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Research Article

Natural Vibrations of A Five-Story Building Consisting of A Steel Frame And Concrete Walls And Roof

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Abstract

Understanding the dynamic behavior of structures under various types of loads is essential for ensuring the safety and durability of buildings, especially in seismically active regions. Natural frequencies and corresponding mode shapes are key dynamic properties that influence a building's response to environmental excitations such as earthquakes, wind, and operational vibrations. When the excitation frequency approaches the natural frequency of a structure, resonance may occur, potentially leading to excessive deformations or structural failure. Therefore, accurately determining these dynamic characteristics is crucial for both design and retrofitting purposes. Composite structures, comprising steel frames and concrete walls or slabs, are increasingly utilized in modern construction due to their combined strength, stiffness, and energy dissipation capacity. Despite their advantages, the modeling of such structures is challenging due to the nonlinear material behavior and the complex interactions between steel and concrete elements. Analytical methods often fall short in capturing these complexities, making numerical simulation techniques such as the Finite Element Method (FEM) essential. In this study, a five-story steel-concrete composite building is modeled and analyzed using Abaqus software. Modal analysis is performed to identify natural frequencies and mode shapes. Furthermore, the research includes a mesh sensitivity study, the implementation of I-beam sections to enhance model realism, and a comparative discussion with theoretical formulations. These efforts aim to improve the accuracy, applicability, and engineering relevance of vibration analysis in mid-rise structures.

Keywords:

Abaqus, Natural Frequency, Structural Vibration, Finite Element Analysis, Steel-Concrete Composite

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1.Article structure

The structure of the paper is explained below. In Section 2, the introduction and analysis of the current state of the subject are presented. Finite element simulation is presented in Section 3. In Section 4, the results of natural frequency modeling are presented. Section 5 describes the earthquake modeling. The results of building earthquake modeling and final findings are presented in Section 6. The concluding remarks are presented in Section 7.

2.Introduction

Understanding the dynamic behavior of buildings is crucial for ensuring their safety and serviceability under dynamic loading conditions, including seismic events and wind forces. The natural frequencies and mode shapes of a structure are fundamental parameters that influence its response to such dynamic loads. Accurate determination of these parameters enables engineers to design structures that avoid resonance phenomena and mitigate potential damage. Composite structures composed of steel frames and concrete walls and roofs have become increasingly common in modern engineering due to their effective combination of strength, stiffness, and ductility. However, the interaction between steel and concrete components introduces complexities in predicting the dynamic response of these structures. Finite element analysis (FEA) has emerged as a powerful tool for modeling and analyzing the intricate behavior of composite structures under various loading conditions.

Over the past decades, considerable progress has been made in the analysis of steel–concrete composite structures, especially with the development of numerical methods. Early works focused on simplified analytical methods, while modern approaches rely on sophisticated numerical techniques like the finite element method (FEM). (Weaver Jr et al., 1991) established the mathematical basis for analyzing vibrational behavior in mechanical and structural systems, introducing key concepts still used in modern engineering. (Moehle, 2015) has played a leading role in developing professional guidance and design standards, including Improved Seismic Design Guidelines for California Highway Bridges (ATC 32); Guidelines for Evaluation and Repair of Masonry and Concrete Walls (FEM A 306); Guidelines for Seismic. Y. (Fan et al., 2024) accurately simulate the stress behavior of reinforced frameworks using finite element modeling. Prefabricated beams increase load-bearing capacity by 18%, reduce residual deformation by 26%, and enhance seismic resilience, allowing older structures to partially regain self-resetting ability under various earthquake conditions. Among modern subjects are major issues that are associated with buildings. These issues include energy efficiency, structural analysis, and the ability of structures to withstand considerable vibrations (Delarami et al., 2024; Golmohammadi et al., 2022). (Jafari & Alipour, 2021) reviewed the available methods and techniques for controlling wind-induced vibrations in tall buildings. Vibrations occur in both directions parallel and perpendicular to the wind, depending on the wind direction, building shape, height, and structural characteristics. They examined control systems including passive, active, and semi-active systems, and also evaluated the performance of damping systems in reducing structural vibrations. (Zhang et al., 2022) present a comprehensive review of recent advances in the application of signal processing techniques in vibration-based structural health monitoring (SHM). The main goal of SHM is to enable the estimation of structural health status and the understanding of structural characteristics through the evaluation of physical parameters measured in real time. (Xu et al., 2024) constructed a five-story reinforced concrete building and tested it on the NEES-UCSD shake table from 2011 to 2012. The objective of the test program was to investigate the response of the structure and nonstructural components and systems (NCS) and their dynamic interactions under seismic foundation excitations of varying intensities. The building was tested first under foundation isolation conditions and then under steady-state conditions. Gharib and colleagues have endeavored to enhance the stability performance of both large and small buildings in several projects in recent years, focusing on the control of structural vibrations (Gharib et al., 2010; Gharib et al., 2020).

In this study, a five-story composite building, consisting of a steel frame with concrete walls and roof, was modeled and analyzed using Abaqus. The building's natural frequencies and mode shapes were identified through modal analysis, which is considered crucial for assessing structural performance under dynamic loading conditions. Valuable insights into the vibrational behavior of composite mid-rise buildings are provided, contributing to improvements in their design for enhanced resilience and safety.

3.Finite Element Simulation

Abaqus does not define units explicitly; users must adopt a consistent unit system, such as those shown in Table 1. This study employs the second unit set, which was chosen based on the project's structural scale and typical engineering practice for mid-rise buildings. The second unit system, using meters and kilograms, is well-suited for accurately modeling the physical dimensions, material properties, and forces encountered in this analysis. The selected unit set ensures consistency across calculations and aligns with international standards commonly used in similar structural studies.

