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INFLUENCE OF DESIGN PROCEDURES ON THE SEISMIC RESPONSE OF BI-ECCENTRIC PLAN-ASYMMETRIC SYSTEMS

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SUMMARY

This paper investigates, by means of idealized one-storey models, the seismic behaviour of bi-eccentric plan-asymmetric structures and the influence of different design practices on it. All the examined design procedures are based on the use of modal analysis, in order to grant, in any case, a reliable estimate of the elastic response. The first procedure requires the standard application of modal analysis (nominal positions of mass and stiffness centres), while the others employ a double application of the same analysis to reduce the ductility demand in occurrence of strong ground motions. Furthermore, within the aforementioned procedures, the importance and effectiveness of the combination of design internal forces induced by two orthogonal seismic components are discussed. In order to obtain statistically representative information on the structural response to seismic loads the models are subjected to a set of 30 bidirectional accelerograms. A wide parametric analysis allows observations and conclusions, which may be considered reliable for asymmetric models characterized by a wide range of values of the structural parameters. Copyright © 2005 John Wiley & Sons, Ltd.

1. INTRODUCTION

In the last decade a large number of researchers (Goel and Chopra, 1990; Tso and Zhu, 1992; Chandler and Duan, 1997) have focused their attention on the influence of design procedures on the response of asymmetric structures. Static analysis has been found less adequate than modal analysis in satisfying the requirements of a seismic strategy characterized by a dual design level (Fajfar *et al.*, 1988; Ghersi *et al.*, 2000). Difficult indeed is the correction necessary to the standard application of static analysis to match the elastic response in the occurrence of low-intensity ground motions (Tso and Dempsey, 1980; Calderoni *et al.*, 1995; Anastassiadis *et al.*, 1998). Furthermore, no general technical expedient has been found up to now to limit the ductility demands in systems subjected to strong earthquakes. Conversely, modal analysis effortlessly provides a correct estimate of the elastic response to seismic actions. Nevertheless, as for static analysis, some improvement to its standard application is necessary if limited structural damage is desired in the event of strong ground motions. With this aim, the authors have proposed a design procedure (Ghersi and Rossi, 2000) able to take into account the more translational aspect of the inelastic response with respect to the elastic one. The procedure requires a double application of modal analysis: in addition to the standard one (related to nominal positions of mass and stiffness centres), which provides a correct evaluation of the elastic response to low-intensity earthquakes, a second modal analysis will be performed, which considers the mass centre displaced towards the stiffness centre of a quantity named *design eccentricity*. The suggested formulation of the design eccentricity aims at reducing the damage level and the ductility demand of a *tor-*

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sionally unbalanced system (TU) to the values of the corresponding *torsionally balanced system* (TB), i.e., of a structure which has the same stiffness distribution but a mass distribution such that the centre of mass coincides with the centre of stiffness.

The procedure was first proposed for mass and stiffness mono-eccentric systems subjected to monodirectional ground motions (Ghersi and Rossi, 2000) and later on verified both for systems characterized by the contemporary presence of mass and stiffness eccentricities (Rossi, 1998) and for mono-eccentric systems subjected to bidirectional seismic actions (Ghersi and Rossi, 2001). In this paper attention is focused on the more general bi-eccentric systems, in order to investigate the influence of structural eccentricity along two orthogonal directions on the seismic response of asymmetric models. In particular, the effectiveness of different design procedures and that of the SRSS rule for the combination of internal actions induced by orthogonal seismic components has been examined. The discussion is based on the analysis of *normalized* parameters, obtained by dividing the values calculated for TU systems by those given by the corresponding TB systems.

All the numerical analyses refer to one-storey models. The importance of such a simplified scheme within the study of asymmetry has been strongly remarked in the past by, for example, Hejal and Chopra (1987), who demonstrated that the elastic response of a special class of multistorey asymmetric buildings (named *regularly asymmetric*) may be evaluated by means of multistorey torsionally balanced systems and one-storey asymmetric models. On such a basis the role of simplified models has remained well defined and limited to the analysis of the elastic behaviour of the aforementioned category of asymmetric buildings. In spite of this, the one-storey model was later used also for analyses in the inelastic range, in order to examine the various aspects (displacements, ductility demands, etc.) of the seismic response of in-plan irregular systems (Rutenberg *et al.*, 1995). The reliability of the extension of these findings to the seismic behaviour of multistorey asymmetric structures has been questioned by many researchers, who have pointed out the large differences between elastic and inelastic responses of one-storey and multistorey schemes. Nevertheless, recent studies on multistorey models have provided convincing proof concerning the value of the findings achieved by means of one-storey models for the comprehension of basic aspects of the seismic behaviour of regularly asymmetric framed buildings. Indeed, a comparative study (Ghersi *et al.*, 2000) of one-storey and multistorey schemes has highlighted significant analogies in the response of the two models and, in particular, a strong similarity between the distributions of the global ductility demand of one-storey models and the local ductility demand of the base cross-section of columns in multistorey models designed to develop a global collapse mechanism.

2. STRUCTURAL MODEL

The analysed one-storey model has a deck, rectangular in shape (L = 29·50 m; B = 12·50 m), rigid in its own plane and supported by resisting elements having in-plane stiffness and strength only (Figure 1). The elements are arranged along two orthogonal axes: eight in the Y-direction and three in the X-direction. An elastic perfectly plastic force–displacement relation governs their behaviour. The mass centre location and the mass radius of gyration r_m (0·312 L) are assigned independently of the size and shape of the deck assuming that the mass (m = 1 t/m^2 in mean) can be non-uniformly distributed in plan. Damping has been considered through the Rayleigh formulation. Mass and stiffness coefficients have been derived so as to have an equivalent viscous damping factor equal to 0·05 in correspondence to the first and third natural periods of vibration of the systems.

