SEISMIC RESPONSE OF MONO AND BI-ECCENTRIC IN-PLAN IRREGULAR SYSTEMS

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ABSTRACT

In the past mass and stiffness mono-eccentric models subjected to mono and bi-directional ground motions have been analysed by the Authors with reference to a set of thirty accelerograms matching in mean the elastic response spectrum proposed by Eurocode 8 for hard layer soil. A design procedure, aiming at complying the requirements of a dual-level approach, has been proposed and applied at first to mass and stiffness eccentric models and then to generalised eccentric systems, having both mass and stiffness centre locations different from that of the geometrical centre. The occurrence of bi-directional ground motions has been further considered as more realistic loading condition. In the present study the response of mass bi-eccentric systems subjected to mono and bi-directional ground motions is analysed at the aim of pointing out differences between behavioural characteristics of mono and bi-eccentric systems. Furthermore, a wide parametric analysis assists in defining the limits of validity of the design procedure proposed in the past by the Authors with reference to mono-eccentric systems.

INTRODUCTION

For a long time the seismic behaviour of asymmetric buildings has been analysed by means of idealised one-storey schemes. The adoption of such a model has provided researchers of a simplified tool by which qualitatively examine the aspects of the inelastic behaviour of these systems but it has been recently questioned if these results may be considered representative of the inelastic response of multi-storey structures. The ongoing research on multi-storey models has recently confirmed [8] the importance of these findings in the comprehension of the seismic behaviour of regularly asymmetric buildings designed according to the capacity design criterion. Such a result gives emphasis to past studies carried out on one-storey models and incites to further investigations in the awareness that observations and statements are no more representative of the inelastic response of one-storey systems but also indicative of the translational-torsional coupling of multi-storey buildings.

In the past, as many other researchers [13], also the Authors have analysed the seismic behaviour of asymmetric-plan systems by means of one-storey models. Their attention has focused in particular on the influence of the design criteria on the response

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of such structures. Static analysis has been found in some studies [7] less adequate than multi-modal analysis in limiting the ductility demands of asymmetric-plan systems; equally difficult has further resulted to be the correction necessary to match the elastic response. Conversely multi-modal analysis allows to correctly estimate the elastic response to seismic actions without relevant effort. Nevertheless, as static analysis, it needs some improvement in the application if a limited damage level is desired in occurrence of strong ground motions [6] [7]. A design procedure, aiming at satisfying the requirements of the dual level philosophy, has been presented by the Authors [6] based on a double application of multi-modal analysis: the first time with reference to mass and stiffness nominal positions, the second time with the mass centre displaced towards the stiffness centre of a quantity named *design eccentricity*. The first application of the multi-modal analysis provides a correct evaluation of the elastic response in occurrence of low intensity earthquakes while the second one, by means of a proper formulation of the design eccentricity, reduces the damage level to the values of the corresponding balanced systems. The proposed procedure has been firstly verified with reference to mass and stiffness mono-eccentric systems [6] then to generalised eccentric systems [11], characterised by the contemporary presence of both mass and stiffness eccentricity, subjected to mono-directional accelerograms. An extensive parametric analysis has been carried out involving both torsionally flexible and rigid structures having low and high structural eccentricity.

The attention given by some researchers [2] [3] to the occurrence of bi-directional seismic excitations has then influenced the following work on this topic. The parametric analysis is extended so as to show the effect of the secondary seismic component on the damage distribution and level in asymmetric-plan systems [5]. The results of the numerical analyses point out that the application of the suggested design procedure in combination with the rule proposed by Eurocode 8 [4], which estimates the maximum value of each action effect on the structure by the square of the sum of the squared responses to each horizontal component, limit the ductility demands of both longitudinal and transversal resisting elements to the targeted values even for secondary seismic components having peak ground acceleration equal to 75% of that of the main component.

As proposed by some other authors [1] [9] the analysis of the response has been completed in terms of energy quantities and energy dissipation ductility demands. The study has shown for torsionally flexible and rigid systems with low or high structural eccentricity the distribution of the normalised energy ductility demands and the adequacy of the proposed formulation to reduce the damaging effects due to the accumulation of the hysteretic energy. Some other damage parameters (Park and Ang index, low cycle fatigue equivalent ductility index), depending implicitly or explicitly on the maximum and accumulated ductility demands have confirmed the good results obtained with reference to both displacement and hysteretic energy ductility [10].

The present paper analyses the influence of the design criteria on bi-eccentric one-storey systems subjected to mono and bi-directional accelerograms. Are herein discussed the behavioural aspects characteristic of such models and the effectiveness of the proposed design procedure in decreasing the ductility level to that of the corresponding balanced systems. Is finally examined the importance of a specific design rule suggested by Eurocode 8 to define the strength of the resisting elements in systems subjected to two horizontal seismic components.

