Influence of nonlinearity on general torsion

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

15 WCEE
LISBOA 2012

SUMMARY:
One of the structural types subjected to general torsion are plan irregular structures. Many of the studies that applied simplified methods in order to estimate the seismic response of plan irregular structures showed a high sensitivity of results to the seismic input. This paper analyses two single-story plan irregular structures (twist restricted as well as twist unrestricted) subjected to a natural input and three spectrum compatible records, considering the design spectra of the Romanian Seismic Design Code and of the Eurocode 8. The study compares results obtained using a simplified method called SESA (proposed by the authors) and results obtained from dynamic nonlinear calculation, for a range of earthquake intensity values (from elastic behavior until a PGA of 0,4g). Structural displacements and rotations are checked. The aim of the study is to establish the influence of the amount of nonlinearity on the response of plan irregular structures.

Keywords: plan irregularity, single story structures, nonlinear behavior, simplified approach

1. AIM OF THE STUDY

General torsion is a complex phenomenon that may be explained accurate by dynamic nonlinear analysis.

Because dynamic nonlinear analysis is too complicated for current practical design, research on general torsion focused during the last decades on defining simplified methods (as the N2 method or the MPA method) for computing the displacement amplification due to general torsion.

The authors proposed a simplified method for the estimation of the effects of general torsion on single story plan irregular structures under seismic action. The method (called SESA) is based on superposition of modal effects but it is extended to nonlinear behavior of the structure by using overdamped displacement response spectra. The method can be analytically applied for the estimation of the displacement amplification due to torsion (compared to translational only behavior) using the same steps of a regular spectral analysis.

Past studies (Köber and Zamfirescu, 2009 and 2010; De La Llera and Chopra, 1995; Garcia, Islas and Ayala 2004) showed a high sensitivity of results from simplified design methods, with respect to the seismic intensity. Particularly, the observed variation of the accuracy of results from the SESA method compared to dynamic nonlinear analysis results is not monotone with the seismic intensity and differs for different structural assemblies. In order to apply SESA in practical design, the uncertainty of the accuracy of results should be investigated. Therefor the authors considered a study concerning the influence of the amount of nonlinearity on the response of plan irregular structures to be of interest.

The response of single story plan irregular structures (torsional unrestrained as well as torsional restrained ones) was analyzed for a range of seismic intensity levels. The accuracy of results from the SESA method compared to dynamic nonlinear analysis results was evaluated. Structural displacements and rotations were checked.

Results from 324 cases (considering the variation of structural stiffness, corner period of the ground motion and seismic intensity level) were compared.

This paper tries to answer following principal questions concerning results from the SESA method (compared to dynamic nonlinear analysis results), for different levels of the seismic input:

1. Does a lower accuracy of results correspond to a higher seismic intensity?
2. Is the accuracy of results equal for structural displacements and rotations?
3. Does the accuracy of results vary for TL and TI structures?
4. Is the accuracy of results related to the corner period of the seismic input?

2. SIMPLIFIED METHOD FOR THE ESTIMATION OF THE EFFECTS OF GENERAL TORSION (SESA)

SESA is based on the estimation of the structural response under seismic action of an irregular single story system, by modal response spectrum analysis. In order to take into account the inelastic behavior, the capacity spectrum method is used, by equating the nonlinear system to an elastic one, equivalent in translation. The resulting linear equivalent system is defined by the secant to maximum displacement stiffness, and the viscous damping properties are set through equivalence with the hysteretic damping properties of the initial system. The simplified method can be used to assess the displacement amplification due to general torsion maintaining the simplicity of the spectrum analysis (Goel and Chopra, 1990).

Response values are determined by modal analysis and assembled using the CQC rule.

$$\begin{pmatrix} u_{yi} \\ r u_{\theta i} \end{pmatrix} = \begin{pmatrix} \phi_{yi} \\ \phi_{\theta i} \end{pmatrix} \left| \eta_i(t) \right|_{\max} = \begin{pmatrix} \phi_{yi} \\ \phi_{\theta i} \end{pmatrix} \frac{P_i^*}{M_i^* \omega_i^2} SA_i \tag{2.1}$$

In equation (2.1) u_{yi} and $u_{\theta i}$ are modal displacement and rotation, r is the gyration ratio, ϕ_{yi} and $\phi_{\theta i}$ are modal coordinates, M_i^* is the modal mass, P_i^* is the modal participation factor and ω_i is the natural frequency. SA_i is the pseudo – acceleration, related to equivalent period T_i and equivalent damping ratio ξ. The values of the equivalent damping ratio are set in order to obtain the same displacement of the equivalent linear system with the nonlinear displacement of the inelastic system.

