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CALIBRATION OF CORRECTIVE ECCENTRICITIES FOR NONLINEAR STATIC ANALYSIS OF ASYMMETRIC SINGLE-STOREY SYSTEMS WITH INTERACTION YIELD DOMAIN

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ABSTRACT: The authors of this paper have recently proposed a nonlinear static method for asymmetric structures, which is alternative to that stipulated by seismic codes. According to this method, the maximum dynamic displacements of the deck can be enveloped by two pushover analyses performed applying the lateral force with two different eccentricities with respect to the centre of mass of the deck. These eccentricities, named *corrective eccentricities*, are defined so that the two corresponding pushover analyses provide displacements that are equal to those evaluated by nonlinear dynamic analysis at the two sides of the deck. In the past, analytical equations have been proposed to evaluate the corrective eccentricities based on the response of single-story systems constituted by a rigid deck supported by vertical uni-directional resisting elements. These elements provide lateral stiffness and strength in their plane only and are representative of shear-walls or braced frames, while they are not effective in simulating the inelastic response of columns of framed structures. In fact, columns provide lateral stiffness and strength in all the horizontal directions and are characterised by a bi-axial yield domain. In this paper, new analytical equations for the corrective eccentricities are calibrated by asymmetric single-storey systems with bi-directional resisting elements.

1. Introduction

Nowadays, it is widely recognised that a proper seismic assessment of structures requires to compare the displacement capacity, i.e. the displacements and plastic deformations that the structure can undergo before the achievement of a given limit state, to the displacement demand, i.e. the displacements and plastic deformations caused by the seismic excitation. The most reliable tool for the estimation of seismic demand is the nonlinear dynamic analysis. Unfortunately, the difficulties in correctly modelling the nonlinear cyclic behaviour of structural members and in properly simulating the seismic excitation make this kind of analysis accessible only to a few experts of seismic engineering. The need for a tool that explicitly considers the inelastic deformation experienced by the structural members during earthquakes without carrying out complex and computational costly nonlinear dynamic analyses led researchers to develop the *nonlinear static* methods of analysis (Bosco *et al*., 2009; Fajfar and Gaspersic, 1996; Fajfar, 1999; Freeman, 1998). The use of these methods is already allowed by current seismic codes (for instance CEN EN 1998, 2004). Unfortunately, nonlinear static methods are not very effective in the evaluation of the seismic response of three-dimensional structures because they do not provide a reliable estimate of the deck rotations (Chopra and Goel, 2004; Fajfar *et al*., 2005; Marušić and Fajfar, 2005).

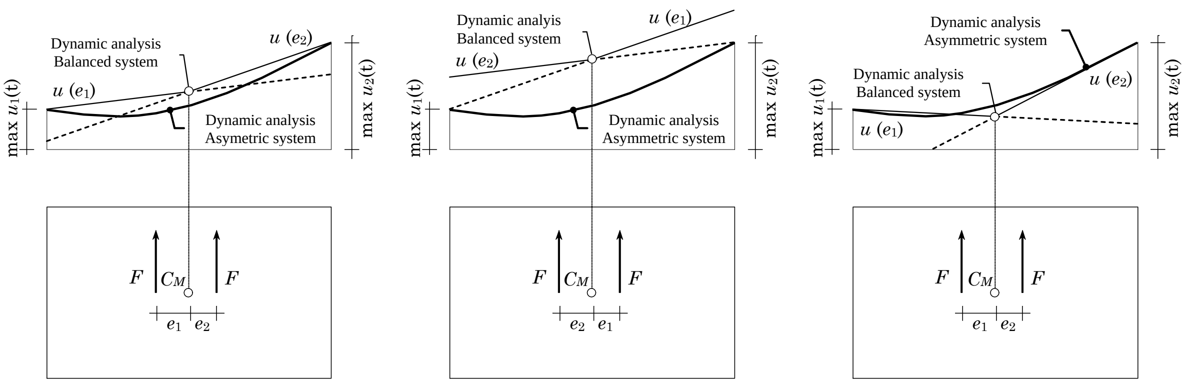
The authors of this paper have recently proposed a nonlinear static approach for asymmetric structures (Bosco *et al*., 2012) which is alternative to that stipulated by seismic codes and will be named hereinafter *corrective eccentricity method*. According to this approach, the nonlinear static analysis is performed twice, applying the lateral forces with two different eccentricities with respect to the centre of mass. These eccentricities, named *corrective eccentricities*, were calibrated by a parametrical study on single-storey systems. These systems were subjected to bidirectional ground motions so that the two corresponding nonlinear static analyses provide displacements that are equal to those evaluated by nonlinear dynamic analysis at the two sides of the deck. The analysed single-storey systems were constituted by a rigid deck, where the mass is lumped, supported by vertical resisting elements with lateral stiffness and strength in their plane only (*uni-directional resisting elements*).

