Role of Ground Motion Characteristics on Inelastic Seismic Response of Irregular Structures

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Abstract: There is no general consensus among researchers for selecting appropriate set of ground motions for the evaluation of inelastic seismic response of plan-asymmetric structures. In this backdrop, the role of important ground motion characteristics on the demand of a plan-asymmetric system is studied by using a number of records with widely varying characteristics but adjusted (using wavelets) to a common spectral shape. An equivalent single-story rigid-diaphragm model with simple elastoplastic hysteresis behavior is employed. Efficient strength design, viz, center of strength–center of mass (CV-CM)–coinciding strategy, is adopted in recognition of the strength-dependent stiffness characteristics of the load-resisting elements. It has been shown that the torsion-induced response of such systems is statistically insensitive to important ground motion parameters such as duration, frequency content, the interrelationship between two horizontal components, and the energetic length scale. Conversely, this study shows that a remarkable correlation exists between the carefully selected ground motion parameters and overall seismic demand as a result of coupled lateral-torsional vibration. The results motivated the authors to conceptualize a master curve that offers an a priori estimate of inelastic seismic demand of asymmetric systems when two widely used ground motion parameters, viz, peak ground acceleration (PGA) and mean period (T_m), are known. Thus, this study provides a background for dispelling the long-held controversy regarding the selection of an appropriate ground motion suite for assessing torsional response. **DOI: 10.1061/(ASCE)AE.1943-5568.0000185.**

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Introduction

Architectural decisions for building planning related to aesthetics, function, cost, circulation, spatial relationships, etc. affect the shape, dimension, and placement of structural and nonstructural elements (viz, lateral load-resisting walls and cores). These factors are known to potentially contribute to earthquake resistance. Buildings with irregular floor shapes have been observed to be susceptible to stronger seismic activity relative to regular buildings (Hart et al. 1975). Some examples of damage to irregular structures occurring were found in the 1985 Mexico earthquake (Chandler 1986; Rosenblueth and Meli 1986; Esteva 1987) and the 1994 Northridge, California, 1995 Kobe, Japan, 1999 Taiwan, and 2001 central-western India earthquakes (Goyal et al. 2001). However, irregular floor plans are widely used and perhaps will continue being adopted for housing, schools, and hospitals because they provide a greater number of perimeter rooms with access to natural lightning and ventilation. Thus, the center of mass (CM) and center of resistance (CR) of buildings do not coincide practically for all structures, which results in the generation of torsion in plan-asymmetric systems, even under pure translational ground shaking.

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After the recognition of this additional seismic vulnerability that results from asymmetry, numerous investigations (e.g., Tso and Dempsey 1980; Kan and Chopra 1981a, b; Chopra and Goel 1991; Tso and Zhu 1992; Zhu and Tso 1992; Humar and Kumar 1998) were carried out to gain insight into the basic trend in both elastic and inelastic behavior of asymmetric systems. These studies used a parametrically defined equivalent single-story model. A recent study (Dutta and Roy 2012) prepared a response envelope for low-rise multistory asymmetric systems using artificial records to account for multimodal contributions. Observations of these studies were reviewed to bring some order to the diverging research orientations (De Stefano and Pintucchi 2008; Anagnostopoulos et al. 2015 and references therein), and the results constitute the basis of the design guidelines embodied in modern seismic codes (IAEE 2000).

Limited studies (Myslimaj and Tso 2002; Tso and Myslimaj 2003; Myslimaj and Tso 2004; Myslimaj and Tso 2005; Sommer and Bachmann 2005; Roy and Chakroborty 2013; Roy et al. 2014a, b) have been conducted to examine the response of asymmetric systems accounting for strength-dependent stiffness of lateral load-resisting structural elements (Paulay 2001a; Aschheim 2002). In the context of interdependency between stiffness and strength, a suitable framework for effective strength distribution was developed recently and represents so-called one-way and two-way asymmetry in a common unique format (Roy and Chakroborty 2013). This study also provided charts for preliminary estimates of torsional amplification.

The authors, however, are unaware of any investigation that systematically addressed the effects of ground motion characteristics on the amplification in seismic demand caused by torsion in plan-asymmetric systems. It is not surprising that the selection of ground motion is often perceived to be the major source of disagreement in reported seismic behavior by researchers (Chandler et al. 1996). In this backdrop, the present investigation evaluates the role of influential ground motion parameters on inelastic seismic demand of plan-asymmetric systems using an idealized single-story analog. The study addresses the impact of (a) the duration of ground motion, (b) frequency content, and (c) statistical dependency (or independency) between two horizontal components of ground motion. The influence of ground motion parameters on earthquake-induced damage caused by torsional and coupled lateral-torsional vibration is discussed. The study, therefore, is believed to prepare a useful framework for the selection of appropriate records.

Review of Ground Motion Parameters

Seismic ground motion at a point includes three translational and three rotational components. In seismic design, when evaluating structural response, it is customary to consider the translational components by presuming the influence of rotational components to be small (Kubo and Penzien 1979). Although the effects of such rotational components may not be small, particularly for spatially extended systems (such as bridges or pipelines) or base-isolated systems, the lack of availability of rotational components of earthquakes often compels researchers to ignore such effects. In addition, the effect of the vertical component of ground motion for buildings is generally small and hence neglected (Beyer and Bommer 2007). Even with these simplifications accepted, characterizing ground motions is essentially challenging to the profession.

The duration of ground motion is an important parameter that regulates the rate of energy directed at a structure during seismic shaking (Trifunac and Novikova 1995). A thorough seismic hazard assessment, therefore, should include strong-motion durations that current design codes do not. It was observed in some studies (Chai and Fajfar 2000; Kunnath and Chai 2004) that inelastic demand may be amplified with an increase in duration, whereas no significant influence on maximum inelastic displacement was noted by other researchers (Shome et al. 1998; Iervolino et al. 2006). An investigation of masonry structures indicated that ground motions with longer durations may cause greater strength degradation (Bommer et al. 2004). From an exploration of inelastic demand of reinforced concrete structures (Hancock and Bommer 2007), it was concluded that the peak response does not depend on duration, whereas hysteretic energy and fatigue damage increase for records with a longer duration. Thus, the role of ground motion duration on seismic demand is controversial. It may be noted that the Hazus methodology for earthquake loss estimation accounts for the duration of earthquake explicitly (Whitman et al. 1997; FEMA 1999).

There exist a number of definitions of strong-motion duration (e.g., Bolt 1973; Trifunac and Brady 1975; Vanmarcke and Lai 1980; Bommer et al. 2006) that may be classified broadly as significant duration (T_d), uniform duration, and bracketed duration (Bommer and Martínez-Periera 1999). Significant duration is based on the accumulation of energy in an accelerogram and is defined as the interval over which a certain portion (in which the motion is deemed strong) of the total Arias intensity (I_a) is accumulated. In the present study, such limits are taken as 5%–75% and 5%–95% to estimate significant durations denoted as $D_{5\text{–}75}$ and $D_{5\text{–}95}$, respectively. Conversely, because these variants of significant duration are based on the use of relative criteria, the effective duration (D_e) constrained by absolute thresholds of Arias intensity has been proposed in the literature (Bommer and Martínez-Periera 1999). D_e is defined as the interval of strong shaking that begins at a point when the Arias intensity of a record accumulates to 0.01 m/s and ends when the remaining I_a in the record equals 0.125 m/s (Bommer and Martínez-Periera 1999). Thus, the duration of all records with an I_a value of less than 0.135 m/s is taken to be of no engineering significance.

Earthquake motions comprise a wide range of frequencies that are expected to potentially contribute to structural response (Rathje et al. 2004). The predominant period (T_p) (i.e., the period at which maximum spectral acceleration occurs) is often used by engineers to measure frequency characteristics. However, two acceleration spectra with the same T_p value may differ in spectral shape (Rathje et al. 1998); hence, this parameter may be inconsistent. T_p also disregards the frequency content around the peak spectral acceleration (Rathje et al. 1998; Rathje et al. 2004). Conversely, the mean period (T_m) is considered relatively stable and independent of structural response. This value is computed from the Fourier amplitude spectrum of an acceleration time history as $\Sigma_i C_i^2/f_i/\Sigma_i C_i^2$ (Rathje et al. 1998), where C_i is the Fourier amplitude of the accelerogram and f_i is the corresponding discrete Fourier transform frequency between 0.25 and 20 Hz.

