369 different seismic isolation systems have been examined for each building and a total of 73,800 nonlinear time-history analyses have been performed. A graphical representation of the averaged peak response ratios for the 3-storey seismically isolated building is presented in Fig. 6 for three different isolation periods T_b = 2.0, 2.5 and 3.0 sec. Also, the mean plus/minus one standard deviation of the response ratios are used to describe their main tendency and variability. Despite the highly irregular variations observed in the peak response ratio under each individual ground motion, the average ratios are relatively smooth.

For the examined isolation periods and normalized characteristic strengths, the mean response ratio of the peak relative displacements at the isolation level fluctuate around 1.0, showing a marginal increasing trend with a slight increase with the isolator yield displacement. However, the standard deviations of the response ratio are positively correlated with the normalized characteristic strength, as the response ratios for higher F_{yi}/W_{tot} ratios show higher standard deviations. The peak response quantities seem to be affected by the characteristics of both the seismic isolators and the selected earthquake excitations. Furthermore, the parametric results indicate that the yield displacement does not considerably influence the average peak responses ratio of the superstructure, which are primarily affected by the post-yield fundamental eigenperiod, the normalized strength of the seismic isolation system and the characteristics of the imposed earthquake excitations. Furthermore, values of the mean response ratios of the inter-storey deflections are larger than 1.0, meaning that when the sharp bilinear model is used for LRBs the

Table 1 Examined cases in the parametric study

Parameter	Values	Number of examined cases
Normalized characteristic strength, F_{yi}/W_{tot}	0.05, 0.075, 0.10	3
Yield displacement, u_y	1.0 : 0.05 : 3.0 cm	41
Isolation period, T_b	2.0, 2.5, 3.0	3
Earthquake ground motion	see Section 2.4	50
Nonlinear hysteretic model for LRB	sharp vs. smooth; bilinear model	2
Base-isolated building	3- and 5-storey building	2

peak inter-storey responses are overestimated, and that that overestimation rises with the increase of the normalized characteristic strength. It should also be noted that the mean peak response ratio of the superstructure for isolation period $T_b = 3.0$ sec is consistently higher. In this particular case, the mean $\Delta u_{superstr}^{max,BL} / \Delta u_{superstr}^{max,BW}$ ratio ranges in the vicinity of 1.04 for $F_{yi}/W_{tot} = 0.05$, while for $F_{yi}/W_{tot} = 0.075$ and 0.10, the mean peak response ratio increases to approximately 1.07 and 1.09, respectively.

According to the results presented in Fig. 6 (bottom row), the peak top-floor accelerations are in general overpredicted when the bilinear inelastic model is used, instead of the smoother Bouc-Wen model. As stated before, for sharp bilinear systems, there is an increased contribution of higher eigenfrequencies in the accelerations of the superstructure due to the sudden changes of the stiffness that occur when shifting from the elastic to the post-yield stiffness of the bilinear model. Overall, the average $A_{abs,top-floor}^{max,BL} / A_{abs,top-floor}^{max,BW}$ ratios and the standard deviation of the response ratio increase with the increase of the F_{yi}/W_{tot} ratio. This tendency is observed for the three investigated

