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Comparison between Spectral Modal Dynamic Analysis and Equivalent Static Seismic Analysis

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Abstract: The study consists of analyzing and comparing the equivalent static behavior and the dynamic behavior, under seismic excitation, of a structure located in the city of Portoviejo (Republic of Ecuador). The building was designed for office occupancy, having five floors and being irregular in plan. The equivalent static analysis uses the Ecuadorian seismic code that defines the maximum acceleration of the soil on the construction site, the soil amplification coefficients, the type of importance of the building, the types of construction irregularity and the factor of reduction of the seismic resistance. In the dynamic analysis of the structure was used the modal analysis and to represent the seismic force, the response spectrum for accelerations. Additionally, a nonlinear static analysis (Pushover) was used to determine the behavior of the structure after overcoming the elastic regime going until the collapse. The results show the values of the basal shear forces, both for the equivalent static analysis and in the spectral modal analysis, demand/capacity curves and transverse displacements in the structure.

Keywords: seismic analysis, modal analysis, response spectrum, equivalent static seismic analysis, Ecuadorian seismic code.

1 Introduction

Seismic Analysis is not a normally studied subject in Civil Engineering courses in Brazil, given that there is no high seismic risk compared to neighboring countries such as Colombia, Peru or Venezuela. Earthquakes are usually caused by the movement of tectonic plates. These solicitations may cause a structure's collapse with the consequence of material losses, economic losses and, even, a human life's losses (Chopra [1]). Structural dynamics is one of the subjects in the scope of Civil Engineering which, due to the implementation of new calculation methods using computers, have had a huge evolution in recent years (Bazán [2]). In particular, seismic engineering has been one of the most developed areas, and it is common to carry out dynamic analyzes to assess the seismic performance of structures with a level of detail that was not possible a few years ago (Belejo [3]). The Republic of Ecuador is in a region of high seismic risk due to its proximity to the junction between two large tectonic plates, the Nazca Plate and the South American Plate. The study building is located in the city of Portoviejo, in the coastal region of Ecuador, and was designed to be occupied by offices, with five floors and an irregular floor plan. The basic structure is made of reinforced concrete and consists of columns, beams and slabs. The building also has a core of reinforced concrete stairs and the outer walls are built with bricks. The objective of the article is to perform an equivalent static seismic analysis of the structure and a dynamic analysis by the response spectrum, making a comparison between these analyzes according to the Ecuadorian code (NEC-SE-DS [4], NEC-SE-CG [5]). In addition, a non-linear analysis (Pushover) was performed, which allows to estimate the seismic capacity of the structure and to verify its performance under earthquakes. This analysis consists of applying a lateral load incrementally, with a defined pattern, until the structure reaches a certain boundary state.

2 Equivalent Static Forces

The Equivalent Static Method takes into account the effects of seismic actions by applying of a set of lateral forces to the structure.

For the calculation of basal shear force (V) by the equivalent static seismic analysis described in (NEC-SE-DS), eq. (1) is used as shown below:

$$V = \frac{IS_a(T_a)}{R\emptyset_p\emptyset_E}W \tag{1}$$

Where, V: basal shear force; I: building importance coefficient; S_a (T_a): elastic response spectrum of accelerations; T_a: fundamental vibration period of the structure; W: reactive seismic load; R: seismic resistance reduction factor; $\emptyset_p$ and $\emptyset_E$: are coefficients of regularity in plant and elevation respectively.

Determination of the vibration period, the approximate fundamental vibration period of the structure (T_a), for each main direction, will be estimated from eq. (2):

$$T_a = C_t h_n^{\propto} \tag{2}$$

Where, T_a: fundamental vibration period of the structure; C_t: coefficient that depends on the type of building; h_n: maximum height of the building of n floors, measured from the base of the structure, in meters; α is a factor called impedance of the semi space (ground).

Vertical distribution of lateral seismic forces: The distribution of vertical forces is similar to a linear (triangular) distribution (eq. (3)):

$$V_x = \sum_{i=x}^{n} F_i \tag{3}$$

Where, V_x: total shear force in the floor x of the structure; F_i: lateral force applied to the floor i of the structure. The basal shear force must be distributed at the height of the structure, using the eq. (4):

$$F_x = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k}V \tag{4}$$

Where, F_x: lateral force applied to the floor x of the structure; V: basal shear force; n: number of floors in the structure; w_x: weight corresponding to the pavement x of the structure, being a fraction of the reactive seismic load W; w_i: weight corresponding to the pavement i of the structure, being a fraction of the reactive seismic load W; h_x: floor height x of the structure; h_i: Floor height i of the structure; k: Coefficient related to the vibration period of the structure (T_a).

