CRITICAL COMMENTS ON EUROCODE 8
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1 INTRODUCTION

In this paper, certain paragraphs and clauses in sections 3 and 4 of Draft No5 (Revised Final Project Draft) of prEN 1998-1/May 2002 are criticized on the basis of theoretical *soundness*, practical *applicability* and substantial *effectiveness and reliability*. The weak points of these provisions are identified and analyzed, while proposals are made in order to improve them. The proposals take into account all current scientific research results, as well as modern analysis software available in today's engineering practice.

2 ORIENTATION OF SEISMIC ACTION

Paragraph (10)P in clause 4.3.3.1 states : *"….. the design seismic action shall be applied along all relevant horizontal directions…" and "For buildings with resisting elements in two perpendicular directions these two directions are considered as the relevant ones".*

However, within the framework of modal response spectrum analysis, it is well known (see [1-6]) that in case of bidirectional isotropic seismic excitation (i.e., assuming equal response spectra for both horizontal orthogonal seismic components) prescribed in paragraph 3.2.2.1 (3)P, the structural response is independant of the seismic action's orientation. As a consequence, examination of more than one seismic input orientation, i.e., application of the bidirectional isotropic seismic action along different horizontal directions, is superfluous, as it leads to identical seismic actions effects in any case.

If the lateral force method is used, two horizontal seismic components shall be applied along the structure's principal axes (axes of maximum and minimum stiffness of the structure). Otherwise, non-unique values for the uncoupled natural periods T_x and T_y , the structural (static) eccentricities e_{ox} and e_{oy}, and the corresponding torsional radii r_x and r_y will result. It is worth mentioning, that for buildings with orthogonally arranged structural elements the principal axes x and y do not necessarily coincide with building's axes X and Y (Figure1).

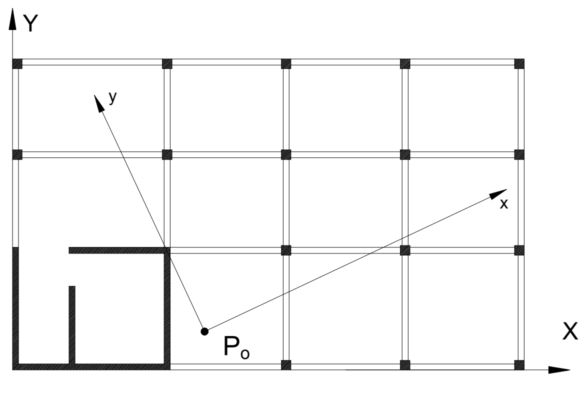

Fig. 1. Building's axes X, Y and principal axes x, y

Proposal:

If the modal response spectrum analysis is used, application of the bidirectional isotropic seismic action along one arbitrarily chosen direction will suffice. If the lateral force method is used, the seismic action must be applied along the principal axes of the structure (see comment in the next paragraph).

3 CRITERIA FOR REGULARITY IN PLAN

In order to formulate criteria for regularity in plan, certain fundamental structural properties or concepts are used such as centre of stiffness, structural (or static) eccentricities and torsional radii. However, the definitions for these concepts given in paragraph 4.2.3.2 refer only to some particular cases (single-story buildings and isotropic multi-story buildings), whereas in the rather usual case of <u>dual systems</u> no such definition can be found. Thus, application of the criteria of paragraphs 4.2.3.2(5) and 4.3.3.1(8)(e) in case of dual systems is not possible.

In addition, the structural eccentricities e_{ox} and e_{ox} are not defined with respect to the '<u>principal directions</u>', which would be a correct and unique definition, but with respect to the '<u>directions of analysis</u>', i.e., according to paragraph 4.3.3.1(10), 'with respect to all relevant horizontal directions'. Thus, for each particular direction of analysis, different values of eccentricities should be determined.

Proposal:

On the basis of previous research [7, 8], we propose the following definitions of the aforementioned fundamental structural properties of any multi-story building which is regular in elevation:

- *Elastic axis (or torsional axis)*
  The elastic axis (real or fictitious) of a building is defined as the vertical line passing through the centre of twist P_o of the floor diaphragm i_o next to level z_o=0,80 H (H: building height). P_o is determined for a loading of the floor diaphragms i consisting of a set of torsional moments about the vertical axis M_{zi}=c F_i, where F_i are the horizontal seismic forces at each floor and c is an arbitrary constant.
- *Principal directions*
  The orientation of the building's principal directions x, y with respect to an arbitrarily choosen reference system P_oXY is given by angle α (Figure 2) as

$$\tan(2\alpha) = 2\, u_{XY} / (u_{XX} - u_{YY}) \qquad (1)$$

where u_{XX}, $u_{YX} = u_{XY}$ displacements of P_o in X- and Y-direction respectively due to seismic forces F_i applied parallel to the X-axis
u_{XY}, u_{YY} displacements of P_o in X- and Y-direction respectively due to seismic forces F_i applied parallel to the Y-axis

- *Structural (or static) eccentricities*
  The structural eccentricities $e_{ox,i}$ and $e_{oy,i}$ at each story i are given by the coordinates of the story mass centres M_i in the reference system P_oxy, where x and y are the principal axes (Figure 2).

