GUIDELINES ON STRUCTURAL REGULARITY

Note: This document aims at providing guidelines on the subject "structural regularity", which may be used both from researchers and practical engineers.
This version of the document is proposed by the research groups of the universities of Catania and Florence, Italy, as a basis of discussion for all the people interested to the subject. This version is specifically devoted to buildings. The possibility of extending its considerations to other civil engineering works has to be carefully discussed.

The basis of our approach is well clarified at the end of the "Introduction": we want to start from single problems, to point out the conditions necessary to simplify their treatment, instead of starting from general definitions of regularity, which might be confusing because related to many different problems.
Another basic aspect of our approach is the attempt of providing, whenever possible, indications on how to perform "a posteriori" a numerical check of the regularity conditions, starting from the results of the analysis performed.

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1 INTRODUCTION

Every structure to be erected in a seismic region has to be designed and constructed in such a way to meet, with an adequate degree of reliability, specific requirements connected to the return period of seismic action. Each seismic code should define a set of return periods of seismic action and the corresponding required performances, ranging from a "damage limitation" requirement to a "no-collapse" requirement. In the first case the structure will remain in the elastic range, while in the last one it will undergo large inelastic deformation.

In order to check the structural performance, it is necessary:

a) to define a geometrical and mechanical model of the building, which may include only the structural elements or also the so-called non-structural elements;
b) to evaluate the seismic response of the building in the elastic range;
c) to evaluate, or to estimate, the seismic response of the building in the inelastic range.

If the building, and its structure, has been conceived respecting the general principles of a good conceptual design (structural simplicity, uniformity, symmetry and redundancy, bi-directional resistance and stiffness, torsional resistance and stiffness, diaphragmatic behaviour at storey level, adequate foundation) it is possible to use standard modelling while checking the structural performance. The above-mentioned principles grant adequate reliability of the numerical analysis and, at the same time, promote a good behaviour under seismic actions more severe than the design ones.

Note: The general principles of a good conceptual design might be recalled here. We believe adequate the presentation of Eurocode 8.

It is thus possible to define "regular" a building, and a structure, the seismic response of which may be foreseen by means of standard geometrical and mechanical models and standard methods of analysis. In order to discuss "regularity" all the different problems connected to the definition of the model and to the selection of the method of analysis have to be analysed. Each problem gives rise to specific "criteria for regularity", which have to be met in order to allow a simplification of the model or of the method of analysis.

Note: The progress of research, together with the availability of more and more powerful computing devices, allows the use of more complex geometrical and mechanical models and methods of analysis. Although this may influence the above-proposed approach to the problem of regularity, it must be reminded that a well-designed structure should always require the simplest numerical approach possible.

2 MODELLING

2.1 Standard and simpler models of the building

A widely adopted model of the building, which is usually able to adequately represent the distribution of stiffness, is the three-dimensional frame with rigid floor diaphragms:

a) Beams and columns of the building are modelled as one-dimensional members, mutually connected in points named nodes.
b) The floor is considered as a diaphragm, infinitely rigid in its plane.
c) Non-structural elements, as partition walls, are usually not included in the model.
d) Fixed restraints are often considered at the base of the three-dimensional frame, thus assuming very stiff soil and foundation; elastic base restraints, or beams on elastic soil, are sometimes used to model more flexible soil and foundation.

When the vertical resisting elements are arranged along two orthogonal directions, a slightly simplified model may be used, which describes the structure as a three-dimensional set of plane frames. All the other hypotheses (one-dimensional members, rigid floor diaphragms, neglected non-structural elements, fixed or elastic base restraints) remain unchanged.

A much simpler model may be in some cases used: the plane frame. It is a poor model, because it cannot give information on the deck rotations, which are generally present even in geometrically symmetric schemes because of the possibility of non-symmetrical distribution of variable loads. Anyway, it may give in some cases useful information on the structural response, provided that proper integrations or corrections are applied.