3 Modal Analysis

For the seismic response, the Spectral Modal Analysis Method was used. The frequencies and modes of vibration of the structure are calculated and, for the seismic response, the so-called modal superposition is performed using the acceleration response spectrum to take into account the design earthquake. The seismic response was assessed using SAP2000-v20. This program, in the case of dynamic analysis, allows to obtain several parameters such as frequencies and modes of vibration, the displacements and forces of seismic design, in addition to other parameters corresponding to the seismic behavior of the structure (Computer and Structure [6]).

4 Response Spectrum

Spectral analysis assesses design spectra to calculate structural responses for external actions. The elastic seismic spectrum of the project represents the maximum responses of the structure to seismic excitation (Gupta [7]). The Ecuadorian seismic code defines the elastic response spectrum of the accelerations (S_a), for the design earthquake, as a fraction of the acceleration of gravity, as shown in Fig. 1. For the construction of the elastic seismic spectrum of the project, we use characteristic values specific of the region where the structure is located and the seismic zoning detailed in the Ecuadorian seismic code (NEC-SE-DS [4]).

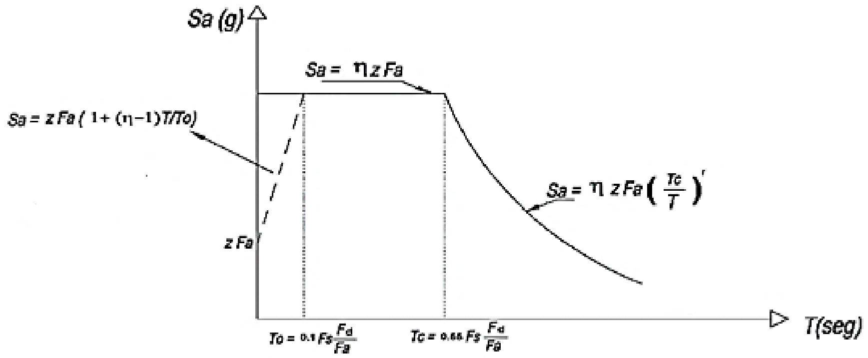


Figure 1. Elastic seismic spectrum of acceleration to represent the design earthquake (Source: NEC-SE-DS [4]).

The aforementioned response spectrum obeys a damping fraction with respect to the critical of 5%, and is obtained through eq. (5) and eq. (6), valid for periods of vibration of the structure (T_a) belonging to two intervals:

para $0 \leq T \leq Tc$;

$$S_a = \eta\ Z\ F_a \tag{5}$$

and for $T > Tc$;

$$S_a = \eta\ Z\ F_a \left(\frac{T_c}{T}\right)^r \tag{6}$$

S_a is the elastic response spectrum of accelerations, expressed as a fraction of the acceleration of gravity; η is the ratio between spectral acceleration S_a (T = 0.1s) and PGA (peak ground acceleration) for the selected return period; r is the factor used in the elastic design spectrum, whose value depend on the geographic location of the project. Therefore, in this work, r = 1.5 according to the study of soil mechanics for the type of soil profile E. Z, is the maximum acceleration in rock expected for the design earthquake, expressed as a fraction of the acceleration due to gravity (g). F_a, F_d, and F_s are the soil amplification coefficient. T or T_a is the fundamental period of vibration of the structure. Equation (7) or T_0 is the limit period of vibration in the elastic seismic spectrum of accelerations that represents the design earthquake. T_c (eq. (8)) is the vibration limit period in the elastic seismic spectrum of accelerations that represents the design earthquake:

$$T_0 = 0.10 * F_s * \frac{F_d}{F_a} \tag{7}$$

$$T_c = 0.55 *\ F_s * \frac{F_d}{F_a} \tag{8}$$

5 Pushover Analysis

The Pushover Analysis considers the nonlinear behavior of the structure. Relates the overall response of the structure to an equivalent structure of a degree of freedom. Sequentially traces the yielding and the collapse of the elements, as well as the overall capacity of the structure in the face of seismic action. It allows the assessment of seismic performance for different limit states. For each degree of freedom, a force-displacement curve can be defined, providing the values of the flow and deformation following the yielding. This can be seen in Fig. 2.

