Static vs. Modal Analysis of Asymmetric Buildings: Effectiveness of Dynamic Eccentricity Formulations

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The use of modal analysis appears necessary in order to reduce both displacement demand under weak seismic events and ductility demand under strong earthquakes. Static analysis can be effective only if used with proper values of additional eccentricities. To overcome the inaccuracy of the code formulations, the authors propose a simple procedure that gives the exact values of these eccentricities and discuss the influence of the main parameters that govern the structural behavior. They also point out the difficulty in evaluating some parameters (stiffness radius of gyration, structural eccentricity) in the case of multistory buildings and discuss the validity of simplified formulations proposed to overcome this problem. The effectiveness of static analysis, applied to three-dimensional multistory structures with properly evaluated corrective eccentricities, is analyzed with reference both to regularly asymmetric multistory schemes and to an actual irregularly asymmetric structure (the main building of the Faculty of Engineering at the University of Catania, Italy). [DOI: 10.1193/1.1494085]

INTRODUCTION

In the past, in-plan irregular buildings have often shown a bad seismic behavior, both in the case of weak earthquakes, which caused large lateral displacements and damage to nonstructural elements, and in the case of strong earthquakes, which produced unexpected collapses due to the early failure of the outermost resisting elements. Although many different aspects may contribute to this (e.g., the influence of nonstructural elements and the difficulty in modeling their contribution or the negative effect of stress concentrations in some members of the frame and in the floor slabs), the torsional movements caused by the lack of symmetry are particularly responsible for such poor seismic response. The elastic behavior (i.e., the effect of weak earthquakes) may be adequately foreseen by means of modal analysis. The inelastic response is less easily predictable, because its study requires both the use of more sophisticated and cumbersome tools of analysis and the investigation of the effect of a wide set of seismic records. Specific design provisions are therefore necessary to the structural engineer in order to improve simply the seismic behavior of irregular buildings (Ghersi and Rossi 2000). It has, however, been proved in another paper (Ghersi et al. 1999) that the use of modal analysis, instead of the static one, is in itself a good way of reducing the ductility demand without

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significantly increasing the structural strengths and costs, mainly in the case of torsionally flexible schemes. Modal analysis therefore appears to be the only correct approach to the design of asymmetric structures.

Nevertheless, all seismic codes allow the use of static analysis, which is still the most common approach followed by structural designers. In the attempt to overcome the inaccuracy of this kind of analysis, the codes prescribe the use of additional eccentricities, also called dynamic or corrective eccentricities. In most cases (e.g., UBC, NZS) simple formulations are provided, in which the additional eccentricity is a given aliquot of the stiffness eccentricity of the system. Much more complex expressions are provided by the European seismic code (EC8), which are related to studies carried on by Müller and Keintzel (1978, 1984), although one of the authors later on recognized the limits of these formulations (Eibl and Keintzel 1996). As a matter of fact, none of the simple formulations provided by the seismic codes seems effective enough (e.g., see Fajfar et al. 1988; Calderoni et al. 1994, 1995, 1996).

A clear and comprehensive study of this subject, recently presented by Anastassiadis et al. (1998), included a set of formulas which, for a single-story scheme, allow the evaluation of the exact additional eccentricities necessary to obtain by means of static analysis the maximum displacements at both sides of the deck, or the maximum deck rotation, given by modal analysis. Because of the necessity for some analytical simplifications, the suggested expressions are only valid if both periods of vibration correspond to the same branch of the response spectrum (either constant or hyperbolic), although more complicated formulations may be used in the general case of a multibranch spectrum. An alternative approach, proposed by some of the authors in a previous paper (Calderoni et al. 1994), requires the use of a procedure, i.e., of a set of simple sequential operations strictly related to the meaning of the modal and static approach, instead of a single complex formula. The procedure leads to a rigorous solution both for single-story schemes and for regularly asymmetric multistory buildings. The approach is thoroughly explained and discussed in the next section and the values of additional eccentricities are plotted versus the main parameters (stiffness eccentricity and uncoupled lateral-torsional frequency ratio), so as to point out some differences connected to the shape of the response spectrum and to other parameters (mass radius of gyration, location of the mass center).

