Comparative Study of a Set of Codes for the Seismic Design of Buildings

S. H. C. Santos
Full Professor, Federal University of Rio de Janeiro, Brazil

C. Giarlelis
Structural Engineer, EQUIDAS Consulting Engineers, Greece

M. Traykova
Professor, University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria

C. Bucur
Professor, Technical University of Civil Engineering, Bucharest, Romania

L. Zanaica
Bridge Engineer at Santiago Calatrava LLC, Zürich, Switzerland

S. S. Lima
Full Professor, Federal University of Rio de Janeiro, Brazil

Contact: sergiohampshire@gmail.com

Abstract

A comparative study of codes from seismically active regions of various countries is presented covering US, European, Italian, Greek, Romanian, Brazilian and Bulgarian Standards. The study focuses on the comparison of certain critical points: recurrence periods; seismic zonation and design ground motion parameter values; shape of the response spectrum; soil amplification; importance levels; seismic force-resisting systems; behavior factors; structural irregularities; story drift limits; procedures for seismic analysis. Following the comparison of the text of the codes, their application on the seismic design of an ordinary reinforced concrete structure is presented. The structure is subjected to the seismic input according to the above set of codes and obtained results are compared highlighting the differences between the codes. Overall this study aims to assist to the future improvement of the various seismic standards.

Keywords: Seismic codes, seismic analysis, comparative analysis

1 Introduction

The Working Group 7 (WG7-Earthquake Resistant Structures) of the International Association for Bridge and Structural Engineering (IABSE) has proposed a comparative study of various seismic codes. So some members of WG7 have been part of a Subgroup (SG-B), in order to work together on this broad subject, finding discrepancies and similarities of the codes.

This paper is aligned with this objective of the WG7- SG-B, presenting a comparative evaluation between seismic design standards, focusing on the design of conventional (residential and commercial) buildings.

This paper continues the work presented previously by the authors [1], [2] enhancing it with more comparisons, using more standards and with more parameters being investigated.

This study focuses on some critical points 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 respective response modification coefficients and definition of the allowable procedures for the seismic analyses. Detailed presentation of these topics can be found in the already mentioned reference [1]. Herein, only the parts directly related with the application for the presented example are commented.

An ordinary reinforced concrete building ("Model Building") has been selected for the comparative analysis of the codes. This building has been modelled using two different computer programs, SAP2000 and SOFISTIK, in order to increase the reliability of the study. Each model is subjected to the seismic input according to the several codes, and obtained results were compared.

2 Standards to be analyzed

The standards for seismic design of building structures listed below are considered in the comparative analysis:

- American Standard - ASCE/SEI 7-10 [3]
- Eurocode 8 – EN 1998-1:2004 [4]
- Italian Code, Technical Standard for the Constructions [5], [6]
- Romanian Code P100-1:2013 and Romanian National Annex to Eurocode 8 [7], [8]
- Brazilian Standard - NBR 15421:2006 [9]
- Bulgarian National Annex to Eurocode 8 [10]
- Chilean Standard - NCh 433.Of1996 [11]
- Greek Seismic Code 2003 [12]

3 Comparative study

3.1 Recurrence periods for the definition of the seismic input

Different criteria have been found in the various codes for defining the recurrence periods. The Eurocode 8 recommends, for the no-collapse requirement of a structure, the consideration of a recurrence period of 475 years. This corresponds to a probability of 10% of the seismic input being exceeded in 50 years.

The Brazilian, Greek and Bulgarian Standards follow the same definition of Eurocode 8. The Italian code defines two seismic levels for the design of conventional buildings: a Damage Limit State level using elastic spectra with recurrence period of 50 years (mainly for checking maximum displacements and non-structural damage) and a Life Preservation Limit State level using design spectra with recurrence period of 475 years (mainly for checking structural resistance, ductility and stability).

The Romanian code defines a MRI (Mean Recurrence Interval) of 225 years for defining the design ground accelerations for the design. This value varies between 0.1g and 0.4g in the Romanian territory. The Chilean Standard does not define explicitly its considered recurrence periods.

The American Standard ASCE/SEI 7/10 defines a recurrence period of 2475 years, i.e., a probability of 2% of the seismic input being exceeded in 50 years, corresponding to the Maximum Considered Earthquake (MCE); however, for the design of ordinary structures, a reduction factor of 2/3 is applied to the resulting values of the seismic design forces corresponding to the Design Basis Earthquake (DBE).