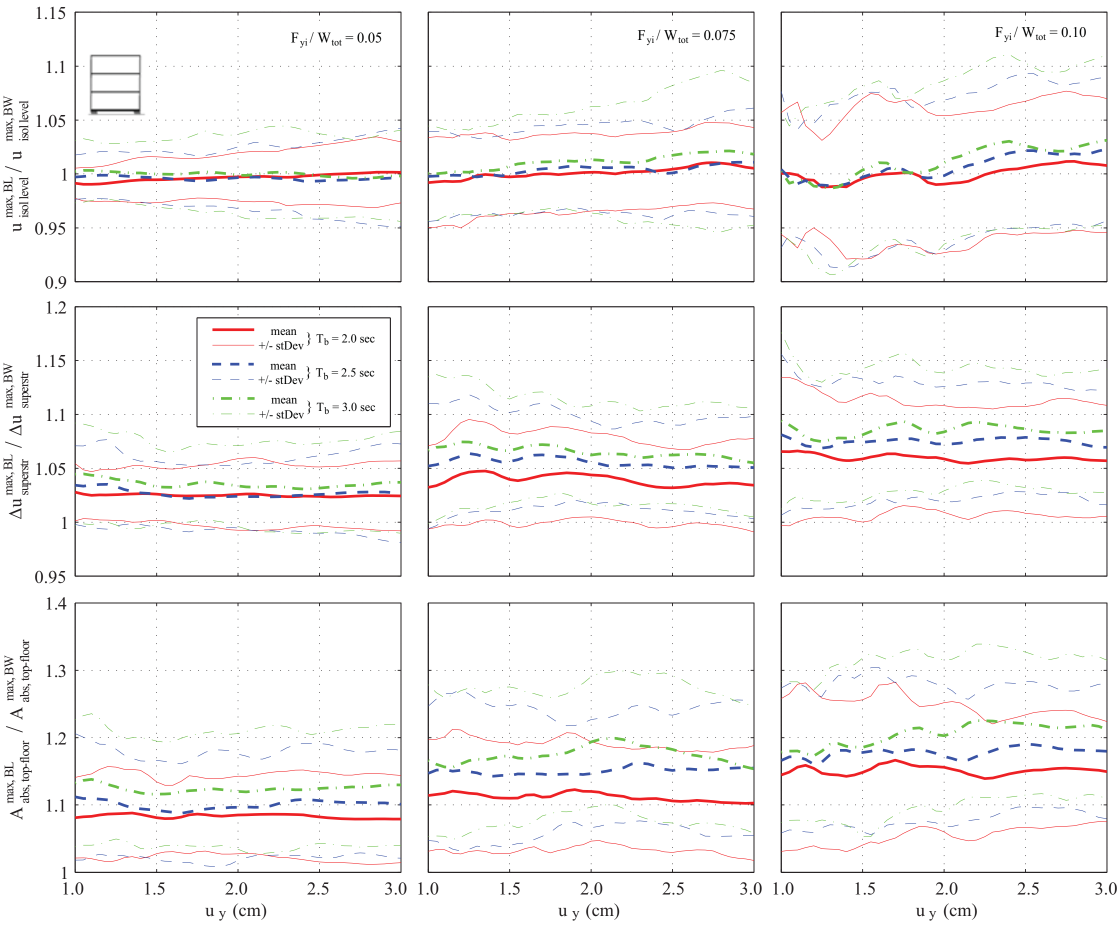

Fig. 6 Variation of peak response ratios of the 3-storey base-isolated building simulated using the sharp vs. the smooth bilinear model, under pulse-like excitations for different isolation characteristics

isolation periods. In general, the mean peak top-floor absolute acceleration ratio is higher than 1.075 (F_{yi}/W_{tot} = 0.05, T_b = 2.0 sec) and reaches values up to about 1.25 (F_{yi}/W_{tot} = 0.10, T_b = 3.0 sec), while the mean plus one standard deviation may be as large as about 1.35 for the3-storey base-isolated building.

Similarly-organized results as those presented above for the 3-storey base-isolated building, are provided in Fig. 7 for the 5-storey building. A remarkably similar trend is observed for the averaged response ratios as well as for the standard deviations of the ratios in the ranges of the considered seismic isolation system characteristics. Similarly to prior results, the deviation of the error increases with the increase of the F_{yi}/W_{tot} ratio, while in the case of F_{yi}/W_{tot} = 0.05 the underestimation of the relative displacements at the isolation level is limited up to 5.0%. The clear conclusion, as before, is that the usage of the sharp bilinear model may lead to significant overestimation of the peak top-floor acceleration response.