PROCEDURE FOR THE EVALUATION OF CORRECTIVE ECCENTRICITIES

The analysis of single-story schemes is necessarily the first step in the study of asymmetric buildings. Only these simplified models can in fact clarify the basic aspects of the dynamic torsional behavior of actual multistory structures. The single-story system (Figure 1) is an idealized one-story structure with lateral load resisting elements connected by a horizontal rigid floor diaphragm, the movement of which is completely described by three degrees of freedom. Most researchers have based their studies on a simpler model, which neglects the transverse motion (e.g., see Tso and Dempsey 1980), although the simultaneous presence of two orthogonal seismic components or the contemporary eccentricity in two orthogonal directions may have some importance, mainly in the inelastic range (Ghersi and Rossi 1999, 2001).

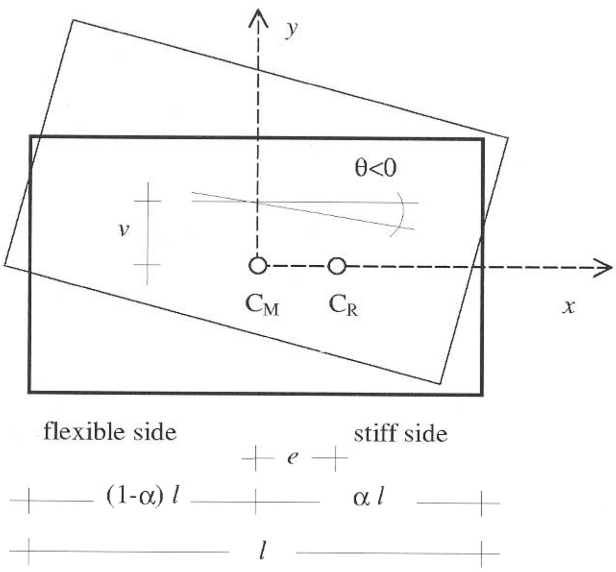

Figure 1. Two-degree-of-freedom system.

While the inelastic behavior depends on stiffness, strength, and location of all the resisting elements, the elastic response of the single-story system is governed by few global parameters (eccentricity between mass and stiffness centers e_s, radius of gyration of mass r_m and stiffness r_k, uncoupled lateral period of vibration T_y). Both static and modal analysis may therefore be performed by means of simple analytical expressions. In order to evaluate the corrective eccentricities, it is first necessary to define the criterion of equivalence between the two types of analyses.

Three eccentricities may be in general defined, Δe_θ, Δe_r, Δe_l, which are necessary to equate the maximum rotation and the maximum displacement at the right and left side of the deck, respectively. The first is considered important by some researchers (e.g., see Anastassiadis et al. 1998), while others, including the authors, judge it insignificant because the maximum internal actions in the members of a generic frame are related only to the maximum horizontal displacements, independent of the rotation of the decks that have caused them. The procedure for evaluating the corrective eccentricities Δe_r, Δe_l may be arranged according to the following steps, using normalized values for the sake of simplicity (see Notation):

1. Evaluation of the uncoupled lateral frequency ω_y and the normalized natural frequencies $\Omega_j\,(j=1-2)$:

$$\omega_y = \sqrt{\frac{K_y}{m}} \qquad \Omega_j^2 = \frac{R_m^2+R_k^2+E_s^2 \mp \sqrt{(R_m^2+R_k^2+E_s^2)^2-4R_m^2R_k^2}}{2R_m^2}$$

2. Evaluation of the normalized spectral acceleration $S_{a,j}$ corresponding to the natural frequencies ω_j of the system $(j=1-2)$. Note that the corrective eccen-

tricities depend only on the shape of the response spectrum, not on its actual values; it is therefore the same to use the spectral acceleration $s_{a,j}$ or any proportional coefficient;

3. Evaluation of the contribution of each mode (normalized displacement of mass center V_j and normalized rotation of the deck θ_j, $j=1-2$):

$$V_j=S_{a,j}\frac{E_s}{\Omega_j^2[E_s^2+R_m^2(\Omega_j^2-1)^2]}E_s;\quad \theta_j=S_{a,j}\frac{E_s}{\Omega_j^2[E_s^2+R_m^2(\Omega_j^2-1)^2]}(\Omega_j^2-1)$$