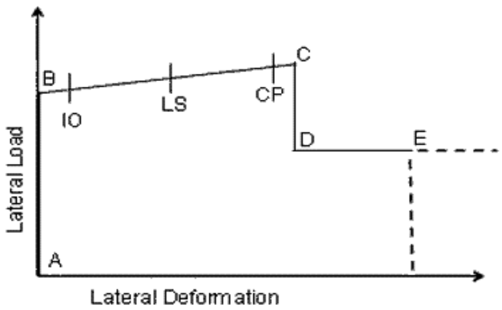


Figure 2. Force-displacement curve A-B-C-D-E-F (Source: Computer and Structures [6]).

The following points must be taken into account: Point A must always be at the origin. Point B represents the flow. Point C represents the ultimate capacity in the Pushover analysis. Point D represents the residual resistance for the Pushover analysis. Point E represents the total failure of the structure. In addition, additional deformation measures can be specified in points IO (Immediate Occupation), LS (Life Safety) and CP (Collapse Prevention). This is additional information reported in the results analysis and used for performance-based projects. These data have no effect on the behavior of the structure (FEMA [8], ATC [9]).

6 Results and Discussion

The analyzed structure was located in the city of Portoviejo, in the coast region of Ecuador. This city is located in seismic zone VI with seismic zone factor Z = 0.50g. The type of soil at the base of the building corresponds to a rigid rock soil with an average shear wave speed of Vs = 360 m/s (Portoviejo [10]). The 5-story building presents regularity in elevation ($\emptyset_e$ = 1) and irregularity in plan ($\emptyset_p$ = 0.9); a structural system with reinforced concrete spatial frames with the factor of reduction of seismic resistance (R = 6). The building will be used for offices with the building's importance factor (I = 1).

The dimensions of the beams and columns are shown in Tab. 1, while the types of loads and corresponding values are presented in Tab. 2. The live load was defined according to the values defined in (NEC-SE-CG [5]). Ten load combinations were created in the SAP 2000 v20, both for the equivalent static analysis and for the spectral modal analysis.

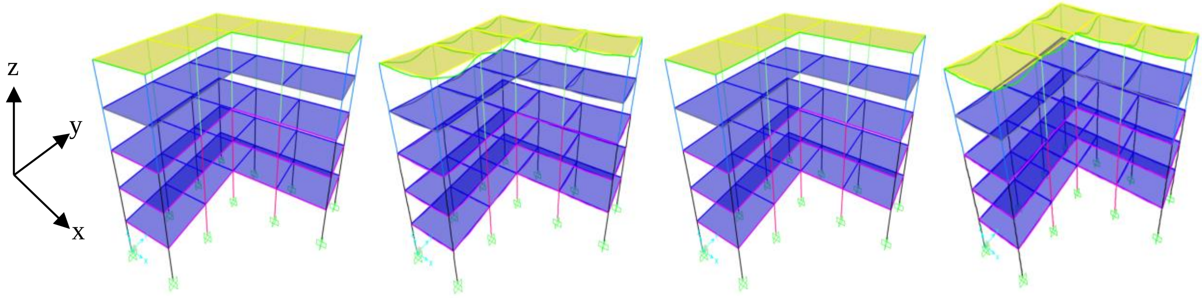
Table 1. Elements of structure

Element	Dimensions (mxm)	Color
Beam	0.40 x 0.25	
Beam	0.50 x 0.30	
Beam	0.60 x 0.40	
Column	0.45 x 0.45	
Column	0.50 x 0.50	
Column	0.60 x 0.60	
Column	0.65 x 0.65	

Table 2. Type of loads

Type of loads	Slab	Slab roof
Live (Kgf/m²)	240	70
Dead (Kgf/m²)	240	240

In the static analysis, seismic forces were defined by applying of a set of lateral forces to the structure. In the spectral modal analysis, the earthquake load was defined using the Response Spectrum function of SAP 2000 v20. Fig. 3 shows the front view of the undeformed and deformed structure for the equivalent static analysis and for the spectral modal analysis.



Static Equivalent Analysis Spectral modal dynamic Analysis

Figure 3. Front view of the undeformed and deformed structure

The verification of relative displacements variations between floors (drifts), in both directions and for both analyzes, is shown in Table 3. The drifts comply with the requirement of the Ecuadorian code (NEC-SE-DS [4]) by presenting values below 0.020. The height between floors is 2.80 m.

