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Seismic isolation performance sensitivity to potential deviations from design values

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Abstract. Seismic isolation is often used in protecting mission-critical structures including hospitals, data centers, telecommunication buildings, etc. Such structures typically house vibration-sensitive equipment which has to provide continued service but may fail in case sustained accelerations during earthquakes exceed threshold limit values. Thus, peak floor acceleration is one of the two main parameters that control the design of such structures while the other one is peak base displacement since the overall safety of the structure depends on the safety of the isolation system. And in case peak base displacement exceeds the design base displacement during an earthquake, rupture and/or buckling of isolators as well as bumping against stops around the seismic gap may occur. Therefore, obtaining accurate peak floor accelerations and peak base displacement is vital. However, although nominal design values for isolation system and superstructure parameters are calculated in order to meet target peak design base displacement and peak floor accelerations, their actual values may potentially deviate from these nominal design values. In this study, the sensitivity of the seismic performance of structures equipped with linear and nonlinear seismic isolation systems to the aforementioned potential deviations is assessed in the context of a benchmark shear building under different earthquake records with near-fault and far-fault characteristics. The results put forth the degree of sensitivity of peak top floor acceleration and peak base displacement to superstructure parameters including mass, stiffness, and damping and isolation system parameters including stiffness, damping, yield strength, yield displacement, and post-yield to pre-yield stiffness ratio.

Keywords: sensitivity analysis; seismic isolation; linear isolation system; nonlinear isolation system; seismic performance

1. Introduction

Research efforts in seismic isolation area are continuing with an ever increasing rate. Following are among the recent representatives of the numerous analytical, numerical, and experimental studies: Morgan and Mahin (2008) proposed a probabilistic framework in which the design criteria of seismic isolated buildings allow consideration of multiple performance goals. Petti *et al*. (2010) presented the effectiveness of a system combining base isolation and a tuned mass damper. The effectiveness of base isolation of framed buildings with high damping rubber bearings is investigated by Mazza and Vulcano (2012) considering combined effects of horizontal and vertical

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components of near-fault ground motions. Kasai *et al*. (2013) discussed the observed behavior of base-isolated buildings in the 2011 Tohoku Earthquake. Alhan and Ozgur (2015) investigated the accuracy of equivalent linear modeling of seismic isolation under near-fault earthquakes. Kamalzare *et al*. (2015) proposed a computationally-efficient methodology for optimal design of passive isolators. Casciati *et al*. (2014) addressed the issues in civil engineering applications of structural control including seismic isolation to form a scientific paradigm and identify future directions of research. Current research efforts on seismic isolation have been discussed recently in the 14th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures organized by Anti-Seismic System International Society (Benzoni 2015). And, Martelli *et al*. (2014a, 2015) has reported the most recent development and applications of seismic isolation.

Besides the results of past research studies, actual behaviors of seismically isolated structures observed during earthquakes prove the success of seismic isolation: The seismic performance of the USC hospital building under the 1994 Northridge Earthquake has shown that peak floor accelerations were below peak ground acceleration owing to seismic isolation (Nagarajaiah and Xiaohong 2000). Similarly, a good acceleration performance was observed in the case of the West Japan Postal Computer Center when it was subjected the 1995 Kobe Earthquake (Komodromos 2000). An L-shaped base-isolated building located in Tokyo Bay area is reported to survive the the 2011 Tohoku Earthquake without structural damage (Siringoringo and Fujino 2015).

While research on various aspects of seismic isolation is under way, its practical application is also increasing worldwide: Pan *et al*. (2005) reported the base isolation design practice in Japan and mentioned that the number of base-isolated buildings had increased from 10 to more than 150 buildings per year after the 1995 Kobe Earthquake. Pan *et al*. (2012) reviewed the state-of-the-practice of Chinese design and informed that while there were 600 seismic isolation applications up to 2008, the 2008 Wenchuan Earthquake triggered a bloom of new applications of seismic isolation in China. Guo *et al*. (2014) presented the retrofitting of school buildings by seismic isolation in China after the recent Wenchuan and Yushu Earthquakes. As reported by Martelli *et al*. (2014a), over 23,000 structures in over 30 countries are protected by anti-seismic systems. Anti-seismic systems can be of passive, semi-active, hybrid (passive and semi-active combined) or active types (Gavin *et al*. 2003). Semi-active, hybrid, and active anti-seismic systems are among “smart systems” which is the main subject of Smart Structures and Systems Journal. As far as the purely active control systems are concerned, owing to the potential stability problems and large energy demands, use of these systems for the protection of structures from large earthquakes is still a controversial issue. And although there is considerable number of examples of the use of hybrid and semi-active systems particularly in Japan and China, most of the aforementioned anti-seismic systems are of passive type such as seismic isolation, energy dissipation systems, systems formed by shape memory alloys or shock transmitter units and the number of passive applications is continuously increasing worldwide (Martelli *et al*. 2014a).

Seismic isolation is often used in protecting mission-critical structures including hospitals, data centers, telecommunication buildings, etc., which typically house vibration-sensitive equipment that has to provide continued service but may fail in case sustained accelerations during an earthquake exceed threshold limit values. Thus, it is important that the selected properties of the isolation system do not lead to amplifications at frequencies of interest for the vibration-sensitive equipment, namely isolation damping should be limited. Additionally, in case peak base displacement exceeds design base displacement during an earthquake, rupture and/or buckling of isolators as well as bumping against stops around seismic gap may occur. Thus, it is important that the selected properties of the isolation system limits peak base displacement, which means high isolation damping may be required. So, main approach in designing seismically isolated structures is to find the optimum characteristic isolation system parameters such that base displacement (or the isolation system displacement) is limited for the safety of the isolation system without increasing floor accelerations which may cause damage to vibration-sensitive contents. Therefore, many researchers focused on this optimization issue: Alhan and Gavin (2004) conducted a parametric study using a benchmark structure with linear viscously damped and nonlinear hysteretic isolation systems. They concluded that there exist appropriate combinations of isolation stiffness and isolation damping for linear isolation systems and appropriate combinations of yield displacement and yield force for nonlinear isolation systems in order to limit base displacements without increasing floor accelerations. Falsone and Ferro (2006) treated the problem of finding the best performing base isolator parameters of a seismic excited structure equipped with a linear or nonlinear isolation system based on the minimization of the power flow transmitted by the isolator to the structure, which aimed a good global behavior of the structure both in terms of relative displacements and accelerations. Jangid (2007) investigated the variation of top floor acceleration and bearing displacement of a benchmark isolated building with a linear shear type superstructure for different system parameters (e.g., isolation period, yield force, yield displacement) and determined that while low yield force results in large base displacement under near-fault motions, there exists an optimum value for yield strength for which top floor acceleration attains the minimum value. Huang *et al.* (2009) proposed a data mining method than can be used to classify proper and improper ranges of design parameters for base-isolated systems. Nigdeli *et al.* (2014) proposed a harmony search optimization method for obtaining optimum isolation system parameters that minimizes peak top floor acceleration without exceeding peak base displacement.

Although optimum nominal design values for isolation system and superstructure parameters may be calculated such that target peak design base displacement and peak floor accelerations are met as summarized above, their actual values may potentially deviate from the nominal design values due to various factors including but not limited to aging, scragging, temperature, contamination, and wear of isolators and design and/or construction errors (Hirata *et al*. 1989, Cheng *et al*. 2008). Using linear isolation system models, Shenton III and Holloway (2000) pointed out to the fact that the random variability just in the stiffness of isolators may lead to changes in structural behavior. And Pan *et al*. (2005) has reported that variations in lateral stiffness may be up to 20% - 25% for low and high damping rubber bearings, with variations more likely to be on the higher end for high damping rubber bearings. More recently, it was stressed by Martelli *et al.* (2014b) that it was crucial for the seismic isolation devices to remain in the same operating and safety conditions for which they were designed for during the entire useful life of the structure. This statement holds true also for semi-active isolation systems which consist of semi-active energy dissipating devices working in parallel with seismic isolators. And in this study, the sensitivity of the seismic performance of structures equipped with linear and nonlinear seismic isolation systems to such potential deviations is assessed in the context of a benchmark shear building model excited by different earthquake records with near-fault and far-fault characteristics. In addition to two response parameters - peak top floor acceleration and peak base displacement- that mainly control the design of seismically isolated structures, structural base shear is also included in the sensitivity assessments. Sensitivity to (i) superstructure parameters including superstructure mass, superstructure stiffness, and superstructure damping and (ii) isolation system parameters including isolation system stiffness, isolation system damping, isolation system yield strength, isolation system yield displacement, and post-yield to pre-yield stiffness ratio are investigated.