4. Evaluation, for each mode, of the normalized displacements at both sides of the deck:

$$V_{r,j}=V_j+\alpha\theta_j;\quad V_{l,j}=V_j+(\alpha-1)\theta_j$$

5. Evaluation of the combined normalized displacements V_r and V_l at both sides of the deck by means of modal superposition (according to CQC rules):

$$r_{1,2}=\frac{\Omega_2}{\Omega_1};\quad \varepsilon_{1,2}=\frac{8\zeta^2(1+r_{1,2})r_{1,2}^{3/2}}{(1-r_{1,2}^2)^2+4\zeta^2 r_{1,2}(1+r_{1,2})^2}$$

$$V_p=\sqrt{V_{p,1}^2+V_{p,2}^2+2\varepsilon_{1,2}V_{p,1}V_{p,2}},\quad \text{being}\quad p=r,l$$

6. Evaluation of the normalized spectral acceleration $S_{a,y}$ corresponding to the uncoupled lateral frequency ω_y (see note at step 2);

7. Evaluation of the normalized displacement at both sides of the deck caused by a unit force applied at C_M ($V_{r,F}$, $V_{l,F}$) and a unit moment ($V_{r,M}$, $V_{l,M}$)

$$V_{r,F}=1+\frac{E_s^2}{R_k^2}-\alpha\frac{E_s}{R_k^2};\quad V_{l,F}=1+\frac{E_s^2}{R_k^2}-(\alpha-1)\frac{E_s}{R_k^2}$$

$$V_{r,M}=-\frac{E_s}{R_k^2}+\alpha\frac{1}{R_k^2};\quad V_{l,M}=-\frac{E_s}{R_k^2}+(\alpha-1)\frac{1}{R_k^2}$$

8. Evaluation of the corrective eccentricities ΔE_r and ΔE_l:

$$\Delta E_r=\frac{V_r/S_{a,y}-V_{r,F}}{V_{r,M}};\quad \Delta E_l=\frac{V_l/S_{a,y}-V_{l,F}}{V_{l,M}}$$

According to the sign convention adopted, the procedure is valid both for positive and negative stiffness eccentricities, i.e., independent of whichever is the stiff or the flexible side of the deck. The corrective eccentricities ΔE_r and ΔE_l have to be taken into account only when they increase the edge displacement, i.e., when $\Delta E_r>0$ and $\Delta E_l<0$, respectively, independent of the stiffness eccentricity sign.

DISCUSSION OF CORRECTIVE ECCENTRICITY VALUES

Figures 2 and 3 synthesize the results of a wide numerical analysis, performed by applying the above procedure to schemes having different values of R_m (0.30, 0.35, 0.40) and of the position of the mass center ($\alpha=0.40$, 0.50, 0.60) and using different design spectra (constant, hyperbolic, or constant-hyperbolic, with the exponent of the hyperbolic branch equal to -1 and $-2/3$). In each case the uncoupled lateral-torsional frequency ratio $\Omega_\theta=R_k/R_m$ has been varied in the range 0.4 to 1.8 and the structural eccentricity E_s in the range 0 to 0.20.