Table 1 - Unit Systems in Abaqus

Variable	**Set 1**	**Set 2**
Length	Millimeter (mm)	Meter (m)
Weight	Ton (Ton)	Kilogram (Kg)
Force	Newton (N)	Newton (N)
Time	Second (S)	Second (S)
Pressure	Mega Pascal (MPa)	Pascal (Pa)

The mass of each layer is denoted by m_1, m_2, m_n, the stiffness of each layer by k_1, k_2, k_n, and the damping by c_1, c_2, c_n. The dynamic equilibrium equation can be expressed as follows:

$$[M]\{\ddot{x}\}+[c]\{\dot{x}\}+[k]\{x\}=-[M]\{I\}\ddot{x}_g \quad (1)$$

where, m_i is the quality of the i floor, M is the mass matrix, the equation is as follows (2).

$$M=\begin{bmatrix} m_1 & 0 \\ 0 & m_n \end{bmatrix} \quad (2)$$

k_i is the stiffness of layer i, K is the stiffness matrix, the equation is as follows (3)– (6).

$$K=\begin{bmatrix} k_1+k_2 & -k_2 & & \\ -k_2 & k_2+k_3 & -k_3 & \\ & \cdots & \cdots & \cdots \\ & -k_{n-1} & k_{n-1}+k_n & -k_n \\ & & -k_n & -k_n \end{bmatrix} \quad (3)$$

$$C=a[M]+b[K] \quad (4)$$

$$a=\frac{2\left(\dfrac{\xi_i}{\omega_i}-\dfrac{\xi_{i+1}}{\omega_{i+1}}\right)}{\dfrac{1}{\omega_i^2}+\dfrac{1}{\omega_{i+1}^2}} \quad (5)$$

$$b=\frac{2\left(\xi_{i+1}\omega_{i+1}-\xi_i\omega_i\right)}{\omega_{i+1}^2-\omega_i^2} \quad (6)$$

where, C is the damping matrix ξ_i , ω_i is the damping ratio of the i mode, natural frequency; $\ddot{x}_g$ is ground motion acceleration; $\{x\}$ is the displacement vector $\{x\}=\{x_1,x_2\cdots x_n\}^T$; $\{\dot{x}\}$ is the velocity vector, $\{\dot{x}\}=\{\dot{x}_1,\dot{x}_2\cdots\dot{x}_n\}^T$; $\{\ddot{x}\}$ is the acceleration vector, $\{\ddot{x}\}=\{\ddot{x}_1,\ddot{x}_2\cdots\ddot{x}_n\}^T$.

In the dynamic analysis of structural systems, the motion of a multi-degree-of-freedom (MDOF) system can be described using the following matrix form:

$$F(t)=M\ddot{u}(t)+C\dot{u}(t)+Ku(t) \quad (7)$$

where, **M** is the global mass matrix [kg], **C** is the damping matrix [N·s/m], **K** is the global stiffness matrix [N/m], **u(t)** is the displacement vector [m],

$\dot{u}(t)$ is the velocity vector [m/s], $\ddot{\mathbf{u}}(\mathbf{t})$ is the acceleration vector [m/s²], **F(t)** represents the external force vector, such as seismic loading or wind [N].

The consistent global **mass matrix** for a typical 3D solid element (e.g., C3D8R) can be expressed as:

$$M = \int_V \rho N^T N dV \tag{8}$$

where, $\boldsymbol{\rho}$ is the **material density** [kg/m³], **N** are the shape functions, ***V*** is the volume of the element.

Similarly, the **global stiffness matrix** is defined as:

$$K = \int_V B^T D B dV \tag{9}$$

where, **B** is the strain-displacement matrix, **D** is the constitutive (material) matrix depending on isotropic/orthotropic material properties.

The **Rayleigh damping** matrix is often used in dynamic analysis, given by:

$$C = \alpha M + \beta K \tag{10}$$

where, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ respectively are mass and stiffness proportional damping coefficients.

For undamped free vibration (no external force), the system simplifies to:

$$M\ddot{u}(t) + Ku(t) = 0 \tag{11}$$

Assuming harmonic motion, $\mathbf{u}(t) = \phi \sin(\omega t)$ the eigenvalue problem becomes:

$$(K - \omega^2 M)\phi = 0 \tag{12}$$

Solving this yields the natural frequencies $\boldsymbol{\omega}$ and mode shapes ∅.

These relations form the mathematical basis for modal analysis used in this research. All simulations are performed under the assumptions of linear elasticity, small deformations, and full bonding between steel and concrete interfaces. Material damping is considered using Rayleigh coefficients extracted from empirical studies.

3.1 Natural Frequency Modeling

Understanding the natural frequency of a structure is fundamental for ensuring its safety and performance. Natural frequencies and associated vibration modes determine how a building responds to dynamic loads, such as wind and earthquakes. If the natural frequency of the building aligns with the frequency of an external force, resonance may occur, leading to amplified vibrations and potential structural damage or failure. By identifying these frequencies, engineers can design structures to avoid resonance conditions and optimize their dynamic performance.

The finite element simulation of the five-story composite building was carried out using Abaqus/Standard, focusing on its dynamic response and modal characteristics. The structure was modeled as a combination of three-dimensional deformable solids representing the steel frame, reinforced concrete walls, and roof slab. The geometry was defined in accordance with realistic mid-rise construction dimensions, and all components were assembled with precise tie constraints to simulate monolithic behavior between the steel and concrete elements. Material properties were defined based on standard engineering values: steel was assigned a density of 7800 kg/m³, an elastic modulus of 200 GPa, and a Poisson's ratio of 0.3, while concrete was defined with a density of 2400 kg/m³, a modulus of 30 GPa, and a Poisson's ratio of 0.29. These properties were entered into the material modules of Abaqus, and assigned to the respective parts accordingly using section assignments. The composite nature of the structure required accurate mechanical interactions, which were implemented using surface-to-surface tie constraints between the walls, roof, and steel frame. The modeling and analysis process in Abaqus/Standard involved several key steps, including part creation, property definition, assembly, analysis step setup, interaction modeling, application of loads, and meshing. These stages are detailed as follows:

- **Part**: The building's three main components are modeled as three-dimensional deformable solids. Figure 1 illustrates the designed geometry of these components.
- **Property**: Table 2 lists the mechanical properties of steel and concrete assigned to the frame, walls, and roof. Figures 2 and 3 illustrate how these properties are defined and assigned in Abaqus.
- **Assembly**: The geometric constraints between the building's components are defined in this stage. Figure 4 shows the placement of walls and roofs on the building frame.