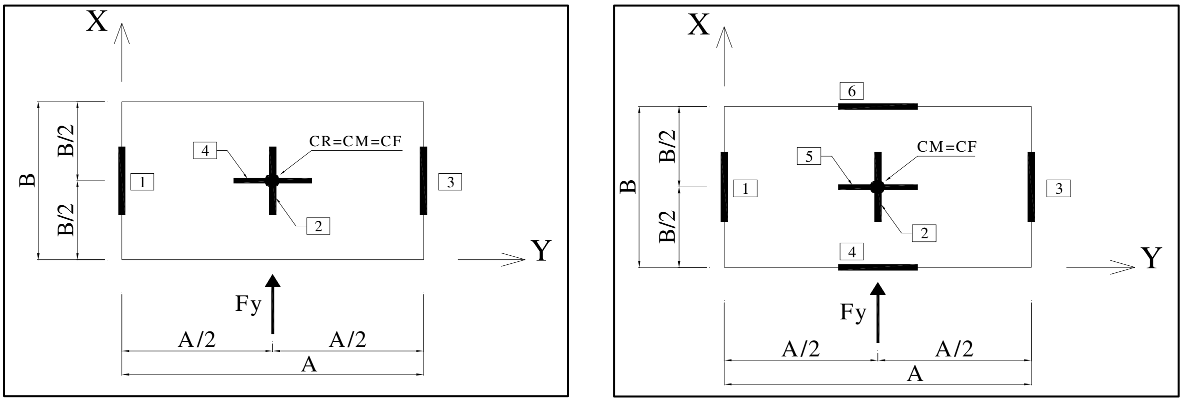
It is important to mention that the simplified method is entirely consistent with the assumptions used for the capacity spectrum method. Consequently, the SESA method results for torsional amplification are decisively influenced by the inaccuracy given by substitution of the inelastic behavior by a translation equivalent elastic structure. The equivalence process has shortcomings particularly for periods lower than the corner period of the ground motion (T_c). In order to minimize this influence the equivalent damping coefficient was determined by trial and error, iteratively, from the computed inelastic and elastic displacement spectra.

By applying the SESA method, results show a relatively good match to the structural response determined by dynamic nonlinear analysis and a better estimation of the structural response of irregular structures (influenced by general torsion) than the ones that can be obtained by using code provisions, for most of the cases, (Köber and Zamfirescu, 2009).

3. COMPARATIVE STUDY. INPUT DATA

3.1 Analyzed structures

In this paper two single story structures, a torsional flexible (twist unrestrained, TL) structure and a torsional stiff (twist restrained, TI) structure, were analysed (see Fig. 1). Both are idealized structures 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).



a) b)

Figure.1 Layout of symmetric structures: a) torsional flexible (TL); b) torsional stiff (TI)

The structures of Fig. 1 are symmetric structures, 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 total weight (G) of the floor is 4840kN (considering a uniform load p = 10kN/m^2). The structural walls were modeled as elastic-perfectly plastic springs acting on x and y direction.

The stiffness of the structural elements was chosen for both main directions 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 (for TL) and of walls P2 and P5 (for TI) remain constant.

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

3.2 Seismic input

The seismic input for this study is unidirectional (along x direction) and is given by original records as well as by spectrum compatible accelerograms, acting along the x axis. Therefor design spectra from Eurocode 8 and 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 four intensity levels of seismic input for the inelastic behavior. Therefor each accelerogram was scaled for four levels of strength: 0.1g, 0.2g (Ultimate Limit State, SLU), 0.3g and 0.4g (Survivability Limit State, SLSV). For each seismic intensity level the authors considered an original record and three spectrum compatible accelerograms.

4. COMPARATIVE STUDY. OUTPUT DATA

4.1 General remarks

The target of this comparative study was to identify how well the SESA method based on modal analysis and overdamped response spectra can estimate the seismic response obtained by dynamic nonlinear calculation, for different seismic intensity levels. The results of the SESA method were compared to the ones obtained by three-dimensional dynamic analysis in terms of displacement values at characteristic points of the structure: total displacement of the center of mass (u_x^{CM}), structural rotation (θ), displacements of walls P1 and P3 (u_{x1}, u_{x3}).

For comparison dynamic nonlinear results were computed using the Torsdin program elaborated at the Technical University of Civil Engineering Bucharest.

A sample for the comparative study is shown in Fig.2. It corresponds to the TI structure with a translational eigenperiod of 0.7s, subjected to a seismic input scaled for a PGA of 0.1g. Mean response values from three accelerograms compatible to the response spectrum for corner period equal to 1.6s (acc. to the Romanian Seismic Design Code) are shown. The horizontal axes shows eccentricity values up to ±20% of the plan dimension perpendicular to the direction of the seismic input.

