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# Behavior of in plan irregular buildings subjected to bi-directional ground motions

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ABSTRACT: In the paper the authors apply to mass eccentric systems subjected to bi-directional ground motions a design approach, already presented with reference to mass and stiffness eccentric systems subjected to uni-directional seismic excitations. The proposed procedure, aiming to reduce the damage level in asymmetric systems, evaluates the strength of the resisting elements by means of a double application of the multi-modal analysis. The numerical tests are carried out using thirty pairs of artificial accelerograms consistent with the elastic response spectrum proposed by Eurocode 8 for hard layer soil. The principal seismic component, acting along the asymmetry direction, is scaled at a 0.35 g peak ground acceleration while the orthogonal one is scaled at peak ground accelerations ranging from 0 to 0.35 g. In order to understand the inelastic structural behavior of asymmetric systems subjected to bi-directional seismic excitations and to verify the proposed design procedure, the parametric analysis involves wide ranges of structural eccentricity, torsional to lateral uncoupled frequency ratio, uncoupled lateral period of vibration and behavior factor.

## 1 INTRODUCTION

In the past a large number of studies on the elastic behavior of asymmetric systems highlighted the change of the structural response on varying the dynamic properties of systems (Hejal & Chopra 1987). This allowed to evaluate the modifications to adopt in the phase of design when using the static analysis in order to fit the actual elastic structural response (Calderoni, Ghersi & Mazzolani 1994). While the elastic response depends only on few global parameters, the inelastic structural response depends on other parameters too, like the global strength, its distribution between the resisting elements and the location of the elements as well (Goel & Chopra 1990). The large number of parameters which in different way might influence the inelastic structural response has delayed the understanding of the seismic behavior of asymmetric structures stressed well into the inelastic range. Elastic design analyses have been proved to be ineffective in predicting the actual inelastic displacements if no change is brought about the application of static or multi-modal analyses (Rossi 1998). An incorrect evaluation of the design displacements of asymmetric systems subjected to ground motions can lead to undesired structural responses in occurrence of either long or short return period earthquakes. While in-depth studies have been carried out on the behavior of asymmetric buildings designed with static analysis without any improvement in the standard application of the design analysis, not the same attention has been paid on the research of a correct design procedure that modifies the traditional application of the design analysis, either static or multi-modal, in order to reduce the damage level of asymmetric systems, characterized by different geometric, dynamic and mechanic properties, to that of the corresponding balanced systems, i.e. of systems having equal positions of mass and stiffness centers. Furthermore quite all the efforts produced in modifying the standard application of the design analysis consider the static one as design analysis. In order to comply with the dual level approach (Uang 1993, Goel & Chopra 1994) the designer has to modify twice the application of the static analysis: once to fit the elastic behavior and the second time to fit the inelastic behavior. Indeed, the static analysis never matches acceptably the actual elastic response of asymmetric structures because it does not consider at all the role of higher modes of vibration. Their influence is remarkably significant in torsionally flexible structures, either at the flexible or at the rigid edge, where static and actual elastic response are in evident contrast, and is not negligible in torsionally rigid structures in which the application of the static analysis requires an amplification of the design displacements of the flexible side in order to fit the dynamic amplification of the structural eccentricity (Rossi 1998). Although particular attention should be paid to the evaluation of the modal correlation coefficients (Falsone 1997), the multimodal analysis provides an accurate estimate of the actual elastic displacements.

Because of the inelastic behavior of asymmetric structures, more translational than the elastic one, either static and multi-modal analyses do not provide a precise evaluation of the inelastic response of asymmetric structures and therefore require corrections to their standard applications in the phase of design. The incorrect evaluation of the inelastic displacements of the asymmetric systems gives rise to different levels of plastic deformations between the resisting elements. This implies values of the ratio of the ductility demand of the resisting elements in unbalanced systems over that in balanced systems (normalized ductility demand) greater than unity in some parts of the structures and less than unity in others.

In previous papers the authors presented a design procedure that, with reference to multi-modal analysis, granted in all the elements of the asymmetric systems a control of the normalized ductility demand (Ghersi & Rossi 1997). The standard application of the multi-modal analysis is modified considering two positions of the mass center in the phase of design: at first the multi-modal analysis is applied considering the mass in its actual position while the second time the center of mass is displaced from its position towards the center of stiffness of a quantity, named *design eccentricity*, for which an analytical expression function of the properties that mostly govern the inelastic structural behavior has been proposed. The step-by-step analyses that led to the evaluation of the design eccentricity were carried out on asymmetric systems, either mass and stiffness eccentric systems (MES- SES), subjected to uni-directional ground motions. The proposed formulation has been further verified with reference to systems with generalized structural eccentricity (Rossi 1998), i.e. with positions of mass and stiffness centers both different from the geometric center, as in most of actual asymmetric structures.

