CRITICAL ANALYSIS OF EC8 APPROACH TO FACE THE PROBLEM OF STRUCTURAL REGULARITY

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Abstract

The paper critically analyses the provisions of part 1.2 of Eurocode 8 (General rules - General rules for buildings). The basic principles of conceptual design (annex B) are useful guidelines for the structural designer. On the contrary, the connection of structural regularity to seismic design (synthesised in table 2.1) appears oversimplified and contradictory. The criteria for regularity in plan, which may appear in some cases even too strict, are substantially overpassed and made useless by the very large criteria provided in annex A, which are fulfilled by most multi-storey buildings. The allowance of "planar" models for the analysis of buildings (which may be accepted as a simplification, although it brings the reminiscence of past days of manual computing) leads to baffling prescriptions (like that of evaluating the effect of spatial eccentricity by means of planar models) when coupled to the approximate analysis described in annex A. The expressions for the additional eccentricity provided in order to match the results of the "simplified modal response spectrum analysis" to those of "multi-modal analysis" are doubtless the most complex among all seismic codes, but give often the worst correction. Finally, no attention is paid to the increase of ductility demand in asymmetric buildings, which constitutes nowadays one of the main topic of research and discussion. The allowance of spatial multi-modal analysis, with no further prescriptions or additional design eccentricities, may cause the ductility demand at the stiff edge of the structure to be even greater than that expected in buildings designed by using static analysis. The critical examination of these aspects is completed by suggestions to improve the effectiveness of this part of Eurocode 8.

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Introduction

The European seismic code, Eurocode 8, which after many years is finally arrived to the final phase of ENV (adopted European prestandard), can be considered under many points of view a very advanced code, able to face the problem of seismic structural design in a complete and up-to-date way Basic principles and general requirements to be fulfilled by constructions are clearly stated; at the same time detailed operative rules are given to designers in order to satisfy those criteria Significant improvements have been made to the code while passing from its first draft (1988) to the present one (1994), particularly for the approach to the problem of structural regularity for buildings (part 1 2) In the first draft an unique definition of "regular building", based on the fulfilment of given geometric conditions, was connected to both the model of analysis and the reduction coefficient of forces, i e in some way to the elastic and the inelastic behaviour of the structure Instead in the last version, as widely described later on in this paper, the implications of regularity on the different aspects of structural behaviour are well distinguished and other important questions have been made clear too Despite of the remarkable improvements, made in many different parts of the code, they led to some loss of coherence by creating some ambiguities and contradictions Furthermore, the scientific research about the inelastic response of asymmetric structures made very important improvements in the last years, which have not yet been fully inserted in the code Therefore a final and clear definition of the problem of regularity and of the design provisions able to face it appears to be really necessary

Basic principles and criteria for regularity

Eurocode 8 - Part 1-2 gives basic principles of conceptual design of the building as guidelines for the structural designers These principles are listed in section 2 1 and explained more in detail in the Annex B, which is named "informative" Criteria describing regularity in elevation and in plan are given in sections 2 2 3 and 2 2 2 In section 2 2 1 structural regularity is related to the structural model of buildings, to the type of analysis to be performed and to the values of behaviour factor: the first one is affected only by regularity in plan, while the others only by regularity in elevation Other criteria related to regularity are defined in Annex A, which is named "normative": the fulfilment of these further criteria allows to perform an approximate analysis of torsional effects