The text is organized as follows: First, the seismically isolated benchmark shear building model and the equations of motion are introduced. Next, nominal values of the characteristic parameters of the linear and nonlinear isolation systems are given. Then, information on the earthquake records used in the time history analyses is provided. Finally, the results of the sensitivity analyses are presented followed by the conclusions reached.

2. Structural model

It is customary in research studies to use simplified single-degree-of-freedom or 2-degree-of-freedom (2DOF) models in representing seismically isolated buildings (e.g., Liu *et al.* 2014, Vassiliou *et al*. 2013). However, instead of SDOF or 2DOF models, it may be preferable to use shear building models in representing the superstructure (e.g., Contento and Di Egidio 2014, Charmpis et al. 2012) in order to take the superstructure flexibility and damping into account. And generic shear building models are shown to successfully represent the class of superstructures of realistic seismically isolated buildings with same fixed-base natural period and distribution of stiffness over the height (Alhan and Sürmeli 2011). The seismically isolated shear building model shown in Fig. 1 is used as a benchmark structure in this study. The seismically isolated structure is formed of five floors including four superstructure floors and a rigid base floor connecting all isolation system elements.

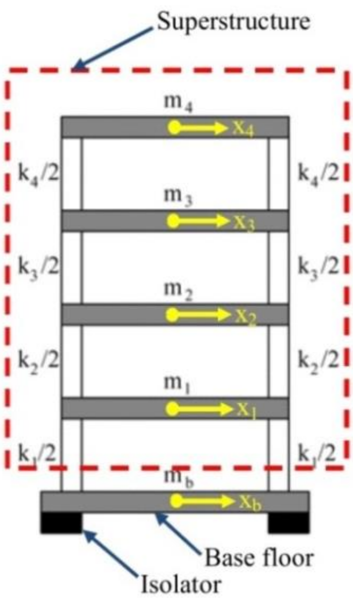

Fig. 1 Seismically isolated benchmark shear building model

The isolation system is considered as both linear and nonlinear in the investigation. In case a building structure is equipped with a linear isolation system, the equation of motion under the influence of horizontal ground acceleration $\ddot{z}$ is given as (Chopra 2001)

$$\mathbf{M}\ddot{\mathbf{X}}(\mathrm{t}) + \mathbf{C}\dot{\mathbf{X}}(\mathrm{t}) + \mathbf{K}\mathbf{X}(\mathrm{t}) = -\mathbf{M}\mathbf{1}\ddot{z}(\mathrm{t}) \quad (1)$$

where $\mathbf{X} = [x_b, x_1, x_2, x_3, x_4]^T$ is the displacement vector containing the displacement of the centers of masses of the floors (Fig. 1) and **M** is the diagonal structural mass matrix, **C** is the structural damping matrix, and **K** is the structural stiffness matrix of the seismically isolated building. In case a building structure is equipped with a nonlinear isolation system, the equation of motion is then given by

$$\mathbf{M}\ddot{\mathbf{X}}(\mathrm{t}) + \mathbf{C}\dot{\mathbf{X}}(\mathrm{t}) + \mathbf{K}\mathbf{X}(\mathrm{t}) + R(x_b(\mathrm{t}), \dot{x}_b(\mathrm{t})) = -\mathbf{M}\mathbf{1}\ddot{z}(\mathrm{t}) \quad (2)$$

where $R(x_b(\mathrm{t}), \dot{x}_b(\mathrm{t}))$ accounts for the nonlinear restoring forces (Alhan and Gavin 2004). Note that in Eqs. (1) and (2), an over-dot represents differentiation with respect to time and **1** represents the earthquake input vector of ones.

2.1 Superstructure

All story stiffness and all floor masses of the superstructure are assumed to be equal to each other ($k_1=k_2=k_3=k_4$ and $m_1=m_2=m_3=m_4$) and they are tuned to provide a fundamental *fixed-base* period of $T_S=0.4$ s. The mass matrix of the superstructure, $\mathbf{M}_S$, which is a part of the global structural mass matrix **M** that appears in Eqs. (1) and (2) is given by

$$\mathbf{M}_S = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix} \quad (3)$$

and the stiffness matrix of the superstructure, $\mathbf{K}_S$, which is a part of the global structural stiffness matrix **K** that appears in Eqs. (1) and (2) is given by

$$\mathbf{K}_S = \begin{bmatrix} (k_1+k_2) & -k_2 & 0 & 0 \\ -k_2 & (k_2+k_3) & -k_3 & 0 \\ 0 & -k_3 & (k_3+k_4) & -k_4 \\ 0 & 0 & -k_4 & k_4 \end{bmatrix} \quad (4)$$

The superstructure damping matrix $\mathbf{C}_S$, which is a part of the global structural damping matrix **C** (Alhan and Gavin 2004) that appears in Eqs. (1) and (2), is formed via superposition of modal damping matrices method

$$\mathbf{C}_S = \mathbf{\Phi}_S{}^T \mathbf{c}_S \mathbf{\Phi}_S \quad (5)$$

where $\mathbf{\Phi}_S$ is the mass normalized eigenvector matrix of the fixed-base superstructure and the modal damping matrix of the superstructure $\mathbf{c}_S$ is given by

$$\mathbf{c}_S = \begin{bmatrix} 2\zeta_{S1}\omega_{S1} & 0 & 0 & 0 \\ 0 & 2\zeta_{S2}\omega_{S2} & 0 & 0 \\ 0 & 0 & 2\zeta_{S3}\omega_{S3} & 0 \\ 0 & 0 & 0 & 2\zeta_{S4}\omega_{S4} \end{bmatrix} \tag{6}$$

where ω_{si} and ζ_{si} are the undamped modal circular frequency and modal damping ratio of the ith mode of the fixed-base superstructure. The fixed-base modal damping ratios of the superstructure for all modes are assumed to be the same and 5%: $\zeta_S = \zeta_{S1} = \zeta_{S2} = \zeta_{S3} = \zeta_{S4} = 0.05$.

2.2 Isolation systems

2.2.1 Linear isolation systems

For linear isolation systems, Kelvin-Voigt viscoelastic model is appropriate, which is a rheological model that consists of a linear spring and a linear viscous damper connected in parallel to each other forming a restoring force

$$f = K_I x_b + C_I \dot{x}_b \tag{7}$$

where K_I and C_I are the stiffness and viscous damping constant of the isolation system. The isolation period for a seismically isolated building structure equipped with such an isolation system is given by

$$T_I = 2\pi \sqrt{\frac{M}{K_I}} \tag{8}$$

where $M = m_b + m_1 + m_2 + m_3 + m_4$ is the total mass of the structure including isolation floor. The viscous damping ratio of the isolation system is given by

$$\zeta_I = \frac{C_I}{2M\omega_I} \tag{9}$$

where $\omega_I = 2\pi / T_I$ is the isolation circular frequency.

In the context of this sensitivity analyses study, in order to cover a practical range of typical linear isolation system characteristics, six different linear isolation systems with three different isolation periods and two different damping levels are considered (Hışman 2011) and the corresponding nominal design values (K_I, C_I) are provided in Table 1.

2.2.2 Nonlinear isolation systems

For nonlinear isolation systems, a hysteretic isolation system model where the damping effects are due to material yielding is considered. Thus, the nonlinear restoring forces $R(x_b(\mathrm{t}), \dot{x}_b(\mathrm{t}))$ of the isolation system that appears in Eq. (2) is described by (Nagarajaiah *et al*. 1991)

$$f = \alpha \frac{F_y}{d_y} x_b + (1-\alpha) F_y Z \tag{10}$$

Table 1 Nominal values of the characteristic parameters of the linear isolation systems

Isolation System	T_I (s)	ζ_I (%)	K_I/W (1/m)	C_I/W (s/m)
LA1	2	10	1.00	0.064
LB1	3	10	0.45	0.043
LC1	4	10	0.25	0.032
LA2	2	20	1.00	0.128
LB2	3	20	0.45	0.086
LC2	4	20	0.25	0.064

where α is the post-yield stiffness to pre-yield stiffness ratio ($\alpha = K_2 / K_1$), d_y is the yield displacement, F_y is the yield force ($F_y = K_1 d_y$). Here, Z is a hysteretic dimensionless quantity (Park *et al.* 1986). The isolation period based on the post-yield stiffness (also known as the rigid-body-mode period) is given by (Nagarajaiah *et al.* 1991)

$$T_b = 2\pi\sqrt{\frac{M}{K_2}} \tag{11}$$

and the characteristic strength of the isolation system is given by (Naeim and Kelly 1999)

$$Q = (K_1 - K_2)d_y \tag{12}$$

In order to cover a practical range of typical nonlinear isolation system characteristics, six different nonlinear isolation systems with three different isolation periods and two different damping levels (i.e., two different characteristic strength ratio, *Q/W* levels) are considered (Hışman 2011) and the corresponding nominal design values (α, F_y, and d_y) are provided in Table 2.

