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RELIABILITY-BASED DESIGN SPECTRA MODIFICATION FACTOR FOR REINFORCEMENT OF TILTED STRUCTURES

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Abstract

A reliability-based methodology to estimate the additional strength required for the reinforcement of existing tilted structures, is proposed. Several nonlinear time history analyses of structural systems with different levels of asymmetric yielding are carried out. The seismic analyses consider the effect of two orthogonal components of the seismic ground motions as well as the influence of soil-structure interaction. Results indicate that the annual rate of exceedance of the ductility demand for asymmetric yielding structures may be much higher than those corresponding to symmetric structures, such increment depends on several factors: tilting angle, ductility demand of the structure, and ratio between the vibration period of the system and that of the soil. Based on the results, a simplified mathematical expression to estimate strength amplification factors of tilted structures to achieve a similar reliability to that of symmetric structures, is proposed. The expression depends on the tilt angle, the ductility of the structure, and the ratio of the fundamental vibration period of the structure to the dominant period of the soil. Finally, the proposed expression is compared with that recommended by the Mexico City Building Code, and its advantages and disadvantages are discussed.

Keywords: reliability assessment; asymmetric yielding; tilted structures; seismic analysis

1. Introduction

Some structures built on soft soil may suffer tilting due to differential settlements, which causes that the plastic deformation demands accumulate in only one direction (i.e. the direction of tilting). Consequently, the force-deformation relationship of the structure is asymmetric in opposite directions. This behavior may significantly affect the seismic performance of such structures especially when subjected to long duration intense seismic ground motions. Because of this, an asymmetric yielding structure needs to be designed for a higher lateral strength than a symmetric one. This fact leads to the necessity to estimate amplification factors of the base shear coefficient design spectrum in order to offset the detrimental effect of the asymmetric yielding. In addition, modern seismic design codes must be oriented not only to ensure a good seismic performance of the structures, but also an adequate level of reliability. For this reason, a reliability-based methodology is proposed in this study with the objective to develop a simplified mathematical expression to estimate strength amplification factors for structures with asymmetric yielding due to tilting. The proposed methodology is applied to simplified structural systems subjected to a set of seismic ground motions recorded in the soft soil of Mexico City.

2. Literature Review and Objectives

Ruiz et al. [1] proposed mathematical expressions to consider the increment in the ductility demand of systems with asymmetric yielding with respect to that of symmetric systems; they used single degree of freedom (SDOF) systems with elasto-plastic hysteretic behavior. Ruiz [2] proposed an expression to consider, in addition to other aspects, the duration of the seismic ground motion in the response of systems with asymmetric yielding. Terán-Gilmore et al. [3] studied the dynamic response of tilted SDOF systems, and concluded that the design of structures with asymmetric yielding should consider the lateral strength of the structure, the frequency content and the duration of the seismic excitation, as well as the interaction between the dynamic characteristics of the structure and those of the ground motion. Meanwhile, Terán-Gilmore and Arroyo-Espinoza [4] proposed expressions to estimate strength amplification factors for structures with asymmetric yielding located in soft soil of Mexico City, using SDOF systems with different hysteretic structural behaviors; however, their mathematical expressions are very similar for all the hysteretic behaviors considered.

Despite the contributions of the mentioned studies, most of them are limited to the analysis of SDOF systems subjected to unidirectional analyses. In addition, the asymmetric yielding was considered by means of an idealized SDOF model. The explicit consideration of the *tilting angle*, the influence of two orthogonal components of the ground motions, the soil-structure interaction, and the implicit levels of reliability in the development of the strength amplification factors were not considered.

The main objectives of the present study are: a) to propose a reliability-based methodology to take into account the additional strength requirement of structures with asymmetric yielding, b) to develop a simplified mathematical expression for this purpose, considering the influence of the soil structure interaction as well as the influence of two orthogonal horizontal seismic ground motions, and c) to compare the proposed expression with those existing in the literature, discussing its advantages and disadvantages.

3. Methodology

3.1. Evaluation of the Structural Reliability

One of the main objectives of *Earthquake Engineering* is to quantify the levels of reliability in the structures by considering the possible ground motions intensities that may occur at a site. In the seismic design guidelines exist several reliability based formats [5], for example: a) the semi-probabilistic [6], b) first order and second moments (FOSM) [7], c) load and resistance factors design (LRFD) format [8], d) those based on seismic hazard analysis [9,10]), and e) those based on optimization [11,12]. In the present study, the structural reliability is evaluated with the format based on a *seismic hazard analysis*. This format evaluates the structural reliability through the mean annual rate of exceedance (ν) of certain values of the structural demand (ductility demand, inter-story drift, etc.) d, for a given level of intensity (in this study, the spectral acceleration S_a); this is represented by *structural demand hazard curves* $\nu_D(d)$, obtained by means of Eq. (1) [13,14]:

$$\nu_D(d) = \int_0^{\infty} \left|\frac{d_\nu(S_a)}{d(S_a)}\right| P(D \geq d|S_a) d(S_a) \tag{1}$$

where $\left|\frac{d_\nu(S_a)}{d(S_a)}\right|$ is the derivative of the *seismic hazard curve* associated to the site where the structure is considered located and to its fundamental vibration period. A seismic hazard curve represents the average number of occurrences of an event that exceeds per unit of time a certain level of intensity. $P(D \geq d|S_a)$ is the conditional probability that the structural demand of interest, D, exceeds certain specified value d, for a given intensity S_a. In this study the *global ductility demand of the systems (μ)* is selected as structural demand of interest.