3.2 Seismic zonation and design seismic ground motion values

Eurocode 8 transfers the responsibility for defining the seismic zonation to each of the National Authorities creating thus the National Annexes. In this standard, the parameters that define the local seismicity are the ZPA ("Zero Period Acceleration"), value of the reference peak ground acceleration on rock (a_g) and the magnitude that prevails in the seismic risk of the analysed site, that defines two different spectral types to be used in the design. The definition by a single parameter ("Zero Period Acceleration") is found in all other codes with the exception of ASCE/SEI 7/10. In the latter, the seismic input is defined through three basic parameters, i.e., the peak ground accelerations at spectral periods 0.2s and 1.0s and the period TD that defines the displacement governed region of the spectrum. These parameters are defined in the standard through very detailed maps.

3.3 Shape of the horizontal elastic response spectra

In order to make possible the comparison between the horizontal elastic response spectra defined in the several standards, Fig. 1 next reproduces Fig. 3.1 of Eurocode 8, as a basis that establishes the shape of the elastic response spectrum, including the several parameters that define it.

In the elastic response spectrum of Eurocode 8, as well as in the elastic spectra of all the other analyzed standards, the pseudo-accelerations (S_e) are given as a function of the structural periods (T). The spectra vary proportionally to the peak ground acceleration (a_g), times a soil coefficient S, related to the soil amplification and consider the parameter η, correction factor for damping values different from 5%. All other analyzed standards consider, for the definition of the spectra, the nominal structural damping of 5%.

The region between reference periods T_B and T_C is controlled by acceleration (constant acceleration); the region between periods T_C and T_D is controlled by velocity (accelerations varying with the inverse of T); the region for periods superior to T_D is

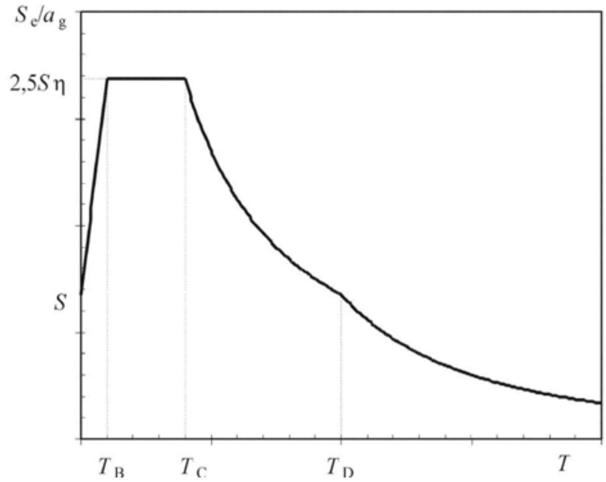


Fig. 1 –Shape of the elastic response spectrum

governed by displacement (accelerations varying with the inverse of T^2). The region between 0 (ZPA, "zero period acceleration") and T_B is the transition region between the peak ground acceleration and the maximum spectral accelerations. For Eurocode 8, the values of S, T_B, T_C and T_D are defined as a function of the type of subsoil in the two spectral types defined in the code, Types 1 or 2, related respectively to higher and lower seismicity regions, respectively. The ASCE/SEI 7/10 defines this region showing the period T_D through maps. In the Greek code there is no definition of T_D and subsequently there is no consideration of a region in the spectrum governed by displacement.

3.4 Soil conditions

All the analyzed standards classify the ground conditions taking into account the shear wave propagation velocities (v_s) and/or the number of blows of the Standard Penetration Test (N_{SPT}). For non-homogeneous sites, criteria for averaging these parameters in the upper soil layers (typically the first 30m) are proposed in the standards. The soil classes, varying from very stiff to soft deposits, are defined in Eurocode 8 as A to E, S_1 and S_2; in ASCE/SEI 7/10 and in Brazilian Standard, they vary from A to F; in the Italian code the soil classes vary from A to E. in the Greek code the soil classes vary from A to D. In the Romanian code the local ground conditions are defined by the values of the control period (corner period) T_C of the response spectrum for the zone of the site under consideration. The Bulgarian code presents very detailed tables defining the design spectra as functions of the soil conditions.