Table 2 Nominal values of the characteristic parameters of the nonlinear isolation systems

Isolation System	T_b (s)	**Q/W** (%)	α (-)	F_y/W (%)	d_y (mm)
NLA1	2	5	0.1	5.55	5.52
NLB1	3	5	0.1	5.55	12.42
NLC1	4	5	0.1	5.55	22.08
NLA2	2	10	0.1	11.11	11.04
NLB2	3	10	0.1	11.11	24.84
NLC2	4	10	0.1	11.11	44.16

3. Earthquake records

The properties of the earthquake records used in this study, including the peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD) along with their code names, are shown in Table 3. The earthquake records obtained from the Pacific Earthquake Engineering Research Center database (PEER, 2005) are selected such that both near-fault and far-fault records are included since the behavior of seismically isolated structures may differ depending particularly on this characteristics of earthquakes.

While EL is a typical far-fault record, RI, SYL, and KO are near-fault records with high ground velocities (higher than 100 cm/s) including long-period pulses in their ground velocity histories. The 10% damped response spectra for the records are also given in Fig. 2. As it can be clearly seen from Fig. 2(b), the spectral displacements for near-fault records in the long-period range are much higher than those for the far-fault records.

Table 3 Properties of the earthquake records

Earthquake	Record Station	Code Name	Record Date	Record Name	PGA (g)	PGV (cm/s)	PGD (cm)
Imperial Valley	El Centro	EL	19/05/1940	I-ELC180	0.313	29.8	13.32
Northridge	Rinaldi	RI	17/01/1994	RRS228	0.838	166.1	28.78
Northridge	Sylmar	SYL	17/01.1994	SYL360	0.843	129.6	32.68
Kobe	Takatori	KO	16/01/1995	TAK000	0.611	127.1	35.77

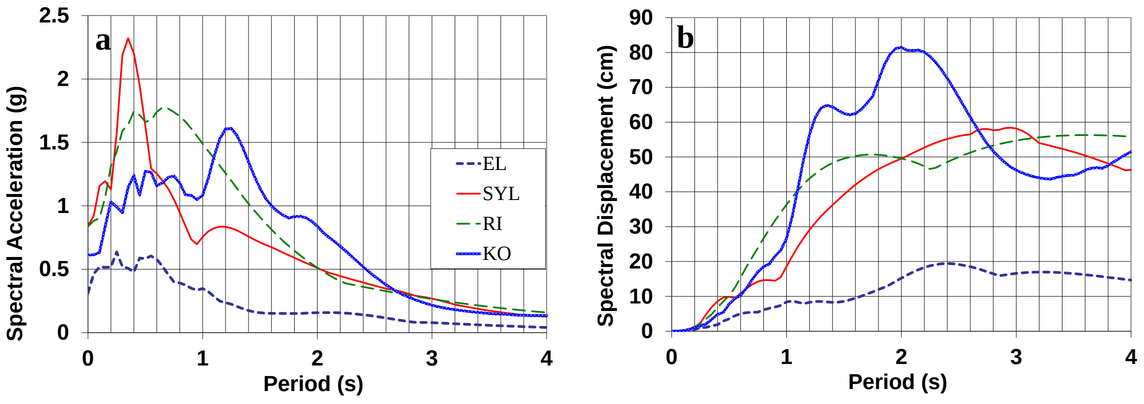

Fig. 2 Response spectra, 10% damped

4. Sensitivity analyses

The sensitivity of the seismic performance of the seismically isolated benchmark shear buildings (see Fig. 1) -6 of them with linear isolation systems (see Table 1) and 6 of them with nonlinear isolation systems (see Table 2)- to potential deviations in characteristic parameters of the isolation system and the superstructure from the design values are investigated in this section via the time history analyses carried out for four different earthquakes (see Table 3 and Fig. 2) using 3DBASIS (Nagarajaiah *et al.* 1991) which is an academic software that allows for modeling of both linear and nonlinear isolation systems which are described in Section 2. The subject parameters considered for the sensitivity analyses are listed in Table 4.

Two main structural response parameters, peak top floor acceleration and peak base displacement (i.e., peak isolation system displacement) are monitored as representatives of the superstructure and the isolation system responses, respectively. The peak top floor acceleration and the peak base displacement corresponding to the seismically isolated structure with the nominal design values are given as $\mathrm{a} = \max\ (\mathrm{abs}\ (\ddot{x}_4))$ and $\mathrm{d} = \max\ (\mathrm{abs}\ (x_b))$, respectively.

Up to a 25% deviation (in increments of 5%) in each sensitivity parameter (see Table 4) from its nominal design value is considered in the sensitivity analyses. Thus, provided that the parameters with deviations are shown with a star-superscript (M_s^*, K_s^*, ζ_s^*, K_I^*, C_I^*, F_y^*, d_y^*, and α^*), modeling and time history analyses are carried out for cases with M_s/M_s^*, K_s/K_s^*, ζ_s/ζ_s^*, K_I/K_I^*, C_I/C_I^*, F_y/F_y^*, d_y/d_y^*, and α/α^* being equal to 0.75, 0.80, 0.85, 0.90, 0.95, 1.00, 1.05, 1.10, 1.15, 1.20, and 1.25. In order to explicitly see the influence of each parameter, in each analysis only one parameter is considered to deviate from its nominal design value and others are kept to be equal to their nominal design values.

Table 4 Parameters considered for the sensitivity analyses

Seismically Isolated Structures Equipped with *Linear* Isolation Systems	**Seismically Isolated Structures Equipped with *Nonlinear* Isolation Systems**
Superstructure mass, M_s	Superstructure mass, M_s
Superstructure stiffness, K_S	Superstructure stiffness, K_S
Superstructure damping, ζ_S	Superstructure damping, ζ_S
Isolation system stiffness, K_I	Isolation system yield strength, F_y
Isolation system damping, C_I	Isolation system yield displacement, d_y
	Post-yield stiffness to pre-yield stiffness ratio, α

The peak top floor acceleration and the peak base displacement responses corresponding to the seismically isolated structure with the aforementioned parameters deviating from their nominal design values are represented by a^* and d^*, respectively. In order to observe how these responses deviate from the nominal structural responses, a/a^* and d/d^* ratios as well as absolute error percentages e_d and e_a shown in Eqs. (13) and (14), respectively are calculated and presented in the form of comparative sensitivity plots in the next subsections.

$$e_d(\%) = \left| \frac{d^* - d}{d} \right| \times 100 \tag{13}$$

$$e_a(\%) = \left| \frac{a^* - a}{a} \right| \times 100 \tag{14}$$

4.1 Seismically isolated structures with linear isolation systems

Sensitivities to deviations in M_s, K_s, ζ_s, K_I, and C_I (see Table 4) in the form of a/a^* and d/d^* ratios for all linear isolation systems are calculated for all earthquakes, seperately. However, due to space limitiation, the plots are presented as a representative case for SYL earthquake, only (Figs. 3 and 4).

It is clearly seen from Fig. 3 that –for all linear isolation systems studied– while peak base displacement is sensitive to the superstructure mass (M_s), isolation system stiffness (K_I), and isolation system damping (C_I), it is not sensitive to superstructure stiffness (K_s) or superstructure modal damping (ζ_s) at all. It is also observed that the sensitivity trends are not always monotonic: For example, while a positive deviation in a certain parameter (e.g., K_I) may result in an increase in the peak base displacement of one linear isolation system (e.g., LC1) it may on the other hand cause a decrease in the peak base displacement of another linear isolation system (e.g., LA1) – see Fig 3a.

When Fig. 4 is examined, it is observed that peak top floor acceleration is also sensitive to the superstructure mass (M_s), isolation system stiffness (K_I) and isolation system damping (C_I) but unlike peak base displacement, it is also sensitive to superstructure stiffness (K_s) and superstructure modal damping (ζ_s), with its sensitivity to superstructure modal damping being much less. It is observed that trends of sensitivities are not always monotonic and may vary with respect to isolation system type: For example, while a positive deviation in C_I results in an increase in the peak top floor acceleration of the linear isolation system LC2, it causes a decrease in the peak top floor acceleration of the linear isolation system LB1 – see Fig. 4(b).