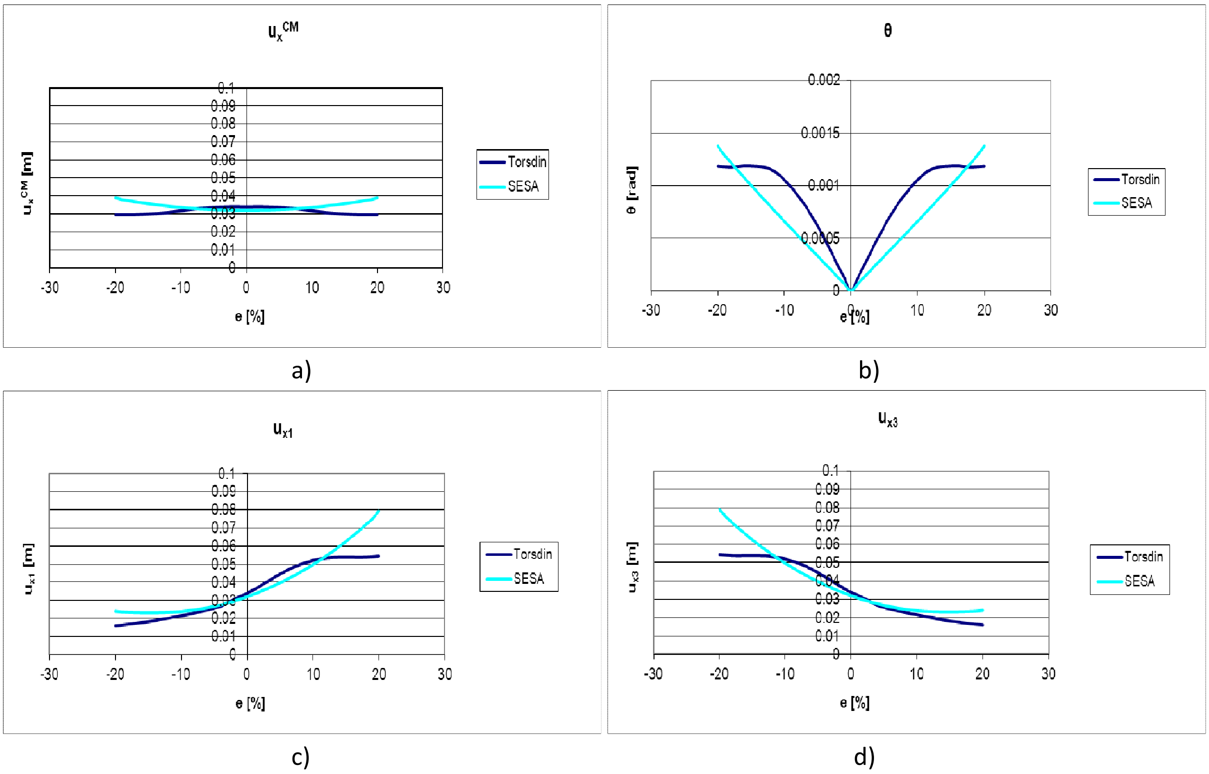


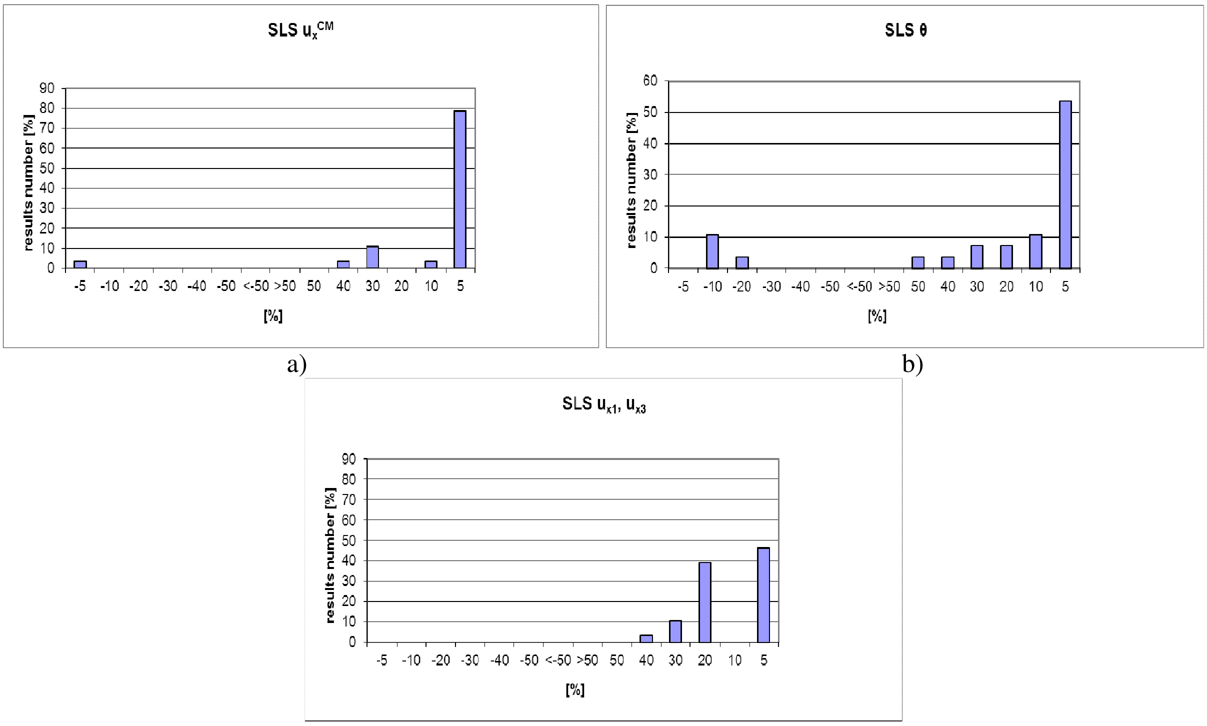
Figure.2 Structural response: a) displacement of the CM; b) structural rotation; c) displacement of wall P1; d) displacement of wall P3