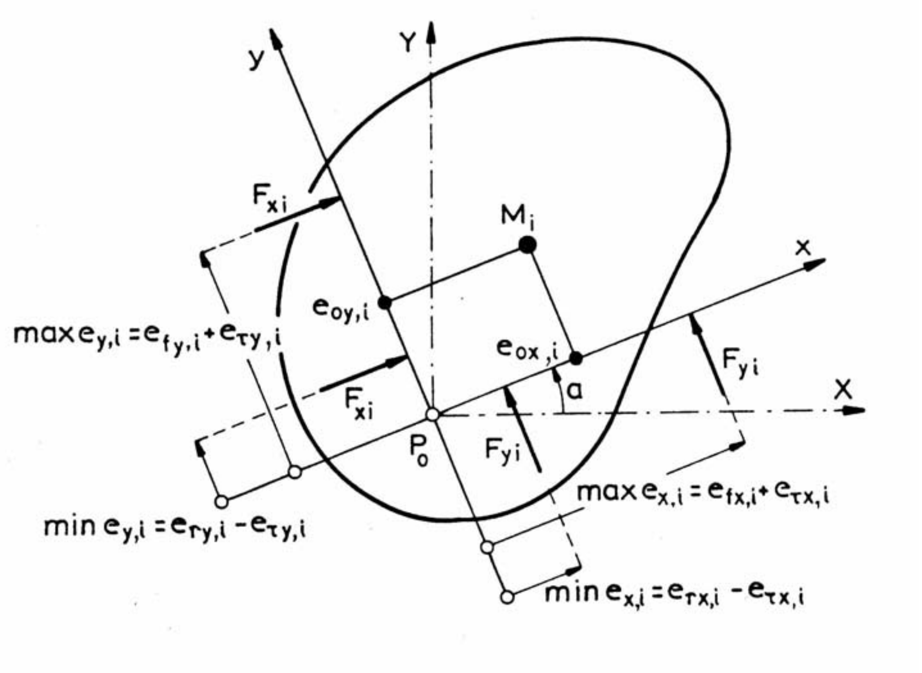

Fig. 2. Design eccentricities e_{max} , e_{min}

- *Torsional radii*
  The structure's torsional radii with respect to the elastic axis are given by

$$r_x = (c\, u_y / \theta_z)^{1/2} \qquad r_y = (c\, u_x / \theta_z)^{1/2} \qquad (2a,b)$$

where u_x , u_y displacements of P_o due to seismic forces F_i applied along the principal directions x and y respectively
θ_z rotation angle about z-axis at diaphragm level i_o due to a torsional loading consisting of torsional moments $M_{zi}=+cF_i$.

4 ACCIDENTAL TORSIONAL EFFECTS

The approximative calculation of accidental torsional effects by using factor $\delta=1+0{,}6x/L_e$ (see paragraph 4.3.3.2.4) is based on the assumption that lateral stiffness is not only symmetrically but also uniformly distributed in plan. It is obvious that this paragraph cannot be applied to 'core-systems', for which the above assumption is not valid. Furthermore, it should be mentioned that this approximate calculation does not take into account the effect of torsion on the load-resisting elements perpendicularly oriented to the seismic direction considered.

Proposal:
Reformulation of paragraph 4.3.3.2.4 with explicite mentioning of the underlying assumption that mass and stiffness must be symmetrically and uniformly distibuted in plan, and explicit exclusion of 'core-systems'.

5 USE OF TWO PLANAR MODELS AND TORSIONAL EFFECTS

According to clauses 4.3.3.1(7) and (8), linear-elastic (static and dynamic) analysis may be performed using two planar models in the following two cases:

- Buildings satisfying the criteria of paragraph 4.2.3.2 for regularity in plan, i.e., torsionally nonsensitive buildings with small eccentricities.
- Buildings satisfying the specific regularity criteria of clause 4.3.3.1(8). The torsional sensitivity and the eccentricities of these buildings may be disregarded, "*provided all seismic action effects from the analysis are multiplied by 1,25*".