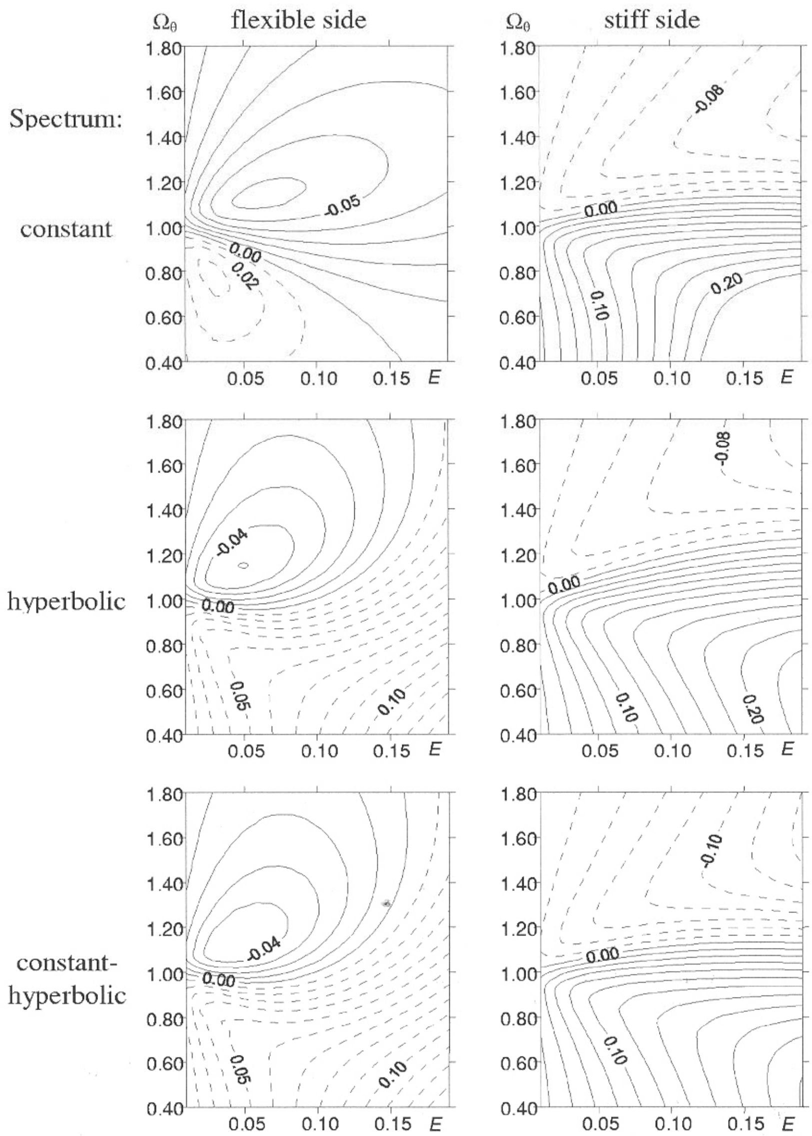

Figure 2. Corrective eccentricity for flexible and stiff side, in the case of constant, hyperbolic, and constant-hyperbolic spectra (α=0.50, R_m=0.30).

It may be firstly noted that, in general, a corrective eccentricity Δe is necessary to improve the behavior at the flexible side only in the case of torsionally stiff systems (Ω_θ>1). It reaches a maximum of about 0.05 L for schemes having medium eccentricity (from 0.05 to 0.10 L) and only slightly torsionally rigid (Ω_θ=1.10÷1.20). It is important to point out that a large number of actual buildings are included in these ranges. On the contrary, a corrective eccentricity is necessary for the stiff side only in the case of torsionally flexible systems (Ω_θ<1). It increases with stiffness eccentricity and as the