2.2 Local problems

The three-dimensional frame model considers one-dimensional members connected in nodes. In actual buildings, the axes of beams and columns may not converge in single points; the dimensions of cross-section may be not small, compared to the length of the member, and may abruptly vary from one member to another. This may cause problems in action transfer, which are not pointed out by the model.

Problems in action transfer may arise also when vertical members are not continuous, e.g. when a column is missing at a storey. The three-dimensional frame model is able to evaluate the effect of such a discontinuity. On the contrary, the three-dimensional set of plane frames model may give unreliable results, if the column belongs to different plane frames, because the model does not consider the vertical compatibility of nodes belonging to different plane frames.

A building is considered regular, under this aspect, when:

– The axes of beams and columns are properly aligned, so as to converge in single nodal points.
– The dimensions of the cross-sections of beams and columns are small, compared to their length, and do not abruptly vary in adjacent elements.
– The vertical members (columns, walls, cores, etc.) are continuous, from the foundation to the top of the building.

Note: Proper limits for the eccentricity of the member axes and for the variation of cross-section of members framing into the same joint should be provided.

The lack of regularity imposes:

– Local checks, with models able to provide more detailed information about the stress distribution in the non-regular zones.
– More detailed constructive provisions for the non-regular zones.

2.3 Floor diaphragm

In the model, the floor slabs are considered as mutual restraints among the nodes they connect. In actual buildings the stiffness or the strength of the floor may be not adequate. This may depend on the floor typology: e.g., in reinforced concrete structures a floor with reinforcements in two orthogonal directions is by itself able to provide large stiffness and strength; on the contrary, a floor with bricks and one-directional main reinforcements requires an adequately thick slab, with bi-directional reinforcement, in order to be considered a rigid diaphragm. It may depend also on the shape of the floor: very elongated in-plan shapes, large re-entrant corners, large openings in the floor for lifts or technical plants and the discontinuity of horizontal slab in correspondence of the stairs may reduce the stiffness and may give rise to localised high values of stress. Finally, it may depend on the distribution of the main resisting elements: e.g., abrupt variation of size or location of steel bracings, or r.c. walls, from one storey to another may cause a relevant re-distribution of horizontal actions, which may lead to very high values of stress and strain in the floor.

A building is considered regular, under this aspect, when:
- The floor is adequately conceived in order to bear horizontal actions.
- The floor shape is compact.
- The main horizontal-action resisting elements are uniformly distributed in plan and their stiffness and location do not abruptly change from one storey to another.

Note: In some cases, the first two requirements may be achieved by subdividing the entire building into dynamically independent units by means of seismic joints

Although simple geometrical conditions may be suggested by codes in order to check the above regularity conditions, it is recommended to perform a numerical check of stiffness and strength of the floor diaphragm, whenever it is deemed necessary:
- The floor may be modelled as a plate, or as a grid, subjected to in-plan actions.
- The horizontal actions may be obtained by the results of the three-dimensional frame model (distributed seismic action along the floor, concentrated reactions of the horizontal-load resisting elements of the above and below inter-storey. These actions should be increased in order to comply with the capacity design criterion, so as to consider the maximum reactions of the horizontal-load resisting elements.
- The stress induced in the floor slab by the above horizontal actions should be smaller than given reference limits. In most cases, this condition may be satisfied by adopting adequate reinforcements (in r.c. slabs) or adequate cross-section of the bracings (in steel slabs).
- The deformation of the floor slab should be as small as not to induce relevant changes in the stress distribution of vertical resisting elements. This condition may be deemed satisfied when, applying to the elements of the three-dimensional frame relative displacements corresponding to the slab deformation, the internal actions vary less than 10%.

The lack of regularity imposes:
- The use of a more general structural model, which accounts for the deformability of the floor diaphragm, or of additional simplified models able to estimate, in a safe way, the variation of beam and column internal actions caused by floor deformation.
- More detailed constructive provisions for the weak zones of the floor diaphragm.