In order to quantitavely observe the average range of variations in the structural response, their sensitivities to deviations in the superstructure and the nonlinear isolation parameters are presented in terms of absolute error percentages (see Eqs. (13) and (14)) in Figs. 5 and 6, respectively. The error percentages presented are average values obtained for the linear isolation systems listed in Table 1. Fig. 5 shows that regardless of earthquake type, peak base displacement is not sensitive to superstructure stiffness or superstructure damping at all, with average absolute error being less than 1% even for a 25% deviation. On the other hand, although the level of sensitivities to superstructure mass, isolation system stiffness, and isolation system damping may vary with respect to the earthquake, it is still clear that their influence level is similar and monotonically increase with a low rate as deviations increase.

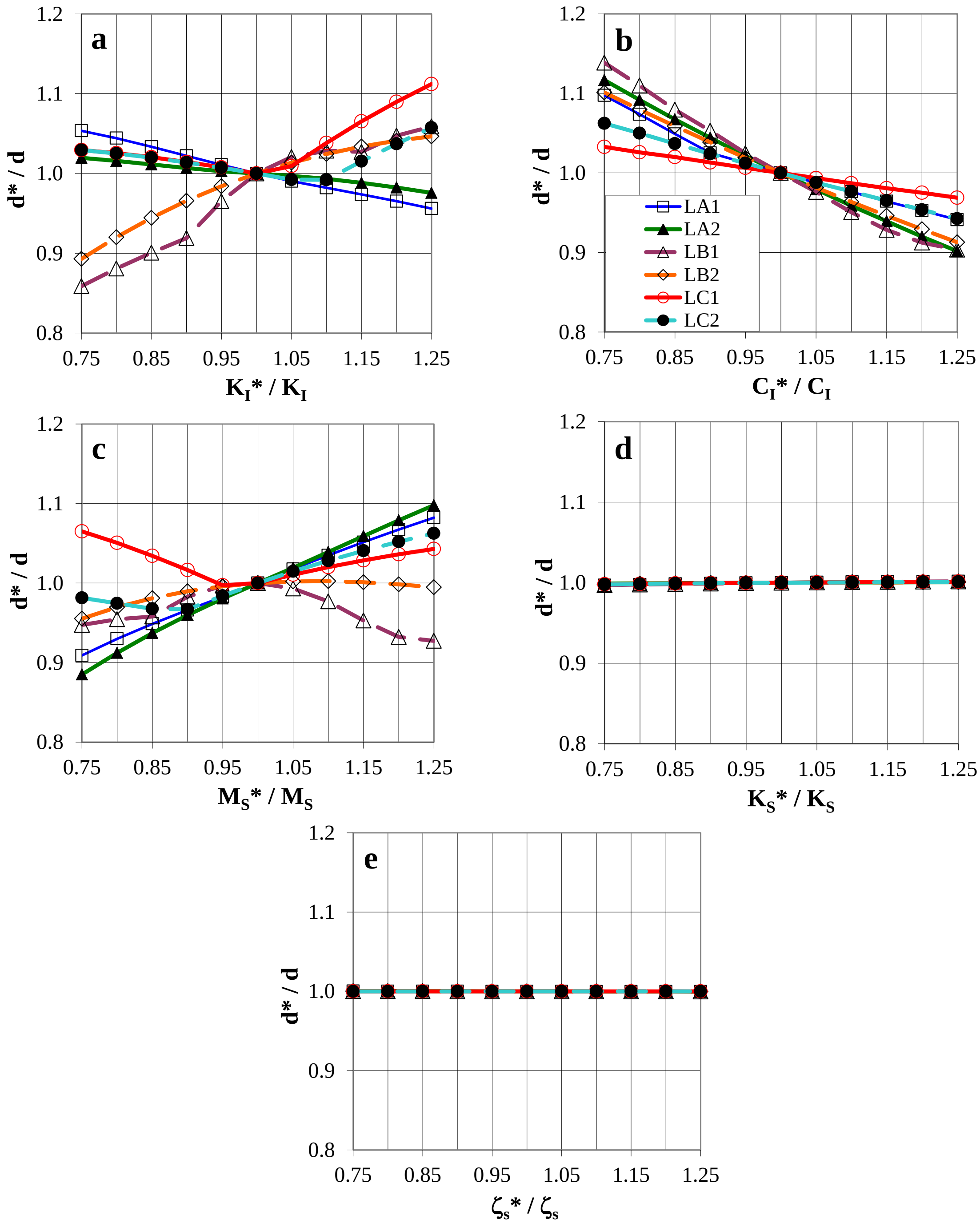

Fig. 3 Sensitivity of peak base displacement to deviations in characteristic parameters of linear isolation systems and superstructure from design values – *SYL*

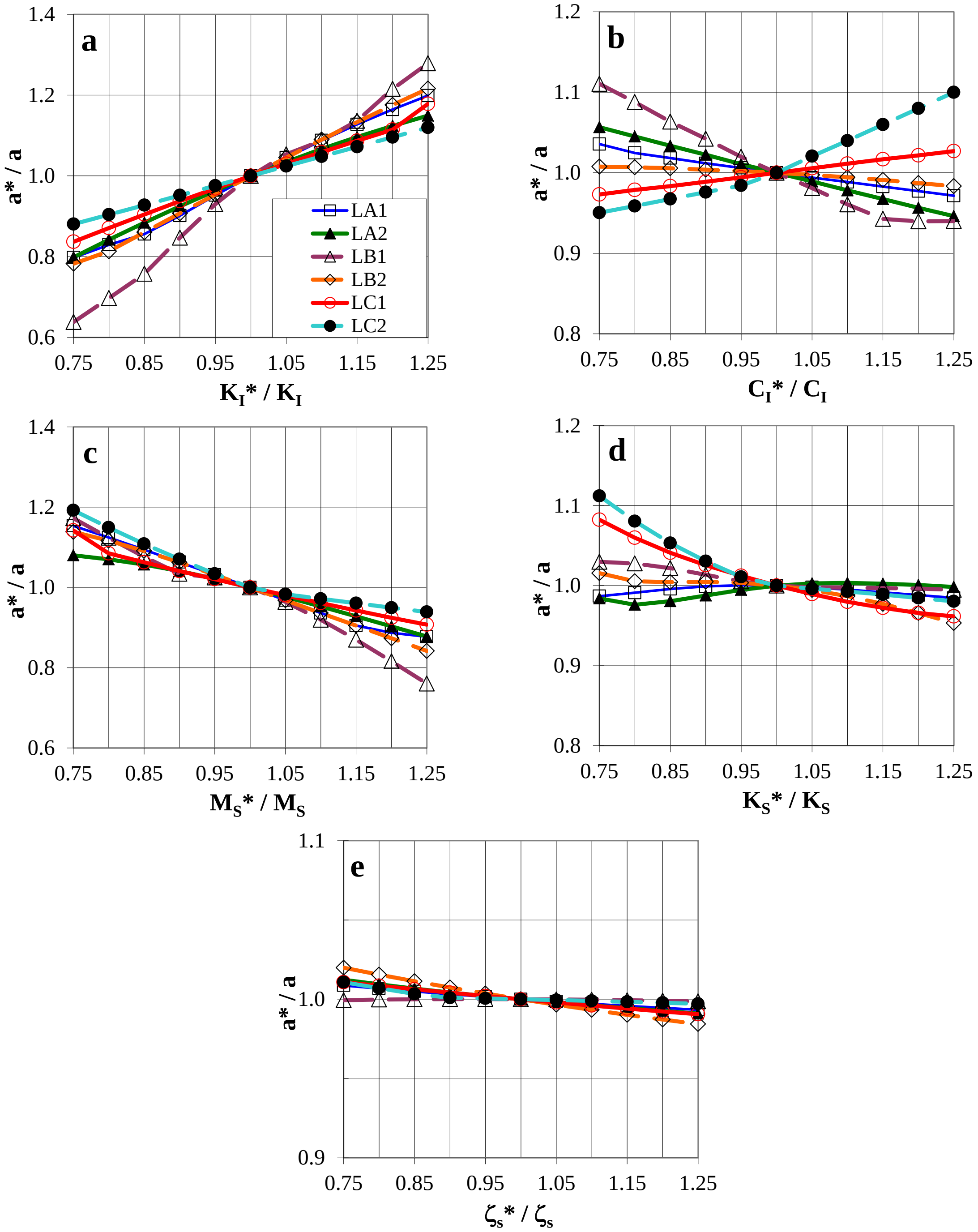

Fig. 4 Sensitivity of peak top floor acceleration to deviations in characteristic parameters of linear isolation systems and superstructure from design values – SYL earthquake