Single-storey models are widely adopted to investigate the torsional behaviour of buildings (Bosco *et al*., 2012). In fact, these systems represent the extreme schematization of a real building and, although they do not cover some peculiarities related to the heightwise distribution of structural properties (Anagnostopoulos *et al*., 2010; De Stefano *et al*., 2013, De Stefano *et al*. 2014; Ghersi *et al*., 2007), they are able to describe the main aspects of the torsional seismic behaviour of actual asymmetric buildings which are regular in elevation (Fujii, 2014; Palermo *et al*., 2013; Peruš and Fajfar, 2005). However, the single-storey models with uni-directional resisting elements adopted by Bosco *et al*. (2012) may be considered representative of multi-storey buildings in which seismic forces are sustained by braced frames or shear walls. Instead, these models are less effective in simulating the response of r.c. and steel framed structures (Bosco *et al*., 2015). The vertical resisting elements of these structures, i.e. the columns, provide lateral stiffness and strength in all the horizontal directions and are characterised by a bi-axial yield domain such that the presence of bi-axial bending reduces their strength capacity (interaction phenomena). These aspects are neglected when using uni-directional resisting elements.

Based on the above considerations, in this paper the corrective eccentricities are re-determined for a set of single-storey systems with resisting elements that provide lateral stiffness and strength in all the horizontal directions and possess a bi-axial yield domain (*bi-directional resisting elements*). The results of the numerical investigation are used to define new equations, which provide the values of the corrective eccentricities as functions of the structural parameters that control the seismic response of asymmetric single-storey systems. These parameters are the rigidity eccentricity e_r (distance between the centre of rigidity C_R and the centre of mass C_M), the ratio Ω_θ of the torsional to lateral frequencies of the corresponding torsionally balanced system (obtained by shifting C_M into C_R), the strength eccentricity e_s (distance between the centre of strength C_S and C_M) and the ratio R_μ of the elastic strength demand to the actual strength of the system. Finally, the effectiveness of the proposed equations is demonstrated showing that they lead to an estimate of the maximum dynamic displacements significantly better than that obtained by a single pushover analysis performed applying the seismic force to the mass centre of the deck, as stipulated in seismic codes.

2. Corrective eccentricities

The corrective eccentricity method is based on the observation that the distribution of the maximum dynamic displacements of the deck is nonlinear (because such displacements are reached in different times) and generally cannot be approximated adequately by a nonlinear static analysis which, being the deck rigid, always provides a linear distribution of displacements. Thus, the maximum dynamic displacements of the asymmetric single-storey system subjected to ground motions is estimated by two pushover analyses. For each pushover analysis the point of application of the seismic force F is shifted from C_M by a corrective eccentricity e_i. The two corrective eccentricities are defined so that the two pushover analyses provide exactly the maximum dynamic displacements of the two sides of the deck.



(a) **(b)** **(c)**

Fig. 1 – Envelope of dynamic displacements vs. displacements determined by the nonlinear static method and corrective eccentricities: (a) $u_{CM,b}$> $u_{CM,a}$, e_1<e_2, (b) $u_{CM,b}$> $u_{CM,a}$, e_1>e_2, (c) $u_{CM,b}$< $u_{CM,a}$

Figure 1.compares the in-plan distribution of the maximum horizontal displacements determined by nonlinear dynamic analysis to those obtained by the two pushover analyses. Note that the use of a conventional displacement spectrum in nonlinear static method of analysis for estimating the displacement demand usually provides errors even for symmetric systems (Bosco *et al*., 2009). In order to avoid this, each pushover analysis is stopped when the displacement of the centre of mass of the asymmetric system equals the value of the maximum displacement provided by the nonlinear dynamic analysis of the *corresponding planar system* (i.e. of the system obtained by restraining the deck rotation of the asymmetric system). For the intermediate points of the deck, the envelope of the displacements obtained by the two pushover analyses provides a conservative estimate of displacements if the dynamic displacement of the centre of mass of the asymmetric system is smaller than that of the corresponding planar system (Fig. 1a and Fig. 1b), otherwise it can be slightly unconservative for some points (Fig. 1c).