Basic principles of conceptual design

Structural simplicity and uniformity are rightly presented as guiding principles governing the conceptual design against seismic hazard The concept itself of structural regularity is directly connected to these aspects, which rule the transmission of the inertia forces to the resistant elements and both the elastic and the inelastic seismic response of the structure The importance of symmetry and that of a close relationship between the distribution of mass and the distribution of stiffness and strength is well explained The necessity to give the structure sufficient stiffness and strength in two directions as well as against torsional motion is highlighted too The very important role of floor decks in the overall seismic behaviour of the structure and the attention to be paid in designing adequate foundation (especially for building having structural walls) are finally clarified be performed In fact the static analysis (named in EC8 "simplified modal analysis") is not able to give a reliable distribution of the horizontal seismic forces along the height, when mass and/or stiffness present significant variations from one storey to another one. Nevertheless static analysis provides a base shear (e.g global horizontal forces) greater than the one given by multi-modal analysis Many researchers demonstrated that static analysis gives nearly always greater internal forces, even if irregularities in elevation exist So it seems a nonsense that irregular buildings (which have a more uncertain and generally worst behaviour) must be calculated by using a procedure which, although more exact, gives a smaller value of design base shear, while the regular ones, which have a clear seismic behaviour, can be designed according to a more safe method, like static analysis (Fajfar et al 1988) For this reason many present codes (SEAOC/UBC, NBC, NZS) require to scale the results of multi-modal analysis up to the values corresponding to the base shear given by static analysis (or to a large percentage of this, if the building is regular) The use of multi-modal analysis for irregular buildings without any correction (as allowed by EC8) is therefore justified under a purely theoretical point of view, but it is not in line with the other seismic codes

The reduction of the behaviour factor (i e. the increase of design horizontal forces) for buildings with irregularities in elevation is justified by the bad inelastic behaviour and the high ductility demand showed when sudden variation of resistance occurs at one storey ("soft-storey"). For this purpose the EC8 regularity criteria seem to be quite vague, just asking that lateral stiffness and mass "remain constant or reduce gradually, without abrupt changes, from the base to the top" A range of values of the resistance variation should be clearly defined; probably two limits should be necessary: if the actual variation is smaller than the lower one no reduction to the behaviour factor shall be applied, while if it is greater than the upper one the structure shall be considered unacceptable and then modified.

Regularity in plan: model of the building

About this topic, EC8 basically affirms the principle that the structural model of the building shall adequately represent the distribution of stiffness and mass, but also adds that this model can be planar or spatial In particular, if a building fulfils the restrictive criteria of regularity listed in the clause 2 2.2 or the wider requirements explained in point A 1 of Annex A, the analysis can be performed using two planar models, one for each main direction

The use of a planar model is reasonable for buildings being approximately symmetrical in plan with respect to two orthogonal directions (as requested in the first criterion of regularity in plan in 2 2 2); in this case, in fact, the building does not really show significant torsional rotations. But for buildings fulfilling the criteria of Annex A, no limit is given for the eccentricity between centres of mass and stiffness. Therefore, allowing for these typologies of structures the use of a planar model (which considers no floor rotation) and requiring contemporary the evaluation of the torsional effects (clause A4-1) appears a nonsense This contradiction is evident in Annex A (clause A4), but can be found also in other points of part 1-2: it seems that the reference to the wider criteria of A1 be simply appended to the reference to the regularity criteria of 2.2 2, without any attention to the remarkable differences between the two cases under the point of view of torsional behaviour

Although these general principles are not so detailed as the ones given by other codes (i e in SEAOC/UBC the problems induced to the structure behaviour by each kind of irregularity are clearly described), they are globally very effective For this reason, and because it is very important for a good design to take into account the aspects there explained, we believe that it should be better to define the Annex B as "normative" rather than "informative".

Criteria for regularity in elevation

The criteria for regularity in elevation are specific provisions, according to the basic principles, to be respected for defining a building as regular These criteria, although fulfilled by most usual buildings, seem to be even too conservative (Mazzolani and Piluso 1996). Furthermore some more explicit indications about the influence of non structural elements should be necessary, especially with reference to the gradual variation of resistance along the height of building: often vertical irregularities and/or soft-storey problems are due to the masonry infilled, even if the structure is itself very regular. In effect, the code gives a cross-reference to clause 2 9 of Part 1.3, which regards the special aspects of masonry infilled concrete frames; here several interesting provisions are given Nevertheless it should be better and more consistent with the global format of the code that these questions shall be discussed in part 1-2, as they concern all typologies of buildings, independently of the material (steel, concrete or other)

Criteria for regularity in plan and criteria for approximate analysis of torsional effects