This paper discusses the influence of the contemporary action of the two orthogonal horizontal components of the earthquake on the structural inelastic behavior. The analysis has been carried out with reference to thirty pairs of artificial accelerograms consistent with the elastic response spectrum proposed by the Eurocode 8 for hard layer soil (class A). While a value of 0.35 g has been fixed for the peak ground acceleration of the seismic component acting along the asymmetry direction, hereafter called *principal*, the orthogonal component, called *secondary*, has been scaled at different peak ground accelerations ranging from 0 to 0.35 g. The numerical analyses allow to verify both the influence of bi-directional ground motions on the ductility demand of asymmetric structures and the effectiveness of the proposed design procedure. Furthermore the study allows to establish the limits of the seismic intensity of the secondary horizontal component for which the proposed formulation of the design eccentricity provides an accurate and effective control of the ductility demand.

## 2 THE NUMERICAL MODEL

Asymmetric buildings have been schematized by means of idealized one story models having one symmetry axis. The deck, rectangular in shape ($29.50 \times 12.50$ m²), is rigid in its plane and supported by resisting elements having in-plane stiffness and strength only. The resisting elements are characterized by an elastic perfectly plastic behavior. The mass center and its radius of gyration $r_m$ (0.312 L) are assigned independently of the size and the shape of the deck supposing that the mass ($m$ = 1 t/m² in mean) can be non uniformly distributed in plan. The models have eight resisting elements in the principal direction and three resisting elements in the secondary direction (Fig.1).
An automatic procedure (Ghersi & Rossi 1997) allows to define structural systems having established torsional to lateral frequency ratios and fixed global torsional and lateral stiffness.

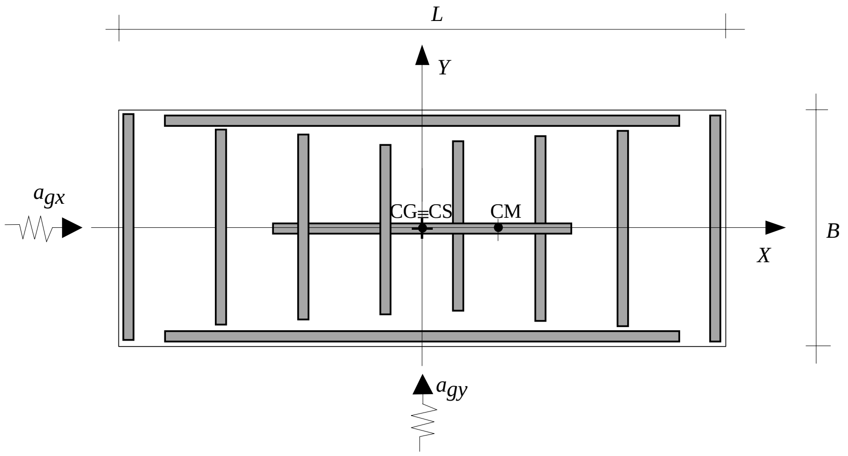


Figure 1. The numerical model

## 3 GROUND MOTIONS

In order to examine the seismic response of asymmetric systems to bi-directional accelerometric signals two uncorrelated (Penzien & Watabe 1975) sets of thirty accelerograms have been artificially generated (SIMQKE, Gasparini & Vanmarcke 1976) matching the elastic response spectrum proposed by Eurocode 8 for hard layer soil (class A) and characterized by a 5% damping coefficient. The target elastic response spectrum proposed by Eurocode 8 provides the maximum elastic response having a 50% uniform exceedence probability in 275 years.
The two horizontal seismic components are defined by:

$$\begin{aligned} a_{gx} &= \varsigma(t)\, b_x(t) \\ a_{gy} &= \varsigma(t)\, b_y(t) \end{aligned} \tag{1}$$

where $b_x$(t) e $b_y$(t) are stationary random processes and ζ(t) is a deterministic intensity function that gives appropriate non-stationarity to the ground motion process. The accelerograms $a_{gx}$ e $a_{gy}$ present a trapezoidal intensity function and are characterized by a duration of the strong motion phase of 22.5 s (Eurocode 8) and by starting and ending parts of 3 and 5 seconds respectively (Fig. 2). According to the rules of Eurocode 8, no value of the mean spectrum of each set of artificial accelerograms is more than 10% below the corresponding value of the code elastic response spectrum and the mean value of the maximum elastic responses of each set of artificial accelerograms in the constant acceleration region of the code elastic response spectrum is not smaller than the value of the spectral acceleration proposed by Eurocode 8 for the constant acceleration region of the elastic response spectrum.

