Issues concerning general torsion in code provisions

D. Köber, D. Zamfirescu
Technical University of Civil Engineering, Bucharest

SUMMARY:
Nowadays seismic design codes recommend as current design methods for plan irregular structures the static elastic calculation method with equivalent horizontal forces and the modal response spectrum analysis method. Effects of general torsion are taken into account in the elastic range of behavior by considering a static eccentricity (equal to the distance between the mass center and the stiffness center) combined with an accidental eccentricity (up to 10% of the floor dimension perpendicular to the direction of seismic input). Nevertheless most structures are designed to behave nonlinear, so the importance of the stiffness center is overtaken by the strength center. Also, elastic calculation (for the main limit state) is provided by code regulations although inelastic response of plan irregular structures is highly different from the elastic one and depends essentially on the intensity of seismic input. This paper investigates the limitations of code provisions concerning plan irregular structures by comparing code design results with dynamic nonlinear analysis results on single-story models. Torsional irregularity, displacements and structural rotations are checked.

Keywords: plan irregularity, single story structures, linear and nonlinear behavior

1. AIM OF THE STUDY

For plan irregular structures coupling between translation and torsion produces uneven displacements in structural elements.

In order to understand the influence of structural irregularity on structural displacements, research was limited for a long time to an elastic analysis and determined most of the code provisions in this field.

Nowadays design methods are based on the inelastic response, which is influenced by more factors than the elastic one. The elastic response can be defined through global reverse forces, whereas the inelastic response has to be characterized by local displacements and ductility demands.

Nevertheless, coupling between translation and torsion for plan irregular structures makes it difficult to understand the proportionality indicated by code provisions (and represented by the behavior factor, q) between the elastic and the inelastic structural response.

The authors applied code provisions from the EC8 and the Romanian Seismic Design Code to single story plan irregular structures. Following aspects were analyzed: regularity conditions, differences between static and dynamic elastic behavior and effects of code regulations for plan irregular structures on the seismic behavior of the analyzed structures. Displacement results from static elastic calculation with equivalent forces and dynamic nonlinear (or linear) analysis were compared.

Considering the variation of eccentricity, eigenperiod of the structure and corner period of the seismic input, a total of 1845 cases were analyzed in this paper.

2. CODE PROVISIONS FOR PLAN IRREGULAR STRUCTURES

Given the fact that general torsion is an undesired phenomenon, rules for structural design have been established. Therefor each structure needs sufficient torsional stiffness and strength in order to avoid structural rotation that could raise structural forces and horizontal displacements. The best solution for diminishing structural rotation is to place structural elements with enough stiffness and strength on the perimeter of the structure (at least two in each direction).
A plan regular structure has to respect a range of assemblage rules, for example:

(i) On each level and each principal direction of the structure, the structural eccentricity has to match:

$$e_{0x} \leq 0{,}30 r_x \quad (2.1)$$

$$e_{0y} \leq 0{,}30 r_y \quad (2.2)$$

Where:
e_{0x}, e_{0y} - distance between the stiffness center and the strength center, measured perpendicular to the computation direction
r_x, r_y - torsional ratio equal to the square root of the ratio between the torsional stiffness and the translational stiffness, along the computation direction. The Eurocode 8 gives the radius of gyration (l_s) as an inferior limit for r_x and r_y (see eq. (2.3) for x direction).

$$r_y \geq l_s \quad (2.3)$$

Structures without the minimum torsional stiffness defined in this paragraph, are considered to be central-core structures or torsional sensitive structures.

(ii) As an alternative to (i), P100-1/2006 considers plan regularity when the maximum displacement registered at one floor edge, d_{max}, is less than 1,35 the mean displacement of the two floor edges, d_{mean}.

$$d_{\max} \leq 1{,}35 d_{mean} \quad (2.4)$$

A variant for this rule is given in FEMA and UBC, where the factor is equal to 1,2 for plan irregularity and to 1,4 for extreme plan irregularity.

