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STRUCTURAL ANALYSIS, WITH DIFFERENT INTERNATIONAL STANDARDS, OF BUILDINGS SUBJECTED TO SEISMIC LOADS

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ABSTRACT

This article provides an analysis of a software-modelled reinforced concrete residential building, which has characteristics that would allow it to be constructed in different countries. The model was subjected to a high level of earthquake loading with properties specific to its site of construction. Using applicable and compatible earthquake and reinforced concrete codes, results were obtained and compared. The comparison results range from the consideration of seismic forces to the quantities of steel reinforcement required to strengthen the structural elements by examining their impact per square meter. In this study, CYPECAD, a software program from CYPE Ingenieros (http://www.cype.com), was used as a tool for calculating the seismic response of the structure according to the seismic codes from a selection of countries in Europe, Northern Africa, and South and Central America. It was concluded that the seismic action depends heavily on the definition of the spectrum and the variability of the seismic factors considered according to each code, and that the American codes are more restrictive in terms of reinforcement requirements than the European codes. Furthermore, it was demonstrated that CYPECAD serves as an effective and powerful tool in obtaining results for the seismic analysis and design of structures.

Key words: Seismic Standards, Seismic Action, Modal Spectral Analysis, Amount of Earthquake Reinforcement, Seismic Shear.

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Introduction

The aim of this paper is to compare the construction requirements of identical buildings that are located in regions of similar seismicity, but in different countries, and hence, subject to different regulations governing the design of earthquake-resistant structures. The consequences of this study were estimated in the form of seismic forces and amounts of reinforcing steel required for each model according to its corresponding seismic and concrete code.

Structural and Site Characteristics

The structure analysed in this paper is a reinforced concrete residential building that consists of three floors, each with a surface area of $340m^2$, and a flat roof. The structural system consists of a set of frames of columns and beams and a central core formed by walls. The floors are one-way slabs, and the joists are constructed of concrete. The structure is assumed to be located in cities of different countries, all of which are characterized by high seismicity. Section 4 of this article lists the adopted values representative thereof.

Calculations by CYPECAD

The calculation of the structure's resistance to seismic loads for each of the regulations under consideration was performed by a spectral modal analysis using CYPECAD software. A brief description of the method of analysis is provided in the subsequent text.

Description of the Analysis by the Program

The analysis, a three-dimensional spatial calculation, was performed using the stiffness matrix method. All elements that define the structure (columns, walls, beams and slabs) were defined using bar-type elements, meshes of bars and nodes, and triangular finite elements. The compatibility of nodal displacements was established with the consideration of 6 degrees of freedom and the assumption that there is no plane deformability, so as to simulate the rigid behaviour of the floor slab. As a result, there were no relative displacements between nodes.

Spectral Modal Analysis with Seismic Regulations Implemented

The dynamic analysis method that the program uses is generally referred to as modal spectral analysis. The design spectra depend on the earthquake-resistant standards and parameters selected therein. To perform the dynamic analysis, the program carries out a linear elastic calculation using the stiffness and mass matrices of the condensed structure, so as to say that the analysis only deals with the dynamic degrees of freedom which contribute to the decay of modes. There are a total of three dynamic degrees of freedom per floor: two translations on the horizontal plane, and the corresponding rotation generated.

The seismic modes and vibration frequencies were first obtained. Next, the selected design spectrum provided the acceleration for each mode and each dynamic degree of freedom with which the corresponding maximum displacement was calculated. Finally, a displacement equation was obtained and the other (static) degrees of freedom were solved. This resulted in a distribution of displacements and stresses over the entire structure for each mode of vibration and each dynamic hypothesis.

CYPECAD deals with the implementation of different seismic regulations according to the spectral modal analysis procedure selected to perform the calculations. Sections 4 and 5 present details about the seismic regulations considered in this analysis.

Data and Parameters Required for the Calculation of the Seismic Action

To achieve a significant analysis of the results obtained in this model, which were calculated using different seismic regulations, it was necessary that the seismic loads applied to the building were as similar as possible in each case. Therefore, in entering data for the calculations according to each code into the software, analogous values were used for the various factors involved since it was not always possible to use identical ones.

In this chapter, the most influential factors that defined the seismic loading, and the values that were taken for each of them from each regulation, are analysed. This is a necessary step prior to any subsequent analysis of the results provided by the calculations.

Factors Influencing the Seismic Response

The distribution of mass and stiffness of the construction: The gravitational loading was the same in all cases, as well as the geometry and strength of materials wherever possible. Given, there were local factors that accounted for small differences in the calculation; however, they did not significantly influence the results.