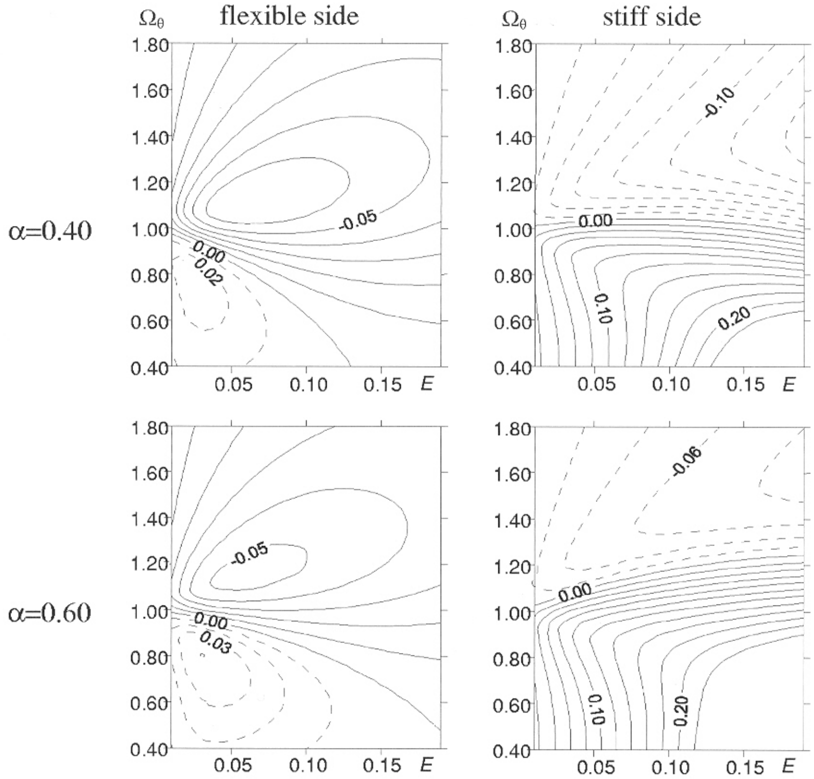

Figure 3. Corrective eccentricity for different locations of mass center (constant spectrum, R_m=0.30).

torsional stiffness decreases, and it may reach very high values (even more than 0.20 L). Preliminary numerical analyses led in the past some of the authors to suggest simplified formulations (Calderoni et al. 1996), which are now substantially confirmed, although the use of the procedure here proposed appears to be always recommendable, because it gives more reliable results with a minimum of computational effort. On the contrary, the values, provided by EC8 for the flexible side, are in agreement only in a narrow range (approximately, Ω_θ>1+10E); outside this, the EC8 additional eccentricity may reach unnecessarily high values (more than 0.10 L).

The influence of the shape of the design spectrum is particularly remarkable for the flexible side (Figure 2). When a constant spectrum is used, as for stiff structures, large values of corrective eccentricity are necessary for nearly all torsionally stiff schemes; not negligible are also the values required for torsionally flexible schemes with large eccentricity. When a hyperbolic or constant-hyperbolic spectrum is used, as for flexible structures, the corrective eccentricity decreases when the stiffness eccentricity becomes large: no corrective eccentricity is necessary both for torsionally rigid schemes having

$E>0.15$ and for torsionally flexible schemes. Less relevant is the influence for the stiff side; a slight reduction of the corrective eccentricity may be noted when a hyperbolic or constant-hyperbolic spectrum is used.

A different location of the mass center (Figure 3) may increase the corrective eccentricity necessary for the flexible side (when $\alpha=0.40$) and for the stiff one (when $\alpha=0.60$). Less relevant is the influence of R_m (not shown in the figures).

REGULARLY ASYMMETRIC MULTISTORY BUILDINGS

Although the study of single-story systems gives useful information about the torsional behavior, a basic question is whether and in what way it is possible to extend the relative results to multistory schemes. Even the fundamental definitions used in the single-story model (SS) are questionable when a multistory scheme (MS) is under discussion. The stiffness of each element of the SS is easily definable and the center of rigidity may likewise be individuated. On the contrary, each plane frame of the MS is characterized by a stiffness matrix, which makes the definition of stiffness as in the traditional meaning (scalar quantity) impossible and therefore also the evaluation of a center of rigidity. Based on the properties of the center of rigidity of SS, different researchers have proposed referring to different centers, which coincide in a unique point (*elastic center*) in single-story schemes (Cheung and Tso 1986, Hejal and Chopra 1987):

- *Centers of rigidity*, i.e., the points on the floor diaphragms through which a given set of horizontal forces causes no rotation of the floors.
- *Centers of twist*, i.e., the points on the floor diaphragms that remain fixed when a given set of torsional moments is applied to the building.
- *Shear centers*, i.e., the points on the floor diaphragms through which the resultant of the interstory shear forces passes when the floors are subjected to a given set of horizontal displacements (with no rotation of the floors).

The approach here adopted consists of defining as *lateral stiffness of a plane frame at a floor* the ratio of the global shear at that level over the interstory drift; this value depends on the force distribution along the height of the frame. Starting from this definition, for a given force distribution it is possible to evaluate both the location of C_R and the value of R_k. In most cases these parameters vary story by story and this makes it necessary to analyze the elastic response by means of multistory three-dimensional models. Only those systems characterized by equal C_M, C_R and R_k at every story (named *regularly asymmetric*) may be studied by superimposing the response of a multistory plane scheme and a single-story asymmetric model (Hejal and Chopra 1987). A sufficient (but not necessary) condition in order that a structure be regularly asymmetric is that it be constituted by plane frames equal to each other, or having the same geometrical scheme and members with proportional second order moments of the cross sections, and it present the same distribution of masses at every level.

