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COMPARATIVE STUDY OF SOME SEISMIC CODES FOR BUILDING DESIGN REGARDING CRITERIA FOR NON-LINEAR METHODS OF ANALYSIS

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ABSTRACT

The Working Group 7 (WG7 - Earthquake Resistant Structures) of the International Association for Bridge and Structural Engineering (IABSE) has proposed, inside its Field of Activities and Objectives, the comparisons between seismic codes. Some of the members of WG7 have been part of a Subgroup (SG-B – Seismic Codes Comparisons), in order to work together on this broad subject, finding discrepancies and similarities of the codes. This paper, aligned with this objective of the WG7- SG-B continues the work presented by the authors in previous papers. In these papers, aspects related to the seismic design of usual reinforced concrete buildings, such as definition of the recurrence periods for establishing the seismic input; definition of the seismic zonation and shape of the design response spectra; consideration of local soil conditions; definition of the seismic force-resisting systems and definition of the allowable procedures for the seismic analyses have been thoroughly examined. Several codes for the seismic design of buildings (US, European, Italian, Romanian, Brazilian, Bulgarian, and Chilean Standards) have been examined. In the present paper, more aspects are investigated, especially the ones related to non-linear methods of analysis, such as the non-linear static (pushover) methods. An ordinary reinforced concrete building ("Model Building") has been used for permit the comparative analysis between the codes. This building has been modeled with the computer program SOFiSTiK. Each model is subjected to the seismic input according to the several codes, and obtained results were compared.

Keywords: seismic analysis, seismic standards, comparative analysis, non-linear pushover method

1. INTRODUCTION

The Working Group 7 (WG7 - Earthquake Resistant Structures) of the International Association for Bridge and Structural Engineering (IABSE) has proposed, inside its Field of Activities and Objectives, the comparisons between seismic codes. Some of the members of WG7 have been part of a Subgroup (SG-B – Seismic Codes Comparisons), in order to work together on this broad subject, finding discrepancies and similarities of the codes.

Previous papers of the authors, for instance Santos *et al*. (2017a, 2017b), presented a comparative evaluation between some international, European and American, seismic design standards, focusing on the design of conventional (residential and commercial) buildings. In the present paper, more aspects are investigated, especially the ones related to non-linear methods of analysis, such as the non-linear static (pushover) methods. Results are compared with those obtained by the linear static procedures.

A typical reinforced concrete building ("Model Building") has been selected in order to perform a series of analyses using different codes. This building has been modeled with the computer program SOFiSTiK (2014).

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2. METHODS OF SEISMIC ANALYSIS

The classical methods of Seismic Analysis are the Equivalent Static Analysis and the Response Spectrum Analysis. The former is a very simplified approach to the seismic design which is not much in use nowadays due to its inherent limitations. The latter, the Response Spectrum Analysis is a linear method which considers the use of factors, like the behavior factor, established in the standards with the objective of compensating the non consideration of the materials non-linearity. Those factors affect the obtained results from the analyses. A more advanced approach are the non-linear time-history methods which can furnish more accurate results, but in detriment of a considerable processing effort.
In between these two methods stands, in terms of accuracy and efficiency, the pushover analysis which has been progressively accepted in the standards with several restrictions though, so far. General guidelines were proposed since 1996 by the Applied Technology Council, supported by the California Seismic Safety Commission (ATC-40, 1996). European Standard, Eurocode 8 – EN 1998-1:2004 has accepted the method with some restrictions. In the work of Pinho *et al*. (2013) the adequacy of the Non-Linear Static Procedures was confirmed.
The non-linear Static Procedures herein analyzed are the Capacity Spectrum Method and the N2 Method defined by ATC-40 (1996) and Eurocode 8 (2004), respectively. Both methods consider the energy dissipation in the non-linear range. The main difference between them is how the idealized model dissipates the earthquake energy. The CSM considers equivalent super-damped single degree of freedom systems in which the energy dissipation in the nonlinear cycles is added to the histeretic damping of the structures. The N2-Method considers equivalent elastoplastic single degree of freedom systems using curves relating response modification coefficients (R_y), ductility factors (μ) and periods (T) which that account for the actual energy dissipation in the systems.
Herein Pushover Analyses are applied for obtaining Performance Points (PP), as shown in Figure 1.

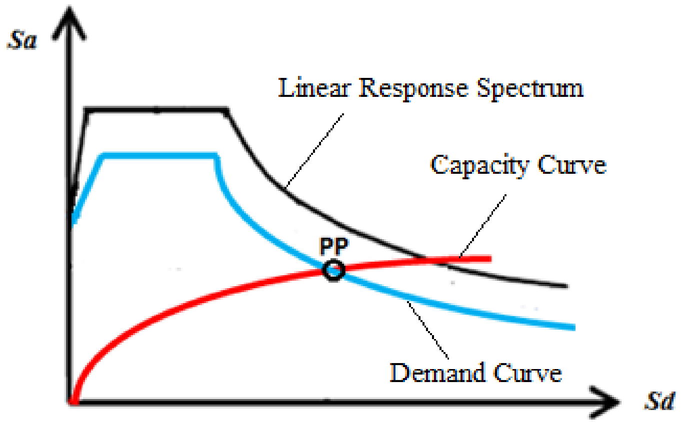


Figure 1. Performance Point (PP).

In Figure 1, the Linear Response Spectrum, the Demand Curve and the Capacity Curve are shown. The process for obtaining the PP depends on the method utilized. Herein, the methodologies developed in the ATC-40 (ATC, 1996) and in the Eurocode 8 (CEN, 2004) are applied.

3. COMMENTS ON THE STANDARDS

Regarding the standards previously analyzed by the authors, Santos *et al*. 2017a and 2017b, there is no reference to Non-Linear Static Procedures in the following standards:

- Italian Code - Technical Standard for the Constructions (2008)
- Romanian Code P100-1:2013 and Romanian National Annex to Eurocode 8 (2010)
- Brazilian Standard - NBR 15421 (2006)
- Bulgarian National Annex to Eurocode 8 (2005)
- Chilean Standard - NCh 433.Of1996 (2009)

With respect to the American Standard, ASCE/SEI 7-16 (2016), in this last revision, according to its Chapter 16, pushover analyses are still not allowed.
The Greek Code for Structural Interventions (2013), follows a procedure similar to the N2 method of Eurocode 8.
In the Romanian Annex to Eurocode 8 (2010), "*upper level methods"* are allowed as checking methods for structures fully dimensioned using a current method. The "*upper level methods*" are:

- the linear dynamic calculation method;
- the non-linear static calculation method. This method allows the evaluation of the deformation capacities. Lateral displacement or ductility requirements are separately established from the spectra of the non-elastic seismic response, or using the approximate methods given in the Code;
- the non-linear dynamic calculation method.