Seismicity of the area: The modelled building was analysed in regions with high seismic activity located in different countries. Due to the variability of seismicity from one country to another and the differentiation of seismic zones with discrete values of acceleration, the base acceleration values ranged from 0.20g to 0.30g with the exception of Morocco which had a value of 0.16g. These values are displayed in Table 1 of Section 4.1.5 of this article.

Local geology of the site and type of foundation: The soil types, considered equivalent in each code, were highly fractured rock, dense granular soils or hard cohesive soils characterized by a shear wave velocity (v_S) ranging from 750 m/s to 400 m/s.

Importance of building: As an apartment building, the importance (or use, or threat) level of the structure was considered "normal", which corresponds to an importance coefficient of unity, and therefore the seismic response was not amplified.

Seismic behaviour of the structure: For design purposes, it is necessary to take into account the inelastic behaviour of the structure. The *reduction factors* allow linear calculation tools to obtain a reasonable quantification of the actual response of the structure. In order to obtain the seismic forces reduced by ductility, the spectral ordinates are reduced by dividing them by a reduction factor. Its value depends, in general, on the structural system of the building and its ductility requirements.

The structural resistance, in this analysis, was provided both by a system of portal frames and a core of reinforced concrete walls, which were assumed to have medium ductility. The response reduction factors adopted in the analysis for each of the standards are listed in Table 1, which aims to highlight the significant differences that exist between the values of R for the same structural typology according to different standards.

Table 1 : Values of the factors that define the seismic activity

Country	Seismic Regulations	Concrete Regulations	a_b / g	R	S_{terr}	A_{calc}/g
Spain	NCSE – 02	EHE-08	0.23	3.0	1.023	0,196
Eurocode 8	EC – 8	Eurocode 2	0.23	3.5	1.20	0,197
Romania	P100 – 1	Eurocode 2	0.28	4.0	---	0,192
Bulgaria	DECR 2	Eurocode 2	0.27	4.0	---	0,169
Algeria	RPA – 99	BAEL-91	0.25	5.0	---	0,156
Morocco	RPS – 2000	BAEL-91	0.16	3.5	1.20	0,137
Costa Rica	CSCR – 02	ACI 318-08	0.33	4.0	---	0,156
Panama	REP – 04	ACI 318-08	0.25	5.0	---	0,160
Cuba	NC – 46	ACI 318-99	0.30	5.0	---	0,150
Dominican Rep.	M-001	ACI 318-99	0.25	5.0	1.20	0,127
Mexico	CFE – 93	ACI 318-99	0.25	4.0	---	0,160
Colombia	NSR – 98	ACI 318-99	0.30	5.0	1.20	0,150
Peru	E.030	ACI 318-99	0.30	5.0	1.20	0,180
Chile	NCh 433	ACI 318-99 Chile	0.30	5.1	---	0,165
Argentina	CIRSOC-103 1991	CIRSOC 201-05	0.25	5.0	---	0,150

a_b: basic acceleration (fraction of g)
R: reduction factor
S_{terr}: Terrain Coefficient (in some standards the effect of terrain is included in spectral ordinate)

A_{calc}: design acceleration, as fraction of g, defined as:

$$A_{calc} = \frac{a_b \cdot S \cdot \alpha(T)}{R} \qquad (1)$$

α (T): spectral ordinate defined by each standard

The damping coefficient of the structure was selected as 5% of critical damping in all cases.

Degree of regularity of the structure: The influence of the degree of irregularity, both in plan and elevation, can be included directly in the value adopted for the reduction factor, or by using factors that amplify the final value of the seismic response.

The studied building had no significant horizontal or vertical discontinuities resistant to its lateral loading configuration, therefore, the structure was considered as regular, both in plan and elevation. The coefficient regarding the type of structure was taken as unity and did not affect the seismic response.

Factor to reduce accidental loads: The combinations of the seismic loading with other forces that are applied to a structure depend upon both the applicable seismic regulations as well as the concrete code compatible with it.

Entering Data into the Program CYPECAD

All the aforementioned factors are entered into the dialog panel of each of the seismic standards of the program. Figure 1 shows the panel for the Algerian code as an example.

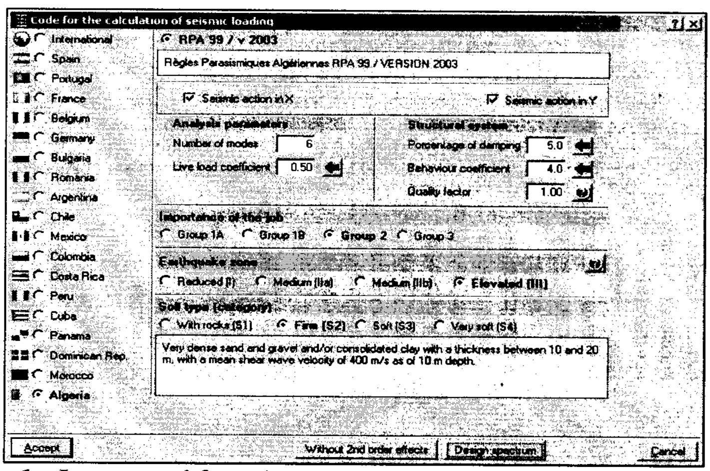

Figure 1 : Input panel for seismic data entry according to a seismic code

Analysis of Results

The construction requirements of the building were estimated in the form of forces and amounts of reinforcing steel. The analysis of the results obtained in the calculation of the building's resistance to earthquakes focuses on the comparison of these values.

