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Torsional response of base-isolated structures due to asymmetries in the superstructure

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Abstract

The torsional response of base-isolated structures when eccentricities are set in the superstructure is presented. Nonlinear dynamic analyses were used to study peak responses for different ratios of static eccentricities (e_s) between the center of mass and the center of rigidity for the superstructure. Unidirectional and bidirectional actions of selected ground motions typical of firm soils of the Mexican Pacific Coast were used in the study. An effective period range between 1.5 and 3.0 s (1.5 s$\leq T_I \leq$3.0 s) for the base-isolated structures was considered in the present study. Bilinear isolator systems with yield forces of 5% and 10% the weight of the complete structure ($V_y/W = 0.05$ and $V_y/W = 0.10$) and a postyield stiffness of 10% their elastic stiffness ($k_2/k_1 = 0.10$) were considered. Peak dynamic responses such as maximum isolator displacements and peak displacement ductility demands were studied and compared to the ones obtained for symmetric systems of reference for the different ground motions under consideration, assessing the importance of the relative value of e_s on those response quantities.

Keywords: Torsional response; Torsional coupling; Base isolation; Seismic isolation; Base-isolated structures; Elastomeric bearings displacement ductility demands; Static eccentricities

1. Introduction

Base isolation has emerged as a viable structural option in seismic zones to reduce the vulnerability of structural systems subjected to earthquakes. The major application of seismic isolation is on rigid structural systems located on firm or relatively firm soils, as these structural systems usually have short natural periods that make them vulnerable to earthquakes in such sites. As base isolation increases the lateral flexibility of the entire base-isolated structure, plus increases its effective damping through the energy dissipated on the isolation system, the dynamic response of a base-isolated structure located on firm soils is considerably reduced when compared to its counterpart fixed-based structure, as documented in the sizeable literature available on base isolation.

There are many structural aspects that have been extensively studied regarding base isolation and that have allowed the evolution of this novel technology. However, among the aspects that have received less attention is the torsional response. There are only a few works available in the literature where the torsional response of base-isolated structures has been studied.

Lee [1] studied the effectiveness of bilinear hysteretic isolation systems in lowering the shear forces and torques generated in a single-story structure having asymmetries in both horizontal directions subjected to the bidirectional ground motions of the 1940 El Centro record. He showed that structural torques are drastically reduced with base isolation even if the structural eccentricity is large, and that this reduction is greatest when the center of stiffness of the isolation system coincides with the center of mass of the structure. However, Lee also concluded that the superstructure eccentricity has little effect on the magnitude of the isolators' displacements, a conclusion that was contradicted later by Nagarajaiah et al. [2].

Jangid and Datta [3,4] studied the nonlinear response of torsionally coupled base isolated systems subjected to

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random ground motions. The base isolator consisted of an array of elastomeric bearing assumed to have an elasto–plastic hysteretic behavior. Among their conclusions, are the following: (a) The effectiveness of torsionally coupled base isolation is less than that of the corresponding symmetric system, especially for reducing the superstructure displacement perpendicular to the direction of eccentricity, (b) effectiveness of base isolation is reduced for higher eccentricity of the superstructure; however, the eccentricity of the superstructure does not have any significant influence on base displacements, (c) effectiveness of base isolation decreases with increase in the yield strength of the isolator, (d) the isolator eccentricity decreases the effectiveness of isolation for torsional deformation, increase the base displacements and decreases the superstructure displacement perpendicular to the direction of eccentricity to a much lesser extent and, (e) the angle of incidence of earthquake excitation moderately influences the effectiveness of base isolation when identical records are used for the two directions.

Nagarajaiah et al. [2] studied torsion in multi-story base-isolated structures with inelastic elastomeric isolation systems due to bidirectional lateral ground motions of the 1940 El Centro and 1952 Taft earthquakes. The objective of this study was to identify important system parameters and to investigate the influence of various system parameters on the lateral torsional response of such systems. Among their conclusions are: (a) the main source of torsionally motions in elastomeric isolated structures is the isolation system eccentricity (e_b/L), (b) asymmetry and dynamic characteristics of the superstructure are as important as that of the isolation system, (c) the number of bearings in an elastomeric isolated structure has very little influence on the response and, (d) although the magnitude of shear and torque generated in an elastomeric isolated structure is less than that of the fixed-base structure, the torsional amplifications cannot be ignored.

Nagarajaiah et al. [5] also studied torsion in base-isolated structures with sliding isolation systems due to bidirectional lateral ground motions of the 1940 El Centro and 1985 Michoacán (SCT records) earthquakes. The objective of this study was to identify the key parameters that influence the torsional coupling in such systems. Among their conclusions are: (a) the main source of torsionally motions in sliding isolated structures is the superstructure stiffness eccentricity (e_s/L), (b) the torsional coupling in sliding isolated structures is important, as the dynamic torque amplification in the superstructure has in many cases the same order of magnitude as that of the nonisolated structure, although in base-isolated structures, the generated torques are one order of magnitude less than that of the elastic fixed-base structure, and (c) the higher mode effects on the lateral-torsional response of sliding isolated structures is important in systems with flexible superstructures.

Tena-Colunga et al. [6] concluded on the study of a specific structure with eccentricities in both the superstructure and the isolation system (lead-rubber bearings) that torsional responses diminish the effectiveness of base isolation, as some LRB yield and displace substantially while others respond in the elastic range, and that the torsional response of the isolation system was greatly affected by the own torsional response of the superstructure.

Recently, Almazán and De la Llera [7] studied the torsional response of symmetric but slender structures isolated with the friction pendulum system (FPS), finding that torsional stiffness is reduced when the slenderness ratio of the structure increases and that non-uniform distribution of lateral displacements increases when the slenderness ratio increases.

Most studies were conducted on single-story structures subjected to earthquakes records typical of California. The only studies that considered multi-story buildings on elastomeric bearings are Nagarajaiah et al. [2] and Tena-Colunga et al. [6]. In addition, most studies considered a fixed value for the effective period of base-isolated structures (i.e. Nagarajaiah et al. [2] considered $T_I = 2.12$ s).

The study presented herein is part of a comprehensive parametric research where the torsional response of a three-story rigid structure with bilinear (elastomeric) isolators when subjected to bidirectional lateral ground motions typical of subduction earthquakes of the Mexican Pacific Coast is studied when the eccentricity exists in: (a) the superstructure, (b) the isolation system and, (c) in both the superstructure and the isolation system. Both unidirectional and bi-directional eccentricities were considered. In this study, an effective period range for isolated structures 1.5 s$\leq T_I \leq$3 s was selected. The study concentrates on peak responses for specific helpful design parameters for isolators, such as (1) displacement ductility demands, (2) peak displacements, (3) angle with respect to the global coordinates of the structural system where peak displacements occur, (4) amplification factors due to bidirectional seismic input (with respect to unidirectional input) and, (5) amplification factors because of bidirectional eccentricity (with respect to unidirectional eccentricity). In addition, amplifications of asymmetric systems with respect of counterpart symmetric systems of reference are also presented. The details of the described study can be consulted in Gómez-Soberón [8]. Some of the most relevant aspects of this research when the torsional response is due exclusively to eccentricities in the superstructure are summarized in following sections. A companion paper [9] discusses the aspects when the torsional response is due exclusively to eccentricities in the isolation system.

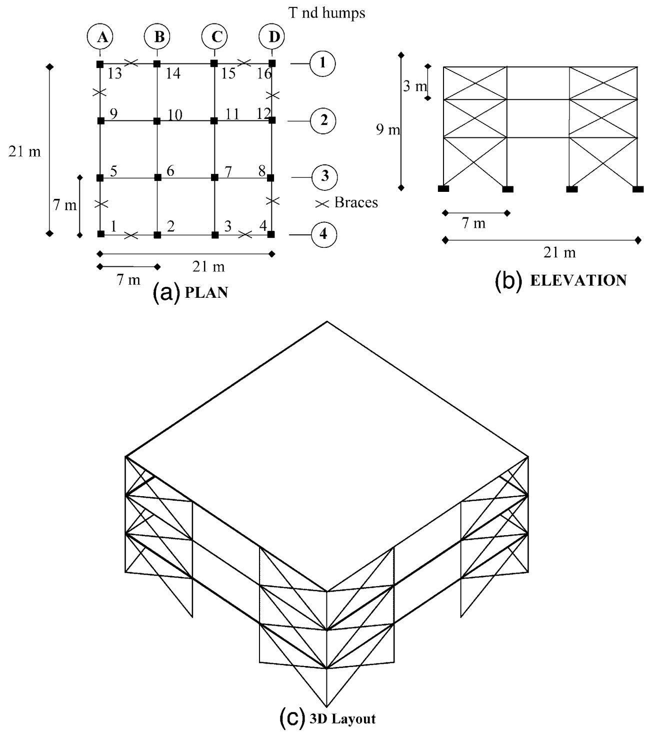

Fig. 1. Model under study.