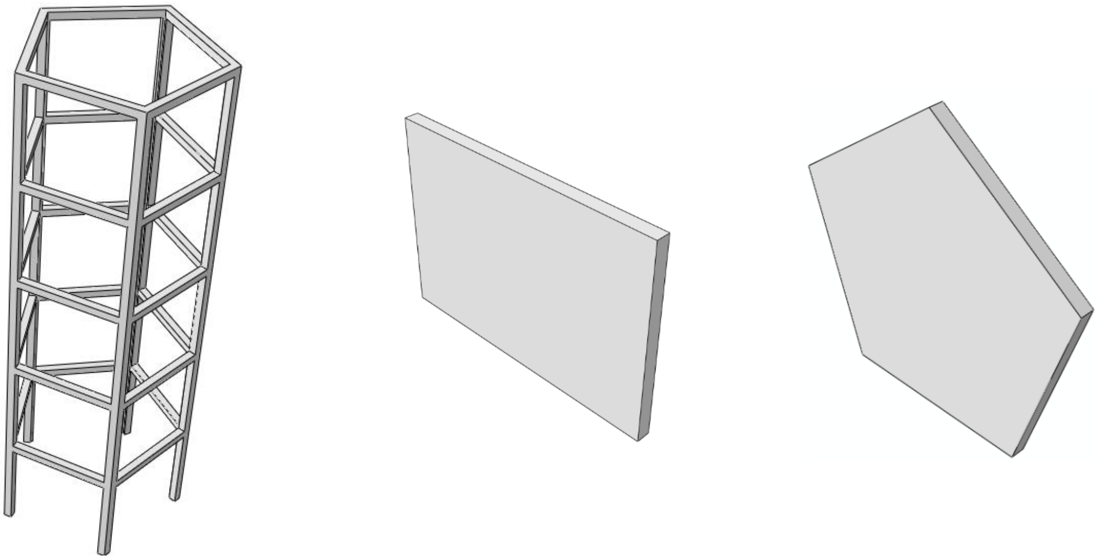
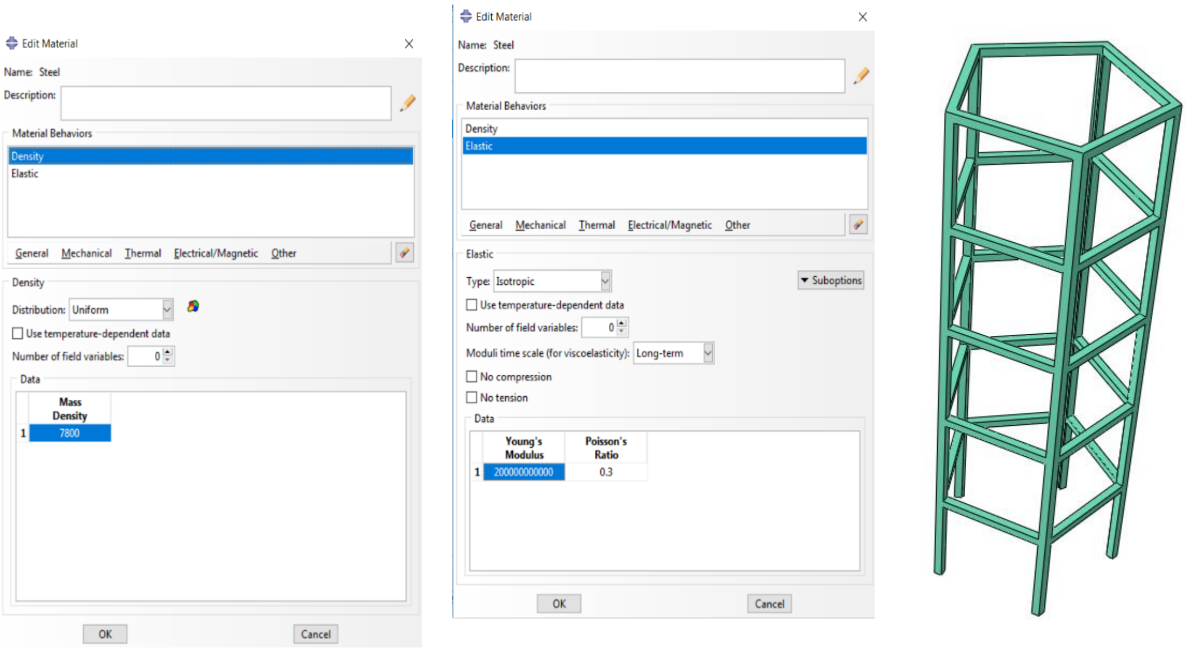


Figure 1 - Building components: a) Frame b) Wall c) Roof

Table 2 - Mechanical Properties of Steel and Concrete

Material	**Density (Kg/m³)**	**Elastic Modulus (GPa)**	**Poisson's Ratio**
Steel	7800	200	0.3
Concrete	2400	30	0.29



Name: Steel
Description:
Material Behaviors
Density
Elastic
Density
Distribution: Uniform
☐ Use temperature-dependent data
Number of field variables: 0
Data