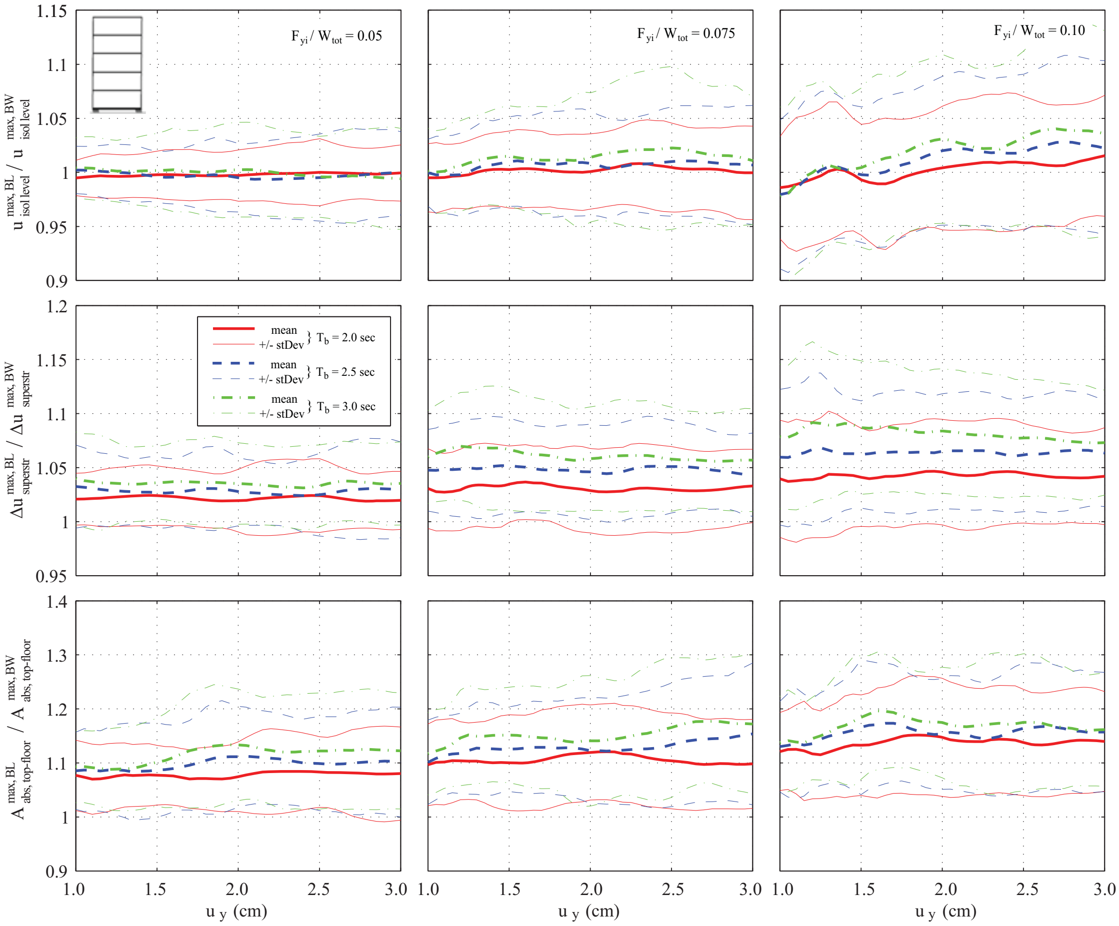

Fig. 7 Variation of peak response ratios of the 5-storey base-isolated building simulated using the sharp vs. the smooth bilinear model, under the 50 pulse-like excitations for different isolation characteristics

3.3 Effect of superstructure stiffness

The scope of this parametric study is to assess the influence of the superstructure's flexibility on the accuracy of modelling the nonlinear LRBs behaviour with the sharp bilinear model. Considering that it will be interesting to compare the peak seismic response of the 3- and the 5-storey base-isolated buildings, more that 60,000 numerical simulations are conducted by adjusting the inter-storey stiffness of the superstructure, while using both bilinear models for the seismic isolation system. Fig. 8 shows the variation of the superstructure response of a 3-storey structure against the superstructure's fundamental eigenperiod, T_s. The following values are selected for the seismic isolation characteristics: isolation period, $T_b = 2.0$ sec, yield displacement, $u_y = 1.0$ cm and normalized characteristic strength $F_{yi}/W_{tot} = 0.05$.

An examination of the computed responses showed that the peak inter-storey deflections and the peak absolute top-floor accelerations of the base-isolated structures increase as the fundamental eigenperiod of the superstructure increases. The influence of the superstructure's flexibility on the peak inter-storey drifts becomes more pronounced as the superstructure flexibility increases. However, the simulations results indicate that the relative displacements at the isolation level are kept relatively constant as the flexibility of the superstructure is varied. This is in line with the conclusions of Kulkarni and Jangid (2002) and Matsagar and Jangid (2008), who noted that the response of the seismic isolation system regarding the peak base drifts is not really influenced by the flexibility of the superstructure. In contrast, the peak absolute roof accelerations increase when the flexibility of the superstructure increases.