Table 3. Displacements (D) and checking relative displacements (drifts)

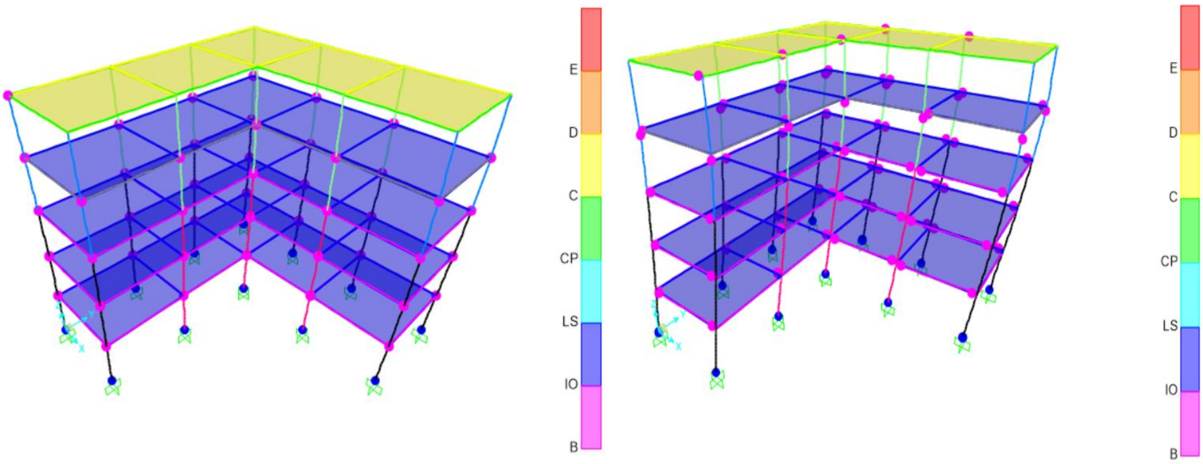
	Static Equivalent Analysis				Spectral modal Analysis			
Floor	Dx (cm)	Drift x	Dy (cm)	Drift y	Dx (cm)	Drift x	Dy (cm)	Drift y
5	2.13650	0.0018	1.91573	0.0016	0.77595	0.0000	0.59699	0.0000
4	1.62419	0.0020	1.47305	0.0017	0.77185	0.0006	0.59906	0.0005
3	1.07095	0.0015	0.99382	0.0014	0.59885	0.0008	0.46509	0.0006
2	0.64518	0.0015	0.6122	0.0014	0.38860	0.0008	0.30683	0.0006
1	0.23349	0.0008	0.23352	0.0080	0.15406	0.0006	0.12597	0.0004

Table 4 shows the basal shear forces obtained in the two analyzes and in both main directions.

Table 4. Basal shear forces

Direction	Basal shear forces (kN)	
	Static Equivalent Analysis	Spectral modal Analysis
V_x	1667.279	1048.258
V_y	1667.278	1048.186

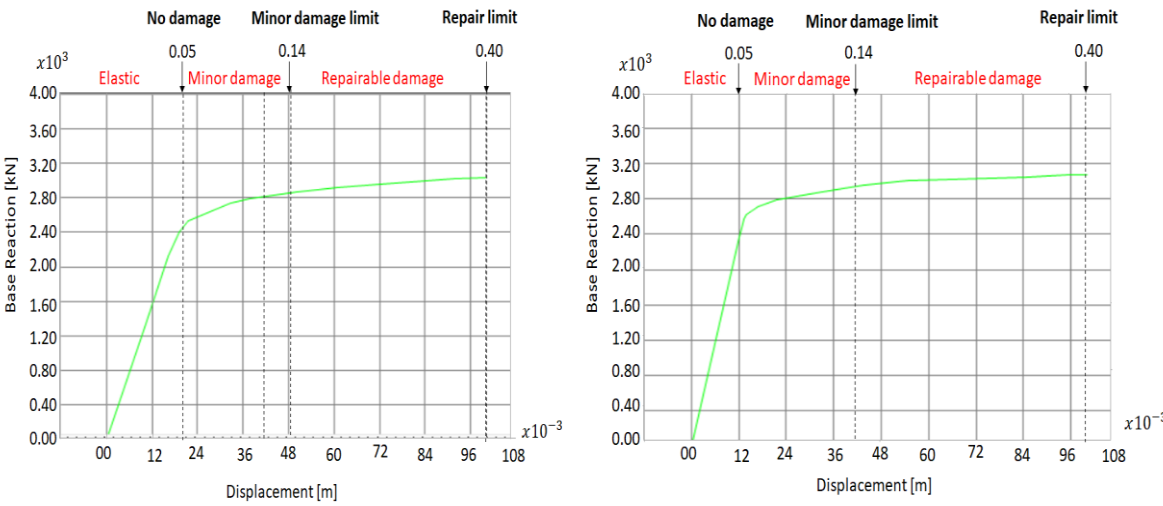
As can be seen in Fig. 4, the sequence of failures of the structure under study starts first whit the degradation in the beams and then in the columns.