According to clause 4.3.3.2.4(2), the torsional effects of the aforementioned buildings (which are, in general, asymmetrical buildings with or without torsional sensitivity) may be accounted for in the following way:

- Accidental torsional effects are taken into account according to clause 4.3.3.2.4(1), i.e., by making the assumption that lateral stiffness is symmetrical and uniformly distributed in plan.
- The natural (structural) torsion of the building is equated (!) to the accidental torsion and its effects are taken into account as before, i.e., by considering lateral stiffness as symmetrical and uniformly distributed in plan.
- The amplification of natural eccentricities due to lateral-torsional coupling is neglected in all cases.

All these provisions are at least unusual in earthquake engineering. They are lacking theoretical foundation and may lead to unacceptable results, especially with respect to the influence of the natural (structural) eccentricity e_o. The latter is arbitrarily equated to the accidental eccentricity $e_1=0{,}05L$, disregarding its actual value. The possibility of major errors shall be demostrated with the aid of a simple example. The single-story building in Figure 3 consists of three walls W_1, W_2, W_3 of equal dimensions which resist the lateral loads and of a number of columns with negligible lateral stiffness for carrying the dead loads. For seismic action along the y-axis,

$$e_{ox} = a \ , \quad l_s^{\,2} = (5/12)\, a^2 \qquad (3a,b)$$

$$r_x^2 = K_z / K_y = k\, a^2 / (2k) = a^2 / 2 \qquad (3c)$$

where k is the lateral stiffness of each individual wall. Because of

$$r_x^2 < l_s^{\,2} + e_{ox}^{\,2} \qquad (4)$$

and according paragraph 4.3.3.2.4(1) and (2), the action of the seismic force F along the y-axis produces the following results:

Displacements: $u_r = u_f = 1{,}25\ (1 + 1{,}2)\ F/k = 2{,}75\ u_o$,
where $u_o = F/k$ is the displacement of the planar system

Forces: $F_1 = 1{,}25\ F$ and $F_2 = F_3 = 0$.

However, exact static analysis of the system taking into account the natural torsion of the system alone (i.e., neglecting the accidental eccentricity e_1 and the additional eccentricity e_2) gives:

Displacements: $u_r = u_o$, $u_f = F/k + [a\ F\ /\ (ka^2/2)]\ 2a = 5u_o \gg 2{,}75\ u_o$

Forces: $F_1 = F$ and $F_2 = F_3 = F$ (instead of zero).

This simple analysis shows that the torsional provisions of paragraph 4.3.3.2.4 may lead to erroneous results which are not compatible with real torsional behavior.

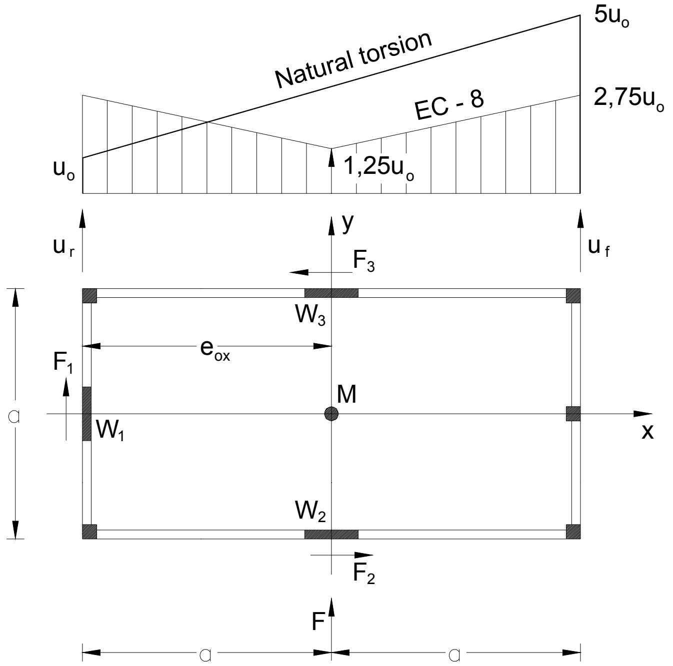

Fig. 3. Asymmetric single-story building

Proposal:

Analyses using two planar models should be restricted only to the case of buildings which are symmetrical about two orthogonal axes and whose lateral stiffness is uniformly distributed in plan. For this specific class of buildings, the accidental torsional effects may be acounted for according to paragraph 4.3.3.2.4 (1). In any other case, torsional effects (accidental torsion, natural torsion and amplification of natural torsion) shall be taken into account by using 3D models.
In particular, when the lateral force method is used, design eccentricities along each of the building's principal directions x and y are given by (see Figure 2)

$$e_{max} = e_f + e_T \quad \text{and} \quad e_{min} = e_r - e_T \tag{5}$$

where e_T=0,05L is the accidental eccentricity and e_f , e_r are the *equivalent* static eccentricities, which account for natural torsion as well as for the amplification effects. In case of buildings which are torsionally stiff (i.e., not torsionally sensitive, $r^2 + e_o^2 > l_s^2$) these eccentricities are given by the simple relations:

$$e_f = 1.5\ e_o \quad \text{and} \quad e_r = 0.5\ e_o \tag{6}$$

In case of torsionally sensitive buildings, either a more exact calculation of these eccentricities must be carried out (see [9]) or, alternatively, the modal response spectrum method must be applied.

