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Influence of near-fault ground motions characteristics on elastic seismic response of asymmetric buildings

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Abstract. The elastic seismic response of plan-asymmetric multi storey steel-frame buildings is investigated under earthquake loading with particular emphasis on forward-rupture directivity and fling records. Three asymmetric building systems are generated with different torsional stiffness and varying static eccentricity. The structural characteristic of these systems are designed according to UBC 97 code and their seismic responses subjected to a set of earthquake records are obtained from the response history analysis (RHA) as well as the linear static analysis (LSA). It is shown that, the elastic torsional response is influenced by the intensity of near-fault ground motions with different energy contents. In the extreme case of very strong earthquakes, the behaviour of torsionally stiff buildings and torsionally flexible buildings may differ substantially due to the fact that the displacement envelope of the deck depends on ground motion characteristics.

Keywords: near-fault; seismic response; torsionally stiff; torsionally flexible

1. Introduction

The main step in a performance-based evaluation is the prediction of seismic demands in both structural and non-structural elements in the structure, due to the imposed earthquake loads. The prediction of deformation demands is arguably the most critical step in seismic performance-based design. Determining demands necessitates the development of a structural model of reasonable complexity. Errors in estimating the demand as a result of an inadequate structural model can propagate through and lead to misleading conclusions on the performance of the structure. Disregard the torsional effects is one of the important errors in estimating the demand of asymmetric building systems during strong earthquakes (Karavasilis *et al.* 2008).

In recent years some innovative ideas have appeared which complement the traditional approaches and help to better understand the elastic torsional response. Most researchers have based their studies on a simpler model of single-storey system, which neglects the transverse motion (Tso and Dempsey 1980, Trombetti and Conte 2005). Dempsey and Tso proposed a scheme for estimating the equivalent static seismic eccentricity in buildings with torsionally unbalanced distributions of

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mass and stiffness (Dempsey and Tso 1982). De la Llera and Chopra verified that the discrepancies between the computed and actual stiffness values of the structural elements. They further showed that a building with nominally symmetric plan is actually asymmetric to some unknown degree and undergoes torsional vibrations, subjected to purely translational ground motion (De la Llera and Chopra 1994, 1995). It is of note that some of the principles of torsional mechanism used in code recommendations have been scrutinized by some researchers and ideas have been expressed correspondingly (Anechitei *et al.* 2010). The main difference between the torsional responses of the building systems lies in their torsional stiffness and strength. More importantly, the seismic response of the systems, especially in the torsionally flexible structure is qualitatively different from that obtained in the case of static loading at the center of mass. A comprehensive study of the "equivalent static eccentricity" was presented by Anastassiadis *et al.* (1998). They also developed a set of formulas which, for a single-storey scheme, allow determination of the actual and additional eccentricities. The static analysis necessitates determination of these eccentricities based on modal analysis in order to estimate the maximum edge displacements and deck rotation. In seismic response analysis, the determination of "equivalent static eccentricities" is known as an allowable and approximate method.

Research over the last decade has shown that pulse-type earthquake excitations which results from forward-rupture directivity mechanism can result in significant damage to the structures, (Rodriguez-Marek and Cofer 2007). It should be noted that, the torsional response is influenced by the intensity of ground motion which is a representative of different energy content of near-fault records (Howard *et al.* 2005). In utmost strong ground motions, the behavior of torsionally stiff and flexible buildings may differ substantially due to the fact that the displacement envelope of the deck depends on ground motion characteristics. However, the inelastic torsional response is less easily predictable, because the location of the center of rigidity on each floor cannot be readily determined and the eccentricity varies from one storey to the other at each non-linear static analysis step. It is well known that torsionally unbalanced buildings are more vulnerable to near-fault earthquake hazards than are the regular structural systems (Bayraktar *et al.* 2008). In response to the realization of the importance of considering pulse-type motions when predicting structural performance, significant work towards developing equivalent pulse models characterizing the special effects of pulse-type motions is carried out (Xu and Xie 2006). Recently, Effects of spatial variability of earthquake ground motion in cable-stayed bridges have been investigated (Ferreira and Negrao 2006). A number of studies have been carried out to investigate the torsional vibrations in flexibly supported structures resulting from structural asymmetry and foundation rotation (Juárez and Avilés 2008).