In addition, it is intuitive to think that the dependency between earthquake components may be an important factor in assessing response under bidirectional shaking. Because ground motion components are generated from the same earthquake source and seismic waves that travel through the same medium, strong dependence between the temporal and spectral characteristics of the two components is expected. The correlation coefficient (ρ_{xy}) between the earthquake components may characterize such dependency (Rezaeian and Kiureghian 2011) and is defined as

$$\rho_{xy} = \frac{\mu_{xy}}{\sigma_{xx}\sigma_{yy}} \tag{1}$$

where

$$\sigma_{xx}{}^2 = \frac{1}{D}\int_0^D [a_x(t) - a_{mx}(t)]^2 dt; \qquad \sigma_{yy}{}^2 = \frac{1}{D}\int_0^D [a_y(t) - a_{my}(t)]^2 dt$$

and

$$\mu_{xy} = \frac{1}{D}\int_0^D [a_x(t) - a_{mx}(t)][a_y(t) - a_{my}(t)] dt$$

where $a_{x/y}(t)$ is the time history; and $a_{mx/y}(t)$ is the mean value of the time history in the x- or y-direction over the duration D. Orientation of the ground motion axis with respect to the structural axis has been shown to play an important role in regulating response (Beyer and Bommer 2007; Hong and Goda 2007). It is evident that a change in the orientation of ground motion components is associated with a corresponding change in ρ_{xy} (Rezaeian and Kiureghian 2011). Records with different ρ_{xy} values, therefore, may implicitly capture the influence of relative orientation between the ground motion and the structure. In fact, this coefficient has been considered an important parameter for record selection in bidirectional analysis [ASCE 4-98 (ASCE 2000)].

The existence of a special type of symmetry for seismic response in the nonlinear range was shown by Makris and his coworkers for both pulselike and nonpulselike motions (Dimitrakopoulos et al. 2009; Karavasilis et al. 2010; Makris and Vassiliou 2011). Such studies (viz, Dimitrakopoulos et al. 2009) identified the usefulness of a simple yet physically rational energetic length scale of record (L_e). Such an energetic length scale may be expressed as $a_g T_m{}^2$, where a_g represents peak ground acceleration (PGA) and T_m represents the mean period.

On the basis of the foregoing review, it is contended that duration, defined as significant duration T_d (represented through $D_{5\text{–}75}$ and $D_{5\text{–}95}$ and D_e), frequency content (represented by T_m), and the correlation coefficient (ρ_{xy}) between two horizontal components of a record may be chosen as characteristic ground motion parameters. Furthermore, the relevance of the energetic length scale (L_e) on the inelastic responses of plan-asymmetric systems is explored. It may be noted that the parameters identified herein are independent of structural properties (unlike spectral acceleration) and, hence, are equally valid for every structure, which is a strong reason for favoring selection of the ground motion parameters discussed.

Spectral Matching of Ground Motions

Target Spectrum

It is well known that the period of a structure elongates as a consequence of inelastic damage. Conversely, higher modes may also participate in structural response, which implies that the spectral shape of an earthquake should be in the neighborhood of the fundamental period of the structure. One potential alternative to account for this spectral shape effect is to adjust real records through wavelet adjustment. Response spectral matching over a period range of interest reduces variance in the resulting structural response; hence, a smaller number of analyses are required to obtain confidence in median structural response quantities (Hancock et al. 2008).

For spectral matching, a popular choice for the reference spectrum is a uniform hazard spectrum (UHS), the ordinate at each period of which is the spectral value that has a specified probability of being exceeded each year, defined by a hazard level. However, in the traditional UHS, the joint probability of exceeding a number of spectral ordinates at different periods is ignored. It seems conservative to assume the probability of exceeding at a specific period and that at all other periods are identical (Baker and Cornell 2006). The conditional mean spectrum (CMS) is defined by the conditional mean and standard deviation of the spectral ordinates at all other periods, given a spectral ordinate at a period known as the conditioning period, T^* (often chosen as the fundamental period of the structure, T). The conditional mean and standard deviation of spectral ordinates are obtained by using seismic hazard deaggregation information and regression equations based on statistical observations of correlations between spectral ordinates (Baker and Jayaram 2008). In fact, it has been concluded that the CMS is often a preferred choice (Roy et al. 2014a, b; Nicknam et al. 2014). Further discussion on these hazard spectra is available elsewhere (Baker 2011).

For the present investigation, the CMS of Los Angeles, CA [latitude 34.0890° N, longitude 118.4350° W; Soil Class D (USGS 2008)], was chosen as a reference target for different conditioning periods T^* (0.2, 1.0, and 3.0 s representative of a short, a medium, and a long period, respectively). Fig. 1(a) illustrates such reference hazard spectra collected from the USGS corresponding to 2% probability of exceedance (PE). A related UHS (USGS 2012) is superimposed therein for comparison only. These spectra are associated with the attenuation relationships [i.e., relationship of "ground motion parameters to the magnitude of an earthquake and the distance away from the fault rupture" developed for western North America by Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008)]. A sophisticated correlation model (Baker and Jayaram 2008), valid over a period range of 0.01 to 10.0 s, is used to develop such a CMS.

Spectral Adjustment

To eliminate the effect of distinction of spectral shape, approximately 70 strong-motion real accelerograms collected from the PEER database are scaled to the CMS considering a period range of $0.2T$ to $1.5T$ [as recommended in SEI 7-05 (ASCE 2006)], where T is the fundamental period of the structure selected as 0.2, 1.0, or 3.0 s. Evidently, for the selection of the target CMS, T^* is identical to T. This scaling is performed in multiple sweeps (i.e., successively incorporating longer periods into the matching process as recommended in GCR 11-917-15 (NIST 2011) to better preserve the nonstationary characteristics of the seed motions using *SeismoMatch 1.3.0*. Further details of the methodology are available elsewhere (Abrahamson 1992; Hancock et al. 2006).

Response of the asymmetric structure is computed under bidirectional seismic excitation. For this purpose, it is desirable for the components of ground motions to be scaled pairwise (Grant 2011) by selecting appropriate major axis and minor axis spectra derived from orientation-dependent ground motion measures (Hong and Goda 2007). However, such major and minor axis spectra are often identical (Grant 2011). The adequacy of such identical spectra for assessing torsion-induced damage in plan-asymmetric systems has been shown in recent works (Roy et al. 2014a, b). Thus, each component of the selected records is matched to that of the reference CMS. Finally, observing the goodness in match, 30 records (of 70 scaled) are used in the analysis.

Fig. 1(b) presents the target spectrum, the associated spectrum of each scaled history, and the mean spectrum in the sample form ($T^* = 1.0$ s), which offers a visual impression of a reasonable spectral match, at least qualitatively. In addition, it was shown elsewhere (Roy et al. 2014b) that changes in the ground motion characteristics caused by spectral matching are well correlated to those of the scale factor. The scale factor is defined as $\Sigma_{0.2T}^{1.5T} S_a{}^* / \Sigma_{0.2T}^{1.5T} S_a$, where $S_a{}^*$ and S_a refer to the spectral acceleration of postmatched and seed records, respectively. The scale factor demonstrates a propensity to increase in the long period (Roy et al. 2014b), perhaps as a result of the widening of the domain of matching. Scale factors so computed are less than 10 in a majority of the cases, which has been shown to be satisfactory for assessing torsion-induced amplification in plan-asymmetric systems (Roy et al. 2014b).

Influence on Ground Motion Parameters

To determine the impact of ground motion parameters, it seems important to select ground motions that cover a broad range of variation of the identified parameters. Therefore, no restriction on the other seismological issues are placed for the selection of the records, which is another crucial factor that guided the selection of 30 accelerograms from the 70 chosen initially.

In the chosen bin of 30 records, $T_d{}^*$ varies in the range of approximately 2.0–200 s, whereas $T_m{}^*$ varies in the bandwidth of 0.34–2.11 s. The correlation coefficient, ρ^*, between two horizontal components varies from –0.11 to 0.99. Ground motion parameters for spectrally matched records used for structural performance assessment are indicated by asterisks.

In scaling, ground motions with different spectral shapes are adjusted by suitable wavelets to bring some compliance with a target spectrum. Thus, the ground motion characteristics are expected to be affected in this process. Fig. 2 presents the variation of the ratio of the postmatched to that of the prematched ground motion parameters as a function of the scale factor defined previously. A normalized duration of record ($T_d{}^*/T_d$) is furnished in Fig. 2(a) for records scaled to different conditioning periods (T^*). A change in significant duration caused by spectral matching is marginal, whereas such changes in effective duration may be potential. Hence, significant duration may be considered a better estimator of the duration of record because of its relative stability. Changes in the normalized mean period ($T_m{}^*/T_m$) and correlation coefficient