Requirements for regularity in plan are very restrictive and at the same time not homogeneous The first one requires a practically symmetric plan configuration, so that a lot of usual buildings cannot satisfy it, even those which, even if asymmetric, have the mass centre coincident with the stiffness centre and therefore show a pure translational behaviour The second and the third ones require a compact plan configuration and a great stiffness and resistance of the floor decks: they are therefore related to the diaphragm action at storey level, which is not directly connected to the problem of regularity in plan Finally the fourth one actualises the basic principle of having a suitable torsional stiffness, but in the way it is posed it can be only an "a posteriori" judgement criterion, as it is based on the evaluation of the storey displacements which requires the calculation of the structure (with a spatial model). For such reason the structural model of the building cannot be chosen on the basis of this requirement

On the other hand these quite restrictive criteria, affecting only the choice of structural model, are substantially overpassed and deprived of their meaning by the wider regularity requirements given in Annex A According to this, the planar model can be used also for buildings having the centres of lateral stiffness and mass each approximately located on a vertical line A large set of multi-storey buildings fulfil this requirement, even if they present very great stiffness eccentricity

Regularity in elevation: type of analysis and behaviour factor

Regularity in elevation affects the type of the structural analysis and the value of behaviour factor When the building is not regular in elevation, multi-modal response spectrum analysis must

A possible explaining of the above contradictions may be suggested: the term "two planar models, one for each main direction", used by EC8 in A4-1 and added in 3.1-4 for buildings complying the criteria of Annex A, might be used with reference to the model which considers the structure as a spatial set of planar frames This model, commonly used in the recent past, requires to evaluate the lateral rigidity of each frame of the buildings and to subdivide the global horizontal forces among the frames in proportion to their rigidities, taking into account the torsional moment due to eccentricity. Whether EC8 prescriptions are referred to this model or not, a clarification should be necessary and the expression "spatial simplified model" instead of the misleading "planar model" should be used In this way Annex A finds again a clear significance and many contradictions are resolved, even if a scrupulous check of all references is however needed

We believe that the best way to avoid misunderstandings should be the cancellation of all references to "planar model" in the single clause The first basic principle, given in 3.1, states that the model of the building shall adequately represent the spatial behaviour of the structure Therefore it implicitly allows the designer to use a planar model for a symmetrical structure (without any need of explicit code statements) or a simplified spatial one for all cases in which it appears to be possible, e g in structures constituted by two sets of orthogonal frames, when eccentricity exists but the simplified modal analysis is permitted In any case we think that structural models should be discussed in a general way just in 3.1, because their choice is not connected to the use of static or modal analysis or to the approximate evaluation of torsional effects. On the contrary Annex A should examine just this last aspect: this is to say how to catch the torsional elastic behaviour (exactly given by a multi-modal analysis) by performing a static analysis (simplified modal analysis), independently by the used structural model (spatial or simplified spatial one).

Torsional effects in asymmetric buildings

As it is well known, the seismic design has to comply contemporary with two different requirements: to avoid the collapse of the structure under the action of a strong earthquake (having a large return period) and to limit damages under the action of a moderate earthquake (having a large probability of occurrence) Only Japanese code explicitly prescribes to perform two different design procedures, one for each different level of earthquake All other seismic codes implicitly consider this fact, by assuming the design actions against moderate earthquakes (to be withstood in elastic range) coincident to those necessary to face strong earthquakes in the inelastic range, since the elastic response spectrum is reduced by means of behaviour factor q This approach makes difficult to give useful criteria for designing asymmetrical structure In this case, in fact, the torsional effect in the elastic range can largely differ from the inelastic behaviour; while most researchers clearly consider this peculiarity in their works, the codes do not take explicitly into account these distinct behaviours, giving rise to misunderstandings and ambiguities in their prescriptions Further aspects to be taken into account, which risk to add confusion to the already complex problem of elastic and inelastic behaviour, are the effect of simultaneous action of the two horizontal components of the ground motion and the uncertainty about the location of mass centre, which may vary in function of the in-plan distribution of live loads

In order to face these problems, every code requires to design each structural element for the maximum actions given by two different values of eccentricity, e_{d1} and e_{d2}, correlated both to the stiffness (or static) eccentricity e_s between the mass and stiffness centres and to the length L of the building in the direction orthogonal to the seismic action The expressions given by codes may be written in the general form

$$\begin{aligned} e_{d1} &= \alpha\, e_s + \beta\, L \\ e_{d2} &= \delta\, e_s - \beta\, L \end{aligned} \tag{1}$$