3.2. General steps

Next, the steps involved in the proposed methodology are described.

(1) First, several nonlinear time history analyses were carried out for systems with different characteristics of base-shear coefficient (c), tilting angle (α), and vibration period (T_1), with the aim to obtain the structural demand as a function of the seismic intensity.

(2) Next, the median ($\widehat{D}$) and standard deviation ($\sigma_{ln\widehat{D}}$) of the ductility demand logarithm are calculated.

(3) Vulnerability curves for several values of the global ductility demand are obtained, using Eq. (2):

$$P(D \geq d|S_a) = 1 - \Phi\left(\frac{ln\left(d/_{\hat{D}}\right)}{\sigma_{ln\hat{D}}}\right)$$
(2)

(4) The *ductility demand hazard curves (DDHC)* are calculated using Eq. (1). Ductility demand hazard curves are obtained for symmetric systems, and alternatively, systems with different levels of asymmetric yielding.

(5) With the ductility demand hazard curves for systems with a wide variety of characteristics, *ductility uniform exceedance rate spectra* (*μ-UERS*) are obtained for several annual rate of exceedance values. In order to explicitly display the increment in the expected ductility demand of asymmetric yielding systems with respect to symmetric systems, ratios of *μ-UERS* corresponding to asymmetric yielding systems with respect to symmetric systems are calculated.

(6) The next step in the proposed methodology is to obtain *base-shear coefficient uniform exceedance rate spectra* (*c-UERS*) for symmetric and asymmetric yielding systems. In addition, ratios between *c-UERS* of systems with different levels of asymmetric yielding with respect to symmetric systems are calculated.

(7) A simplified mathematical expression is fitted to the ratios of the base shear coefficient spectra obtained in step 6. The least square method is used for this purpose. The proposed expression is function of the tilting of the systems, the ratio of the fundamental vibration period of the system to that of the soil, and the ductility demand of the system. The expression is compared with those existing in the literature, and its advantages and disadvantages are discussed.

4. Structural Models

Tridimensional structural systems are used in this work to study the aspects mentioned before. The systems have a SDOF in each horizontal direction. All the mass of the systems is lumped at the center of mass of the deck. Systems are symmetric in both geometry and strength. The hysteretic behavior of the structural members is considered as elasto-plastic. The soil-structure interaction was taken into account by means of springs attached to the bottom of the columns. The plan and elevation of the structural systems are shown in Figs. 1a and 1b. It is noted that the systems studied in this work are not essentially SDOF systems since axial forces can be developed in columns under the seismic excitation. The asymmetric yielding (i.e. tilting angle) is characterized by means of the parameter α, as shown in Fig. 1c. The tilting angle is considered to occur by a differential settlement in only two columns (i.e., columns 1 and 2 in Fig. 1a) which causes tilting in only one direction. Because of this, the yield strength of the systems in the direction of tilting becomes smaller than in the opposite direction, leading to an asymmetric yielding behavior of its structural members (see Fig. 1d).

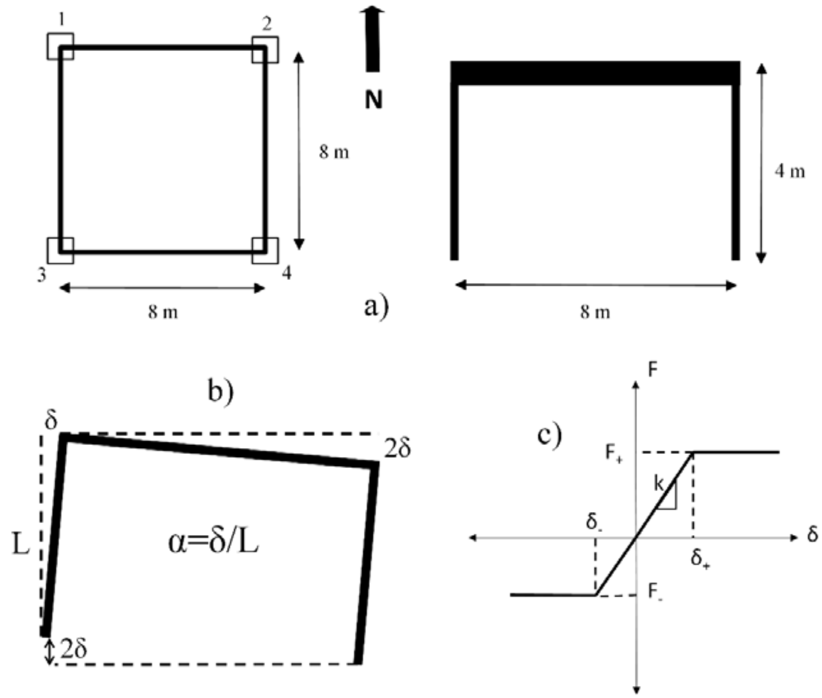


Fig. 1. Characteristics of the simplified structural systems: a) Plan and elevation, b) definition of the parameter α, and c) asymmetric force-displacement relationship.