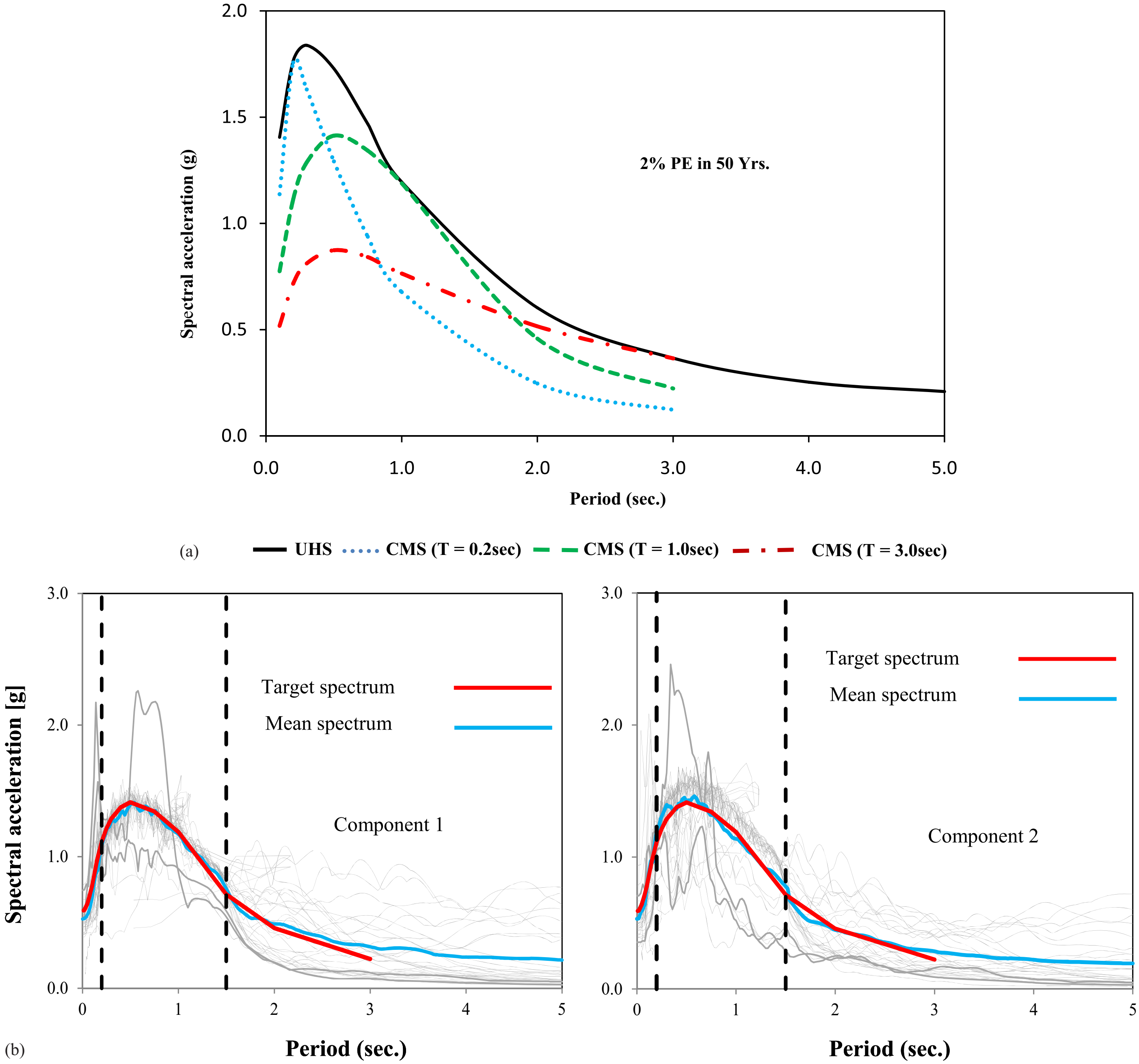


Fig. 1. (a) Conditional mean spectra (CMS) at Los Angeles (latitude 34.0890° N, longitude 118.4350° W; Soil Class D) corresponding to different condition periods (T^*) (the UHS is also superimposed for comparison); (b) response spectra for 30 ground motions scaled to the CMS (2% PE in 50 years) at a condition period T^* of 1.0 s for two mutually perpendicular horizontal components (Components 1 and 2; a mean of 30 spectra and target CMS are also superimposed)

($\rho*/\rho$) are shown in Figs. 2(b and c), respectively . It may be interesting to note that the identified ground motion parameters are marginally affected because of spectral adjustment up to a scale factor of at least 10 or even higher. In another recent study (Roy et al. 2014b), the authors showed that the responses of plan-asymmetric structures are hardly affected by changes in ground motion characteristics within these limits.

Thus, 30 records spectrally matched to the CMS at three different conditioning periods (viz, $T^* = 0.2$, 1.0, and 3.0 s) are used to explore the influence of ground motion parameters. Ranges of variation of characteristic parameters for postmatched records at different condition periods are summarized in Table 1.

Idealization of Structure

A single-story rigid-diaphragm model with three degrees of freedom, two translations in two mutually orthogonal directions, and one in-plane rotation is used in the present study. A typical structural layout of such an asymmetric plan system along with a symmetric companion is shown in Fig. 3. In the parametric study, the mass of the system is adjusted to achieve certain uncoupled lateral periods (T), whereas different torsional periods (T_θ) are set by changing the distribution of mass as regulated by the radius of gyration. In the relevant asymmetric system, the stipulated amount of eccentricity is introduced by increasing the stiffness of the lateral load-resisting element of one

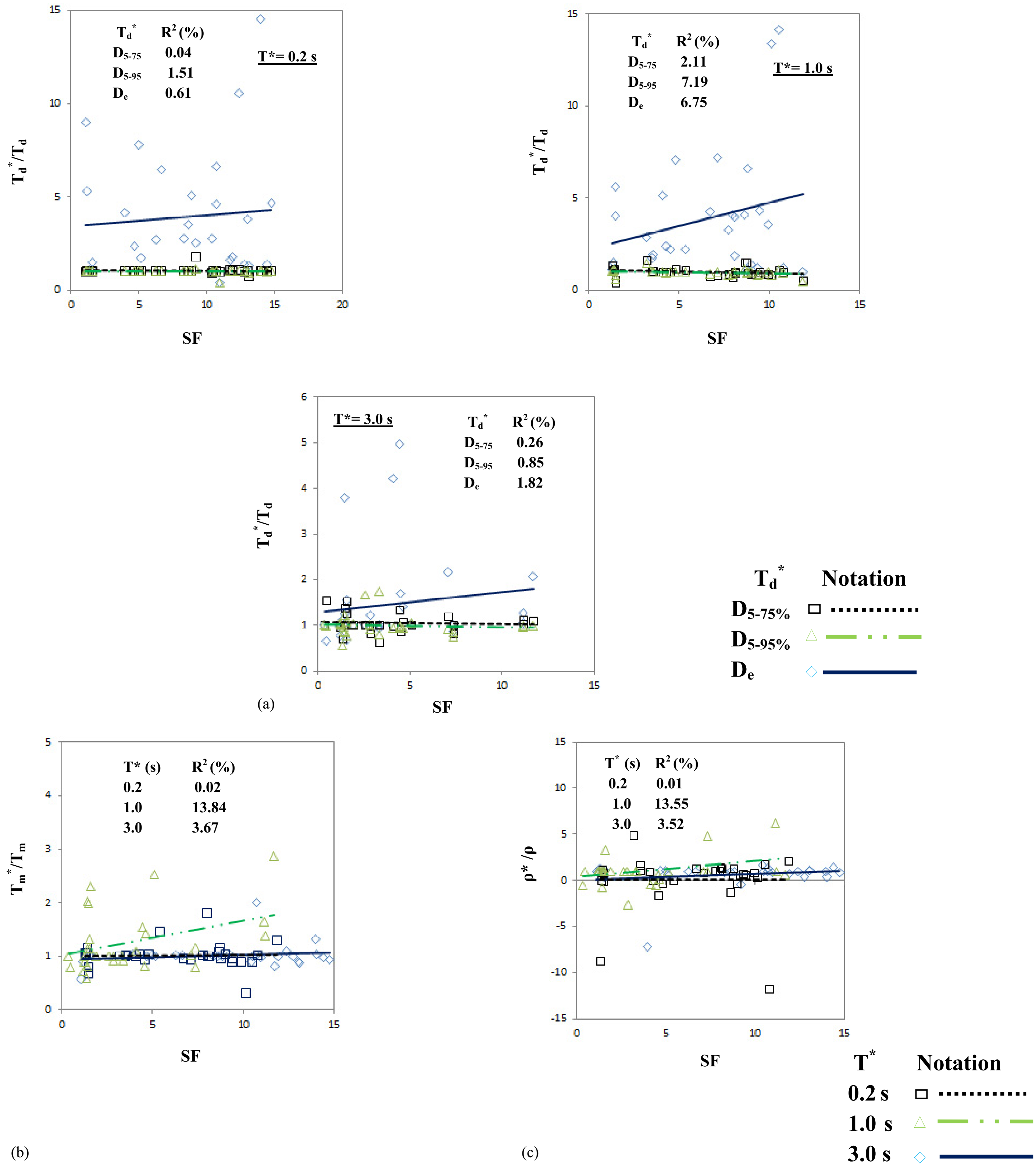


Fig. 2. Normalized ground motion parameters resulting from spectral matching to the (a) duration; (b) mean period; and (c) correlation coefficient of a real accelerogram

edge by a calculated amount and decreasing it at the opposite edge by an equal amount. These differences do not cause any change in the overall stiffness of the idealized system. The lateral load-resisting edge element with lesser stiffness is designated the flexible element, and the opposite-edge element with greater stiffness is referred to as the stiff element. Eccentricity of the asymmetric system is expressed in the terms of e_{rr}/D and $e_{r\theta}$ [Fig. 3(b)] following a previous study (Roy and Chakroborty 2013).