2.4 Non-structural elements

The model does not include non-structural elements, like partition or external walls. In actual buildings, these elements participate to the bearing of seismic actions, with aspects that may be either safe or unsafe for the structure. They reduce the global shear on the structure (safe) but, at the same time, they may modify the location of stiffness centre and stiffness radius of gyration, giving rise to in-plan rotation of the floor that may increase the shear in the outmost elements (unsafe). They produce relevant changes in the axial force of adjacent columns, together with local increment of shear force and bending moment in the contact zone (unsafe). They increase the global stiffness and reduce the fundamental period of vibration of the building, thus reducing the horizontal displacements (safe) but in most cases increasing the horizontal accelerations (unsafe). The variation of stresses they induce may lead to unexpected structural collapse mechanisms, like soft storey (unsafe).

A building is considered regular, under this aspect, when:
– The non-structural elements (partition and external walls) are not particularly rigid, compared to the structural elements.
– Their in-plan distribution is uniform and not very different from that of the structural elements.
– Their stiffness and in-plan location do not abruptly vary from one storey to another.

The lack of regularity imposes:
– The inclusion of non-structural elements in the model. In the elastic range, they may be modelled as plates or struts, although the uncertainties about their connection to the structure make not easy to define whether their contribution starts immediately, or if it must be considered the presence of a gap. Much more complex is the definition of a model that accounts for their cyclic behaviour in the inelastic range; simplified models, able to give safe results, should be used in this case.
– More detailed constructive provisions for the contact zones of the adjacent columns.

2.5 Soil and foundation

Usually, the model assumes fixed restraints at the base. In actual buildings, the vertical displacement and the rotation of the base, due to the flexibility of soil and foundation, may modify the distribution of internal actions among the elements of the frame. Furthermore, even when the foundation is very rigid, the rocking due to the soil flexibility or to the limited extension of the foundation may increase the first period of vibration of the structure.

A building is considered regular, under this aspect, when:
– The foundation elements connect at the base all the elements of the frame and have flexural stiffness higher than that of the elements of the frame.
– The soil stiffness and the extension of the foundation are such as to avoid rocking of the building.

Although simple geometrical conditions may be suggested by codes in order to check the above regularity conditions, it is recommended to perform a numerical check of the stiffness of soil and foundation, whenever it is deemed necessary:
– The analysis of soil and foundation, subjected to the actions given by the over-standing frame, provides displacements and rotations of the nodes that connect frame and foundation.
– The deformation of the foundation should be as small as not to induce relevant changes in the stress distribution of beams and columns. This condition may be deemed satisfied when, applying to the elements of the three-dimensional frame the displacements and rotations, above evaluated, the internal actions vary less than 10%.
– The rotation of the base, considered as a rigid block, should induce small variation of the horizontal displacement of the frame. This condition may be deemed satisfied when, taking into account the effect of a rigid rotation of the base, the top displacement vary less than 10%.

The lack of regularity imposes:
– The inclusion of soil and foundation in the model, by considering elastic restraints instead of fixed restraints or by adding more structural elements, e.g. beams on elastic soil.
– A careful modelling of the soil, in order to account for the effect of the possible variability of its mechanical characteristics in different points of the base of the building.

2.6 Plane frame model

The plane frame model gives correct results only in the case of balanced schemes, i.e. when mass centre and stiffness centre coincide at every storey. Obviously, two plane frames have to be considered, in order to analyse the seismic response of the building to the seismic actions applied along two orthogonal directions. Anyway, if the structural eccentricity e_s (distance between mass centre and stiffness centre) and the radius of gyration of stiffness r_k are constant along the height of the building, it is possible to evaluate the internal actions – due to static forces – in a member at a distance x from the stiffness centre, by multiplying the results of the plane frame model by the normalised factor $\delta = 1 + e_s\, x / r_k^2$. Under the same conditions, plus the hypothesis that the radius of gyration of mass r_m is constant along the building height, it is possible to obtain correct values of modal analysis, by multiplying the results of this type of analysis, performed for the plane frame, by a coefficient δ that represents the normalised displacement of a one-storey three-dimensional system having the same structural eccentricity and radius of gyration of stiffness. The correction is easier when the building is torsionally rigid: r_k has a quite large value; the corrective factor δ for static analysis is less relevant; the corrective factor δ for modal analysis is not so far from the linear values expressed for static analysis.