4. NUMERICAL EXAMPLE

4.1 Linear Design Response Spectrum

In order to obtain more representative results for the pushover analysis, a site with more strong seismicity is chosen, relatively to the previous studies of Santos *et al*. (2017). Considered peak ground acceleration is a_g = 2.5 m/s^2. The design response spectrum for this site is defined according to ASCE 7-16 (2016), and is shown in Figure 2. The considered spectral values are S_{DS} = 6.25 m/s^2, T_0 = 0.11s, T_S = 0.55s, and T_L= 12s. This spectrum is used in the pushover analyses presented herein.

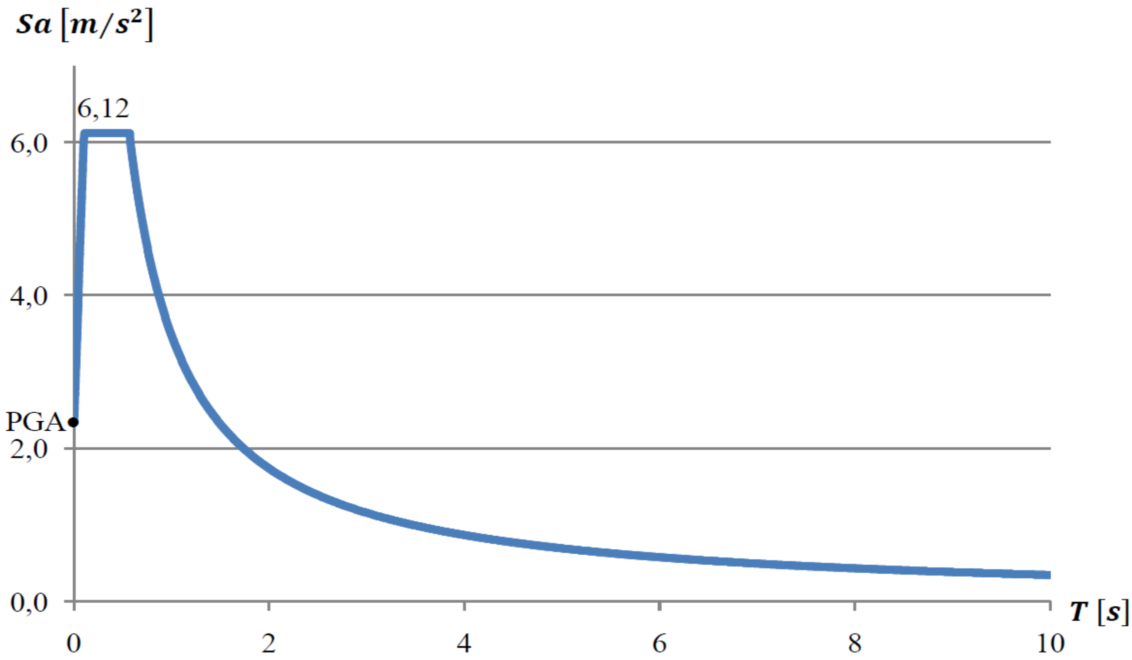


Figure 2. Design response spectrum

4.2 Structural and dynamic characteristics of the building

A simple and symmetrical building structure (the "Model Building") has been chosen as an example for illustrating the comparison between the procedures. This model is an adaptation of the one already analyzed by Gosh and Fanella (2003). The main data of the building are:

- Nominal concrete strength: f_{ck} = 28 MPa.
- Young modulus of concrete: E_c = 32 GPa.
- Concrete specific weight: γ_c = 25 kN/m³.
- Non-structural finishing weight, typical floors: 1.5 kN/m^2.
- Non-structural finishing weight, top floor: 0.5 kN/m^2 plus four concentrated loads of 900 kN.
- Plan dimensions: 20.1 m x 55.3 m (between axes of columns).

- Total building height: 45.15 m, in 12 floors.
- Dimensions of the columns: 60 cm x 60 cm
- Dimensions of the beams: 30 cm x 80 cm
- Thickness of the slabs: 20 cm
- Thickness of the two shear-walls: 30 cm
- Total mass = 13228 t.

It is considered that the building will be used for commercial purposes. The building has two Seismic Force-Resisting Systems: ordinary reinforced concrete moment frames in X (longitudinal) direction and a dual system with ordinary reinforced concrete shear walls in Y (transversal) direction. For the sake of the simplicity, criteria of ordinary reinforced concrete moment frames are considered in both directions. For the ATC-40 Procedure, the building is considered as Structural Behavior Type A.
The first story of the building is 4.90 m height and the remaining ones are 3.65 m height each. Figure 3 shows a perspective view of the building and Figure 4 shows a plan view. The decrease in stiffness due to non-linear effects (cracking) is taken into account by taking 60% of the elastic stiffness.

