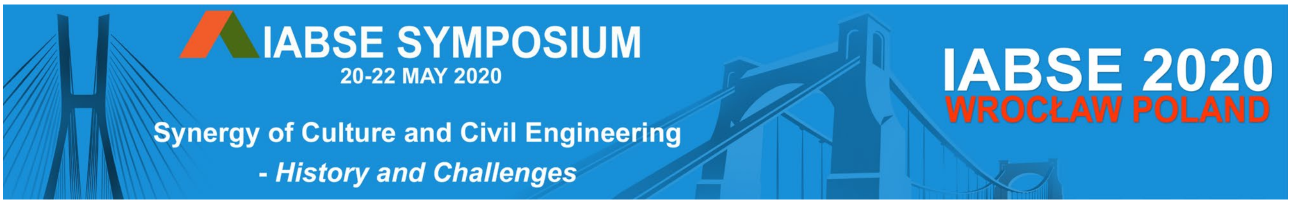

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COMPARATIVE STUDY OF INTERNATIONAL MAJOR CODES FOR THE SEISMIC DESIGN OF BUILDINGS

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SUMMARY

The Task Group 1.1 of IABSE has proposed studies of comparisons among seismic codes, in order to find out discrepancies and similarities among them. The idea of the study is to select major international seismic design codes to be analyzed and compared among them. A comparative study of codes from seismically active regions of various countries is presented herein covering European, United States, Brazilian, Bulgarian, Canadian, French, Italian, Greek, Japanese, Mexican, New Zealander, Portuguese and Turkish codes and National Annexes of Eurocode 8. The study is focused in the criteria for the design of conventional (residential and commercial) buildings, analyzing some critical topics. A prototype reinforced concrete building is analyzed, considering all the codes under analyses and main results derived form the seismic design are compared.

Keywords: *Seismic codes, seismic analysis, comparative analysis.*

1. INTRODUCTION

The Task Group 1.1 (TG 1.1 - "Improving Seismic Resilience of Reinforced Concrete Structures") of IABSE has proposed studies of comparisons among seismic codes, in order to find out discrepancies and similarities among them, and to identify and fulfil grey areas of knowledge. The idea of the study is to select major international seismic design codes to be analyzed and compared among them.

Therefore, a comparative study of codes from seismically active regions of various countries is presented herein, covering European [1], United States [2], Brazilian [3], Canadian [4], French [5], Greek [6], Italian [7], New Zealander [8], Turkish [9], Japanese [10], Mexican [11], Bulgarian [12] and Portuguese [13] codes.

The study is focused on criteria for the design of conventional (residential and commercial) buildings, analyzing some critical topics, regarding the definition of:

- recurrence periods;
- seismic zonation and design seismic ground motion values;
- shape of the design response spectra;
- soil amplification;
- importance classes/importance levels;
- seismic force-resisting systems and response modification coefficients;
- structural irregularities and allowable procedures for the seismic analyses.

The application of the different codes on the analysis of a reinforced concrete building is presented. Obtained results are compared highlighting the differences between the codes, aiming to assist to the future improvement of these various seismic codes.

2. ANALYSED STANDARDS

The following seismic design codes, or National Annexes to Eurocode 8, are herein analysed:

- Eurocode 8 - EN 1998-1:2004 [1]
- American Standard - ASCE/SEI 7-16 [2]
- Brazilian Standard - NBR 15421:2006 [3]
- Canadian Code – NBCC2015 [4]
- French National Annex to Eurocode 8 – NF EN 1998-1:2005 [5]
- Greek Seismic Code - EAK 2000 [6]
- Italian Technical Standard for Structures 2018 [7]
- New Zealand Standard – NZS1170.5:2004 [8]
- Turkish Building Seismic Code 2018 [9]
- Japan Building Standard Law 1981 [10]
- Design Manual for Civil Structures in Mexico: Seismic Design 2015 [11]
- Bulgarian National Annex to Eurocode 8 – BDS EN 1998-1 (EC 8-1) [12]
- Portuguese National Annex to Eurocode 8 - NP EN 1998-1:2010 [13]

Some important works have been previously published focused in the comparison of seismic codes. Among them, it should be cited the work Critical Comparison of Major Seismic Codes for Buildings [14], developed by the Fédération Internationale du Béton (*fib*), comparing the codes of United States, Europe, Japan, Mexico, Chile, Canada and New Zealand.