2. Structural model considered

The subject three-story building model is depicted in Fig. 1. The building is regular in elevation and symmetric with respect to two main orthogonal axes. The building has four frames in each direction with a typical bay width of 7 m and a story height of 3 m. Typical RC columns are of square cross section 50×50 cm and typical rectangular RC beams are 35×75 cm. The building is supported by 16 elastomeric bearings, one below each base column (Fig. 1). Braces of A-36 steel are located as shown in Fig. 1 and are of square box section 25×25 cm with a plate thickness of 0.8 cm. The total weight of the structure above the isolation system is $W = 991$ ton.

The first six fixed-based periods of vibration for the building model computed with ETABS are summarized in Table 1. These structural periods plus their corresponding mode shapes were used in the nonlinear dynamic analysis according to this modeling option allowed by the 3D-Basis program [10]. The mode shapes obtained in ETABS are purely translational and rotational, as the structural model was completely symmetric in stiffness and mass.

Table 1
Periods of vibration for the first six fixed-base mode shapes

Mode	Period (s)	Mode	Period (s)
1 (Translation X)	0.187	4 (Translation X)	0.063
2 (Translation Y)	0.187	5 (Translation Y)	0.063
3 (Rotational)	0.156	6 (Rotational)	0.054

3. Selected acceleration records

A set of accelerograms typical of strong subduction earthquakes recorded in firm soil sites or rock during the past two decades in the Mexican Pacific Coast were used in the present study (Fig. 2). The two horizontal components of the following records were considered: (a) La Unión station (**UNION**), recorded in the Mexican state of Guerrero during the September 19, 1985 Michoacán earthquake ($M_s = 8.1$), (b) San Marcos station (**SMRZA**), recorded in the Mexican state of Guerrero during the April 25, 1989 earthquake ($M_s = 6.9$), epicentral accelerograms and, (c) Termoeléctrica station (TMANZ) recorded in the Mexican city of Manzanillo (state of Colima) during the October 9, 1995 Manzanillo earthquake ($M_w = 8.0$), accelerograms where important site effect amplifications have been detected. Some characteristics of the records shown in Fig. 2 are summarized in Table 2.

4. Characteristics of the bilinear isolators

In this study, bilinear isolators with a post to pre yielding stiffness of 10% ($k_2/k_1 = 0.10$) were selected. The isolators were designed following some available recommendations of the New Zealand practice [11] and the 1997 Uniform Building Code (UBC-97) [12], as presented in greater details elsewhere [13,14].

The mechanical properties of the bilinear isolation system were set to comply with a recommendation of the UBC-97 Code [12] that establishes that the effective stiffness of the isolation system at the design displacement (k_{eff}) must be greater than one third of the effective stiffness at 20% of the maximum design displacement (k_{eff2}), this is, $k_{eff} > 1/3\ k_{eff2}$, as depicted in Fig. 3.

In order for a bilinear isolator with $k_2/k_1 = 0.10$ to satisfy the requirements mentioned above (illustrated in Fig. 3), the following relations must be satisfied, as demonstrated in Tena-Colunga [13]:

$$k_1 = 5k_{eff} \tag{1}$$

$$V_y = 0.555V_{\max} \tag{2}$$

$$\Delta_y = 0.111\Delta_{\max} = \frac{1}{9}\Delta_{\max} \tag{3}$$

$$\mu_{\max} = \frac{\Delta_{\max}}{\Delta_y} = 9 \tag{4}$$

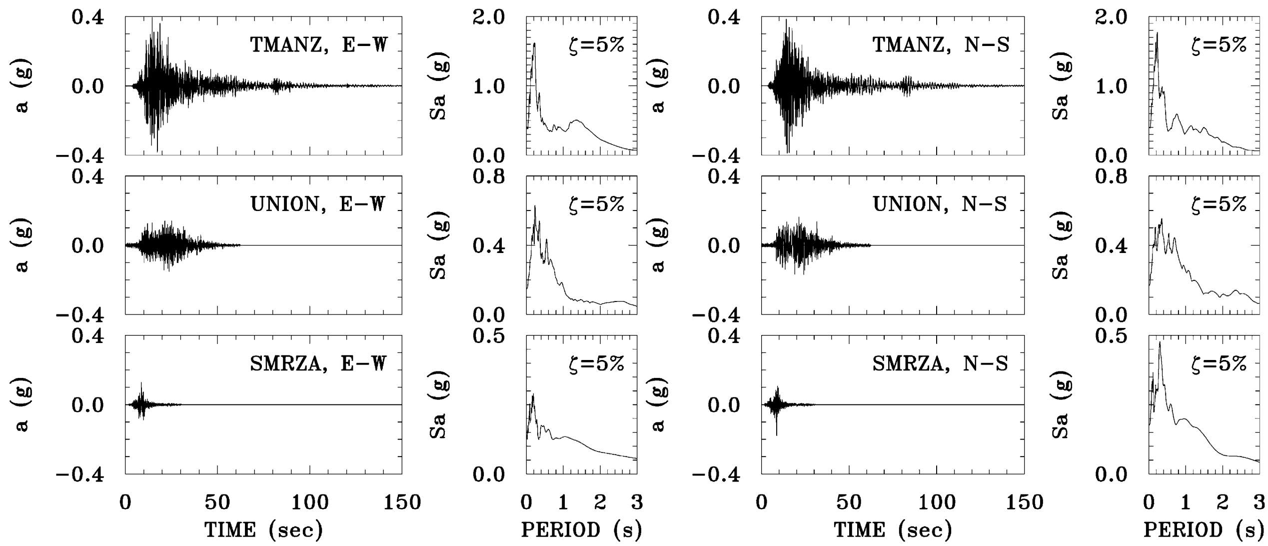

Fig. 2. Selected acceleration records.

Table 2
Some characteristics of the selected earthquake records

Station	Duration (s)	E–W Record		N–S Record	
		A_{max} (cm/s^2)	V_{max} (cm/s)	A_{max} (cm/s^2)	V_{max} (cm/s)
UNION	62.3	127	12.6	174	21.0
SMRZA	30.4	148	16.7	165	17.7
TMANZ	154.6	387	30.7	381	28.9

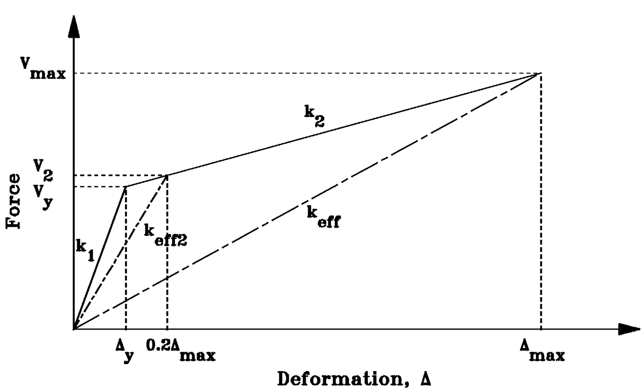

Fig. 3. Design envelope curve for bilinear isolators that follow the restrictions of the UBC code.

5. Generalities of the parametric studies

In order to study the influence of static torsional eccentricities on the dynamic response of base-isolated structures, the following range was selected for the effective period of isolated structures (T_I): 1.5 s$\leq T_I \leq$ 3 s. The lower limit ($T_I = 1.5$ s) is taken from the recommendations available in Skinner et al. [11] and the upper limit ($T_I = 3$ s) is taken from the UBC code [12], as this value is the limiting period set by the code for using static design procedures and some options for dynamic design procedures. Nonlinear dynamic responses of base-isolated models were computed in the selected effective period range with an effective period increment of 0.1 s, this is, there were 16 models in the period range 1.5 s$\leq T_I \leq$3 s. Two yield strength ratios for the isolation system were considered: $V_y/W = 0.05$ and $V_y/W = 0.10$, where $W = 991$ Ton is the total weight for the structure above the isolation system.

