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Spectral modal dynamic analysis of a reinforced concrete building in Acre, Brazil

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Abstract. This study aims to analyze the structural performance of a building under seismic action using spectral modal analysis, with the aid of the SAP2000 software and in accordance with Brazilian codes NBR 6118:2023, NBR 6120:2019, and NBR 15421:2023. Results related to base shear, modal participation, displacements, and verification of structural elements are presented and compared with equivalent static analysis, highlighting the importance of adopting dynamic methods for the seismic design of irregular structures.

Keywords: seismic analysis, equivalent static method, spectral modal method, Brazilian seismic code

1 Introduction

One of the most important applications of structural dynamics theory is the analysis of structural response to ground motions caused by earthquakes [1]. Seismic analysis of buildings in Brazil has become increasingly important in recent years due to updates in local technical codes and the recognition of seismic risks in various regions, even those with low to moderate levels of seismic activity. Brazilian code NBR 15421:2023 [2], in particular, establishes procedures for designing earthquake-resistant structures based on structural behavior, requiring the use of dynamic methods in specific situations, such as in cases of structural irregularities.

In this context, spectral modal analysis emerges as a more advanced technique compared to the equivalent static method, especially for structures with irregular geometries or those prone to torsion. This study focuses on the dynamic evaluation of a 12-story reinforced concrete building located in the state of Acre, Brazil, a region classified as seismic zone 4 according to NBR 15421. The building has a U-shaped floor plan, a common arrangement in commercial constructions.

The objective of this study is to compare the results obtained by the equivalent static and modal spectral methods for this structure, evaluating displacements, drifts, and base shear forces in accordance with the criteria of the Brazilian seismic code.

2 Analysis Methodology

2.1 Equivalent Static Analysis

The equivalent static analysis method, as established in NBR 15421:2023 — *Design of seismic resistant structures*, involves replacing the dynamic action of an earthquake with equivalent horizontal forces applied at each floor of the structure. These forces are proportional to the mass and height of each level and simulate the inertial effects caused by an earthquake. The total horizontal force acting at the base of the structure (H) is obtained by eq. (1) :

$$H = C_s \cdot W \tag{1}$$

Where, H is the total horizontal force (kN);); W is the total seismic weight, including permanent loads plus 25% of variable loads; C_s is the seismic response coefficient, defined in eq.(2):

$$C_s = \frac{2.5 \cdot \left(\frac{a_{gs_0}}{g}\right)}{\frac{R}{I}} \tag{2}$$

Where, a_{gs_0} is the spectral acceleration for period 0.0s; g is the gravitational acceleration (9.81 m/s²); R is the response modification coefficient; e I is the importance factor.

The code establishes a minimum value for C_s and adjustments based on the fundamental period (T_1).

The total horizontal force at the base is distributed vertically to each elevation of the structure according to eq. (3):

$$F_x = C_{vx} \cdot H \tag{3}$$

Where C_{vx} is the vertical distribution coefficient calculated by eq. (4):

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

Where, w_x and w_i are the portions of the effective weight corresponding to elevations x and i; h_x and h_i are the heights from the base to elevations x and i, respectively and e k is the distribution exponent related to the natural period of the structure.

2.2 Seismic Analysis by the Spectral Modal Method

The spectral modal analysis method is a dynamic technique that considers the structural response to seismic excitation, taking into account vibration modes. This approach allows for a more accurate representation of structural response, especially for buildings with complex geometries or stiffness variations. In this study, 20 vibration modes were considered to ensure that more than 90% of the modal mass was captured in each analysis direction (X and Y). Modal combination was performed using the SRSS (Square Root of Sum of Squares) rule, with directional combinations of 100% in X and 30% in Y, and vice versa. The seismic action for this project was defined according to NBR 15421 shown in Figure1, adopting the elastic response spectrum of the project, with the characteristic parameters detailed in Section 3.1.