In order to analyse the behaviour of both torsionally flexible and stiff systems having either low or high structural eccentricity the uncoupled torsional–lateral frequency ratio Ω_θ has been considered, ranging from 0·6 to 1·4, while the structural eccentricities e_{sx} and e_{sy} have been varied from 0 to 0·20 L and 0·20 B, respectively. In most cases mass eccentric systems have been considered, having uncou-

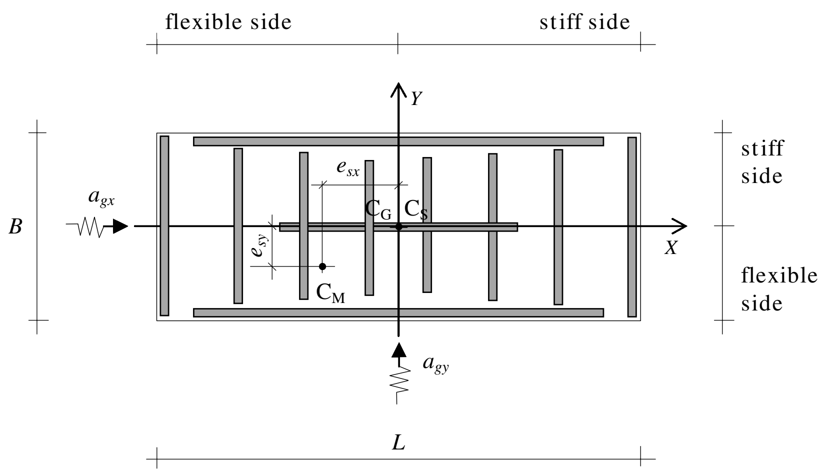

Figure 1. The structural model

pled lateral periods of vibration T_x and T_y equal to 1 s and ratio γ_x of the torsional stiffness due to the elements along the X-axis to the total torsional stiffness equal to 0·2. Stiffness eccentric systems or structures with different values of the above-mentioned characteristics have been analysed only in a few cases, owing to the lower influence of such parameters on the effects of asymmetry, already underlined in previous studies (Ghersi and Rossi, 2000; Rossi, 1998).

In all the numerical analyses an automatic procedure (Ghersi and Rossi, 2000) has been used to define structural systems having the established uncoupled torsional–lateral frequency ratios, global lateral and torsional stiffness and locations of the stiffness centre.

3. DESIGN PROCEDURES

The design has been carried out using a response spectrum derived from the elastic one proposed by Eurocode 8 (1994) (EC8) for hard layer soil (class A) by means of scaling through a value of the behaviour factor q equal to 5. The equivalent viscous damping factor adopted in the design is equal to 0·05, while the design peak ground acceleration (PGA) is equal 0·35 g.

Three different design practices, based on the application of multimodal analysis, have been investigated with the aim of highlighting their qualities or deficiencies and their influence on the structural response of bi-eccentric systems subjected to bidirectional ground motions.

The first one (procedure #1) consists of a *standard* modal analysis, i.e., related to nominal locations of mass and stiffness centres. As usual, the analysis considers the seismic excitation acting separately along two orthogonal directions; with reference to each direction the modal contributions are superimposed according to the complete quadratic combination (CQC) rule by means of the modal combination factors proposed by Der Kiureghian (1981).

The other procedures require a double application of modal analysis. In addition to the standard one, a second modal analysis has to be performed, with the mass centre located in a conventional position, displaced from the nominal one towards the stiffness centre of a quantity named *design eccentricity*. Consequently, each element is designed for internal actions equal to the maximum values given by the two analyses. In such an approach, the first analysis aims at estimating the elastic response of the scheme, while the second one aims at producing a better correspondence between the design displacements and the less rotational trend of the inelastic displacements.

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Procedure #2 assumes that the design eccentricity is equal to the structural eccentricity ($e_d = e_s$ as suggested also by the Uniform Building Code, 1997). As pointed out by some researchers (e.g., Wong and Tso, 1995) the use of such an approach globally leads to good inelastic structural performances of one-way plan-asymmetric models designed by means of static analysis. The second modal analysis corresponds, in this case, to a pure translation of the model, without any regard to the dynamic and structural characteristics of the systems.

Procedure #3 uses a more refined formulation of the design eccentricity, proposed by Ghersi and Rossi (2000) as a function of the uncoupled torsional–lateral frequency ratio Ω_θ, structural eccentricity e_s and behaviour factor q:

$$e_d = \max\begin{cases} k(e_s - e_r) \\ 0{\cdot}6\, e_s \end{cases} \tag{1}$$

where

$$k = \max\begin{cases} 3{\cdot}3 - 2{\cdot}5\Omega_\theta + 0{\cdot}04\, q \\ 1 \end{cases}$$

$$e_r = \max\begin{cases} 0{\cdot}1(0{\cdot}5\Omega_\theta - 0{\cdot}4)L \\ 0.01\, L \end{cases} \tag{2}$$

This formulation, based on the study of the seismic response of one-storey models subjected to monodirectional ground motions, is calibrated so as to limit the mean and characteristic values of the maximum normalized displacement ductility demands of asymmetric systems to 1·0 and 1·3 respectively (Ghersi and Rossi, 2000, 2001).

A comparison between procedure #2 and #3 highlights that the more refined formulation leads, with respect to the simplified one, to smaller values of the design eccentricity in torsionally stiff systems and to larger values in torsionally flexible systems (Figure 2). They instead provide similar values in models characterized by uncoupled torsional–lateral frequency ratios close to unity.