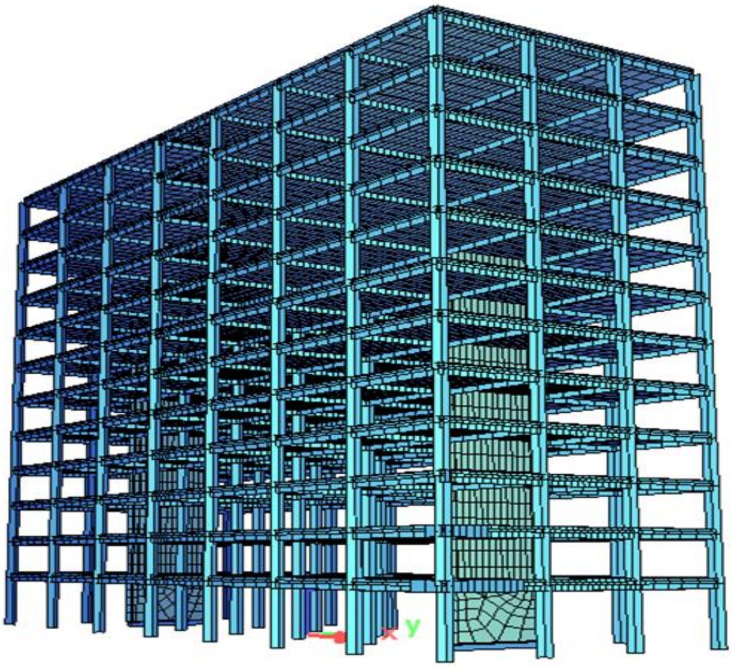


Figure 3. Model building, perspective view

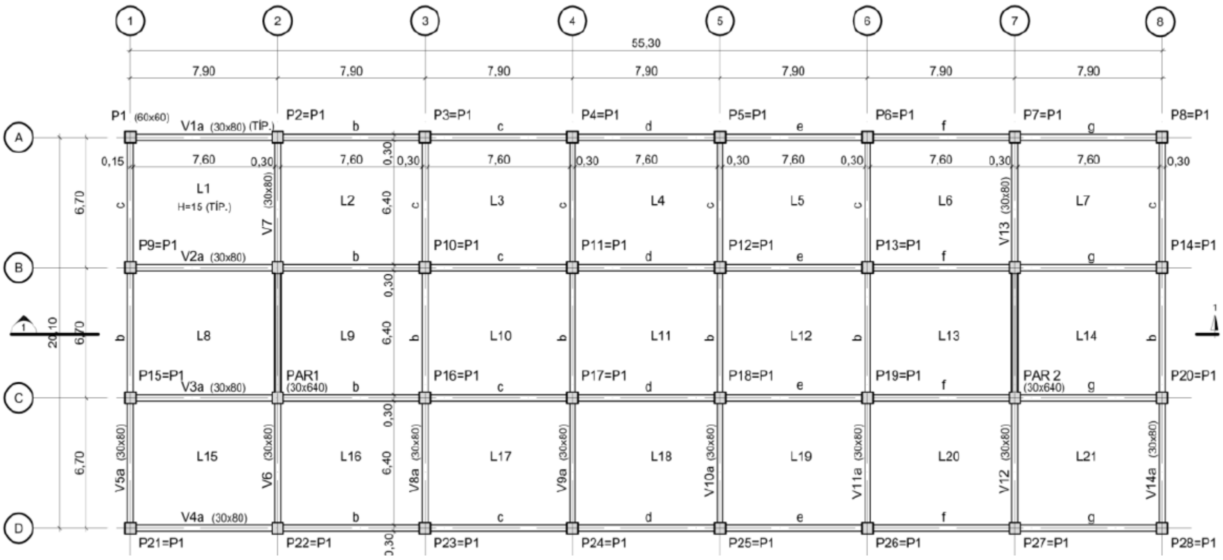
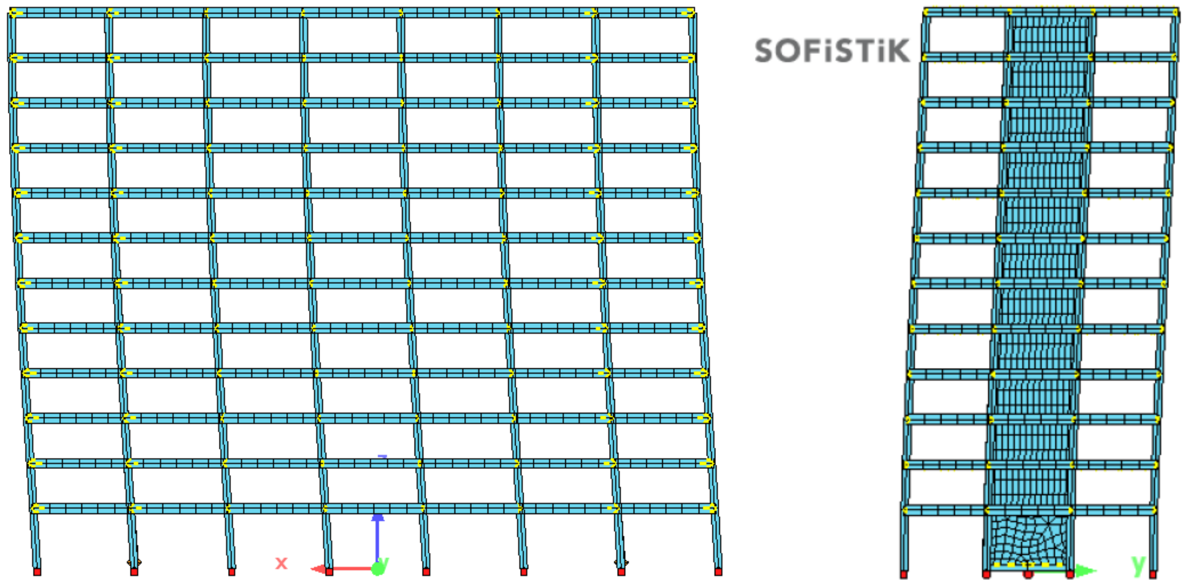


Figure 4. Model building, typical floor plan

Previously to the pushover analysis, the reinforced concrete structural sections have to be designed, considering the results obtained in linear seismic analyses.
The most important parameters for the dynamic analysis are the total mass of the system, 13228 t, and the elastic periods in the longitudinal direction X (T_1=1.84 s) and in the transversal direction Y (T_2=1.26 s).
Up to the 5th mode, 90% of the total mass is accounted for in both horizontal directions. Figure 5 shows the first modal shapes.



(a) Longitudinal Direction X (b) Transversal Direction Y

Figure 5. Modal shapes

The model of the structure consists of line and area finite elements. Slabs are considered as diaphragms, by means of constraint links in the horizontal plans of each floor.
In the start-points and end-points of each frame-element, rigid-plastic links are placed, in order to permit for plastic hinge formation when a determined strength is reached. Regarding the 3D non-linear model, yield strengths for bending moment are defined for each member, Orrala (2017).