	Mass Density
1	7800

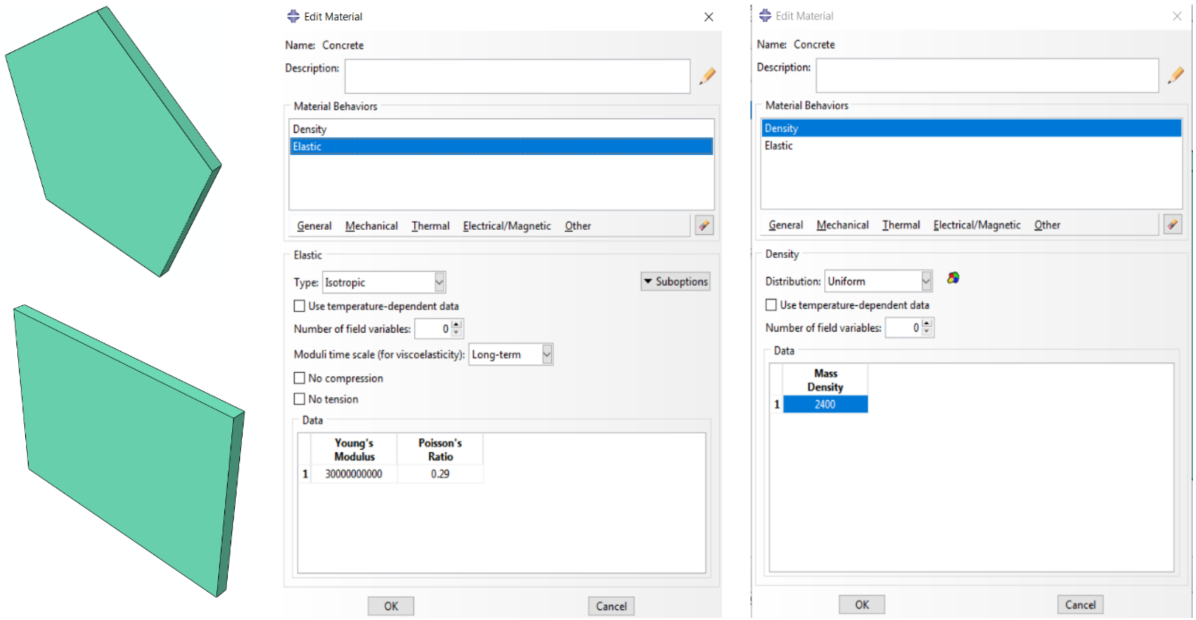
Name: Steel
Description:
Material Behaviors
Density
Elastic
Elastic
Type: Isotropic
☐ Use temperature-dependent data
Number of field variables: 0
Moduli time scale (for viscoelasticity): Long-term
☐ No compression
☐ No tension
Data

	Young's Modulus	Poisson's Ratio
1	200000000000	0.3

(A) (B) (C)

Figure 2 - A and B) Definition of steel properties in the software C) Assignment of properties to the skeleton

- **Step**: The analysis is set to solve for the natural vibrations of the structure, specifying four vibration modes (Figure 5).
- **Interaction**: Mechanical constraints between building components are established. Figures 6 and 7 illustrate the application of tie constraints between walls, roofs, and the frame.
- **Load**: Boundary conditions are shown in Figure 8, where the base of the building is assumed to be fully constrained in all directions for natural frequency analysis.



(C) (B) (A)

Edit Material

Name: Concrete

Description:

Material Behaviors

Density

Elastic

Elastic

Type: Isotropic

☐ Use temperature-dependent data

Number of field variables: 0

Moduli time scale (for viscoelasticity): Long-term

☐ No compression

☐ No tension

Data

	Young's Modulus	Poisson's Ratio
1	30000000000	0.29

Edit Material

Name: Concrete

Description:

Material Behaviors

Density

Elastic

Density

Distribution: Uniform

☐ Use temperature-dependent data

Number of field variables: 0

Data

	Mass Density
1	2400

Figure 3 - A and B) Definition of concrete properties in thesoftware C) Assignment of properties to walls and ceilings

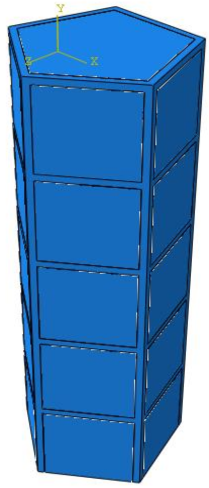


Figure 4 - Definition of geometric constraints between components and placement of walls and ceilings on the skeleton

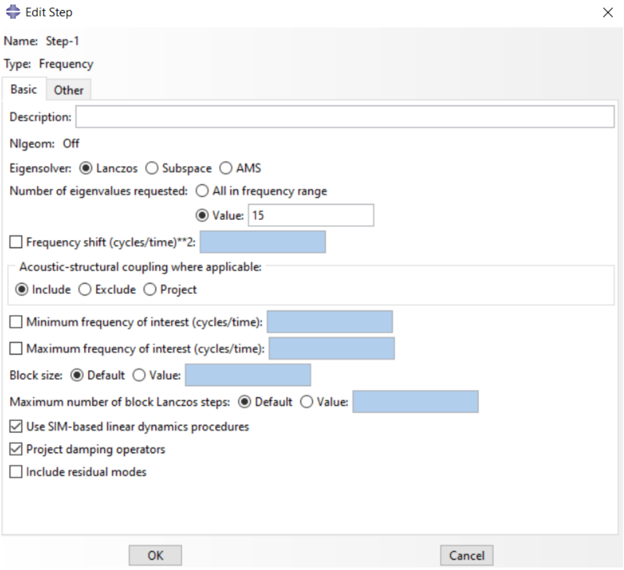
- **Mesh**: Three-dimensional eight-node elements (C3D8R) are used. Figures 9 and 10 demonstrate the meshing of walls, roofs, and the building frame.

The building base was fully fixed in all degrees of freedom to simulate a rigid foundation during modal analysis. Meshing was performed using linear 8-node brick elements (C3D8R), which offer a balance between computational efficiency and accuracy in structural dynamics problems. A mesh sensitivity study was conducted by refining the element size to ensure that the resulting natural frequencies were independent of the mesh resolution, thereby enhancing the credibility of the numerical results.

To determine the vibrational characteristics, a frequency step was defined to extract the first four eigenfrequencies and their corresponding mode shapes. These modal parameters form the basis for subsequent dynamic evaluations, including seismic response analysis.

4.Natural frequency modeling results

Natural frequencies of the building, which represent the specific frequencies at which the structure tends to vibrate when subjected to dynamic loads. These frequencies are critical in understanding the dynamic stability and resonance potential of the structure. Resonance occurs when external forces match a building's natural frequency, amplifying vibrations and potentially causing significant structural damage. Accurate determination of these frequencies allows for safer structural designs in which resonance conditions are avoided and dynamic stability is ensured. Table 3 provides the first four natural frequencies of the building, and Figure 11 shows the corresponding vibration modes.