Independently of the design procedure, the usual modal approach considers separately the effects of two orthogonal seismic components. Therefore, it underestimates the elastic displacements actually experienced by asymmetric systems during bidirectional ground motions. In order to overcome this

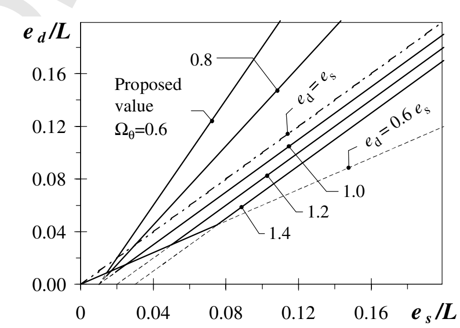

Figure 2. Design eccentricity: comparison between the more refined proposed formulation $e_d/L = f(\Omega_\theta, e_s, q)$ and the simplified one ($e_d = e_s$)

problem, some seismic codes prescribe combination rules to superimpose the effects of the two components, such as the square root of the sum of the squared values rule (later on called the SRSS rule, in short). In order to point out the influence of the adoption of this superposition on the inelastic response, the design of each scheme has been carried on twice: the first time neglecting and the second time accounting for the aforementioned rule.

Finally, no accidental eccentricity has been considered both in the design analysis and in the nonlinear dynamic response analyses of the models.

3.1 Design displacements

The effectiveness of a design procedure may be assessed by examining the ductility demand caused by strong earthquakes, which depends on the ratio of the maximum inelastic displacements actually experienced by structures to the values prescribed in the design phase. To this end it is useful to examine the displacements that the different design procedures impose on the scheme.

In torsionally flexible schemes (e.g., $\Omega_\theta = 0{\cdot}6$ in Figure 3) procedure #2 leads to displacements (and strengths) in the middle of the scheme larger than those provided by procedure #1, while procedure #3 gives significant increments on the flexible side. In torsionally stiff schemes (e.g., $\Omega_\theta = 1{\cdot}4$) the use of design eccentricity always increases displacement and strength both in the middle and on the stiff side, with values slightly larger when procedure #2 is used (in particular when the structural eccentricity is high).

The combination of the effects of two orthogonal seismic components according to the SRSS rule may have a relevant influence because of the bi-eccentricity of the scheme. In particular, when the structural eccentricity along one axis is much higher than the orthogonal one the increase is more evident for the outermost resisting elements parallel to the larger eccentricity (e.g., for *Y*-elements when $e_{sy} = 0{\cdot}15\,B$ and $e_{sx} = 0{\cdot}05\,L$, as in Figure 4). The most remarkable differences appear on the flexible side of torsionally flexible systems and on the stiff side of torsionally rigid systems. A nearly constant increase along almost the whole length of the structure is instead noticed in models characterized by the contemporary presence of high eccentricity in both directions (e.g., $e_{sx} = 0{\cdot}15\,L$ and $e_{sy} = 0{\cdot}15\,B$, not shown in the figure).

Finally, it has to be noted that, owing to the elongated shape of the floor slab ($B/L \cong 0{\cdot}4$), the trend of the displacements parallel to the *X*-axis is always flatter than that of the displacements parallel to the *Y*-axis, because a plan rotation induces displacements of the outermost *X*-elements much lower than those produced in the other direction.

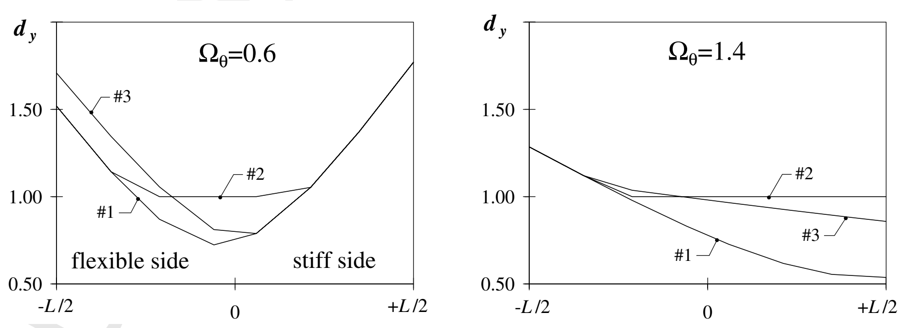

Figure 3. Normalized design displacements of elements along the *Y*-direction in bi-eccentric systems designed by means of the three procedures ($e_{sx} = 0{\cdot}15\,L$; $e_{sy} = 0{\cdot}15\,B$; no combination of orthogonal seismic actions)

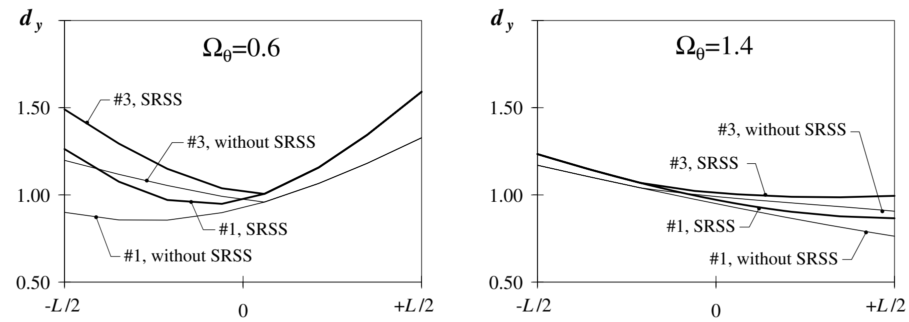

Figure 4. Normalized design displacements of elements along the *Y*-direction in bi-eccentric systems designed with and without combination of orthogonal seismic actions ($e_{sx} = 0{\cdot}05\,L$; $e_{sy} = 0{\cdot}15\,B$; procedures #1 and #3)

