Computational Modeling for Evaluation of Plane Frames in Seismic Zones

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Abstract. Seismic events, also known as earthquakes, induce dynamic effects on structures due to the abrupt ground movement, potentially leading these structures to collapse. These earthquakes are often associated with the movement of tectonic plates and primarily occur in regions near the edges of these plates, where interactions are more intense. However, a particular category of earthquakes is called 'induced seismic events', triggered by human activities such as mining, natural resource extraction, and fluid injection into the ground. There has been an increase in these earthquakes in some countries, raising concerns among authorities, especially in urban areas. In this context, our work aims to present a computer program for the dynamic analysis of plane frames, focusing on the structural behavior of such frames under the influence of seismic events. We consider seismic actions as stipulated in the Brazilian standard NBR 15421/23. The results obtained are essential for understanding the behavior of the analyzed structures. They are necessary to ensure proper structural design, thereby providing greater safety when these structures are subjected to such actions.

Keywords: Computational Modeling, Seismicity, Dynamic analysis.

1 Introduction

Earthquakes, known as seismic tremors, are primarily caused by the relative movement of tectonic plates. This movement generates stress where the plates meet, accumulating energy until, upon reaching the rocks' resistance limit at the contact point, there is a sudden release of stored energy in the form of seismic waves. Reid [1] was the first to describe this mechanism in his report on the 1906 earthquake in California. According to Shearer [2] and McGarr et al. [3], in addition to plate tectonic movement, other factors such as human activities can also trigger seismic events, including dams, extraction and injection of fluids or gases into the ground, and mining.

According to Soriano [4], earthquakes are dynamic, unpredictable, and highly destructive events. Ground motion during an earthquake can cause buildings to collapse, resulting in significant material damage and human lives lost. Therefore, structural engineers must develop earthquake-resistant structures to ensure that constructions in seismic hazard zones can withstand these movements.

The structural analysis of these buildings involves assessing seismic risk, which Bommer and Stafford [5] define as the combination of seismic hazard, exposure, and vulnerability. Seismic hazard refers to the intensity of the earthquake and its destructive potential. According to Datta [6], determining seismic hazard is complex and can be done through deterministic or probabilistic approaches to estimate the most likely ground motion.

Structural engineers rely on regulatory documents that guide the process to determine seismic risk. In Brazil, the standard NBR 15421/23 [7] defines the procedures and requirements for assessing structural safety against seismic actions. This study aims to dynamically and linearly model plane frames under seismic action, applying ground motion records following NBR 15421/23 guidelines.

2 Structural analysis

Soriano [4] states that earthquakes can induce nonlinear effects in structures. However, linear analyses can still be conducted and corrected to account for nonlinear effects, thereby continuing to provide reliable results. This is why, as noted by Williams [8], linear analysis is widely used in seismic studies. Although standards like NBR 15421/23 allow static seismic analyses by imposing equivalent horizontal forces, seismic action is dynamic. Therefore, for a precise analysis of structures under seismic effects, it is essential to understand their dynamic behavior.

Next, we will discuss basic concepts of structural dynamics and methodologies to obtain structural response under seismic effects, as described in the literature and the standard.

2.1 Dynamic of the structures

For a linear dynamic analysis, it is essential to understand three properties of the structure: stiffness, damping, and mass. Stiffness (k) relates to the relationship between displacement and force. For a given displacement, stiffness is the property of the structure responsible for generating a restoring force that equals the product of displacement and structural stiffness. According to Williams [8], damping (c) can be understood as internal mechanisms that dissipate energy from the structure when it undergoes motion. Finally, combining these insights with the mass distribution (m) of the structure allows for a proper structural analysis using

$$f(t) = kx + c\dot{x}(t) + m\ddot{x}(t) \quad (1)$$

where $x(t)$, $\dot{x}(t)$ and $\ddot{x}(t)$ are displacement, velocity, and acceleration, respectively. Equation (1) is known as the equation of motion for a single-degree-of-freedom system, where $kx(t)$ represents the elastic force, $c\dot{x}(t)$ damping force, and $m\ddot{x}(t)$ inertial force.

For earthquakes, where the foundation undergoes displacement without an external force causing it, we have the following equation:

$$kw(t) + c\dot{w}(t) = -m\ddot{x}(t) \quad \text{or} \quad kw(t) + c\dot{w}(t) + m\ddot{w}(t) = -m\ddot{x}_{\mathrm{g}}(t) \quad (2)$$

where $w(t) = x(t) - x_g(t)$ is the relative displacement and $f(t) = -m\ddot{x}_g(t)$ is the equivalent seismic force.

For a system with multiple degrees of freedom, the equation becomes:

$$\boldsymbol{Kx}(t) + \boldsymbol{C\dot{x}}(t) + \boldsymbol{M\ddot{x}}(t) = \boldsymbol{F}(t) \quad (3)$$

in which $\boldsymbol{K}$, $\boldsymbol{C}$ e $\boldsymbol{M}$ are the stiffness, damping, and mass matrices of the structure, respectively. The vectors $\boldsymbol{x}(t)$, $\dot{\boldsymbol{x}}(t)$ and $\ddot{\boldsymbol{x}}(t)$ contain the displacement, velocity, and acceleration of each degree of freedom, and $\boldsymbol{F}(t)$ is the vector of external forces.