When buildings are subjected to monotonically increasing lateral deformation, the strain hardening and the gradual yield of its structural members produce a positive post-elastic slope when the second order effects (P-Δ) are neglected. However, when the analysis considers the secondary moments produced by the gravity loads, such effects tend to counteract the strain hardening and the gradual yield, leading to a post-elastic slope close to zero for deformations in the range of interest [3]. For this reason, the second order effects in this study are implicitly considered by assigning a post-elastic slope equal to zero in the hysteretic behavior of the structural members. It is important to consider that this assumption is valid only for structures which exhibit moderate P-Δ effects. The study of structures with excessive P-Δ effects that may produce a negative post-elastic slope is out of the scope of this work.

5. Seismic Records

Thirteen pairs of seismic ground motions corresponding to earthquakes with magnitude $M \geq 6.9$ and recorded in different stations of the Mexico City soft soil with dominant periods between 1.25 and 1.74s were selected for the analysis. Their characteristics are presented in Table 1. The mean of the dominant periods for both components is ≈1.4 s (see Table 1). The dominant period of each record is defined as the period where the pseudo-acceleration reaches its maximum. The seismic records are scaled in terms of the spectral acceleration at the fundamental vibration period of the structure, using the *quadratic mean*, as show in Eq. (3):

$$S_a = \sqrt{\frac{S_{aEW}^2 + S_{aNS}^2}{2}} \quad (3)$$

where S_{aEW} and S_{aNS}, are the pseudo-accelerations of the elastic response spectra associated to the fundamental vibration period of the system under consideration, for 5% of critical damping, corresponding to E-W and N-S directions, respectively.

Table 1. Characteristics of the seismic ground motions

Event	Date	Magnitude	Epicenter coordinates	PGA	Dominant period, T_s

					(m/s^2)	(s)	
			Lat. *N*	Long. *W*		Component	
						E-W	N-S
1	95/09/14	7.3	16.31	98.88	0.311	1.74	1.58
2	97/01/11	6.9	17.90	103.00	0.164	1.70	1.54
3	97/01/11	6.9	17.91	103.04	0.199	1.32	1.28
4	89/04/25	6.9	16.60	99.40	0.554	1.25	1.19
5	95/09/14	7.3	16.31	98.88	0.373	1.29	1.38
6	89/04/25	6.9	16.60	99.40	0.397	1.29	1.38
7	89/04/25	6.9	16.60	99.40	0.239	1.35	1.41
8	95/09/14	7.3	16.31	98.88	0.287	1.57	1.40
9	95/09/14	7.3	16.31	98.88	0.278	1.34	1.42
10	97/01/11	6.9	17.90	103.00	0.130	1.35	1.35
11	97/01/11	6.9	17.91	103.04	0.260	1.36	1.48
12	95/09/14	7.3	16.31	98.88	0.287	1.45	1.28
13	97/01/11	6.9	17.91	103.04	0.175	1.26	1.27
					Mean	**1.41**	**1.38**

6. Discussion of the results

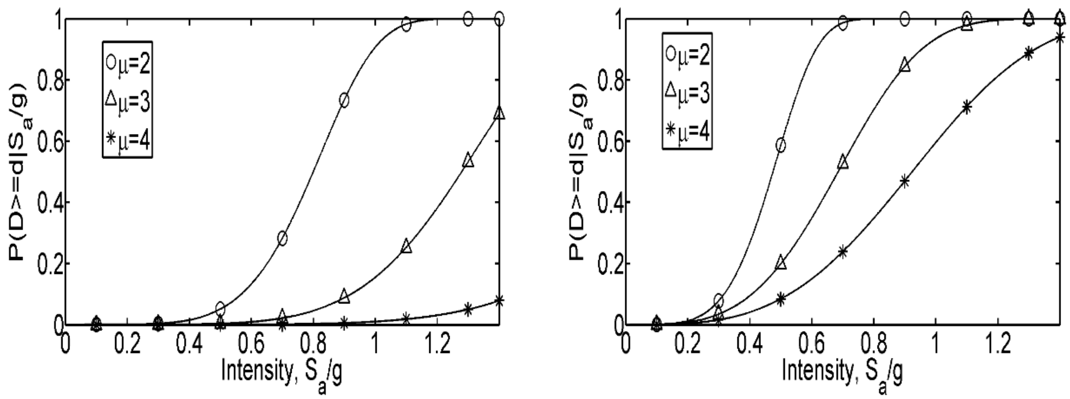
In this section, all the steps involved in the proposed methodology (mentioned in Section 3.2) are applied to structural systems with different levels of asymmetric yielding. As mentioned above, the global ductility demand of the systems is taken as structural demand of interest. The ductility in each horizontal direction (μ_x, μ_y) is obtained as the maximum horizontal displacement of the center of mass of the structural systems in E-W (x) and N-S (y) directions when they are subjected to both horizontal components of the seismic ground motions acting simultaneously, divided by their yield displacement, d_{yield}. Thus, the global ductility demand of the systems is obtained as:

$$\mu = \max(\mu_x, \mu_y) \tag{4}$$

where μ_x and μ_y are the ductility demands calculated in the x *(E-W)* and y (N-S) directions, respectively.