## 4 THE DESIGN OF THE RESISTING ELEMENT STRENGTH

The strength of the resisting elements has been designed by using the multi-modal analysis with the above-mentioned EC8 elastic response spectrum reduced by a constant value of the behavior factor *q*. The proposed procedure for the design of asymmetric buildings implies a double application of the multi-modal analysis: once the analysis is carried out with reference to the nominal values of the mass and stiffness centers, while the second time the analysis is performed with reference to the location of the mass center displaced towards the stiffness center of a quantity $e_d$, named *design eccentricity*. The two elastic analyses aim to match the actual inelastic response under strong ground motions. Furthermore the first analysis with nominal values of the mass and stiffness centers

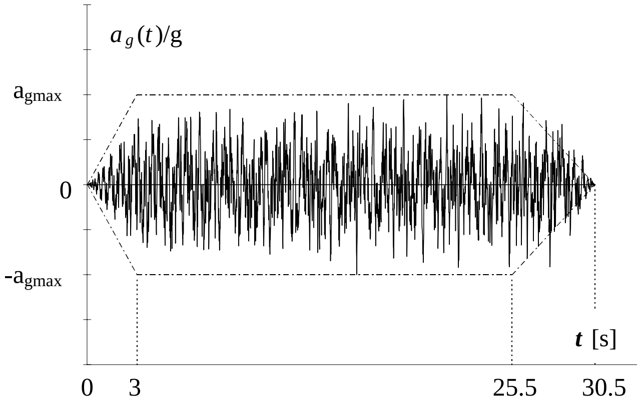


Figure 2. Artificial accelerogram

catches the elastic response of the asymmetric structures to earthquakes having short return period.

At the same time, aiming at a comparison between balanced and unbalanced torsionally structures, the corresponding torsionally balanced systems with coincident positions of mass and stiffness centers have been analyzed.

In a previous study, in order to evaluate the optimum values of the design eccentricity, the authors have considered mass and stiffness eccentric systems characterized by different values of the design parameters that govern the structural elastic and inelastic response. The numerical analyses have highlighted the influence of structural eccentricity $e_s$, torsional to lateral frequency ratio $\Omega_\theta$, lateral uncoupled period of vibration $T_y$ and behavior factor $q$ on the structural inelastic response. For each model a range of the design eccentricity $e_d$ from 0 to 1.5 $e_s$ has been closely examined. The maximum responses to a set of thirty accelerograms in terms of ductility demand, normalized to the corresponding values of the torsionally balanced systems, have been concisely taken into account by means of a gaussian density probability function of the normalized ductility demand having the same mean value and standard deviation of the experimental data. The optimum value of the design eccentricity has been obtained as the value of the design eccentricity that reduces to 1.3 the characteristic value of the gaussian density probability function of the normalised ductility demand. The proposed analytical expression of the design eccentricity linearly interpolates the experimental data, adapting to the variation that the design eccentricity presents because of different values of the design parameters. The optimum value of the design eccentricity also breaks down the value of the mean normalized ductility demand to values close to unity.

The proposed formulation of the design eccentricity, further verified with reference to generalized eccentric systems, having either mass and stiffness eccentricities different from the geometric center, depends on the torsional to lateral frequency ratio $\Omega_\theta$, the behavior factor $q$ and the structural eccentricity $e_s$:

$$e_d = k\,(e_s - e_r) \tag{1}$$

where:

$$k = \max \begin{cases} 3.3 - 2.5\,\Omega_\theta + 0.04\,q \\ 1 \end{cases} \qquad e_r = \max \begin{cases} 0.1\left(0.5\Omega_\theta - 0.4\right)L \\ 0.01\,L \end{cases} \tag{2}$$

When using bi-directional ground motions the strength of each resisting element has been obtained by combining the effects of the principal and secondary seismic components by means of the square root of the summation of squares formula (SRSS) (Wilson & Button 1982, Wilson et al. 1995, Reed & Kennedy 1996, Lopez & Torres 1996, Smeby & Der Kiureghian 1985) according to Eurocode 8. The total effect of the two components of the earthquake on the resisting element can be therefore calculated in the phase of design by the following expression:

$$E_E = \sqrt{E_{Edx}^2 + E_{Edy}^2} \tag{2}$$

where:

$E_E$ is the global effect

$E_{Edi}$ is the effect of the seismic component in the $i^{th}$ direction

When designing the strength of the elements in the secondary direction no design eccentricity has been considered in the orthogonal direction.

## 5 THE PARAMETRIC ANALYSIS

In order to understand the behavior of asymmetric systems subjected to bi-directional ground motions a parametric analysis involving broad ranges of the design parameters has been carried out. Owing to the similar behavior of mass and stiffness eccentric systems designed with multi-modal analysis with or without design eccentricity, in the present study only mass eccentric systems have been analyzed. The principal seismic component acting along the Y direction has been scaled to a 0.35 g value of the peak ground acceleration deemed to be representative of strong ground motion. The secondary seismic component, acting along the X direction, has been scaled to different values of the peak ground acceleration (0-0.25-0.50-0.75-1 $Pga_y$) in order to catch the influence on the structural inelastic response of different levels of seismic intensity of the secondary seismic component.