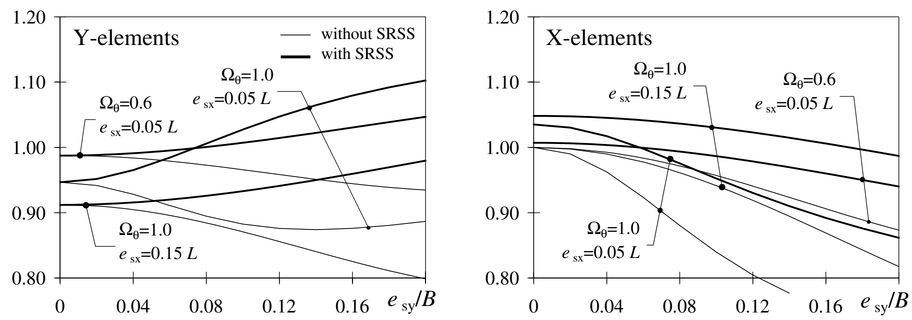

Figure 5. Ratio of costs of structural elements of asymmetric and torsionally balanced systems designed by standard modal analysis (procedure #1)

3.2 Structural cost

An important aspect to be considered in design is the cost of the structural elements, which may be assumed proportional to the provided strength, i.e., to the design displacements. An asymmetric building may cost more or less than the corresponding TB system, depending on the design approach. When procedure #1 is applied without the SRSS rule with reference to a mono-eccentric system ($e_{sy} = 0$), the cost of the elements along the symmetric direction (X) is obviously equal to that of the TB system, while that of the orthogonal elements (Y) is always lower. The cost of all the elements reduces as the eccentricity e_{sy} increases, in particular when Ω_θ is close to unity (Figure 5). The application of the SRSS rule does not modify the *Y*-direction elements of mono-eccentric systems, while it increases their cost in bi-eccentric models as much as the eccentricity e_{sy} is higher. On the contrary, it increases the cost of the *X*-direction elements in mono-eccentric systems. Such increment is evident also in bi-eccentric schemes but, in spite of that, the cost of these elements is in any case decreasing with the eccentricity e_{sy}.

The use of design eccentricity to enhance structural safety necessarily leads to higher costs, as is shown by the ratio of the cost of schemes designed according to procedures #2 and #3 to that of schemes designed according to procedure #1 (Figure 6). In particular, the cost of the elements along

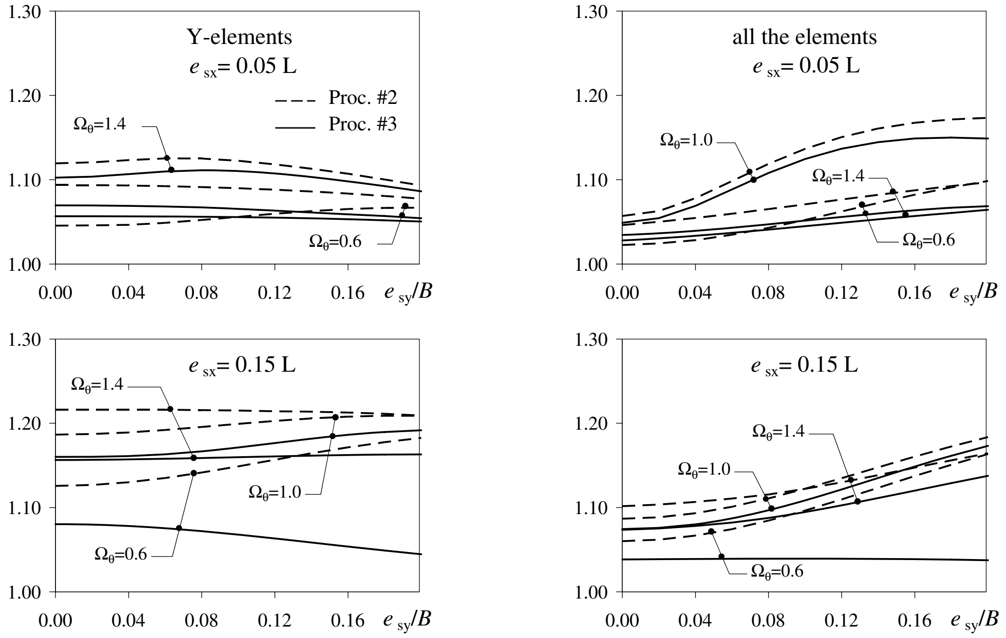

Figure 6. Ratio of costs of structural elements of asymmetric systems designed with combination of orthogonal seismic actions by procedures #2 and #3 over those obtained using procedure #1

a direction seems to be only marginally influenced by the value of the structural eccentricity in the same direction (e.g. Y-elements with e_{sy}). Instead, it rapidly amplifies on increasing the structural eccentricity in the orthogonal direction (e.g., X-elements with e_{sy}), particularly in structures with Ω_θ close to unity, giving rise to higher global costs. It may finally be observed that the cost expected by the application of procedure #2 is almost always higher than that obtained by procedure #3. The difference may in some cases be really remarkable, e.g. in torsionally stiff systems ($\Omega_\theta = 1{\cdot}4$) and, even more, in torsionally flexible systems ($\Omega_\theta = 0{\cdot}6$) with large structural eccentricity ($e_{sy} = 0{\cdot}15\,L$).

4. EARTHQUAKE GROUND MOTIONS

With the aim of examining the response of asymmetric systems to bidirectional accelerometric signals two sets of 30 couples of accelerometric components have been artificially generated matching the elastic response spectrum proposed by Eurocode 8 for hard layer soil (class A) with reference to a damping ratio equal to 0·05. As suggested by Penzien and Watabe (1975) the horizontal seismic components of each ground motion are generated as uncorrelated. Each accelerometric component is defined by a stationary random process modulated by means of a trapezoidal intensity function characterized by a strong motion phase of 22·5 s (as recommended by EC8 for peak ground accelerations equal to $0{\cdot}35\,g$) and by starting and ending connecting branches of 3 and 5 seconds respectively. Complying with EC8 no value of the mean elastic response spectrum of each set of accelerograms is more than 10% below the corresponding code value; furthermore, the mean value of the pseudo-accelerations in the constant acceleration region is not smaller than the value of the code response spectrum.