3. COMPARATIVE STUDY

3.1. Definition of the recurrence period for the definition of the seismic input

Different criteria have been found in the various codes for defining the recurrence periods. The Eurocode 8 [1] recommends, for the non-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 [3], French [5], Portuguese [13], Greek [5] and Bulgarian [12] standards follow the same definition of Eurocode 8 [1].

The Italian code [7] defines two seismic levels for the design of conventional buildings: a Damage Limit State level using elastic spectra with recurrence period of 30 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 (for checking structural resistance, ductility and stability).

The American Standard ASCE/SEI 7/16 [2] and the Canadian Code [4] define 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.

3.2. Definition of the seismic zonation and design seismic ground motion values

Eurocode 8 transfers the responsibility for defining the seismic zonation to each of the National Authorities, introduced in the respective 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 only a single parameter ("Zero Period Acceleration") is found in all other codes with the exception of Canadian Code [4] and ASCE/SEI 7/16 [2].

In ASCE/SEI 7/16 [2], the seismic input is defined through three basic parameters, i.e., the peak ground accelerations at spectral periods 0.2 s and 1.0 s and the period T_D that defines the displacement governed region of the spectrum. These parameters are defined in the standard through very detailed maps.

In Canadian code [4] it is possible to draw equal probability design spectra for a specific location from information given in the sites of the National Research Council of Canada (NRCC).

In New Zealand code [8], the return period depends on the Importance Level (IL) assigned to a building. For the Life-Safety LS, the following return periods are defined:

- IL1 (e.g. farm buildings): 100 years
- IL2 (standard commercial or residential building): 500 years
- IL3 (high occupancy building, school, airport): 1000 years
- IL4 (hospital, fire station, post-disaster facility): 2500 years

In Turkish code, the seismic input levels depend on the building type and target performance level:

- DD-1: 2475 years return period;
- DD-2: 475 years return period;
- DD-3: 72 years return period;
- DD-4: 43 years return period.

The seismic design input in Japan [10] corresponds to a return period of approximately 500 years.

Mexico code [11] defines an optimum design criterion, based on an additive function of the initial cost of the buildings and the expected value of losses. This approach conducts to optimum return periods in zones of high seismicity close to 200 years and in zones of low seismicity, to more than 2000 years.

The elastic response spectrum as defined in Eurocode 8, is presented in Fig 1.

In this spectrum, 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 considers the parameter η, correction factor for damping values different from 5%. All other analyzed standards, excepting the Italian standard, consider, for the definition of the spectra, the nominal structural damping of 5%.

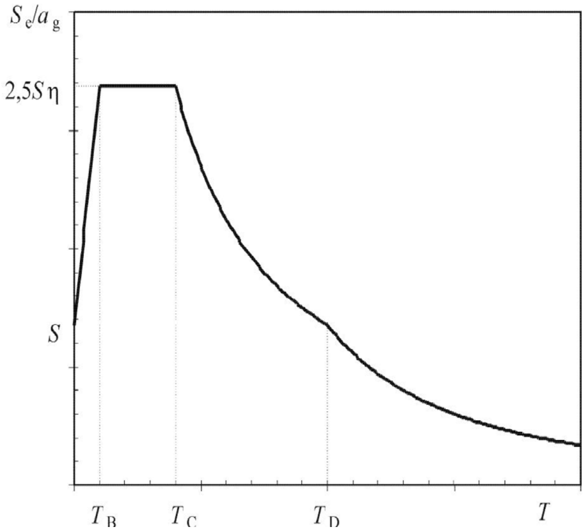

***Fig. 1**. Shape of elastic spectrum in Eurocode 8*

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; the region for periods superior to T_D is governed by displacement. The region between 0 (ZPA) and T_B is the transition region between the peak ground acceleration and the maximum spectral accelerations. For Eurocode 8 [1], 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 7/16 [2] defines this region showing the period T_D through maps.

All analyzed standards show the seismicity in their respective countries through maps defining accelerations to be considered in the design.