A simple procedure for evaluating the basic parameters R_k and E_s and for checking if the structure is regularly asymmetric may be arranged in the following steps:

1. Evaluation of the static forces F according to the seismic code;

2. Evaluation of the normalized displacement of the mass center V_F and the deck rotation θ_F at every story caused by these forces applied at C_M;
3. Evaluation of the normalized displacement of the mass center V_M and the deck rotation θ_M at every story caused by torsional moments equal to $F\,E_1$ (E_1 being an arbitrary eccentricity, e.g., the accidental one);
4. Evaluation of R_k and E_s at each floor by means of the following expressions:

$$R_k=E_1\sqrt{\frac{V_F}{\theta_M E_1}-\left(\frac{\theta_F}{\theta_M}\right)^2};\quad E_s=-E_1\frac{\theta_F}{\theta_M}$$

The previous procedure may be applied using either relative or absolute displacements and rotations. If the same value of R_k and E_s is obtained for every floor, the scheme is regularly asymmetric. It is therefore possible to evaluate the corrective eccentricities ΔE_r and ΔE_l according to the procedure described on pages 220 to 222. The design internal actions in the members will be the maximum among those provided by the forces applied at C_M and at the positions $C_M+\Delta E_r$ and $C_M+\Delta E_l$.

The above given formulas, obtained by Calderoni et al. (1994) for single-story systems, are strictly valid also for regularly asymmetric multistory schemes. Different formulations, substantially coincident with them, have been proposed by Tso and Moghadam (1998), as a function of the edge displacements of the deck due to analogous load conditions (force applied at the mass center and force shifted by an accidental eccentricity).

In order to confirm the effectiveness of the proposed approach, four seven-story RC buildings, already examined by Tso and Moghadam (1998), have been analyzed here. They present a rectangular plan (24×17 m), constant story height (3 m), and three identical resisting frames along the direction of seismic action (y-axis). The frames have three bays of 6, 5, and 6 m, respectively, and rectangular beam (30×50 cm) and column (50×50 cm) cross sections. One frame is located at the center of the floor slab, while the others are placed symmetrically at opposite sides of the central one; the stiffness center C_R is thus coincident to the geometrical center of the deck. A fourth frame, along the orthogonal direction, is located at the center of the deck so as to give no contribution to the torsional stiffness of the scheme. The mass on each floor is 400 t and the corresponding translational period T_y is 1.45 s for all the buildings. The mass is assumed to be distributed so that the mass center C_M is 2.4 m to the right of C_R. The buildings are therefore asymmetric, with $E_s=-0.10$; as the eccentricity is negative, the right edge is the flexible one. The only difference among the four buildings is the distance of the lateral frames from the center of the deck, which assumes the values 3 m (B3), 6 m (B6), 9 m (B9), and 12 m (B12). Because of this, the behavior of the four buildings varies from torsionally flexible (B3, $\Omega_\theta=0.29$) to torsionally rigid (B12, $\Omega_\theta=1.15$). The buildings are designed according to the EC8 design spectrum for soil A, with $\alpha=0.25$ and $q=5$.

The proposed procedure has been applied to all the schemes, taking into account the exact shape of the EC8 spectrum. The obtained results are reported in Table 1. It can be

Table 1. Basic parameters and corrective eccentricities

	E	R_k	R_m	$\Omega_\theta = R_k/R_m$	ΔE_l	ΔE_r
B3	−0.10	0.102	0.354	0.288	**−0.1826**	−0.0169
B6	−0.10	0.204	0.354	0.577	**−0.1778**	−0.0380
B9	−0.10	0.306	0.354	0.865	**−0.1770**	−0.0296
B12	−0.10	0.408	0.354	1.153	0.0037	**0.0271**

noted that the B12 system (which is torsionally rigid) needs corrections only at the flexible side (in this case the right one), while the others, torsionally flexible, require a corrective eccentricity only at the stiff side (bold values).