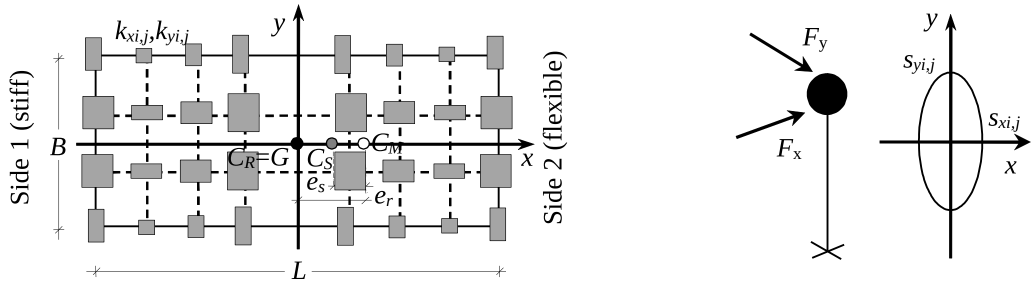
2.1. Determination of corrective eccentricities

Pushover and nonlinear dynamic analyses are carried out to determine the corrective eccentricities for the evaluation of the dynamic response of asymmetric systems. The numerical investigation is conducted on a wide set of mono-symmetric single-storey systems with bi-directional resisting elements. For both pushover and nonlinear dynamic analyses, an elastic-perfectly plastic constitutive relation following the normality rule is adopted for the resisting elements, and interaction phenomena arising in the nonlinear range of behaviour are accounted for by means of an elliptical yield domain. A Rayleigh viscous damping is used for nonlinear dynamic analysis and set at 5% for the first and the third mode of vibration. The dynamic response is evaluated by step-by-step integration of the equations of motion by the Newmark method with parameters α and δ set at 0.25 and 0.5, respectively. Bi-directional ground motions are used for nonlinear dynamic analysis while the seismic force applied for pushover analysis is orthogonal to the axis of symmetry of the system. A computer program developed by the authors is used to perform all the numerical analyses.

2.2. Structural systems

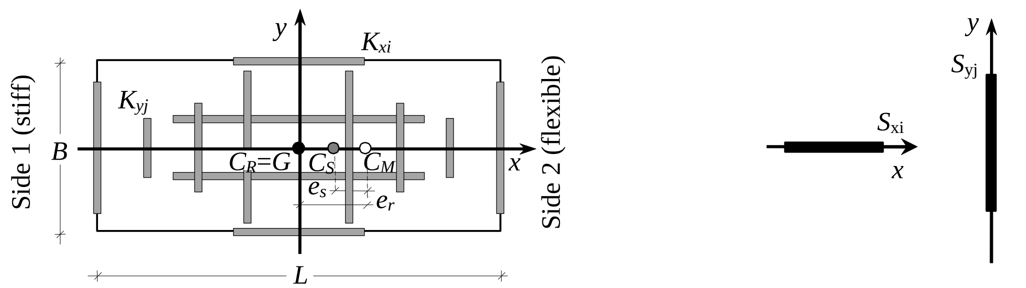
The deck of all the analysed systems is rectangular in plan and have dimensions, denoted as *B* and *L* in Fig. 2, equal to 12.5 m and 29.5 m, respectively. The mass of the deck *m* is equal to 1416 t, while the mass radius of gyration r_m about the centre of mass C_M is equal to 0.312 *L*.

The considered systems have values of Ω_θ which range from 0.8 to 1.2 in steps of 0.05. These values of Ω_θ are representative of actual framed structures, which generally range from moderately torsionally flexible (Ω_θ = 0.8) to moderately torsionally stiff systems (Ω_θ = 1.2). For each value of Ω_θ several values of e_r, from -0.1 *L* to 0 in steps of 0.025 *L*, are considered to include both systems with small and large rigidity eccentricity. The analysed systems are characterised by ratios R_μ from 2.0 to 6.0 in steps of 1.0. This range of R_μ include systems that experience moderate or large inelastic deformations. In fact, systems that behave almost elastically during the earthquake may be adequately assessed by linear methods of



(a) **(b)**

Fig. 2 – Analysed single-storey systems: (a) Plan layout of the systems; (b) bi-axial yield domain of the resisting elements



(a) **(b)**

Fig. 3 – Analysed single-storey systems: (a) Plan layout of the systems; (b) uni-directional resistance of the resisting elements

analysis and, therefore, are out of the scope of this paper. Finally, for each value of R_μ, values of e_s, from -0.1 L to 0.1 L in steps of 0.025 L, are considered.

The position and the mechanical properties of the resisting elements are derived from the systems with uni-directional resisting elements analysed by Bosco *et al*. (2012). In these systems (Fig. 3), the resisting elements are arranged along the axes of the assumed reference system. The contribution γ_x of the resisting elements arranged along the *x*-axis to the total torsional stiffness of the system about the centre of rigidity C_R is equal to 20%. The total lateral stiffnesses of the resisting elements arranged along the *x*- and *y*- directions are determined so that the periods of the corresponding planar system in the *x*- and *y*-direction are equal to 1 s. Then, the stiffnesses are distributed among the resisting elements arranged along the *x*- and *y*-direction (K_{xi}, K_{yi}) to obtain the prefixed values of Ω_θ. Symmetry is maintained with respect to the *x*-axis. Structural systems with prefixed values of e_r are generated by modifying the position of C_M. The total lateral strengths in the *x*- and *y*-direction are assigned so as to have pre-fixed values of the ratio R_μ of the corresponding planar system. Then, the lateral strength is distributed among the resisting elements in order to have the assigned values of the strength eccentricity e_s. Furthermore, in order to consider the influence of the strength distribution on the inelastic seismic response of the systems, ten random distributions of strength S_{xi}, S_{yi} are generated for each value of e_s. Further details may be found in Bosco *et al*. (2012). The (bi-directional) resisting elements of the analysed systems (Fig. 2a) are located at the intersection of the axes of the resisting elements of the systems analysed by Bosco *et al*. The components along the *x*- and *y*-directions of the lateral stiffness ($k_{xi,j}$, $k_{yi,j}$) and strength ($s_{xi,j}$, $s_{yi,j}$) of the bi-directional resisting element located at the intersection of the corresponding *i*-th and *j*-th uni-directional elements are obtained by the relations:

$$k_{xi,j} = \frac{K_{xi}}{n_y} \qquad k_{yi,j} = \frac{k_{yj}}{n_x} \tag{1}$$

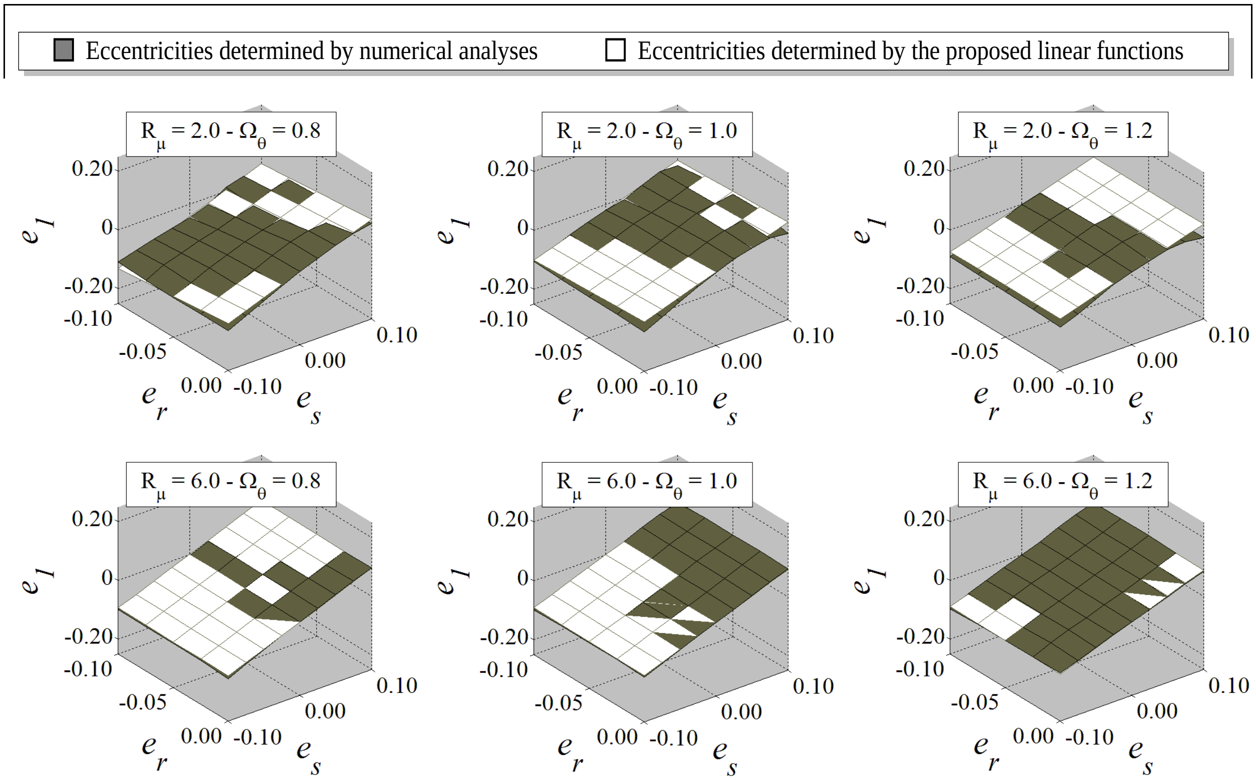


Fig. 4 – Corrective eccentricities for side 1 (stiff side) as a function of e_r and e_s

$$s_{xi,j} = \frac{S_{xj}}{n_y} \qquad s_{yi,j} = \frac{S_{yj}}{n_x} \qquad (2)$$

where $n_y = 8$ and $n_x = 4$ are the number of resisting elements arranged along the *y*- or *x*-direction in the systems with uni-directional resisting elements.