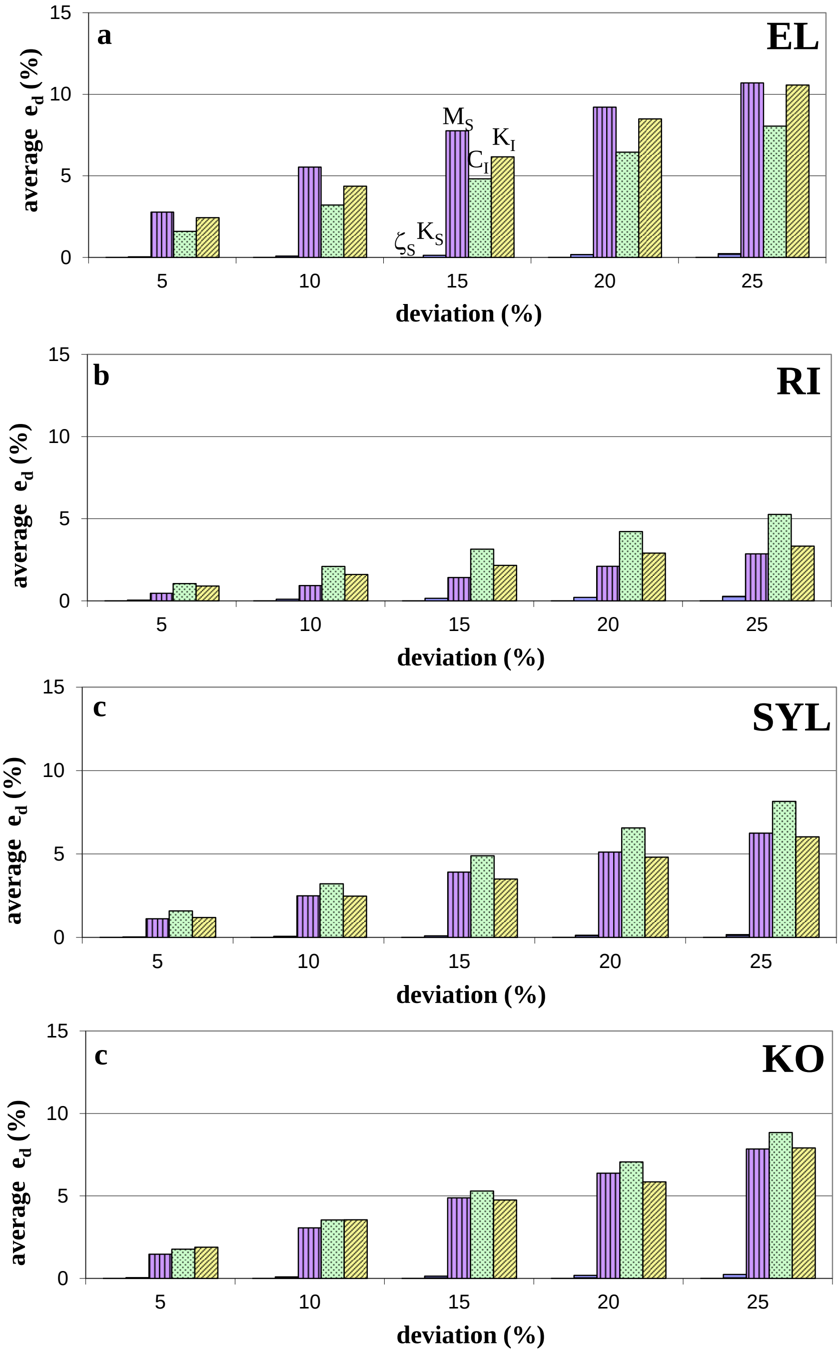

Fig. 5 Sensitivity of peak base displacement to deviations in characteristic parameters of linear isolation systems and superstructure from design values – *Average of all isolation systems*

Fig. 6 shows that although actual values may vary with respect to earthquake, as a general tendency, peak top floor acceleration is sensitive to all parameters considered except for superstructure damping. And the sensitivity to superstructure stiffness is very low (causes considerable response variation only for large, 20-25% deviations). The level of sensitivities to other parameters are in the decreasing order of isolation system stiffness, superstructure mass, and isolation system damping, which monotonically increase with a low rate as deviations increase.

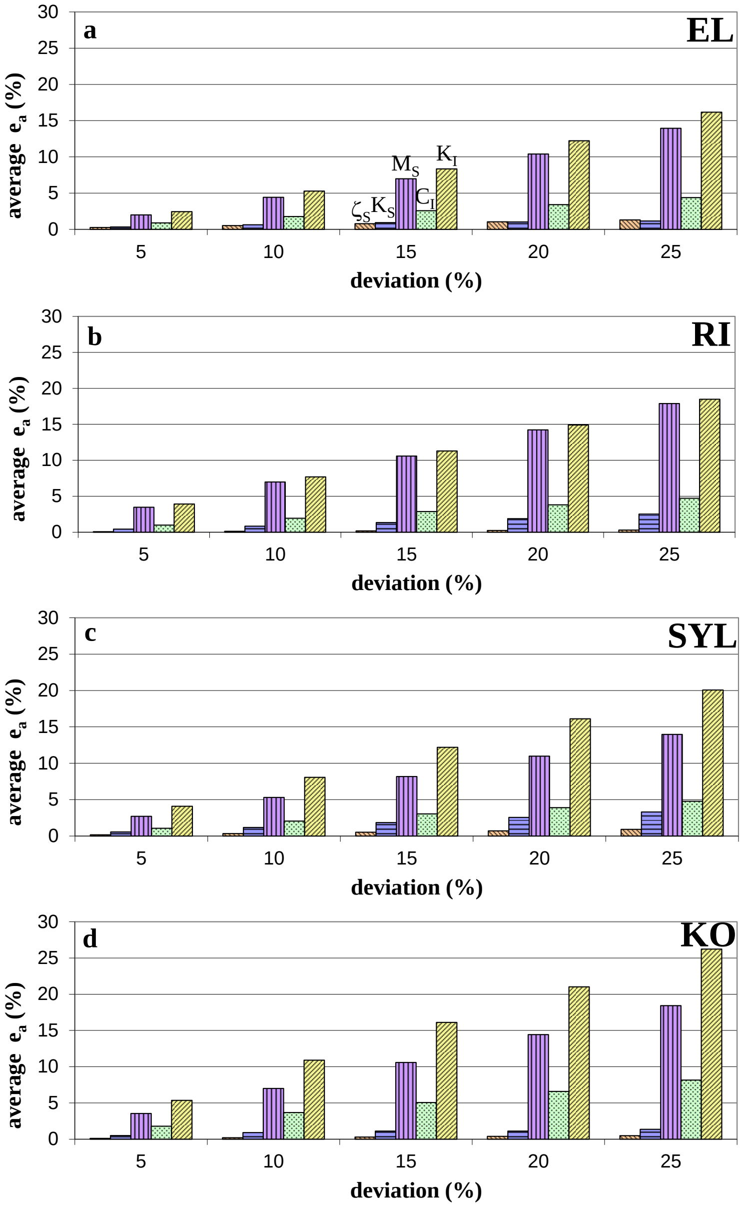

Fig. 6 Sensitivity of peak top floor acceleration to deviations in characteristic parameters of linear isolation systems and superstructure from design values – Average of all isolation systems

Discussion on the sensitivity of the aforementioned structural responses for linear isolation systems are finalized in Section 4.3 where a global perspective is given by plots showing absolute error percentages averaged for all linear isolation systems and earthquakes studied herein.

4.2 Seismically isolated structures with nonlinear isolation systems

Sensitivities to deviations in F_y, d_y, α, K_s, M_s, and ζ_s (see Table 4) in the form of a/a^* and d/d^* ratios for all nonlinear isolation systems are calculated for all earthquakes, seperately. However, the plots are presented for as a representative case of SYL earthquake, only (Figs. 7 and 8).