Shear Stress at the Base of the Building

The program provides a list of forces on columns and walls separated by hypothesis and floor. The seismic loading is applied in two perpendicular directions, and considering different modes of vibration. A value representative of the seismic loading upon the model is taken as the total shear produced at the base of the building. The combination, in each direction of analysis, of the global shear on the ground floor for each of the vibration modes provided the value of maximum shear at the base of the building. Figure 2 shows the values obtained by the SRSS combination method.

Analysis of results: The calculated shear force at the base of the building is dependent on the design acceleration obtained from each code. Comparing the graphs of figure 2 with the values in table 1, an inverse relationship between the applied shear and the selected reduction factor is observed. For a similar base acceleration, the shear calculated with the European-African codes was greater than the values obtained from the North and South American codes. This is a result of the higher reduction factors specified in the American codes than in the European codes for structures with identical typology.

Also of note is the low value of shear obtained with the M-001 code of the Dominican Republic. This was due to the definition of the design spectrum in Section 6.4.3 of the code itself, which imposes an upper limit upon the spectral ordinates. Since Morocco is a region of lower seismicity, and hence, the structure was subjected to less seismic loading than structures located elsewhere, a lower value of shear was obtained than that from the other codes.

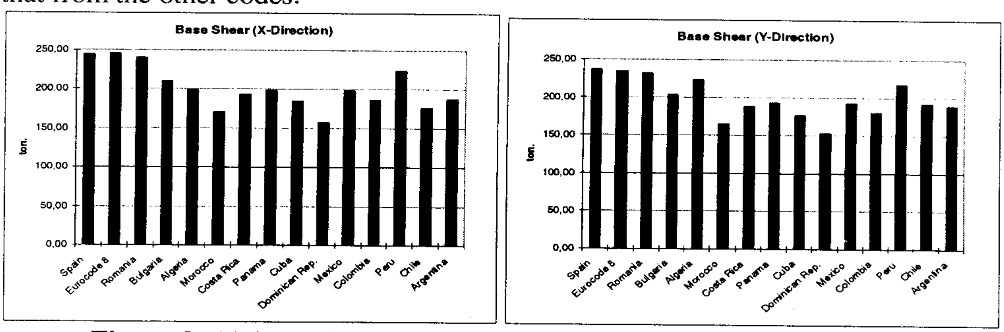

Figure 2 : Values of seismic shear resulting at the base of the building

Amounts of Steel Reinforcement

A comparison of the quantities of reinforcement obtained in each of the tests was performed by using the amount of reinforcing steel per element per floor, received as a result from CYPECAD. Figure 3 shows the total amount of reinforcement obtained for each of the considered seismic regulations.

Analysis of results: The total amount of reinforcement not only depends on the seismic loads applied to the structure, but reflects, above all, the reinforcement requirements set out in each of the seismic regulations and relevant concrete standards compatible with them.

In addition to comparing the total amounts of reinforcement required, an analysis was also made for the amounts of reinforcement required for specific building components. Figure 4 shows the individual reinforcement requirements for beams, columns, walls, and slabs.

The analysis of the reinforcement amounts was calculated using groups based on geographical proximity as well as the concrete code used in the calculation. On one hand, the data grouped with European standards has its corresponding concrete standard for each country (Spain, Romania, Bulgaria and Eurocode 8). On the other, for the countries of North Africa, the French concrete standard BAEL-91 (Algeria and Morocco) is used. Within the group for Southern and Central American codes, there are three subgroups based on concrete standard used: ACI 318-08 (Costa Rica and Panama), ACI 318-99 (Cuba, Dominican Republic, Mexico, Colombia and Peru) and other country-specific regulations (Chile and Argentina).

As shown in Table 1, higher reduction factors were used in the calculation for the American standards, which represents a greater reduction of the seismic design load, however, the reinforcement amounts obtained are similar or even greater than those of the European standards. This implies more stringent reinforcement requirements. In addition, it can also be noted that the ACI 318-99 is more conservative than the ACI 318-08.