Edit Step

Name: Step-1

Type: Frequency

Description:

Nlgeom: Off

Eigensolver: ● Lanczos ○ Subspace ○ AMS

Number of eigenvalues requested: ○ All in frequency range

● Value: 15

☐ Frequency shift (cycles/time)**2:

Acoustic-structural coupling where applicable:

● Include ○ Exclude ○ Project

☐ Minimum frequency of interest (cycles/time):

☐ Maximum frequency of interest (cycles/time):

Block size: ● Default ○ Value:

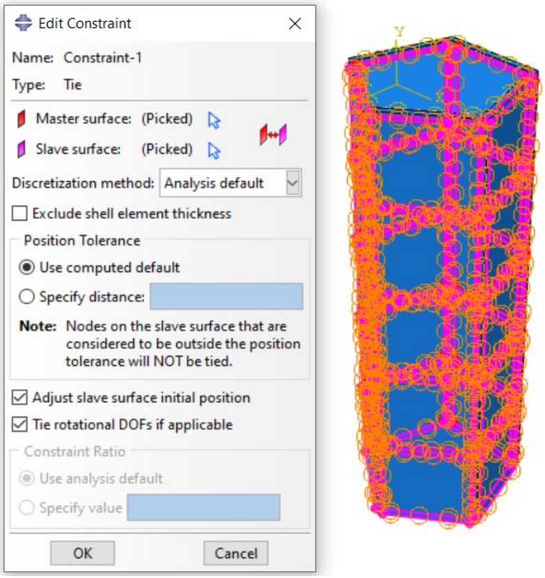
Maximum number of block Lanczos steps: ● Default ○ Value:

☑ Use SIM-based linear dynamics procedures

☑ Project damping operators

☐ Include residual modes

Figure 5 - Definition of the vibrational solution of the problem



Edit Constraint

Name: Constraint-1

Type: Tie

Master surface: (Picked)

Slave surface: (Picked)

Discretization method: Analysis default

☐ Exclude shell element thickness

Position Tolerance

● Use computed default

○ Specify distance:

Note: Nodes on the slave surface that are considered to be outside the position tolerance will NOT be tied.

☑ Adjust slave surface initial position

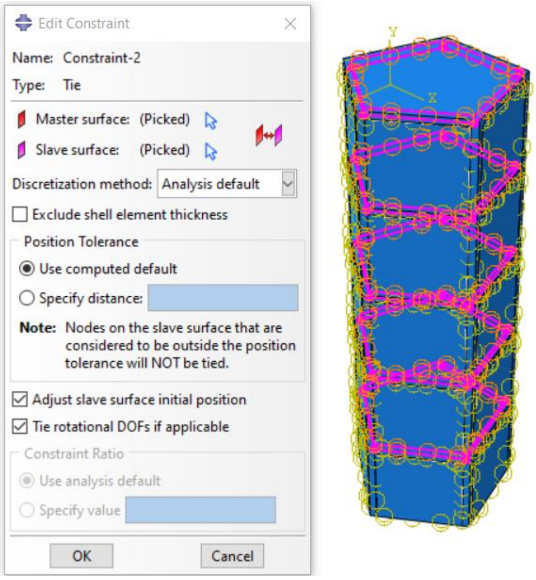
☑ Tie rotational DOFs if applicable

Constraint Ratio

● Use analysis default

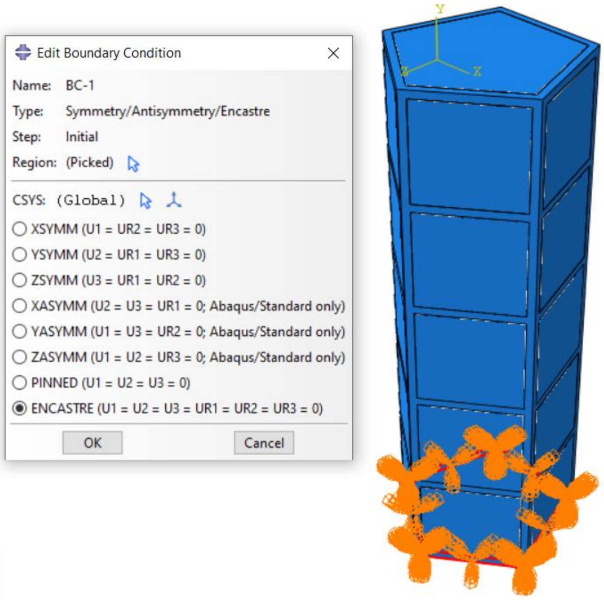
○ Specify value

Figure 6 - Fastening between walls and frame



Name: Constraint-2
Type: Tie
Master surface: (Picked)
Slave surface: (Picked)
Discretization method: Analysis default
☐ Exclude shell element thickness
Position Tolerance
● Use computed default
○ Specify distance:
Note: Nodes on the slave surface that are considered to be outside the position tolerance will NOT be tied.
☑ Adjust slave surface initial position
☑ Tie rotational DOFs if applicable
Constraint Ratio
● Use analysis default
○ Specify value

Figure 7 - Clamp between roof and frame



Name: BC-1
Type: Symmetry/Antisymmetry/Encastre
Step: Initial
Region: (Picked)
CSYS: (Global)
○ XSYMM (U1 = UR2 = UR3 = 0)
○ YSYMM (U2 = UR1 = UR3 = 0)
○ ZSYMM (U3 = UR1 = UR2 = 0)
○ XASYMM (U2 = U3 = UR1 = 0; Abaqus/Standard only)
○ YASYMM (U1 = U3 = UR2 = 0; Abaqus/Standard only)
○ ZASYMM (U1 = U2 = UR3 = 0; Abaqus/Standard only)
○ PINNED (U1 = U2 = U3 = 0)
● ENCASTRE (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0)