The seismic soil amplification in softer or stiffer layers influences: a) the definition of the shape of the response spectra; b) the soil amplification; in softer deposits, the soil amplification is higher, leading to greater values of the soil coefficients *S*. For the Greek code only (a) applies.

3.5 Classification of the structures in different importance levels

All the analyzed standards recognize the necessity of classifying the structures in Importance Classes. This implies a reliability differentiation, according to the estimated risk and/or consequences of a failure. This reliability differentiation is simply defined in the standards by the application of a multiplying factor *I* to the evaluated seismic forces. Three or four Importance Classes are defined. In all of them, the factor $I = 1$ is assigned to ordinary structures, such as residential and commercial buildings.

3.6 Seismic force-resisting systems & response modification coefficients

All the analyzed standards recognize that pure elastic behavior under seismic loading is not possible and cannot be enforced. The structures are expected to behave in the non-linear range, developing large deformations and dissipating a large amount of energy. For this, the structures shall be designed and detailed in order to assure the necessary capacity of energy dissipation. As long as the necessary degree of ductility is assured, it is possible to consider the transformation of the elastic spectra in design spectra, in which the considered ductility is implied.

All the standards define reduction factors for transforming elastic spectra in design spectra as a function of the structural systems and of the structural materials. The reduction factors are expressed as a function of the ductility classes (e.g., medium and high ductility in the Eurocode 8 or ordinary, intermediate and special detailing in the ASCE/SEI 7/10). The numerical value of these coefficients is often empirically defined in the standards with basis in past experience and/or good engineering judgement.

3.7 Structural irregularities and allowed procedures for the seismic analysis

All the analyzed standards are strict in recommending the following basic principles in the conceptual design of a construction: structural simplicity, uniformity and regularity in plan and in elevation, bi-directional and torsional resistance and stiffness, diaphragmatic behaviour in the floor plans and adequate foundation.

Irregularity in plan or elevation are not recommended by the standards, that in this case accordingly require more elaborated methods of analysis, more stringent criteria for the consideration of design forces, etc.

For regular and simple structures, all the standards allow for a lateral force (static equivalent) method of analysis, in the cases that the contribution of the fundamental mode in each horizontal direction is predominant in the dynamic response. All the standards provide also formulas for the approximate evaluation of the fundamental periods of a structure.

All the standards allow the use of the modal response spectrum analysis. The standards allow also linear time-history analysis, using recorded or artificial time-histories matching the design response spectra, applied simultaneously at least in the two horizontal directions. Some codes (e.g. Eurocode 8) admit non-linear analyses in the time domain, but as long as substantiated with respect to more conventional methods. Some codes (e.g. Eurocode 8) allow also for non-linear static (pushover) analyses.

4 Numerical example

4.1 Considered seismic data

In order to make possible the comparison between the several standards, a particular location has been carefully chosen. It is supposed that the building is located in city of Reevesville, South Carolina (ZIP code 29471), U.S. Considering a 475 years return period, the design ground acceleration, for rock conditions, in this location can be taken as a_g = 0.15g. This relatively small level of seismicity has been chosen is order to make possible the comparison among all the analyzed standards, since this is the highest level of seismicity considered in the Brazilian standard.

Figure 2 shows the elastic spectra obtained according to the several standards. The two types of spectra defined by Eurocode 8 are presented, the Type 1, applicable to regions of higher seismicity and the Type 2, adequate for regions of smaller seismicity. In the Type 2 spectrum, the higher accelerations are concentrated in the 0.1s – 0.25s periods range; due to this, in the range of the fundamental periods of the analyzed structure, the accelerations given by Eurocode 8 Type 2 are much smaller than the ones given by the other codes. The Italian code spectrum follows the same trend of Eurocode Type 2 spectrum.

It should be noticed that all the presented spectra consider the same ground acceleration, a_g = 0.15g, and the same type of soil, rock. Also, as long as only the ASCE/SEI 7/10 considers the recurrence period of 2475 years, its spectrum presents numerical values much higher compared to the corresponding ones of the other codes (however for the design of ordinary structures a reduction factor of 2/3 is allowed by ASCE/SEI 7/10 as it has been already mentioned in 3.1).

