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Critical Analysis of Torsional Provisions in Seismic Codes

B. Calderoni[1], A. Ghersi[2] and F.M. Mazzolani[1]

ABSTRACT

The general approach of different seismic codes to the problem of in-plan regularity is examined. The criteria used to define regularity, based on geometrical characteristics or on behavioural aspects (response to given actions) are critically compared. The effectiveness of the additional eccentricity, used to relate the results of static versus modal analysis, is tested both on single-storey systems and on multi-storey buildings, pointing out some inadequacy in code provisions. Alternative formulations of the additional eccentricity are finally proposed.

INTRODUCTION

The influence of in-plan irregularities on the dynamic response of structures to seismic actions is relevant and it is therefore considered, in a more or less detailed way, by all seismic codes. Nevertheless, significant differences may be found both in the global approach and in the numerical values provided by different codes. In order to critically analyse such differences, it is important to keep in mind the different problems connected to the structural regularity, which may influence:

- the *elastic behaviour*: many aspects must be examined to select a proper elastic model, such as the type of analysis (static or modal), the model for the evaluation of design actions, both for static and modal analysis (plane or spatial), the model for the evaluation of internal actions and stresses in structural elements (plane or spatial), the model for the horizontal diaphragms (flexible or rigid) and, if necessary, also the model for non-structural elements;
- the *inelastic behaviour*: the distribution of strength and local ductility of structural elements and the presence of non-structural elements, like partition or in-fill walls, influence the global ductility of a structure and the coefficient used to reduce the design actions;
- the *action transfer*: discontinuity of structural elements, sharp reduction of sections, re-entrant corners in the floor diaphragms influence the force transfer and require specific checks and careful detailing.

The analysis of the elastic behaviour of a single storey system shows that the entity of the torsional response depends on three parameters, E, R_m and R_k, which are respectively the distance between the stiffness center and the nominal mass center, the radius of gyration of masses and the radius of gyration of lateral stiffness, made adimensional by dividing them by L, i.e. the floor dimension perpendicular to the direction of seismic action. A previous paper (Calderoni et al. 1994) gives the equations which describe the modal and the static response and evaluates the additional eccentricities ΔE_f and ΔE_s necessary to obtain by means of a static analysis the same displacement given by the dynamic one both at the flexible (ΔE_f) and stiff (ΔE_s) side (fig. 1). These values, which in a lesser way depends also on the parameter α, adimensional distance of the nominal mass center from the stiff side of the building, are shown as a function of E and R_k/R_m in fig. 2, for R_m=0.30 and α=0.50.

The inelastic behaviour is much more complex because it involves both the stiffness and the strength of the structural components. Many general studies (e.g. Rutenberg et al. 1986, Sedarat and Bertero 1990) shows the opportunity to improve the inelastic response by using a suitable strength

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[1] Department of Structural Analysis and Design, University of Naples, Italy
[2] Istituto di Scienza delle Costruzioni, University of Catania, Italy

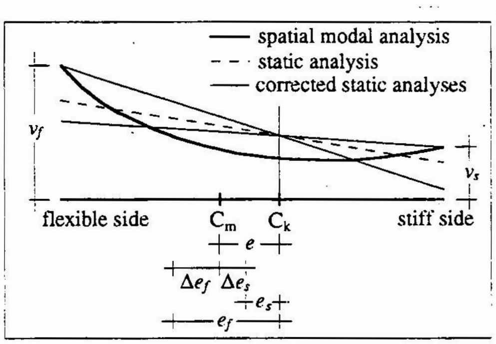

Fig. 1 - Static and spatial-modal deformed shapes

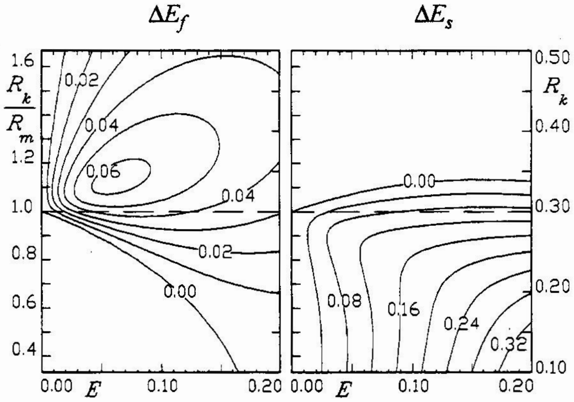

Fig. 2 - Additional eccentricities ΔE_f and ΔE_s as a function of E and R_k/R_m, in the case $R_m=0.30$ and $\alpha=0.50$