5. INELASTIC RESPONSE

The non-linear dynamic analyses of the selected systems have been carried out with reference to principal seismic components acting along the *Y*-axis ($\text{PGA}_y = 0{\cdot}35\,g$) and to secondary components acting along the *X*-axis ($\text{PGA}_x = 0$, $0{\cdot}5$ and $1{\cdot}0\,\text{PGA}_y$).

The value $\text{PGA}_x = 0{\cdot}5\,\text{PGA}_y$ is deemed very probable by the authors in the case of bidirectional ground motions and thus representative, in mean, of the actual nature of seismic excitations. For this reason most figures in the present paper refer to this ratio of peak ground accelerations. Nevertheless, the numerical analyses have been carried out also with reference to $\text{PGA}_x = \text{PGA}_y$ in order to investigate the behaviour of asymmetric systems in the presence of very unfavourable seismic conditions.

Within the post-processing of the numerical results for each accelerogram the maximum values of the output parameters have first been normalized to those of the corresponding TB systems. For each resisting element the mean of the 30 maximum normalized values has then been assumed as the parameter of comparison, selected so as to represent the influence of asymmetry on the seismic response of one-storey models.

5.1 Displacements

As already noted in the past with reference to mono-eccentric systems, the maximum inelastic displacements of the structural elements of the selected bi-eccentric schemes (Figure 7) are more uniform than the elastic ones, as can be seen by comparing them to the values given by standard modal analysis (procedure #1 in Figure 3), which are representative of the elastic response. For the sake of synthesis we could say that the inelastic response is less rotational than the elastic one, although this assertion is referred only to the maximum displacements, not to the rotation actually experienced by the scheme as a consequence of the seismic action.

With respect to mono-eccentric systems, the schemes with eccentricity in two directions present greater inelastic displacements of the outermost resisting elements; this is particularly evident on the flexible side of systems having uncoupled torsional–lateral frequency ratio Ω_θ close to unity (not shown in the figure). When a design eccentricity is used (procedures #2 and #3), the trend of the maximum inelastic displacements is in general more similar to that of the elastic ones. This effect is more remarkable in torsionally stiff systems. It is easily understandable in mono-eccentric systems where the use of such eccentricity provides the stiff side elements with higher strengths, reducing the time in which they are yielded and thus leading to lower inelastic displacements. In bi-eccentric systems the tendency to greater displacements of the outermost elements, produced by structural eccentricities in both *X* and *Y*-directions, is in some way reduced by the application of the SRSS rule in the phase of design.

5.2 Damage parameters

The structural damage has been computed in terms of kinematic ductility. The choice has been guided by previous studies (Rossi, 2000) in which the in-plan distributions of different damage parameters (hysteretic ductility, Park and Ang index, low cycle fatigue index) in both torsionally flexible and stiff systems have been found to present shapes almost equal to that of the more simple kinematic ductility.

The use of procedure #1 (Figure 8), in spite of the application of the SRSS rule (which often grants higher design strength at the edges and in some cases also at the centre of the structure), is always inadequate to reduce the ductility demands of asymmetric schemes to the same values of the corre-

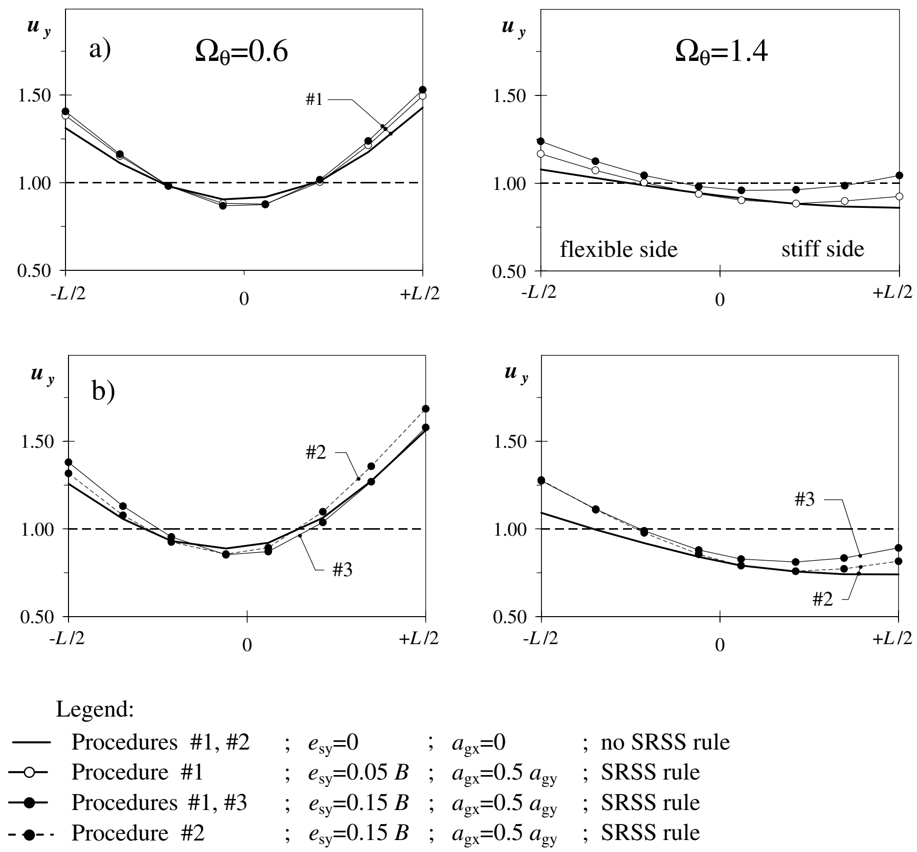

Figure 7. Normalized inelastic displacements of longitudinal elements in asymmetric systems designed by means of procedures #1(a), #2 and #3 (b) ($e_{sx} = 0{\cdot}15\,L$)