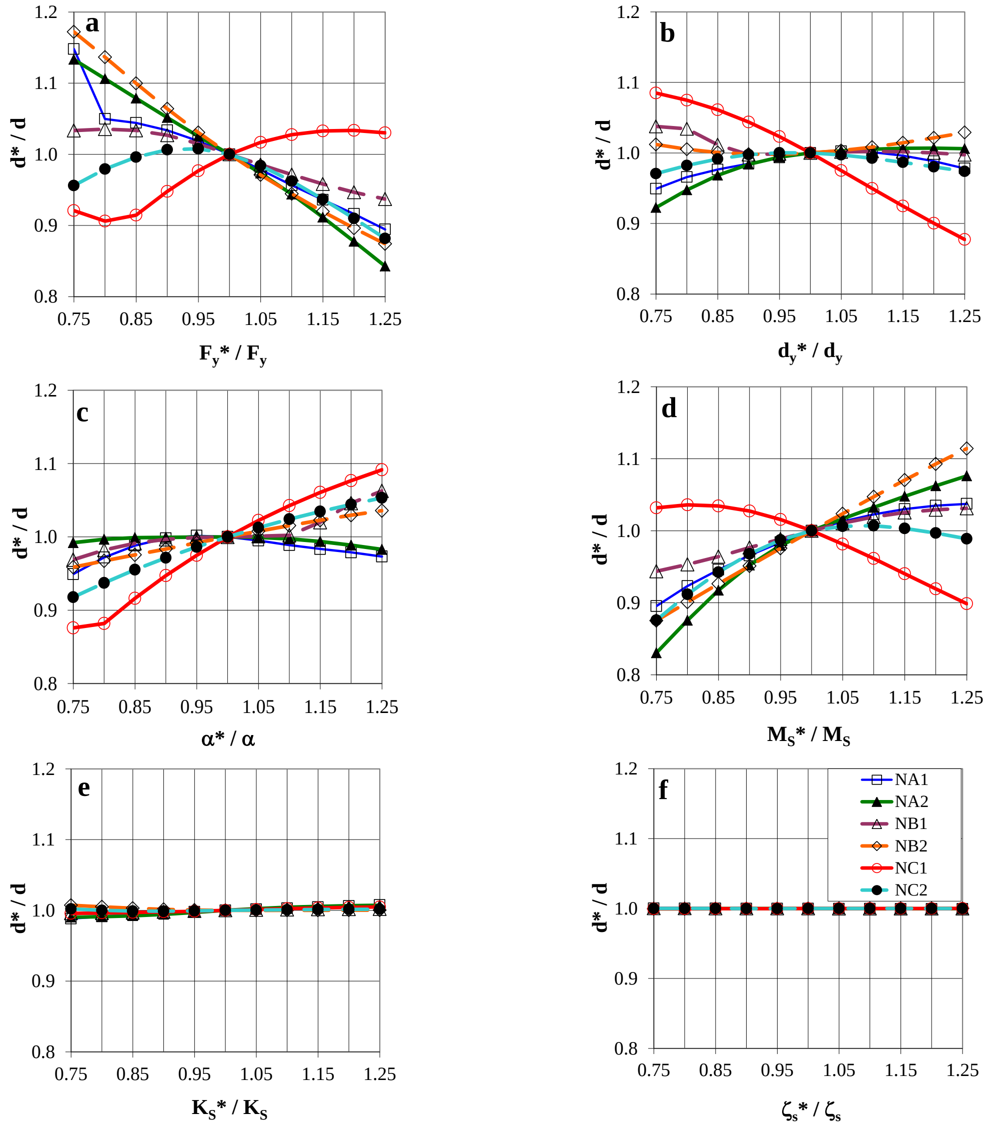

Fig. 7 Sensitivity of peak base displacement to deviations in characteristic parameters of nonlinear isolation systems and superstructure from design values – SYL earthquake

Fig. 7 shows that while peak base displacement is sensitive to superstructure mass (M_s), isolation system yield strength (F_y), isolation system yield displacement (d_y), and post-yield stiffness to pre-yield stiffness ratio (α), it is not sensitive to superstructure stiffness (K_s) or superstructure modal damping (ζ_s) at all. It is also observed that the trends of the sensitivities are not always monotonic: For example, while a positive deviation in a certain parameter (e.g., F_y) may result in an increase in the peak base displacement of one nonlinear isolation system (e.g., NC1) it may on the other hand cause a decrease in the peak base displacement of another linear isolation system (e.g., NA) – see Fig. 7(a).

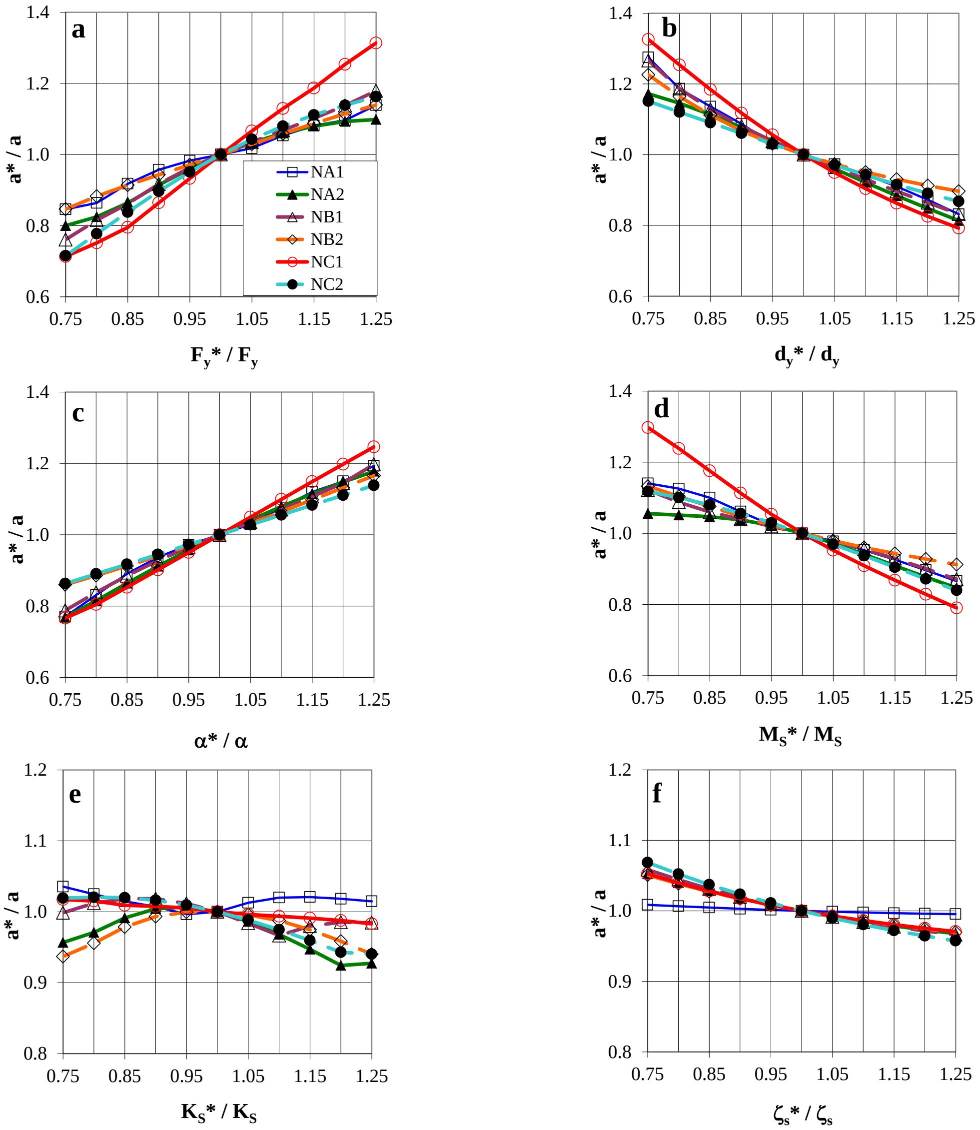

Fig. 8 Sensitivity of peak top floor acceleration to deviations in characteristic parameters of nonlinear isolation systems and superstructure from design values – SYL earthquake

Fig. 8 shows that, peak top floor acceleration is sensitive to all parameters except that the level of sensitivity to superstructure modal damping ratio is much less compared to other parameters.

The average range of structural response variation due to deviations in the superstructure and nonlinear isolation parameters are presented in Figs. 9 and 10, respectively in terms of absolute error percentages (see Eqs. (13) and (14)) averaged over nonlinear isolation systems listed in Table 2.