The displacement diagrams of the edges of the deck provided for each floor by modal analysis (MA), standard static analysis (SA), and corrected static analysis (CSA) are reported in Figure 4. As is well known, for a multistory scheme, modal and static analyses lead to a different base shear (usually greater in the static case); therefore, for a correct comparison of the results, the reported displacements of the static analyses have been multiplied by the ratio between the modal and static base shear, evaluated for a translational scheme. The agreement between the results of modal and corrected static analysis, confirmed by the comparison of the values of internal actions in the members, shows the effectiveness of the proposal for all the analyzed buildings, independent of their torsional stiffness.

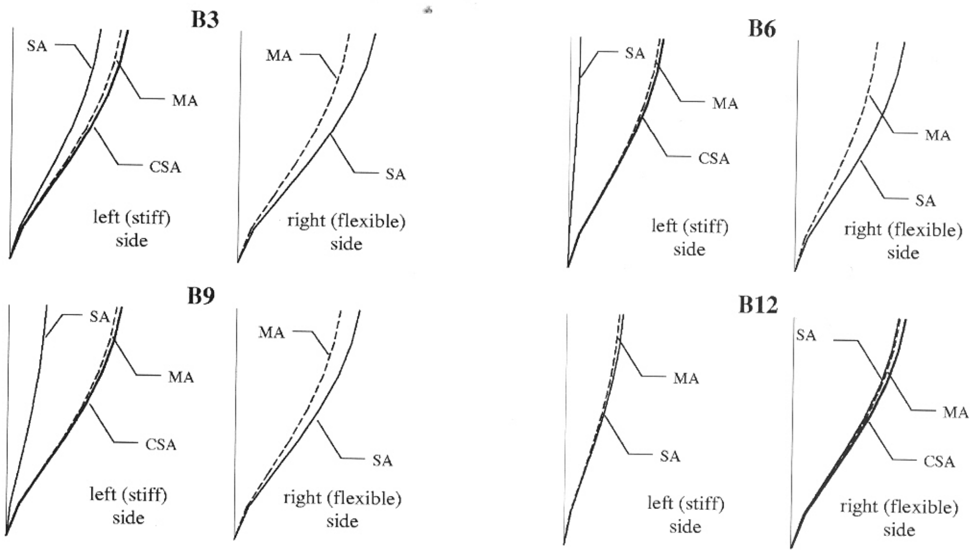

Figure 4. Displacement diagrams provided by modal analysis (MA), standard static analysis (SA), and corrected static analysis (CSA).

Figure 5. Faculty of Engineering in Catania.

AN IRREGULARLY ASYMMETRIC MULTISTORY BUILDING

The procedures described in the previous sections may give some information also in the case of irregularly asymmetric buildings. As an example, they have been applied to a very irregular six-story building, the office of the Faculty of Engineering in Catania, Italy (Figures 5 and 6). The deck size is not equal at all floors. Furthermore, the building presents different stiffness and strength along the orthogonal directions, so as to be quite rigid but torsionally flexible along the y-axis and extremely flexible but torsionally rigid along the x-axis. Although the actual structure of the building has not been designed to resist seismic action, in this study it has been analyzed according to the EC8 design spectrum for soil A, with $\alpha=0.25$ and $q=3$.

The values of R_k and E_s, evaluated at each level according to the procedure defined in the section above and referring to relative displacements and rotations, are quite different (Table 2). Therefore, the building is not regularly asymmetric and the modal analysis should be applied. Nevertheless, if the corrective eccentricities are evaluated for each story and the maximum value is used, the results appear to be quite safe (Table 3).

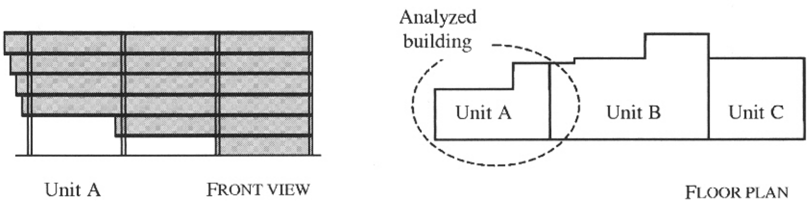

Figure 6. Front view and plan of the building.