4.2 Building data

A simple and symmetrical building structure (the "Model Building") has been chosen as an example for illustrating the comparison between the seismic standards. This model is an adaptation of the one already analyzed by Gosh and Fanella [13]. 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 (distributed) 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: 0.6m x 0.6m
- Dimensions of the beams: 0.5m x 0.8m
- Thickness of the slabs: 0.2m
- Thickness of the two shear-walls: 0.3m
- Total weight of the building (dead weight): 154.14 MN

A typical storey layout of the Model Building is presented in Figs 3. Schematic perspectives of the building, from the models used in programs SOFISTIK and SAP2000 are shown in Figs. 4 and 5.

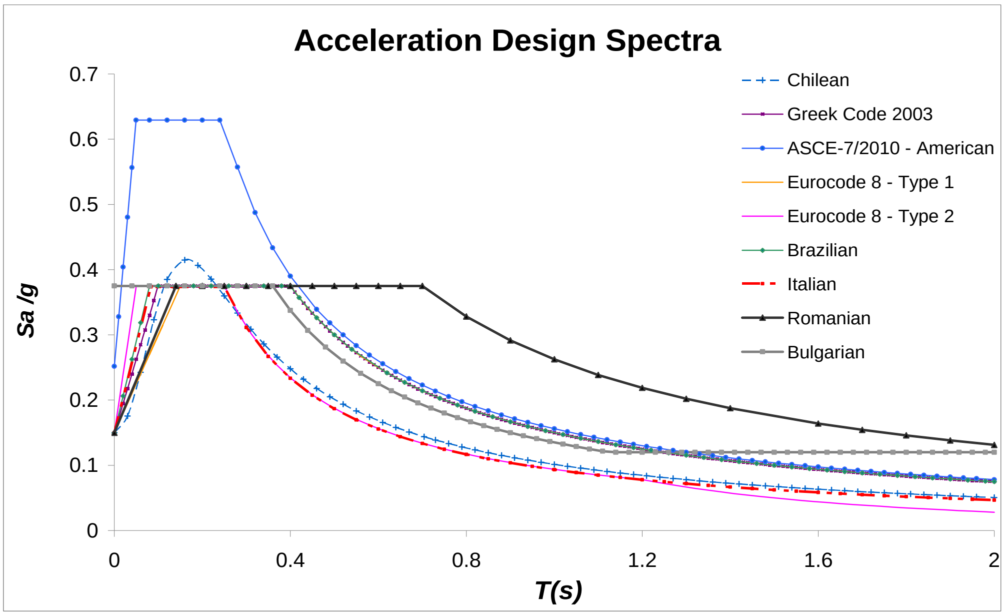


Figure 2. Elastic response spectra for the analyzed building according to the standards