Statistic evaluation of the results was made in order to identify whether the SESA method overestimates (graphics right side, positive percentage) or underestimates (graphics left side, negative percentage) dynamic nonlinear analysis results. In the graphics below the vertical axes represents the percentage of results (from the total number of results of an analyzed category) that fit into a range of accuracy.

Results were gathered with respect to the seismic intensity level and with respect to the corner period of the ground motion.

4.2 Results gathered with respect to the intensity level of the seismic input

Fig. 3 shows results for the elastic range of behavior (Serviceability Limit State, SLS).



a) b)

c)

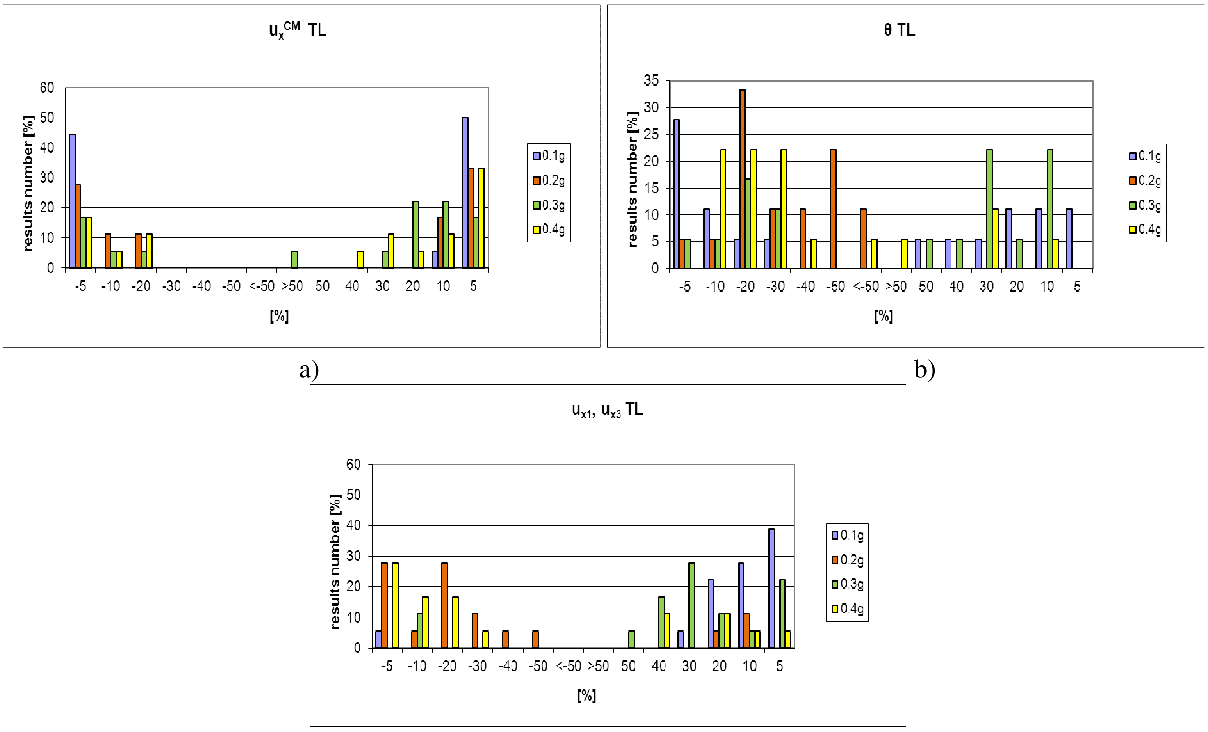
Figure 3. Results for SLS: a) displacements of the mass center; b) structural rotations; c) displacements of walls P1 and P3

For SLS, the SESA method mostly overestimates dynamic nonlinear analysis results. As expected, results are better for u_x^{CM} and θ as for u_{x1} and u_{x3}.

Fig. 4 and Fig. 5 show results for the nonlinear range of behavior, separately for torsional unrestrained (TL) and for torsional restrained (TI) structures.

For TL it was considered that the torsional stiffness of all walls is affected in the same way as their translational stiffness. For TI, the preliminary results showed that the walls situated perpendicular to the direction of seismic input yield also, and the consideration of their full lateral stiffness to the rotational stiffness of the structure leads to unconservative results. Consequently, for the comparative study the perpendicular walls participate with half of their lateral stiffness to the rotational stiffness of the structure to take into account the yielding effect.