A building is considered regular, under this aspect, when:
- The mass centres (or the points of application of static forces) and the stiffness centres are located along two vertical lines, the distance of which is e_s.
- The radius of gyration of stiffness r_k and radius of gyration of mass r_m are constant along the building height.
- The building is torsionally rigid, i.e. r_k is larger than r_m. This last condition is not strictly necessary, but it may give some simplification, avoiding the necessity of an accurate evaluation of r_k.

Although some geometrical conditions may be suggested by codes in order to check the above regularity conditions, it is recommended to perform a numerical check of the alignment of mass and stiffness centres and of the constancy of the radius of gyration of stiffness and mass, whenever it is deemed necessary:
- Knowing the distribution of masses (permanent and variable loads) it is possible to evaluate at each inter-storey the location of the centre of masses and their radius of gyration.
- Basing on the results of the analysis of the two plane frames subjected to horizontal forces, it may be defined “lateral stiffness” of a column (or a r.c. wall, or a sub-frame constituted by elements aligned in plan) – at a given inter-storey and in a given direction – the ratio between the adsorbed shear force and the relative displacement of the ends of the element.
- It is thus possible to evaluate at each inter-storey the location of the centre of the above-defined quantities and their radius of gyration.
- The non-alignment of the centres and the differences in radius of gyration should be such as not to modify the structural response and the distribution of internal actions more than 10%. This may be checked, if necessary, by repeating the afore-mentioned correction using both the maximum and minimum value assumed by each variable quantity (eccentricity or radius) along the height.

Note: Researchers should investigate if the results corresponding to a variation, storey-by-storey, of eccentricity and radius are included between those obtained using maximum and minimum values of eccentricity and radius.

The lack of regularity imposes to use the three-dimensional frame or three-dimensional set of plane frames model.

2.7 Model for masses

In order to adequately represent the distribution of masses, it is necessary to take into account the in-plan distribution of permanent (dead) and variable (live) loads. Although in actual buildings some masses are concentrated in points (columns) or distributed along lines (beams, partition and external walls), they are usually considered uniformly distributed in the floor. Also the value of variable loads, which may differ from point to point, is considered uniformly equal to a reduced value. The centre of masses and their radius of gyration are thus assumed coincident to those of the floor.

The possible variation of the location of mass centre, due to non-uniform distribution of variable loads, is taken into account by means of a so-called accidental eccentricity e_a. Although present seismic codes suggest for such eccentricity a unique value (e_a = 0.05 L, being L the floor dimension perpendicular to the seismic action), the influence of variable loads should be connected both to the use destination of the building and to the structural material used. E.g., the accidental eccentricity should be smaller in masonry building and larger in steel structures.

Note: We should provide here a set of values for accidental eccentricity, connected to the use destination of the building and to the structural material used.
These values could also include a quantity, which cover uncertainties in the evaluation of the location of permanent loads and in the spatial variation of the seismic motion.

A building is considered regular, under this aspect, when:
- The masses are distributed in the floor in a nearly uniform way.
- The entity of permanent and variable loads is properly connected to the value assumed for accidental eccentricity.

The lack of regularity imposes:
- A more detailed evaluation of the location of mass centre and of radius of gyration of masses.
- A more detailed evaluation of the variation of the mass-centre location, due to the most unfavourable disposition of variable loads.

3 ELASTIC RESPONSE

3.1 Standard and simpler models

Nowadays, modal analysis may be considered the standard approach in evaluating the elastic response of a structure. Modal analysis provides a correct estimate of the elastic response of any structure in the elastic range, provided that:
- The effect of each horizontal component of seismic action is evaluated using a more accurate combination procedures, like Complete Quadratic Combination (CQC), instead of Square Root Sum of Squares (SRSS) combination whenever the periods of two vibration modes differ less than 10%, i.e. for nearly all three-dimensional schemes.
- The effect of the contemporaneous presence of two orthogonal components of seismic action is properly evaluated, e.g. by combining the separate effects of the two components by means of the SRSS combination.