Present study concentrates on earthquake characteristics with particular emphasis on near-fault records and their impacts on the seismic responses of both torsionally stiff and torsionally flexible buildings. Using equivalent static eccentricity, a number of asymmetric buildings having different torsional stiffnesses have been analyzed. Results have been compared with those given by response history analyses (RHA) of those buildings subjected to some known near fault ground motion records.

2. Torsionally stiff buildings and torsioally flexible buildings

The analysis of asymmetric buildings using the single-storey models is one of the most frequently

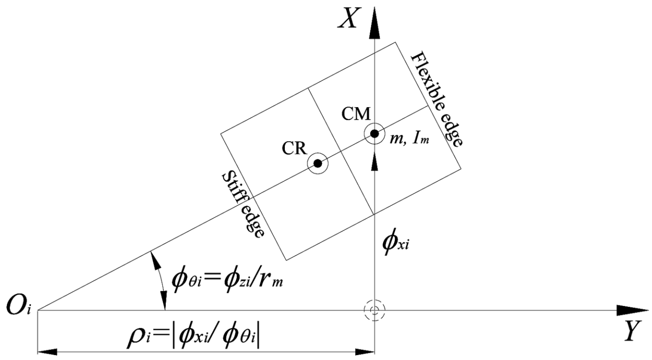

Fig. 1 The distance from the center of mass (CM) to the center of rotation of i-th mode O_i

used approaches. These simplified models are only capable of verifying the basic aspects of the dynamic torsional behavior of actual multi-storey structures. Therefore, the asymmetric building models are classified based on their dynamic characteristics. The equation of motion of undamped free vibration of monosymmetric single-storey asymmetric buildings subjected to the earthquake excitation in X-Direction can be written as follows (see also Fig. 1)

$$\begin{bmatrix} m & 0 \\ 0 & I_m \end{bmatrix} \begin{Bmatrix} \ddot{y} \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} K_x & K_x \cdot e \\ K_x \cdot e & K_\theta \end{bmatrix} \begin{Bmatrix} y \\ \theta \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{1}$$

In this equation, $[M] = \begin{bmatrix} m & 0 \\ 0 & I_m \end{bmatrix}$ is mass matrix, $[K] = \begin{bmatrix} K_x & K_x \cdot e \\ K_x \cdot e & K_\theta \end{bmatrix}$ is elastic stiffness matrix, $\{d\} = \{y \;\; \theta\}^T$ is vector representing displacement at the center of mass and rotation; m: mass, I_m: moment of inertia, K_x: elastic lateral stiffness in X-direction, $K_\theta = K_x \cdot r_k^2$: elastic torsional stiffness with respect to the center of mass, e: static eccentricity (eccentricity between mass and stiffness centers), r_k: radius of gyration of storey stiffness and r_m: radius of gyration of storey mass.

$$z = r_m \cdot \theta, \quad E = e/r_m, \quad J = r_k/r_m \tag{2}$$

$$\omega_x = \sqrt{K_x/m}, \quad \omega_\theta = \sqrt{K_\theta/I_m} = (r_k/r_m) \cdot \sqrt{K_x/m} = J \cdot \omega_x \tag{3}$$

Substitution of Eqs. (2) and (3) into Eq. (1), results in

$$\begin{Bmatrix} \ddot{y} \\ \ddot{z} \end{Bmatrix} + \omega_x^2 \cdot \begin{bmatrix} 1 & E \\ E & J^2 \end{bmatrix} \begin{Bmatrix} y \\ z \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{4}$$

where E is the eccentricity ratio, J is the radius ratio of gyration of storey (the ratio of uncoupled torsional frequency to uncoupled translational frequency), ω_x and ω_θ are the uncoupled translational frequency and uncoupled torsional frequency, respectively. The i-th natural frequency ω_i and i-th mode shape vector $\{\phi_i\} = \{\phi_{xi}, \phi_{zi}\}^T$ of the single-storey asymmetric building models can be obtained from Eq. (4) as