In the nonlinear range of behavior results are almost equally under- and overestimated.



a) b)

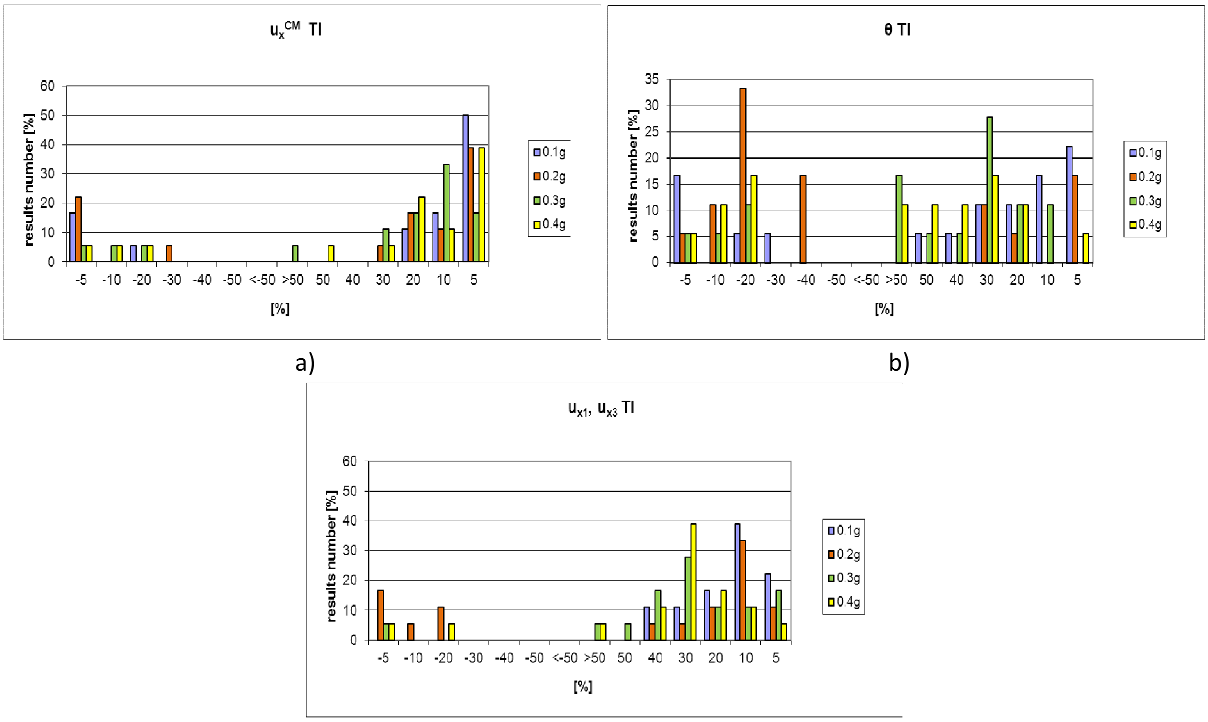
c)

Figure 4. Results for TL nonlinear behavior: a) displacements of the mass center; b) structural rotations; c) displacements of walls P1 and P3

For TL structures accuracy seams to drop with the rising of seismic intensity, although it is not a monotone variation. Structural displacements are estimated far better by the SESA method than structural rotations. Due to the fact that for practical design usually displacements are needed, the rotations loss of accuracy is not inconvenient. For 0.1g seismic intensity, up to 65% of the structural displacements are overestimated by less than 10% by the SESA method. This percentage changes into 40% for 0.2g and 0.3g seismic intensity and into 45% for 0.4g seismic intensity. Notice the fact that those percentages are computed for eccentricities up to ±20% from the plan dimension of the structure, perpendicular to the direction of seismic input.

According to the Eurocode 8, the TL structures analyzed in this paper experience torsional sensitivity for eccentricity values greater than ±12% of the plan dimension perpendicular to the direction of seismic input. By restraining the statistic evaluation of results to eccentricities up to ±12%, the percentages mentioned before become 85% for 0.1g seismic intensity and 65% for 0.2g, 0.3g and 0.4g seismic intensity.

Accuracy of results is better for TI structures due to the positive influence of the structural walls perpendicular to the direction of seismic input. The amount of overestimated results is greater than for TL structures. For 0.1g seismic intensity and eccentricity values up to ±20%, up to 70% of the structural displacements are overestimated by less than 10% by the SESA method. This percentage changes into 50% for 0.2g, 0.3g and 0.4g seismic intensity.



a) b)

c)

Figure 5. Results for TI nonlinear behavior: a) displacements of the mass center; b) structural rotations; c) displacements of walls P1 and P3

For this comparative study constant accuracy is obtained for seismic intensities greater than 0.1g. This may be explained by the constancy of the structural response for the entire eccentricity range considered when getting more and more into the nonlinear range of behavior.