sponding TB systems; e.g. the normalized ductility demand at the stiff edge of torsionally rigid systems with high structural eccentricity ($\Omega_\theta = 1{\cdot}4$; $e_{sx} = 0{\cdot}15\,L$, $e_{sy} = 0{\cdot}15\,B$) is equal to 1·6. Slight increases of the ductility demands are found with respect to the corresponding mono-eccentric system subjected to monodirectional ground motions, the greatest increments being in any case not such as to produce ductility demands greater than those of the corresponding torsionally balanced systems. Obviously, if no combination of the effects of the two seismic components is considered in design, the seismic response of bi-eccentric systems designed by procedure #1 emphasizes problems which have already been noted in the past with reference to mono-eccentric systems. Indeed, the normalized ductility demand of the elements is greater where the design displacements are mostly decreased with respect to those corresponding to a pure translation, i.e. on the flexible side of torsionally flexible systems with low eccentricity (d_y grows from 1·18 when $e_{sy} = 0$ to 1·46 when $e_{sy} = 0{\cdot}15\,B$), at the centre of systems with Ω_θ close to unity (from 1·12 to 1·40) and on the stiff side of torsionally rigid structures with high eccentricity (from 1·5 to 2·0) and increases with the eccentricity orthogonal to the plane of strength of the same elements (e.g., d_y with e_{sy}). In addition, normalized ductility demands above unity appear also in some elements for which a good performance was deemed to be granted in mono-eccentric systems (e.g., on the flexible side in systems characterized by $\Omega_\theta = 1$ and $e_{sx} = 0{\cdot}05\,L$).

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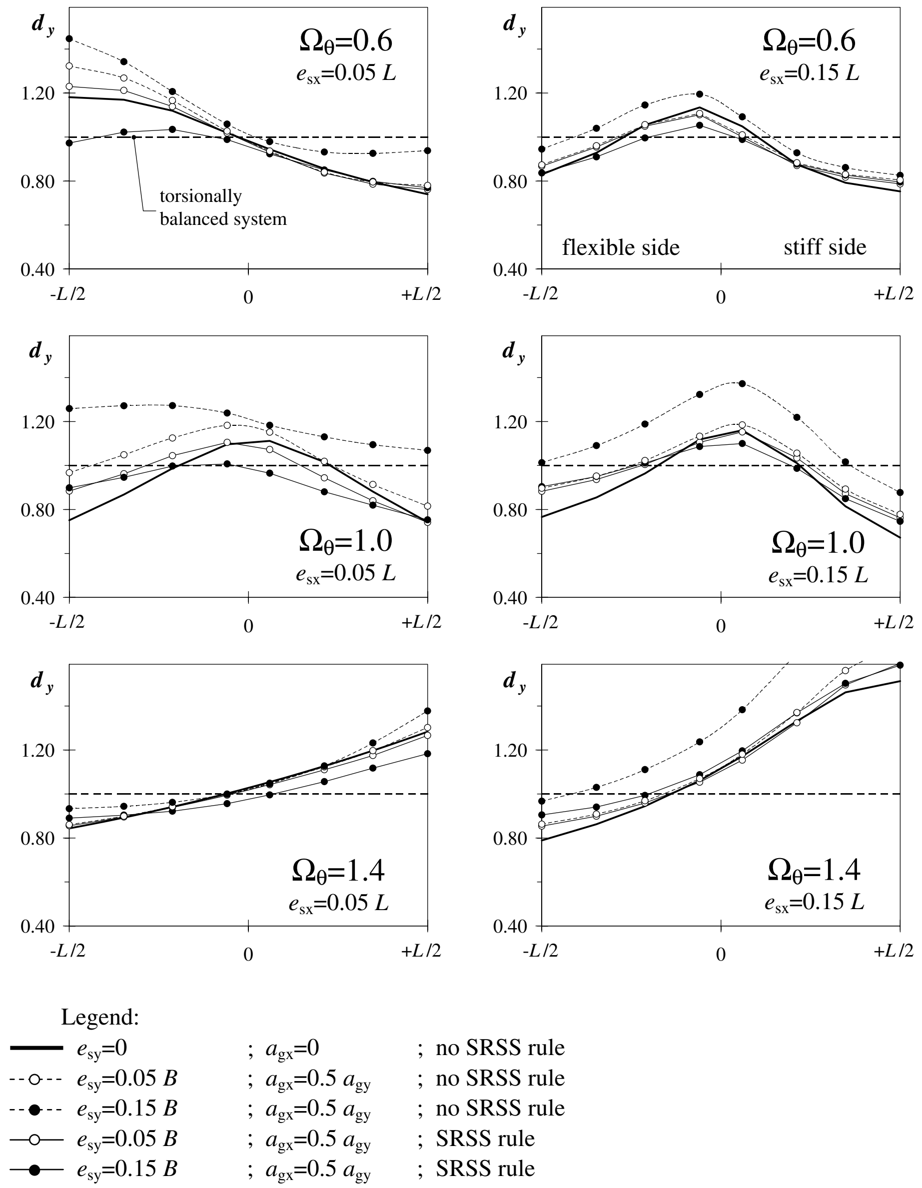

Figure 8. Normalized ductility demands of longitudinal elements in asymmetric systems designed by means of procedure #1