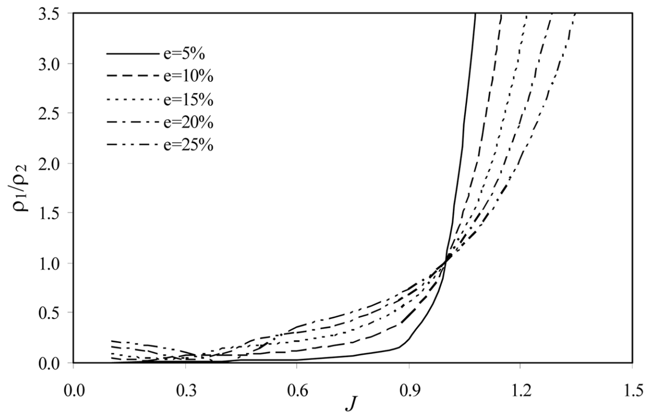

Fig. 2 The ρ_1/ρ_2 ratio obtained for varying of J for different static eccentricity, e and aspect ratio = 1

$$\left.\begin{matrix}\omega_1^2\\ \omega_2^2\end{matrix}\right\} = \frac{(1+J^2) \mp \sqrt{(1-J^2)^2+4E^2}}{2}\cdot\omega_x^2 \quad \text{and} \tag{5}$$

$$\phi_{xi}/\phi_{zi} = \{J^2-(\omega_i/\omega_x)^2\}/E \tag{6}$$

In Fig. 1, the distance from the center of mass (CM) to the center of rotation of i-th mode O_i is obtained as follows

$$\rho_i = |\phi_{xi}/\phi_{\theta i}| = z\cdot|\phi_{xi}/\phi_{zi}| \tag{7}$$

The building model is classified as torsionally stiff (TS) building when ρ_1 is larger than ρ_2, and it is classified as torsionally flexible (TF) building when ρ_1 is smaller than ρ_2. Substantiation of Eq. (6) into Eq. (7) leads to the following relation

$$\rho_i/r = \left|\{J^2-(\omega_i/\omega_x)^2\}/E\right| \tag{8}$$

using Eqs. (5) and (8) on obtains

$$(\rho_1/r)^2-(\rho_2/r)^2 = \{(\omega_2/\omega_x)^2-(\omega_1/\omega_x)^2\}(J^2-1)/E^2 \tag{9}$$

In Eq. (9), $(\omega_2/\omega_x)^2-(\omega_1/\omega_x)^2>0$, since the relation $\omega_2>\omega_1$ applies. Therefore the relationship between ρ_1 and ρ_2 is expressed as follows

$$\begin{cases}\rho_1<\rho_2 & \text{for} \quad J<1\\ \rho_1=\rho_2 & \text{for} \quad J=1\\ \rho_1>\rho_2 & \text{for} \quad J>1\end{cases} \tag{10}$$

Eq. (10) reveals that the buildings with $J > 1$ that are classified as TS buildings, while those with $J < 1$ are classified as TF buildings. For example, Fig. 3 shows the ρ_1/ρ_2 ratio obtained for variation of J for different static eccentricity, e and aspect ratio = 1.

3. Near fault ground motion effects

In the near fault region of a large earthquake, there are two conditions that can lead to large, long period pulses of ground motion: rupture directivity and tectonic fling. Rupture directivity occurs on the fault normal component of motion at site located close to the fault, but away from the epicenter. The directivity motions are controlled by the far-field SH waves, which results in a two-sided pulse in ground velocity which attenuates with inverse distance. Fling results from the tectonic displacement on the fault and occurs on the fault parallel components for strike slip rupture, or on the fault normal component for reverse rupture. Fling effects are independent of epicenter location. The fling motions are controlled by the near- and intermediate radiation terms, and are manifested by a one-sided pulse in ground velocity which generally attenuates as inverse distance squared.

Failures of modern engineered structures, observed within the near-fault region in 1994 Northridge earthquake, revealed the vulnerability of existing steel buildings against pulse-type ground motions. In addition, strong directivity effects during the 1999 Kocaeli, Duzce and Chi-Chi earthquakes renewed the attention on the consequences of near-fault ground motions on structures. The objective of this study, therefore, is to examine the torsional response of typical asymmetric buildings to near-fault ground motions.