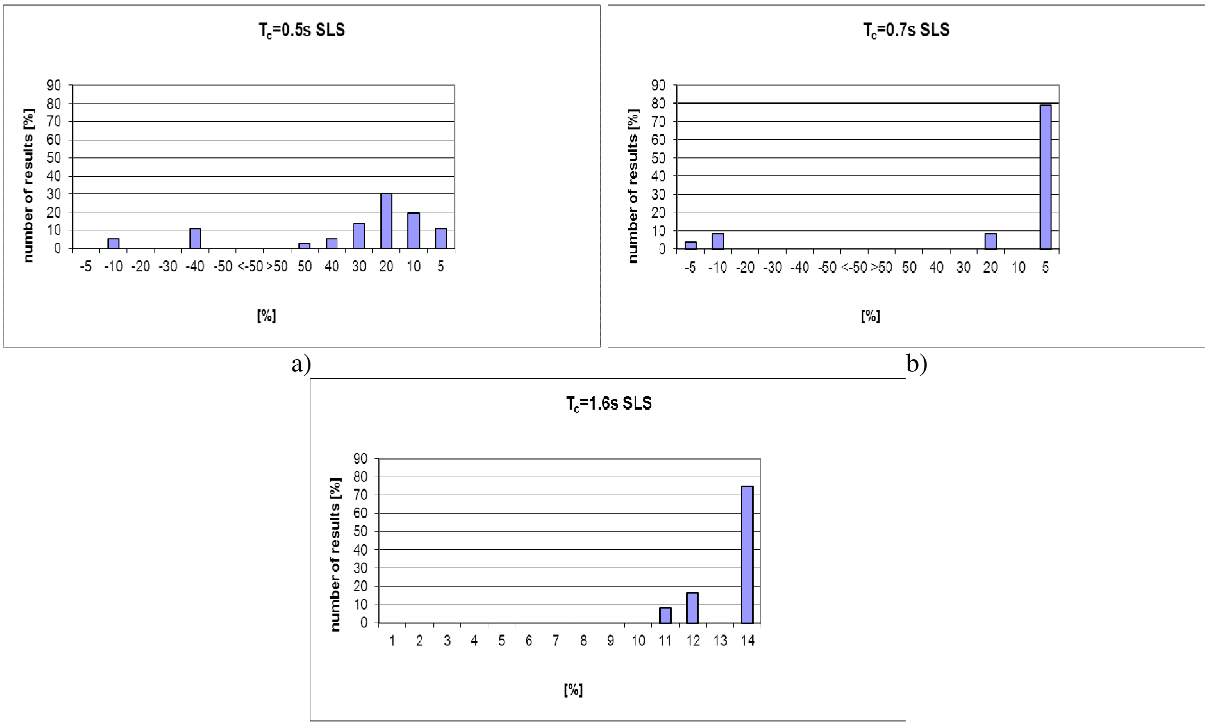
4.3 Results gathered with respect to the corner period of the ground motion

Following figures show the same results for different corner period values (T_c) of the seismic input, separately.

Results for the elastic range of behavior are shown in Fig. 6. SESA results computed for T_c=0.5s were determined using the design elastic response spectrum from EC8 and the damping correction factor η, leading to greater errors in the equivalation process. For T_c=0.7s and T_c=1.6s computed overdamped spectra were used and the results are better.

Fig. 7 and Fig. 8 show results for the nonlinear range of behavior, separately for torsional unrestrained (TL) and for torsional restrained (TI) structures.

The greater the corner period of the ground motion, the SESA method results scatter more, showing that the simplified method is entirely consistent with the assumptions used for capacity spectrum method. Consequently, the SESA method results for torsional amplification are decisively influenced by the inaccuracy given by substitution of the translational inelastic behavior by a translation equivalent elastic structure. The equivalence proved to have shortcomings for periods lower than the characteristic period of ground motion.