Minimum requirements for the seismic design of a plan irregular structure are:

(i) 3D structural model. 2D structural models are not allowed.
(ii) Modal analysis. Simplified equivalent lateral force calculation (based on response spectra) is allowed according to the EC8 if the behavior factor is reduced by 20%.

3. COMPARATIVE STUDY. INPUT DATA

3.1 Analyzed structures

In this paper one single story, torsional flexible (twist unrestrained) structure was analysed (see Fig. 1). It is an idealized structure with a rigid diaphragm floor and columns and walls as vertical structural elements. The vertical structural elements are disposed symmetric about the x and y axis. The structural mass is lumped at the center of mass (CM).

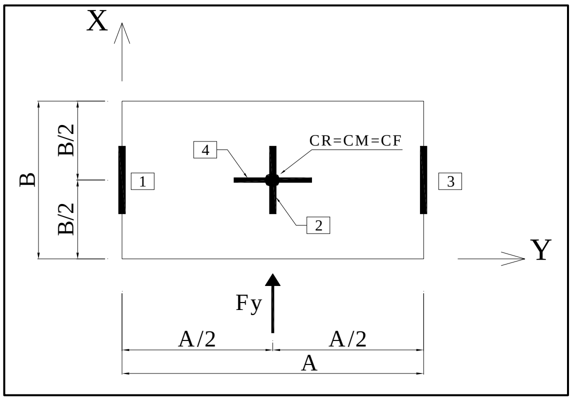


Figure.1 Symmetric torsional flexible structure

The structure of Fig. 1 is a symmetric structure, beeing characterized through a coincidence between the center of stiffness (CR), the center of mass (CM) and the center of resistance (CF). The corresponding eccentric systems are obtained by translating gradually CR and CF along the y axis, from its initial position up to ± 20% of the plan dimension of the structure normal to the direction of the seismic input.

The floor is considered to be a rigid diaphragm. The total weight (G) of the floor is 4840kN (considering a uniform load p = 10kN/m^2). The total strength of the structural elements has been computed considering a behavior factor q equal to 4.

The structural walls were modeled as elastic-perfectly plastic springs acting on x and y direction.

The stiffness of the structural elements was chosen so that the initial translational period of the structure equals 0.3s, 0.7s or 1.6s. The stiffness and the strength of walls P2 and P4 remain constant.

Displacements of the center of mass, structural rotations and displacements of walls parallel to the direction of seismic input were computed.

3.2 Seismic input

The seismic input for this study is unidirectional (along x direction) and is given by spectrum compatible accelerograms, acting along the x axis. Therefor design spectra from the Eurocode 8 (for soil type B) and from the Romanian Seismic Design Code, were used. Design spectra for corner periods equal to 0.5s, 0.7s and 1.6s were considered.

The results were obtained for elastic behavior (Serviceability Limit State, SLS) and two intensity levels of seismic input for the inelastic behavior. Therefor each accelerogram was scaled for two levels of strength: 0.2g (Ultimate Limit State, SLU) and 0.4g (Survivability Limit State, SLSV). For each Limit State the authors considered three spectrum compatible accelerograms.

4. COMPARATIVE STUDY. OUTPUT DATA

4.1 Serviceability Limit State

For the elastic range of behavior plan regularity code provisions were checked. Therefor equations (2.2), (2.3) and (2.4) were applied to the analyzed structures.

Static elastic calculation with equivalent forces was used in order to compute structural displacements and rotations according to code provisions.

Both equations (2.2) and (2.3) indicate torsional irregularity for eccentricities greater than ±13% from the floor dimension perpendicular to the direction of seismic input. The same regularity border (of ±13%) is obtained when applying equation (2.3) to results from dynamic elastic calculation.

According to equation (2.4) the analyzed structures are torsional insensitive. This observation is explained by the presence of structural walls on the floor edges, parallel to the direction of seismic input. Nevertheless, in the nonlinear range of behavior, after yielding of walls parallel to the direction of seismic input, the structure might become torsional sensitive. This is one of the limitations of nowadays code provisions concerning plan irregular structures.