6.1 Vulnerability curves

In order to obtain the vulnerability curves for systems with different characteristics of asymmetric yielding, lateral strength and vibration period, it is necessary to perform several nonlinear time history analyses to estimate their global ductility demand as a function of the seismic intensity. With the data, it is possible to estimate the median and standard deviation of the ductility demand logarithms. Next, the vulnerability curves for values of the global ductility demand equal to 2, 3 and 4, are calculated using Eq. (2). The results are presented only for systems corresponding to c = 0.30 and T_1=1.5 s; however, a wide range base-shear coefficients and vibration periods were considered. The vulnerability curves corresponding to a symmetric system and to an asymmetric yielding system with α = 0.02, are presented in Figs. 2a and 2b, respectively. It is observed that the conditional probability of exceeding a certain value of the global ductility demand is much higher for the asymmetric yielding system than for the symmetric one. This indicates that the effect of asymmetric yielding leads to an inferior seismic performance of the structural systems in comparison with that of the symmetric systems.

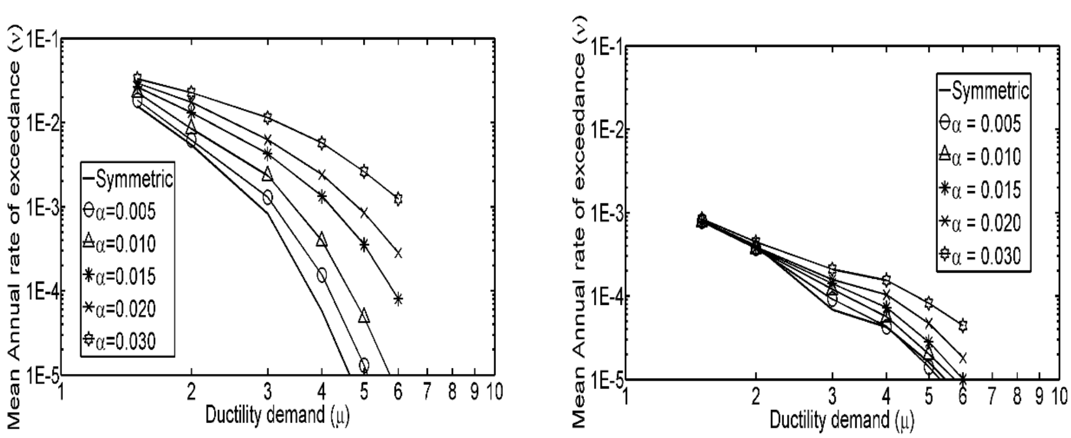


a) Symmetric system b) Asymmetric yielding system with α=0.020

Fig. 2. Vulnerability curves for systems with different levels of asymmetric yielding.

6.2 Ductility Demand Hazard Curves (*DDHC*)

The next step in the proposed methodology is to obtain ductility demand hazard curves for systems with different values of α, using Eq. (1). The ductility demand hazard curves (*DDHC)* show the influence of the asymmetric yielding in the annual rate of exceedance of the global ductility demand of the systems. In addition, *DDHC* are calculated for systems with different vibration period values, with the objective to analyze the influence of the ratio of the vibration period of the system to that of the soil (T_1/T_s) in the expected ductility demand of the systems. Fig. 3a shows the *DDHC* for systems with different values of α and T_1=1.5 s, and Fig. 3b shows the *DDHC* for systems with the same values of α, and T_1=2.2 s. It is shown in Fig. 3 that the expected global ductility demand is higher as the level of asymmetric yielding increases, also it can be seen that the increment is more significant for systems with vibration period close to the soil dominant period. For example, for the system with T_1=1.5 s (Fig. 3a), and for the annual rate of exceedance values equal to 0.008, 0.004, 0.002, and 0.001 (which correspond to return periods T_r = 125, 250, 500, and 1000 years, respectively), the expected ductility demands of asymmetric yielding systems are much higher than those corresponding to the symmetric systems. On the other hand, for the system with vibration period away from the dominant period of the soil (Fig. 3b), the expected ductility demand is similar, no matter the level of yielding asymmetry of the system, for all the values of ν considered. This indicates that the effect of asymmetric yielding is more important for systems with vibration period close to the dominant period of the soil, and it is almost negligible for systems with vibration periods away of it.