Deformed shape (push)-Step12 static analysis Deformed shape (push)-Step12 dynamic analysis

Figure 4. Inelastic configurations

The methodology of the Pushover analysis aims to determine the behavior of the structure after exceeding the elastic region and until the moment of the structural failure. In the curve of Fig. 5 below (basal shear force vs. displacement), elastic and inelastic limits are defined in each case under analysis. According to Ghobarah [11], the damages are defined by the following limits: damages less than 0.05, the structure behave elastically; damage between 0.05 to 0.14, minor damage is observed (hinges in beams) and damage between 0.14 to 0.40, defines repairable damage (hinges in beams and columns).



Static analysis

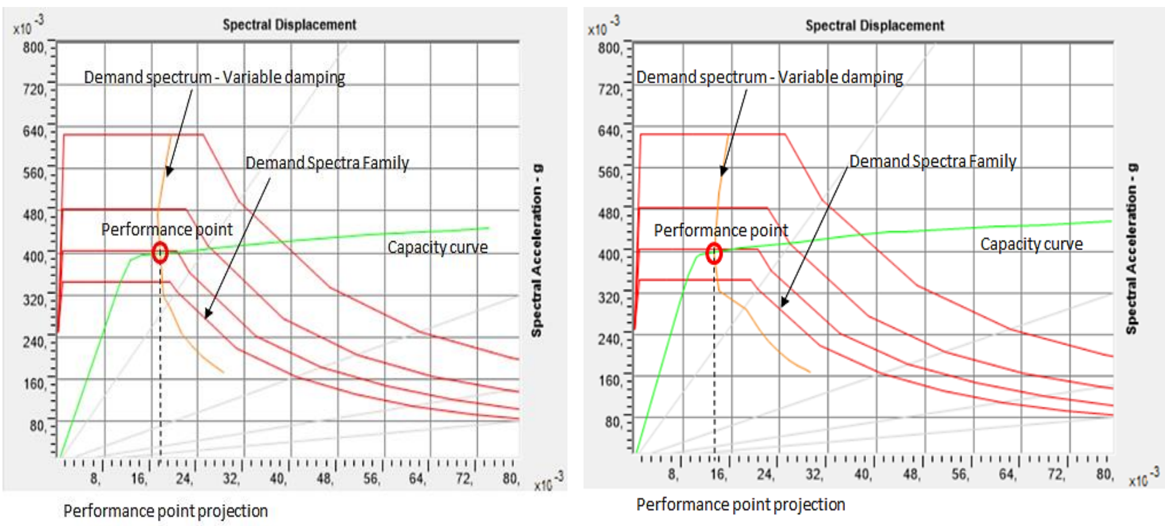
Dynamic analysis

Figure 5. Basal shear force vs monitored displacement (Source: Authors)

In Figure 6, the performance point results from the intersection between the demand spectrum (seismic requests) and the capacity curve (structure arrangement to resist loads).

The capacity curve of a structure is similar to the stress-strain curve of a material, where there is initially a section of linear behavior, until a yield stress is reached. After that there is a degradation until finally the material (or the structure) fails.

In the next figure, we can easily determine the coordinates of the performance point. The performance point's values provide an answer to the overall structure. The performance point refers to the demand for displacement of a structure when it is subjected to an earthquake.



Static analysis

Dynamic analysis

Figure 6. Performance point (Source: Authors)

Evaluating the demand-capacity curves of the structure in the study, it is observed that the performance point projection occurs in the static analysis in 0.0175 and for the dynamic analysis it occurs in approximately 0.014.

7 Closing Remarks

The floors displacements were smaller in the case of the spectral modal analysis compared to the analysis by the equivalent static forces and the relative displacements between the floors (drifts), for the two analyzes, were always less than the limit of 0.020 specified in the Ecuadorian seismic code.

The Pushover Analysis showed that the maximum displacement of the structure cannot exceed 0.10 m approximately. Above this value, the inelastic hinges on the structural elements begin to increase, until the collapse. It also showed that the sequence of failures of the structure under study is in accordance with what was desired, with structural degradation beginning to occur first in the beams and then in the columns.

The performance curves show that for displacements smaller than 0.02 m (equivalent static analysis), the structure behaves elastically. From this point the structure enters the plastic region. In the dynamic case, for displacements smaller than 0.013 m, the structure behaves elastically. From this point the structure enters the plastic region. In the example, it is shown that the structure subjected to the earthquake presents repairable damages and at the same time life safety (LS) is considered as a limit.

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