Dynamic elastic calculation takes into account mass inertia. Therefor displacements from dynamic elastic analysis are up to 30% smaller than static elastic results. Structural rotations from dynamic elastic analysis are up to 10% greater than static elastic results. Differences rise with eccentricity. Nevertheless for eccentricity values up to 5% of the plan dimension perpendicular to the direction of the seismic input, displacement and rotation values from dynamic and static elastic analysis are quite similar.

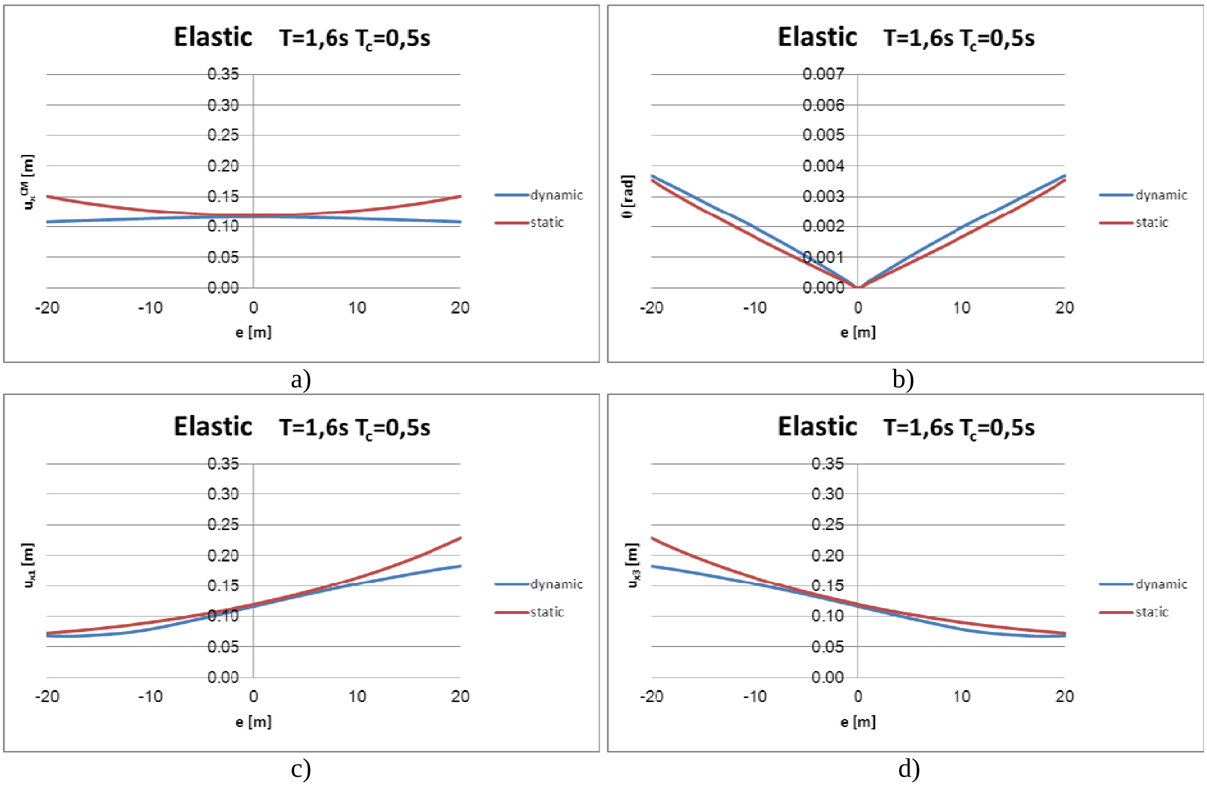


Figure 2. Results for SLS: a) displacements of the mass center; b) structural rotations; c) displacements of wall P1; d) displacements of wall P3

For example, Figure 2 shows results from serviceability limit state for the structure characterized by an eigenperiod of 1,6s. Figure 2 shows mean values from seismic input represented by three spectrum compatible accelerograms characterized by a corner period equal to 0,5s. Each graphic contains two curves, representing dynamic linear analysis results ("dynamic") and static elastic analysis results ("static").