For the mass eccentric systems subjected to bi-directional ground motions the variation of the design parameters considered in the analysis is described below:

$$0 \le e_s \le 0.20\, L \tag{3}$$

$$0.6 \le \Omega_\theta \le 1.6 \tag{4}$$

$$0.4\ \text{s} \le T_y = T_x \le 2.0\ \text{s} \tag{5}$$

$$1 \le q \le 5 \tag{6}$$

$$0.001 \le \gamma_x \le 0.4 \tag{7}$$

where $\gamma_x$ is the ratio of the torsional stiffness of the elements in the secondary direction over the total torsional stiffness.

## 6 RESPONSE OF ASYMMETRIC SYSTEMS SUBJECTED TO BI-DIRECTIONAL GROUND MOTIONS

At first the authors have studied the effect of the secondary seismic component on the structural response of asymmetric systems characterized by different design parameters and designed by means of multi-modal analysis without any design eccentricity.

The analysis of the mean value of the damage parameter of each resisting element has allowed to examine the influence of different values of the intensity of the secondary components (0-0.25-0.50-0.75-1.00 $Pga_y$) on the inelastic response of each element of either flexible and rigid structures characterized by different values of the structural eccentricity.

Flexible torsionally systems ($\Omega_\theta$ <1) are negligibly influenced by the value of the intensity of the secondary seismic component (Fig.3). The mean normalized ductility demand of the resisting elements does not show remarkable variations, particularly for very low values of the torsional to lateral uncoupled frequency ratio. Only small increasing of the mean normalized ductility demand is noticeable, on increasing the intensity of the secondary seismic component, on the stiff side of torsionally flexible structures with torsional to lateral uncoupled frequency ratio close to one.

Rigid torsionally systems highlight a greater dependence on the value of the seismic intensity of the secondary excitation. On increasing the value of the seismic intensity of the secondary seismic component the maximum displacements increase on the flexible edge of the structures while they decrease on the rigid edge. Consequently, the mean normalized ductility demand of resisting elements at the flexible side of torsionally rigid systems increase on increasing the intensity of the secondary seismic component and reaches values close but not greater than unity. At the same time at the rigid side, where in uni-directional conditions of seismic excitation torsionally rigid structures sustain greater damages, the mean normalized ductility demand decreases.

The same analyses have been carried out with reference to mass eccentric systems designed by means of multi-modal analysis with different values of the design eccentricity.

The contemporary action of both horizontal seismic components does not change the effect of the design eccentricity on the inelastic response of torsionally flexible systems (Fig.4). Like in asymmetric systems subjected to uni-directional seismic excitation, the increasing of the design eccentricity provides a decreasing of the mean ductility demand in the flexible and central part of torsionally flexible structures. Slight increasing of the mean normalized ductility demand is highlighted, on increasing the value of the secondary seismic component intensity, at the rigid side of the systems, particularly for values of the torsional to lateral uncoupled frequency ratio close to unity.

Increasing values of the intensity of the secondary seismic component significantly modify the effect of the design eccentricity on the inelastic response of torsionally rigid systems. Indeed, design eccentricity being equal, the increasing of the intensity of the secondary seismic component significantly decreases the mean value of the normalized ductility demand on the rigid edge of the structures and increases it on the flexible edge to values always minor than unity.

Contemporarily, by analogy with the procedure adopted to analyze the inelastic response of asymmetric systems to uni-directional seismic excitations, the experimental values of the maximum normalized ductility demands achieved each one with reference to one pair of artificial seismic components independently of the resisting element that experiences the maximum value of the normalized ductility demand have been calculated. The mean and characteristic values of the gaussian density probability function having the same mean value and standard deviation of the experimental thirty maximum normalized ductility demands have been then analyzed.

In Figure 5 are shown the mean and characteristic values of the density probability function of the maximum normalized ductility demand for asymmetric systems with different values of the torsional to lateral uncoupled frequency ratio designed by means of multi-modal analysis without any design eccentricity. In torsionally flexible systems, on increasing the intensity of the secondary seismic component, different results are highlighted only for structures with low values of structural eccentricity, with greater values of the mean and characteristic values of the normalized ductility demand in correspondence of higher values of the intensity of the secondary seismic component. Quite equal values of the mean and characteristic values of the normalized ductility demand, on increasing the intensity of the secondary seismic component, are shown by higher values of the structural eccentricity.

Torsionally rigid structures are influenced more strongly by the intensity of the secondary seismic component; in a wide range of values of the structural eccentricity the increase of the intensity of the secondary seismic component produces greater values of the characteristic value of the normalized ductility demand. The mean value of the normalized ductility demand seems to be influenced less by the intensity of the secondary seismic component.