In a plan-asymmetric system during an earthquake, inertia force acts through the CM and resultant resistive force through the CR

Table 1. Range of Variation of Ground Motion Parameters of a Scaled Accelerogram

Serial number	Parameter	Ground motion parameter at a conditioning period T^* (s) of 0.2 Max	0.2 Min	1.0 Max	1.0 Min	3.0 Max	3.0 Min
1a	T_d^* (s) = D_{5-95}	139.32	5.02	144.44	5.35	146.54	7.34
1b	T_d^* (s) = D_{5-75}	99.94	2.32	72.94	2.33	99.96	2.32
1c	T_d^* (s) = D_e	219.62	8.10	218.70	12.52	78.25	3.77
2	T_m^* (s)	1.92	0.34	2.11	0.29	1.90	0.34
3	ρ^*	0.99	–0.14	0.99	–0.11	0.13	–0.38

Note: Max = maximum; Min = minimum

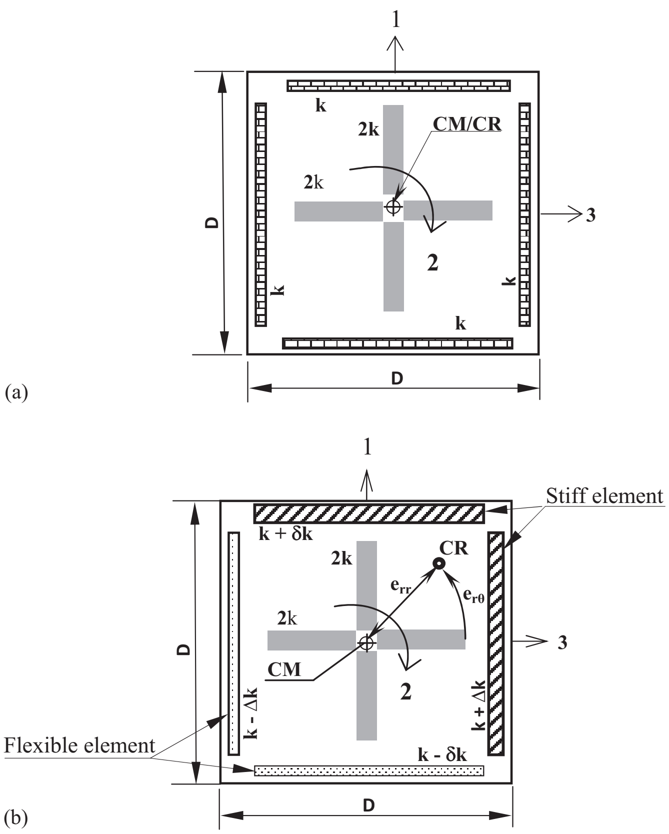


Fig. 3. Unified representations of an equivalent single-story system (adapted from Roy et al. 2014a): (a) typical symmetric model; (b) typical asymmetric model

when all the load-resisting elements are in elastic state of vibration. On the contrary, net resistive force passes through the center of strength (CV) when every element is in plastic condition. Because under severe seismic shaking, structural elements may endure large inelastic shaking, it is postulated that minimizing plastic torque through reducing the strength eccentricity e_v (distance between CM and CV) may be a desirable strength-distribution strategy. In fact, it has been shown (Paulay 1998, 2001b) useful, on the basis of plastic mechanism analyses of a number of systems, that displacement ductility demand may be minimized by reducing strength eccentricity, in the limit, through CV-CM–coinciding design (i.e., strength eccentricity, $e_v = 0$). However, doing so results in stiffness eccentricity in a system consisting of structural walls with different lengths as a consequence of interdependence between stiffness and strength. Observing the efficacy of CV-CM–coinciding philosophy (Roy and Chakroborty 2013), the current investigation also adopts this strength distribution. To this end, elastic strength of the reference symmetric system resulting from each ground motion, reduced by the strength reduction factor (R), is distributed among the elements in proportion to the tributary area of each element (i.e., in proportion to mass distribution) so that CV and CM coincide. A similar modeling scheme was adopted in other recent studies (Roy and Chakroborty 2013; Roy et al. 2014b). A bilinear elastoplastic hysteresis model was adopted in the present study to represent the constitutive characteristics of the load-resisting elements.

Methodology

Standard equations of motion (Clough and Penzien 1993; Chopra 2007) of the system are solved in the time domain by using Newmark's $\beta - \gamma$ scheme, which considers constant average acceleration over each incremental time step. While Newmark's parameters γ and β are chosen to be 0.5 and 0.25, respectively, the iterations are performed in each incremental time step by using modified Newton–Raphson technique. The time step of integration is taken as less than T/1,000 second to ensure convergence. Two percent of critical damping in each mode of vibration is considered to constitute the damping matrix.

During bidirectional seismic shaking in so-called bidirectionally eccentric structures, eccentricities along two principal directions result in two torsional moments. The effect of torsion seems to be amplified if the moments generated as a result of eccentricities in each direction are additive in nature, whereas the mutually cancelling nature of such moments tends to lower the impact of torsion. Such addition or cancellation of two torsional moments depends on the relative sense of eccentricities. Interaction between such a pair of torsional moments (additive/cancelling) may also depend on the ground motion characteristics (in phase or out of phase). Accounting for such issues, the responses for flexible and stiff sides (the lateral load-resisting edge element with lesser stiffness is designated as the flexible element, and the opposite-edge element with greater stiffness is referred to as the stiff element) are noted separately. Additional details of the idealization and computational scheme are available elsewhere (Roy and Chakroborty 2013).

Does Seismic Demand of Plan-Asymmetric Systems Relative to Symmetric Systems Depend on Ground Motion Characteristics?

To address the question of whether seismic demand of plan-asymmetric systems depends on ground motion characteristics, systems with different uncoupled lateral periods of vibration (T) (viz, 0.2, 1.0, and 3.0 s, representative of short, medium, and long periods, respectively) are analyzed. Fundamental torsional-to-lateral period ratios (τ) of the corresponding uncoupled systems are chosen as 0.5, 1.0, and 1.5, representative of torsionally stiff to flexible systems. Parameters that quantify asymmetry, viz, e_{rr}/D and $e_{r\theta}$, are considered to vary in the range of 0.02–0.22 (with an interval of 0.04) and 0–90° (with an interval of 15°), respectively.

Maximum in-plane deformation of the edge elements caused by translation and torsion together in an asymmetric system is computed for each record. This deformation for load-resisting elements oriented in both the principal directions are compared for flexible and stiff sides separately, and the greater ones are normalized by those of the reference symmetric model. This normalized response representing torsion-induced damage is examined to identify the impact of asymmetry alone. The responses of the structures are calculated under simultaneous application of two perpendicular horizontal components. Thus, the ground motion parameters are represented through a combined index expressed as the (a) arithmetic mean (AM) and (b) geometric mean (GM) of the component characteristics. Results for selective cases are summarized below.

Duration of Ground Motion

Fig. 4(a) describes the variation of maximum normalized element displacement (for both flexible and stiff sides) for representative structural systems as a function of duration of record. Variations in normalized responses of similar systems are presented as a function of record duration (T_d^*), viz, $D_{5–75}$, $D_{5–75}$, and D_e. In the absence of any previous knowledge about the expected trend, a best-fit straight line is regressed through the response data. Results suggest that the maximum normalized displacement demand is generally insensitive to the record duration and does not hold any statistical correlation (because R^2 is approximately 2%–5% only, refer to Fig. 4(a)). Earlier studies (Bommer et al. 2004; Hancock and Bommer 2007) also indicated little or no influence of duration on the peak response of structures.

Because it is perceived that structural damages measured through cumulative damage "usually find a positive correlation" with the duration of records (Bommer et al. 2004; Hancock and Bommer 2007), normalized hysteretic energy ductility demand (NHEDD, denoted as μ_H) (Mahin and Bertero 1981) is also computed for the edge elements (flexible and stiff sides). Physically, this NHEDD implies that the ratio of the equivalent displacement required by a similar elastoplastic system dissipates an amount of energy equal to that in the original system under monotonic loading to the yield displacement. The NHEDD computed for the reference symmetric system is denoted μ_{H0}. Variations of μ_H/μ_{H0} values for a set of system parameters are presented in Fig. 4(b). The linear trend line fitted similarly shows that the NHEDD may marginally increase with duration of record. However, μ_H/μ_{H0} clearly holds no correlation with duration of the accelerogram (refer to the R^2 values summarized in Fig. 4(b)).

Frequency Content of Ground Motion

Variations of similar normalized responses in the form of displacement demand and NHEDD with the mean period of ground motion (T_m^*) are presented in Figs. 5(a and b), respectively. This parameter seems adequate for representing the frequency content in real records for engineering purposes. Best-fit straight lines are constructed to identify the general trend in responses. The results suggest that the maximum normalized displacement response is not affected by the variation of frequency content of ground motion, whereas μ_H/μ_{H0} may decrease little with an increase in T_m^*.