2.2 Stiffness, mass and damping matrices

The structure matrices in eq. (3) can be constructed by assembling the matrices of the elements that compose them. Once the element matrices are obtained, they contribute to each degree of freedom associated with them. The plane frame element has 6 degrees of freedom, with 3 degrees for each element node, as illustrated in Fig. 1.

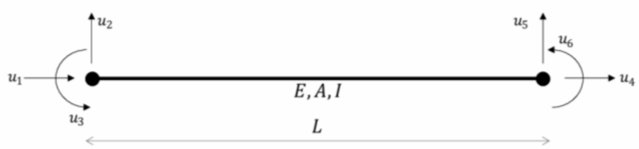


Figure 1. Graus de liberdade do elemento de pórtico plano

The stiffness and mass matrices of the element can be obtained through the formulation of the finite element method. The derivation of these matrices is beyond the scope of this work; therefore, only the results are presented in eqs. (4) and (5), representing the stiffness and consistent mass matrices.

$$\boldsymbol{K} = \frac{1}{L^3}\begin{bmatrix} EAL^2 & 0 & 0 & -EAL^2 & 0 & 0 \\ 0 & 12EI & 6EIL & 0 & -12EI & 6EIL \\ 0 & 6EIL & 4EIL^2 & 0 & -6EIL & 2EIL^2 \\ -EAL^2 & 0 & 0 & EAL^2 & 0 & 0 \\ 0 & -12EI & -6EIL & 0 & 12EI & -6EIL \\ 0 & 6EIL & 2EIL^2 & 0 & -6EIL & 4EIL^2 \end{bmatrix} \tag{4}$$

$$\boldsymbol{M} = \frac{m'L}{420}\begin{bmatrix} 140 & 0 & 0 & 70 & 0 & 0 \\ 0 & 156 & 22L & 0 & 54 & -13L \\ 0 & 22L & 4L^2 & 0 & 13L & -3L^2 \\ 70 & 0 & 0 & 140 & 0 & 0 \\ 0 & 54 & 13L & 0 & 156 & -22L \\ 0 & -13L & -3L^2 & 0 & -22L & 4L^2 \end{bmatrix} \tag{5}$$

where, L, EA, EI and m' are length, axial rigidity, flexural rigidity and linear mass of the element.

The structure's damping is a parameter that is difficult to obtain directly; therefore, handling it through the so-called damping ratio is practical. As stated by Williams [8], a damping ratio of 5% is typically adopted.

2.3 Seismic analysis

Deterministic seismic analysis can be conducted using estimates derived from the response spectrum, which are graphs depicting the approximate maximum response of a single-degree-of-freedom system as a function of the system's period. Alternatively, seismic analyses can utilize motion records applied to the base or equivalent horizontal forces, as noted by Soriano [4]. Motion records are typically obtained from an accelerogram, a graphical representation of the ground acceleration over time, from which velocity and displacement histories are obtained through numerical integration. Figure 2 below illustrates an example of an accelerogram record from the 1940 El Centro earthquake, with the data available on Vibrationdata.com [9].

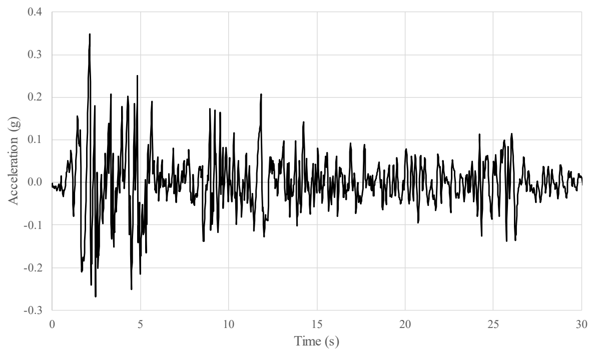


Figure 2. Accelerogram El Centro earthquake (N-S component)

In accelerogram-based analysis, it is crucial to use local response spectra as a reference, as established by design standards. Obtaining accelerograms compatible with local seismic activity can be challenging due to limited historical earthquake data, and it is common for standards to require a minimum of three accelerograms for a complete structural analysis, as specified in NBR 15421/23. Artificial accelerograms can be employed to address this limitation. There are several methodologies for generating them, and many of them are based on the principle that periodic functions can be represented as superpositions of sinusoidal waves:

$$a(t) = I(t)\sum_{i=1}^{n} A_i \sin(\omega_i t + \theta_i) \tag{6}$$

where $a(t)$ represents acceleration over time; $I(t)$ is the envelope that simulates the transient nature of an earthquake; n is a factor that enhances the compatibility of the accelerogram with the target response spectrum when increased; A_i is the amplitude or artificial signal, which ensures the accelerogram's compatibility with the design spectrum as it is calculated from the spectral density function obtained from the spectrum itself. ω_i and θ_i are the frequency and phase of the i-th sinusoidal function.