distribution, different from the stiffness distribution. Other studies were explicitally devoted to the analysis of code prescriptions (e.g. Tso and Wong 1993, 1994), in order to judge if the torsional provisions are able to ensure no additional ductility demand to the elements.

Finally, the problems of action transfer have been mainly pointed out by the analysis of damage and collapse of buildings after major seismic events, although few theoretical studies are devoted to this topic.

Following the above scheme, in the present paper the torsional provisions given by Eurocode 8 (EC8), Structural Engineers Association of California (SEAOC), National Building Code of Canada (NBC) and New Zealand Standard (NZS) are compared. Their global approach is discussed in the next section, while the prescribed values of additional eccentricity and the numerical results obtained by using them for single-storey schemes and for actual buildings are examined in the following sections.

GLOBAL APPROACH

In the first draft of EC8 (1988) an unique definition of "regular building", based on the fulfilment of given geometric conditions, was contemporaneously connected to the model of analysis and to the reduction coefficient of forces, i.e. to the elastic and the inelastic behaviour. A significant improvement is given by its second draft (1993), which in Part 1-2 distinguishes the implication of regularity on method of analysis, structural model and value of behaviour factor. The criteria for regularity in plan examine both geometry (structure approximately symmetrical in plan, plan configuration compact, rigid floor diaphragm) and response to static actions (ratio of maximum over average storey displacement, due to horizontal forces applied with the accidental eccentricity, smaller than 1.2) and appear to be quite restrictive. Nevertheless, they are substantially overpassed and deprived of their meaning by the wider regularity criteria given in annex B, which only require that the centers of lateral stiffness and of mass be each approximately located on a vertical line.

The definition of regularity is used by EC8 first of all to select the method of analysis. Dynamic (multi-modal response spectrum) analysis is in fact prescribed for buildings which do not meet the above criteria (restrictive or large) for regularity in plan. Obviously, for EC8 and for most other codes, dynamic analysis is also necessary in presence of vertical irregularities or when the fundamental periods of vibration in the two main directions are greater than given values; these problems are not object of the present paper. It must however be noted that no lower limit is given by EC8 to the actions provided by the dynamic analysis, which might thus be significantly smaller than those evaluated by the static (simplified modal response spectrum) analysis.

Concerning to the model to be used in the analysis, some misunderstanding may be ingenerated by an ambiguous use of the term "plane model". We believe that, to give a proper sense to the text of EC8, it must be referred only to the evaluation of the design actions and we base on this assumption our further considerations, even though some contradictions still remain in less important points. In this way the torsional effects may be evaluted by directly including eccentricity in a spatial modal analysis or by considering the effect of a set of static forces applied with a conventional eccentricity.

SEAOC bases the definition of torsional regularity only on the response to static actions, i.e. on the parameter above described for EC8 (ratio of maximum over average displacement smaller than 1.2), but uses it mainly to prescribe additional eccentricities when a static analysis is performed. Strict limits are provided in order to avoid that the use of sophisticated analysis may lead to a strong reduction of design actions. A conventional method for the evaluation of the structure period is imposed; a more exact one may be used, but the design base shear shall be not less than 80 percent than the value obtained by the conventional one. Furthermore, when adopting the response spectrum analysis the results obtained shall be scaled so that the base shear is the same as for static analysis if the structur is irregular, or not less than 90 percent of it for regular structures.

Other types of in-plan irregularities are defined by SEAOC and used to overpass problems of action transfer. For example, the presence of re-entrant corners, diaphragm discontinuity or out-of-plane offsets require the use of lower allowable stresses and more idoneous models for the analysis of the diaphragm elements and of their connections to the vertical elements.