4.2 Ultimate Limit State

For the ultimate limit state static elastic calculation was applied to the analyzed structures. Nonlinear displacement and rotation values were determined by amplifying results from the elastic range of behavior according to EC8 annex B. For comparison dynamic nonlinear results were computed using the Torsdin program elaborated at the Technical University of Civil Engineering Bucharest.

The same analysis was made considering a reduced value for the behavior factor q, as code provisions indicate for plan irregular structures.

Differences between dynamic nonlinear analysis results and static elastic calculation with equivalent forces as well as the influence of the reduction of the behavior factor on the computed results were investigated.

For the analyzed structures, structural rotation values are always greater from dynamic nonlinear calculation compared to static elastic calculation with equivalent forces. Differences scatter between 20% and 60%.

Displacement values are usually greater from dynamic nonlinear analysis compared to static elastic calculation with equivalent forces, for eigenperiods greater than the corner period of the seismic input. Displacement values are usually greater from static elastic calculation with equivalent forces compared to dynamic nonlinear analysis, for eigenperiods smaller than the corner period of the seismic input.

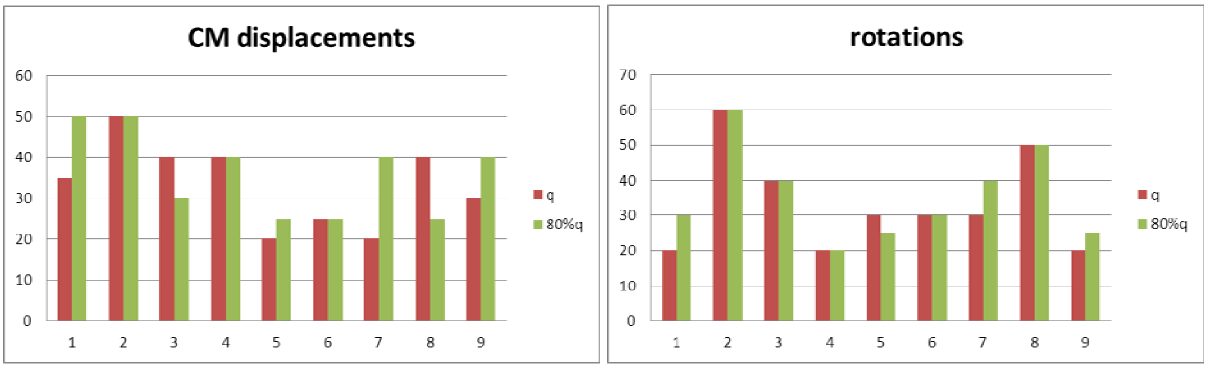
For some of the analyzed cases results from dynamic nonlinear analysis are greater than static elastic analysis results only for a part of the eccentricity range considered.

For structures with greater stiffness, not only displacement and rotation values, but also differences between dynamic nonlinear analysis and static elastic calculation with equivalent forces, become smaller.

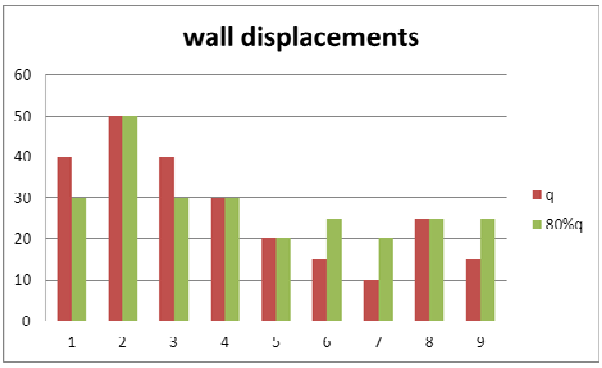
No monotonic variation of results with the corner period of the seismic input can be observed.

In order to establish the influence of the reduction of the behavior factor upon the structural response, comparison was made between static elastic calculation with equivalent forces and dynamic nonlinear analysis. Displacement and rotation values from both computation methods, with and without reduction of the behavior factor, were compared (see Figure 3).