Note: We believe modal analysis always able to provide a correct estimate of the elastic response. Anyway, if some researcher will point out cases in which it is unsafe – and it is necessary to use a step-by-step response analysis – regularity conditions necessary to avoid such a more complex procedure may be added here.
Furthermore, an alternative approach might consider standard a modal analysis with SRSS combination and without combination of the effects of orthogonal components. In this case, regularity conditions should be added to define when this approach is safe and when, on the contrary, CQC and combination of orthogonal actions are necessary.

An alternative, widely used, approach is the static analysis. Although this is a poor approach, which gives no information on the periods of vibration of the scheme and on the effects of higher modes of vibration, its simplicity and physical evidence makes it an important tool for evaluating seismic elastic response, provided that the effect of the first mode of vibration is prevailing in the scheme and proper integrations or corrections are applied when necessary.

A building is considered regular, under this aspect, when:
- The structural typology, the structural material used, the entity and location of non-structural elements allow a reliable estimate of the first period of vibration.

– The effect of the first mode of vibration is prevailing in the scheme. This condition may be deemed satisfied if the estimated period of vibration is smaller than given values, related to the expected response spectrum, i.e. to the mechanical characteristics of the soil.
– The conditions described in the following sections, in function of the geometrical characteristics and the model used for the building, are respected.

Note: Limits of the first period of vibration, for the application of static analysis, should be explicitly added here.

Although seismic codes should provide formulations able to allow an easy and reliable estimating of the first period of vibration, it is recommended to perform a numerical check of the first period, whenever it is deemed necessary:
– Knowing value and distribution of masses along the height, it is possible to evaluate the total mass M and the elevation z of it centre.
– Basing on the results of the static analysis, it may be defined "lateral stiffness" K of the frame the ratio between the base shear-force and the displacement of the frame at the elevation z.
– It is thus possible to evaluate the first period as $2\,\pi\sqrt{M\,/\,K}$.

The lack of regularity imposes the use of modal analysis.

3.2 Plane frames

Static analysis of plane frames provides safe results, compared to the modal one, if mass and stiffness do not abruptly vary along the height. It is anyway well known that, for frames having more than one storey, the base shear-force used in static analysis is quite larger than the corresponding value obtained by means of modal analysis (from 10 to 30% more). For a better correspondence between the results of the two analyses, many codes conventionally prescribe to increase the results of modal analysis, so as to obtain at the base the same shear force used in static analysis (some codes accept a smaller shear force when the scheme is regular). With a theoretically more correct approach, although less safe, Eurocode 8 (2002) allows a 15% reduction of the results of static analysis, provided that the first period of vibration does not exceed given limits. This tendency to equalize the two analyses is acceptable, and theoretically desirable, but it reduces the safety intrinsically connected to static analysis and requires a more careful check of its applicability.

It must be furthermore taken in mind that static analysis gets the effect of horizontal acceleration only. In the case of very large span or of discontinuity of the vertical elements (columns) the effect of vertical acceleration cannot be neglected.

A building is considered regular, under this aspect, when in addition to the regularity conditions of section 3.1:
– There is no abrupt variation of mass or stiffness along the height.
– The vertical members (columns, walls, cores, etc.) are continuous, from the foundation to the top of the building.
– The span of the horizontal elements (beams) does not exceed given limits.

Note: Both specific limits for mass and stiffness variation and simple procedures for a numerical check of this regularity conditions should be provided here.

The lack of regularity imposes:
– The use of modal analysis.
– The evaluation of the effects of vertical acceleration, if the last two conditions are not satisfied.