Figure 8 - Natural frequency modeling boundary conditions

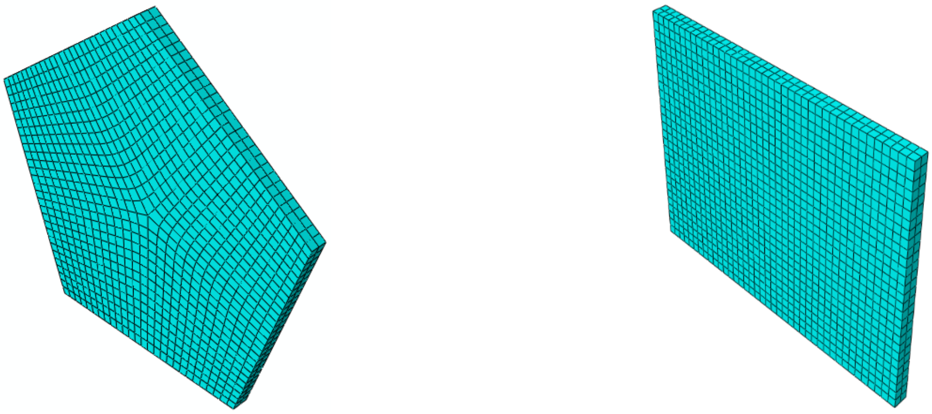

(b) (a)

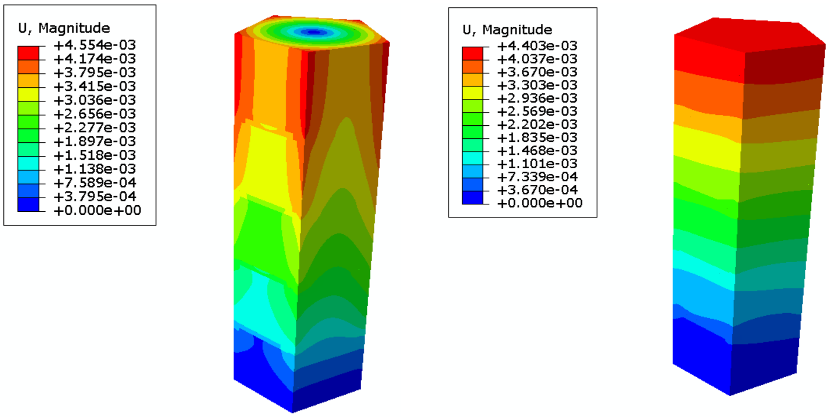
Figure 9 - Element arrangement: a) Wall b) Roof

(b) (a)

Figure 10 - a) Unauthorized model for elementing b) Skeleton elementing

Table 3 – Natural frequency of the building

Frequency Number	Frequency (Hz)
First	11
Second	25.68



(b) Second mode shape (a) First mode shape

Figure 11 – Two forms of the first vibration mode of the building

In the finite element analysis of reinforced concrete structures, due to the existence of numerous nonlinear factors, many parameters are usually introduced to take these nonlinear factors into account, and these parameters may affect each other. Some of these parameters cannot be easily determined by experiment, and in addition, the complexity and dispersion of the bonded material itself also contribute to this problem. The mechanism of some cracks and failures is not completely clear, so the results of nonlinear analysis of structures often show a large range of variations. For this reason, various simplified material models are usually used for analysis.(Lee & Fenves, 1998; Rots, 1988)

An isotropic modulus with a variable modulus E (t) is used to simulate the nonlinear characteristics of concrete materials. For the stress-strain relationship of isotropic linear elastomers, the equation is as follows (7):

$$\sigma_{ij} = \frac{E}{1+\mu}\varepsilon_{ij} + \frac{\mu E}{(1+\mu)(1-2\mu)}\varepsilon_{kk}\delta_{ij} \qquad (13)$$

where the elastic modulus and Poisson’s ratio μ are constant. Replace the elastic modulus E in the equation with tangent elastic modulus E (t), and obtain the relationship between the stress increment $d\sigma_{ij}$ and the strain component, the equation is as follows:

$$d\sigma_{ij} = \frac{E(t)}{1+\mu}\varepsilon_{ij} + \frac{\mu E(t)}{(1+\mu)(1-2\mu)}\varepsilon_{kk}\delta_{ij} \qquad (14)$$

For concrete under moderate compressive stresses, the Poisson's ratio can be assumed approximately constant. However, as stress levels increase, nonlinear effects begin to emerge, when the stress increases, the value of μ gradually increases.(Bazant & Planas, 2019; Broujerdian et al., 2018) Therefore, in general, the nonlinearity of the material can be reflected by the numerical changes of E (t).

According to the results of the uniaxial test, the tangential elastic modulus can be obtained by using the relationship between the equivalent stress and the equivalent strain. The stress-strain relationship can be expressed by a hyperbolic, parabolic or exponential curve.

4.1 The stress-strain relationship under monotonic axial compression

Saenz’s formula is widely used, the equation is as follows (Saenz, 1964):

$$\sigma = \frac{\mathrm{E}\varepsilon}{a + b\left(\frac{\varepsilon}{\varepsilon_c}\right) + c\left(\frac{\varepsilon}{\varepsilon_c}\right)^2 + d\left(\frac{\varepsilon}{\varepsilon_c}\right)^3} \tag{15}$$

where F is the modulus of elasticity and a, b, c, and d are constants.

a, b, c, and d are determined by:

$$\begin{aligned} &\varepsilon = 0, d\sigma / d\varepsilon = \mathrm{E}_0 \\ &\varepsilon = \varepsilon_c, \sigma = R_c \\ &\varepsilon = \varepsilon_c, d\sigma / d\varepsilon = 0 \\ &\varepsilon = \varepsilon_u \text{ (ultimate strain)}, \sigma = \sigma_{u_{\circ}} \end{aligned} \tag{16}$$

After the coefficients a, b, c, and d are determined by the above conditions, it can be obtained, the equation is as follows:

$$\sigma = \frac{\mathrm{E}_0\varepsilon}{1 + \left(R + \frac{E_0}{E_s} - 2\right)\frac{\varepsilon}{\varepsilon_c} - (2R-1)\left(\frac{\varepsilon}{\varepsilon_c}\right)^2 + R\left(\frac{\varepsilon}{\varepsilon_c}\right)^3} \tag{17}$$

$$R = \frac{\left(\mathrm{E}_0 / \mathrm{E}_S\right)\left(R_c / \sigma_u - 1\right)}{\left(\varepsilon_u / \varepsilon_c - 1\right)^2} - \frac{\varepsilon_c}{\varepsilon_u} \tag{18}$$