For the current study, the software SeismoArtif was used to generate artificial accelerograms, employing the methodology developed by Vanmarcke and Gasparini [10] for creating compatible accelerograms.

2.4 Design spectrum

To develop the design spectrum according to NBR 15421/23, we initially determined the structure's seismic zone and site class, which are seismic zone 4 and site class D, respectively. Based on this information, we calculated the characteristic horizontal seismic acceleration (a_g), which is 0.15g. Additionally, we applied the seismic amplification factors $C_V = 1.5$ and $C_a = 2.2$. Using these parameters, we constructed the target response spectrum according to the equations given in the standard. Figure 3 shows the resulting target response.

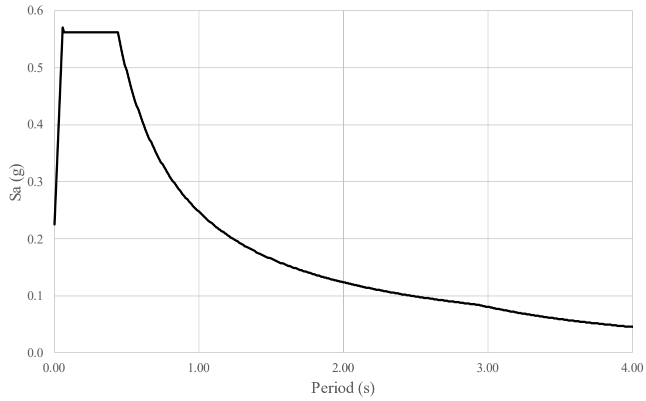


Figure 3. Target response spectrum.

2.5 Structural model

The structural model employed will be the shear building model of a 10-story building. This model is a structural simplification where the columns are considered inextensible, the slabs are rigid, and all mass is concentrated at the floor levels.

3 Example and results

For the analysis, we use the shear building frame in Fig. 4, with a mass of 20 Mg on each floor above the baseline and each column segment having a height of 3 meters. Each column has $EI = 200\ MN \cdot m^2$. Its representation is shown in Fig. 4.

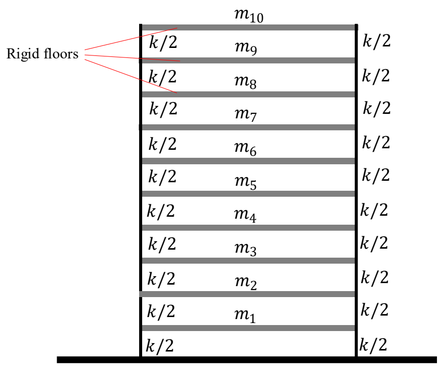
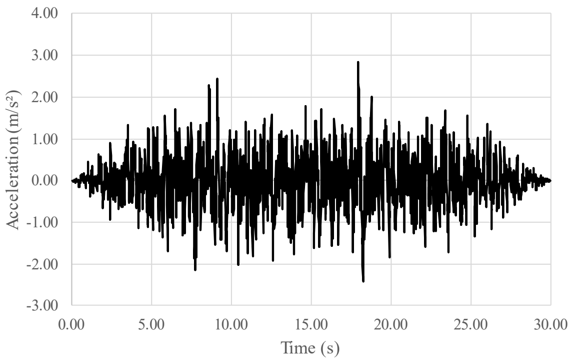
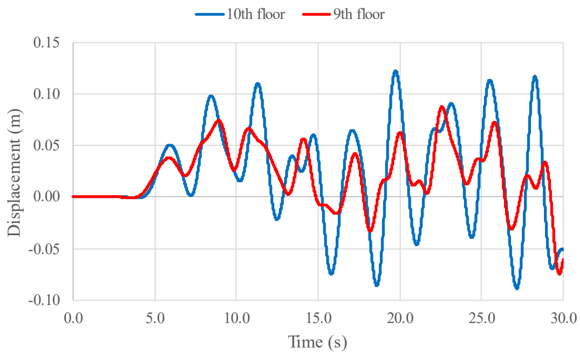


Figure 4. A ten-story shear building model

For the construction of the accelerogram, we chose a trapezoidal envelope proposed by Hou [11], with a rise time of 5 seconds, a fall time of 24 seconds, and a seismic duration of 30 seconds. Figure 5 shows the generated accelerogram and the displacement experienced by the 10th and 9th floors. At each moment, the displacement variation corresponds to the deflection of the columns connecting these floors.



a) Artificial accelerogram at the base



b) Displacement of the 10th and 9th floor

Figure 5. Artificial accelerogram and displacement of the 10th and 9th floor

4 Conclusions

Therefore, it is evident that seismic analysis is not limited solely to understanding the structure itself but also requires a profound understanding of the seismic activity in the region where construction will take place. Characterizing potential earthquakes through estimates of maximum displacements or historical ground motion records is crucial for this process. Standards like NBR 15421/23 provide guidelines and simplifications that enable the creation of the response spectrum, reflecting the local specifics of earthquake effects on structures. These normative approaches significantly facilitate the execution of seismic analysis, ensuring greater safety and effectiveness in the design of structures in regions susceptible to seismic events

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