6 DESIGN SPECTRUM FOR ELASTIC ANALYSIS

The design spectrum is defined by Eqs. (3.12) to (3.15) in clause 3.2.2.5 of section 3. These expressions do not contain the damping correction factor

$$\eta = \{ 10/(5+\xi) \}^{½} \geq 0.55 \tag{7}$$

because, according to clause 3.2.2.5(3) "*The value of the behaviour factor q, which also accounts for the influence of the viscous damping being different from 5%, are given for the various materials and structural systems and according to the relevant ductility classes in the various Parts of EN 1998*". Furthermore, according to the Sumary Report of prEN1998-1, the design spectrum follows from the elastic spectrum *"by replacing the damping factor η by the behaviour factor q*", i.e., by setting η=1/q.

In the authors' opinion, the incorporation of the damping correction factor η into the behaviour factor q is not possible. The reason is that by calculating the displacements according to the expression:

$$d_s = q_d \, d_e \tag{8}$$

(see clause 4.3.4(1)P, Eq. (4.23)), the behaviour factor $q=q_d$ is eliminated from the final result. This means that the influence of any damping ratio ξ different from 5% on the displacements is also eliminated. As a consequence, the displacements are always calculated for a damping ratio equal to 5% regardless of the material the structure is made of! Due to this fact, the calculated displacements of welded steel structures with a damping ratio smaller then 5% are underestimated by roughly 20%.

It is worth noticing, that, in general, the roles of the factors η (or ξ) and q are not interchangeble, because they represent different physical properties. By replacing, e.g., the ductility factor μ by some equivalent viscous damping ratio ξ_{eq} (as in ATC-40), erroneous results are obtained [10].

Proposal:

It is proposed to incorporate the damping correction factor η in Eqs. (3.12) to (3.15) of clause 3.2.2.5 by multiplying *2.5* by η. Furthermore, as no information about the ξ-values is given in the following paragraphs, a table prescribing ξ-values for different materials should be also incorporated.

7 P-Δ-EFFECTS

According to paragraph (2) in clause 4.4.2.2, the *P-Δ*-effects need not be considered when the following condition is fulfilled for each story of the building:

$$\theta = (P_{tot} \, d_r) \,/\, (V_{tot} \, h) \leq 0.10 \tag{9}$$

In this relation d_r denotes the design interstory drift, evaluated as the difference of the average lateral displacements at the top and the bottom of the story under consideration and V_{tot} denotes the total seismic story shear.

It is well known [11], that the above expression is valid only for planar frames with predominant shear deformation under static loading. In particular, Eq. (9) is not valid in the following two cases :

- Dual planar systems with λH<6, where $\lambda^2=GA_S/EI$ (GA_S=shear stiffness, EI=flexural stiffness) and H=heigth of the system. Thus, e.g., for λH=1 the value of θ according to Eq. (9) turns out to be about 50% of the correct value.
- All asymetrical spatial systems.

Proposal:

The following general relation for θ is proposed:

$$\theta = P \,/\, P_{cr} = q \,(P \,/\, P_{cr,el}) \tag{10}$$

where $P_{cr,el} = v_{cr}P$ is the critical buckling load of the system and q is the behaviour factor. In the most general case, v_{cr} can be calculated using either the uncorrelated buckling coefficients v_x, v_y, v_z (see [12], [13]) or a relevant computer program.

8 PUSHOVER ANALYSIS

General comments:

- Pushover analysis is a non-linear analysis method. Therefore, application of the principle of superposition is not allowed. In spite of that, the superposition principle is used in paragraph 4.3.3.5.1(6) for the determination of the response due to the two simultaneously acting horizontal seismic components, as well as in paragraph 4.3.3.4.2.7 in order to take the torsional effects into account.
- The theoretical foundation of the method is, in case of planar structures, insufficient, while in case of space structures (which is of particular interest in engineering practice) it is non-existent.
- Numerical testing, validation and verification of the method's reliability are limited.

Proposals:

- For the time being, pushover analysis should not be used for *quantitative* investigations of structural response. It may solely be used for a *qualitative* evaluation of the structural behavior in the inelastic range.
- The superposition principle should be applied within each particular step of the pushover analysis procedure. It must not be applied at the end of the procedure.
- In case of asymmetric buildings, the seismic forces should not be applied directly at the mass centre. Specific design eccentricities (similar to those prescribed by the design codes for linear static analysis) must be taken into account.

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