Fig. 9 provides the variation of the average ratios of the peak relative displacements at the isolation level, inter-storey deflections and top-floor acceleration for the two buildings against the superstructure's fundamental eigenperiod, T_s for the 50 pulse-like ground motions. The average ratios are shown for three values of the isolation period based on post-yield stiffness, yield displacement $u_y = 1.0$ cm and normalized characteristic strength $F_{yi}/W_{tot} = 0.05$. A minor deviation of the mean $u^{max,BL}_{isol\,level} / u^{max,BW}_{isol\,level}$ ratios close to 1.0 is observed. Furthermore, the mean peak response ratios of the superstructure are kept to values larger that 1.0. In general, the mean ratios of the peak inter-storey drifts among all stories $\Delta u^{max,BL}_{superstr} / \Delta u^{max,BW}_{superstr}$ are not really influenced by the flexibility of

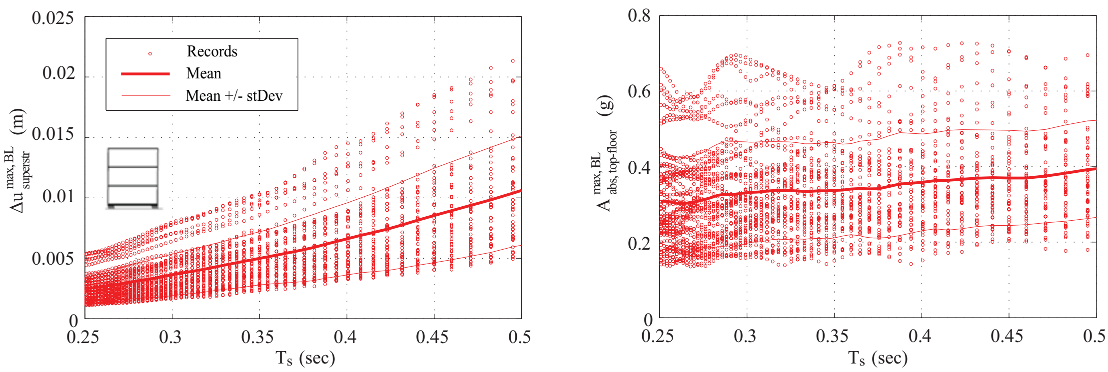

Fig. 8 Peak response of the inter-storey deflections, and the absolute roof accelerations of the 3-storey building as a function of the superstructure stiffness ($T_b = 2.0$ sec, $F_{yi}/W_{tot} = 0.05$ and $u_y = 1.0$ cm)