2.3. Numerical analyses

The response of each single-storey asymmetric system to a set of artificial accelerograms is first determined by nonlinear dynamic analysis. The set of ground motions is constituted by ten pairs of artificial accelerograms, generated by the SIMQKE computer program (1976), and is compatible with the EC8 elastic spectrum for soil type C and characterised by 5% damping ratio and peak ground acceleration a_g equal to 0.35 *g*. The displacement demand along the *y*-direction of the points of the deck is the mean value of the 10 maximum displacements obtained for the 10 pairs of ground motions. Afterwards, pushover analysis of the system is conducted several times considering different positions of the point of application of the seismic force C_F. The seismic force is applied along the *y*-direction. The pushover analysis is always stopped when the displacement of the centre of mass of the asymmetric system is equal to the average of 10 maximum displacements of the corresponding planar system evaluated by nonlinear dynamic analysis. Consistently with the nonlinear static analysis, when the corresponding planar system is considered, ground motions are considered along the *y*-direction. The position of C_F is defined by its eccentricity *e* with respect to C_M. The eccentricities that provide displacements at the first (left) and the second (right) sides of the deck which are equal to those determined by nonlinear dynamic analysis are the corrective eccentricities e_1 and e_2, respectively. Their values are searched in the range from -0.25 *L* to 0.25 *L* by the bisection method. Note that if e_1 is larger than e_2, the displacements obtained by the envelope of the results of the two pushover analyses are always conservative. In this case, each corrective eccentricity between e_2 and e_1 is suitable for the estimation of the deck displacements by pushover analysis. For given values of e_r, e_s, Ω_θ and R_μ the COV of the values of the corrective eccentricities found for the ten strength distributions considered is very small; as a consequence, the average of these values is assumed as the corrective eccentricity.

3. Analytical formulation of corrective eccentricities

Corrective eccentricities e_1 and e_2 are represented as a function of e_r and e_s for the considered values of Ω_θ and R_μ. In Fig. 4 the grey surfaces provide the corrective eccentricities for side 1 (stiff side) of systems with Ω_θ = 0.8, 1.0 and 1.2 and R_μ = 2.0 and 6.0. When e_1 is smaller than e_2, the corrective eccentricity represented in Fig. 4 is the same for both sides and is conventionally taken as the mean value of e_1 and e_2. The obtained surfaces have a regular trend, similar to planes, and depend on Ω_θ and R_μ. Hence, the surfaces describing the corrective eccentricities are approximated by linear functions of e_r and e_s. This consideration is also valid for the Ω_θ-R_μ pairs which are not shown in Fig. 4 and for side 2. The coefficients that define these functions are first determined for each Ω_θ-R_μ pair. Then, the obtained values of each coefficient are interpolated by analytical functions of Ω_θ and R_μ.

3.1. Linearization of corrective eccentricity surfaces

The corrective eccentricities e_1 and e_2 have to be equal to zero if $e_r = e_s = 0$. In fact, a system with $e_r = e_s = 0$ is torsionally balanced and does not need any corrective eccentricity. Based on these considerations the function for the determination of the corrective eccentricity e_i may be written as follows

$$e_i = a_i\ e_s + b_i\ e_r \qquad \text{with } i = 1 \text{ or } 2 \tag{3}$$

where the coefficients a_i and b_i depend on Ω_θ and R_μ. These coefficients are determined for all the considered pairs of Ω_θ and R_μ by minimizing the standard deviation of the differences between the corrective eccentricities provided by Eq. (3) and those obtained by the numerical investigation. When e_2 is smaller than e_1, if the corrective eccentricity calculated by Eq. (3) is between e_2 and e_1, the scatter is conventionally assumed null because, as shown in Section 2, each value of corrective eccentricity between e_2 and e_1 is suitable. Instead, if the value of the corrective eccentricity provided by Eq. (3) falls out of the range e_2-e_1, the scatter considered is the minimum of the scatters between the value of e_i obtained by Eq. (3) and the values of e_1 and e_2 determined by the numerical analyses.

3.2. Equations for the evaluation of corrective eccentricities

The results of the numerical analyses presented in Section 3.1 are used for the determination of analytical equations which express the coefficients a_i and b_i of Eq. (3) as functions of Ω_θ and R_μ.

$$\begin{aligned} a_1 &= \begin{cases} m_{a1}\ R_\mu + t_{a1} & R_\mu \le 3 \\ k_{a1} & R_\mu > 3 \end{cases} \\ & m_{a1} = 0.272\ \Omega_\theta - 0.167 \\ & t_{a1} = -0.975\ \Omega_\theta + 1.583 \\ & k_{a1} = 3\ m_{a1} + t_{a1} \end{aligned} \tag{4a}$$

$$\begin{aligned} b_1 &= m_{b1}\ R_\mu + t_{b1} \\ & m_{b1} = 0.266\ \Omega_\theta - 0.319 \\ & t_{b1} = -\ 0.532\ \Omega_\theta + 0.638 + 2^\beta\ \alpha \\ & \alpha = -1.955\ \Omega_\theta + 2.346 \\ & \beta = -0.236\ \Omega_\theta - 0.778 \end{aligned} \tag{4b}$$

$$a_2 = -0.513\ \Omega_\theta + 1.444 \tag{4c}$$

$$\begin{aligned} b_2 &= m_{b2}\ R_\mu + t_{b2} \\ & m_{b2} = 0.187\ \Omega_\theta - 0.131 \\ & t_{b2} = -\ 1.467\ \Omega_\theta + 0.992 \end{aligned} \tag{4d}$$