3.3 Balanced buildings analysed by means of plane frame model

As mentioned before, the plane frame model should be used only in the case of balanced schemes, i.e. if the decks translate without any rotation when the seismic forces are applied at mass centres of the building (or, equivalently, if mass centre and stiffness centre coincide at every storey). Even in this case, the possibility of non-symmetrical distribution of variable loads (i.e. the above-defined accidental eccentricity e_a) requires an estimation of the in-plan rotation of the floors. It is possible to account for the static effect of this eccentricity, in a member at a distance x from the stiffness centre, by multiplying the results of the plane frame model by the normalised factor $\delta = 1 + e_a\, x / r_k^2$. In torsionally rigid schemes (for which static and modal analysis do not differ too much) this approach gives results approximately valid also for modal analysis; further simplifications may be used in this case: e.g., Eurocode 8 suggests to use the expression $\delta = 1 + 12\, e_a\, x / L^2$, which is equivalent to assume $r_k \geq 0.3\, L$ approximately.

A building is considered regular, under this aspect, when in addition to the regularity conditions of sections 3.1 and 3.2:

- The nominal position of mass centre (corresponding to a uniform distribution of loads) and the position of stiffness centre coincide at every storey.
- The radius of gyration of stiffness r_k and radius of gyration of mass r_m are constant along the building height.
- The building is torsionally rigid, i.e. r_k is larger than r_m.

The lack of regularity imposes:

- The use of modal analysis, if the building cannot be considered balanced or it is not torsionally rigid.

Or:

- A more detailed evaluation of the corrective factor δ, if the only non-satisfied condition is the torsional rigidity of the scheme (see references in section 3.4).

3.4 Single-storey buildings

In an asymmetric (or non balanced) single-storey scheme, the force applied with static analysis is not very different from the base shear-force provided by modal analysis. Nevertheless, the horizontal displacements given by static analysis may be very different from the maximum displacements of modal analysis. In particular, the first ones vary in-plan in a linear way, while the second ones present a curved shape, because the maximum displacement at different points is reached in different times. Static analysis is therefore always safe for some structural elements, unsafe for other. In order to get safe results, it is necessary to evaluate the internal actions as the envelope of the results of two static analyses, performed applying horizontal force in points displaced, from the mass centre, by a quantity named corrective eccentricity e_c.

Under this aspect, a building can never be rigorously considered regular.

The peculiarity of single-storey asymmetric schemes imposes:

- The use of modal analysis.

Or:

- The use of two static analyses, performed applying the force in points displaced, with respect to the mass centre, of proper values of corrective eccentricity.

Although many seismic codes and research groups provide simple formulations for estimating the value of corrective eccentricity, it is recommended to use more reliable formulations or procedures.

Note: See, for example, the papers:
Anastassiadis, K., Athanatopoulos, A. and Makarios, T., 1998, Equivalent static eccentricities in the simplified methods of seismic analysis of buildings, Earthquake Spectra, 14, 1-34.
Calderoni, B., D'Aveni, A., Ghersi, A. and Rinaldi, Z., 2002, Static versus modal analysis of asymmetric buildings: effectiveness of dynamic eccentricity formulations, Earthquake Spectra.

3.5 Multi-storey buildings

Multi-storey buildings denote the same problem of non-correspondence of the shape of static and modal deformation discussed for single-storey schemes. The safety intrinsically connected to the static analysis of schemes having more than one storey, already recalled for plane frames, may be in many cases (although not always) sufficient to counterbalance the above-mentioned inadequacy, but it may be nullified by the attempt of equalizing static and modal base shear-force. For this reason, a correct use of static analysis should consist, as proposed for single-storey schemes, in evaluating the internal actions as the envelope of the results of two static analyses, performed applying horizontal forces in points displaced, from the mass centre, by proper values of corrective eccentricity e_c.

Being corrective eccentricity connected to structural eccentricity e_s and radius of gyration of mass and stiffness, r_m and r_k, in multi-storey buildings the proposed approach may be applied only if these quantities do not vary along the height. Schemes that respect this condition are usually named regularly asymmetric.

Note: See, for example, the paper:
Hejal, H. and Chopra, W.K., 1987, Earthquake response of torsionally-coupled buildings, Report No. UBC/EERC-87/20, University of California at Berkeley, Berkeley.