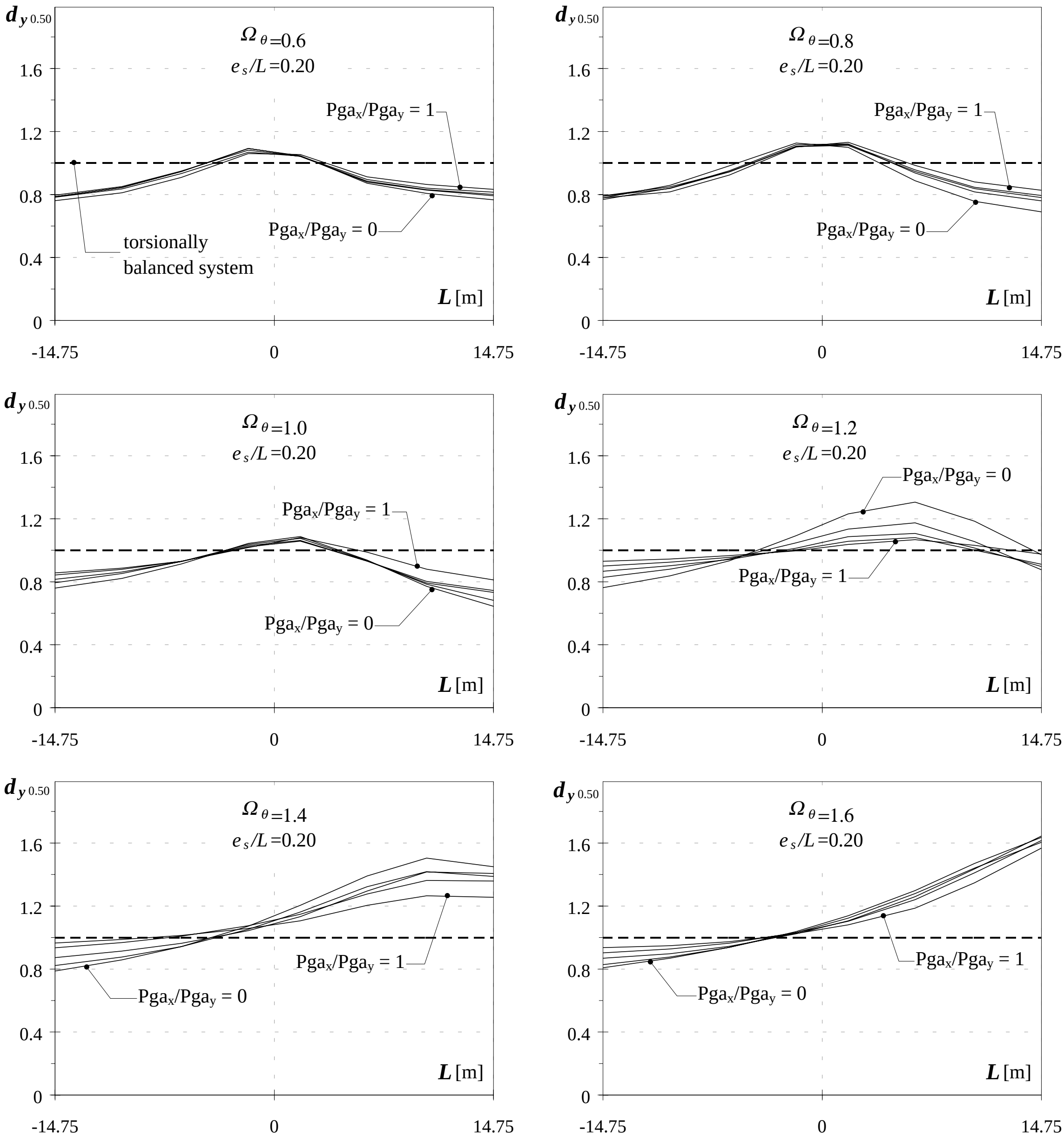


Figure 3 Mean normalized ductility demand in the principal direction of asymmetric models designed by means of multi-modal analysis without any design eccentricity for different values of the intensity of the secondary seismic component -$Pga_x$ = 0-0.25-0.50-0.75-1.00 $Pga_y$-
(design parameters: MES, $\Omega_\theta$ = variable, $T_y$ = 1 s, $\gamma_x$ = 0.2, $q$ = 5)