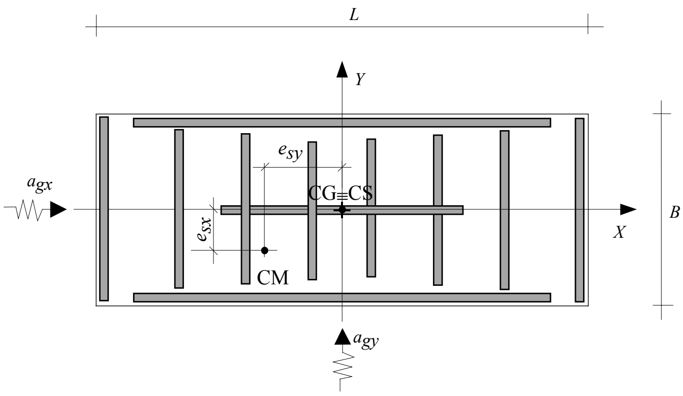


Figure 1. The numerical model

NUMERICAL MODEL

Asymmetric buildings have been schematised by means of an idealised one-storey model having one symmetry axis. The deck, rectangular in shape (29.50 × 12.50 m), is rigid in its plane and supported by resisting elements having in-plane stiffness and strength only. The resisting elements are characterised by an elastic perfectly plastic behaviour. The mass centre 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 model has eight resisting elements in the principal direction and three resisting elements in the secondary direction (Fig. 1). An automatic procedure [6] allows to define structural systems having established torsional to lateral frequency ratios and fixed global torsional and lateral stiffness.

A wide range of structural parameters has been considered in the numerical analyses. In order to investigate both torsionally flexible and rigid structures with low and high structural eccentricity, the uncoupled lateral-torsional frequency ratio Ω_θ has been varied from 0.6 to 1.4 while the structural eccentricity e_s, both in the longitudinal and transversal directions, has been considered ranging from 0 to 0.20 L. The uncoupled lateral periods of vibration T_x and T_y have been assumed equal to 1 s while the ratio γ_x of the torsional stiffness due to the elements along the x-axis to the total torsional stiffness has been fixed to 0.2. Only mass eccentric systems have been analysed in this study because stiffness eccentric systems have shown in the past similar behaviour [11].

GROUND MOTIONS

In order to examine the seismic response of asymmetric systems to bi-directional accelerometric signals two uncorrelated sets of thirty accelerograms have been artificially generated [14] matching the elastic response spectrum proposed by Eurocode 8 for hard layer soil (class A) and characterised by a 5% damping coefficient. The accelerograms are scaled to a peak ground acceleration equal to 0.35 g and enveloped by a trapezoidal intensity function characterised by a duration of the strong motion phase of

22.5 s and by starting and ending parts of 3 and 5 seconds respectively. According to 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.

DESIGN CRITERIA

The strength of the resisting elements along x and y-direction has been firstly assigned by means of separate analyses and, in a second time, combining the effects of horizontal actions along x and y-axis according to the rule proposed by Eurocode 8 (design value of displacements or internal actions estimated as the sum of the squared responses to the two components, later on called as SRSS rule in short).

The effect of each seismic component has been accounted in different ways: by means of a standard application of multi-modal analysis and according to the design approach proposed by Ghersi and Rossi [6]. This one involves a double application of the multi-modal analysis in which modal contributions are combined according the complete quadratic combination rule; the first analysis is carried out with reference to the nominal locations of the mass and stiffness centres, while the second one it is performed with reference to the location of the mass centre displaced towards the stiffness centre of a quantity named *design eccentricity*; the envelope of the results of the two multi-modal analyses defines the strength of the resisting elements. Two values of design eccentricity have been separately considered: a value equal to the structural eccentricity, which makes the second analysis to be a translational one (as suggested by Uniform Building Code); the value provided by the formulation proposed by Ghersi and Rossi [6] depending on structural and design parameters:

$$e_d = \max \begin{cases} \mathrm{k}\,(e_s - e_r) \\ 0.6\, e_s \end{cases} \tag{1}$$

where:

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

No accidental eccentricity has been taken into account both in the design and in the numerical analyses.