The previous observation is inspiring in the context of estimating responses under real records. Ground motions recorded by digital instruments are often available (such as at the Pacific Earthquake Engineering Research Centre) after correcting for baseline shift and filtering. Such methods of processing (Boore et al. 2002) real records are often approximate and empirical (Boore et al. 2002). It has been shown that depending on the choices of relevant parameters, such as corner frequency, filter type, etc., the processed ground motion record may be inflicted with some changes in its characteristics. In this backdrop, the apparent insensitivity of normalized response to the frequency content of the ground motion is good news, at least for the building structures. The implication is that torsion-induced amplification in plan-asymmetric systems may be reasonably estimated by using available records without specific reference to the processing details of a recorded accelerogram.

Statistical Dependency between Two Horizontal Components

It may be restated that the responses of plan-asymmetric systems are evaluated under simultaneous application of two horizontal components of accelerograms. Code (ASCE 4-98) recommends that two components used in bidirectional analysis be "statistically independent." Two time series may be assumed statistically independent if the absolute value of the correlation coefficient does not exceed 0.3. This coefficient for the selected time-series pairs is well within the limit for a majority of the cases. To examine the dependency of torsion-induced amplification, normalized responses are plotted as a function of ρ^* in Fig. 6(a) for displacement and in Fig. 6(b) for NHEDD. The results indicate that the normalized response may be arbitrarily different for a small change in ρ^*, even for the choice of statistically independent pairs. Response quantities are clustered arbitrarily in the narrow band of ρ^*, and hence it does not seem logical to set a trend line. The results do not evidently manifest any systematic trends.

The implication of the observation is that the mutual relationship between ground motion pairs may influence the normalized response of structures even when the pair is uncorrelated. It may be noted that the correlation coefficient between two records depends on the orientation of the records. Two horizontal earthquake components are conventionally applied along two principal directions of the structure (also in this investigation). A possibility of change in normalized response with ρ^* seems to indicate that normalized response may also be affected because of a change in the angle of incidence of records. This issue deserves further investigation.

Energetic Length Scale

It has been shown, using formal dimensional analysis, that the seismic demand in the nondimensional format assumes a self-similar order (Dimitrakopoulos et al. 2009; Roy et al. 2015) irrespective of the ground motion characteristics. Such interesting similarity is established by using a physically rational energetic length scale (and a time scale that is T_m itself) of record (L_e). Such energetic length scale values are expressed as $a_g T_m^2$, where a_g represents the PGA and T_m represents the mean period (Vassiliou and Makris 2011). Therefore, it may be interesting to examine the variation of normalized seismic demand with changes in L_e. Thus, the normalized displacements and hysteretic energy ductility demands are plotted as a function of L_e^* in Figs. 7(a and b), respectively. A best-fit straight line through the observed response points clearly holds no statistical relation.

Thus, the study brings forward the fact that the inelastic seismic demand of plan-asymmetric systems relative to their symmetric counterpart is generally insensitive to individual ground motion characteristics. Such apparent insensitivity is true for peak displacement demand and for hysteretic energy dissipation. Thus, the torsion-induced damage of plan-asymmetric systems may not be biased by the choice of ground motions with a similar spectral shape. However, the torsion-induced damage may be strongly affected by the statistical dependency of the horizontal components of the accelerogram.

The three most traditional parameters for selecting earthquakes are moment magnitude (M_w), source-to-site distance (R), and site class (S) because the important characteristics of the record, such as frequency content, spectral amplitudes, spectral shape, and duration, from a seismological standpoint, are well correlated to magnitude, distance, and site class. Thus, a practical selection of ground motion may be based on M_w, R, and S to evaluate torsion-induced

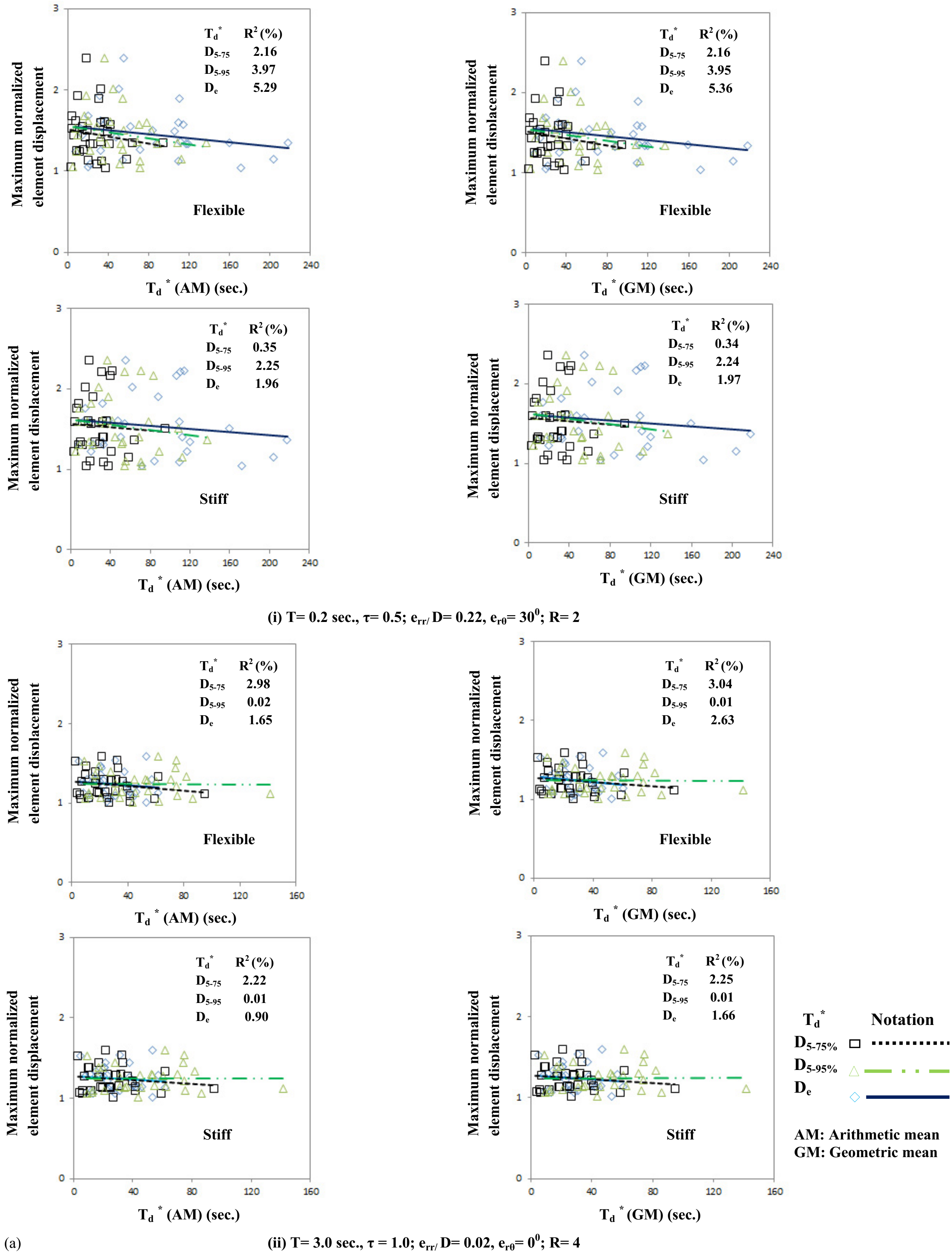
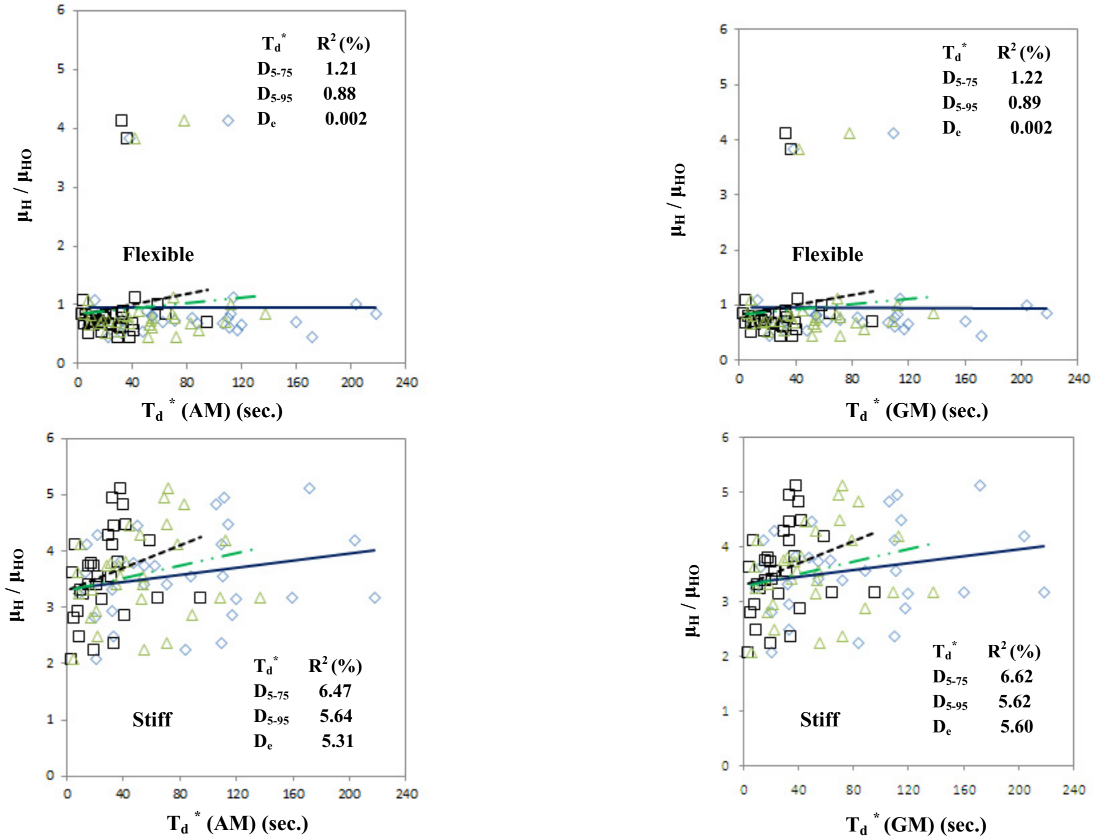
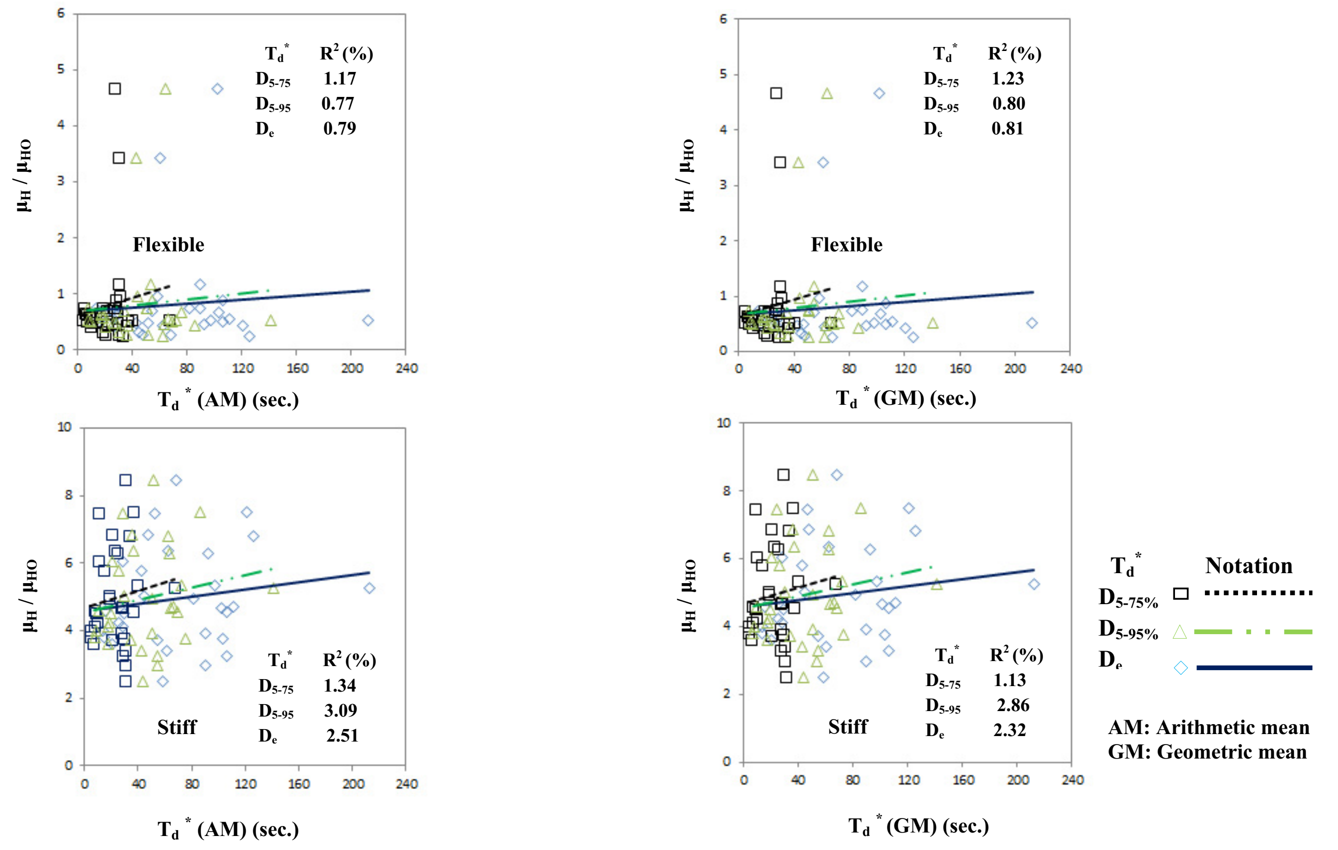