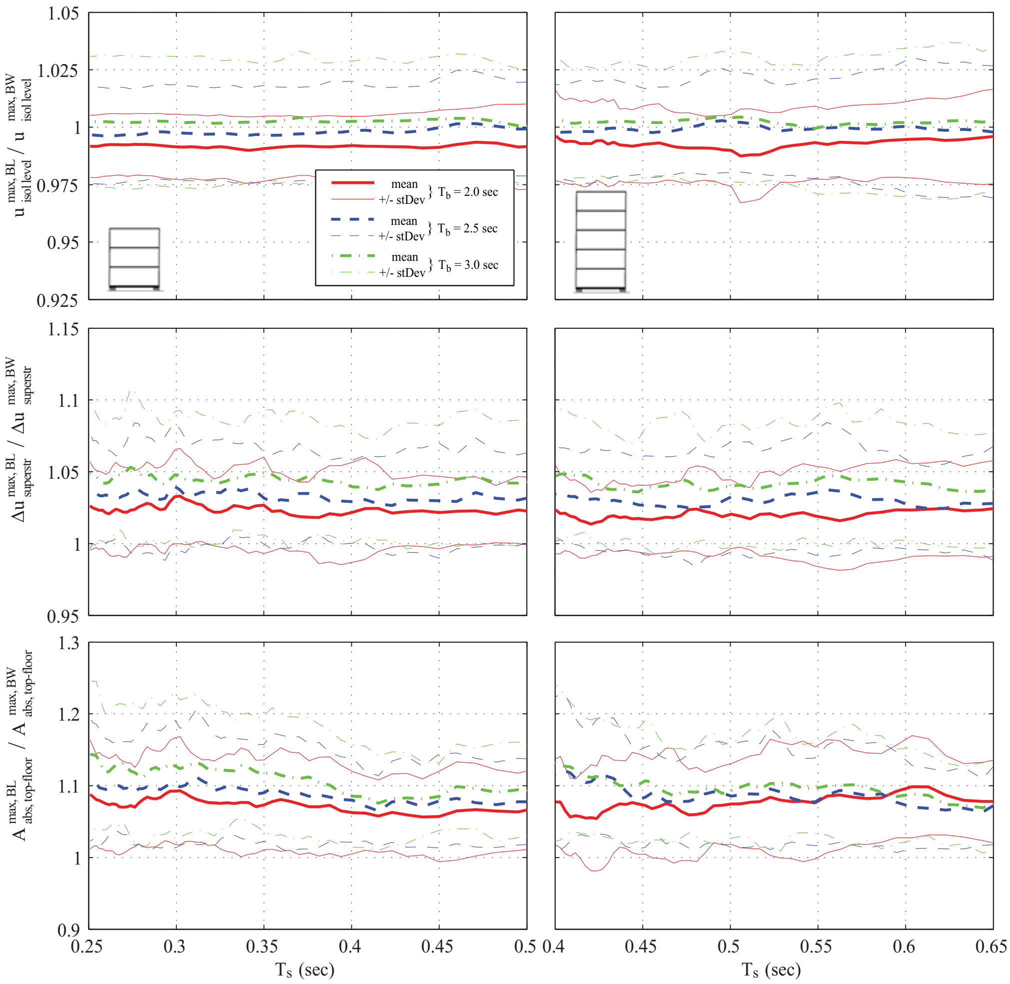

Fig. 9 Effects of the superstructure's flexibility on the average peak response ratios of the 3- and the 5-storey base-isolated buildings with $F_{yi}/W_{tot} = 0.05$ and $u_y = 1.0$ cm

the superstructure and, in general, are kept in the vicinity of 1.04 for $T_b = 3.0$ sec. On the other hand, as shown by the plots in the bottom row of Fig. 9, the mean $A^{max,BL}_{abs,top-floor} / A^{max,BW}_{abs,top-floor}$ ratio tend to increase with the stiffening of the superstructure. In general, the response ratio deviations are similar for both buildings. The general conclusions drawn in the previous subsection in relation to the effect of the post-yield eigenperiod on the superstructure's response ratios persist.

Similar effects of the superstructure's flexibility are exhibited in Fig. 10 where the corresponding averaged peak response ratios are shown for a normalized characteristic strength $F_{yi}/W_{tot} = 0.075$. The average response ratios of the superstructure increase for the higher F_{yi}/W_{tot} ratio. This tendency is observed for all three investigated isolation periods, in line with what has been already presented in Section 3.2. In general, the mean ratios of the peak inter-storey drifts are kept higher than 1.06 for $T_b = 3.0$ sec, while the mean peak top-floor acceleration ratios reach values up to about 1.20 in the respective case.