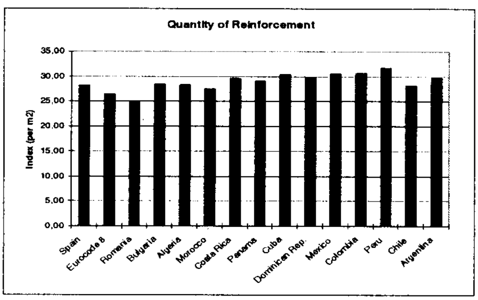

Figure 3 : Values of the total amount of reinforcement per m^2 of structure.

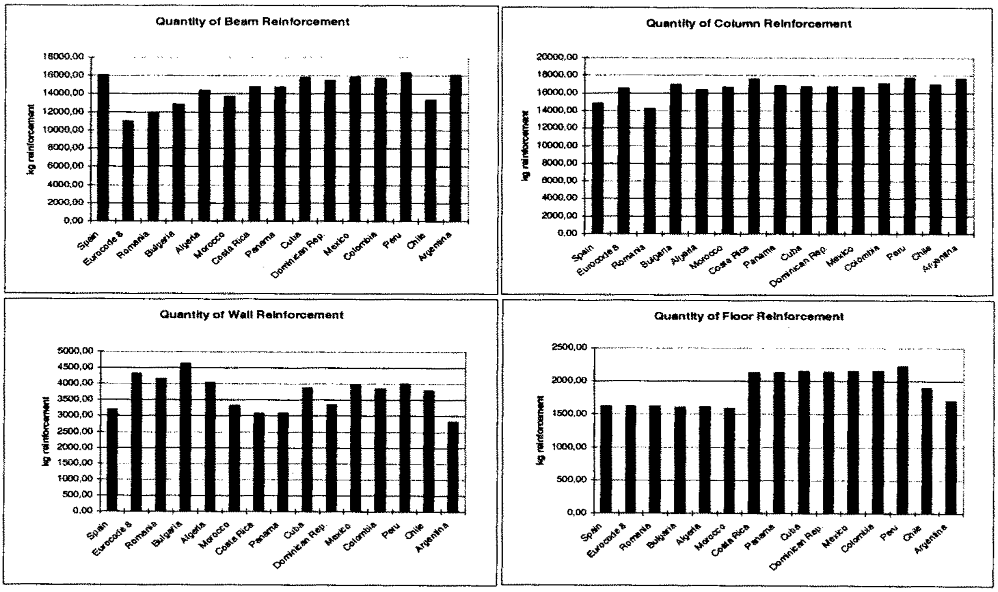

Figure 4 : The amount of reinforcement required for beams, columns, walls and slabs.

Reinforcement of beams. The quantity of reinforcement required in the North and South American codes exceeds the requirements set out in the European and African codes. With regards to the variability within each group, the American rates are extremely similar since their criteria for reinforcement are based on the provisions contained in the ACI-318 code. Meanwhile, the regulations from Europe and Northern Africa present a greater difference in values since the reinforcement requirements are based upon distinct concrete codes.

Similar to the American codes, the Spanish seismic regulations specify a quantity of reinforcement in beams greater than the other European codes. This is due to the requirements demanded in the case of elevated seismicity regarding the minimum longitudinal reinforcement of beams: 2Ø16 or 0.4% (ratio). Furthermore, skin reinforcement is required every 250mm.

Reinforcement of columns. Similar to the reinforcement of beams, the requirements for columns are very similar in all South American codes, while the European and North African codes present a greater variability. The reinforcement amount obtained from the American codes is greater than that obtained from the European codes.

Reinforcement of slabs and walls. There exists a clear distinction between the African-European standards and the American standards with regards to the required slab reinforcement, the latter having significantly higher requirements than the former. As for the assembly requirements for walls, the observed variability in the results is higher, but it can be established that the requirements of the European standards and those compatible with ACI 318-99 are higher than the rest.

Conclusion

For a meaningful comparison, the analysis tries to consider a similar seismic action in all cases. While the site and structural conditions are the same in every case, the definition of the seismic spectrum and the values of the factors that account for the aforesaid conditions differ depending on the code and generate different seismic actions. Hence, the first significant issue is that the analysis has to start from an action that will take different values depending on the considered code.

With regards to the structural reinforcement, not only does it depend on the forces produced by the actions to which the structure is subjected, but also upon the seismic requirements for reinforcement specified by each code. Although, for the considered conditions, the calculated shear is greater in the European codes, the quantity of steel reinforcement is greater in the American codes. Therefore, it can be concluded that the American codes are more restrictive than the European codes in this regard.

Finally, it has been demonstrated that the CYPECAD software excels as a calculation tool in its capacity to study and compare the results presented in this paper. With the use of a software implementation of a variety of seismic codes and reinforcement requirements for each code, such as CYPECAD, results are easily and immediately obtained by simply selecting the corresponding national code and introducing the parameters required therein to perform the seismic analysis.

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