3.3. Consideration of specific 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}).

Soil classes, varying from very stiff to soft deposits, are accordingly defined in the standards.

The seismic soil amplification in softer or stiffer layers influences the definition of the shape of the response spectra; in softer deposits, the soil amplification is higher than in stiffer ones.

All the standards include values for modifying the design spectra, according to the soil classes.

3.4. Classification of the structures in different importance levels

All the analyzed standards recognize the need for classifying the structures in Importance Classes. This implies a reliability differentiation, according to the estimated risk or consequences of a failure. This reliability differentiation is 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 codes under analysis.

3.5. Seismic force-resisting systems and response modification coefficients

All the analyzed standards recognize that pure elastic behavior under seismic loading cannot be enforced. The structures are expected to behave in 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 ductility and energy dissipation capacity.

All the analysed standards define reduction factors for transforming the elastic spectra in design spectra as a function of the structural systems types and of the structural materials, among other parameters. The reduction factors are expressed as a function of the ductility classes (e.g., low, medium and high ductility in the Eurocode

8 [1] or ordinary, intermediate and special detailing in the ASCE/SEI 7/16 [2]). The numerical value of these coefficients is often empirically defined in the standards with basis in past experience and/or good engineering judgement.

3.6. Structural irregularities and allowed procedures for the seismic analysis

All the standards recommend 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 behavior in the floor plans and adequate foundation.

Irregularities in plan or in elevation are not recommended by the standards, that in this case accordingly require more elaborated methods of analysis, more stringent design criteria, 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. Some codes (as the Eurocode 8 [1]) admit non-linear analyses in the time domain, but as long as substantiated with respect to more conventional methods. Some codes (as the Eurocode 8 [1]) allow also for non-linear static (pushover) analyses.

4. NUMERICAL EXAMPLE

This item presents the application of some points discussed previously in the seismic analysis of a prototype reinforced concrete building. The item reproduces partially the work developed by Santos *et al.* [15], where some of the presently analyzed codes were considered.