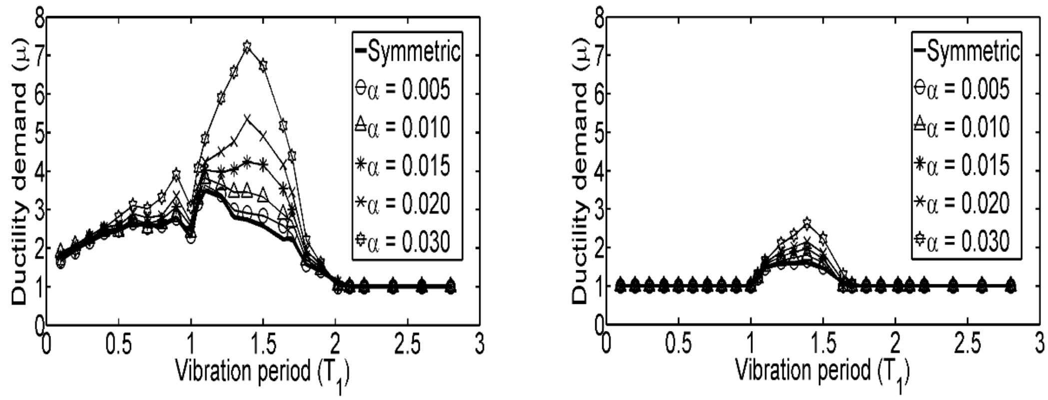


a) T_1=1.5 s b) T_1=2.2 s

Fig. 3. Ductility demand hazard curves for systems with different levels of asymmetric yielding and vibration period.

6.3. Ductility Uniform Exceedance Rate Spectra (*μ-UERS*)

Once the *DDHCs* are obtained for all the range of base shear coefficient of the systems, *μ-UERS* curves are calculated for several values of the mean annual rate of exceedance. This is in order to study the influence of asymmetric yielding on the seismic behavior of systems with different strength. Also, these curves allow to explicitly visualize the increment in the expected ductility demand of systems with different levels of asymmetric yielding. Figs. 4a and 4b show the *μ-UERS* corresponding to systems with different strength (c=0.20 and c=0.40) and ν=0.008 (which corresponds to a return period of 125 years). It is observed from Fig. 4 that the expected ductility demand is higher as the value of α increases. Also, such increment is more noticeable for systems with a low strength and vibration period close to the dominant period of the soil (which in this case is ≈ 1.4 s).



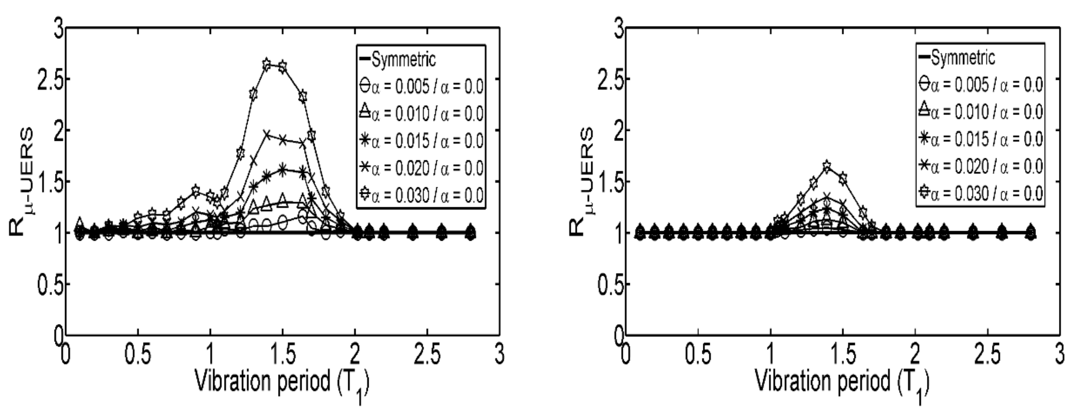
a) c = 0.20 b) c = 0.40

Fig. 4. Ductility uniform exceedance rate spectra for systems with different lateral strength.

In order to explicitly display this increment, ratios of *μ-UERS* corresponding to asymmetric yielding systems to those of symmetric systems are required; these are calculated as follows:

$$R_{\mu-UERS} = \frac{\mu[\mu-UERS(T_1,\nu,\alpha)]}{\mu[\mu-UERS(T_1,\nu,\alpha=0)]} \tag{5}$$

The values of the parameter $R_{\mu\text{-}UERS}$ for the same cases shown in Fig. 4 are presented in Fig. 5. It is observed that the increment in the expected ductility demand is much higher for the system with lower strength (Fig. 5a). For example, the maximum increment for the system with c=0.20 is about 170% while for the system with c=0.40 is only about 70%, which represents a significant difference. As commented above, the increment is more important in the range of systems with vibration period close to the soil dominant period. This behavior shows that the effect of asymmetric yielding is particularly detrimental for systems with low lateral strength and vibration period close to the dominant period of the soil.



a) c = 0.20 b) c = 0.40

Fig. 5. Values of the parameter $R_{\mu\text{-}UERS}$ corresponding to systems with different strength.