4. Description of building systems used for evaluation

The 5-storey steel frame buildings used in this study are those systems which were previously investigated by Marusic and Fajfar (2005). These systems with different torsional stiffness are denoted as structures S, F1, and F2. The square plan of the buildings measures 22.5 m × 22.5 m and the storey heights are 4.0 m and 3.5 m for the first storey and for the other storeys, respectively.

The plan and elevation of these buildings are shown in Fig. 3, where moment-resistant frames are indicated by bold lines, and pin-connections by circles. The mass at the top level is 33100 kg, for all the other levels are 31500 kg. The mass moment of inertia at the top level is 279 E 4 kg·m^2 and 266 E 4 kg·m^2 at all the other levels. The first three periods of vibration for all buildings are listed

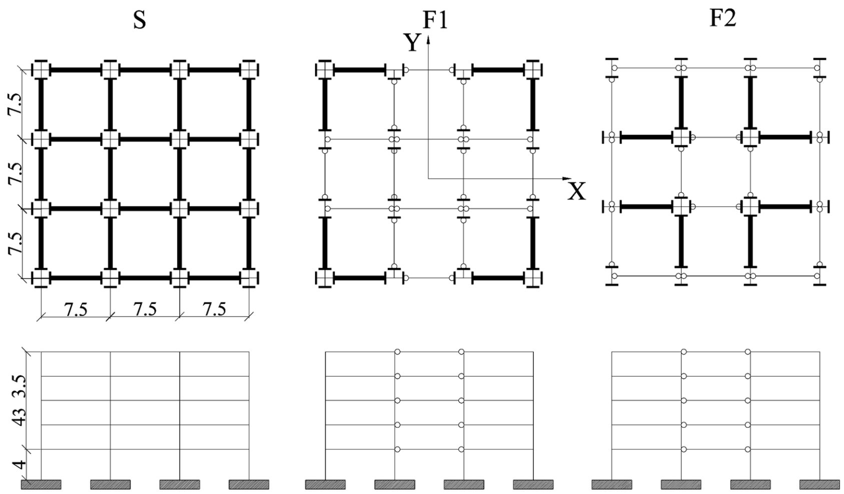

Fig. 3 Plan and elevation configurations for the 5-storey buildings (Marusic and Fajfar 2005)

Table 1 The first three periods of vibration for three asymmetric buildings S, $F1$ and $F2$

System	S				$F1$				$F2$			
Eccentricity e%	0	5	10	15	0	5	10	15	0	5	10	15
T1 [s]	1.25	1.27	1.34	1.42	1.26	1.27	1.29	1.34	2.13	2.18	2.30	2.48
T2 [s]	1.25	1.25	1.25	1.25	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26
T3 [s]	0.96	0.94	0.90	0.85	0.73	0.72	0.71	0.68	1.26	1.23	1.16	1.08

in Table 1. The second mode of vibration is purely translational in the diagonal direction and therefore equal for all eccentricities.

The structural characteristics of these systems are designed according to UBC 97, and the elastic and elastic torsional response is investigated under ground motion characteristics with particular emphasis on forward-rupture directivity and fling records. The general-purpose computer program DRAIN-3DX, is used to perform the elastic analysis of the test structures (Prakash *et al.* 1994).

5. Benchmark ground motion records

A set of 14 strong ground motions; with a magnitude range of 6.6 to 7.5 were used, these records represent near-fault ground motions from a variety of tectonic environments. Such a complete set of

Table 2 Ground motion ensemble

No	Year	Earthquake	M_W	Mech.[a]	Recording station	Dist. (km)[b]	Site Class[c]	Data Source[d]	Comp.	PGA (g)
Near-fault ground motions with forward directivity										
1	1989	Loma Prieta	7.0	OB	LGPC	3.5	C	1	000	0.56
2	1989	Loma Prieta	7.0	OB	Lexington Dam	6.3	C	2	090	0.41
3	1992	Cape Mendocino	7.1	TH	Petrolia, General Store	15.9	C	1	090	0.66
4	1992	Erzincan	6.7	SS	Erzincan	2.0	C	1	EW	0.50
5	1994	Northridge	6.7	TH	Rinaldi Receiver Stn.	8.6	D	2	275	0.84
6	1994	Northridge	6.7	TH	Olive View	6.2	D	1	360	0.84
7	1995	Kobe	6.9	SS	KJMA	0.6	C	1	000	0.82
Near-fault ground motions with fling										
1	1999	Kocaeli	7.4	SS	Sakarya (SKR)	3.20	C	3	EW	0.41
2	1999	Kocaeli	7.4	SS	Yarimca (YPT)	3.30	D	3	NS	0.24
3	1999	Chi-Chi	7.6	TH	TCU052	3.01	D	4	NS	0.44
4	1999	Chi-Chi	7.6	TH	TCU068	3.01	D	4	EW	0.50
5	1999	Chi-Chi	7.6	TH	TCUO74	13.8	D	4	EW	0.59
6	1999	Chi-Chi	7.6	TH	TCUO84	11.4	C	4	NS	0.42
7	1999	Chi-Chi	7.6	TH	TCU129	2.20	D	4	NS	0.61