The use of procedures #2 and #3 combined with the application of the SRSS rule (Figure 9), instead, almost always prevents normalized ductility demand from overcoming unity, even in the presence of bi-eccentricity and bidirectional ground motions: normalized ductility demands are, indeed, slightly higher than unity only in a few torsionally flexible schemes designed by procedure #2 (e.g., $\Omega_\theta = 0{\cdot}6$, $e_{sx} = 0{\cdot}15\,L$, $e_{sy} = 0{\cdot}05\,B$, not shown in the figure). Differently, in the absence of the SRSS rule the use of procedures #2 and #3 limits to unity only the normalized ductility demands of mono-eccentric

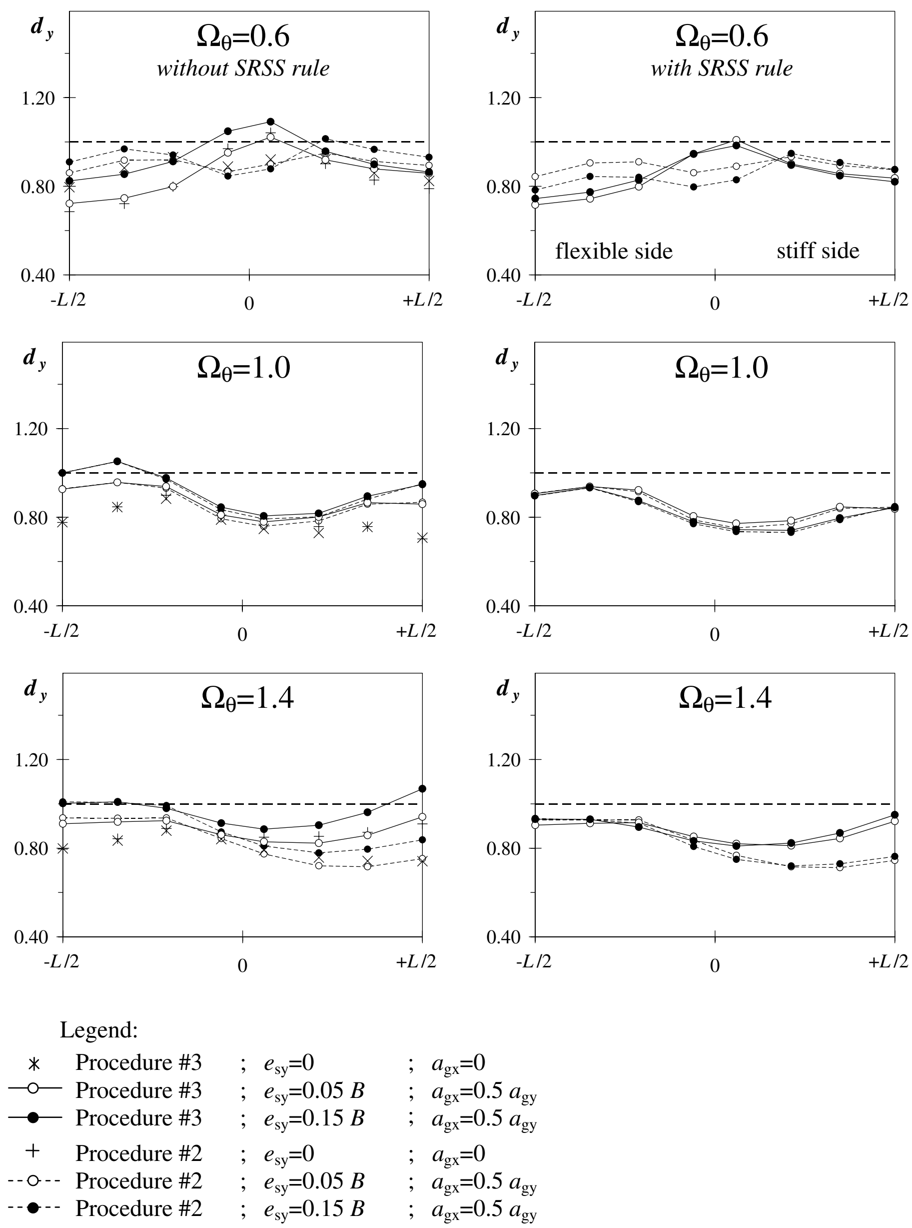

Figure 9. Normalized ductility demands of longitudinal elements in asymmetric systems ($e_{sx} = 0{\cdot}15\,L$) designed by means of procedures #2 and #3

systems subjected to monodirectional ground motions (Ghersi and Rossi, 2000, 2001; Rossi, 1998): values slightly higher than unity are found only at the flexible edge or in the middle of torsionally flexible systems. In some cases, particularly for the stiff side elements of torsionally rigid systems designed by procedure #2, the approach is even too safe, because the normalized ductility demands are very small. In bi-eccentric systems, still in the absence of the SRSS rule, procedures #2 and #3