NBC do not explicitely gives a definition of regular building, but it uses the same criterion given in annex B of EC8 (centers of lateral stiffness and centers of masses each approximately located on a vertical line) as a condition to avoid the use of dynamic analysis. Following an approach similar to that by SEOC, the design base shear is given as a function of the structure period, which cannot exceed 1.2 times the period calculated with conventional formulas; the same base shear is furthermore prescribed both for static and dynamic analysis.

NZS gives two alternative criteria to verify the horizontal regularity. The first one, based on geometric considerations, requires that the distance between shear center and center of mass be less than 0.3 times the maximum plan dimension. The second one concerns the response to static forces and asks that the ratio of minimum over maximum storey displacement be greater than 3/7 (which is the same as to say that the ratio of maximum over average displacement be less than 1.4). It must be noted that the two criteria are quite different; the first one, in particular, is a very light limitation, easily satisfied also by structures which have a really bad torsional behaviour; the second one, if referred to the diplacements evaluated including the accidental eccentricity, appears extremely restrictive, and for this reason we intended it to be related to the effect of forces applied to the nominal center of mass. The static analysis may be used only for regular buildings having a fundamental period less than 2 seconds or for irregular structures with period less than 0.45 seconds. Once again the design base shear used in dynamic analyses must be the same as for static analysis in the case of irregular structures or not less than 80 percent of that value in the case of the regolar ones. Concerning to the model to be used in the analysis to take into account the torsional effects, NZS prescriptions (spatial modal analysis with center of mass conventionally modified or addition of the effect of static or modal forces with a conventional eccentricity) are substantially equivalent to, and surely more comprehensible than, those of EC8.

The detailed presentation of the global approach to the torsional problems, above reported, shows that all codes mostly connect in-plan regularity to the type of analysis to be used and that, for a very wide set of buildings, they allow to evaluate the dynamic torsional effects by means of static analysis performed by using the eccentricities discussed in the next section. The use of geometric considerations to assess regularity seems not always satisfying, while the ratio of horizontal displacements of different points of the floor diaphragm (i.e. the in-plan rotation) due to forces with given eccentricity is always considered a good parameter. Although some prescription are implicitly intended to check the torsional flexibility, which constitutes a critical parameter of the torsional behaviour, no consideration or limitation is explicitly based on the parameter R_k/R_m. Concerning to the inelastic behaviour, it has to be noted that the coefficient used to reduce the design action (named behaviour factor q by EC8, R_w by SEAOC, force modification factor R by NBC, structural ductility factor μ by NZS) is never connected to the in-plan irregularities, in spite of the great influence of strength distribution revealed by the mentioned studies. Finally only SEAOC, and somehow also the Canadian Commentary to NBC, rightly connect each case of geometrical irregularity to its effects and give prescriptions able to enhance the action transfer.

ADDITIONAL ECCENTRICITY

Most codes prescribe that the point of application of the inertial forces be considered displaced from the nominal location of the center of mass by two quantities, usually named "accidental" and "additional" eccentricity. The first one mainly intends to cover the uncertainties in the distribution of masses and in the spatial variation of seismic motion and it is therefore to be used both in static and dynamic analysis. It indirectly provides also an additional strength to the elements located near the periphery of the building, thus reducing the probability of a sharp reduction of torsional stiffness due to the plasticization of those elements. The value imposed by EC8 and SEAOC, expressed in a dimensionless form by dividing it by L, is 0.05, while NBC and NZS consider a greater value,equal to 0.10.

The additional eccentricity is prescribed when the static analysis is performed and it aims at taking into account the possibility of the increase of in-plan torsion due to dynamic effects. The values proposed by the four codes are quite different and need to be compared to those actually necessary.

EC8 impose an additional eccentricity only to correct the effect at the flexible side. According to the symbols previously defined, it must be calculated as the lower of the following two values

$$\Delta e_f = 0.1\,(1+B/L)\sqrt{10\,E} \quad \leq \quad 0.1\,(1+B/L)$$

$$\Delta e_f = \frac{1}{2E}\left[R_m^2 - E^2 - R_k^2 + \sqrt{(R_m^2 + E^2 - R_k^2) + 4\,E^2\,R_k^2}\right]$$

where B is the floor dimension in the direction of seismic action.