Fig. 4. (a) Maximum normalized displacement with change of duration of the accelerogram; (b) NHEDD of edge elements with change of duration of the accelerogram



(i) T= 0.2 sec., τ= 1.0; e_{rr}/D= 0.14, $e_{r\theta}$= 30^0; R= 2



(b) (ii) T= 1.0 sec., τ = 1.5; e_{rr}/D= 0.22, $e_{r\theta}$ = 75^0; R= 4

Fig. 4. (*Continued.*)

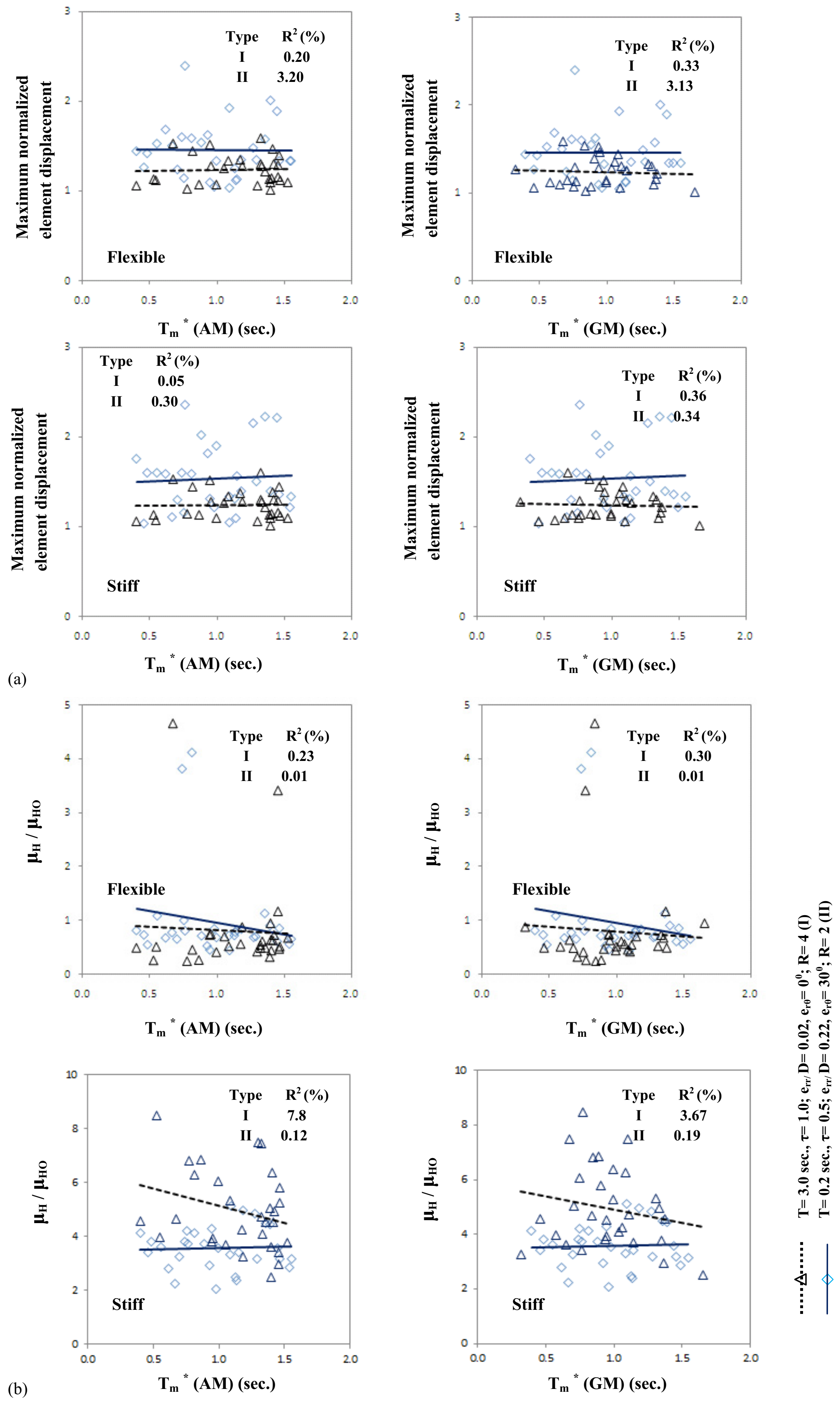


Fig. 5. Normalized seismic demand of edge elements: (a) maximum displacement and (b) hysteretic energy with frequency content of an accelerogram