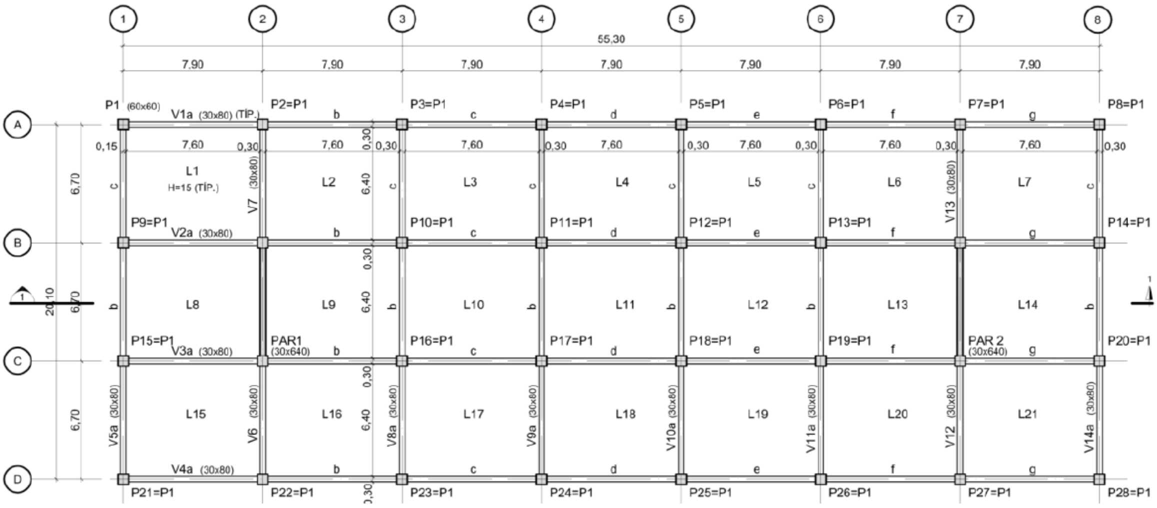
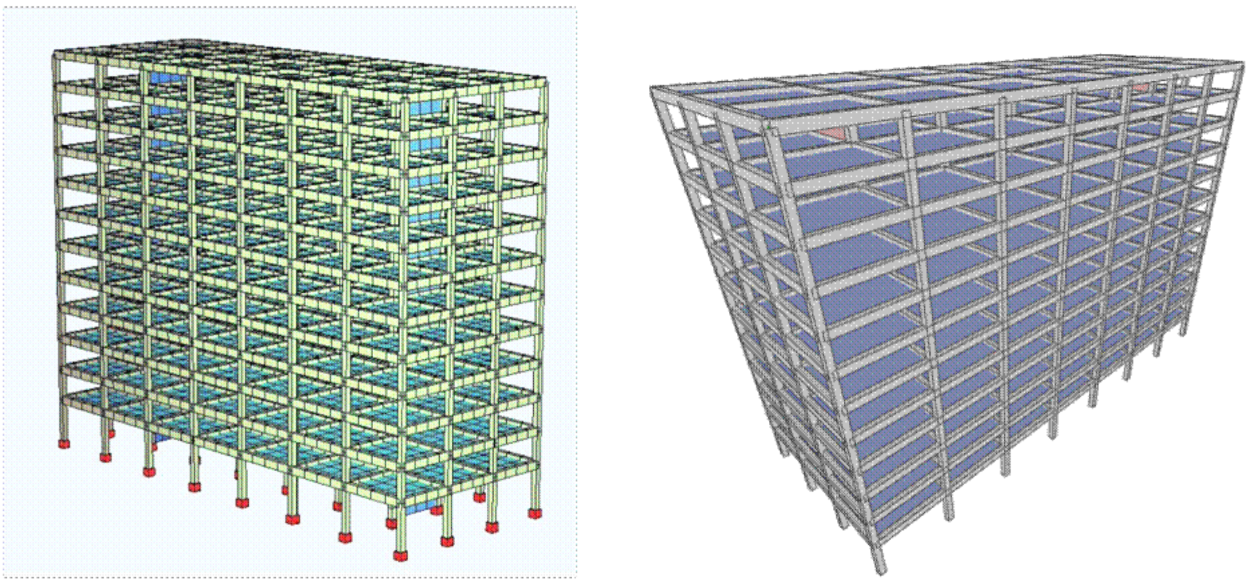


Figure 3. Model Building, Typical floor plan



Figures 4, 5 - Model Building in SOFISTIK and SAP2000, respectively

The dynamic analyses performed by these two programs have been already thoroughly compared in a previous study, [1].