If condition 4 is ignored, that is, the descending segment of the curve is ignored, then the equation is as follows:

$$\sigma = \frac{\mathrm{E}_0\varepsilon}{1 + \left(\frac{\mathrm{E}_0}{\mathrm{E}_s} - 2\right)\frac{\varepsilon}{\varepsilon_c} + \left(\frac{\varepsilon}{\varepsilon_c}\right)^3} \tag{19}$$

5. Earthquake Modeling

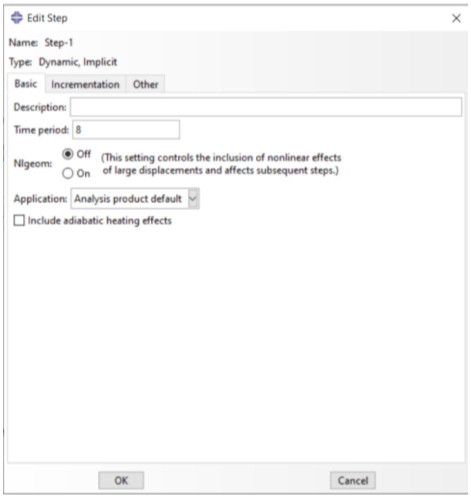
Earthquake modeling builds upon the principles used in natural frequency analysis, but it introduces specific differences, particularly in terms of step definition and loading conditions. While natural frequency analysis focuses on identifying the inherent vibrational properties of a structure—such as its modal frequencies and mode shapes—earthquake modeling aims to capture the dynamic behavior of the building under realistic, time-dependent external excitations, such as seismic ground motions.

The key distinction lies in the purpose of each analysis: modal analysis is primarily used to avoid resonance and ensure structural stability under general dynamic loads, whereas earthquake modeling is designed to evaluate how the structure performs during actual earthquake events. This includes assessing the distribution of stresses, the extent of deformations, and the ability of the structure to dissipate energy through its composite elements.

To conduct this simulation, a dynamic time-history analysis was performed in Abaqus using ground acceleration data as input. The setup and configuration of this step are discussed in the following section.

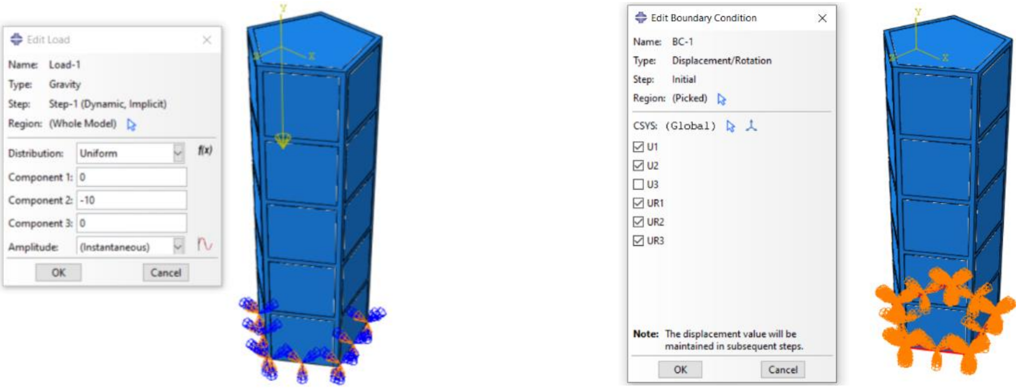
Step: As shown in Figure 12, dynamic implicit analysis is used with a time period of 8 seconds.

- **Load**: Figure 13 illustrates boundary conditions, while Figure 14 depicts the application of gravity and earthquake accelerations. An amplitude curve (Figure 15) defines acceleration over time.



Name: Step-1
Type: Dynamic, Implicit
Description:
Time period: 8
Nlgeom: ● Off ○ On (This setting controls the inclusion of nonlinear effects of large displacements and affects subsequent steps.)
Application: Analysis product default
☐ Include adiabatic heating effects

Figure 12 - Definition of dynamic problem solving

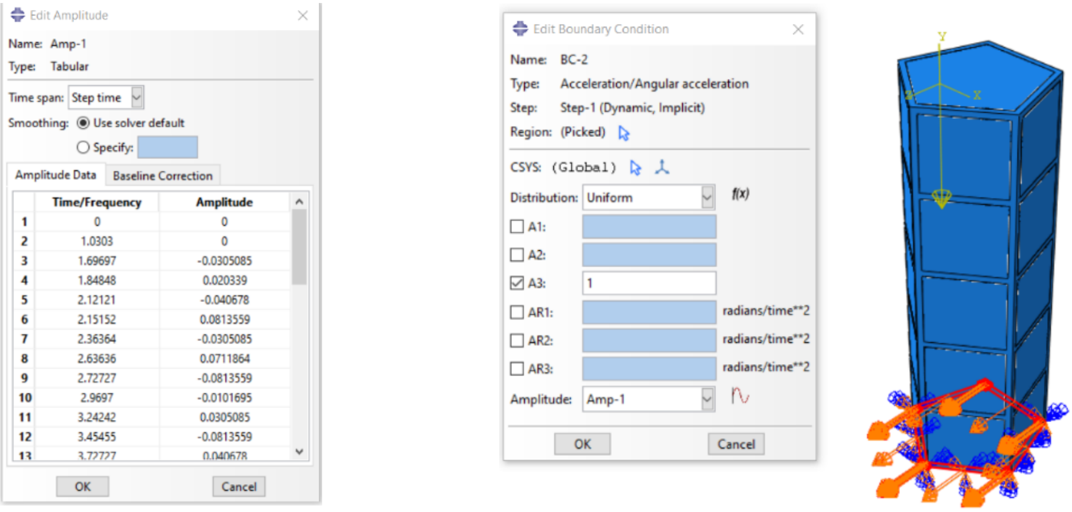


Name: Load-1
Type: Gravity
Step: Step-1 (Dynamic, Implicit)
Region: (Whole Model)
Distribution: Uniform
Component 1: 0
Component 2: -10
Component 3: 0
Amplitude: (Instantaneous)

Name: BC-1
Type: Displacement/Rotation
Step: Initial
Region: (Picked)
CSYS: (Global)
☑ U1
☑ U2
☐ U3
☑ UR1
☑ UR2
☑ UR3
Note: The displacement value will be maintained in subsequent steps.