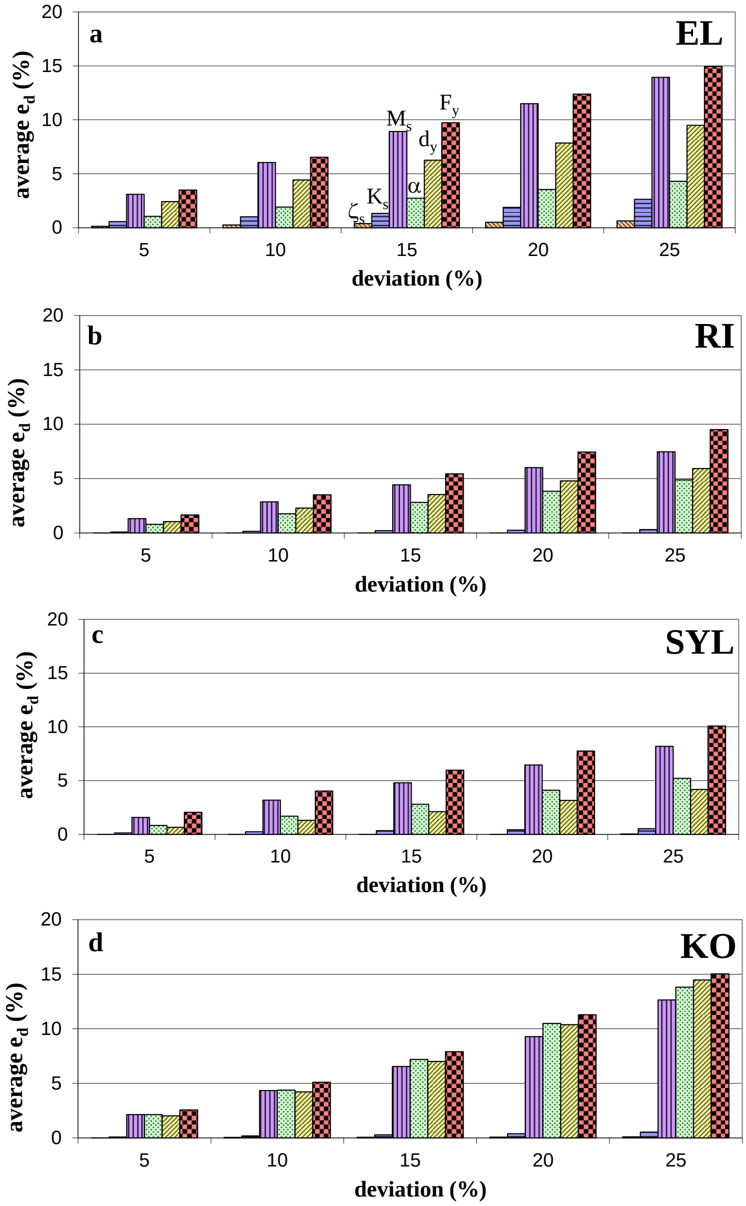

Fig. 9 Sensitivity of peak base displacement to deviations in characteristic parameters of nonlinear isolation systems and superstructure from design values – Average of all isolation systems

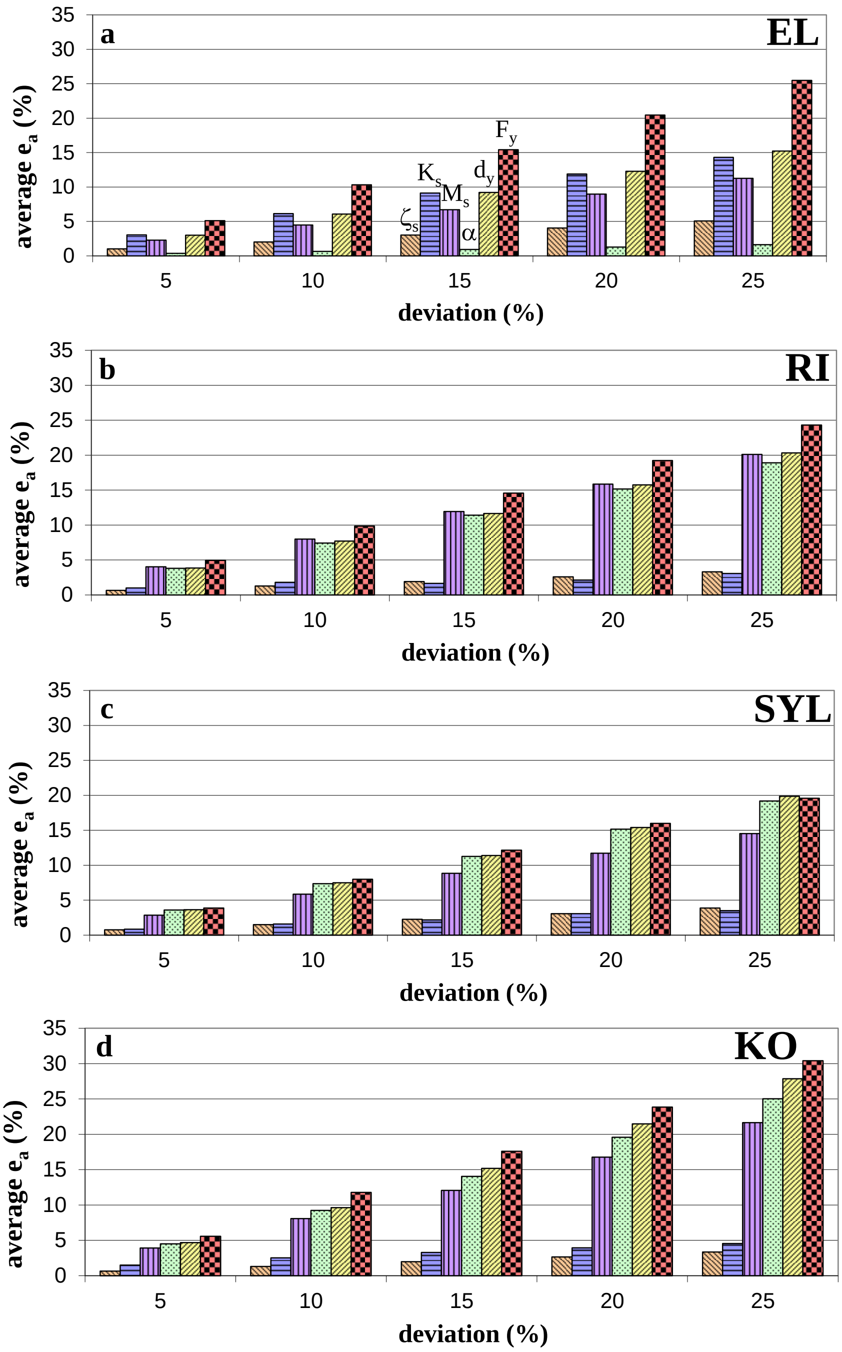

Fig. 10 Sensitivity of peak top floor acceleration to deviations in characteristic parameters of nonlinear isolation systems and superstructure from design values – Average of all isolation systems

According to Fig. 9, it can be said that peak base displacement is not sensitive to superstructure stiffness or superstructure damping at all but shows a sensitivity to superstructure mass. Regarding isolation system parameters, it is seen that peak base displacement is mostly sensitive to yield strength and then comes the yield displacement and the post-yield stiffness to pre-yield stifness ratio.

Fig. 10 shows that although actual values may vary with respect to earthquake, as a general trend, peak top floor acceleration is sensitive to all parameters with superstructure stiffness and superstructure damping being the least influential. There is a considerable sensitivity to the third superstructure parameter, i.e superstructure mass. The level of sensitivities of isolation system parameters are about the same with yield strength being the most influential.

4.3 Summary

In this section, in order to provide an overall perspective, the sensitivity of the structural responses for both linear and nonlinear isolation systems are presented in Fig. 11 in terms of absolute error percentages (see Eqs. (13) and (14)) where their averages are taken over all isolation systems and all earthquakes. Included in Fig. 11 are the results for peak structural base shear (e_V) which are obtained following a similar procedure but presented only in this figure due to space limitation.

Figs. 11(a)-11(c) show that for linear isolation systems, peak base displacement, peak top floor acceleration, and peak structural base shear are not sensitive to superstructure damping or superstructure stiffness. As an exception, peak top floor acceleration varies only slightly (less than 3%) for large deviations (20%-25%) in superstructure stiffness. The sensitivity of peak base displacement to superstructure mass, isolation system stiffness, and isolation system damping is almost equivalent and increases with a low rate with increasing deviations in the subject parameters. The variation in peak base displacement is less than 8% even for a large deviation of 25% (Fig. 11(a)).

The sensitivity trend of peak top floor acceleration and peak structural base shear are similar for linear isolation systems (Figs. 11(b) and 11(c)). They are most sensitive to isolation system stiffness, which causes about 10% variation when a moderate deviation of 10%-15% is considered and about 20% variation when a large deviation of 25% is considered. Their sensitivity to isolation system damping is much less where even a large deviation of 25% causes only about 5% variation in the response. Finally, it is observed that moderate deviations (10%-15%) in superstructure mass cause about 8% variation in peak top floor acceleration and 5% variation in peak structural base shear.