4.3 Considered seismic loads

The applied horizontal loads vary depending on the chosen method for predicting the seismic demands. The horizontal loads in X direction are different from those in Y direction. The considered force profiles are taken as proportional to the first vibration mode in each direction.
The dynamic analyses of the building have been performed by four methods: Linear Static Procedures of Equivalent Horizontal Forces and Multimodal Response Spectrum Analysis and Non-Linear Static Procedures according to ATC-40 and EC8.
One of the main objectives of this paper is the comparison of the results obtained by each method. For that reason, although the Non-Linear Static Procedure of EC8 (Pushover) establishes the use of other lateral force profiles, only the ones corresponding to the fundamental vibration modes are considered.
The program code used for the analysis is the SOFiSTiK (2014).

4.4 Linear Static Procedure of Equivalent Horizontal Forces (EHF)

This procedure is just a Linear Static Analysis. The coefficients defined by ASCE 7 (2016) for ordinary reinforced concrete moment frames are considered: R = 3 (response modification coefficient) and C_d = 2,5 (deflection amplification factor).
The first mode is the most relevant in X direction, with period T_1 = 1,84s and the second mode, with period T_2 = 1,26s is the most relevant in Y direction. The results of the EHF are shown in Table 1.

Table 1. EHF - results.

Direction	Mode	Period	S_a	V	u
		s	m/s^2	kN	mm
X	1	1.84	1.868	8237	254
Y	2	1.26	2.728	12028	206

4.5 Multimodal Spectrum Analysis (MSA)

This analysis is a multimodal spectral type, where each vibration mode has its own response (forces, displacements, base shear, etc.). Final responses are obtained from the combination of all individual response. 20 modes have been considered for the Multimodal Spectrum Analysis. For obtaining the combined response, the Complete Quadratic Combination (CQC) is used. Results are shown in Table 2.

Table 2. MSA - results.

Direction	V	u
	kN	mm
X	8366	192
Y	11176	144

4.6 Non-Linear Static Procedures of ATC-40 and EC-8

The horizontal loads to be applied to the structure are established by the criteria of efficiency at plotting the Capacity Curve. Those primary loads are: P_X = 106.02 kN and P_Y = 98,64 kN.
The force distribution profiles are the first mode displacement profile (in X direction) and the second mode displacement profile (in Y direction). The loads above are regarded as Exceptional Actions (E) as defined in ASCE 7-16.
The non-linear analyses are carried out regarding only the combination weighted factors of ASCE, as shown in Table 3.

Table 3. Considered combination weighted factors.

Actions	Symbol	γ_{ASCE}
Dead	D	1.2
Live	L	1.0
Seismic	E	1.0

Pushover curves for ASCE-7 and Eurocode are plotted for the load cases created from Equation (1).

$$F = 1.2\,D + 1.0\,L + i \cdot 1.0\,E \qquad (1)$$

where i is the progressive factor whose value, herein, varies from 1 to 20. When X direction is analyzed, the exceptional term (E) becomes exclusively P_X. The same way, it happens in Y direction.
The Performance Points calculated from the Pushover Analyses carried out with the ATC and Eurocode methods, in the X and Y directions are presented in Table 4.

Table 4. Performance Points

Direction	Methods	V (kN)	u_C (mm)
X	ATC-40	9785	251
X	EC-8	10178	314
Y	ATC-40	8207	254
Y	EC-8	8721	332

Figures 6 and 7 show, respectively, the pushover curves for directions X and Y. Figures 8 to 11 show the Linear Demand, Non-Linear Demand, Capacity Curves and the Performance Points (PP) for directions X and Y, for ATC-40 and Eurocode 8 methods, respectively.