SEAOC prescribes to correct the effect at the flexible side when the maximum storey drift $\delta_{\max}$, computed including accidental torsion, is more than 1.2 times δ_{avg}, average of the storey drifts at the two ends of the structure. In this case, the accidental eccentricity must be increased by a factor A_x

$$A_x = \left[\frac{\delta_{\max}}{1.2\,\delta_{\mathrm{avg}}}\right]^2 \quad \leq \quad 3$$

which correspond to consider an additional eccentricity

$$\Delta E_f = 0.05\,(A_x - 1)$$

As for EC8, no correction is instead required by SEAOC at the stiff side of the building.

Finally, NBC prescribes to increase or decrease the nominal eccentricity E by 50 percent, whichever produces the worst effect, i.e. to consider $\Delta E_f = \Delta E_s = E/2$, while NZS requires no additional eccentricity but limits, as previously mentioned, the use of the static analysis to the cases which present a ratio of minimum over maximum end displacement greater than 3/7. Nevertheless, in order to correctly judge the effectiveness of the additional eccentricities provided by the examined codes, also the differences in the values of accidental eccentricity must be taken into account. For this reason the comparison has been carried out by considering the accidental eccentricity 0.10, given in NBC and NZS, as composed of a value 0.05 (equal to the accidental eccentricity given by EC8 and SEAOC) and a further 0.05 directly summed to the additional eccentricity, which has been thus considered to be

$$\Delta E_f = \Delta E_s = 0.05 + E/2 \qquad \text{for NBC}$$

$$\Delta E_f = \Delta E_s = 0.05 \qquad \text{for NZS}$$

The values provided by the four codes are reported in fig. 3 as a function of E and R_k/R_m. The differences between these values and those actually necessary, given in fig. 2, are evident. It must be first of all noted that the real influence of the basic parameter R_k/R_m is not well interpreted by any code. EC8 gives a close approximation only when $R_k > R_m + 2E$, but it overestimates Δe_f (more than two times) in the case of torsionally stiff structures ($R_k > R_m$) with high proper eccentricity and prescribes high values of it in the case of torsionally flexible schemes, when no additional eccentricity is necessary. Similar differences may be found in SEAOC values, which moreover are smaller than the ones given by EC8 and

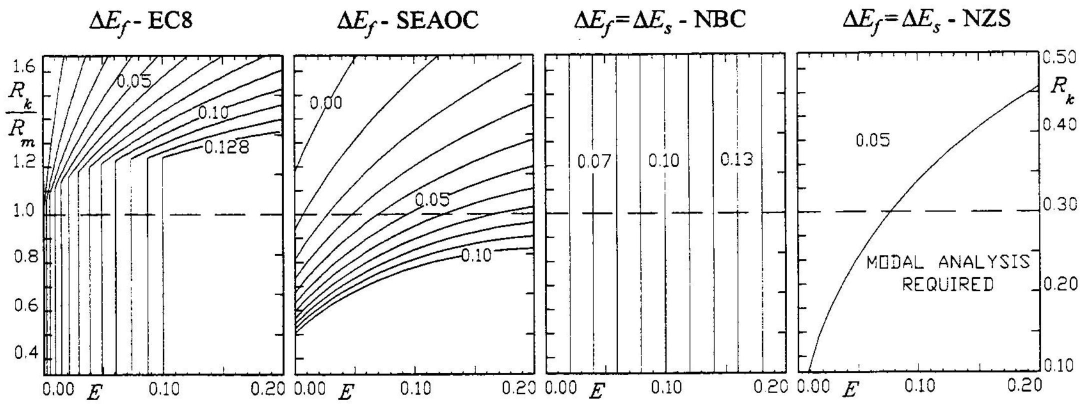

Fig. 3 - Additional eccentricities prescribed by EC8, SEAOC, NBC and NZS in the case $R_m = 0.30$.