Thus, 16 sets of data were computed for a considered yield strength, static eccentricity and action of the ground motions (unidirectional or bidirectional). For a given combination of yield strength and static eccentricity, three different actions were considered: unidirectional E–W, unidirectional N–S and bidirectional. Static eccentricities in the superstructure of 5%, 10%, 15% and 20% the floor plan dimension ($L = 21$ m) were selected, for both one direction and acting on a 45% angle, as depicted in Fig. 4, plus the completely symmetric case ($e_s = 0\%$).

Therefore, in order to study the influence of the static eccentricity in the superstructure in the torsional response of base isolators, a total of 2592 simulations

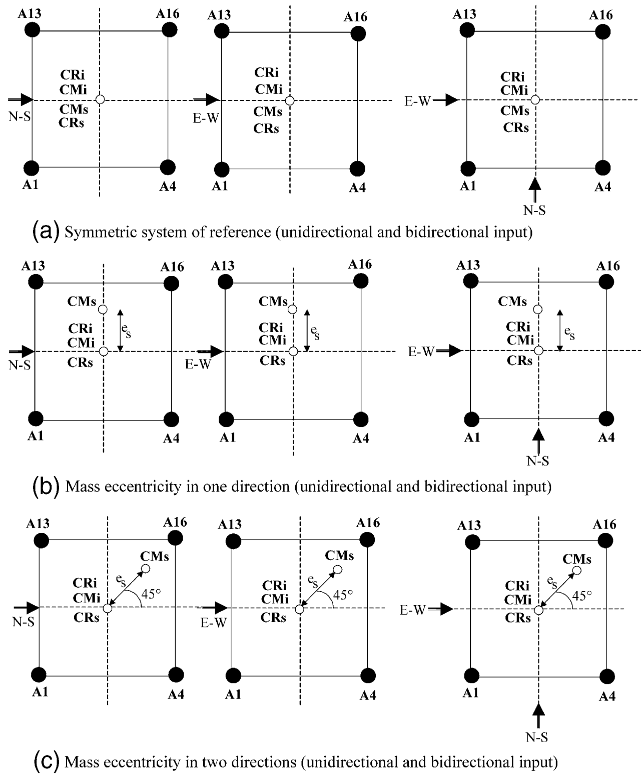

Fig. 4. Definition of the static eccentricities on the superstructure, e_s.

were needed for the set of ground motion records considered (Table 2, Fig. 2).

In this study, the static eccentricities e_s where obtained by shifting the centers of mass of the superstructure (CMs) from the center of stiffness of the superstructure (CRs), that are located in the geometric center of the plan, as depicted in Fig. 4. This modeling was done as the 3DBasis software [10] allows this modeling and it is a considerably much simpler modeling for a parametric study with a large number of simulations. The ratio between the torsional and lateral frequencies for the superstructure ($\Omega_{\theta s}$) remains constant for all simulations, $\Omega_{\theta s} = 1.20$.

By shifting CMs instead of CRs, one should expect higher torsional responses, as previous studies [1,2,10] have shown that when the center of stiffness of the isolation system (CRi) coincides with the center of mass of the structure (CMs), structural torques are reduced to a minimum. Nevertheless, as the static eccentricities that can be present in a base-isolated structure can be associated to either modeling (CMs shifted from CRi or CRs shifted from CRi), the results presented herein (CMs shifted from CRi, Fig. 4) are of practical interest.

From the existing 16 isolators, four were selected to monitor the nonlinear response. These isolators are corner isolators A1, A4, A13 and A16 depicted in Fig. 4. Isolators A4 and A13 were selected as they are located on intermediate distances when bidirectional eccentricity is considered (Fig. 4c) instead of concentrating on the isolator that have the shortest (A16) and largest (A1) distance from CMs, that have the smallest and higher demands, as previously done in other studies. However, when the static eccentricity is in one direction, these isolators are indeed nearest (A13) and/or farthest (A4) placed from the corresponding CMs (Fig. 4b). For the completely symmetric systems (e_s = 0%, Fig. 4a), all isolators experience the same peak responses, as the selected ground motions induce no torsional response.

This study concentrated on peak responses for the isolation system instead of superstructure parameters. Previous studies reported in the sizeable literature in base isolation have documented that peak responses in the superstructure are considerably reduced, in addition to what has been concluded in previous studies where torsional response was considered (for example Jangid and Datta [3,4], Nagarajaiah et al. [2,5]). Among the peak responses studied for the isolators in this work are: (1) peak displacements, (2) angle with respect to the global coordinates of the structural system where peak displacements occur and, (3) ductility demands. The details of this study are presented in Gómez-Soberón [8] and some interesting results are summarized in following sections.

6. Symmetric systems of reference

In order to assess the impact of static eccentricities in the superstructure alone in the seismic response of the isolators, a frame of reference is needed first to compare such response. Therefore, it was studied the seismic response of systems where all isolators have the same properties and are uniformly distributed within the plan; in addition, the superstructure is assumed to present no eccentricity in any floor (e_s = 0%, Fig. 4a).

An interesting response to study is the ratio between peak displacements for the isolators when subjected to bidirectional seismic input (Δ_{2D}) compared with those obtained for unidirectional input (Δ_{1D}). Currently, there is not a specific recommendation to combine peak displacements in orthogonal directions for the design of base isolators available in the literature, so the 100% + 30% combination rule prescribed by many seismic codes worldwide to account for orthogonal effects in the design of conventional structures is sometimes used with little reflection about if this rule to account for lateral forces still applies for the design displacements of isolated systems.

On this regard, FEMA-273 [15] document under section 9.2.4.5.C. basically endorses the 100% + 30% combination rule to compute the maximum displacement of the isolation system. For the design of the isolation system using dynamic analyses, the 1997 UBC code [12] requires an increase of 30% in the target design spectra to account for bilateral ground motions. As shown by Naeim and Kelly [16], the resulting vector summations of the requirement of the UBC-97 code and the 100% + 30% rule (FEMA-273) are very different. In the humble opinion of the authors, the questions to answer regarding orthogonal effects for the design of isolation systems are: (1) is the 100% + 30% combination rule still valid and reasonable to compute design displacements? and, (2) whether a rational rule for the combination of orthogonal effects can be independent of the structural period and the characteristics of the ground motion.

Therefore, in order to gain some insight on this topic, the ratio between peak displacements of the isolators when subjected to bidirectional seismic input (Δ_{2D}) are compared in Fig. 5 with those obtained for the unidirectional input of the N–S component acting alone (Δ_{1D}). In general, larger displacements for the isolators were obtained with the N–S component of the records than with the E–W component in the effective period range considered in this study. It is observed in the curves of Fig. 5 that, in general, amplifications occur under bidirectional input, but this amplification is not constant, but depends on the effective period of the base-isolated structure, and on the characteristics of the ground motions and the yield strength ratio (V_y/W). Peak amplification factors of 1.5 were obtained for station SMRZA. From the relatively small simulations done in this study it is not clear how a constant 100% + 30% combination rule could apply for the design of base isolators in the selected period range. However, the applicability of the 100% + 30% combination rule has to be determined by a specific parametric study using a reasonable set of ground motions. The first author is conducting specific studies that may allow one to arrive at some recommendations in this regard in the near future.

The relation between the effective period for the base-isolated structure and the angle where the peak displacement for the isolation system occur (Fig. 6) when subjected to bilateral ground motions is depicted in Fig. 7. It is observed that peak displacements do not generally occur in the same angle even for the same set of motions in the period range under consideration, and that this angle may also depend on the yield strength of the isolation system. Therefore, it is confirmed that it is good practice to use isolators of circular cross section that have the same displacement capacity in any given direction.