Figs. 12(d) and 12(f) show that for nonlinear isolation systems, peak base displacement and peak structural base shear are not sensitive to superstructure damping or superstructure stiffness but peak top floor acceleration is slightly sensitive to superstructure damping and relatively more sensitive to superstructure stiffness. As seen from Fig. 12(e), the variation of top floor acceleration is about 5% for deviations of 15% to 25% in superstructure stiffness and superstructure damping. The most influential parameter for all response parameters is found to be isolation system yield strength and isolation system yield displacement. For a range of 5%-25% deviation in yield strength, the variation in peak base displacement, peak structural base shear and peak top floor acceleration is about 3%-13%, 4%-22%, and 5%-25%, respectively. Results for isolation system yield displacement are also found to be similar. As seen, peak top floor acceleration and peak structural base shear is influenced more than peak base displacement from a deviation in yield strength or yield displacement.

Of the nonlinear isolation system parameters investigated, post-yield stiffness to pre-yield stiffness is the third most influential parameter which affects peak top floor acceleration and peak structural base shear more than peak base displacement. While a moderate deviation (10%-15%) causes about 4% variation in peak base displacement (Fig. 12(d)), it results in a range of 6%-10% variation in peak top floor acceleration and peak structural base shear (Figs. 12(e) and 12(f)).

Finally, the most influential superstructure response parameter regarding nonlinear isolation systems is the superstructure mass. And deviations in superstructure mass affects superstructure acceleration, the most as it can be seen from Fig. 12(e) where a moderate deviation of 6%-10% causes a variation 10%-15%.

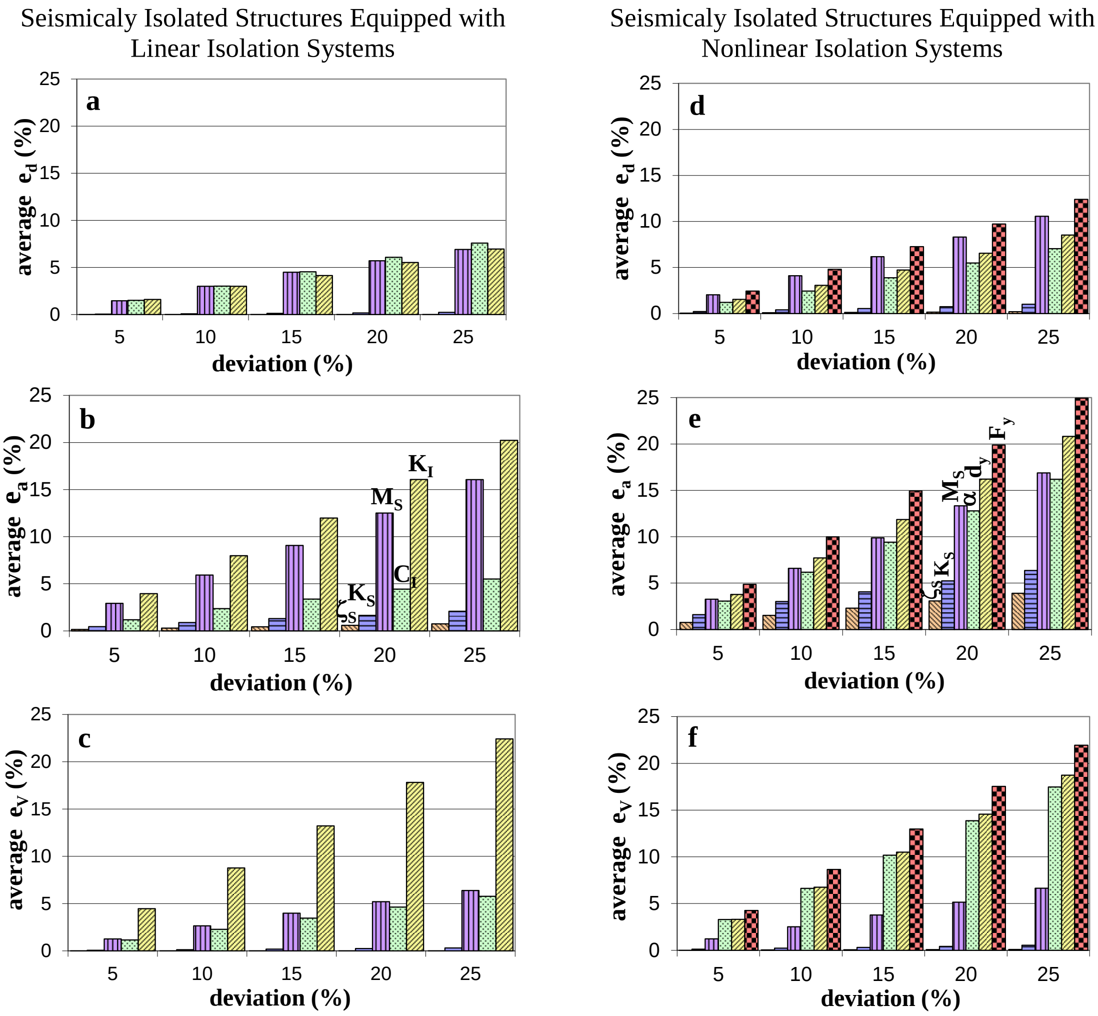

Fig. 11 Summary of sensitivity analyses – Average of all isolation systems and all earthquakes

6. Conclusions

Peak base displacement, peak floor accelerations, and peak structural base shear are the most important design parameters for seismically isolated structural systems as peak base displacement controls the safety of the isolation system and thus the safety of the overall structural system, peak structural base shear controls the safety of the superstructure and peak floor accelerations control the safety and serviceability of the contents. In this study, time history analyses on benchmark seismically isolated shear buildings are conducted under representative historical earthquakes in order to assess the sensitivity of the seismic performance of structures equipped with linear and nonlinear seismic isolation systems to potential deviations in superstructure and isolation system parameters from nominal design values and following conclusions are reached:

- Base displacement and structural base shear are not sensitive to superstructure damping and superstructure stiffness in linear and nonlinear isolation systems. However, large variations in superstructure stiffness and superstructure damping (but to a lesser degree) may have some effect on floor accelerations particularly in nonlinear isolation systems. 25% deviation in superstructure stiffness from its nominal design value may cause about 6% variation in peak top floor acceleration in case of nonlinear isolation systems.
- Of the superstructure parameters investigated, superstructure mass is the only one that significantly affects seismic performance with floor accelerations being most affected for both linear and nonlinear isolation systems. For a range of 5%-25% deviation in superstructure mass, peak top floor accelerations vary in the range of 3%-16% for linear and nonlinear isolation systems.
- The most influential parameter in linear isolation systems is the isolation system stiffness causing 2%-7%, 4%-20%, and 4%-23% variations in peak base displacement, peak top floor acceleration, and peak structural base shear, respectively for a range of 5%-25% deviation. The other isolation system parameter, i.e. isolation system damping is less influential on floor acceleration and structural base shear responses and equally influential on base displacement. For a range of 5%-25% deviation in isolation system damping, the variation in peak base displacement, peak top floor acceleration, and peak structural base shear are 2%-7%, 2%-5%, and 2%-6%, respectively.
- The most influential parameter in nonlinear isolation systems is the yield strength, followed closely and almost equally by the yield displacement and finally by the post-yield stiffness to pre-yield stiffness ratio. For a range of 5%-25% deviation in yield strength, the variation in peak base displacement, peak top floor acceleration, and peak structural base shear are 3%-13%, 5%-25%, and 4%-22%, respectively. For a range of 5%-25% deviation in yield displacement, the variation in peak base displacement, peak top floor acceleration, and peak structural base shear are 2%-8%, 4%-16%, and 3%-17%, respectively. Finally, for a range of 5%-25% deviation in post-yield stiffness to pre-yield stiffness ratio, the variation in peak base displacement, peak top floor acceleration, and peak structural base shear are 2%-7%, 4%-16%, and 4%-17%, respectively.

The results of this study support that ensuring that the selected isolation system keeps its design features during the entire useful time of the structure is vital. Thus, it is critically important that the isolators be fully qualified through three-dimensional tests performed on prototypes using time-histories of historical earthquake ground motion records. It should finally be noted here that the current study is conducted under unidirectional earthquake excitation and the influence of bidirectional time history analysis on the sensitivity results requires more consideration which may be the subject of a future study.

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