6.4. Base Shear Coefficient Spectra (*BSCS*)

From the results presented above, it is obvious that a structure with asymmetric yielding requires an additional lateral strength than a symmetric structure to achieve a similar seismic performance in terms of the expected global ductility demand. Thus, it is necessary to define strength amplification factors (*AF*) for this type of structures. In order to estimate the *AF*, *BSCS* needs to be obtained from the μ-*UERS* corresponding to systems with different levels of asymmetric yielding. An interpolative procedure was developed for this purpose (Valenzuela-Beltrán et al., 2016 [15]).

BSCS associated to ductility demands of 2, 3, and 4 are shown in Figs. 6a to 6c. Only the results for ν=0.008 are presented, because the increment in the ductility demand of systems with asymmetric yielding with respect to symmetric systems is independent of the mean annual rate of exceedance value [15]. It can be observed from Fig. 6 that, consistent with the results presented before, the strength requirement of systems with asymmetric yielding is more important for systems with vibration period close to the dominant period of the soil; furthermore, this strength requirement is higher as the μ increases. To explicitly show the lateral strength requirement of the systems, ratios of *c-UERS* corresponding to systems with asymmetric yielding to those of symmetric systems, are calculated. These ratios are denoted as R_{BSCS} and are obtained in a similar way that the parameter $R_{\mu\text{-}UERS}$ (see Eq. (5)), the only difference is that the ratios are calculated from *BSCS* instead μ-*UERS*. The calculated values of the parameter R_{BSCS} are shown in Fig. 7. It is noticed in the figure that the R_{BSCS} values depend significantly on the following parameters: the vibration period of the system, the α values, and the ductility demand. The maximum values of R_{BSCS} vary from 1.6 to 2.5, for ductility demands of 2 and 4, respectively.

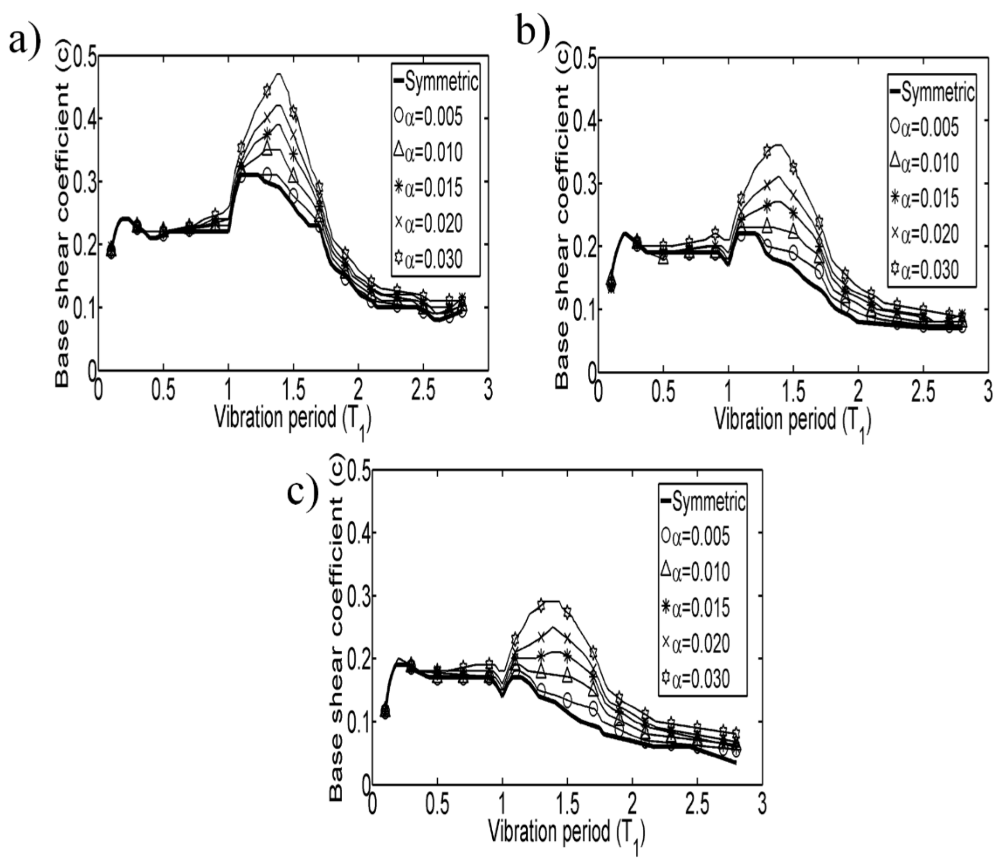


Fig.6. *BSCS* for systems with ductility demand of: a) μ = 2, b) μ = 3, c) μ = 4.