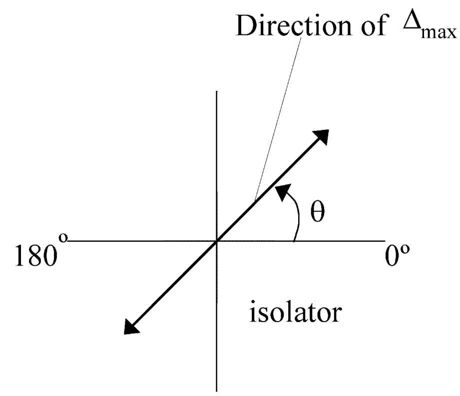

Fig. 6. Measurement of the angle θ where the peak dynamic displacement on the isolator (Δ_{max}) occur.

Displacement ductility demands (μ) obtained in the period range of interest when subject to bidirectional input of the ground motions under study are depicted in Fig. 8. It is observed that for $V_y/W = 0.05$ the response of the isolation system is clearly nonlinear, but for $V_y/W = 0.10$, some elastic responses are detected for SMRZA records. Peak ductility demands around eight are found for TMANZ records for $V_y/W = 0.05$ and $T_I = 1.5$ s, being less than the maximum value $\mu = 9$ associated to the primary curve recommended by the UBC provisions (Fig. 3, eq. (4)) for the isolators under

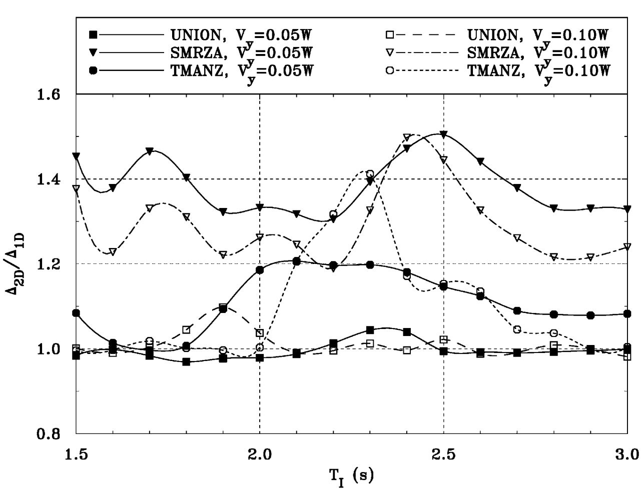

Fig. 5. Relation between T_I and Δ_{2D}/Δ_{1D} ratio for base isolators of a completely symmetric system.

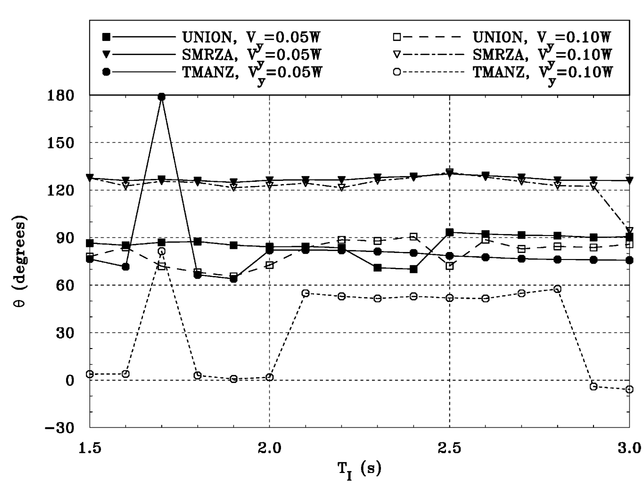

Fig. 7. Relation between T_I and θ for base isolators of a completely symmetric system for bilateral ground motions.

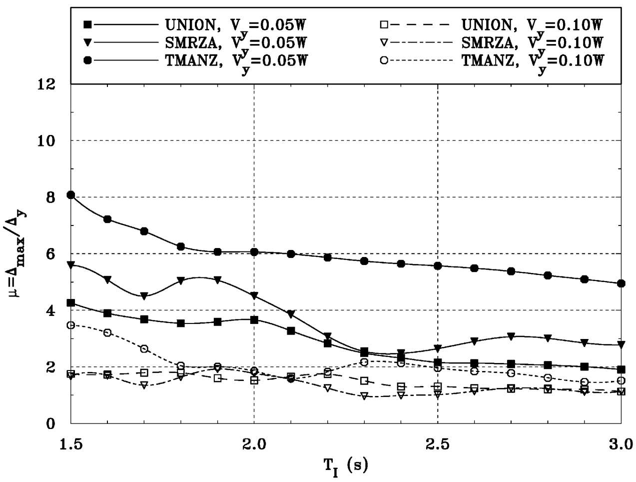

Fig. 8. Relation between T_I and θ for base isolators of a completely symmetric system for bilateral ground motions.

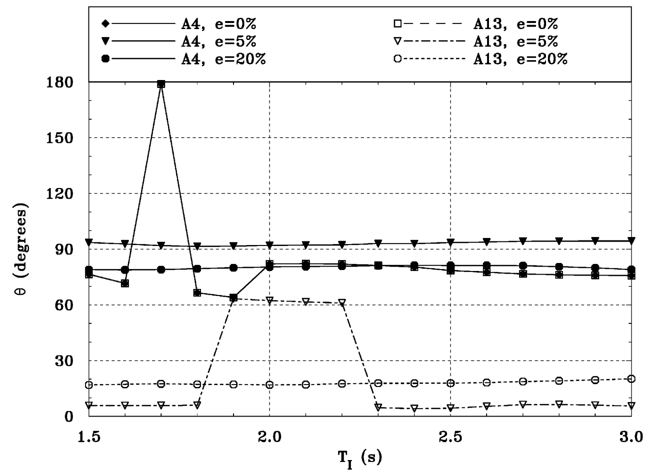

Fig. 9. Relation between T_I and θ for base isolators for $V_y/W = 0.05$ and for bilateral TMANZ ground motions.

study. In general, it is clear that the responses for $V_y/W = 0.10$ have reduced ductility demands and are then of less interest, because a good design for bilinear isolators under severe ground shaking should not be associated to near-elastic responses, whereas the curves for $V_y/W = 0.05$ are within reasonable μ values and then, are more interesting to study further, thinking on the design of isolators for strong earthquakes.

7. Systems with eccentricities in the superstructure

As stated earlier, the models of reference were studied for static eccentricities of 5%, 10%, 15% and 20% of the plan dimension ($L = 21$ m), for both one direction and acting on a 45% angle, as depicted in Fig. 4. For illustration purposes, some results for static eccentricities of 5% and 20% will be first presented and discussed. In addition, the results obtained for bidirectional and unidirectional eccentricity will be directly compared in following sections for all the considered static eccentricities under study.

The relation between the effective period for the base-isolated structure and the angle where the peak displacement of the isolation system occur when subjected to bilateral ground motions of station TMANZ for $V_y/W = 0.05$ is depicted in Fig. 9. It is observed again that peak displacements of specific isolators do not generally occur in the same angle, and that they also depend on the eccentricity level. In fact, the angle is different for isolator A4 and A13 for a given static eccentricity, except for the symmetric system ($e_s = 0\%$, Fig. 4a). Therefore, this figure supports again that it is good practice to use isolators of circular cross section that have the same displacement capacity in any given direction, as peak displacements may occur in any direction depending on parameters such as the specific characteristics of the ground motions, the static eccentricity of the structure and/or the isolation system, the yield strength of the isolation system, etc.