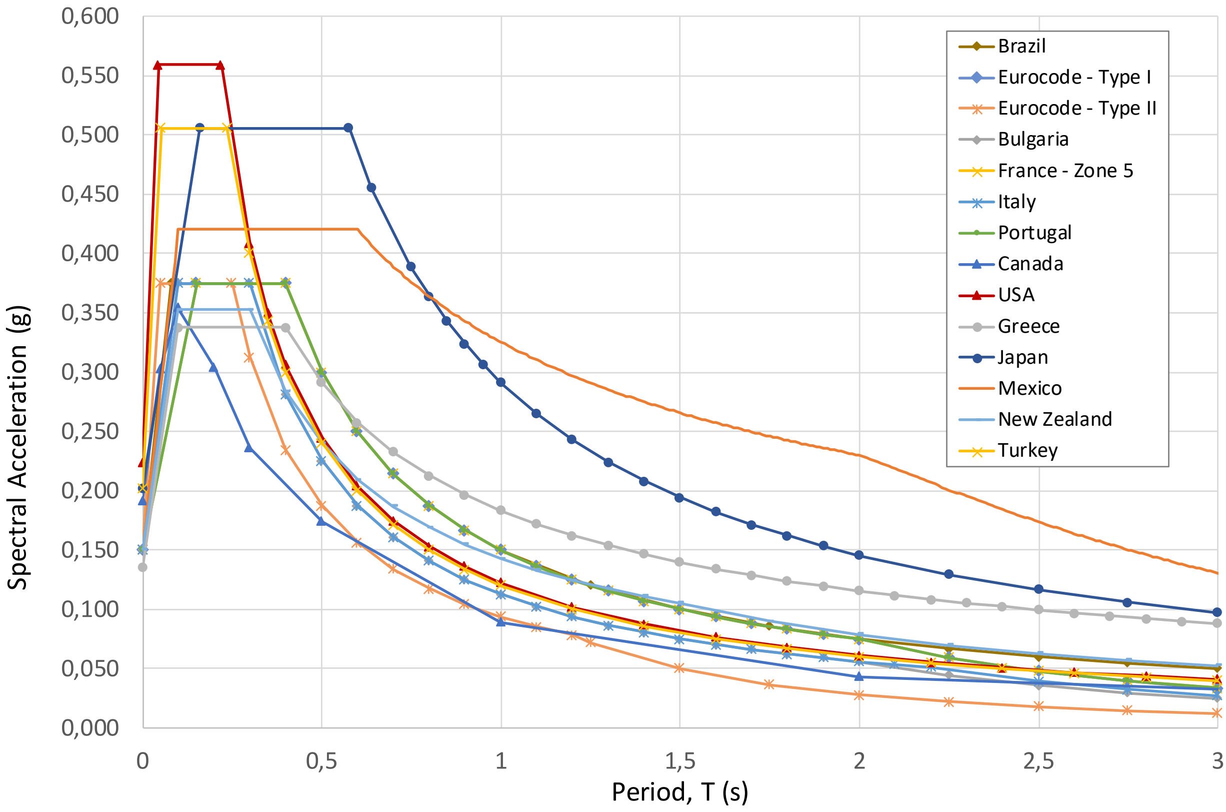

Fig. 2. *Elastic response spectra for the analyzed building according to the standards*

4.1. Considered building data

A simple, regular and symmetrical building structure was chosen as an example for illustrating the comparison between the standards. This model is adapted from a structure analyzed by Gosh and Fanella [16]. The main data of the building is:

- Dimensions in plan: 20.1 m x 55.3 m (between axes of columns)
- Building height: 45.05 m (12 floors), 1st floor with 4.90 m and others with 3.65 m
- Young modulus of concrete: E_c = 32 GPa
- Columns cross-sections: 600 x 600 mm
- Beams cross-sections: 300 x 800 mm
- Thickness of the slabs: 200 mm
- Thickness of the shear-walls: 300 mm
- Concrete specific weight: γ_c = 25 kN/m³
- Non-structural dead load: 1.5 kN/m^2 for current floors and 0.5 kN/m^2 for the top floor plus four concentrated loads of 900 kN
- Total weight of the building (dead weight): 126.6 MN

Elastic response spectra according to the analyzed standards is presented in Figure 2. A typical floor plan is presented in Figure 3, including the definition of the considered main axes.

It is to be noticed that all the presented spectra consider the same ground acceleration for the reference period of 475 years (a_g = 0.15g) and the same type of soil (rock).