Unfortunately no explanation is provided by codes about the connections between these expressions and the two aspects of the problem, so that it is practically impossible to understand their scientific background and to judge on their effectiveness The term $\beta\, L$ usually intends to cover the uncertainties in the evaluation of the centre of masses (accidental eccentricity), due especially to the live loads, but some connection to the torsional inelastic behaviour cannot be excluded Notice that the eccentricities provided by the codes are always referred to the stiffness centre (see point A4-5 of EC8): this fact confirms that the prescriptions are related to the above recalled calculation procedures, used in the past, in which the distance of frames from the stiffness centre had to be evaluated in order to distribute the storey shear and the torsional moment among the frames Nowadays, the use of spatial models solved by automatic computing procedures makes necessary to define only the centre of mass, because the horizontal forces (for static analysis) or the floor mass (for modal analysis) must be applied in it Anyway the evaluation of static eccentricity is very important, especially in order to catch exactly the inelastic behaviour The codes give only vague indications about the determination of the stiffness centre, often relegated in annexes (see EC8 Annex A - A3-4), showing a kind of embarrassment in handling this matter Simple procedures able to provide a correct value of the stiffness eccentricity may be found in some papers, like the one proposed by Calderoni et al 1994, which, on the base of two spatial static analysis, gives results rigorous for a single-storey scheme and substantially exact for multi-storey buildings having both centres of stiffness and of mass each approximately located on a vertical line

Torsional effects in the elastic range

The elastic behaviour is exactly valuable by means of a step by step time-history analysis. The multi-modal response spectrum analysis gives very good results too, provided that in the spatial model the C Q C (Complete Quadratic Combination) method for combination of modal response is adopted, because of the possibility of similar periods for translational and torsional vibration modes Therefore the elastic problem can be considered solved from the theoretical point of view; moreover a number of computer programs allows structural designers to perform this kind of analysis also practically Nevertheless, the elastic aspect is still important, since static analysis is allowed and often suggested by several recent codes, due to its simplicity and reliability

It is well known that static analysis gives displacements and internal actions smaller than the actual ones at the flexible side of an asymmetrical structure Correct results, coinciding to those provided by multi-modal analysis, can be obtained by amplifying the stiffness eccentricity e_s of the structural system We may assume that the aliquot $(\alpha\text{-}1)\, e_s$ of the eccentricity prescribed by seismic codes aims at solving this problem. Particularly, the National Building Code of Canada NBC gives the value α=1 5, i e increases the torsional effects by 50 per cent Also a part of the

Torsional effects in the inelastic range

The non-linear behaviour of asymmetric structures is very important for seismic design, since it is substantially different from the elastic one In order to evaluate in a correct way the increase of ductility demand of the resistant elements due to the torsional rotation of the storey, the design displacements (obtained in elastic range) must be compared to the peak displacements supplied by the inelastic analysis. Obviously this kind of analysis cannot be performed practically by the designer, so that the code has to give the necessary provisions for modifying the elastic results and giving to the structure the sufficient strength and ductility to avoid collapse under the strong seismic event. At the moment no seismic code gives prescriptions clearly related to the inelastic behaviour, either to reduce the behaviour factor or to increase the eccentricity, although both the higher values of accidental eccentricity (β>0 05) and the reduction of stiffness eccentricity (δ<1) of some codes may be useful for this purpose

To face this problem in a correct way, any confusion among different types of elastic analyses must be eliminated As said in the previous section, the spatial multi-modal analysis is able to catch exactly the elastic displacements of the structures and then it must be assumed as reference design method. On this base, the results of this analysis must be modified for taking into account the inelastic effects, without considering, at the moment, the possibility of performing the static analysis