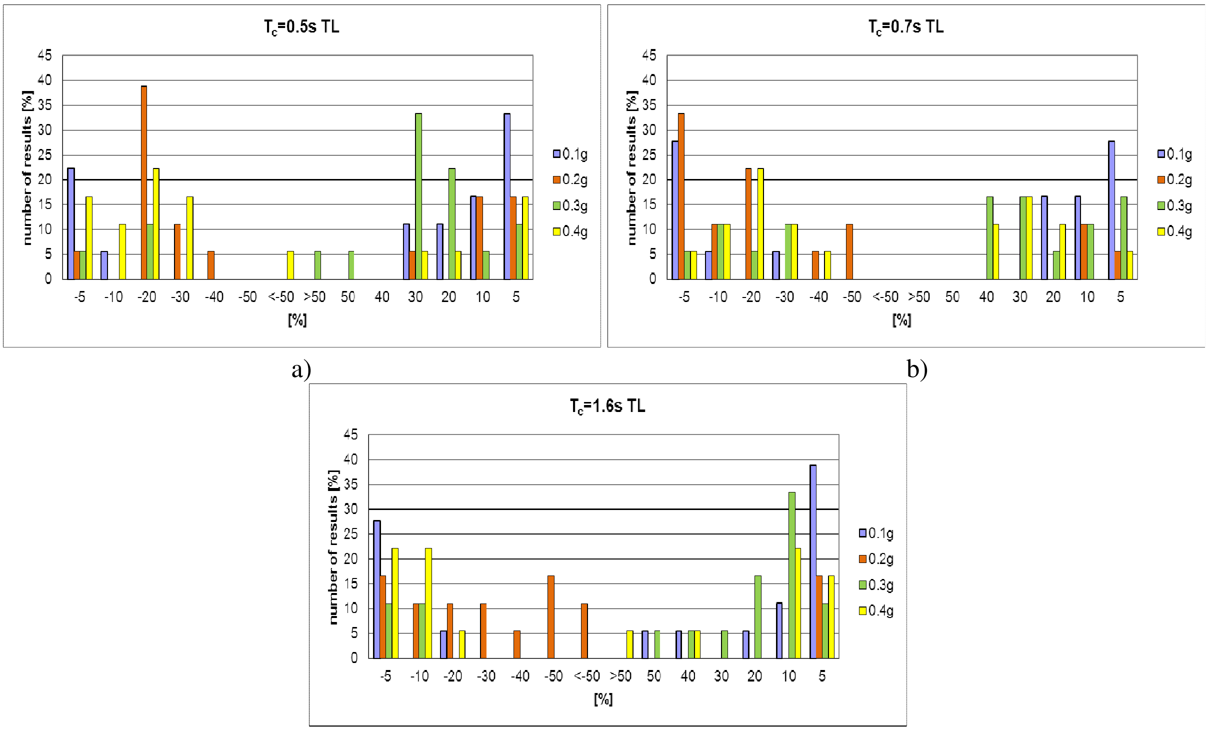
a) b)

c)

Figure 6. Results for SLS: a) T_c=0.5s; b) T_c=0.7s; c) T_c=1.6s

In the nonlinear range of behavior overdamped spectra were computed for all corner periods of the ground motion, in order to minimize errors from the equivalation process.

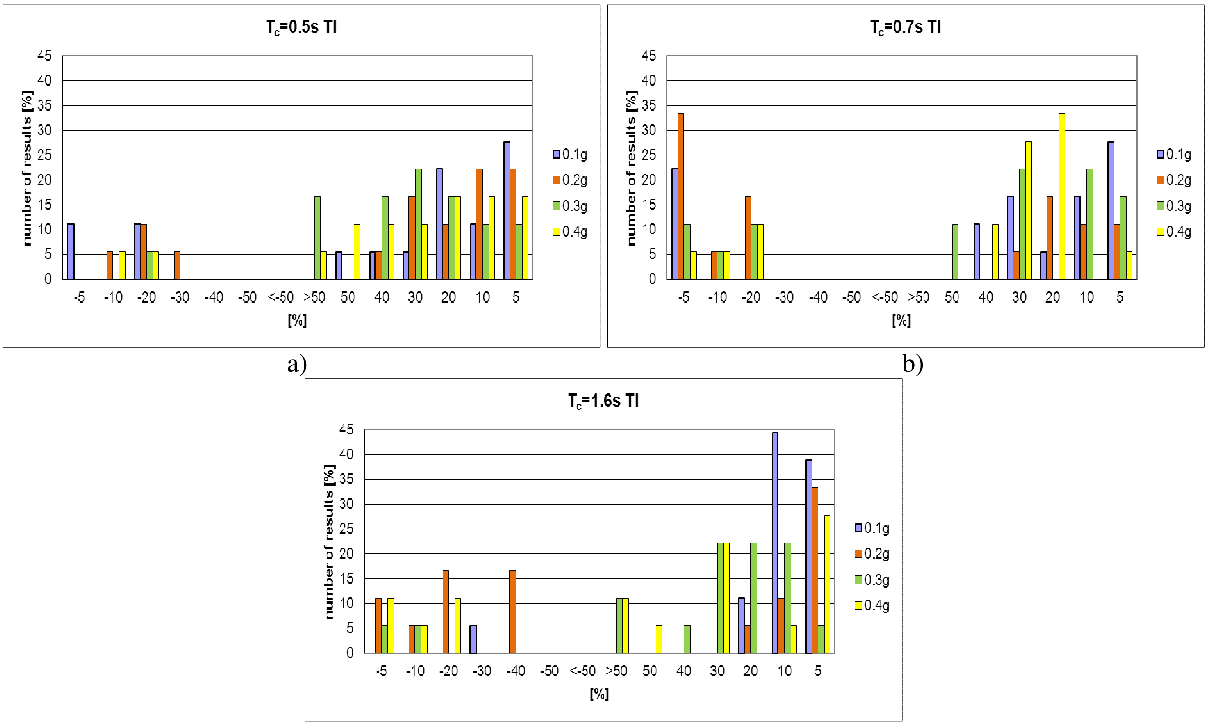
Results for TI structures are estimated better than results for TL structures.



a) b)

c)

Figure 7. Results for TL nonlinear behavior: a) T_c=0.5s; b) T_c=0.7s; c) T_c=1.6s



a) b)

c)

Figure 8. Results for TI nonlinear behavior: a) T_c=0.5s; b) T_c=0.7s; c) T_c=1.6s

4.3 Comments regarding the equivalation process

The simplified SESA method combines modal analysis with nonlinear behavior, by using the capacity spectrum method. Therefor the nonlinear system is equated to an elastic one, equivalent in translation. The resulting linear equivalent system is defined by the secant to maximum displacement stiffness, and the viscous damping properties are set through equivalence with the hysteretic damping properties of the initial system.