The displacement ductility demands μ obtained when the static eccentricity $e_s = 5\%$ is unidirectional (Fig. 4b) and for $V_y/W = 0.05$ when subjected to bidirectional input of the ground motions under study is depicted in Fig. 10 for isolators A4 and 13. It is observed that peak responses are obtained for TMANZ records whereas the smaller demands are associated to station UNION. As expected, it is also observed that torsional coupling causes that the ductility demands for isolator A13 differ from those of isolator A4, although the ductility demand curves are somewhat similar. Peak ductility demands are associated to isolator A4 for all the ground motion records under study, and are within the 1.5 s to 2 s period range approximately. In any case the peak ductility demands surpass the maximum value $\mu = 9$ associated

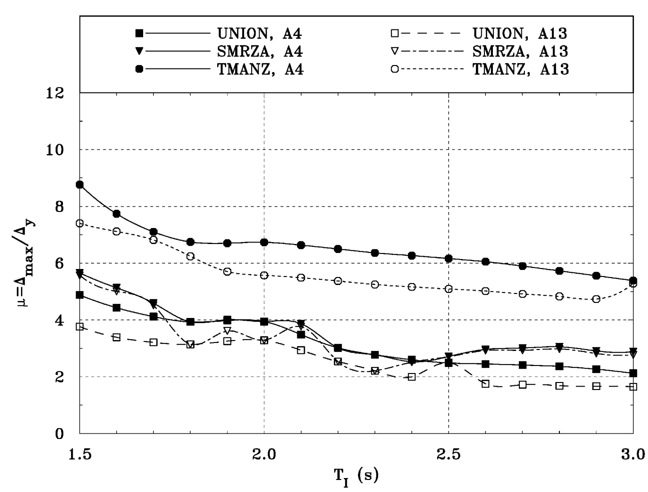

Fig. 10. Relation between T_I and μ for base isolators of a system with $V_y/W = 0.05$ subjected to bilateral ground motions when the static eccentricity $e_s = 5\%$ is unidirectional.

to the primary curve recommended by the UBC provisions (Fig. 3, eq. (4)) for the isolators under study. It is worth noting that for unidirectional eccentricity, peak displacements for isolators A1 and A4 are identical, and the same happens for isolators A13 and A16.

The displacement ductility demands μ obtained when the static eccentricity $e_s = 5\%$ is bidirectional (Fig. 4c) for $V_y/W = 0.05$ when subject to bidirectional input of the ground motions under study is depicted in Fig. 11 for all corner isolators. It is also observed that peak responses are obtained for TMANZ records whereas the smallest demands are associated to station UNION. In general, peak ductility demands do not surpass the maximum value $\mu = 9$ associated to the primary UBC curve, except for isolator A1, $T_I = 1.5$ s and TMANZ records. As expected (Fig. 4c), highest demands are obtained for isolator A1 and smallest demands are obtained for isolator A16. According to Fig. 4c, and taking as a reference the CMs, for bidirectional eccentricity isolator A4 and A13 are located in the flexible side with respect to one ground motion component (A4 with E–W, A13 with N–S) and on the stiff side with the corresponding orthogonal component (A4 with N–S, A13 with E–W), so in this case, it is not clear, a priori, which isolator will experience higher demands. This is an important difference of this study with respect to other studies that have just concentrated on the isolators subjected to smallest (A16) and highest (A1) demands, but give no insight on what may happen in isolators that may be placed somewhat in between (A4 and A13).

It is observed in Fig. 11 that for stations UNION and SMRZA, isolator A4 is subjected to higher ductility demands than isolator A13 over all the considered period range, but for TMANZ higher ductility demands are observed for isolator A13 (with respect to A4) in the period range of 1.6 s to 1.8 s. If the results plotted in

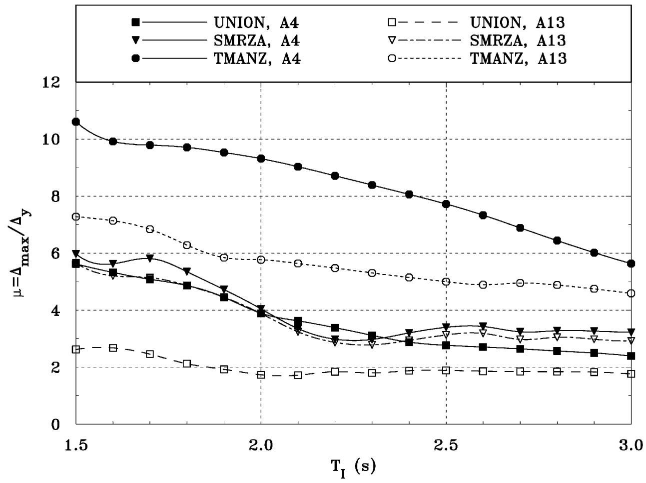

Fig. 12. Relation between T_I and μ for base isolators of a system with $V_y/W = 0.05$ subjected to bilateral ground motions when the static eccentricity $e_s = 20\%$ is unidirectional.

Fig. 11 for TMANZ are compared with those of Fig. 10, one can observe that, in general, torsional coupling with bidirectional input increases the response of isolator A13 more than the response of isolator A4, but these increments are small so there are no big differences between the curves for unidirectional input (Fig. 10) and bidirectional input (Fig. 11) for the ground motions under consideration.

The trend observed on the variation of μ for other static eccentricities (10%, 15% and 20%) are similar to those shown for $e_s = 5\%$, but associated to higher demands, so for illustration purposes only the curves for $e_s = 20\%$ when $V_y/W = 0.05$ are shown. The displacement ductility demands μ obtained for $V_y/W = 0.05$ and $e_s = 20\%$ under bidirectional input of the ground motions is depicted in Fig. 12 when e_s is unidirectional (Fig. 4b) and in Fig. 13 when e_s is bidirectional (Fig. 4c).

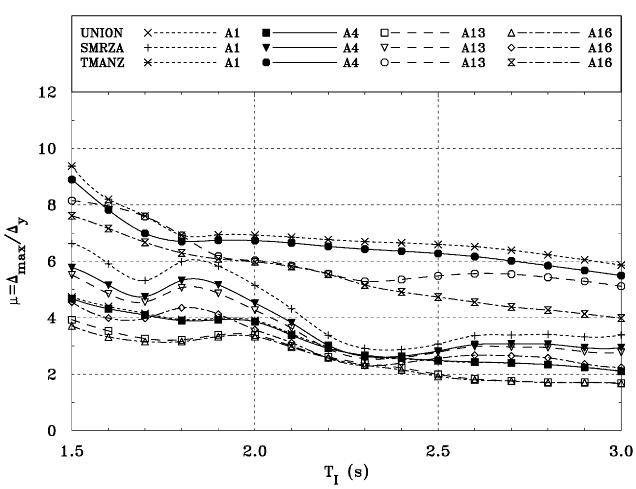

Fig. 11. Relation between T_I and μ for base isolators of a system with $V_y/W = 0.05$ subjected to bilateral ground motions when the static eccentricity $e_s = 5\%$ is bidirectional.

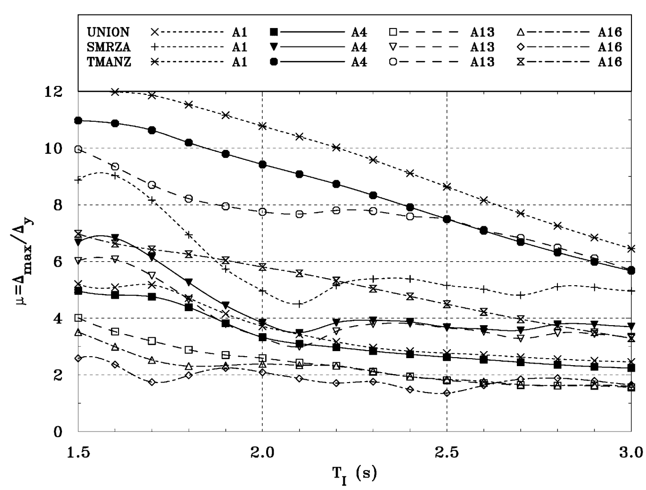

Fig. 13. Relation between T_I and μ for base isolators of a system with $V_y/W = 0.05$ subjected to bilateral ground motions when the static eccentricity $e_s = 20\%$ is bidirectional.

It is observed with respect to the results plotted in Figs. 10 and 11 for $e_s = 5\%$ that: (a) as expected, as the static eccentricity increases, ductility demands (μ) clearly increase for isolator A1 and decrease for isolator A16 for both unidirectional and bidirectional static eccentricities, (b) ductility demands (μ) clearly increase for isolator A4 and decrease for isolator A13 for unidirectional static eccentricity, but for bidirectional static eccentricity, the relation is much more complex. The curves for isolators A4 and A13 differentiate more when the static eccentricity is unidirectional, because for this case it is clear that one isolator is located on the flexible side while the other is on the stiff side, whereas this difference is smaller when the e_s is bidirectional, where no isolator is really located on a flexible or stiff side, so the amplifications depends on the characteristics of each ground motion component and its directivity as assumed in this study and, (c) For TMANZ records, peak ductility demands for isolators A1 and A4 surpass the maximum value $\mu = 9$ associated to the primary curve recommended by the UBC provisions when $e_s = 20\%$ bidirectional in the period range 1.5 s to 2.4 s (Fig. 13), and in the period range 1.5 s to 2.1 s when $e_s = 20\%$ is unidirectional (Fig. 12). High demands occur under bidirectional eccentricity for many other isolators for TMANZ records (for example, A13), so it is clear that under this eccentricity, many isolators do not comply with the primary curve of the UBC code (Fig. 3) in the period range of consideration.