[a]Faulting mechanism = TH: Thrust; REV: Reverse; SS: Strike-slip; OB: Oblique
[b]Closest distance to fault.
[c]NEHRP site Class = B for V_s (Shear-wave velocity) = 760-1500 m/s; C for V_s = 360-760; D for V_s = 180-360
[d] Data source = 1: PEER; 2 COSMOS; 3 ERD; 4: CWB

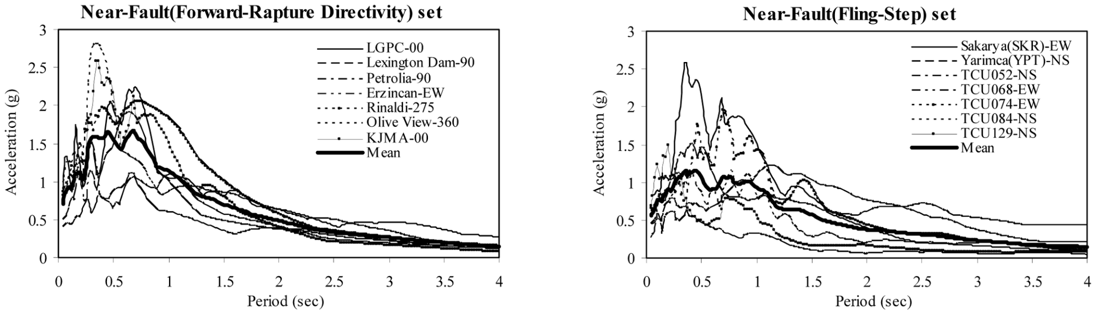

Fig. 4 Elastic response spectra sets for 5% damping

records was selected to cover a range of frequency content, duration, and amplitude. These ground motion records are recommended by SAC steel project (Somerville *et al.* 1997) and the CDMG Strong Motion Instrumentation Program (Somerville 1998). Characteristics of these records are given in Table 2 and their elastic response spectra corresponding to 5% damping ratio are shown in Fig. 4 for each set of building systems. To facilitate the comparison with the static analysis, the selected ground motions are scaled to a PGA of 0.5 g.

The first set includes seven near-fault ground motions, characterized with forward directivity effect. These ground motions are contained records either taken from soil or stiff soil sites. These records are from earthquakes with moment magnitude (M_W) range of 6.7 to 7.1, which were recorded at closest fault distance of 0.0 to 15 km. In the second set, a total of seven near-fault ground motions, characterized with fling displacement, were collected. They are recorded from 1999 (M_W 7.4) Kocaeli (Turkey) and 1999 (M_W 7.6) Chi-Chi (Taiwan) earthquakes at distances of 2.2 to 13.8 km.

6. Evaluation of the elastic torsional response

In order to determine the elastic torsional response, the edges displacements of deck of the asymmetric buildings studied are evaluated using elastic response history analysis (RHA). The results obtained are compared with those given by linear static analysis (LSA) considering "equivalent static eccentricity". Plots of normalized edge displacements (at both the stiff edge and flexible edge) evaluated by dynamic and static analyses are shown in graphs of Fig. 5. In these graphs, the normalized edge displacements are plotted for different values of static eccentricity for each earthquake records set (U_d and U_s are dynamic and static responses, respectively).

It is seen that the dynamic response of torsionally flexible building (system $F2$) is qualitatively different from that observed in torsionally stiff buildings (system $F1$ and S). As a result, the displacement at stiff edge increases due to torsion in torsionally flexible building and the displacement at flexible edge is generally larger than the displacement at stiff edge in torsionally stiff buildings.