Table 2. Basic parameters and corrective eccentricities for the examined building: x-direction and y-direction

			x-direction T_x=0.609 s				
story	L	L_r	R_m	R_k	E_s	Δe_l	Δe_r
6	9	3.90	9.70	43.39	−0.64	0.07	**0.00**
5	9	3.76	9.31	34.46	−0.69	0.10	**0.01**
4	9	3.75	9.28	29.18	−0.72	0.14	**0.02**
3	9	3.93	8.77	24.79	−0.65	0.14	**0.04**
2	9	4.50	5.88	21.33	−0.52	0.07	**0.02**
1	18	9.00	6.62	19.12	−1.88	0.50	**0.07**
			y-direction T_y=1.731 s				
story	L	L_r	R_m	R_k	E_s	Δe_l	Δe_r
6	27	15.33	9.70	6.17	0.16	0.24	**0.26**
5	27	15.12	9.31	6.25	0.32	0.52	**0.59**
4	27	14.92	9.28	6.19	0.78	1.04	**1.48**
3	27	14.09	8.77	6.03	1.47	1.11	**2.80**
2	18	9.00	5.88	6.06	2.55	**−0.76**	**0.86**
1	9	5.25	6.62	6.35	3.27	0.47	−4.50

CONCLUSIONS

The present research leads to the following general observations:

- The use of a conventional definition of the lateral stiffness of plane frames or the evaluation of R_k and E_s by means of simple formulations allows an easy classification of structures as regularly or non-regularly asymmetric.
- For regularly asymmetric structures, a simple procedure allows the evaluation of corrective eccentricities able to equate the maximum design displacements (and internal actions) of static and modal analysis.
- For irregularly asymmetric structures, modal analysis is undoubtedly the most reliable approach; nevertheless, the use of static analysis still seems possible, provided that for the whole building a unique value of the corrective eccentricity, i.e., the maximum value evaluated for all the stories, is used.

Table 3. Displacement (in mm) of the right side of the building

story	MA	SA	CSA
6	28.9	20.4	**31.8**
5	25.9	18.0	**28.3**
4	21.0	14.4	**22.8**
3	15.1	10.0	**16.2**
2	8.9	5.8	**9.4**
1	3.3	2.2	**3.6**

NOTATION

	Basic parameter	*Normalized value*
C_M	mass center	
C_R	center of rigidity	
e_s	stiffness eccentricity, i.e., distance between C_R and C_M (positive if C_R is to the right of C_M)	$E_s = e_s/L$
K_y	total lateral stiffness of the elements parallel to the y-axis (i.e., parallel to the seismic action)	
K_θ	total torsional stiffness about C_R	
L	dimension of the deck along the x direction (orthogonal to the seismic action)	
L_r	distance of the right side of thedeck from the mass center	$\alpha = L_r/L$
ζ	damping ratio (%)	
m	mass of the deck	
r_k	stiffness radius of gyration about C_R $r_k = \sqrt{K_\theta/K_y}$	$R_k = r_k/L$
r_m	mass radius of gyration about themass center	$R_m = r_m/L$
s_a	spectral acceleration (subscripts 1 and 2 indicate spectral acceleration of modal shapes; subscript y indicates spectral acceleration of translational motion along the y direction)	$S_a = s_a m/K_y L$
T_y	uncoupled translational period along the y direction $T_y = 2\pi\sqrt{m/K_y}$	
v	displacement of the mass center along the y direction	$V = v/L$
v_r, v_l	displacement of the right and left side of the deck along the y direction	$V_r = v_r/L, \quad V_l = v_l/L$
$\Delta e_r, \Delta e_l$	corrective eccentricities, necessary to obtain by means of static analysis at the right and at the left side the same displacement given by the modal analysis (positive if the point where the static force has to be applied is to the right of C_M)	$\Delta E_r = \Delta e_r/L$
θ	rotation of the deck	
ω_1, ω_2	natural frequencies of the system	$\Omega_j = \omega_j/\omega_y, \ j = 1,2$
ω_y	uncoupled translational frequency along the y direction $\omega_y = \sqrt{K_y/m}$	

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