Many researchers are studying the influence of different parameters on the inelastic behaviour of asymmetric structure, obtaining results which sometimes appear contradictory and strictly related to the single system examined Nevertheless it has been often pointed out that the inelastic displacements are substantially independent of the strength of resistant elements and that the inelastic response is more translational with respect to the elastic one Starting from these considerations and on the base of a large set of numerical analyses, Ghersi et al (1996) proposed to assign the strength of the structural elements of asymmetric buildings basing on the maximum actions given by two different elastic multi-modal spatial analyses: the first one (more severe for the flexible side) performed by considering the mass centre in its actual location and the second one (more severe for the stiff side) by shifting it toward the centre of rigidity by a quantity named design eccentricity. The proposed expression for this eccentricity is

$$e_d = k\,(e_s - e_r) \tag{2}$$

where k depends on design behaviour factor q and e_r depends on Ω This proposal is a significant improvement of the prescription given in the general part (<u>not</u> in the seismic provisions) of Uniform Building Code UBC, which impose not to reduce actions on the stiff side when spatial analysis is performed, i e to use e_d=e_s.

Final considerations about the EC8 approach

As described above, the approach of the last draft of EC8 to the problem of regularity of buildings is quite detailed, but the relations between structural regularity and design provisions are not so clear and consistent to be correctly used for practical applications In order to improve the effectiveness of the part 1 2 of the code, the authors want to propose a logical procedure to face eccentricity βL may be related to this aspect In fact both NBC and the New Zealand Standard NZS prescribe a value 0 10 L which is double with respect to those provided by other codes (0 05 L): it can be considered as composed of a 0 05 L representing the actual accidental eccentricity and a further 0 05 L which takes into account the other problems, even if no explanation is given by the codes on this aspect However this last eccentricity has to be used also in the modal analysis and then the prescription of a greater value could represent a particular attention of the codes also to the torsional behaviour in the inelastic range (see the next section) Moreover it is important to notice that the static analysis may give results smaller than the actual ones also at the stiff side for torsionally flexible structures The aliquot $(1-\delta)\,e_s$ of the eccentricity prescribed by seismic codes (e g δ=0 5 in NBC) may cover this aspect, although it is mainly useful for the inelastic torsional behaviour The seismic codes do not explicitly consider this problem, but some of them (like NZS) do not allow the simplified analysis for torsionally flexible schemes

Also Eurocode 8 prescribes an additional eccentricity for approximate analysis of torsional effects The two given expressions, derived from Müller e Keintzel researches (1978, 1984), are surely the most complex among all seismic codes In the referred papers the effectiveness of the expressions is limited to a strict range of values of e_s and Ω (uncoupled lateral-torsional frequency ratio, equal to the ratio between the radius of gyration of stiffness and the radius of gyration of mass); particularly for structural system having Ω equal to 1 or a little greater (like the majority of multi-storey buildings), the formulations may be used if the stiffness eccentricity is less than 0 05 L, while only for Ω greater than 1 6 (exceptional values for usual buildings) this limit reaches 0 20 L On the contrary the code gives no information about the range of validity of this eccentricity, while it provides the unnecessary indication to neglect the torsional correction for structural system having Ω greater than 5, that is a value really impossible for actual structures (the maximum realistic value is about 1 5-1 7) Strict restrictions in using the EC8 relations should be then applied, but in this way the simplified modal analysis can be used just in few cases

Previous analyses performed by the authors of this paper (Calderoni et al 1994, 1995) have confirmed that the additional eccentricities provided by the codes (particularly by the EC8) are consistent just for limited range of values of e_s and Ω, giving both too much safe or too much unsafe results according to the different possible combinations of e_s and Ω In order to overpass these limitations, a very simple alternative formulation for such eccentricity, which should be named more properly corrective eccentricity because it aims at correcting the inaccuracy of static analysis, was presented in (Calderoni et al 1995), giving:

for the flexible side:	0 05 L	when $\Omega > (1-e_s/L)$
	no additional eccentricity	when $\Omega <= (1-e_s/L)$
for the stiff side:	the lower of 1 5 e_s and $(1\ 1-\Omega)\,L$	when $\Omega <$ 1 1
	no additional eccentricity	when $\Omega >=$ 1 1