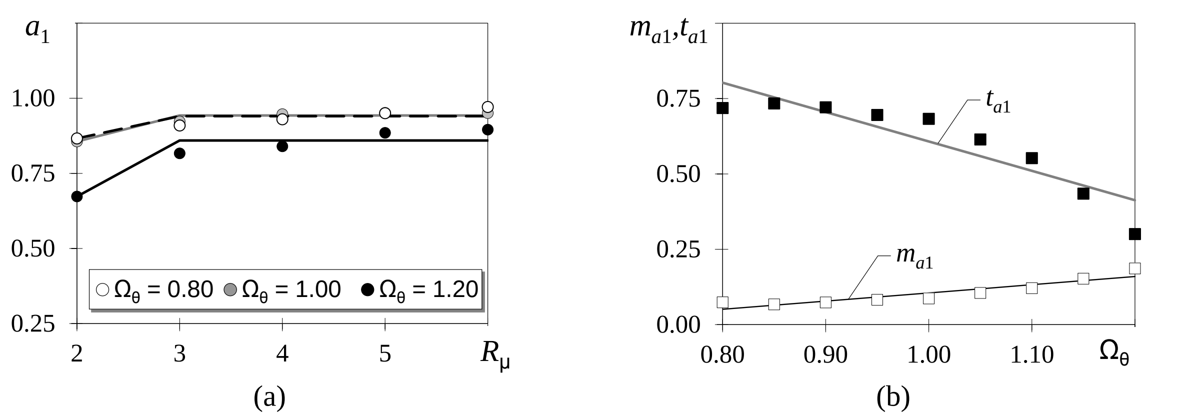


Fig. 5 – (a) Calibration of the coefficient a_1, (b) m_{a1} and t_{a1}

Two equations are determined for the evaluation of the coefficient a_1 (first coefficient of Eq. (3) for the corrective eccentricity of side 1). The first equation, which is a linear function of R_μ, is valid for $R_\mu \leq 3$, while the second equation is independent of R_μ and applies for $R_\mu > 3$. Furthermore, the two equations relate a_1 to Ω_θ by the coefficients m_{a1}, t_{a1} and k_{a1}. In order to determine the two equations, the obtained values of a_1 are plotted for different values of Ω_θ as a function of R_μ (Fig. 5a). Then, for each Ω_θ, the values of a_1 are fitted by the linear function of Eq. (4a) for $R_\mu \leq 3$ and by the constant function of Eq. (4a) for $R_\mu > 3$. For $R_\mu = 3$, the two unknown functions have to be coincident. This conditions relates k_{a1} to m_{a1} and t_{a1} in Eq. (4a). Instead, the coefficients m_{a1} and t_{a1} are calibrated for each value of Ω_θ by minimizing the standard deviation of the differences between the values of a_1 provided by the proposed equations and those obtained by the numerical investigation presented in Section 3.1. The obtained values of m_{a1} and t_{a1} are plotted as functions of Ω_θ (Fig. 5b) and fitted by linear functions. The procedure provides Eq. (4a). The same procedure applies for the determination of Eqs. (4b), (4c) and (4d), which provide the coefficients b_1, a_2 and b_2. However, in these cases, the procedure is simpler because the values numerically determined of each of the coefficients b_1, a_2 and b_2 are approximated by one equation. The procedure is similar to that adopted in (Bosco *et al*., 2012).

The planes for the estimate of e_1 in systems with Ω_θ = 0.8, 1.0 and 1.2 and R_μ = 2 and 6.0 are superimposed in Fig. 4 (white surfaces) to those obtained by the numerical investigation (grey surfaces). The comparison between the grey and white surfaces shows that the values of corrective eccentricities estimated by Eq. (3) are always close to those obtained by the numerical investigation. Similar results are obtained for the cases not shown in Fig. 4 and for the corrective eccentricity e_2.

4. Validation of the proposed equations

The use of corrective eccentricities is proposed by the authors to improve the prediction of the maximum dynamic displacements of asymmetric single-storey systems subjected to seismic excitation that could be obtained by the application of nonlinear static method according to current seismic codes (for instance EC8, 2004). Hence, the benefit that may be obtained by the proposed method is evidenced comparing the error committed for the displacements of the two sides of the deck when the nonlinear static method is applied with or without the corrective eccentricities provided by Eqs. (4a), (4b), (4c) and (4d).