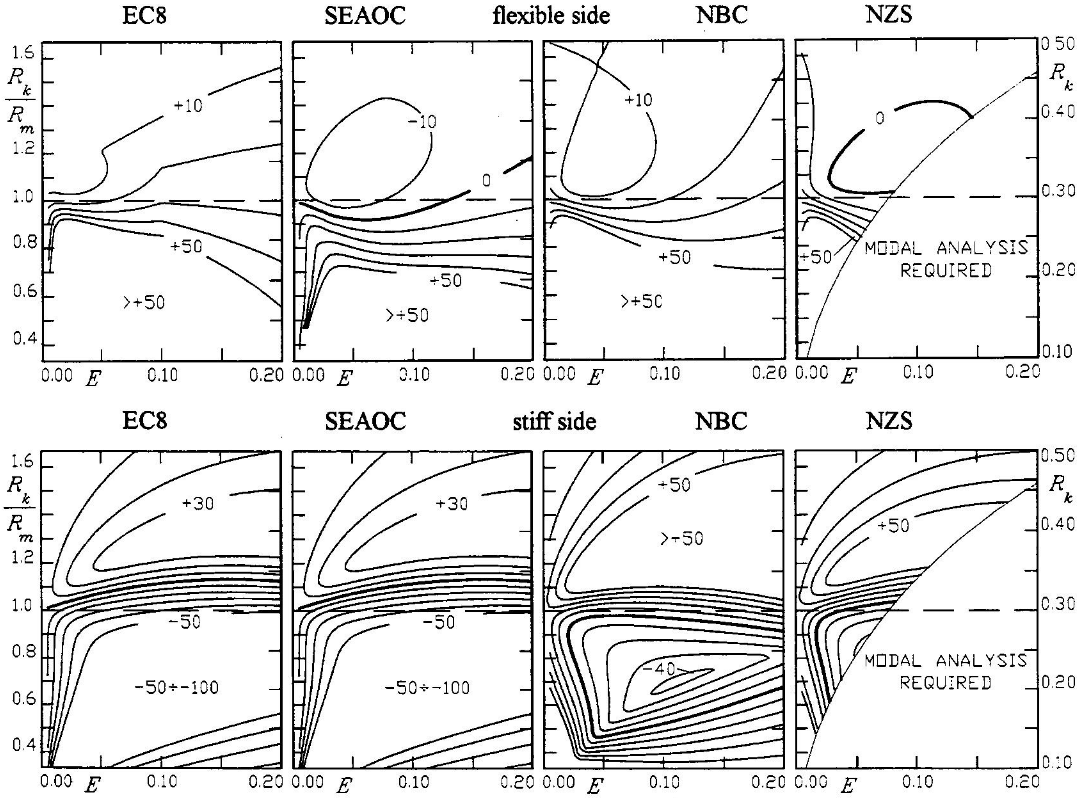

Fig. 4 -Differences in percent between the displacements evaluated following the code provisions and the values calculated by modal analysis, in the case $R_m = 0.30$ and $\alpha = 0.50$.

thus often unsafe for torsionally stiff structures. In the same time is evident that the lack of provisions for the stiff side in both codes may lead to rough approximations in the case of torsionally flexible structures. NBC prescriptions appear really excessive both for the flexible side of all schemes and for the stiff side of torsionally rigid systems, while they may somehow approximate the values necessary to correct the analysis at the stiff side of torsionally flexible schemes. Finally, NZS seems to get the best result with the minimum effort; in fact its constant value is not so far from the maximum one required to correct the flexible side of torsionally stiff systems, while the imposed limit of application of static analysis succeedes in excluding the flexible schemes with the worst torsional behaviour.

A better comprehension of the effect of such differences may be reached by comparing directly the displacements evaluated using the additional eccentricity and those provided by the modal analysis. The results so obtained, expressed as difference in percent of the code versus the modal values, are plotted in fig. 4. EC8 always over-estimate the displacement of the flexible side; the error curve of +30% approximately divide torsionally stiff and flexible scheme, regardeless to the value of the nominal eccentricity. A similar result is provided by NBC, for which only the error curve of +10% has a shape really different from the EC8 one. For the same side SEAOC gives the less safe values; the displacement of nearly all stiff schemes is in fact under-estimated, with a maximum error of -15% when R_k/R_m=1.1 and E= 0.04. NZS provides the best fitting of displacement in the case of torsionally stiff schemes, showing differences in the range -5% to +10%; the over-valutation is still sharply growing up when $R_k<R_m$, although slightly smaller than for other codes.