6.5. Simplified Mathematical Expression

From the data depicted in Fig. 7, a simplified mathematical expression to estimate the strength amplification factors was fitted using the *least square method*. The expression depends on several factors such: tilting angle (α), ductility demand of the systems (μ), and the ratio of the fundamental vibration period of the system to the dominant period of the soil (T_1/T_s). The general form of the proposed expression is that of Eq. (6), and the corresponding values of the parameters involved are summarized in Table 2.

$$AF = \begin{cases} a\left(\frac{T_1}{T_s}\right)^b + c & if\ \frac{T_1}{T_s} \leq 1 \\ e + (d-e)\left(\frac{T_1}{T_s}\right)^{-f} & if\ \frac{T_1}{T_s} > 1 \end{cases}$$

(6)

Table 2. Values of the parameters in Eq. (6)

a	$\alpha\ (16\mu - 9)$
b	$2 + 0.5\mu$
c	$1 + \alpha$
d	$a + c$
e	$7\alpha + 1$
f	3

As it can be seen in Fig. 8, the proposed expression fits properly the R_{BSCS} data (Fig. 7). It must be noted that the values of the parameters involved in Eq. (6) could be more complex by including a greater number of parameters; however, the authors consider that the proposed expression relies in the context of practical seismic design, and leads to sufficiently accurate results.

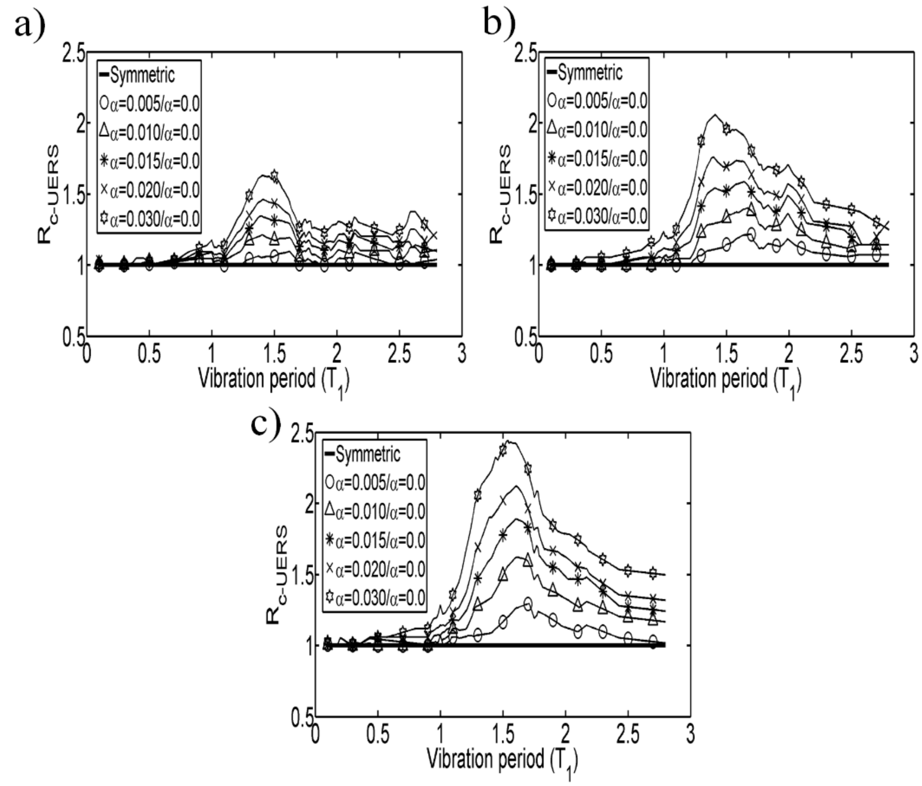


Fig. 7. R_{BSCS} for systems with ductility demands of: a) μ = 2, b) μ = 3, c) μ = 4.

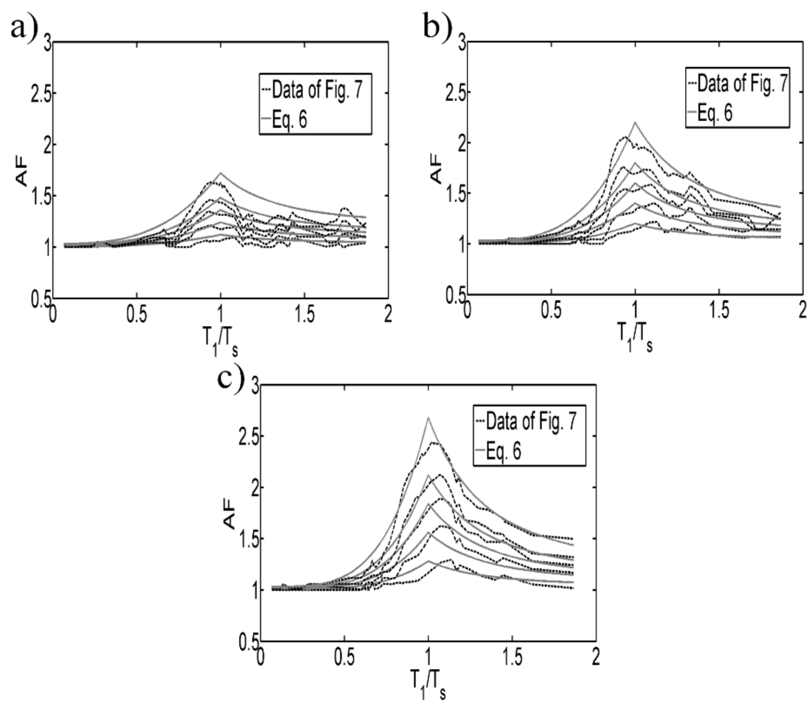


Fig. 8. Fitting of Eq. (6) for systems with: a) μ = 2, b) μ = 3, c) μ = 4.