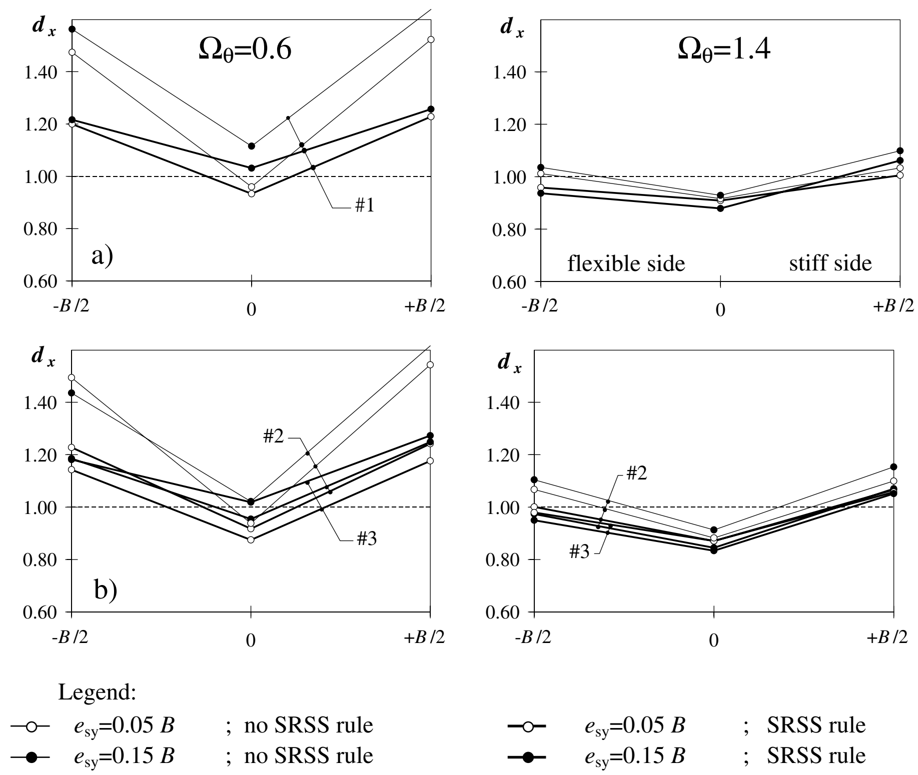

Figure 10. Normalized ductility demands of transversal elements in asymmetric systems designed by means of procedures #1(a), #2 and #3, (b) ($e_{sx} = 0{\cdot}15\,L$; $a_{gx} = 0{\cdot}5a_{gy}$)

generally lead to unacceptable increases of the normalized ductility demand (e.g., if $\Omega_\theta = 0{\cdot}6$, $e_{sx} = 0{\cdot}05\,L$ and procedure #2 is used d_y increases from 0·80 to 1·25 when e_{sy} goes from 0 to $0{\cdot}15\,B$).

Still with reference to bi-eccentric systems, the application of procedure #1 with SRSS rule leads to quite high values of the normalized ductility in the outermost *X*-direction elements of torsionally flexible systems ($\Omega_\theta = 0{\cdot}6$) and to good results in torsionally stiff systems. Such a behaviour is evident in Figure 10 where the ductility of asymmetric systems is normalized with respect to those of the corresponding torsionally balanced systems subjected to seismic actions having peak ground accelerations $a_{gx} = 0{\cdot}5a_{gy}$. In the absence of the SRSS rule, instead, an appreciable growth of the normalized ductility demand appears in torsionally flexible systems, while only a slight increase may be noted with reference to torsionally stiff systems. As evident in the same figure the beneficial effect of the design eccentricity (procedures #2–3) is negligible with respect to that of the SRSS rule.

When $PGA_x = PGA_y$, with respect to the previous results, the normalized ductility demands of the transverse elements grow, but only sometimes and slightly above the ductility demands of the corresponding torsionally balanced systems (e.g., $d_x \cong 1{\cdot}10$ when $\Omega_\theta = 0{\cdot}6$ and $e_{sx} = e_{sy} = 0{\cdot}15\,L$). Finally, the reliability of the results has been checked by analysing this last case ($PGA_x = PGA_y$) with a different set of artificial ground motions, all matching the same elastic response spectrum. The responses obviously present some small differences, but always negligible for the purposes of the study.

6. CONCLUSIONS

This paper analyses the seismic response of bi-eccentric systems, pointing out the differences with respect to mono-eccentric schemes and the influence of different design procedures. Considering that a correct design practice has to satisfy the requirements of a dual-level approach (elastic behaviour in occurrence of low-intensity earthquakes—inelastic behaviour for strong seismic events), all the selected design procedures are based on the application of modal analysis, which grants a reliable estimate of the elastic response. In particular the influence of the following have been investigated:

- the use of design eccentricities, which have been proved to be effective in avoiding in mono-eccentric systems ductility demands larger than those of torsionally balanced schemes;
- the evaluation of internal design actions by the combination (according to the SRSS rule) of the effects of two seismic components along orthogonal directions, separately considered, which has been suggested by Eurocode 8 in order to take into account that in actual seismic events simultaneous accelerations are recorded along both directions.

On this subject, a wide parametric analysis of one-storey plan-asymmetric models has led to these principal observations:

1. The contemporary presence of structural eccentricity in two directions amplifies the inelastic displacements of the outermost elements and their ductility demands, with respect to those of mono-eccentric systems, in both torsionally flexible and stiff systems.
2. If standard modal analysis is applied, the combination of the effects of two orthogonal seismic components according to the SRSS rule constitutes a proper design criterion to limit the ductility demand of the outermost elements of bi-eccentric systems. This effect, already noticed for the transversal elements of mono-eccentric systems, particularly in torsionally flexible schemes, is indeed even more remarkable in bi-eccentric systems. Anyway, it is often not sufficient to keep the normalized ductility demands smaller than unity.
3. The design procedure based on a design eccentricity $e_d = e_s$ may improve the structural behaviour of bi-eccentric systems, providing more uniform values of the normalized ductility demand. Nevertheless, it sometimes induces normalized ductility demands just a little higher than unity in torsionally flexible structures. Furthermore, it is over-conservative in terms of ductility demands in both mono and bi-eccentric torsionally stiff systems ($\Omega_\theta \geq 1{\cdot}2$).
4. The design procedure based on the proposed design eccentricity formulation grants a correct inelastic response of bi-eccentric structures subjected to bidirectional excitations for any combination of the structural parameters herein investigated, providing limited (minor than unity) values of the normalized ductility demand.
5. In both design procedures based on the design eccentricity concept, the combination of the effects of two orthogonal seismic components according to the SRSS rule has a determining importance in granting the reliability and effectiveness of the design method in plan-asymmetric systems characterized by structural eccentricity in two orthogonal directions.

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