8. Comparison of peak isolator displacements between unidirectional or bidirectional static eccentricity in the superstructure

It is important to assess the relative difference in the peak displacement demands for the isolators when the eccentricity in the superstructure is only in one direction (Fig. 4b) or in two directions (Fig. 4c), when the system is subjected to bidirectional input of the ground motions under consideration.

A priori, one would assume that peak responses would generally occur when the static eccentricity is bidirectional (Fig. 4c). However, the relation is more complex, as shown in Fig. 14 for SMRZA records and in Fig. 15 for TMANZ records, where the relative ratio between peak isolator displacements for bidirectional eccentricities [Δ_{max}(e2D)] and unidirectional eccentricities [Δ_{max}(e1D)] for isolator A4 is depicted when subjected to bidirectional ground motion input. From the observation of Figs. 14 and 15, and other figures obtained for $V_y/W = 0.05$ and $V_y/W = 0.10$ for all the ground motion records and isolators considered in this study (not shown), one may conclude that Δ_{max}(e2D)/Δ_{max}(e1D) ratio depends on many parameters, among them: (a) characteristics of the ground motions and their directivity, (b) dynamic coupling of the base isolated structure with the ground motions, (c) the relative eccentricity ratio presented in the superstructure (in this study, assumed to be the same in all floors), (d) the location of a given isolator in plan, (d) the own characteristics of the isolators. For the bilinear isolators considered in this study, it is clear that this depends on the yield strength ratio V_y/W, comparing the results for $V_y/W = 0.05$ (shown) with those for $V_y/W = 0.10$ (not shown). By extension, the authors assume that differences would also be observed for different pre to post yielding stiffness ratio from the one considered in this study ($k_2/k_1 = 0.10$), but this has to be confirmed with specific studies devoted to study this parameter.

It is worth noting that often, peak displacements under

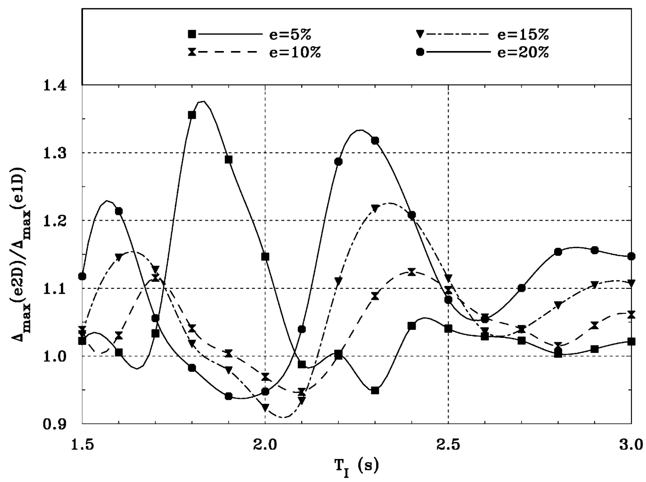

Fig. 14. Ratio between the peak isolator displacements of isolator A4 for bidirectional eccentricities [Δ_{max}(e2D)] and unidirectional eccentricities [Δ_{max}(e1D)] for $V_y/W = 0.05$ under bidirectional input of SMRZA ground motion records.

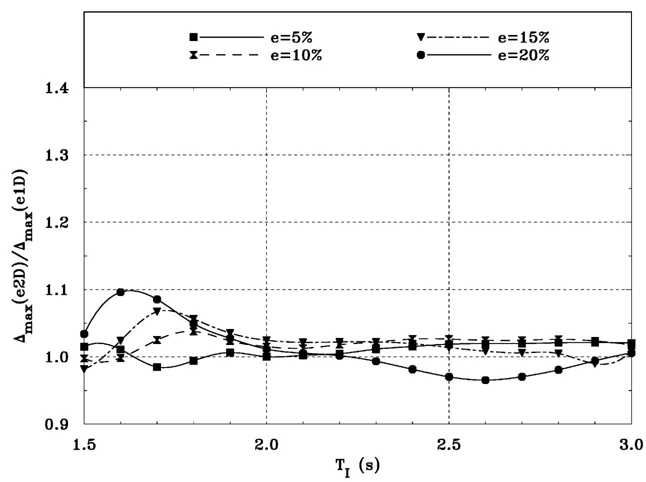

Fig. 15. Ratio between the peak isolator displacements of isolator A4 for bidirectional eccentricities [Δ_{max}(e2D)] and unidirectional eccentricities [Δ_{max}(e1D)] for $V_y/W = 0.05$ under bidirectional input of TMANZ ground motion records.

unidirectional eccentricity could be higher than those for bidirectional eccentricity for a given isolator, in this particular case, isolator A4 (Figs. 14 and 15). Similar curves were obtained for isolator A4 under UNION records and for isolator A13 for all the ground records, as reported in Gómez-Soberón [8].

9. Comparison of peak isolator displacements for systems with asymmetries in the superstructure with respect to symmetric systems

In order to compare the peak displacements experienced by the isolators under study (A1, A4, A13 and A16) when there are no eccentricities in the superstructure (symmetric systems, Fig. 4a) with those when there are eccentricities in the superstructure (asymmetric systems, Figs. 4b and c), peak displacements for the isolators of asymmetric systems [$\Delta_{\max}$(e)] were divided by those of symmetric systems [Δ_{max}(e = 0)]. Both unidirectional (Fig. 4b) and bidirectional eccentricities (Fig. 4c) were considered. In general, the curves obtained for unidirectional and bidirectional eccentricities are somewhat similar; however, peak amplifications and deamplifications were detected for bidirectional eccentricity. Therefore, the results for bidirectional eccentricity (Fig. 4c) and $V_y/W = 0.05$ for isolators A1 and A16 are shown in Figs. 16, 18 and 20, and for isolators A4 and A13 in Figs. 17, 19 and 21.

It is observed from Figs. 16, 18 and 20 that for the period range under consideration, peak displacements (and hence, ductility demands) for isolator A1 are always amplified for asymmetric systems with respect to symmetric systems, particularly for SMRZA and TMANZ records. Peak amplification factors of 1.4, 2.2 and 1.85 are respectively observed for isolator A1 for

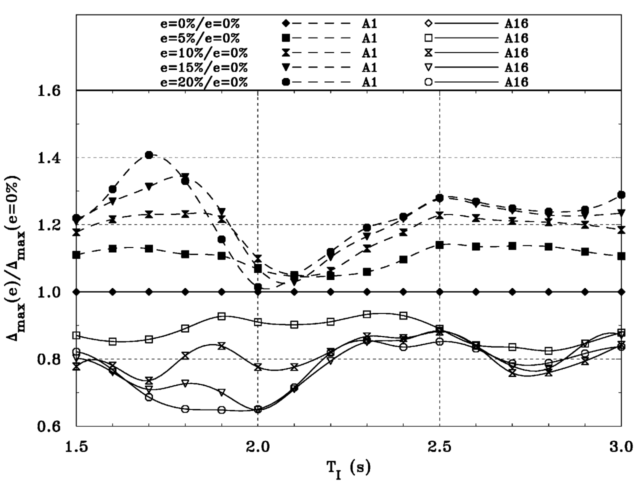

Fig. 16. Ratio between the peak isolator displacements of isolators A1 and A16 for asymmetric systems [$\Delta_{\max}$(e)] and symmetric systems [Δ_{max}(e = 0%)] for $V_y/W = 0.05$ under bidirectional input of UNION ground motion records.