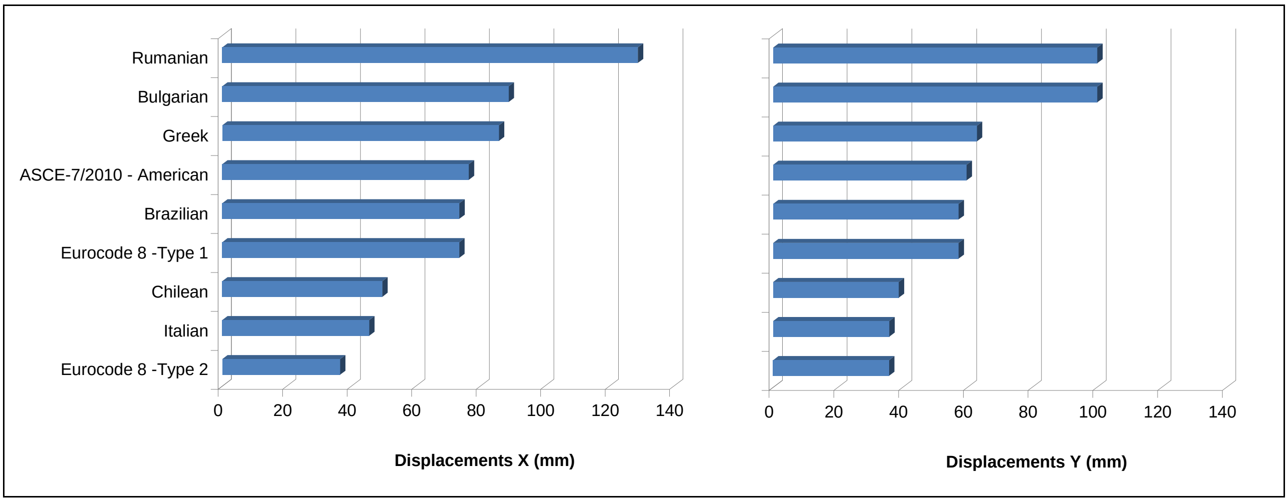
4.3 Analysis results

Spectral analyses of the building have been performed using the computer programs SOFISTIK and SAP2000, for the nine defined design spectra mentioned previously. Good agreement of results between the two programs has been found.

In order to make possible a direct comparison between the standards, the analyses have been performed using the elastic spectra, without the consideration of the response modification factors (reduction factors due to the non-linear behaviour or behaviour factors).

Periods and modal participation mass ratios are obtained as results of the modal analysis. The first mode (T=1.515s) appears in the longitudinal direction X of the building, and the second one (T =1.078s) in the transversal direction Y. Up to the 5th mode, 90% of the total mass is accounted for in both horizontal directions.

Displacements at the top of the building are



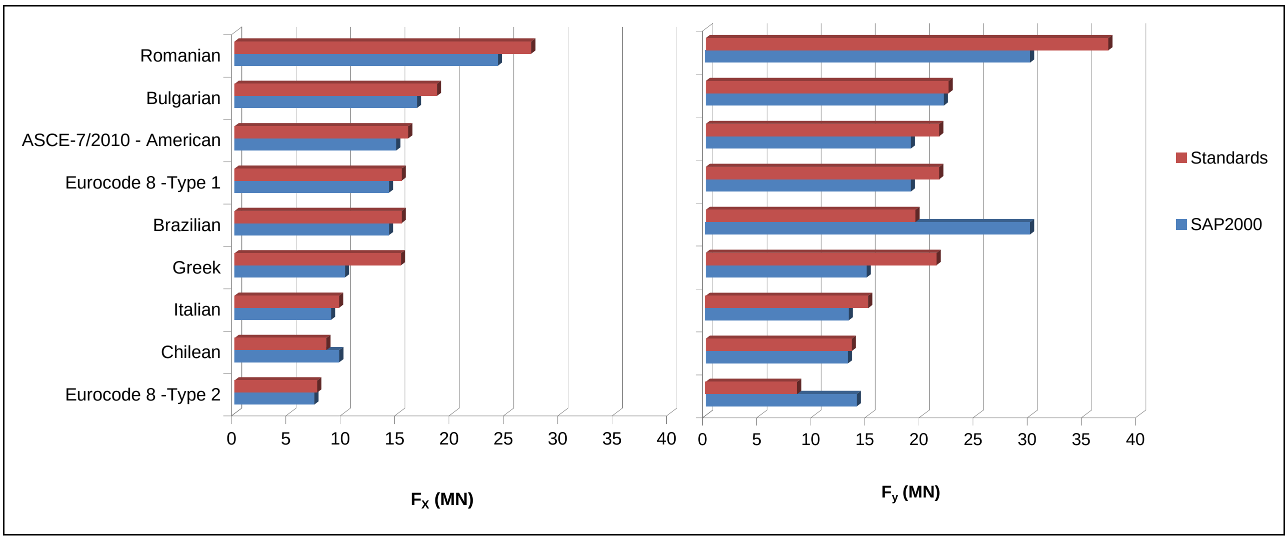
Figures 6, 7 - Displacements at the top, at the longitudinal and transversal directions

presented in Figs. 6 and 7 for longitudinal and transversal directions X and Y, respectively. These displacements are obtained from spectral analyses using the CQC rule for the combination of modal components. Displacements and forces obtained using the Type 2 spectrum of Eurocode 8 and using the spectrum of the Italian code are considerably lower than the ones obtained with the other codes.