As shown in Fig. 5, the behaviour of both the torsionally stiff and flexible buildings is different because the displacement envelope of the deck depends on ground motion characteristics. It is long recognized that near-fault motions characterized by forward directivity effects are potentially more damaging. However, the consequences of fling displacements have not been well understood. In the

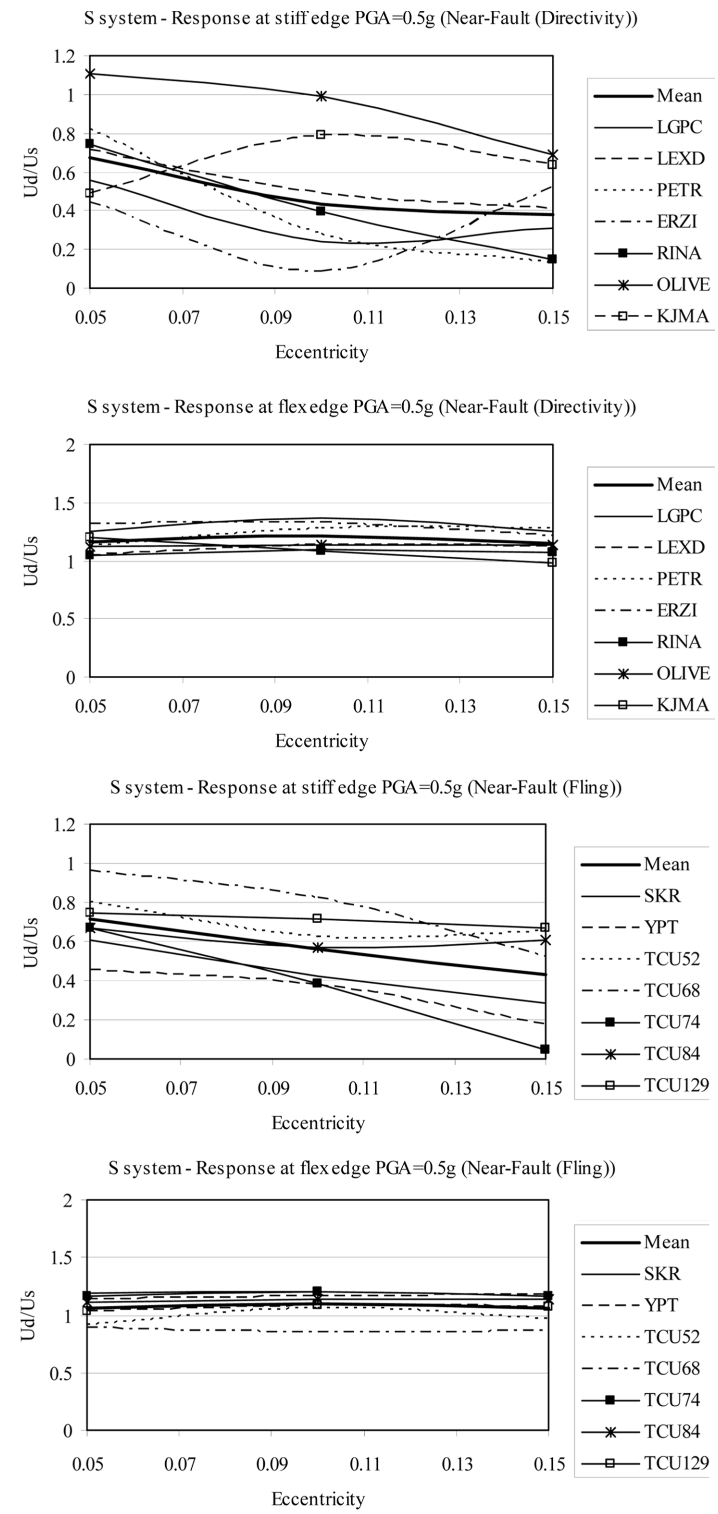

Fig. 5(a) Elastic torsional response at the stiff and flexible edges of the S-system