6.6. Comparison of the Mathematical Expression with that specified in Mexico City Building Code (2004)

In Fig. 9, the proposed mathematical expression (Eq. (6)) is compared with that recommended by the *Mexico City Building Code* (MCBC-2004)[16]. The comparison is made for a wide range of ratios of T_1/T_s, considering several values of μ, and $\alpha=0.02$. Figure 9 shows that the expression given by the *MCBC-2004* leads to conservative results for a wide range of ratios of T_1/T_s; however, there is an important underestimation of the strength amplification factor in the range of $0.8 < T_1/T_s < 1.5$ compared with the expression proposed in this study. The differences are because the expressions proposed in this study were obtained from a reliability-based study, while the expression recommended by *MCBC-2004* was derived from a constant ductility criteria and engineering judgment.

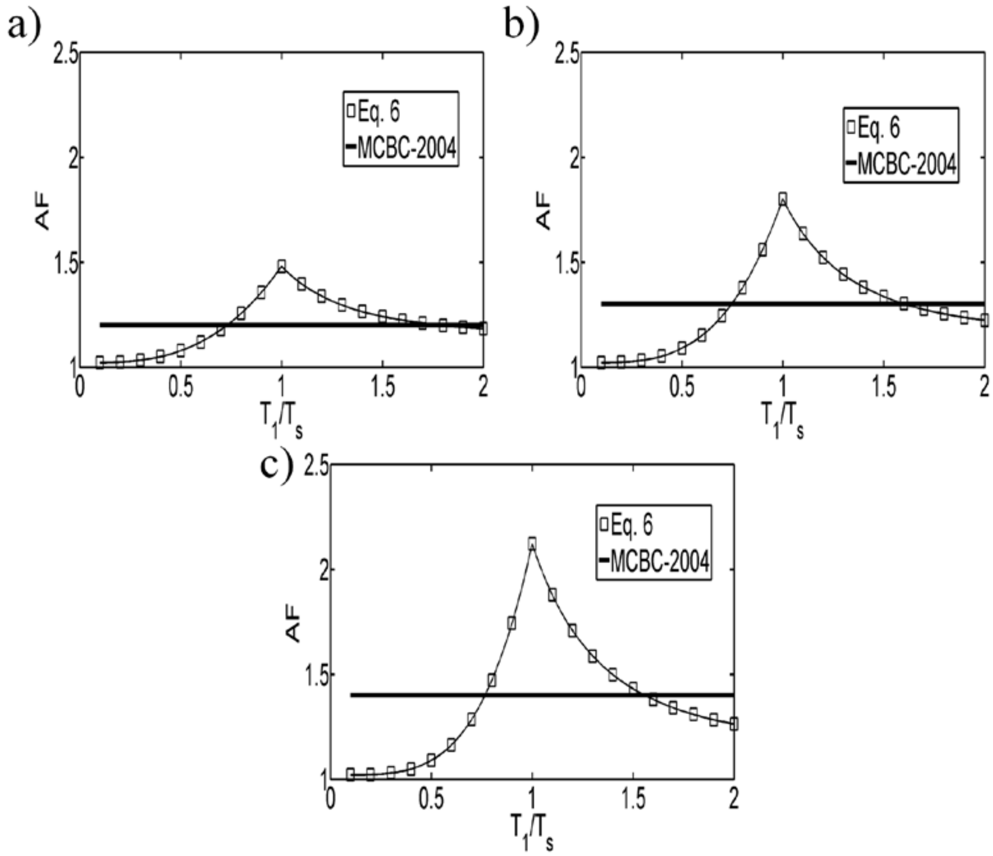


Fig. 9. Comparison of Eq. (6) with that recommended in MCBC-2004 for: a) μ = 2, b) μ = 3, c) μ = 4, assuming α=0.02.

7. Conclusions

A reliability-based methodology is proposed to estimate strength amplification factors for structures with asymmetric yielding produced by tilting. The approach involves the calculation of ductility demand hazard curves of simplified structural systems with different levels of asymmetric yielding. A simplified mathematical expression that depends on several factors such as: tilting angle, ductility of the structure, fundamental vibration period of the structure and dominant period of the soil, was developed. The main conclusions of the study are:

1) The expected global ductility demand of systems with asymmetric yielding may be much higher than that corresponding to symmetric systems. The increment depends on factors such as the strength of the system, and the ratio of the fundamental vibration period of the structure to that of the soil.

2) The detrimental effect of asymmetric yielding is more harmful for systems that meet three characteristics: a low lateral strength, vibration period close to the dominant period of the soil, and high ductility.

3) The strength amplification factor recommended in the Mexico City Building Code (MCBC-2004) leads to non-conservative results for structures with vibration period close to the dominant period of the soil. It was recommended to take it into account in the next version of the *MCBC*, which is now under revision.

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9. Copyright

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