The displacement of the stiff side of torsionally stiff schemes is always greatly over-estimated, in particular by NBC which leads to errors greater than +50% for most of the examined structures, while EC8 and SEAOC limit the maximum error to +35%. On the contrary in the case of torsionally flexible schemes these two codes nearly always provide less than half of the actual modal displacement. Less relevant, but still often unacceptable, is the error of NBC, which is up to -40%, while NZS, imposing the use of modal analysis, wipes off the worst situations, although to be really safe it should be necessary to exclude also all the schemes with $E>0.03$.

MULTI-STOREY BUILDINGS

The comparison up to now carried on is based on the exame of single-storey schemes. In order to check the correctness of the results obtained we examined also four reinforced concrete framed buildings. Their structural plans are shown in fig. 5; the number of storeys varies from five to six. The first three are clearly dissymmetrical, while the fourth one, having a symmetrical plan, has been considered with a dissymmetrical distribution of loads, so as to present a nominal eccentricity E=0.03 at all floors.

A peculiarity of multi-storey buildings is that center of mass and stiffness and their radius of gyration are not exactly coincident at every floor. In the present analysis the approximate formulations proposed in a previous paper (Calderoni et al. 1994) have been used to evaluate at each level R_k and E; the mean value of these quantities along the building height is reported (together with R_m and α) in tab. 1.

All buildings have been calculated in two different ways: a spatial multi-modal response spectrum analysis with C.Q.C. modal combination and a spatial static analysis with the additional eccentricity provided by EC8; the design response spectrum given by EC8 for soil A, peak ground acceleration 0.35 g and behaviour factor q=5 has been used in both analyses; the values of the modal analysis have been scaled in such a way to get the same base shear as the static one. The differences between the results of static and modal analysis appear to be in most cases uniform at all floors. Only in one case (building A, direction y) the first floor showed a slightly different behaviour, with differences up to 15% with respect to the other storeys.

The corrispondent single-storey systems, characterized by the above referred mean values of the basic parameters, have been analysed in the same way, obtaining the differences between static and modal analysis given in tab. 1. A good agreement of multi-storey to single-storey systems is in this way pointed out. For example, the building C subjectd to seismic action along the y-direction showed differences between the static and modal analysis ranging from 24 to 30% and from -10 to -16% for the flexible and the stiff side respectively, which are not so different from the values +24.4 and -17.4% provided by the equivalent single-storey system. Analogous correspondences have been obtained for the other buildings.