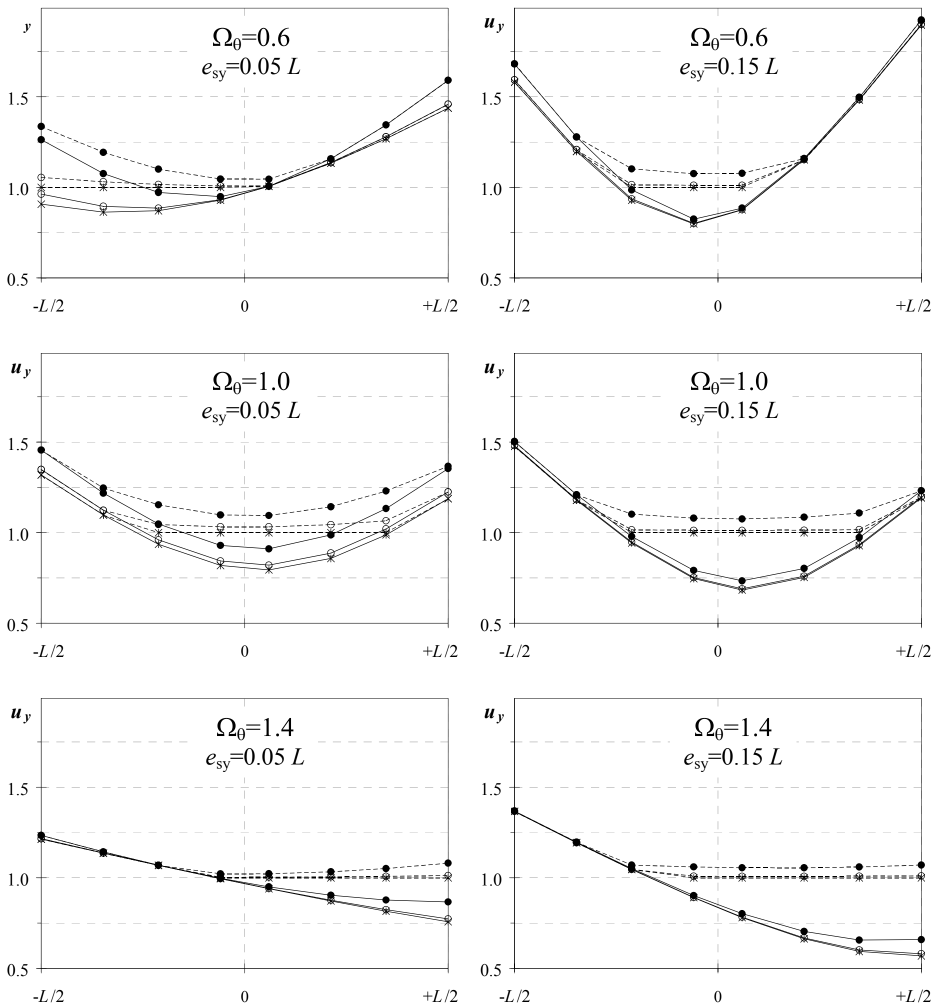


Figure 2. Normalised design displacement of longitudinal elements in mono and bi-directional asymmetric systems.