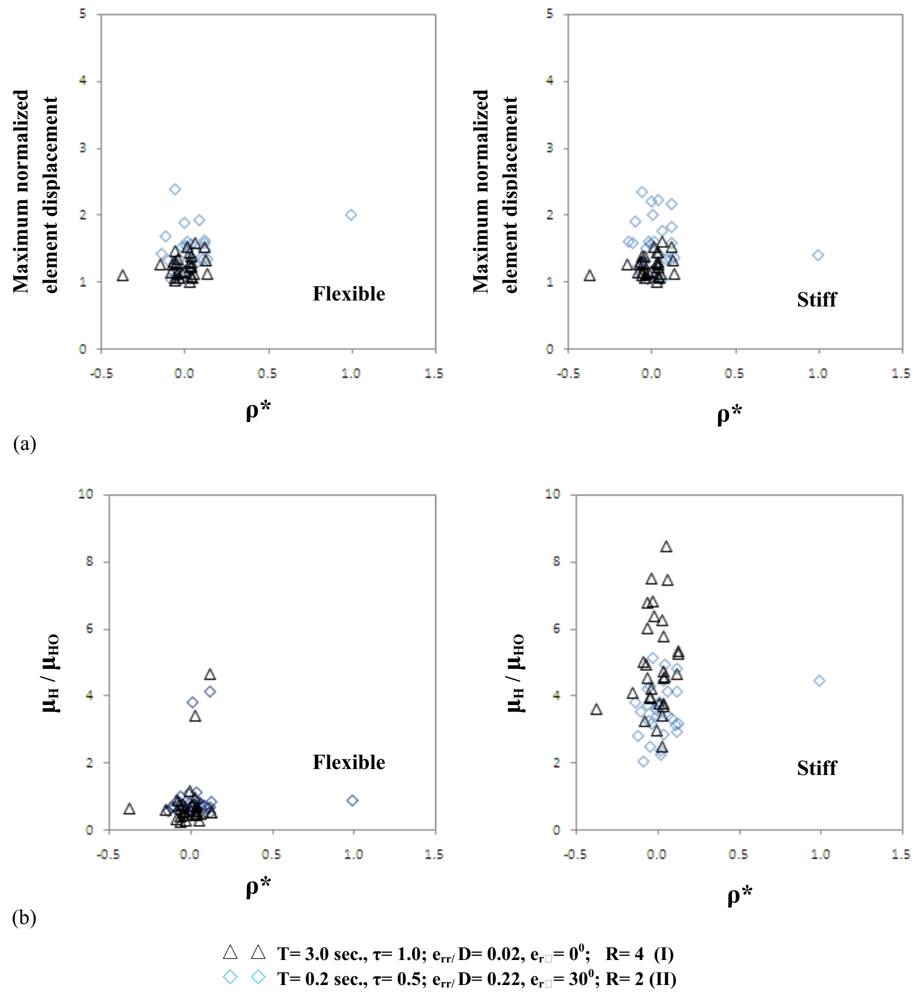


Fig. 6. Normalized seismic demand of edge elements: (a) maximum displacement and (b) hysteretic energy caused by the interrelationship between the horizontal components of an accelerogram, measured by ρ^*

damage with fidelity. A more accurate selection of records with a similar spectral shape is also possible by adjusting real records or by searching for real records with a specified shape (Iervolino et al. 2010; Reyes and Kalkan 2012).

Can We Develop a Simple Strategy for Estimating Seismic Demand of Plan-Asymmetric Systems under a Specific Earthquake?

We have also investigated inelastic displacement using dimensional analysis because of the lack of a consistent trend between such demand and ground motion characteristics. Formal dimensional analysis has been shown to systematically represent earthquake-induced postyielding phenomena (Dimitrakopoulos et al. 2009; Makris and Vassiliou 2011). Because the fundamental aim of CV-CM–coinciding design adopted herein is to minimize inelastic twist, it is presumed that the impact of torsion may not be substantial for asymmetric systems under strong shaking. With this premise, it is postulated that the inelastic element displacement of plan-asymmetric systems is related to the period of structure and the ground motion characteristics, such as length scale and time scale (Vassiliou and Makris 2011), that characterize earthquake excitation. The characteristic length scale, defined as $a_g T_m^2$, where a_g, may be interpreted as a measure of the "persistence of the excitation to produce inelastic action" (Dimitrakopoulos et al. 2009). Thus, the response of the system may be expressed mathematically as follows:

$$\Delta = f(T, T_m, a_g) \tag{2}$$

This calculation results in a group of four variables with two reference dimensions, those of length and time. According to Buckingham's Π theorem (Langhaar 1951), the number of independent dimensionless Π products is two (4 variables, 2 reference dimensions). Choosing characteristics of the excitation (viz, T_m and a_g) to normalize the response, Eq. (2) may be expressed in the dimensionless form as follows:

$$\prod_{\Delta} = F\left(\prod_{T}\right) \tag{3}$$

where $\Pi_\Delta = \Delta / a_g T_m^2$ and $\Pi_T = T/T_m$ and Δ is the element deformation. For a given structure, the maximum element displacement Δ computed herein under a number of records, Π_Δ and Π_T are determined for both flexible and stiff sides separately. Variations of Π_Δ are plotted against those of Π_T for representative systems in Fig. 8. Π_Δ values are plotted in logarithmic scale for clarity. The power curve fitted through the dimensionless data points shows good statistical correlation (because R^2 is more than 80% for R =

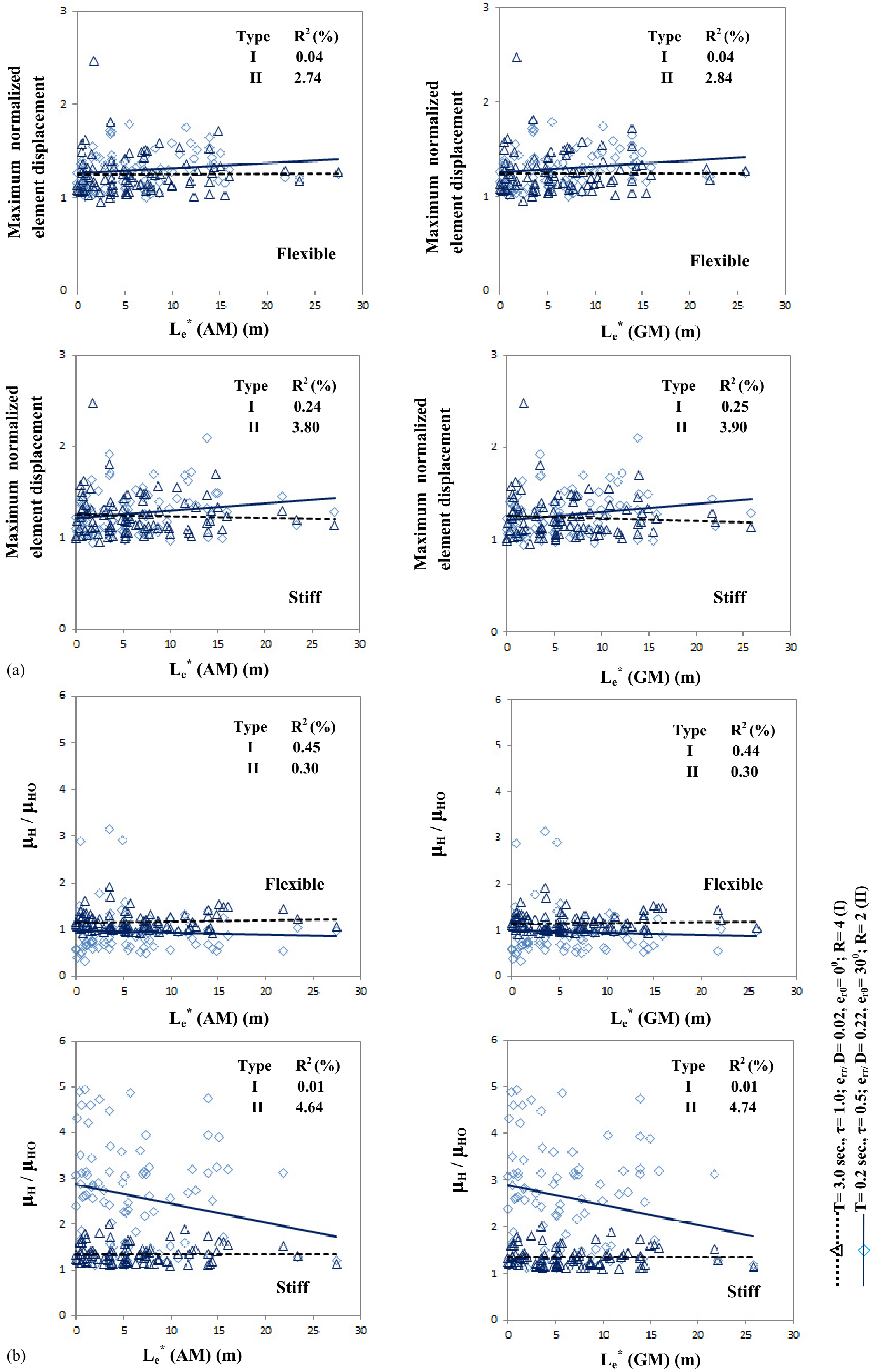


Fig. 7. Normalized seismic demand of edge elements: (a) maximum displacement and (b) hysteretic energy with the energetic length scale