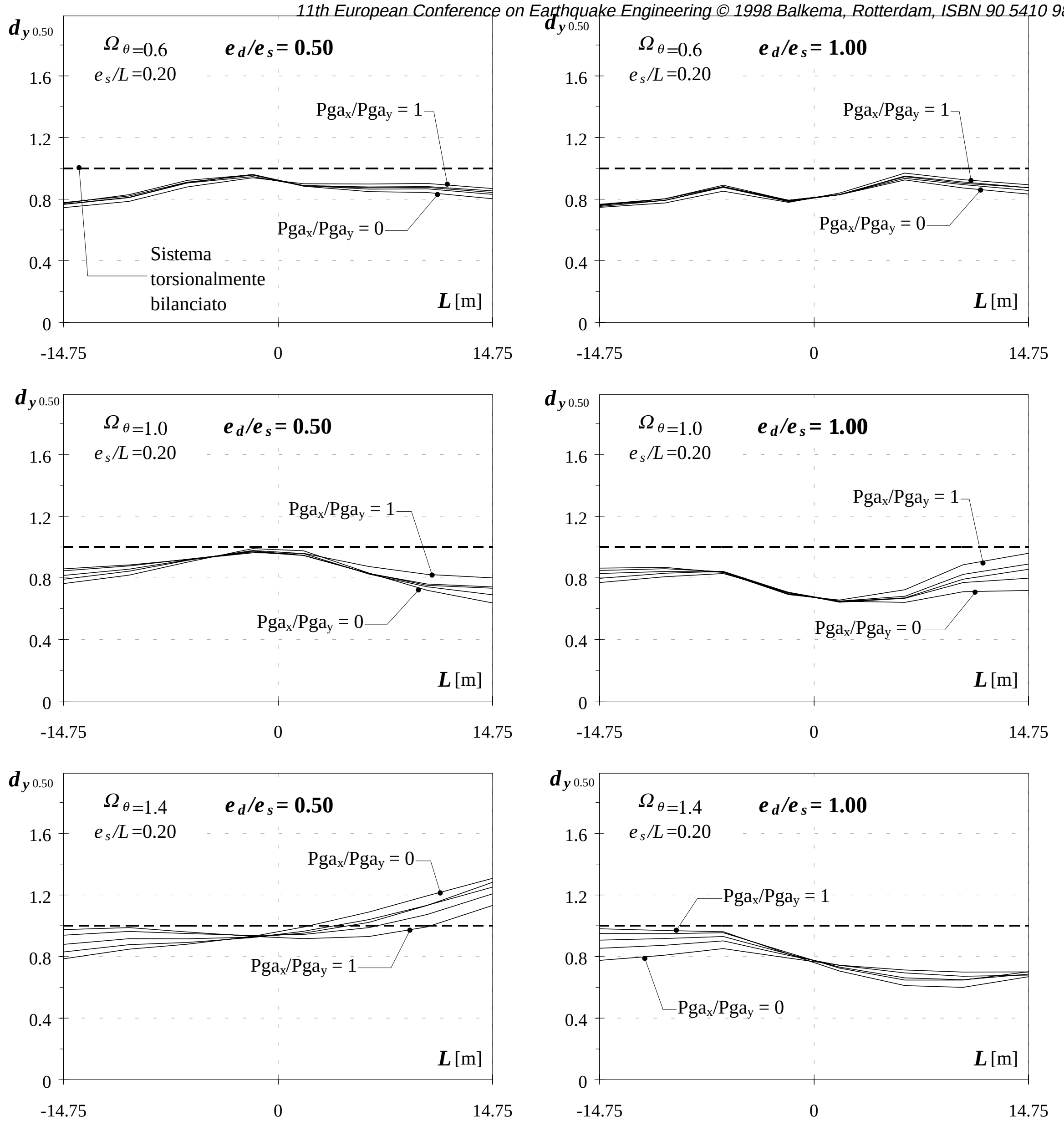


Figure 4 Mean normalized ductility demand in the principal direction of asymmetric models designed by means of multi-modal analysis with design eccentricity for different values of the intensity of the secondary seismic component -$Pga_x$ = 0-0.25-0.50-0.75-1.00 $Pga_y$-

(design parameters: MES, $\Omega_\theta$ = variable, $T_y$ = 1 s, $\gamma_x$ = 0.2, $q$ = 5)

In Figure 6 are shown the mean and characteristic values of the normalized ductility demand experienced by mass eccentric systems designed by means of the proposed procedure and having different values of the torsional to lateral uncoupled frequency ratio. In asymmetric systems characterized by low values of the torsional to lateral uncoupled frequency ratio ($\Omega_\theta$=0.6-0.8) the damage parameter shows slight differences between uni-directional and bi-directional seismic excitation. The inelastic response of systems with torsional to lateral uncoupled frequency ratio close to one highlights greater differences in terms of normalized ductility demand. Indeed, the mean and characteristic values of the normalized ductility demand increase on increasing the intensity of the secondary seismic component and the beneficial effect of the design eccentricity gradually disappears (Fig.5). Nevertheless the proposed design procedure seems to be still quite effective when considering as secondary seismic component a seismic excitation scaled at a half of the value of the design peak ground acceleration ($Pga_x$=0.5 $Pga_y$).

Finally, limited change of the damage is shown by torsionally rigid structures subjected to bi-directional seismic excitations with increasing values of the secondary seismic component.