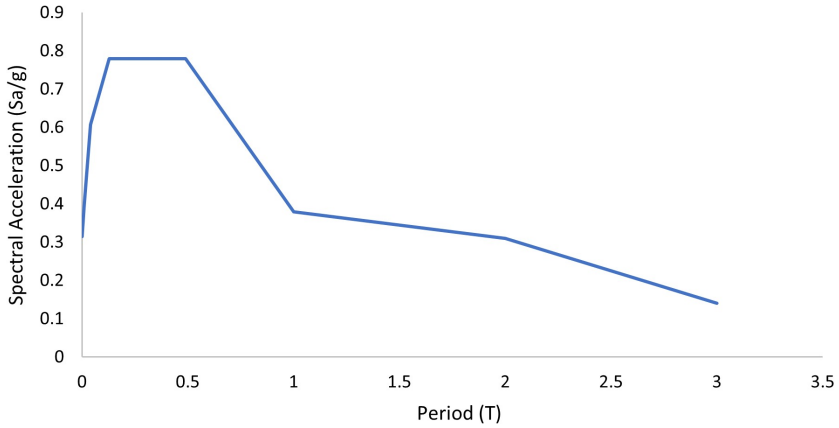


Figure 1. Definition of the response spectrum function

3 Structure to be analyzed

3.1 Building characteristics

The modeled building, located in the state of Acre, is located in seismic zone 4, classified as category C. It has a characteristic design acceleration of $a_g = 0.15g$ and is positioned on a site of class E, categorized as soft

soil. It has a category of use II(commercial), which translates into a factor of importance $I = 1.25$. A basic earthquake-resistant system of reinforced concrete frames with code detailing was used, indicating a response modification coefficient $R = 3$, an overstrength coefficient $\Omega_0 = 3$, and a displacement amplification coefficient $C_d = 2.5$.

The building has 12 stories, with a floor-to-floor height of 3.0 meters, resulting in a total height of 36 meters. This building is intended for commercial use and has an irregular U-shaped floor plan.The three-dimensional model was designed with rigid diaphragms at each floor level and fixed supports.

3.2 Structural Configuration

The structural elements were defined with materials according to NBR 6118:2023 [3]. For reinforced concrete, concrete with a characteristic strength $f_{ck} = 40\,\mathrm{MPa}$, elastic modulus $E_c = 35.4\,\mathrm{GPa}$, and specific weight of $25\,\mathrm{kN/m^3}$ was adopted. The reinforcement was defined using CA-50 steel, with a yield limit $f_{yk} = 500\,\mathrm{MPa}$, elastic modulus $E_s = 210\,\mathrm{GPa}$, and specific weight of $78\,\mathrm{kN/m^3}$. Table 1shows the properties of the assigned sections. Variable loads were also defined according to NBR 6120 [4] and are shown in Table 2.

Table 1. Structural element sections

Element	Dimensions (m)
Beam	0.40 x 0.20
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
Solid slab	thickness = 0.15

Table 2. Variable loads

Load type	Slab
Variable (kN/m²)	2.5

The three-dimensional model was developed to represent the actual structure of the analyzed commercial building, including the distribution of the adopted structural sections and the geometric configuration in plan and elevation. Figure 2 shows an overview of the structural model in SAP2000 [5].