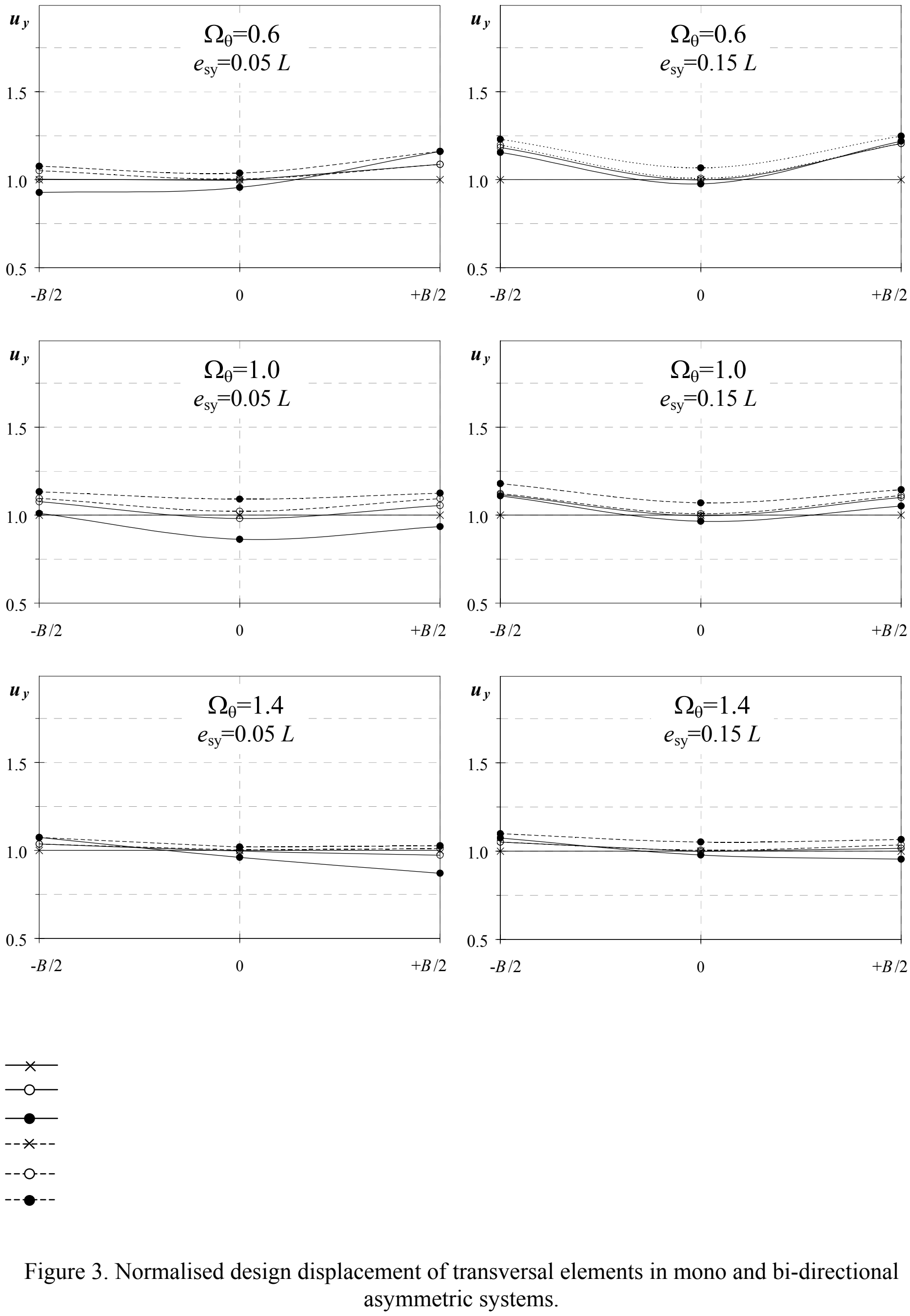


Figure 3. Normalised design displacement of transversal elements in mono and bi-directional asymmetric systems.

STRENGTH DISTRIBUTIONS

In Figures 2 and 3 are respectively shown the normalised design displacements of longitudinal and transversal elements of mono and bi-eccentric systems designed according to different design rules and procedures. The values of strength obtained by means of the standard application of the multi-modal analysis combined or not with the SRSS rule are compared with those resulting from the use of the proposed simplified procedure, characterised by a design eccentricity equal to the structural eccentricity.

The application of the rule proposed by Eurocode 8 to estimate the effect of the contemporaneity of the two horizontal seismic components has obviously no effect on the strength of the longitudinal resisting elements if the structure presents no eccentricity in the transversal direction i.e. e_{sx}=0. Differently, the application of such rule in systems with bi-eccentricity provides strength values in the longitudinal elements higher than those of mono-eccentric models (Fig. 2). The increase of strength for the longitudinal elements generally appears in areas of the structure where, in the corresponding mono-eccentric systems, the ductility demands are higher i.e. at the flexible side or at the centre of torsionally flexible systems and at the stiff side of torsionally rigid structures. Such additional strength would be therefore adequately distributed in plan, so as to improve the inelastic behaviour of bi-eccentric systems, if the ductility demands distributions of such systems were qualitatively the same as the corresponding mono-eccentric structures.

In the transversal elements (Fig. 3) the design displacements at the edges are generally much lower than those of the longitudinal elements because the displacements induced in the first ones by a plan rotation are lower than those in the outermost resisting elements along y-direction owing to the geometrical properties of the model.

RESULTS

For each accelerogram the values of the ductility demands have been normalised to those of the corresponding torsionally balanced system; for each resisting element the mean of the thirty maximum normalised values has been then assumed as parameter of analysis, selected so as to synthesise the seismic response of asymmetric one-storey models.

In systems designed by the standard application of the multi-modal analysis, i.e. without design eccentricity (Fig. 4), the normalised ductility demands in longitudinal elements are often above unity, even in mono-eccentric systems subjected to mono-directional accelerograms; such a result is remarked both by torsionally flexible and rigid asymmetric systems with low and high structural eccentricity. The presence of structural eccentricity in the transversal direction and the occurrence of bi-directional ground motions leads to even higher ductility demands. The inelastic response of asymmetric structures, generally more translation than the elastic one, underlines great damage levels in the elements of the system where the design displacements are remarkably lower than those corresponding to a pure translation. For this reason the greatest normalised ductility demands raise at the flexible side of torsionally flexible systems (d=1.50) with low eccentricity, at the centre of systems with Ω_θ=1.0 (d=1.40) or at the stiff side of torsionally rigid structures (d=2.0). Such values are much higher than those of the corresponding mono-eccentric systems.