A building is considered regular, under this aspect, when in addition to the regularity conditions of sections 3.1 and 3.2:

- The mass centres and the stiffness centres are located along two vertical lines, the distance of which is e_s.
- The radius of gyration of stiffness r_k and radius of gyration of mass r_m are constant along the building height.

Although some geometrical conditions may be suggested by codes in order to check the above regularity conditions, it is recommended to perform a numerical check of the alignment of mass and stiffness centres and of the constancy of the radius of gyration of stiffness and mass, whenever it is deemed necessary:

- Knowing the distribution of masses (permanent and variable loads) it is possible to evaluate at each inter-storey the location of the centre of masses and their radius of gyration.
- Basing on the results of the analysis of the three-dimensional frame model subjected to a set of horizontal forces F_i, applied to the mass centres, and to a set of couples M_i, obtained by multiplying the forces F_i by a whatsoever eccentricity e_0 (e.g., $e_0 = e_a$), it is possible to evaluate at every storey the quantities:

$$e_{s,i} = -e_0 \frac{\theta_{F,i}}{\theta_{M,i}} \qquad\qquad r_{k,i} = e_0 \sqrt{\frac{v_{F,i}}{e_0\ \theta_{M,i}} - \left(\frac{\theta_{F,i}}{\theta_{M,i}}\right)^2}$$

- The procedure may be applied if the variations along the height of the above quantities do not modify the structural response and the distribution of internal actions more than 10%. This may be checked, if necessary, by repeating the analysis using both the minimum and the maximum value assumed by each variable quantity (eccentricity or radius) along the height.

Note: See, for example, the papers:
Calderoni, B., D'Aveni, A., Ghersi, A. and Rinaldi, Z., 2002, Static versus modal analysis of asymmetric buildings: effectiveness of dynamic eccentricity formulations, Earthquake Spectra.
Moghadam, A.S. and Tso, W.K., 2000, Extension of eurocode 8 torsional provisions to multi-storey buildings, Journal of Earthquake Engineering. **4**, 1, 25-41.

Recent studies show that static analysis with corrective eccentricities may give safe results even when the structural eccentricity and radius of gyration of stiffness vary in a more relevant way along the height. It has been proposed the use of other parameters in order to check the applicability of static analysis. See, for example, the paper:
Bosco, M., Ghersi, A., Marino, E. and Rossi, P.P., 2002, Effects of in-elevation irregularity on the elastic seismic response of in-plan asymmetric buildings, Third European Workshop on the Seismic Behaviour of Irregular and Complex Structures, Florence.

The lack of regularity imposes the use of modal analysis.

4 INELASTIC RESPONSE

4.1 Standard approach

Nowadays, the standard design approach to the problem of the inelastic response of buildings is the so-called force-based design. It is assumed that the inelastic response of the building shall be acceptable, i.e. the building will not collapse, if the structure is able to withstand (by means of an elastic analysis, without exceeding allowable stresses or the ultimate limit state of each cross-section) horizontal forces evaluated by a design spectrum. This one is obtained by reducing the elastic response spectrum by a proper coefficient (named *R* in UBC, *q* in Eurocode 8), related to the dissipative characteristics of the scheme and of the cross-sections. Each seismic code should provide standard values of this coefficient, usually calibrated for plane frames with different ductility levels, together with rules for improving both global and local ductility of the structure.

Note: Some indications should be added here about more recent alternative design procedures, like displacement-based design and performance-based design.

A building is considered regular, under this aspect, when its inelastic behaviour does not differ in a relevant way from that of the ductile plane frame, to which the reduction factors proposed by codes are related. Specific regularity conditions are described in the following sections, in function of the geometrical characteristics and the model used for the building.

The lack of regularity may impose, in function of the geometrical characteristics and the model used for the building:

- The use of smaller values of the reduction factor.

Or:

- The use of additional load conditions.

Or:

- The use of step-by-step inelastic response analysis.