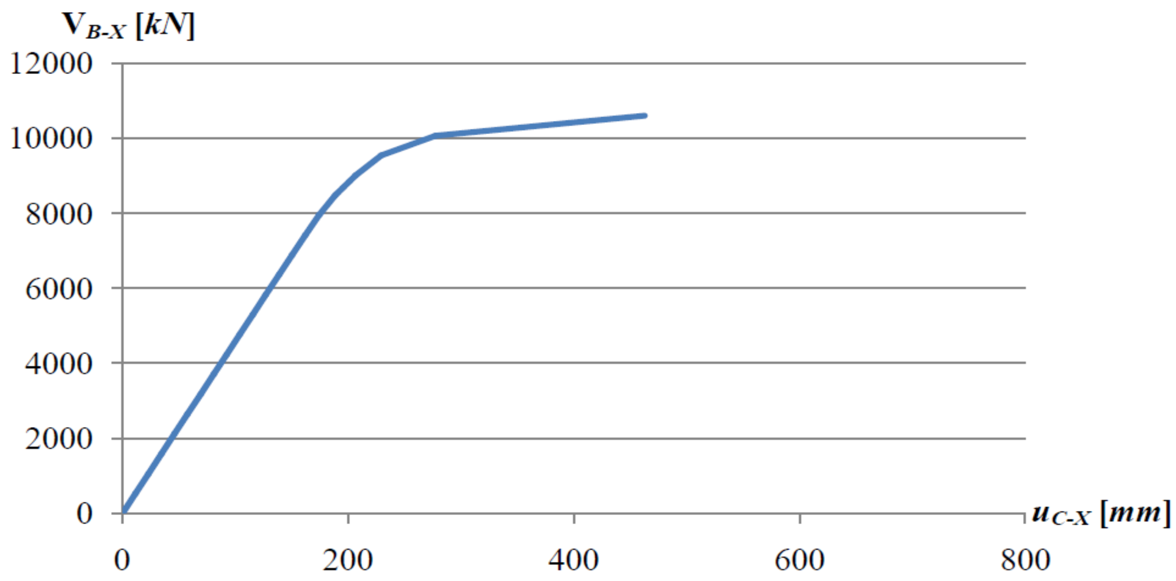


Figure 6 – Pushover curve – Direction X

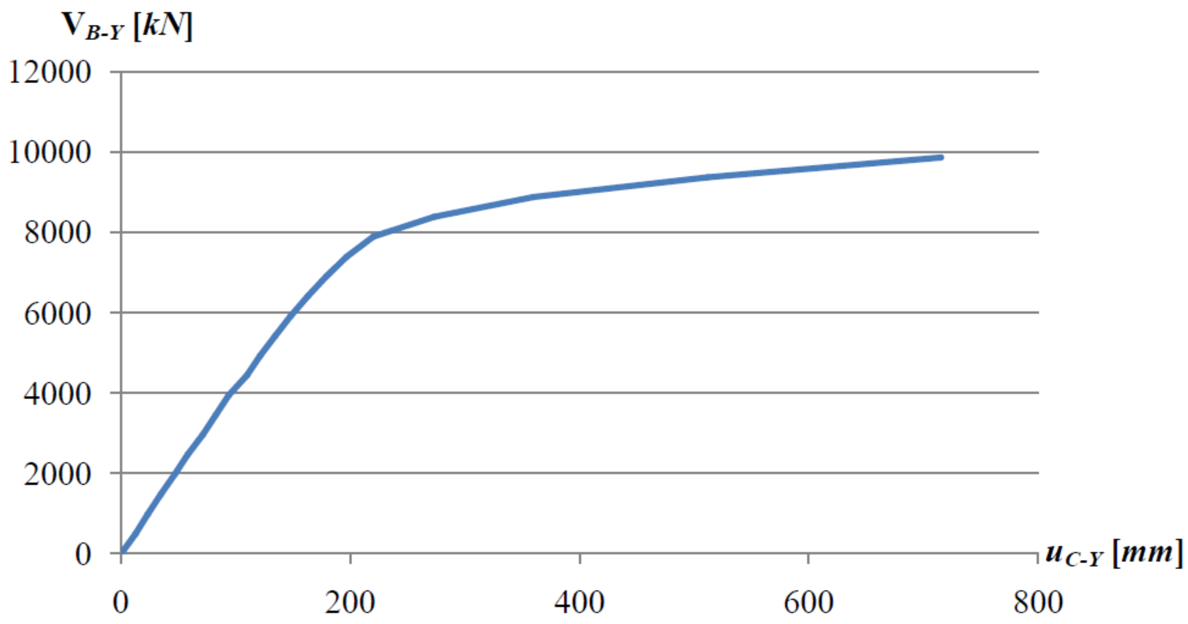


Figure 7 – Pushover curve – Direction Y

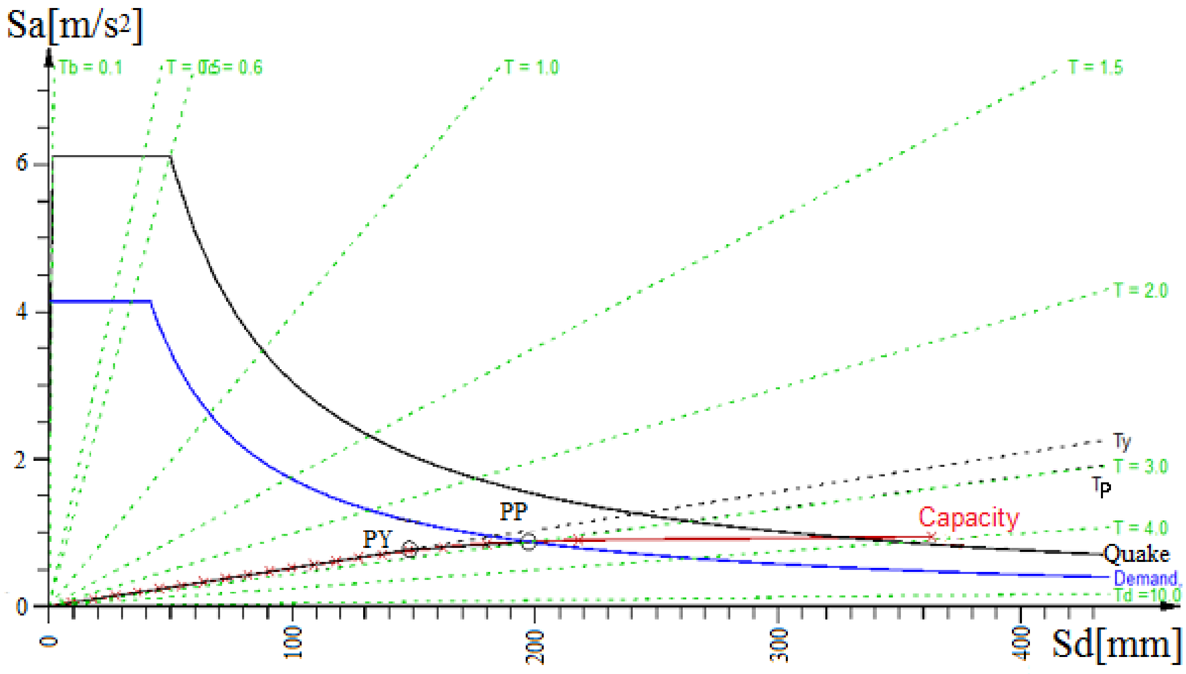


Figure 8 Evaluation of PP in X direction - ATC-40

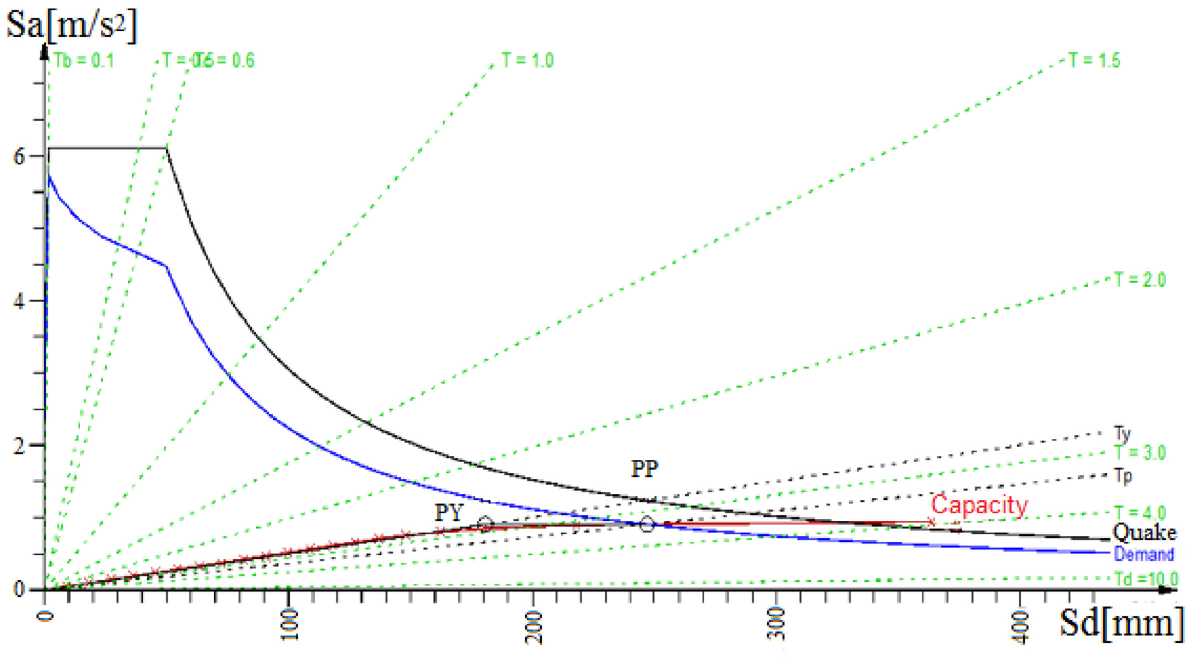


Figure 9.. Evaluation of PP in X direction - EC-8

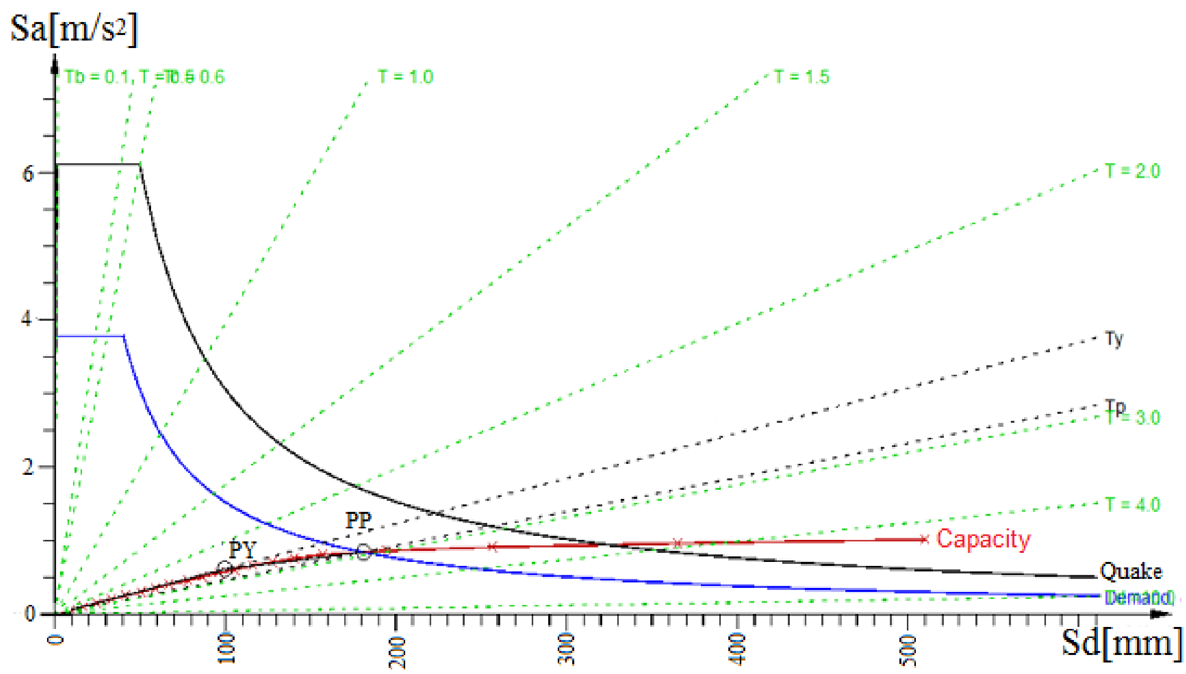


Figure 10 Evaluation of PP in Y direction - ATC-40