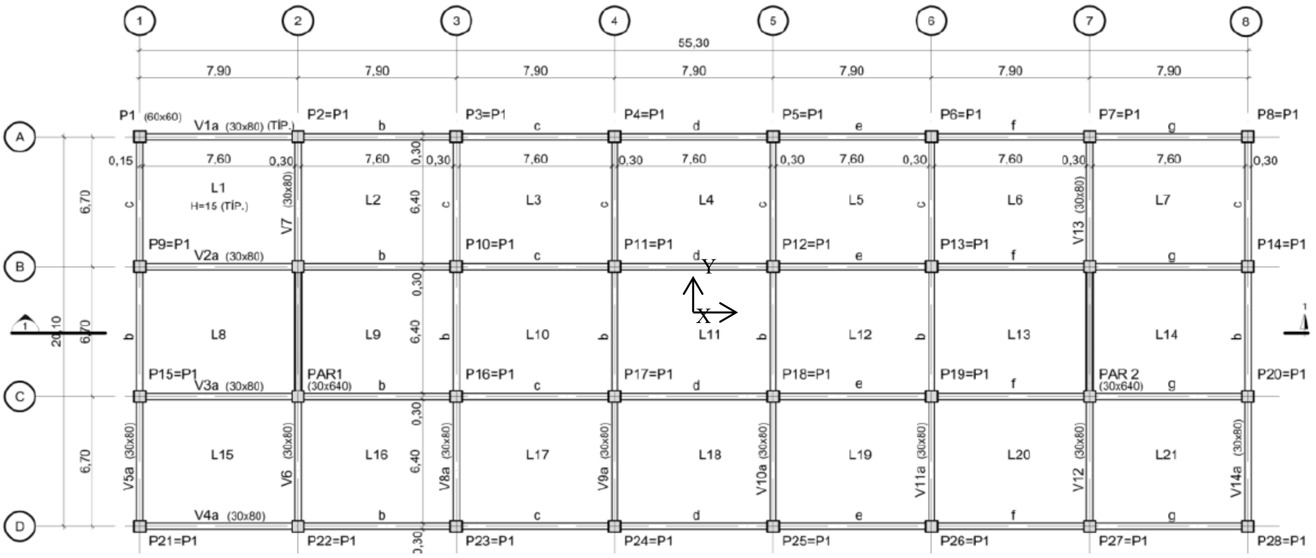

Fig. 3. *Model Building – Typical floor plan*

4.2. Analysis results

Spectral analyses of the building have been performed using the computer program SAP2000 [17], for the fourteen defined design spectra (Figure 2). For a direct comparison among 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 response).

Periods and Modal Participation Mass Ratios are obtained as results of the modal analysis. The first mode (T = 1.625 s) appears in the longitudinal direction X of the building, and the second one (T = 1.099 s) 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 presented in Figure 4 for the transversal direction Y. These displacements are obtained from spectral analyses using the Complete Quadratic Combination (CQC) rule for the combination of modal components. Total base shear forces, obtained through spectral analyses, are shown in Figure 5.

It is to be pointed out that the presented comparisons of results are based on low peak ground acceleration, and that may be not generally applicable in some of the countries of this study.