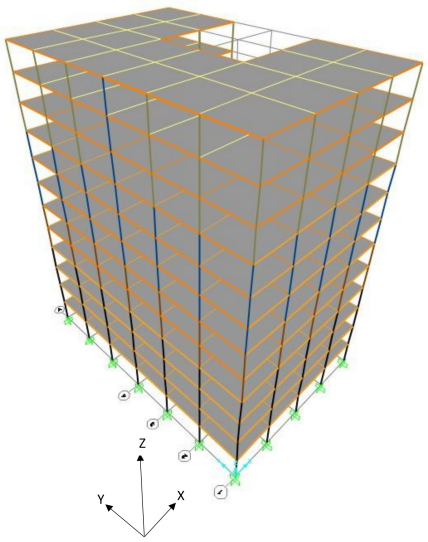


Figure 2. Three-dimensional view of the structural model

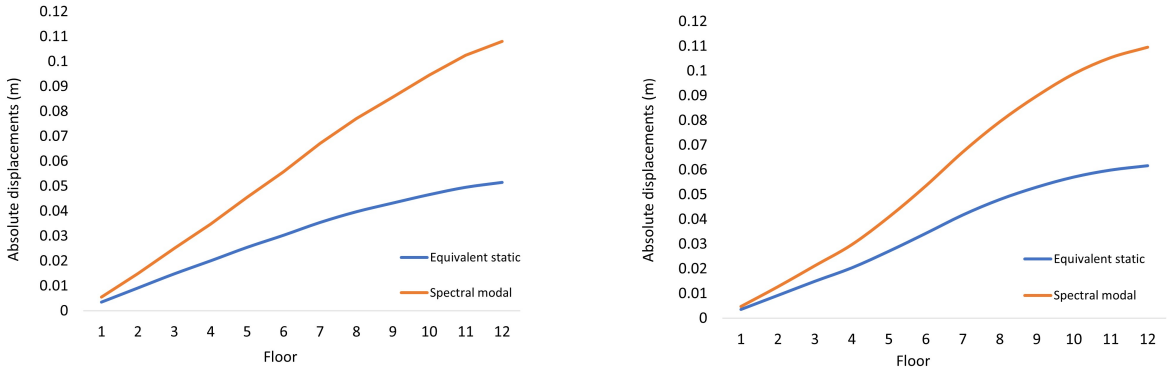
4 Results

The results were analyzed based on three main criteria: absolute displacements, relative displacements, and base shear. Below are the comparative data between the equivalent static analysis and spectral modal analysis methods. Table 3 presents the absolute displacements at each floor. For the verification of relative displacements, the difference between absolute displacements of two consecutive floors was considered. For structures of category of use II, the limit for relative displacements is $\Delta_x \leq 0.015 \cdot h_{sx}$, where h_{sx} is the height between floors, in this case 3.0 m, resulting in a limit value of 0.045. The obtained results show that the displacements are within the normative limits, indicating good overall performance of the structure under the considered seismic action.

Table 3. Comparison of absolute displacements (D_x and D_y) and relative displacements (Δ_x and Δ_y)

Floor	**Equivalent Static Analysis**				**Spectral Modal Analysis**			
	D_x (m)	Δ_x	D_y (m)	Δ_y	D_x (m)	Δ_x	D_y (m)	Δ_y
1	0.00353	0.00353	0.00353	0.00353	0.00555	0.00555	0.00470	0.00470
2	0.00920	0.00567	0.00922	0.00568	0.01499	0.00944	0.01270	0.00799
3	0.01486	0.00566	0.01492	0.00570	0.02501	0.01002	0.02119	0.00849
4	0.02009	0.00522	0.02036	0.00543	0.03483	0.00982	0.02972	0.00853
5	0.02548	0.00539	0.02706	0.00670	0.04557	0.01074	0.04086	0.01114
6	0.03032	0.00483	0.03428	0.00722	0.05575	0.01017	0.05346	0.01260
7	0.03544	0.00511	0.04172	0.00743	0.06711	0.01136	0.06717	0.01370
8	0.03973	0.00429	0.04797	0.00624	0.07716	0.01004	0.07939	0.01222
9	0.04323	0.00349	0.05298	0.00501	0.08574	0.00858	0.08980	0.01040
10	0.04660	0.00337	0.05704	0.00405	0.09451	0.00876	0.09875	0.00895
11	0.04953	0.00292	0.05986	0.00282	0.10253	0.00801	0.10532	0.00657
12	0.05149	0.00195	0.06163	0.00176	0.10804	0.00551	0.10953	0.00421

In Figure 3 shows the graph of absolute displacements for each floor of the analyzed building. It is observed that absolute displacements progressively increase with the elevation of the floors, being more pronounced in the spectral modal method compared to the equivalent static method.



X Direction Y Direction

Figure 3. Comparison of absolute displacements in different directions.

The base shear force was determined for both analysis methods. In the equivalent static analysis, the value was obtained from the total horizontal reaction at the base of the structure, calculated based on the effective weight and seismic coefficients established by the code. In the spectral modal method, the base shear force was obtained

directly from the SAP2000 program, using the SRSS modal combination rule, considering the sum of the horizontal components in the X and Y directions. Table 4 presents the comparative values of the base shear force obtained from the two methods.

Table 4. Basal shear force

Analysis method	X Direction (kN)	Y Direction (kN)
Equivalent static	7671.425	7671.425
Spectral modal	7716.627	6553.655

5 Final considerations

The results show that the displacements obtained by the spectral modal method were generally higher than those from the equivalent static analysis. This is likely due to the irregularity of the building.

In both methods, the relative displacements remained within the limits established by the seismic code for structures of Category of Use II (commercial buildings).

According to NBR 15421, the base shear force obtained by the spectral modal analysis method must be compared with the basal shear force determined by the equivalent static method, meeting the criterion V_{din} as a minimum $0.85\,V_{est}$. In this study, this correction was not necessary. Thus, it is verified that the spectral modal method meets the normative requirement in both horizontal directions.

It is concluded that, although the equivalent static method is a practical tool for initial estimates, the spectral modal method provides a more realistic representation of the dynamic behavior of the structure, especially for irregular buildings. Therefore, the use of the spectral modal method is recommended for the earthquake-resistant design of structures with complexity in plan and/or height.

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