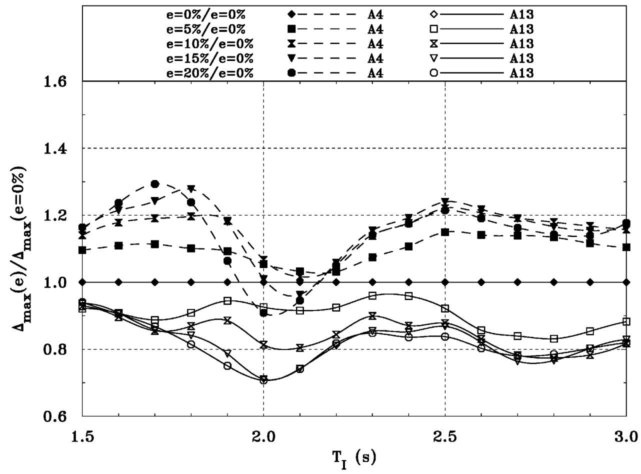

Fig. 17. Ratio between the peak isolator displacements of isolators A4 and A13 for asymmetric systems [$\Delta_{\max}$(e)] and symmetric systems [Δ_{max}(e = 0%)] for $V_y/W = 0.05$ under bidirectional input of UNION ground motion records.

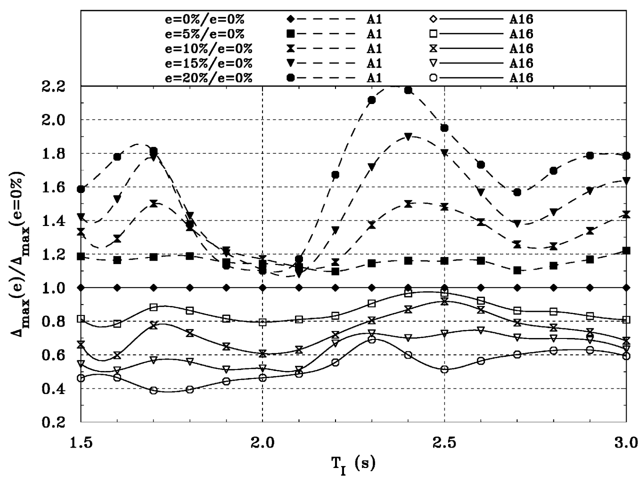

Fig. 18. Ratio between the peak isolator displacements of isolators A1 and A16 for asymmetric systems [$\Delta_{\max}$(e)] and symmetric systems [Δ_{max}(e = 0%)] for $V_y/W = 0.05$ under bidirectional input of SMRZA ground motion records.

stations UNION (T_I = 1.7 s, Fig. 16), SMRZA (T_I = 2.4 s, Fig. 18) and TMANZ (T_I = 1.8 s, Fig. 20) when the static eccentricity is e_s = 20%.

On the other hand, peak displacements for isolator A16 are generally reduced for asymmetric systems with respect to the symmetric systems due to the torsional response, being particularly important for SMRZA records, where it is observed that for e_s = 20% and T_I = 1.7 s, the smallest isolator displacement is only about 0.4 times the one obtained for the symmetric system (Fig. 18).

Therefore, it is concluded that for the ground motions under consideration, extreme cases of torsional response have an important contribution on the total displacement of extreme corner isolators A1 and A16. For SMRZA

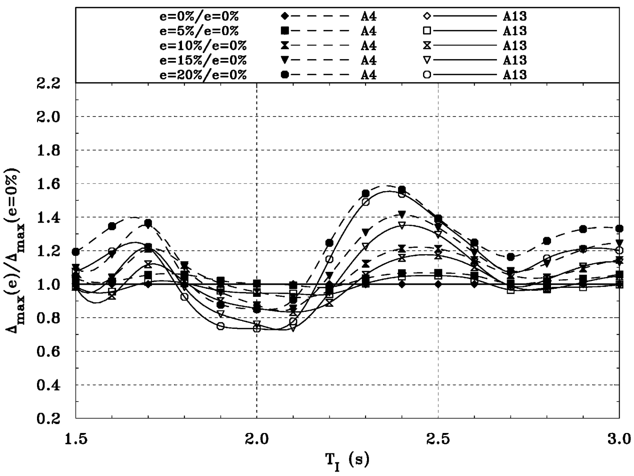

Fig. 19. Ratio between the peak isolator displacements of isolators A4 and A13 for asymmetric systems [Δ_{max}(e)] and symmetric systems [Δ_{max}(e = 0%)] for $V_y/W = 0.05$ under bidirectional input of SMRZA ground motion records.

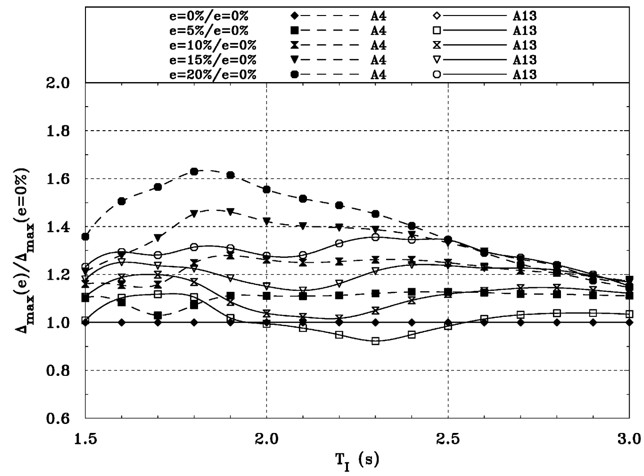

Fig. 21. Ratio between the peak isolator displacements of isolators A4 and A13 for asymmetric systems [Δ_{max}(e)] and symmetric systems [Δ_{max}(e = 0%)] for $V_y/W = 0.05$ under bidirectional input of TMANZ ground motion records.

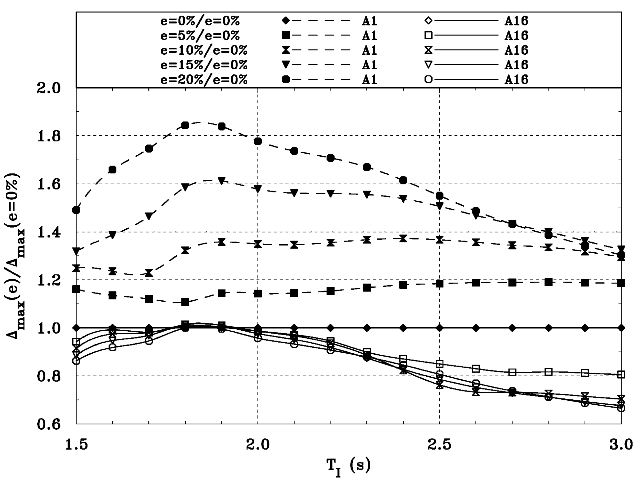

Fig. 20. Ratio between the peak isolator displacements of isolators A1 and A16 for asymmetric systems [Δ_{max}(e)] and symmetric systems [Δ_{max}(e = 0%)] for $V_y/W = 0.05$ under bidirectional input of TMANZ ground motion records.

records and e_s = 20%, the torsional component contributes with up to 55% of the total displacement for isolator A1 and with up to 60% of the total displacement for isolator A16.

It is observed from Figs. 17, 19 and 21 that peak displacements for isolator A4 are generally amplified for asymmetric systems with respect to symmetric systems, particularly for TMANZ records. However, for SMRZA records, there is a period range (1.8 s to 2.1 s) where the displacements for asymmetric systems are smaller than those of symmetric systems for all eccentricities (Fig. 19). This phenomenon is also observed for UNION records for a period range (2.0 to 2.1 s) for static eccentricities of 15% and 20% (Fig. 17). Peak amplification factors of 1.3, 1.58 and 1.63 are respectively observed for isolator A4 for stations UNION (T_I = 1.7 s, Fig. 17), SMRZA (T_I = 2.4 s, Fig. 19) and TMANZ (T_I = 1.8 s, Fig. 21) when the static eccentricity is e_s = 20%.