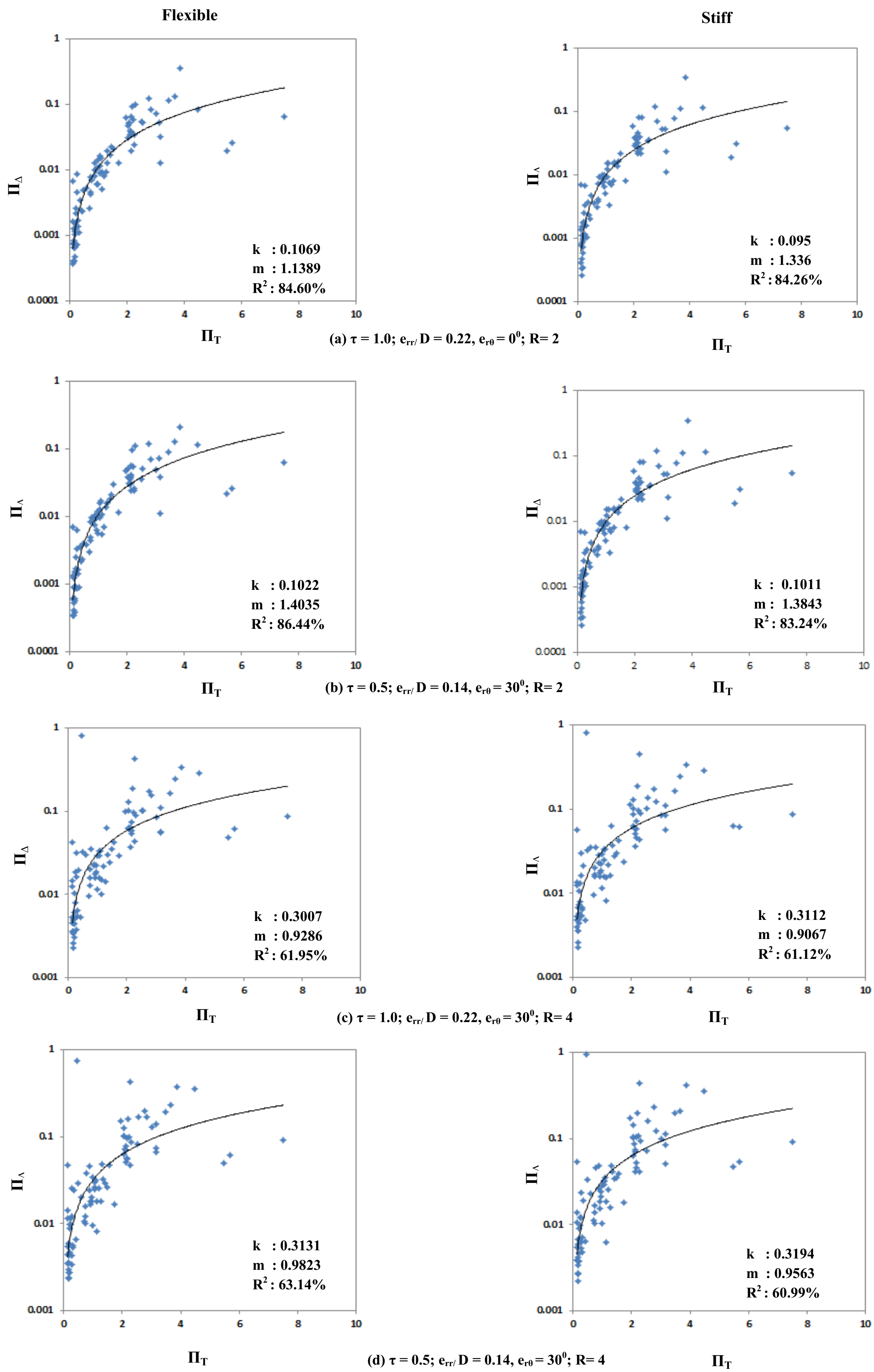


Fig. 8. Dimensionless element displacement as a function of dimensionless uncoupled lateral period of structure

2% and 60% for $R = 4$). It follows from the R^2 values summarized within Fig. 8 that the dispersion, as expected, tends to increase for greater R values. However, the order of R^2 values still suggests good correlation, at least in the context of inherent uncertainties of earthquake engineering and design. Thus, the self-similar kind of symmetry may be used to estimate the inelastic displacement of plan-asymmetric systems by using a simple equation in the form $\Pi_\Delta = k \times \Pi_T{}^m$, where the coefficient k and exponent m may be chosen in the ranges of 0.1–3.2 and 0.91–1.4, respectively.

Careful scrutiny of Fig. 8 also indicates that the response of flexible and stiff sides tends to be similar, particularly as the R value increases, which is a consequence of the CV-CM–coinciding strength-distribution strategy, which minimizes inelastic twist. This observation reconfirms the efficacy of the CV-CM–coinciding strength design philosophy, particularly for systems expected to go well into the inelastic range.

Summary and Conclusions

Responses of symmetric and asymmetric structures are evaluated under a suite of spectrally matched real accelerograms. Variations of the seismic demand of asymmetric systems relative to those of reference symmetric systems are studied to identify the impact of asymmetry alone. The effects of different important ground motion characteristics on such normalized responses indicating torsion-induced damage are evaluated. In addition, formal dimensional analysis is conducted to find simple relationships for estimating inelastic structural demand with known ground motion characteristics. The following broad trends are noted:

- Spectral matching of real records is often used in practice to estimate seismic responses at different hazard states. Because spectral matching is not cosmetic, it causes certain changes in ground motion characteristics. This study reconfirms that such changes for duration and frequency content are marginal, at least up to a scale factor of 10. Significant duration measured by the relative limits of I_a ($D_{5\text{–}75}$ or $D_{5\text{–}95}$) is observed to be a more stable measure of duration relative to the effective duration (D_e) of record because the former is nominally influenced by spectral matching.
- Statistical correlation between two horizontal earthquake components remains nearly unaffected, even when the components are scaled to the same hazard spectrum, which suggests that pairwise scaling of ground motions using rigorous major axis and minor axis spectra, although conceptually appealing, may not be essential to retain the inter-alia component relationship. Such pairwise scaling, in fact, has been shown to be redundant to estimating the torsional vulnerability (Roy et al. 2014b).
- Inelastic responses of plan-asymmetric systems relative to their symmetric counterpart, representing the torsion-induced additional damage of structural elements, do not uphold any statistical correlation with the duration and frequency content of the record. In addition, the fitted linear trend line suggests that the normalized responses, both element deformation and hysteretic energy dissipation (i.e., torsion-induced damage), have no or little dependency on the duration and frequency content of records.
- Torsion-induced damage, however, may be sensitive to statistical correlation between two horizontal earthquake components. Because the component correlation changes with the orientation, the angle of incidence of horizontal components relative to structure may affect response statistics and needs in-depth investigation. Such torsion-induced damage, however, is insensitive to the energetic length scale of an accelerogram, which represents the "persistence of excitation to produce inelastic action."
- Because the changes in ground motion characteristics are subdued because of spectral matching and the torsion-induced damage is insensitive to such ground motion parameters, real accelerograms spectrally matched to the CMS may be used for the purpose of design, which reduces the scatter in the results and eliminates the variability introduced in responses as a result of the difference in spectral shapes.
- Although torsion-induced demand of load-resisting elements in plan-asymmetric systems is relatively indifferent to ground motion characteristics, estimating structural demand at a particular hazard state is another important requirement for design. Dimensionless inelastic displacement presented in terms of the dimensionless period ratio of a system reveals remarkable similarities in the response statistics in the form of a power law, which sets up a useful framework for estimating the inelastic seismic demand of plan-asymmetric systems.

Thus, the current investigation reveals that torsion-induced amplification in the response of plan-asymmetric systems seems to be marginally affected, even when important ground motion characteristics are widely different. Although the correlation coefficient varies within a small range, correlation between two horizontal components may significantly influence torsional response.

The inelastic displacement ratio, defined as the maximum lateral inelastic displacement relative to the maximum elastic counterpart, has been shown to be nearly independent of soil sites, with average shear wave velocities higher than 180 m/s (Miranda 2000). An investigation (Chopra and Chintanapakdee 2004) with SDOF system underground motions collected from different site classes, such as B, C, and D, also led to similar conclusions. Together, these results may be regarded as indicative of the relative insensitivity of soil class to the torsion-induced displacement parameter studied herein. Observations made in the present investigation may also be applicable for multistory regularly asymmetric structures (Kan and Chopra 1981a, b; Hejal and Chopra 1989).

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