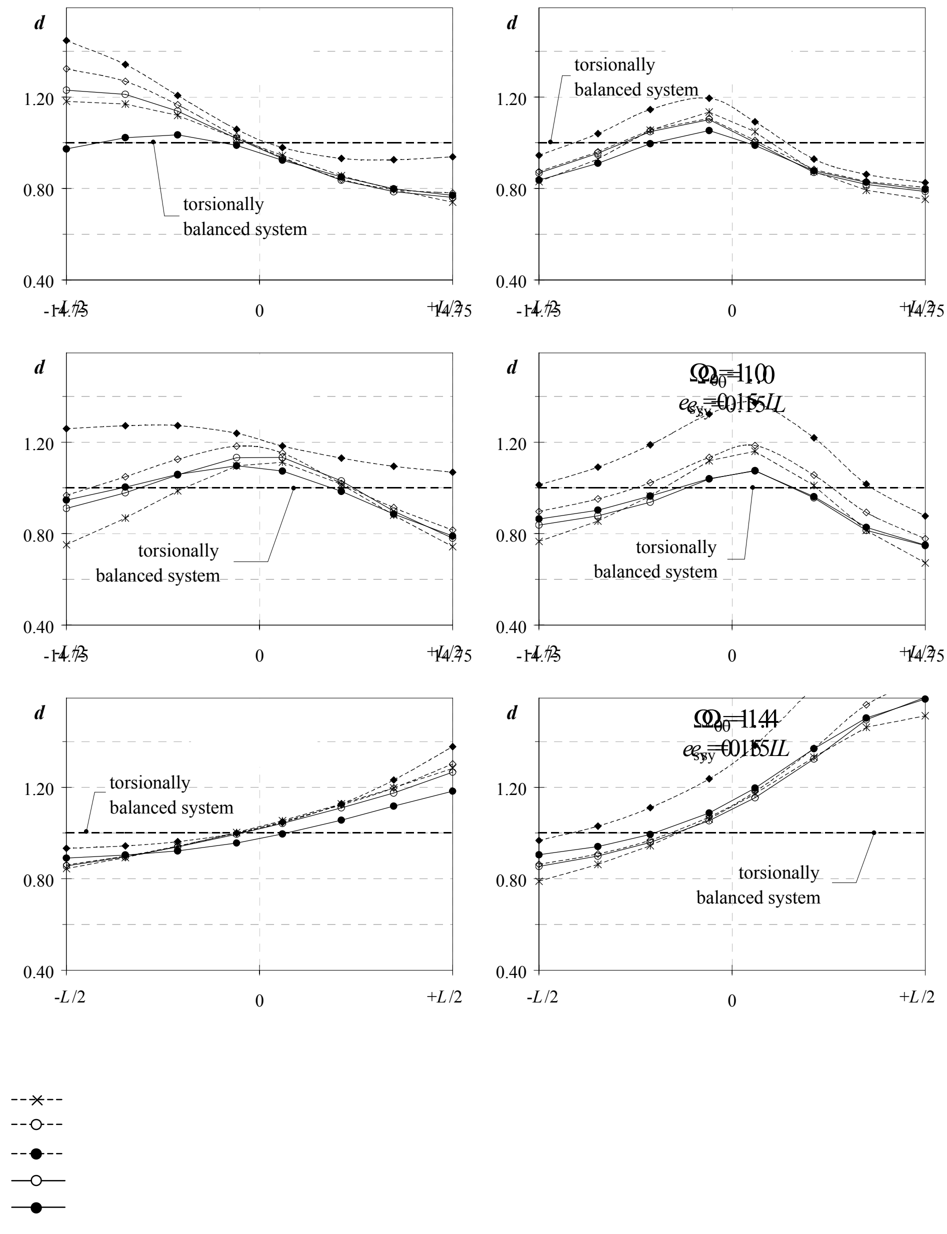


Figure 4. Normalised ductility demands of longitudinal elements in mono and bi-directional asymmetric systems designed without design eccentricity.