It is observed from Figs. 17, 19 and 21 that there is no a particular trend for isolator A13 regarding amplification or deamplification of asymmetric systems with respect to symmetric systems. For example, for UNION records (Fig. 17), peak isolator displacements (ductility demands) are generally deamplified for asymmetric systems with respect to symmetric systems. It is observed that for e_s = 20% and T_I = 2.0 s, the smallest isolator displacement is 0.7 times the one obtained for the symmetric system. On the other hand, under the action of TMANZ records one essentially observes amplifications on the response of asymmetric systems (Fig. 21). For e_s = 20% and T_I = 2.3 s, the peak isolator displacement is 1.4 times the one obtained for the symmetric system. For SMRZA station (Fig. 19) there is a well-defined period range (1.8s to 2.2 s) where the response of asymmetric systems is clearly deamplified (smallest isolator displacement is 0.73 times the one obtained for the symmetric system for e_s = 20%), but in other period ranges the displacements of asymmetric systems are amplified with respect to symmetric systems (peak isolator displacement is 1.55 times the one obtained for the symmetric system for e_s = 20% and T_I = 2.4 s).

The following general observations can be done for all isolators under study (A1, A4, A13 and A16): (a) As expected, amplifications (or deamplifications) on the response of asymmetric systems with respect to symmetric systems increase as the static eccentricity increases, (b) The [Δ_{max}(e)]/[Δ_{max}(e = 0%)] ratio is not constant in the period range under consideration for all the selected ground motions and, (c) The characteristics of these amplification (deamplification) curves vary for each set of ground motion records in shape and the location of peak amplification or deamplification factors. Therefore, it seems that the characteristics of these curves strongly depend on the own characteristics of the selected ground motions, even though all records correspond to firm soil sites.

10. Conclusions

Based upon the parametric study for the bilinear isolators briefly described in this paper and presented in detail in Gómez-Soberón [8], one can make the following observations.

Amplification factors resulting from the ratio between peak displacements for the isolators when subjected to bidirectional seismic input (Δ_{2D}) compared with those obtained for unidirectional input (Δ_{1D}) are not constant for the period range under study, independently if there are eccentricities in the superstructure (asymmetric systems) or not (symmetric systems). From the relatively small simulations done in this study it is not clear how a constant 100% + 30% combination rule to account for orthogonal effects could apply for the design of base isolators in the selected period range. However, the applicability of the 100% + 30% combination rule has to be determined by a specific parametric study using a reasonable set of ground motions.

For the period range under consideration, peak displacements for specific isolators do not generally occur in the same angle for both symmetric ($e_s = 0$) or asymmetric systems ($e_s \neq 0$), and they depend on the static eccentricity ratio (e_s) and the given yield strength ratio (V_y/W) for the isolation system. In fact, for asymmetric systems, the angle associated to peak displacements is different for two or more isolators for a given isolation system for a fixed effective isolation period T_I. Therefore, it is good practice to use isolators of circular cross section that have the same displacement capacity in any given direction, as peak displacements may occur in any direction depending on parameters such as: (1) the specific characteristics of the ground motions, (2) the static eccentricity of the structure and/or the isolation system, (3) the yield strength of the isolation system.

With respect to the ductility demands (μ) for the specific isolators under study, where isolators A4 and A13 were selected as they are located on intermediate distances when bidirectional eccentricity is considered (Fig. 4c), but they are in the stiff side (A13) or flexible side (A4) when the static eccentricity is in one direction (Fig. 4b), a difference with previous studies that always picked isolators located on the flexible corner (A1) and stiff corner (A16), one can conclude that: (a) As expected, as the static eccentricity increases, ductility demands (μ) clearly increase for isolator A1 and decrease for isolator A16 for both unidirectional and bidirectional static eccentricities, (b) ductility demands (μ) clearly increase for isolator A4 and decrease for isolator A13 for unidirectional static eccentricity, but for bidirectional static eccentricity the relation is much more complex, (c) the curves for isolators A4 and A13 differentiate more when the static eccentricity is unidirectional, because for this condition it is clear that one isolator is located on the flexible side while the other is on the stiff side, whereas this difference is smaller when the static eccentricity is bidirectional, where no isolator is really located on a flexible or stiff side, so amplifications depend on the characteristics for each ground motion component and its directivity as assumed in this study and, (d) For $V_y/W = 0.05$ and TMANZ records, peak ductility demands surpass the maximum value $\mu = 9$ associated to the primary curve recommended by the UBC provisions for some isolators when the static eccentricity e_s is primarily bidirectional over a important period range. Although in this paper this is illustrated for $e_s = 20\%$, in Gómez-Soberón [8] one can observe that $\mu > 9$ are observed when $e_s > 10\%$ at a 45 degree angle (Fig. 4c).

In contrast to what it may be assumed a priori, peak displacements for a given isolator do not generally occur when the static eccentricity is bidirectional, as they may occur when the static eccentricity is unidirectional instead. The relative ratio between peak isolator displacements for bidirectional eccentricities [Δ_{max}(e2D)] and unidirectional eccentricities [Δ_{max}(e1D)] is more complex, as this ratio depends on many parameters, among them: (a) characteristics of the ground motions and their directivity, (b) dynamic coupling of the base isolated structure with the ground motions, (c) the relative eccentricity ratio presented in the superstructure (assumed to be constant for all floors in this study), (d) the location of a given isolator in plan and, (e) the own characteristics of the isolators, among some of the most identifiable parameters.

Based upon the comparative study of the peak displacements experienced by the selected isolators when there are no eccentricities in the superstructure (symmetric systems) with those when there are eccentricities in the superstructure (asymmetric systems), one can conclude that: (a) As expected, amplifications (or deamplifications) on the response of asymmetric systems with respect to symmetric systems increase as the static eccentricity increases, (b) The amplification (deamplification) ratio is no constant in the period range under consideration for all the selected ground motions, (c) The characteristics of these amplification (deamplification) curves vary for each set of ground motion records, both in the shape and in the location of peak amplification or deamplification factors, and (d) Extreme cases of torsional response have an important contribution on the total displacement of corner isolators. The torsional component contributed with up to 60% of the total displacement for a corner isolator when the static eccentricity was $e_s = 20\%$ for SMRZA records.

In agreement with previous studies (Jangid and Datta [3], Nagarajaiah et al. [2]), and in contrast to what it was initially stated by Lee [1], this study confirms that the effectiveness of base isolation for torsionally coupled systems decreases with increase of the superstructure eccentricity. Peak displacement and ductility demands of the isolators are not uniform, and this non-uniformity increases with an increment in the superstructure eccentricity. Peak amplifications up to 2.2 times were observed in isolator A1 in asymmetric systems with respect to symmetric systems for the ground motions under study.

Based upon all the observations summarized above, primarily: (a) the differences observed on the shapes and values of the curves for the ductility demands (μ) for the isolators, (b) the amplifications (or deamplifications) on peak displacements and ductility demands for asymmetric systems with respect to symmetric systems increase as the static eccentricity increases and, (c) the confirmation that the effectiveness of base isolation for torsionally coupled systems decreases with increase of the superstructure eccentricity; the authors think that, for design purposes, it would be desirable to restrict the use of static or simplified dynamic methods of analysis in building codes based upon a specific eccentricity ratio for the superstructure. This target eccentricity ratio for the superstructure should be set in order to distinguish when the expected design displacements associated with a given code are not well covered when compared to nonlinear dynamic analyses. It is clear that this study cannot conclude on this regard, as the effects of the superstructure torsional to lateral frequency ratio ($\Omega_{\theta s}$) have also to be carefully assessed. However, it is the opinion of the authors, based upon the observation of all the simulations, that this value might be close to $e_s = 10\%$, that does not seem to be a highly restrictive value. The parametric study of Jangid and Datta [3] suggest that e_s might be close to 15%, but this study was done for unidirectional eccentricity on a single story model. Reasonable values for e_s for specific building codes have to be determined by specific studies where this response quantity should be carefully assessed using a reasonable set of suitable ground motions and specific methods of design associated to their design spectra for different torsional to lateral frequency ratios ($\Omega_{\theta s}$) for the superstructure. Future efforts should be directed on this direction. For now, the methods of analysis advocated by the UBC code specify that the actual (static) eccentricity must be incremented by a 5% accidental eccentricity in the computation of total design displacements, but set no restrictions for the use of the static method of analysis in terms of the static eccentricity, unless the superstructure is considered irregular, both horizontally or vertically, according to the code.

Acknowledgements

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