For all analyzed cases damping coefficients are determined by trial and error. For spectrum compatible accelerograms as well as for original records, the damping coefficients are greater from 0.1g to 0.2g seismic intensity and become lower for 0.3g and 0.4g seismic intensity. This observation is more obvious for greater values of the corner period of the ground motion and may be explained by the fact that for strong nonlinear behavior structural rotations become nearly constant for eccentricity values over ±10% (of the plan dimension perpendicular to the direction of the seismic input). Notice that the SESA method takes into account this behavior.

Usually the damping coefficients are greater the stiffer the analyzed structure is, independent of the seismic input intensity. This observation underlines the fact that stiffer structures experience greater rotations and lead therefor to greater values of the damping coefficients.

5. CONCLUDING REMARKS

The amount of nonlinearity (defined in this paper as seismic intensity level) influences the accuracy of results from the SESA method for plan irregular structures, compared to dynamic nonlinear analysis results.

For strong nonlinear behavior structural rotations remain nearly constant and the structural response tends to an upper limit. For this comparative study constant accuracy is obtained for seismic intensities greater than 0.1g. This may be explained by the constancy of the structural response for the entire eccentricity range considered when getting more and more into the nonlinear range of behavior.This influence is taken into account by the simplified method SESA, although the accuracy of results is better for lower values of the seismic intensity.

Structural displacements are estimated far better by the SESA method than structural rotations. Due to the fact that for practical design usually displacements are needed, the rotations loss of accuracy is not inconvenient.

Regarding results obtained for TL structures and eccentricity values lower than ±12% (considered to be the torsional sensitivity limit according to Eurocode 8), SESA overestimated 85% of displacements by less than 10% for little nonlinear behavior. This percentage drops to 65% for seismic intensity values over 0.2g.

Accuracy of results is better for TI structures due to the positive influence of the structural walls perpendicular to the direction of seismic input. For little nonlinear behavior and eccentricity values lower than ±12%, up to 90% of the structural displacements are overestimated by less than 10% by the SESA method. This percentage changes into 70% for seismic intensity values over 0.2g. The obtained accuracy is encouraging for practical design because most real structures are TI structures.

The greater the corner period of the ground motion, the SESA method results scatter more, showing that the simplified method is entirely consistent with the assumptions used for capacity spectrum method, regardless of the seismic intensity.

Results from the simplified SESA method (based on modal analysis and overdamped response spectra) follow the trend of dynamic nonlinear analysis results. For the analyzed cases over 80% of the structural displacements from the SESA method are overestimated by less than 10%. Therefor the accuracy of results may be considered as satisfactory for eccentricity values lower than ±10% (of the plan dimension perpendicular to the direction of the seismic input).

The results obtained in this and former studies make the authors confident in proposing the SESA method for practical design, as a simplified, analytical applicable design method for single story plan irregular structures.

REFERENCES

Goel, R.K., Chopra, A.K. (1990). Inelastic seismic response of one – story, asymmetric – plan systems. *College of Engineering, University of California at Berkeley*, **Report No. UBC/EERC – 90/14**.

De La Llera, J.K., Chopra, A.K. (1995). Understanding the inelstic seismic behavior of assymetric plan – buildings. *Earthquake Engineering and Structural Dynamics,* **24(4): 549-572**

Garcia, O., Islas A., Ayala A.G.(2004). Effect of the In-Plan Distribution Of Strength On The Non-Linear Seismic Response Of Torsionally Coupled Buildings. *Proceedings of the 13th World Conference on Earthquake Engineering,* **Paper No. 1891**

Köber, D., Zamfirescu, D. (2009). Simplified Methods used for Evaluation of the Displacement Gain due to General Torsion. *Scientific Journal. Mathematical Modelling in Civil Engineering.* **Vol. 5, nr.2:** 32-51.

Köber, D., Zamfirescu, D. (2010). Effects of general torsion on structural displacements. *Proceedings 14 ECEE.* ISBN 978-608-65185-1-6

Zamfirescu, D. (2000). *TORSDIN – program de calcul dinamic neliniar al structurilor cu 3 GLD*

EN 1998-1: 2004. *Design of structures for earthquake resistance. General rules, seismic actions and rules for buildings*, 45-69.

P100 -1/ 2006. *Cod de proiectare seismică. Prevederi de proiectare pentru clădiri*, 32-61.