In figure 3 the vertical axis represents percentage differences between dynamic nonlinear analysis and static elastic calculation results. The horizontal axis shows numbers for the analyzed cases, which are explained in Table 4.1. The green and red colors indicate results from the calculation with and without a 20% reduction of the behavior factor.



a) b)



c)

Figure 3. Comparison DNA – static elastic calculation: a) displacements of the center of mass; b) structural rotations; c) wall displacements

Table 4.2 Legend for analyzed cases in Figure 2

case	1	2	3	4	5	6	7	8	9
T [s]	1,6	1,6	1,6	0,7	0,7	0,7	0,3	0,3	0,3
T_c [s]	1,6	0,7	0,5	1,6	0,7	0,5	1,6	0,7	0,5

In Table 4.2 and Table 4.3, T represents the eigenperiod of the analyzed structure and T_c the corner period of the seismic input.

As shown in Figure 3, the reduction of the behavior factor doesn't lead to a monotonic variation of the differences between dynamic nonlinear calculation and static elastic analysis with equivalent forces.

The reduction of the behavior factor doesn't necessary lead to smaller displacement or rotation values. In some of the analyzed cases, response values are greater for a smaller value of the behavior factor.

Applying equation (2.3) to results from dynamic nonlinear analysis for the ultimate limit state leads to scattering regularity borders, showing once more that elastic and inelastic behavior of plan irregular structures are highly different and that the inelastic behavior of plan irregular structures depends essentially on the seismic input. Eccentricity values for which the analyzed structures experience torsional irregularity according to equation (2.3) are given in Table 4.3.

Table 4.3 Regularity borders for ULS

case	1	2	3	4	5	6	7	8	9
T [s]	1,6	1,6	1,6	0,7	0,7	0,7	0,3	0,3	0,3
T_c [s]	1,6	0,7	0,5	1,6	0,7	0,5	1,6	0,7	0,5
e [%]; q	-	±15	-	±10	±15	-	±5	±15	±7
e [%]; 80% q	-	-	-	±9	±16	-	±4	±7	±7

In Table 4.3 q is the behavior factor and 80% q the reduced behavior factor.

Missing values in Table 4.3 mean that for those cases the analyzed structures are torsional regular for the whole range of considered eccentricities.

The reduction of the behavior factor doesn't necessary restrain the torsional irregularity domain.

4.3 Survivability Limit State

For survivability limit state dynamic nonlinear analysis results were computed on structures designed to withstand an earthquake corresponding to the ultimate limit state.

The analysis was also made by considering a reduced value for the behavior factor q, as code provisions indicate for plan irregular structures.

Differences between the structural response at ultimate limit state and at survivability limit state were analyzed. The influence of the reduction of the behavior factor on the computed results was investigated.

As for the ultimate limit state, the reduction of the behavior factor doesn't necessary lead to smaller displacement or rotation values. In some of the analyzed cases, response values are greater for a smaller value of the behavior factor (see Figure 5).

Figure 4 shows results from ultimate limit state and survivability limit state for the structure characterized by an eigenperiod of 1,6s. Figure 4 shows mean values from seismic input represented by three spectrum compatible accelerograms characterized by a corner period equal to 0,5s. Each graphic contains three curves, representing dynamic nonlinear analysis results for the two limit states ("DNA_ULS" for ultimate limit state and "DNA_SVLS" for survivability limit state) and static elastic analysis results for the ultimate limit state ("code").