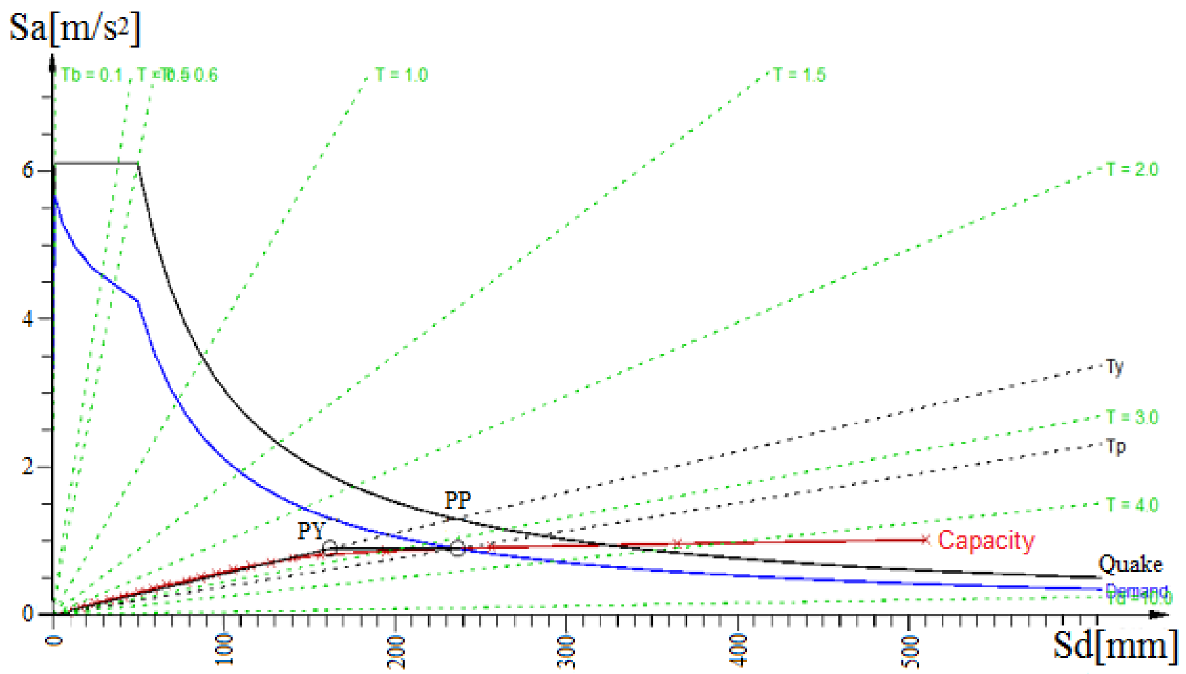


Figure 11. Evaluation of PP in Y direction - EC-8

Figures 12 and 13 present the comparison of shear forces at the base in X and Y direction respectively, while Figures 14 and 15 present the comparison of displacements at the top of the building, obtained by the four methods: Equivalent Horizontal Forces (EHF), Multimodal Spectrum Analysis (MSA), Performance Point by ATC-40 (PP ATC-40) and Performance Point by Eurocode 8 (PP EC-8).