(b) (a)

Figure 13 - a) Boundary conditions for earthquake modeling b) Definition of gravitational acceleration



Name: Amp-1
Type: Tabular
Time span: Step time
Smoothing: ● Use solver default
○ Specify:

	Time/Frequency	Amplitude
1	0	0
2	1.0303	0
3	1.69697	-0.0305085
4	1.84848	0.020339
5	2.12121	-0.040678
6	2.15152	0.0813559
7	2.36364	-0.0305085
8	2.63636	0.0711864
9	2.72727	-0.0813559
10	2.9697	-0.0101695
11	3.24242	0.0305085
12	3.45455	-0.0813559
13	3.72727	0.040678

Name: BC-2
Type: Acceleration/Angular acceleration
Step: Step-1 (Dynamic, Implicit)
Region: (Picked)
CSYS: (Global)
Distribution: Uniform
☐ A1:
☐ A2:
☑ A3: 1
☐ AR1: radians/time**2
☐ AR2: radians/time**2
☐ AR3: radians/time**2
Amplitude: Amp-1

(b) (a)

Figure 14 - a) Definition of acceleration b) Defined amplitude

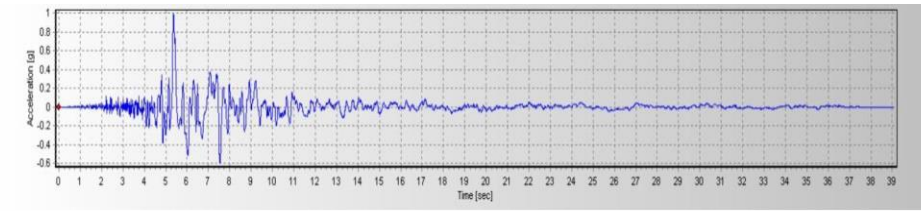


Figure 15 - Earthquake acceleration-time diagram

6. Building earthquake modeling results

The results of the earthquake modeling provide critical insights into the building's performance under seismic loading conditions. The analysis focuses on the distribution of stresses, deformations, and the overall structural response when subjected to realistic earthquake accelerations. This information is pivotal for assessing the safety and resilience of the structure in earthquake-prone regions.

Stress Distribution: Figure 16 highlights the stress concentrations in key structural components during the seismic event. Areas of maximum stress typically occur at the connections between the frame and concrete elements, indicating potential zones of vulnerability.

Deformation Patterns: The simulation reveals how different parts of the building respond dynamically to the earthquake forces. Roof and upper stories show amplified movements compared to lower levels due to the flexibility of the structure and the nature of ground motion transmission.

Energy Dissipation: The interaction between steel and concrete elements plays a significant role in energy absorption. The composite design demonstrates its ability to dampen seismic forces effectively, reducing the overall impact on the building.

These results underscore the importance of accurate finite element modeling in predicting seismic behavior. The insights gained from this analysis can guide design improvements, material selection, and reinforcement strategies to enhance the building's earthquake resilience.

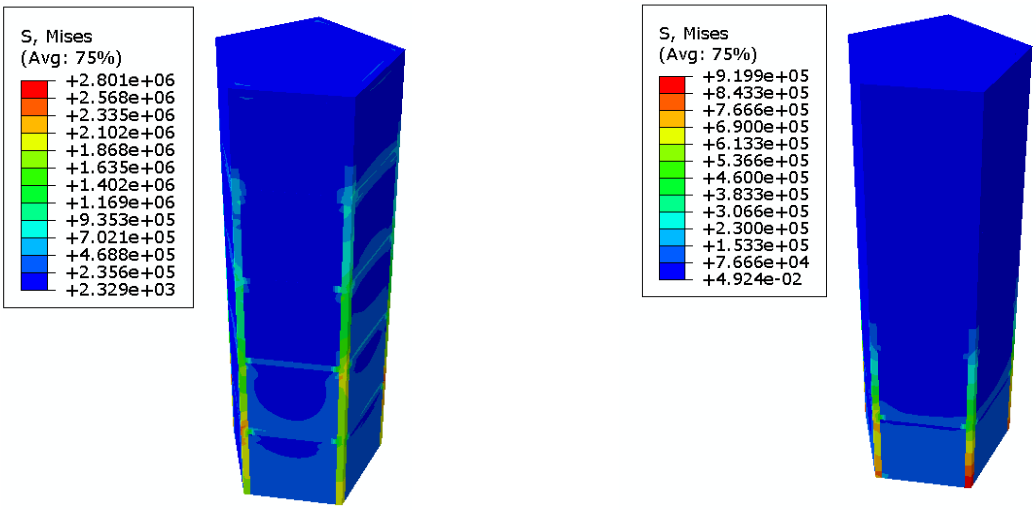


Figure 16 – Stress state of a building under earthquake

7. Conclusion

The vibrational characteristics of a five-story steel-concrete composite building have been examined in this research, emphasizing the importance of conducting precise dynamic analysis to improve structural safety and performance. It has been shown that the accurate identification of the structure's inherent frequencies and mode shapes can prevent the occurrence of detrimental phenomena such as resonance. The outcomes of this study can be utilized in the design and construction of medium-rise structures intended to withstand dynamic loads, including seismic and wind actions. Material optimization and reinforcement techniques have been recommended to enhance the seismic resilience of such buildings, demonstrating that steel-concrete composite systems are capable of dissipating earthquake-induced forces and reducing their overall impact on the structure. Furthermore, the necessity of advanced analytical tools such as Abaqus has been reinforced to ensure compliance with strict safety and performance standards in structural engineering.

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Declaration of competing interest

The authors declare no conflict of interest in preparing this article.

Authors contribution statement

M.R.G. *Conceptualization: evolution of research team to reach aims. Project administration: management and coordination responsibility for the research activity planning and execution. Supervision: oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team.*

A.D. *Conceptualization: evolution of overarching research goals and aims. Programming, software development; designing computer programs.*

S.F.J.P. *Writing: original draft. Preparation and creation of the published work. Formal analysis.*

Date Availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

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