## 7 CONCLUSIONS

The response of asymmetric structures designed with standard application of multi-modal analysis is differently influenced by the contemporary action of two horizontal seismic components according to their structural dynamic properties. The maximum normalized ductility demand of torsionally rigid structures seems to be more strongly influenced by the level of the intensity of the secondary seismic component. The mean normalized ductility demand of the flexible edge increases by increasing values of the intensity of the secondary seismic component but it never reaches the unity value while that of the rigid edge decreases by increasing the values of the intensity of the secondary seismic component. Minor effects have been shown by the response of torsionally flexible structures. A parametric analysis has been performed also on asymmetric structures designed with multi-modal analysis according to a proposed procedure that implies a double application of the multi-modal analysis. The proposed procedure that reduces the mean and characteristic values of the ductility demand has been already verified with reference to asymmetric systems subjected to uni-directional ground motions. When considering bi-directional seismic excitations quite unchanged appears the response in terms of maximum ductility demand of torsionally flexible structures while strongly modified is the response of structures with torsional to lateral uncoupled frequency ratio quite close to one. Indeed, the mean and characteristic values of the maximum ductility demand increase on increasing the intensity of the secondary seismic component. Nevertheless still acceptable seem the mean and characteristic values of damage of such structures subjected to secondary seismic components scaled at a half of the design peak ground acceleration.

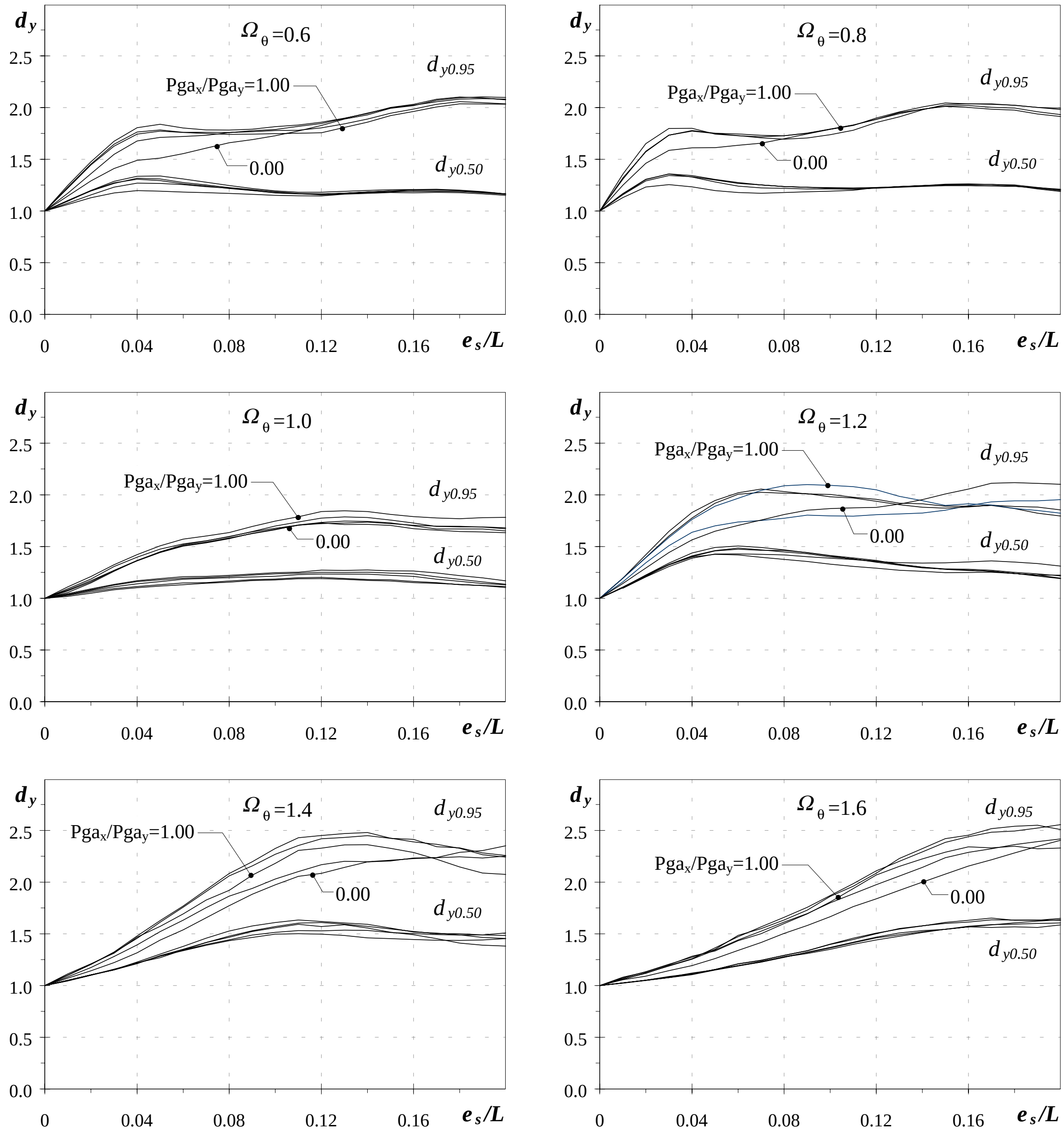


Figure 5 Mean normalized ductility demand in the principal direction of asymmetric models designed by means of multi-modal analysis without any design eccentricity for different values of the intensity of the secondary seismic component -$Pga_x$= 0-0.25-0.50-0.75-1.00 $Pga_y$-