The error is evaluated as the percentage difference between the displacements estimated by the nonlinear static method and the actual maximum displacements determined by nonlinear dynamic analysis. This error is assumed negative when the prediction provided by the nonlinear static method is unconservative. Errors Err_1 obtained for the side 1 of the systems with Ω_θ = 0.8, 1.0 and 1.2 and R_μ = 2 and 6.0 are plotted in Fig. 6 as a function of e_r and e_s. It is notable that, when the nonlinear static method is applied without corrective eccentricities, a reliable estimate of the displacement of side 1 is never obtained. The largest errors are committed for systems with Ω_θ = 0.8 and 1.0 that experience large inelastic deformations (R_μ = 6) independently of e_r; in these cases the prediction of the displacement of side 1 may underestimate the real value even of 100% (e_s = 0.1 L). Instead, when the nonlinear static method is adjusted by the corrective eccentricity e_1 the prediction is significantly improved and the

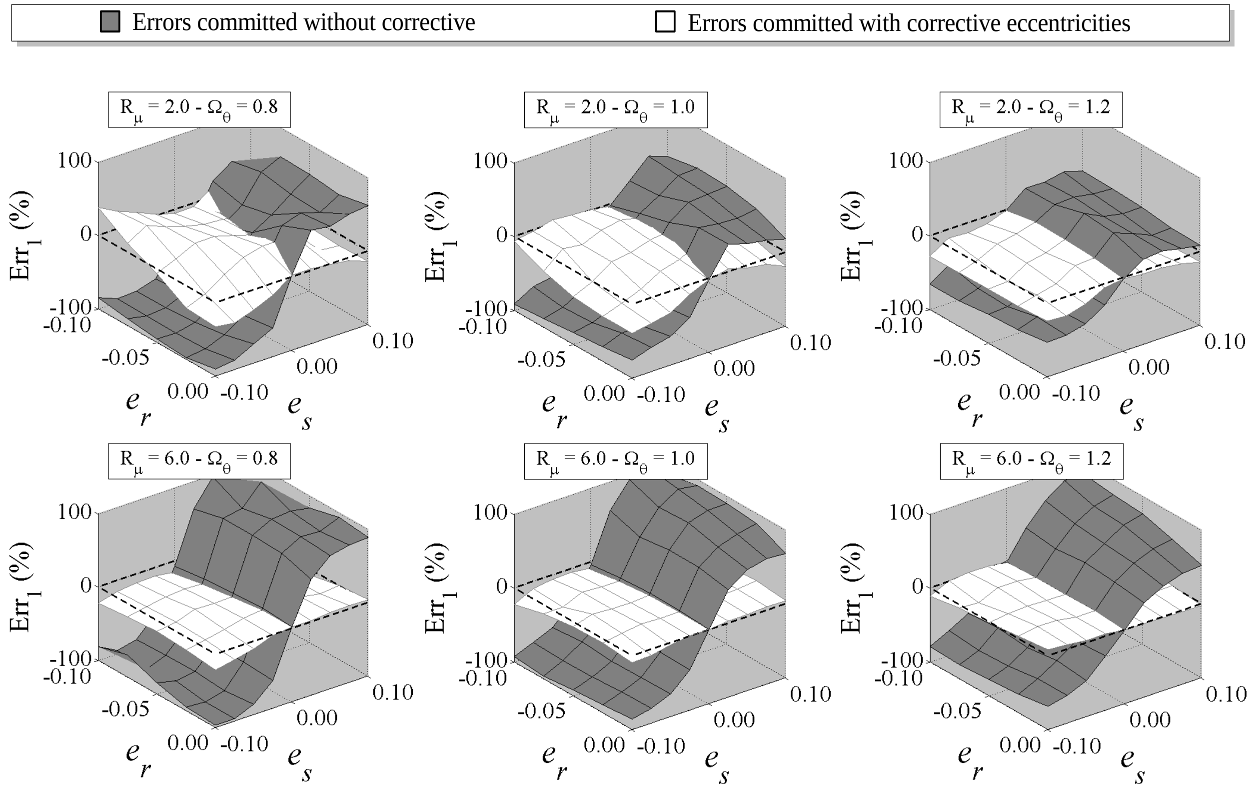


Fig. 6 – Error on the estimation of maximum displacement of side 1 (stiff side)

percentage error is always close to 0; the maximum underestimation of the displacement of side 1, which is obtained for the system with Ω_θ = 0.8, R_μ = 2, e_r = 0 and e_s = -0.1 L, is about 25%. The errors Err_2 committed in the prediction of the displacement of side 2 of the systems with Ω_θ = 0.8, 1.0 and 1.2 and R_μ = 2 and 6.0 are plotted in Fig. 7. The use of the corrective eccentricity e_2 improves the prediction with respect to that obtained when the nonlinear static method is applied without corrective eccentricity. However, in this case the prediction obtained without corrective eccentricities leads to errors smaller than those committed for the displacement of side 1 and are acceptable for some systems (for instance, systems with Ω_θ = 1.2 and R_μ = 2).