On the base of these values, a debate for improving the Annex A of EC8 could start the problem of the in-plan regularity in a more rational way But, for this aim, some conclusive considerations have to be done before

a) The Annex B, explaining the basic principles of the seismic design, should become an essential part of the code: all buildings respecting these indications will not present relevant problems about regularity

b) The regularity in elevation and in plan must be separately faced, as the code does: but their influence on elastic behaviour, inelastic behaviour and action transfer to resistant elements must be better highlighted The corresponding provisions given by the code have to be clearly related to each of these aspects

c) Regularity in elevation is faced by EC8 in a safe way (perhaps even too safe): for irregular in elevation structures the spatial multi-modal analysis is correctly imposed and the behaviour factor decreased According to the majority of seismic codes, the results provided by multi-modal analysis should be increased so as to obtain a global shear at the base of the building not less than the one given by static analysis Moreover specific indications on the reduction to be applied in relation to each type of irregularity should be given General provisions about the influence of non structural elements, independently of the material used for the structure, should be added to part 1 2 too

d) The classification of the building as regular or irregular in-plan cannot be done on the base of morphological parameters only In fact many buildings, having not symmetrical plan configuration or re-entrance or other type of irregularities in plan, may exhibit very good torsional behaviour if they have an appropriate distribution of stiffness On the contrary some structures, even symmetric in plan, can show a bad behaviour if they are not designed in a consistent way, thus presenting a large stiffness eccentricity We believe that any kind of "a priori" classification is not satisfactory, because only the analysis of the actual torsional behaviour of the structure can give reliable indications about in-plan regularity

e) In EC8 the in-plan regularity affects only the structural model, which could be planar or spatial This implication is not understandable, since any torsional problem needs to be analysed by means of a spatial model A planar model can be used just for symmetrical (both for mass and rigidity) systems, while a spatial simplified model (as a set of plane frames) can be used for irregular structures too, if the static analysis is allowed

f) The effects of in-plan irregularity (i e of having a large distance between the centres of mass and stiffness) on the seismic behaviour of the structure mostly consists in the increasing of ductility demand for some structural elements (which require correspondent increment in strength), affecting just the inelastic behaviour On the contrary, if a spatial multi-modal analysis is performed to calculate the structure, the elastic behaviour is exactly caught, even if the actual stiffness eccentricity is large So implications of irregularity on the elastic behaviour exist only if the static analysis (simplified modal analysis) is used

g) The title “Approximate analysis of torsional effects” of Annex A is not appropriate, because the corresponding prescriptions are useful only if the static analysis is performed: they have to be applied for obtaining, by means of the static analysis, results equivalent to those given by the spatial modal one This part of the code is not actually connected to the structural problem of regularity, but only to the correctness of a specific type of analysis For a better comprehension, the words "in elastic range" should be added to the title, or it should be changed to "Approximate analysis of elastic torsional response"

h) The requirement (3) of Annex A-A3 (centres of mass and lateral rigidities each approximately located on a vertical line) is related also to regularity in elevation We believe that when it is not fulfilled it is necessary both to use multi-modal analysis, in order to get the elastic behaviour, and to reduce the behaviour factor, in order to overpass the uncertainties about the inelastic response of multi-stories buildings, which is presently not well assessed by the researchers

i) The accidental eccentricity, prescribed by all seismic codes, is not related to the elastic or inelastic behaviour or to the static or modal analysis It must be used merely for covering the uncertainties in evaluation of actual centre of mass, due particularly to the live loads; obviously it has to be taken into account for both regular and irregular buildings, independently of the type of the performed analysis

j) The plan configuration and the in plan stiffness of floors (referred to in 2 2 2 and in Annex A-A3-1) are not directly related to regularity in plan (as affecting the torsional behaviour of the buildings), but to the problem of action transmission to the lateral resistant elements The corresponding provisions should be put in a specific part of the code, regarding the diaphragm function of the floors (as SEAC/UBC does)

Proposals for an improved design approach

On the basis of the above presented considerations, we think that the seismic design of buildings could be performed according to the following steps:

1) The stiffness eccentricity e_s and the uncoupled lateral-torsional frequency ratio Ω must be evaluated for each floor By means of these values the judgement on regularity in plan can be given "a posteriori" and then the structure can be modified if the torsional behaviour shown by the building is considered not satisfactory (i e too large stiffness eccentricity, too high floor rotation or too small torsional stiffness) The evaluation of this two parameters can be made by using any, approximate or more accurate, method For instance the one proposed by Calderoni et al (1994) appears to be useful for this purpose It requires to perform the static analysis of a spatial model of the structure, subjected to two load conditions (design forces F and torsional moments due to accidental eccentricity $M=F\, e_a$, separately) The stiffness eccentricity at each floor is given by

$$e_s = -e_a \frac{\theta_F}{\theta_M} \tag{3}$$

being θ_F and θ_M the rotation of the floor due to F and M respectively The results obtained from this expression are exact only if the value of e_s is the same at all floors, but this condition may be immediately checked The radius of gyration of stiffness at each floor is given by

$$r_k = e_a \sqrt{\frac{v_F}{L\,\theta_M} - \left(\frac{\theta_F}{\theta_M}\right)^2} \tag{4}$$

where v_F is the displacement of the mass centre due to F Finally Ω is evaluated as the ratio between r_k and r_m, this last one obtained by means of geometrical considerations or simplified assumptions.

2) The design of the structure must be performed by taking into account the different kinds of eccentricity (accidental, design, corrective) in three distinct phases:

a the analysis of the structure should be performed twice, with reference to the two different positions of centre of mass (C_{m1} and C_{m2}) obtained by displacing the nominal one (C_m) in each direction by the accidental eccentricity (0.05 L) fixed by the code (Figure 1a);

b for each one of the above cases, two multi-modal analyses should be performed in order to obtain a sufficient safety against inelastic torsional behaviour: the first one with the mass centre in its current position C_{m1} (or C_{m2}) and the second one with the mass centre in the position C^I_{m1} (or C^I_{m2}), obtained by applying to the centre the corresponding design eccentricity e_{d1} for C_{m1} (or e_{d2} for C_{m2}) toward the stiffness centre (Figures 1b and 1c) Design eccentricity can be evaluated as a function of the current stiffness eccentricity, by the formulations given by Ghersi et al 1996. In practical applications it is sufficient to perform only two multi-modal analyses (instead of four), with the limit positions of mass centre corresponding to the maximum shift of it toward both sides;

c. if the building fulfils the requirements for regularity in elevation and the designer prefers to use static analysis, instead of the multi-modal one, the corrective eccentricity must be used for obtaining proper elastic results. The two limit positions of the mass centre, defined as said in step 2b by using both accidental and design eccentricity, will be furthermore affected by the corresponding corrective eccentricities, evaluated by means of expressions more effective than the ones provided by EC8 (e.g. the formulation proposed by Calderoni et al 1995), with reference to the respective stiffness eccentricities Once again two different analyses are necessary, in which the horizontal floor force will be applied in two different points. Since the shifting of the force corresponds to apply a torque floor moment, the final results can be derived just scaling, by means of a proper factor, the solution provided by the static analysis for the load condition of a floor moment, if this kind of analysis has been already performed at step 1 for evaluating e_s and Ω

3) A check of the in-plan stiffness and strength of the floor must be finally performed to take into account its diaphragm action This is particularly important when the storey plan configuration and the distribution of rigidities in plan are not enough regular; an appropriate part of the code, which has still to be written, is necessary to rule this aspect and to prescribe the proper approach to the problem