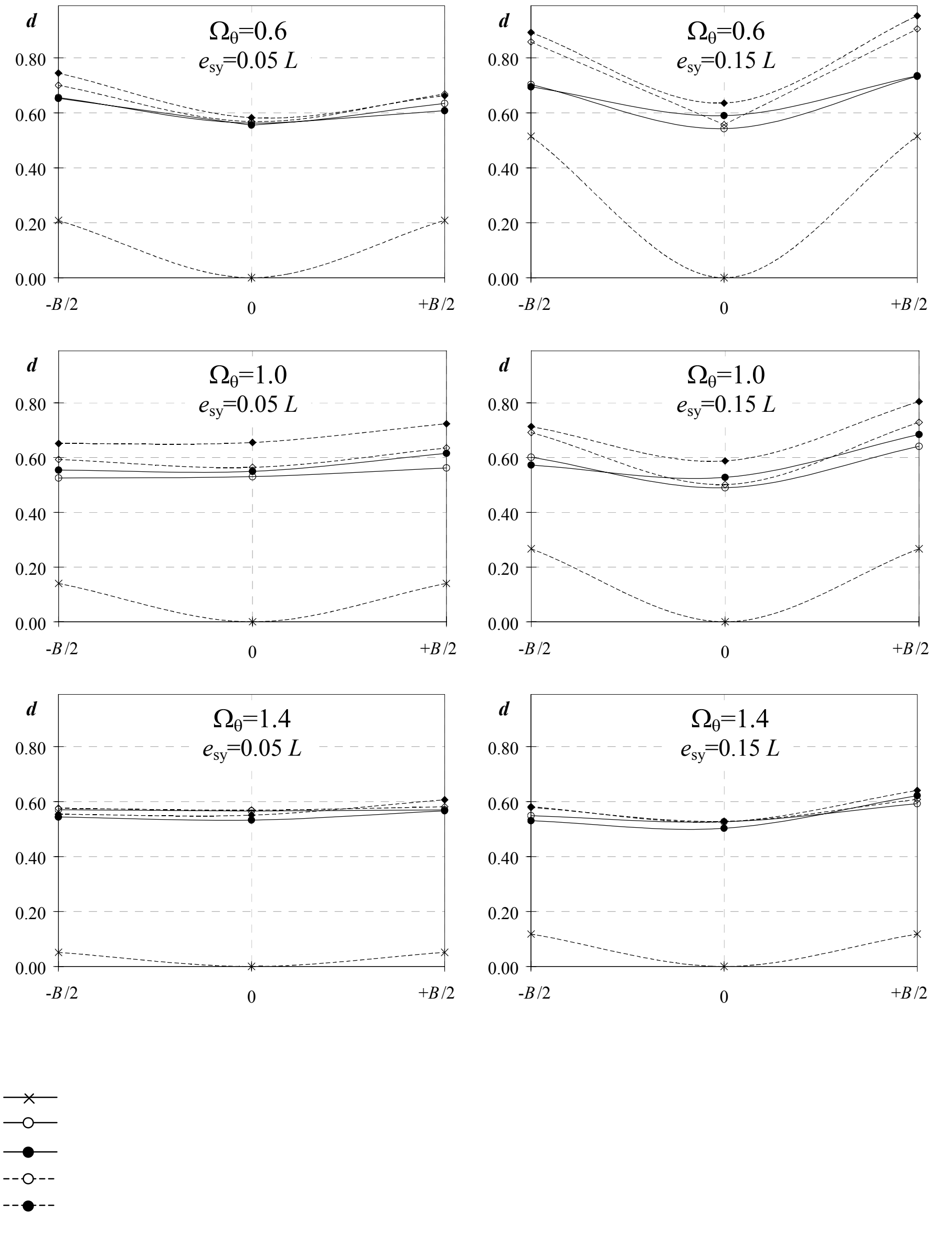


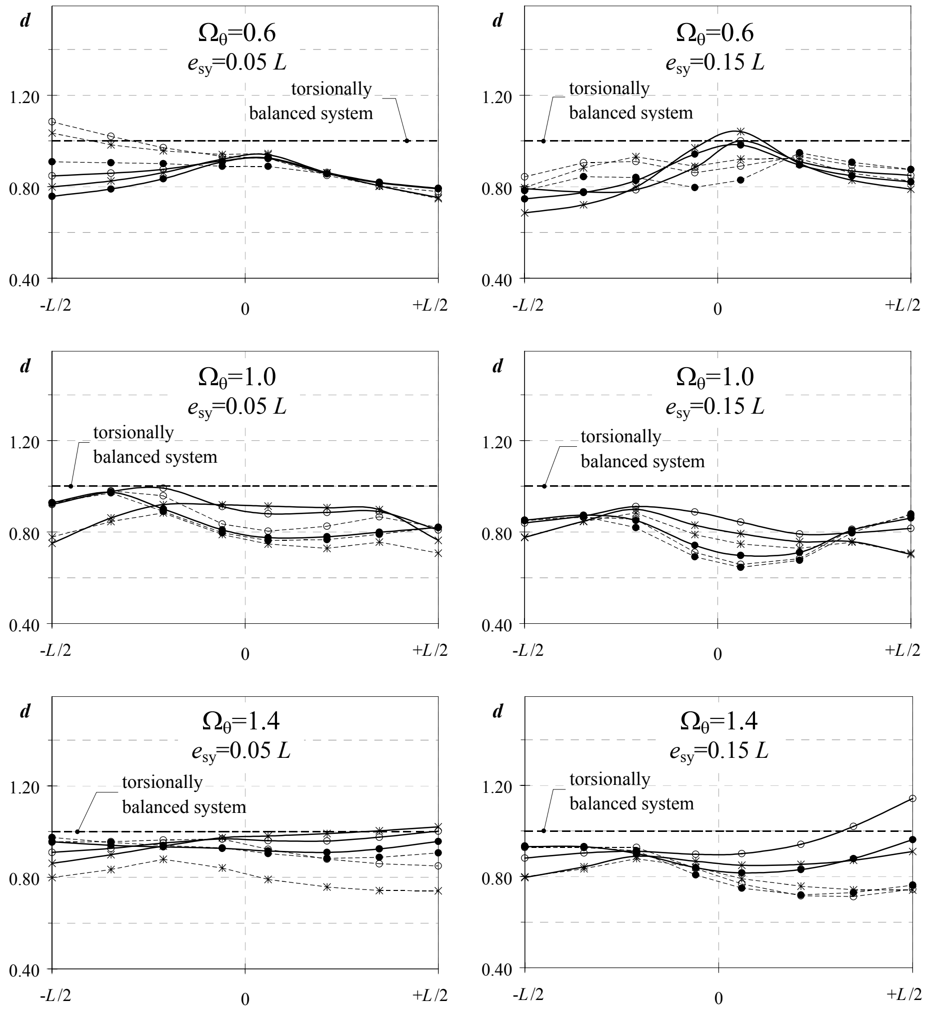
Figure 5. Normalised ductility demands of transversal elements in mono and bi-directional asymmetric systems designed without design eccentricity.