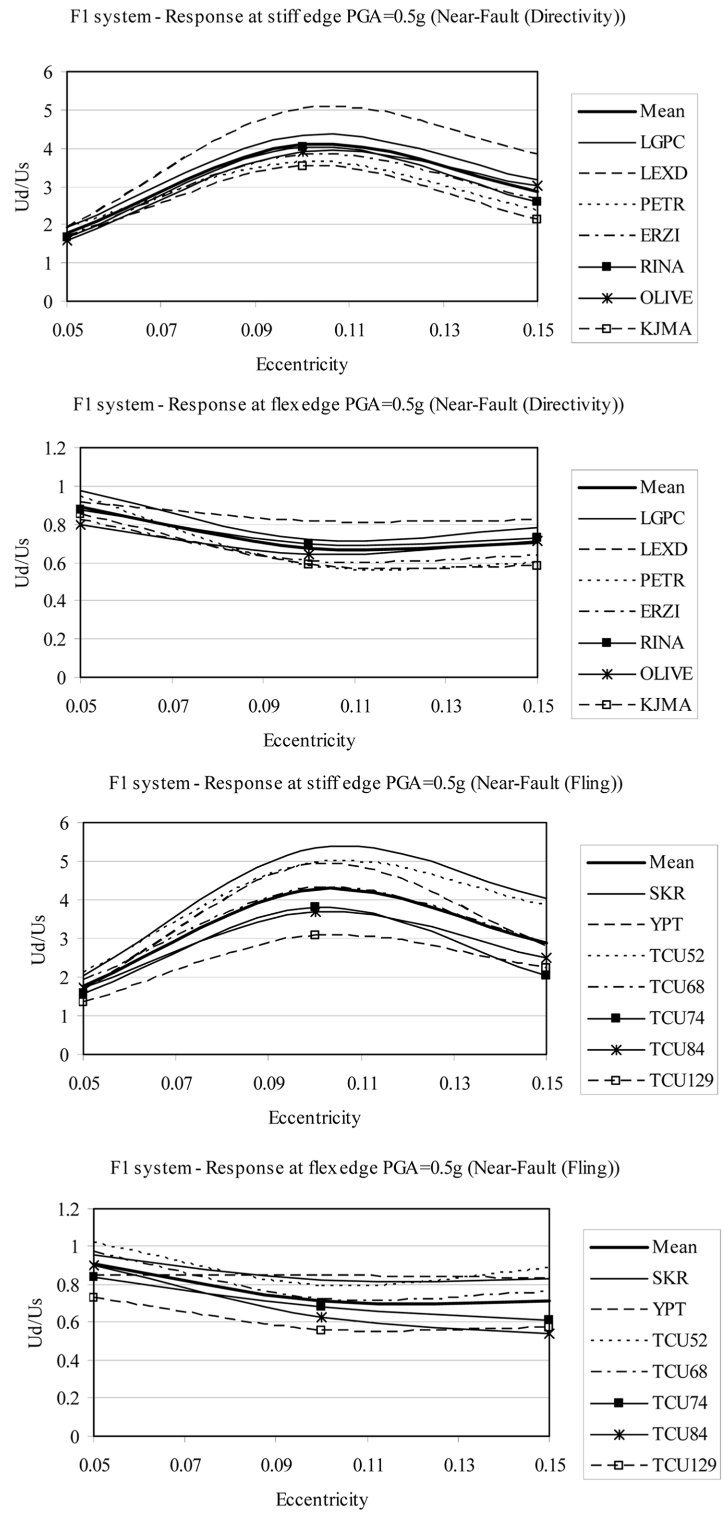

Fig. 5(b) Elastic torsional response at the stiff and flexible edges of the F1-system