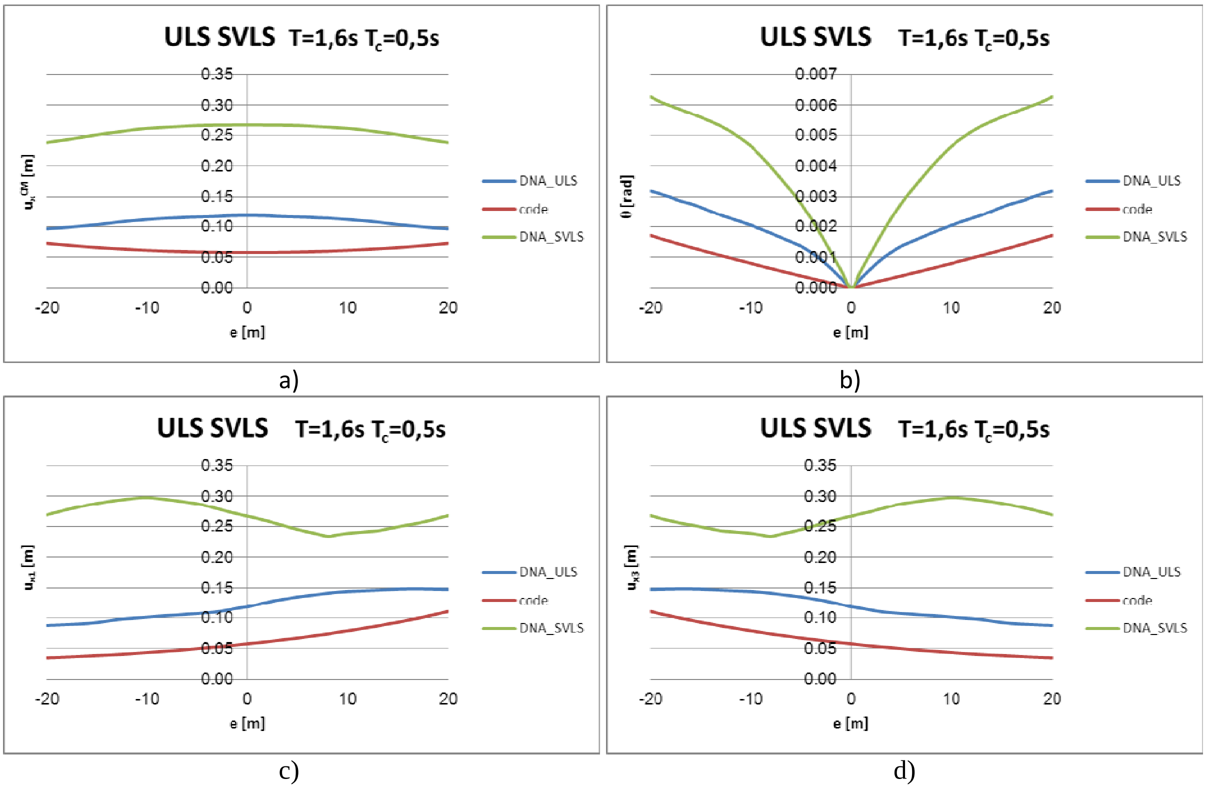


Figure 4. Results for unreduced value of q: a) displacements of the mass center; b) structural rotations; c) displacements of wall P1; d) displacements of wall P3

Walls P1 (stiff side for negative eccentricity values) and P3 (stiff side for positive eccentricity values) can be identified in figure 1. The horizontal axis shows the eccentricity range considered (±20% from the plan dimension perpendicular to the direction of the seismic input).

For the inelastic range of behavior, the variation of structural rotations with eccentricity is smaller than for the elastic range of behavior. Inelastic displacement values tend to a limit or even become smaller, the greater the eccentricity values are. This observation underlines the fact that general torsion is a more violent phenomenon in the elastic range of behavior.

For the particular case shown in Figure 4, another interesting observation can be made: stiff and flexible side change places from the ultimate limit state to the survivability limit state.

For comparison, Figure 5 shows the same results as Figure 4, computed considering a reduced behavior factor q.