(design parameters: MES, $\Omega_\theta$= variable, $T_y$ = 1 s, $\gamma_x$ = 0.2, $q$ = 5)

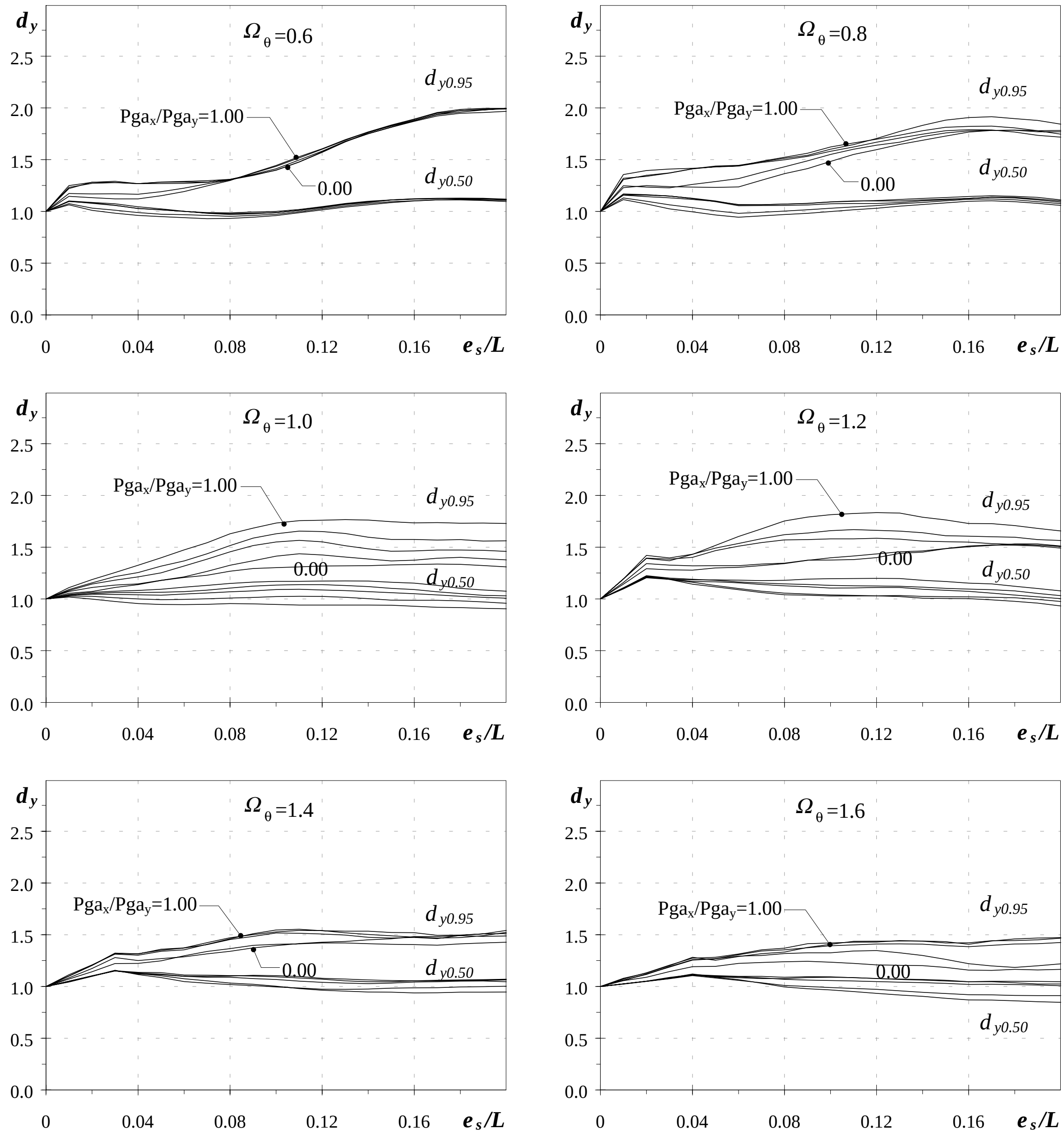


Figure 6 Mean normalized ductility demand in the principal direction of asymmetric models designed by means of multi-modal analysis with design eccentricity for different values of the intensity of the secondary seismic component-Pga$_x$ = 0-0.25-0.50-0.75-1.00 Pga$_y$-

(design parameters: MES, $\Omega_\theta$ = variable, $T_y$ = 1 s, $\gamma_x$ = 0.2, $q$ = 5)

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