The damage distributions present approximately the same aspect as those of the corresponding mono-eccentric systems so that the additional strength due to the application of the SRSS rule is expected to reduce the normalised ductility demands respect to the same schemes for which the afore-mentioned rule has been not applied. The efficiency of the SRSS rule is indeed sometimes remarkable but not so strong to reduce the ductility demands of the asymmetric schemes to those of the corresponding torsionally balanced systems; e.g. the normalised ductility demand at the stiff side element of torsionally rigid systems with high structural eccentricity (Ω_θ=1.4; e_s=0.15 L) decreases from 2.0 to 1.6.

The ductility demand of the transversal elements, shown in Figure 5, are always lower than unity because the damage parameter is normalised to that of the corresponding symmetric model designed by the design peak ground acceleration (0.35 g), independently of the value of the peak ground acceleration a_{gx} adopted in the numerical analyses. In torsionally rigid mono-eccentric systems designed without design eccentricity, subjected to mono-directional seismic input, transversal elements do not generally experience an inelastic behaviour (a value of the normalised ductility demand equal to 0.20 can be approximately roughly considered as limit between the elastic and inelastic behaviour if we consider the ductility demand equal to the behaviour factor q=5). Conversely in torsionally flexible structures characterised by moderate or high structural eccentricity the same elements are well into the inelastic range. Bi-eccentric systems subjected to bi-directional seismic input show a remarkable increasing of the ductility demand of the transversal elements, greater in torsionally flexible systems than in torsionally rigid systems. The application of the SRSS rule slightly reduces the maximum values of the normalised ductility demand at the outer elements.

As shown in Figure 6 the application of the design procedure proposed by Ghersi and Rossi [6] limits the normalised ductility demands of longitudinal elements of mono-eccentric systems subjected to mono-directional ground motions to unity in both torsionally flexible and rigid systems. The simplified approach, which adopts a design eccentricity equal to the structural eccentricity, leads globally to similar results. Nevertheless the normalised ductility demands are just slightly higher than unity at the flexible edge of torsionally flexible systems with low structural eccentricity. Quite good is instead the inelastic response in systems characterised by an uncoupled lateral-torsional frequency ratio Ω_θ equal to 1.0 and 1.4; even too much low seem to be the normalised ductility demands in torsionally rigid systems with low structural eccentricity.

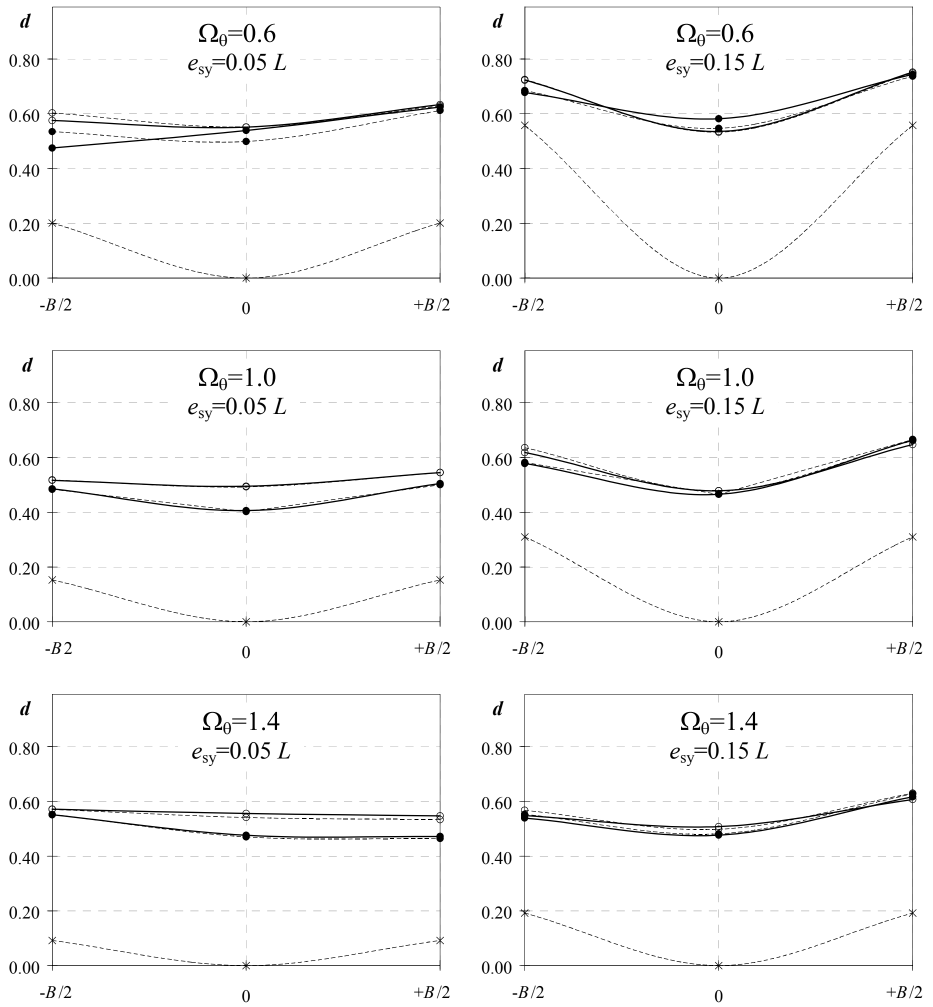
The presence of structural eccentricity in both longitudinal and transversal directions and the occurrence of bi-directional ground motions increase the normalised ductility demands respect to those of mono-eccentric systems, even when the SRSS rule has been applied in the phase of design. The over-conservatism of the simplified procedure in torsionally rigid systems (Ω_θ=1.4) prevents normalised ductility demands from overcoming unity. Conversely, the procedure suggested by the Authors which propose for such structures a design eccentricity lower than the structural eccentricity highlights, for high values of both structural eccentricity e_{sx} and e_{sy}, values of the normalised ductility demand quite higher than unity.