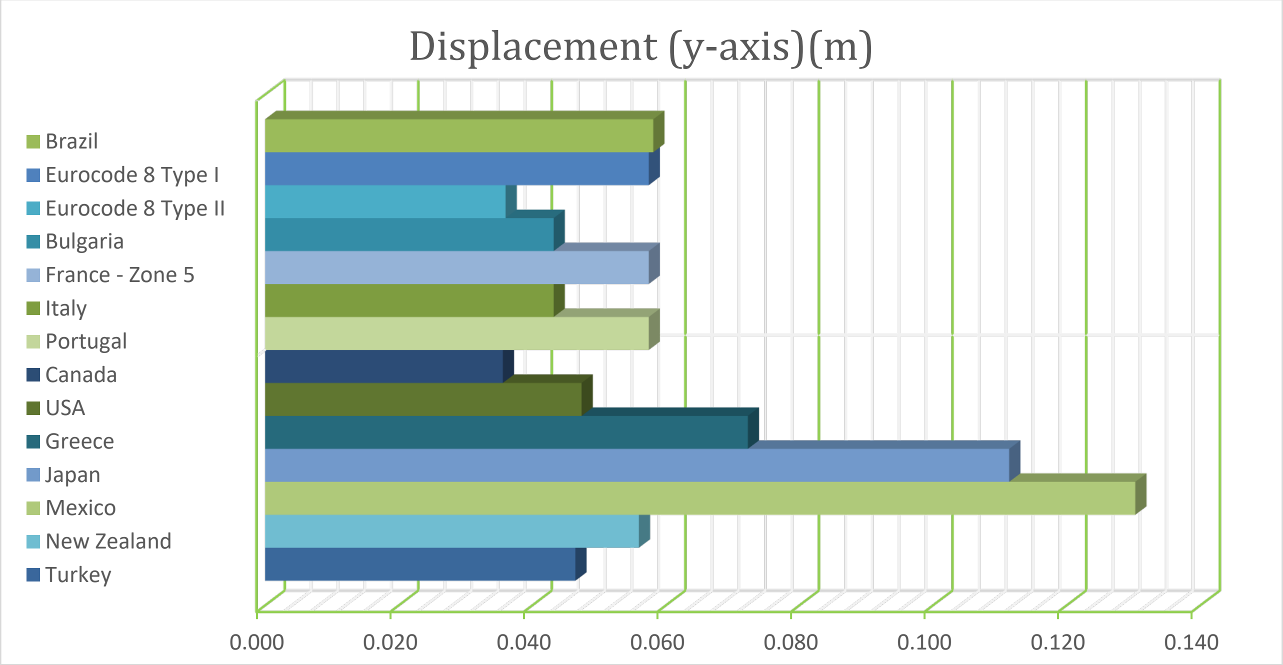

Fig. 4. Displacements at the top of the building, direction Y

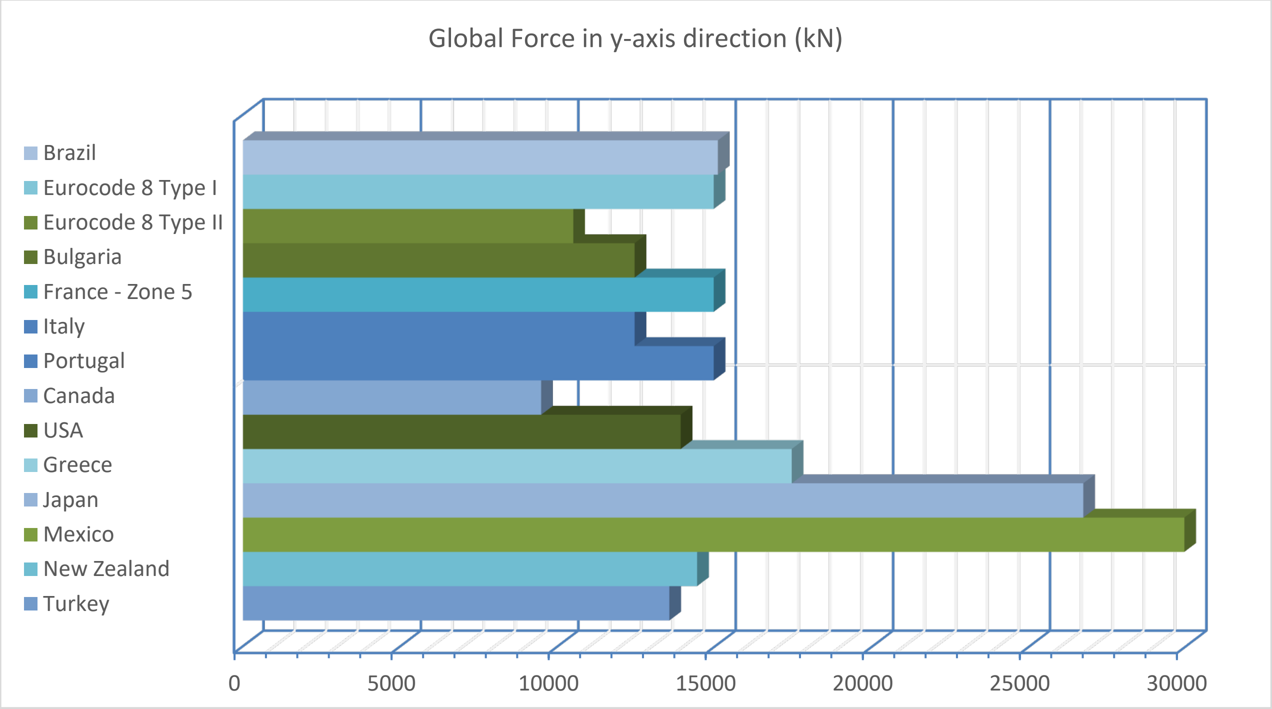

***Fig .5.** Total horizontal forces at the base of the building, direction Y*

5. DISCUSSION AND CONCLUSIONS

The analysis of the different seismic standards indicates a general agreement regarding the desired characteristics of a seismic resistant structure. Structures should be designed and detailed to 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 big differences in results. For instance, due their spectral shapes, the results for Japan and Mexico for displacement and forces are considerably higher than for the other ones.

Regarding the definition of the spectral shapes, for most of the analyzed standards, the shape is governed by a single parameter, the peak ground acceleration. Eurocode 8 defines two spectra, associated with the type of source that prevails in the seismic risk of the analyzed site. In standard ASCE/SEI 7/16 [2], the spectral shape is defined with three basic parameters, i.e., the peak ground accelerations for the spectral periods of 0.2s and 1.0s and the period T_D that defines the displacement governed region of the spectrum.

Another issue is the definition of the recurrence period. The ASCE/SEI 7-16 [2] and NBCC [4] 2015 already redefined this parameter from 475 to 2475 years. This led to an important increase in the design seismic forces, implying in the level of reliability that our constructions will possess.

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