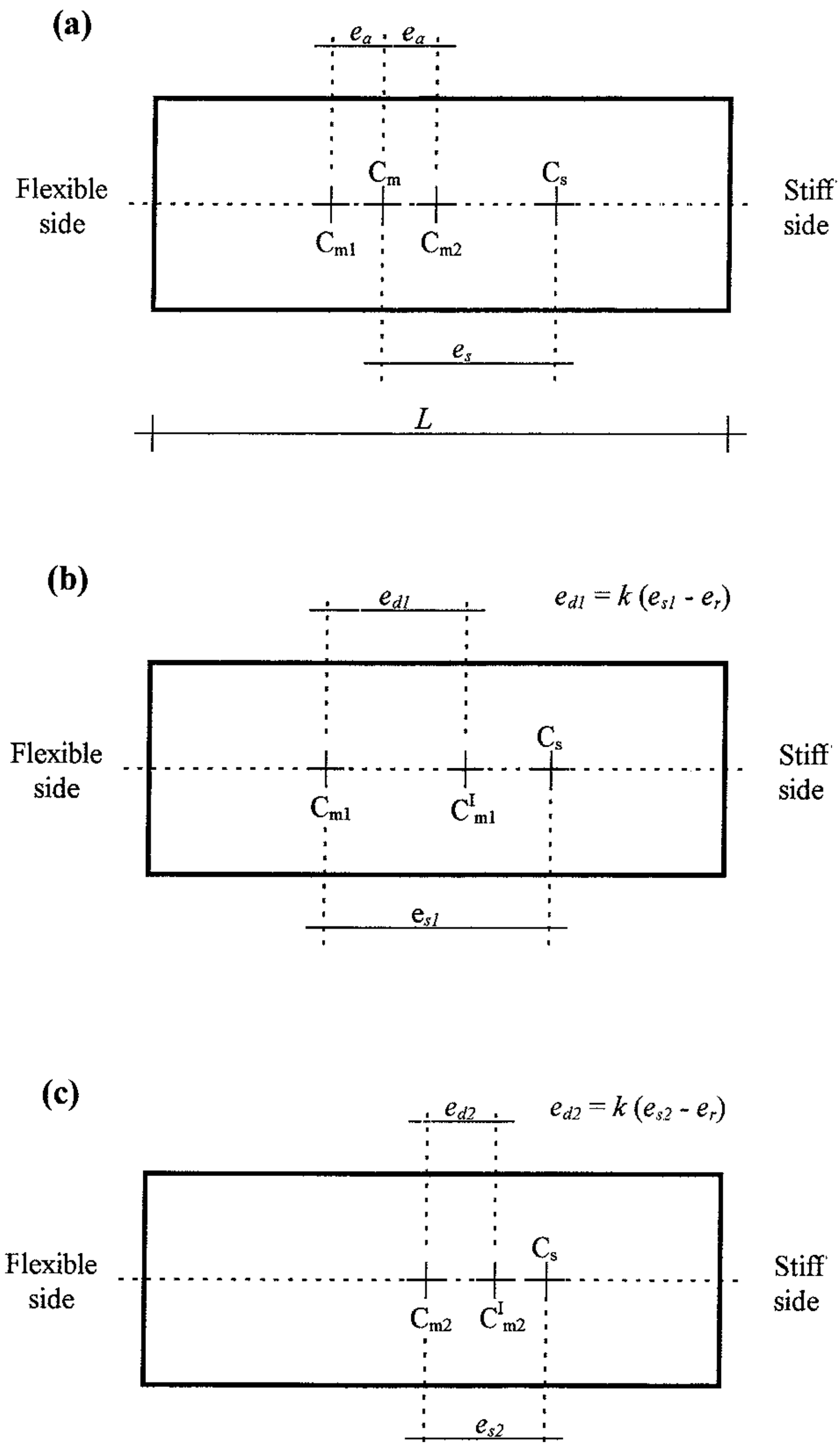

Figure 1 Locations of mass centre to be used in the different phases of design

Conclusions

The critical analysis of EC8 approach to the problem of regularity shows that the last version of this European code presents significant improvements to the previous draft, but it still requires efforts in order to eliminate some ambiguities and to take into account the results of the most recent scientific research

With particular regard to the in-plan regularity, the design procedure proposed in this paper clearly highlights the significance of the different eccentricities:

- the accidental one is unrelated to regularity and it always has to be used;
- the design eccentricity is connected to the inelastic torsional behaviour and it must be always used whether reduction of seismic actions is made by means of the behaviour factor *q*;
- the corrective one is related to the elastic torsional behaviour and it must be used only if static analysis is performed

By using the proposed procedure, the designer can easily and clearly understand the basic parameters which govern the dynamic elastic and inelastic torsional behaviour of the structure At the same time he can judge the regularity of the building on the base of the actual response to static actions rather than of morphological conditions only, and he can perform in most cases the more friendly and understandable static analysis, just by adopting the proper values of corrective eccentricity

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