Legend:

—×— Proposed procedure [6]	; no SRSS rule	; e_{sx}=0	; a_{gx}=0
—○— Proposed procedure [6]	; SRSS rule	; e_{sx}=0.05 L	; a_{gx}=0.5 a_{gy}
—●— Proposed procedure [6]	; SRSS rule	; e_{sx}=0.15 L	; a_{gx}=0.5 a_{gy}
--✳-- Multi-modal analysis + translation	; no SRSS rule	; e_{sx}=0	; a_{gx}=0
--○-- Multi-modal analysis + translation	; SRSS rule	; e_{sx}=0.05 L	; a_{gx}=0.5 a_{gy}
--●-- Multi-modal analysis + translation	; SRSS rule	; e_{sx}=0.15 L	; a_{gx}=0.5 a_{gy}

Figure 6. Normalised ductility demands of longitudinal elements in mono and bi-directional asymmetric systems designed with design eccentricity.



Legend:

Proposed procedure [6]	; SRSS rule	; e_{sx}=0.05 L	; a_{gx}=0.5 a_{gy}
Proposed procedure [6]	; SRSS rule	; e_{sx}=0.15 L	; a_{gx}=0.5 a_{gy}
Multi-modal analysis + translation	; no SRSS rule	; e_{sx}=0	; a_{gx}=0
Multi-modal analysis + translation	; SRSS rule	; e_{sx}=0.05 L	; a_{gx}=0.5 a_{gy}
Multi-modal analysis + translation	; SRSS rule	; e_{sx}=0.15 L	; a_{gx}=0.5 a_{gy}

Figure 7. Normalised ductility demands of transversal elements in mono and bi-directional asymmetric systems designed with design eccentricity.

The influence of the design eccentricity on the inelastic behaviour of the transversal elements is instead shown in Figure 7. The application of the design procedure proposed by the Authors or that of the simplified approach, in which the design eccentricity is equal to the structural eccentricity, shows non remarkable effect in the normalised ductility demands of the transversal elements of mono-eccentric models subjected to mono-directional ground motions. The effectiveness of the design procedure seems not to be particular for such elements even in the case of bi-directional systems; the values of the ductility demands reach approximately those corresponding to the standard application of the multi-modal analysis with the application of the SRSS rule.

CONCLUSIONS

In this paper the influence of different design procedures on the response of mono and bi-eccentric systems has been examined. All the selected design procedures are based on the application of the multi-modal analysis, with or without design eccentricity. The rule proposed by Eurocode 8 to estimate the effect of the contemporary action of the two horizontal seismic components has been furthermore applied so as to evaluate and quantify its effectiveness in reducing the ductility demands in occurrence of bi-directional seismic input. The numerical analyses have lead to these principal observations:

1. The standard application of the multi-modal analysis does not produce dramatic levels of normalised ductility demands in mono-eccentric systems. The presence of structural eccentricity in both longitudinal and translational directions amplifies the ductility demands in both torsionally flexible and rigid systems.
2. As reported in other papers [5] the SRSS design rule proposed by Eurocode 8 constitutes an opportune design criterion to limit the ductility demand of transversal elements in occurrence of moderate or strong secondary components, particularly in torsionally flexible systems. Its action is indeed remarkable also in reducing the ductility demands of the longitudinal elements in bi-eccentric systems. The normalised ductility demands are anyway not yet smaller than unity.
3. Proper design procedures based on the design eccentricity concept may improve such behaviour and provide limited (minor than unity) and more uniform values of the normalised ductility demand. The design procedure proposed by Ghersi and Rossi [6] or that simplified based on the application of a design eccentricity equal to the structural eccentricity constitute two valid alternatives.
4. Even if in mono-eccentric torsionally rigid systems ($\Omega_\theta \cong 1.2$-1.4) the simplified procedure seems to be over-conservative in terms of ductility demands it gives good results in bi-eccentric systems. Conversely the formulation proposed by Ghersi and Rossi [6] which is based on the response of mono-eccentric systems subjected to mono-directional ground motions provides a correct response of mono-eccentric torsionally rigid structures but shows some increase of ductility demand in bi-eccentric systems with high structural eccentricity in both longitudinal and transversal directions. For the same values of structural eccentricity the simplified procedure seems instead to give some increased ductility demands in torsionally flexible structures.

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