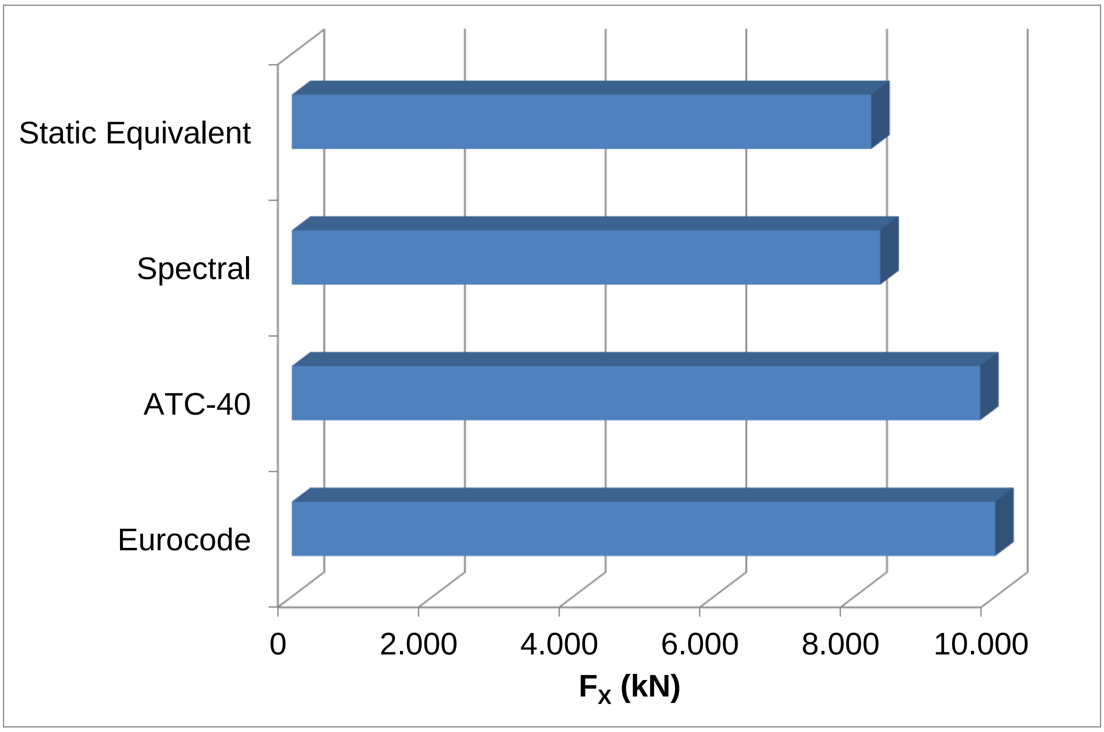


Figure 12. Shear Forces in X direction

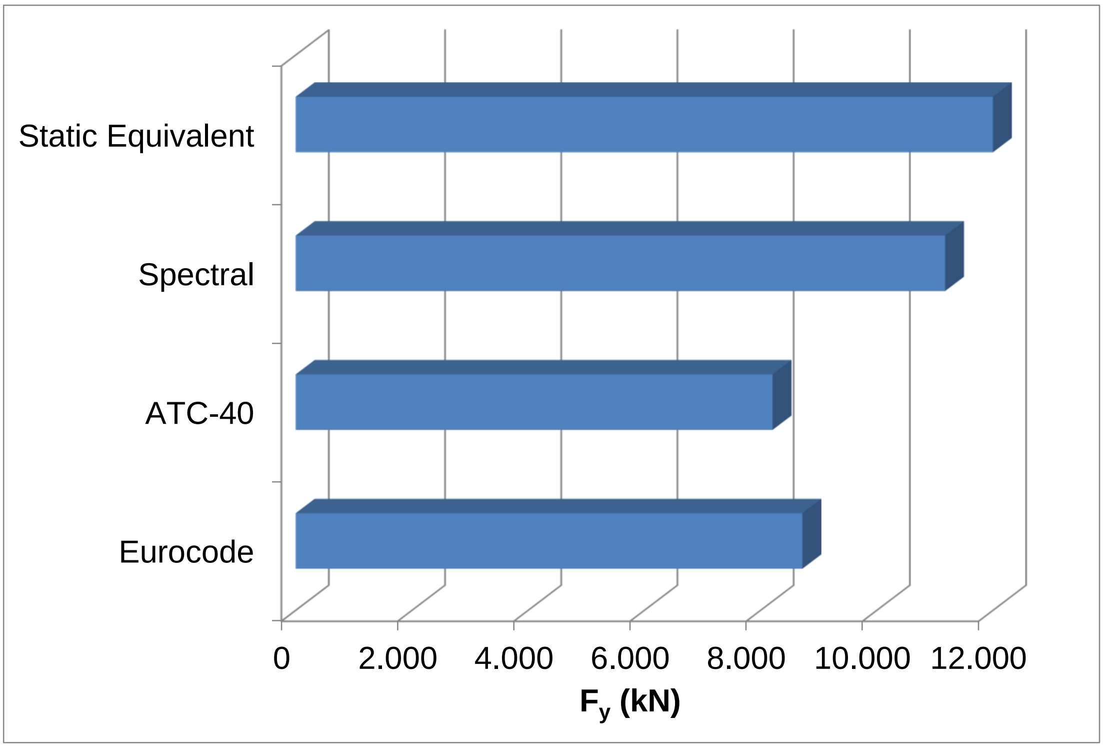


Figure 13. Shear Forces in Y direction

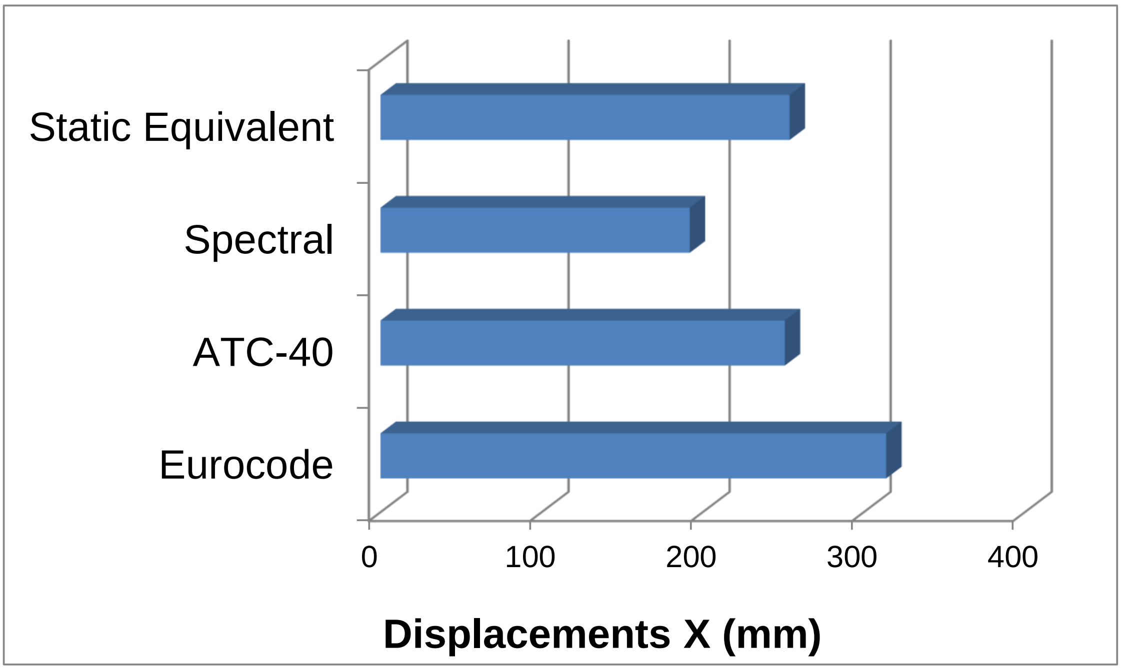


Figure 14. Top-displacement in X direction

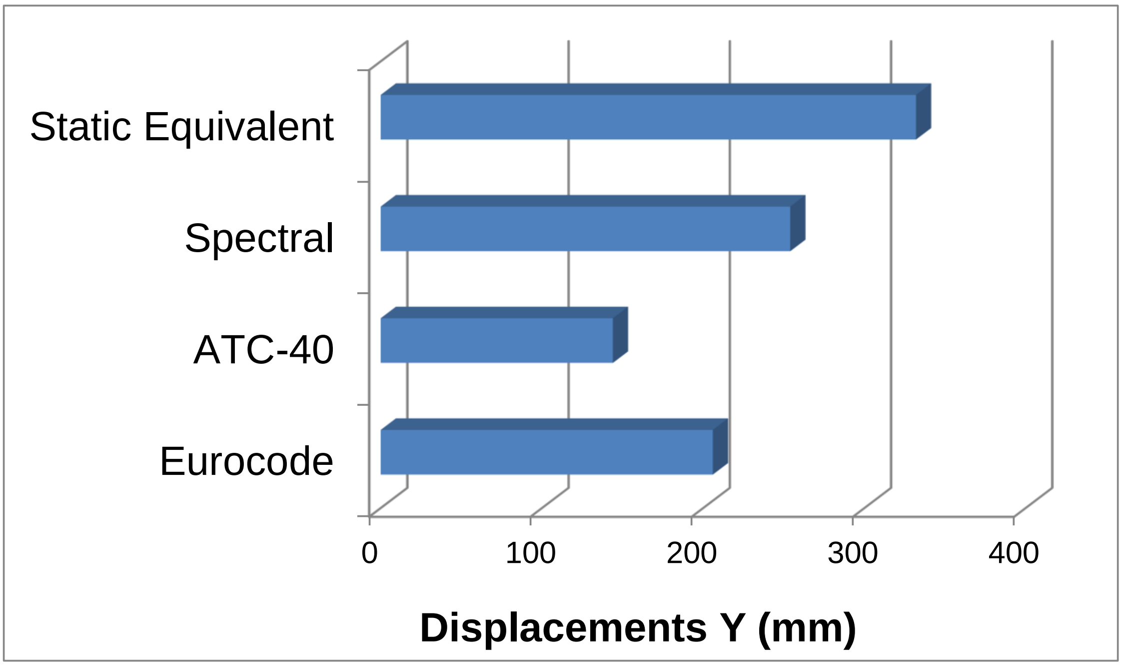


Figure 15. Top-displacement in Y direction

5. CONCLUSIONS

It can be observed that in the case examined the Equivalent Static Analysis (EHF) and the Response Spectrum Analysis (MSA) produce comparable results. Analysis of Figures 8 to 11 indicates that the structure, designed with forces obtained with EHF and MSA methods presents a considered reserve of capacity when analyzed with the pushover methods.
Figures 12 and 13 have to be analyzed carefully. In the direction X and Y the pushover analyses present different predictions for the total shear forces that would be effectively present in the ultimate state relatively to the ones evaluated with the EHF and MSA methods. The same applies for the foreseen maximum displacements in the top of the building.

Pushover analysis can be a very important tool for verifying the structural design in a building, allowing the evaluation of displacements and deformations in the critical stage before collapse.
The design of the structural elements and the reinforcement using the pushover analysis can be done through an iterative process that can adopt the results of the elastic methods as starting points for the estimation of the strengths and the definition of the elastoplastic links. The procedure would end when the materials, geometry, dimensions and reinforcement are set in a situation where they are economically viable and satisfying the requirements established by the standards.

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