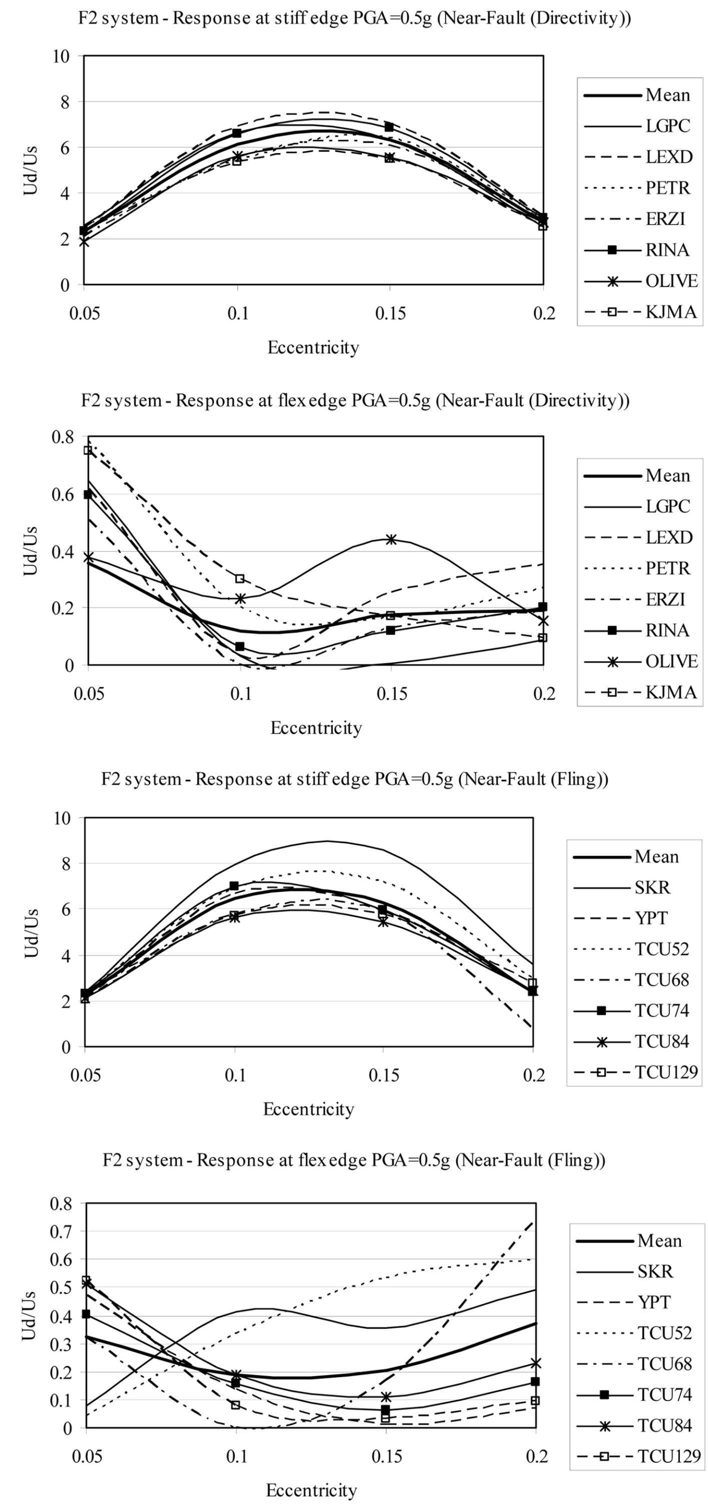

Fig. 5(c) Elastic torsional response at the stiff and flexible edges of the F2-system present study fling effects are considered by examining the response of buildings to recorded ground motions that contain fling effects. Findings from this study indicate that near-fault records with fling can be more damaging than forward-rupture directivity effects. However, they tend to accentuate torsional mode behaviour.

However, at both the flexible and the stiff edge of the torsionally stiff building a consistent trend can be observed over the mean values.

7. Conclusions

Three asymmetric building systems having different torsional stiffnesses were examined for the evaluation of torsional seismic response. In order to facilitate assessment of the effects of near-fault records on structural response, a set of near-fault ground motion records having forward directivity and fling were examined. Results obtained by linear static analysis (LSA) were compared to response of buildings to typical near-fault ground motions estimated using response history analysis (RHA). A subjective comparison of displacements component observed at the stiff and flexible edge for different type of ground motion records was presented.

It was found that torsional response depends strongly on the uncoupled lateral-torsional frequency ratio and the intensity of ground motion representing different energy content of near-fault records.

Further, it was concluded that a careful examination of acceleration and velocity spectra can, collectively, provide a reasonable assessment of the damage potential of near-fault records for practicing engineers. Demands in the torsional modes must be further evaluated by taking into account the fact that modal periods shift to the right of the spectrum as the system moves from the elastic to inelastic state.

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