4.2 Plane frames

Abrupt variations of stiffness along the height of the frame may lead to high values of locally required ductility, thus causing a worsening of the inelastic response and making necessary to provide more strength. Typical example is the so-called soft storey, i.e. a storey having stiffness really smaller than that of the storeys above and below it; notice that this situation may be caused also by an improper distribution of non-structural elements, partition or external walls, even in buildings that present a uniform distribution of stiffness of structural elements.

An analogous problem may be produced by a strong increase in stiffness of on or few vertical elements at a storey, if it is not coupled to a proportional increase in strength. Typical examples are the presence of a shorter column or of an inclined beam connecting a floor to the mid-height of a column (as in a typology of stairs commonly used in Italy).

A building is considered regular, under this aspect, when:

- The total lateral stiffness of structural and non-structural elements does not vary in a relevant way from one storey to another.
- No element has a lateral stiffness much higher than that of other elements of the same storey, unless it has a proportionately higher strength.

The lack of regularity imposes:

- The use of smaller values of the reduction factor. When the irregularity is clearly referred to a limited portion of the frame (e.g. to a single storey) it is possible to perform two numerical analyses: the first one with a standard value of reductive coefficient and the second one with a smaller value of it, using the results of the latter only for the portion of frame in which the irregularity is shown.

Or:

– The use of step-by-step inelastic response analysis.

Note: Although seismic codes provide simple indications for defining this irregularity and for decreasing the reductive coefficient, our opinion is that the research has not, up to now, well clarified this problem and that much more research work has to be done about it.

4.3 Single-storey buildings

The inelastic response of an asymmetric, or non-balanced, three-dimensional scheme presents some peculiarities, with respect to that of a plane frame. Indeed, many researchers pointed out that the inelastic response of a non-balanced single-storey three-dimensional scheme is less rotational than its elastic response. Elastic analysis is therefore safe for some structural elements, unsafe for other. This seems to be confirmed also in the case of schemes subjected to bi-directional ground motions, because of the un-correlation of the orthogonal components of the motion.

Note: see, for example, the papers:
Ghersi, A. and Rossi, P.P., 2000, Formulation of design eccentricity to reduce ductility demand in asymmetric buildings, Engineering Structures, Elsevier Science Ltd, vol. 22, pp. 857-871.
Ghersi, A. and Rossi, P.P., 2001, Influence of bi-directional ground motions on the inelastic response of one-storey in-plan irregular systems, , Engineering Structures, Elsevier Science Ltd, vol. 23, pp. 579-591.

Under this aspect, a building can never be rigorously considered regular.

The peculiarity of single-storey asymmetric schemes imposes:

– The use of two elastic analyses, performed with reference both to the nominal position of the mass centre and to a conventional, less eccentric, locations of it. A simple possibility for the latter is to consider mass centre coincident to stiffness centre, i.e. to analyse a scheme subjected to pure translation. Alternative, more reliable, formulations for this design eccentricity may be found in references.

Or:

– The use of step-by-step inelastic response analysis.

4.4 Multi-storey buildings

The inelastic response of non-balanced multi-storey buildings presents, in addition to the problems discussed for plane frames, the peculiarities above mentioned for single-storey three-dimensional schemes. For this reason, a correct use of elastic analysis should consist, as proposed for single-storey schemes, in evaluating the internal actions as the envelope of the results of two elastic analyses, performed with reference both to the nominal position of the mass centre and to a conventional, less eccentric, locations of it.

A building is considered regular, under this aspect, when in addition to the regularity conditions of section 4.2:

– The mass centres and the stiffness centres are located along two vertical lines, the distance of which is e_s.
– The radius of gyration of stiffness r_k and radius of gyration of mass r_m are constant along the building height.

The lack of regularity imposes:

– The use of step-by-step inelastic response analysis.

Note: The inelastic response of multi-storey buildings has been object of research only in the last few years and it cannot be considered fully investigated. In particular, scarcely known is the behaviour of buildings that are not regularly asymmetric.