Total base shear obtained through spectral analyses and also through the static equivalent methods are shown in Figs. 8 and 9 (in the legend, “SAP2000” and “Standards”, respectively). It would have been expected that in all the reviewed standards, the values of total base shear obtained with the static equivalent methods would be more conservative than the ones obtained from spectral analysis. However this is not always the case. As it is shown in Fig.9, in the transversal direction of the building, results from the Bulgarian and the Chilean codes show that the static equivalent analysis is not always conservative.

It should be pointed out that the presented comparisons of obtained displacements and total horizontal forces are based on low peak ground acceleration, and that may be not generally applicable in some of the countries in this study.

Torsional effects are not discussed and compared in this stage of research. Stiffness reduction factors are also not considered herein.



Figures 8, 9- Base shears at the longitudinal and transversal directions

5 Conclusions

A comparative study of a set of codes for the seismic design of buildings is presented. This comparison indicates a general agreement regarding the desired main characteristics of a seismic resistant structure: simplicity, symmetry, uniformity and redundancy. Also all the examined codes agree on the necessity that the structural detailing should provide enough ductility for the dissipation of energy in the non-linear range. On the other hand, differences in the shapes of the design spectra lead to differences in the results higher than 100%, in some cases. Obviously, this is a point to be better addressed to in future comparative studies.

Another point, already stressed, to be further investigated, regards the definition of the spectral shapes. With the exception of ASCE/SEI 7/10, where the spectral shape is defined with three acceleration parameters and with the soil properties, the shapes of the remaining spectra are only governed by the peak ground acceleration and by the soil properties. Additionally, for considering the magnitude that prevails in the seismic risk of the analysed site, the Eurocode 8 defines two different spectral types.

Another very important issue is the definition of the recurrence periods. The ASCE/SEI 7/10 already redefined this parameter from the traditional 475 years to 2475 years, although that for the design of ordinary structures, reduced values of seismic input are used. However, reference of this consideration is an indirect push towards the direction of an important increase in the design seismic forces presently defined in the standards.

As shown in this paper, there are important issues that should be discussed in the engineering community, envisaging future revisions in the seismic standards. This is an ongoing study aiming to encourage the future improvement of the seismic standards.

6 References

[1] Santos S.H.C., Zanaica L., Bucur C., Lima S.S., Arai A. Comparative Study of Codes for the Seismic Design of Structures. 2013, Math. Modelling in Civil Eng., Vol 9, No 1.

[2] Santos S.H.C., Zanaica L., Bucur C., Traykova M., Giarlelis C., Lima S.S., Arai A. Comparative study of some seismic codes for design of buildings. Paper N° 0942, 16WCEE, Santiago Chile, 2017.

[3] ASCE. Minimum Design Loads for Buildings and Other Structures. (ASCE/SEI 7-10), Washington, D.C. 2010.

[4] European Committee for Standardization. EN 1998-1:2004 – Eurocode 8: Design of Structures for Earthquake Resistance - Part 1, ECS, Brussels, 2004.

[5] Italian Ministry of Infrastructures, Italian Ministerial Decree of 14/01/08 - Norme Tecniche per le Costruzioni. 2008.

[6] Italian Ministry of Infrastructures. Italian Circular No. 617 of 02/02/09 - Istruzione per l'Applicazione delle Norme Tecniche per le Costruzioni. 2009

[7] Romanian Seismic Design Code, Part 1-P100-1/2013, Earthquake Resistant Design of Buildings. 2013

[8] Romanian Standards Association. Eurocode 8: National Annex SR EN 1998-1. 2010

[9] Associação Brasileira de Normas Técnicas. Projeto de Estruturas Resistentes a Sismos - NBR 15421. ABNT, Rio, Brazil. 2006

[10] Bulgarian Institute for Standardization. EUROCODE 8 - Bulgarian National Annex БДС EN 1998-1:2005.

[11] Instituto Nacional de Normalización. NCh 433.Of1996 – Modificada en 2009: Diseño Sísmico de Edificios. Santiago, Chile. 2009.

[12] Earthquake Planning and Protection Organization, Greek Seismic Code 2000.

[13] Gosh SK, Fanella DA. Seismic & Wind Design of Concrete Buildings. International Code Council, Falls Church, VA, USA. 2003.