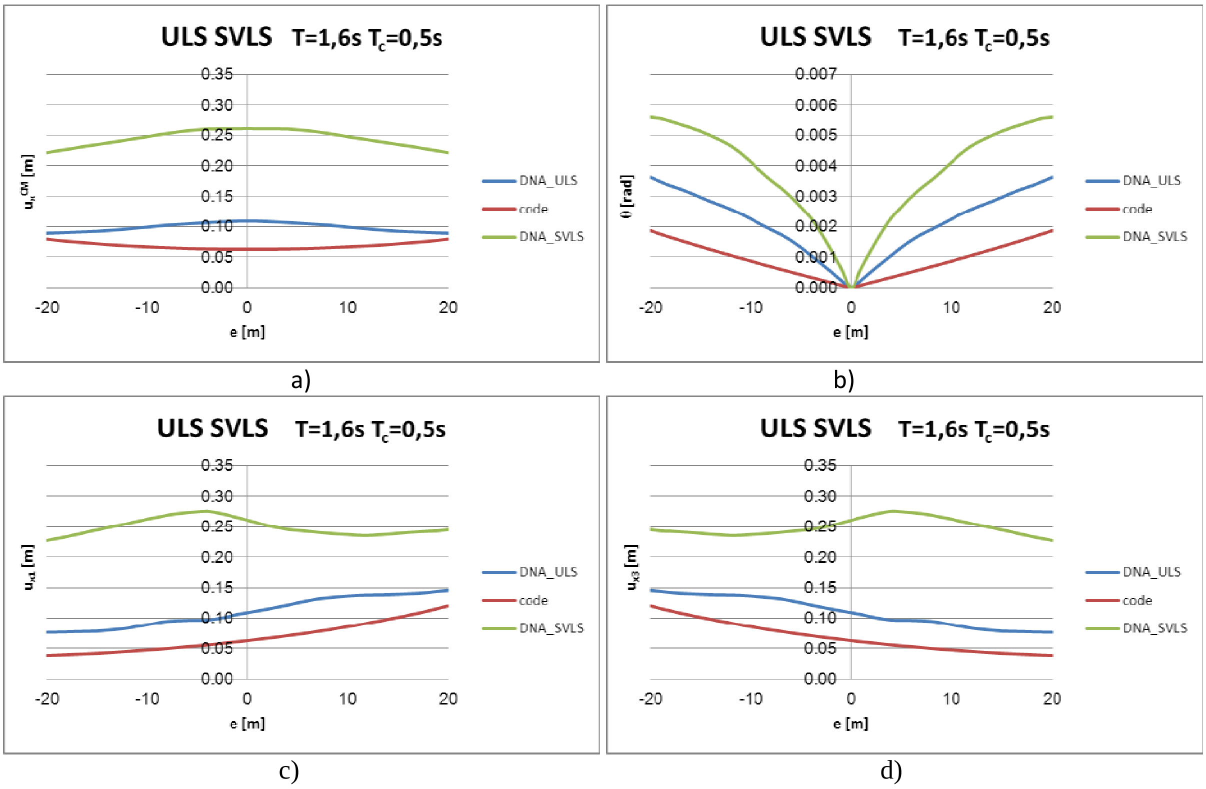


Figure 5. Results for reduced value of q: a) displacements of the mass center; b) structural rotations; c) displacements of wall P1; d) displacements of wall P3

5. CONCLUDING REMARKS

Plan regularity provisions from EC8 and P100 give consistent results for the analysed structures. The regularity condition given by equation (2.3) is suitable for practical design because displacement values are current response results even for multi-story structures. The regularity condition given by equations (2.1) and (2.2) is difficult to apply to multi-story structures because it presumes computation of translational and torsional stiffness for each level.

In the elastic range of behavior mass inertia taken into account in a dynamic analysis, leads to smaller displacement values than those from a static computation. The influence of the seismic input on the structural response of plan irregular structures is negligible for the elastic range of behaviour.

Static elastic calculation with equivalent forces applied to plan irregular structures leads to up to 60% underestimated results.

The reduction of the behavior factor doesn't necessary lead to smaller displacement or rotation values. In some of the analyzed cases, response values are greater for a smaller value of the behavior factor. This observation shows that the elastic and the inelastic response of plan irregular structures differ by more than just a proportionality factor, given by the behavior factor q in nowadays code provisions.

The inelastic seismic response of plan irregular structures is highly sensitive to the seismic input.

The inelastic response of plan irregular structures depends essentially on the amount of nonlinearity. For some of the analyzed structures the stiff and flexible side of the structure change places from the ultimate limit state to the survivability limit state.

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