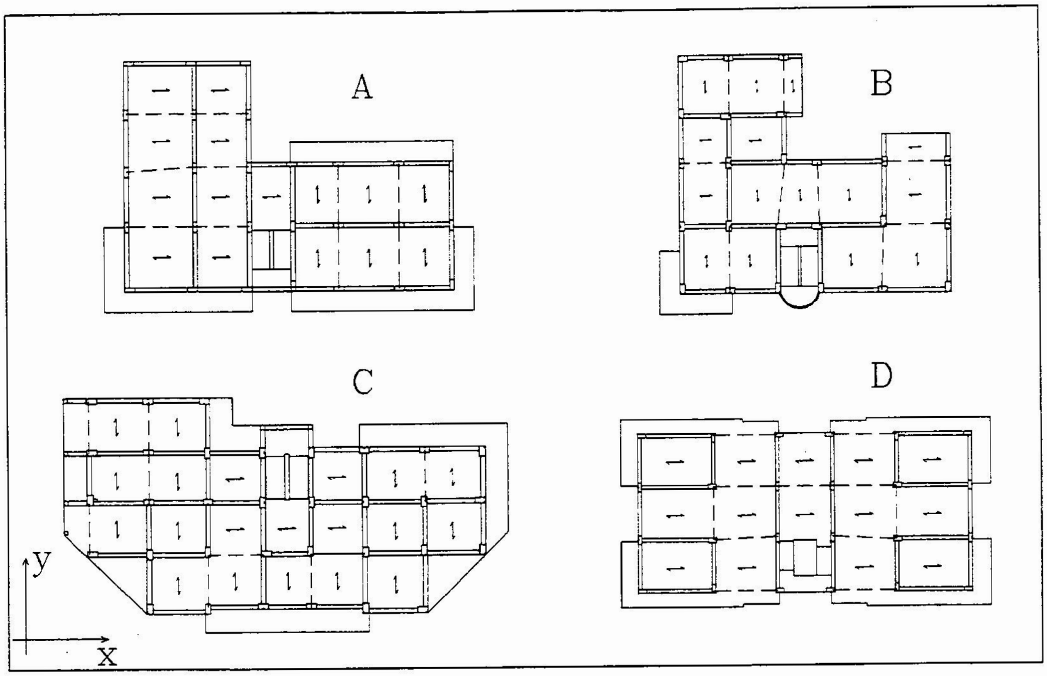

Fig. 5 - Structural plans of the examined buildings

Table 1 - Value of the basic parameters for the examined buildings and the equivalent single-storey systems

building	seismic action	α	R_m	R_k/R_m	E	static versus modal values (difference in percent)	
						flexible side	stiff side
A	x	0.631	0.528	1.130	0.013	+2.3	+5.4
	y	0.447	0.368	1.110	0.078	+21.1	+27.7
B	x	0.587	0.443	1.250	0.031	+2.2	+10.0
	y	0.442	0.388	1.260	0.036	+2.7	+9.5
C	x	0.432	0.629	0.984	0.061	+40.1	+5.7
	y	0.538	0.342	1.018	0.054	+24.4	-17.4
D	x	0.531	0.757	1.292	0.030	+0.6	+2.4
	y	0.531	0.356	0.744	0.030	+107.3	-37.3

PROPOSED PROVISIONS

The performed analysis points out that the torsional provisions of the examined codes lead each one to different results, which do not guarentee the same safety to all structures. A correct evaluation of the torsional effects should directly connect the additional eccentricity to the basic parameters R_m , R_k and E. It must yet be noted that, while the mass distribution is a given design datum, the concept itself of "floor stiffness" is somehow wrong, because it depends on the horizontal load distribution. In a previous paper (Calderoni et al. 1994) a design procedure has been proposed, based on the static analysis of a spatial model of the structure subjected to two load conditions (design forces applied to the nominal center of masses and torsional moments corresponding to the accidental eccentricity, respectively). The obtained displacements may be used to evaluate R_k and E, using expressions which are rigorous for single-storey systems but still substantially correct for multi-storey buildings. The exact relation of the additional eccentricity versus the above parameters is given in the mentioned paper by means of diagrams which directly connect ΔE to the ratio of the minimum over maximum storey displacement calculated for the first load condition.

As an alternative, on the basis of the critical analysis of the code provisions here performed together with the examination of the exact relation (e.g. fig. 2), the following very simple formulations may be suggested to approximate the necessary values of additional eccentricity in a more suitable way than provided by the examined codes:

- for the flexible side:

  when $R_k > (1-E)\, R_m$ $\quad \Delta E_f = 0.05$

- for the stiff side:

  when $R_k < 1.1\, R_m$ $\quad$ the lower of the values $\quad \Delta E_s = 1.5\, E \quad \Delta E_s = 1.1 - R_k / R_m$

For all other values of R_k, no additional eccentricity is required, both for the stiff and the flexible side.

CONCLUSIONS

The comparison of the effect of the additional eccentricities imposed by the examined codes versus the actual values provided by the modal analysis, extended to a wide set of single-storey schemes and confirmed by the analysis of four r.c. framed buildings, shows that the torsional provisions are sometimes too safe and other times not adequate. In particular, the displacement of the stiff side of torsionally stiff systems and that of the flexible side of torsionally flexible schemes are always strongly over-extimated by the static analysis, while the static displacement of the stiff side of the flexible schemes is in many cases less than half of the true modal value. These last cases appear thus to be really unsafe and not adequately covered by the code prescriptions, which do not sufficiently warn the designer against the risk connected to the use of such schemes. Furthermore, although the over-extimation of displacements (and stresses) leads to more safe structures, this higher degree of security appears casual and unwilled, while it should be more correct to guarantee the same safety to all structures. The design procedure proposed in a previous paper or the simplified torsional provisions here referred mayrepresent a significant step in this direction.

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