5. Conclusions

In this paper a set of analytical equations for the determination of the corrective eccentricities is defined. These corrective eccentricities are determined on the basis of a numerical investigation on single-storey systems with bi-directional resisting elements characterised by vales of Ω_θ ranging from 0.8 to 1.2 and R_μ larger than 2. These simplified systems are representative of framed structures that experience moderate or large inelastic deformations. The reliability of the proposed equations is demonstrated by the comparison of the percentage errors committed when the nonlinear static method is applied with and without the proposed corrective eccentricities. The use of the nonlinear static method according to the formulation stipulated by seismic codes often leads to significant underestimation of the displacement of the stiff side of the deck (up to 100% in some cases), while the proposed method provides errors which are definitely smaller in all the analysed cases. The prediction of the displacement of the flexible side obtained by the nonlinear static method without corrective eccentricities is better than that obtained for the stiff side. However, the use of the eccentricity method improves significantly this prediction and leads to errors which are close to zero. In order to generalise the obtained results, systems characterised by different values of periods should be investigated. Finally, it should be noted that single-storey systems are very simplified numerical model and neglect important features of actual buildings. Therefore, the effectiveness of the corrective eccentricities determined in this paper should be investigated by more realistic multi-storey models.

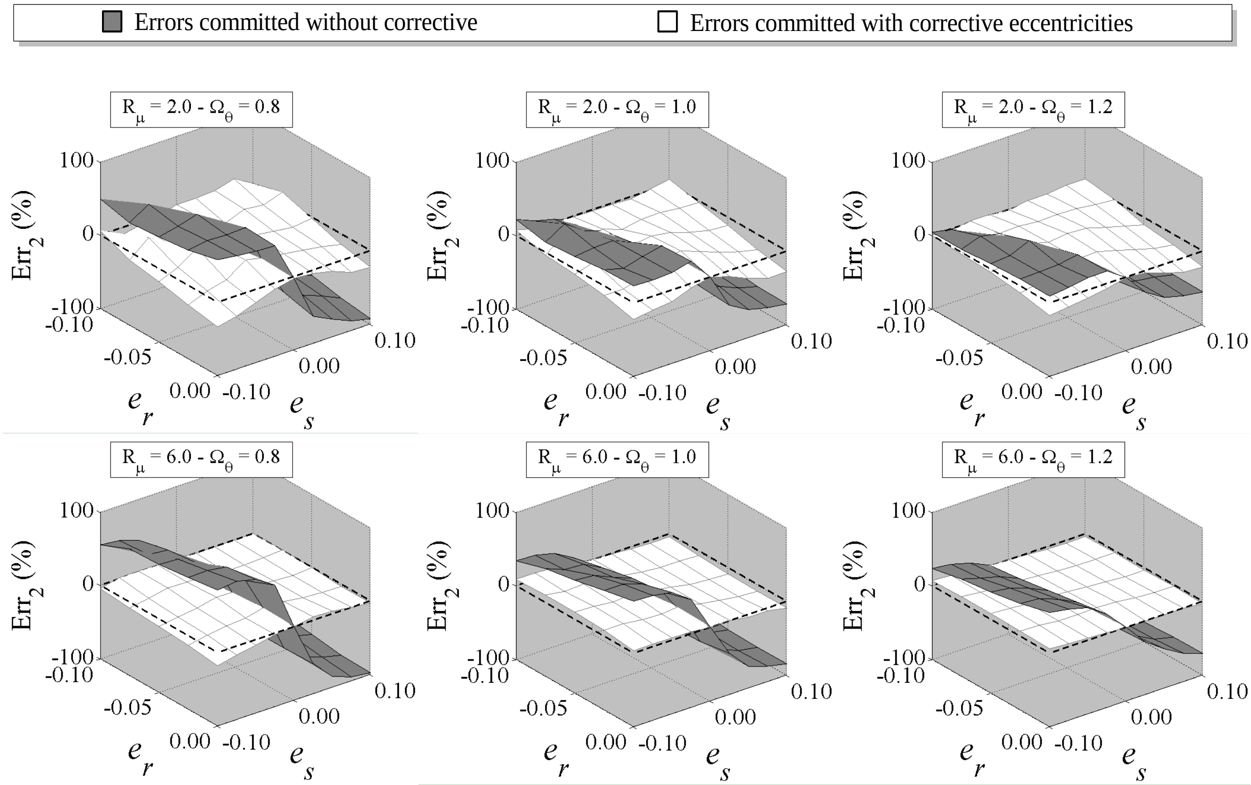


Fig. 7 – Error on the estimation of maximum displacement of side 2 (flexible side)

6. Acknowledgements

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