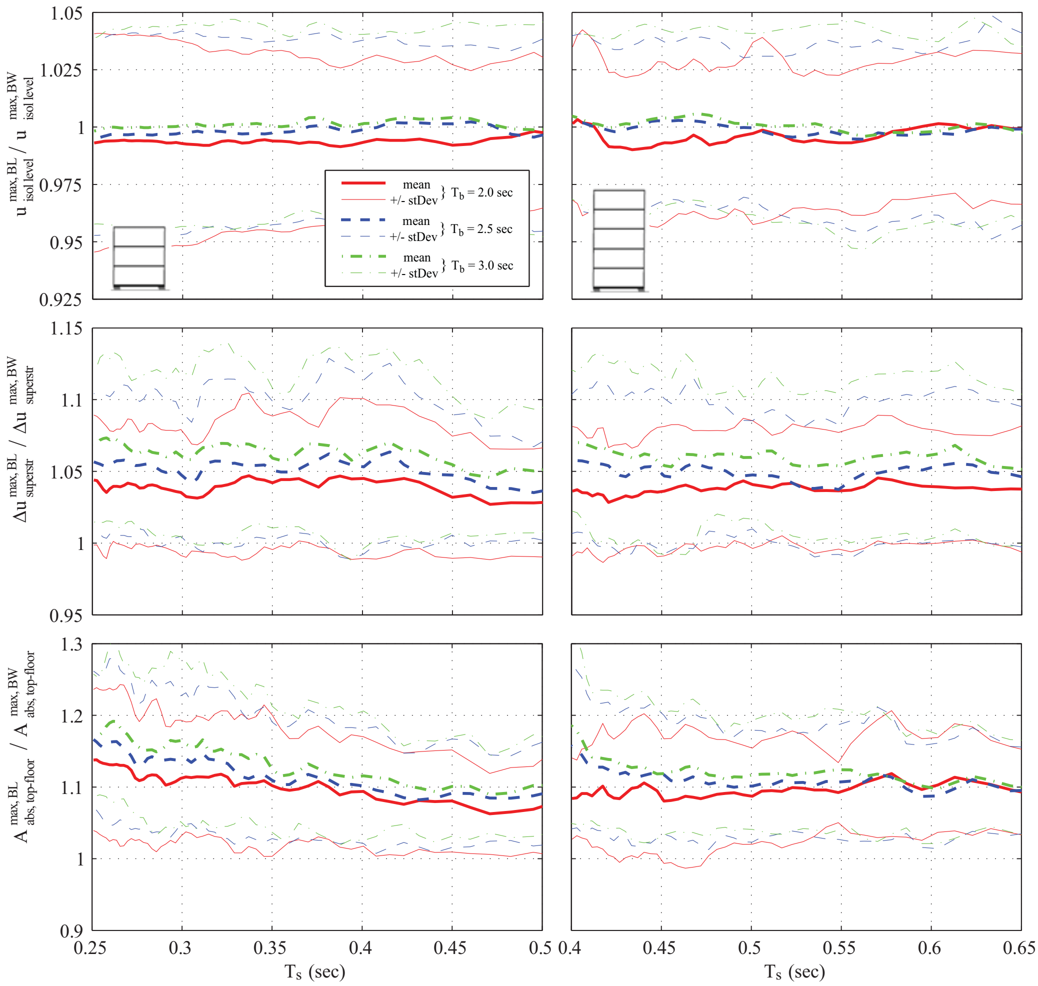

Fig. 10 Effects of the superstructure's flexibility on the average peak response ratios of the 3- and the 5-storey base-isolated buildings with $F_{yi}/W_{tot} = 0.075$ and $u_y = 1.0$ cm

4. Concluding remarks

The effect of the modelling of the non-linear behaviour of seismic isolation systems with LRBs on the computed peak responses of two typical seismically isolated buildings under pulse-like earthquake excitations has been investigated. The appropriateness of modelling the nonlinear behaviour of the LRBs with the sharp bilinear inelastic model has been assessed through simulations and parametric studies performed with specially developed software. The influence of the characteristics of both simulated base-isolated buildings and the earthquake excitations on the computed peak responses of interest ratios, using the bilinear inelastic model, instead of the more accurate and smoother nonlinear model represented by the Bouc-Wen model with certain parameters, has been quantified through relevant parametric studies.

Considering the dispersion of the ratios of the peak relative displacements at the isolation level, the response can be either underestimated or overestimated when the sharp, instead of the smooth, bilinear model is used for the seismic isolation system. The characteristics of the isolation systems do not considerably influence the mean ratio of the peak relative displacements at the isolation level, which seems to be influenced mostly by the characteristics of the earthquake excitations. However, increasing the ratio of the characteristic strength of the seismic isolation system to the total weight acting on the isolation system increases the standard deviation of the ratios of the peak base drifts. Furthermore, from a design perspective, the little underestimation of the relative displacements at the isolation level that is introduced due to the usage of the sharp bilinear model is considered to be insignificant when appropriate safety factors are introduced. This finding is vital since there has been a great concern about the possibility of underestimations of the peak relative displacements across the isolators, which may lead to collisions of base-isolated buildings with the surrounding moat walls or adjacent structures during strong near-fault ground motions.

The peak responses of the superstructure, i.e. peak floor accelerations and inter-storey deflections, are, in general, slightly overestimated when the bilinear model for the LRBs is used, which could be justified by a larger contribution of the higher modes due to the sudden changes of the stiffness upon yielding of the isolation system, compared to the more accurate and smoother force-displacement curves of the Bouc-Wen model. Moreover, the average ratios of the inter-storey drifts and the absolute top-floor accelerations appear to increase with an increasing normalized characteristic strength, post-yield fundamental eigenperiods of the LRBs and the stiffening of the superstructure. Considering the deviation of the superstructure's peak response, a smooth bilinear model or even more advanced models need to be incorporated in order to accurately determine the peak responses of base-isolated structures.

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