

# Seismic Performance Evaluation of Multi-Story Buildings Using Optimal Pozzolanic Material

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## Abstract

### Keywords:

Seismic performance, high-rise buildings, Eurocode 8, Rice Husk Ash (RHA), Silica Fume (SF), pozzolanic concrete.

Earthquakes, characterized by sudden and transient movements of the Earth's surface, have shaped the planet for millions of years, long before human habitation. Modern construction practices continue to face challenges in designing earthquake-resistant structures, prompting interest in pozzolanic additives such as Rice Husk Ash (RHA) and Silica Fume (SF). However, their optimal use in seismic design remains unclear. This study models a 20-story high-rise building in Extended Three-Dimensional Analysis of Building Systems software (ETABS), following Eurocode 8 standards, to evaluate the seismic performance of different concrete types, including conventional concrete (NC) and mixes incorporating RHA and SF. Material properties were sourced from literature, and beams, columns, and slabs were defined accordingly. Results show that NC provides superior dynamic stability, while RHA and SF concretes introduce higher flexibility and deformation, requiring targeted design adjustments. Specifically, NC exhibited modal periods between 0.626 s and 5.012 s, RHA concrete between 0.606 s and 4.86 s (indicating slightly increased stiffness), and SF concrete between 0.822 s and 6.598 s (indicating higher flexibility). RHA improved durability with minimal stiffness reduction, while SF enhanced vertical load transfer but increased lateral forces, leading to greater drift and displacement. Although all drift values remained within Eurocode 8 limits, base shear increased by 9.61% for RHA and 17.14% for SF, confirming improved lateral resistance. These findings highlight that incorporating pozzolanic materials can enhance certain structural properties but requires careful adjustment of seismic design parameters to ensure safe and resilient implementation in real-world high-rise construction. Member-level recommendations suggest using RHA concrete for columns and critical beams, NC/RHA for slabs, and SF selectively, while a hybrid system with RHAC in primary elements and SFC in non-critical members offers the best balance of stiffness, ductility, and seismic resilience.

## 1. Introduction

An earthquake is a sudden and fleeting movement of the Earth's surface (Odeyemi et al. 2018). Geologists assert that the Earth has experienced earthquakes for hundreds of millions of years, predating the existence of humans. A new catalogue of earthquake fatalities for the world, covering 856 BC to March 2022, lists 2795 reports. Since 1927, reporting of fatal earthquakes is complete for events with more than 16 fatalities (Wyss et al., 2022). A total of 8,336,526 fatalities have been recorded, with at least one fatal earthquake reported in 117 countries (Wyss et al. 2022). Nigeria's seismic history, compiled from various sources, challenges the belief that the country is seismically safe. Tremors, linked to the Ifewara–Zungeru

fault and regional stress from the West African Craton, have occurred in faulted basement terrains, with notable events in Abuja (2018), Saki, and Okitipupa (2021). The Modified Mercalli Scale estimates intensities of III–VI, with magnitudes averaging 3.7–4.5. The Ifewara–Zungeru fault poses risks, and areas like Mpape, Kwoi, Ijebu-Ode, and Saki remain vulnerable. Preparedness is essential for mitigating potential damage (Zakka et al. 2024). Table 1 provides a concise summary of historical seismic events in Nigeria, reinforcing the evidence that the country is not immune to earthquake hazards and underlining the importance of this study.

Seismology, derived from the Greek "seismos" (earthquake) and "logos" (science), extends beyond its original focus on earthquakes. While earthquakes remain central, the field now encompasses studying Earth's internal structure using elastic waves recorded globally by seismographs, making this a vital aspect of seismology (Båth, 1975; Beroza & Kanamori 2015). In seismic engineering, the focus extends to inelastic response, ductility, and safety against failure as critical performance requirements for concrete structures. The exploration and implementation of diverse seismic insulation devices and shock absorbers become integral in fortifying the seismic resistance of concrete structures (Bertero, 2019). The increasing frequency and intensity of seismic events underscore the critical need for robust structural designs and materials capable of withstanding earthquake forces. Researchers have extensively studied the seismic performance of reinforced concrete (RC) structures using various analytical approaches, including static, dynamic, and nonlinear methods.

While these studies have provided valuable insights into the behavior of buildings under seismic loads, many have focused primarily on conventional designs and codes without exploring the potential benefits of material innovations, such as pozzolanic additives. Deshpande et al. (2016) conducted a comparative study on seismic responses of vertically irregular RC buildings, highlighting reduced base and story shear for irregular models, especially the soft story model, but did not explore the use of pozzolanic materials to enhance stability. Kale & Shinde (2019) examined seismic responses of G+12 and G+16 RCC buildings using IS 1893:2016 and IS 16700:2017, observing significant increases in responses compared to IS 1893:2002, yet omitted the role of pozzolanic materials in seismic design. Malviya & Pahwa (2017) analyzed a G+50 building using IS codes 1893:2002 and IS 1893:2016, finding decreased shear force, bending moment, and displacement with the newer code, but focused little on material innovations like pozzolans. Vidyashree et al. (2016) compared seismic responses of RC buildings with and without shear walls on a G+29 structure, concluding that static analysis was inadequate for irregular buildings while shear walls improved performance, yet neglected alternative materials like pozzolans. Sultan & Peera (2015) evaluated seismic responses of a 15-story building with different shapes, finding irregular C-shape buildings more susceptible to seismic impacts in high-risk zones, but did not assess sustainable materials like pozzolans.

Kopuri & Priyadharshani (2022) focused on concrete-filled steel tube columns under axial compression using ABAQUS, showing higher concrete grades increase load-carrying capacity, but their study did not extend to multi-story buildings or consider pozzolanic materials. Li, (2021) developed a new precast prestressed concrete frame structure test for seismic resistance, demonstrating satisfactory performance with 5.6% drift and 4.97 displacement ductility ratio, but did not explore how pozzolans could enhance resilience. Similarly, Yan et al. (2020) analysed a new precast prestressed concrete frame structure, finding hysteretic performance comparable to cast-in-place structures under cyclic loading, yet they omitted the evaluation of pozzolanic materials' potential advantages.

Pozzolan is defined as a siliceous or alumino-siliceous material that, in finely divided form and in the presence of moisture, chemically reacts at ordinary room temperature with calcium hydroxide, released by the hydration of Portland cement, to form compounds possessing cementitious properties (Shukla et al. 2020). Incorporating pozzolans into cement offers multiple benefits, such as enhancing long-term compressive strength (with adequate curing) and boosting resistance to chemically aggressive conditions (Adisa et al. 2025). However, efficiency diminishes as the pozzolan-to-cement ratio increases, indicating a threshold for optimal use. Reported optimum pozzolan-to-cement replacement levels vary with pozzolan type, fineness, and curing: for example, Rice Husk Ash (RHA) is commonly found to give optimal performance at roughly 10–20% cement replacement in many studies, while Silica Fume (SF) typically

performs best at much lower replacement levels (around 7–12%) — although exact optima depend on the material processing and the performance metric used (Endale et al. 2023; Tak et al. 2023). This optimization approach is valuable for producing blended cements efficiently. Researchers have worked on the optimal percentage of pozzolans: El-Nadoury (2022) investigated the effects of replacing varying proportions of cement with ceramic waste powder (CWP) and Rice husk ash (RHA), and evaluated the properties of the concrete mixture for producing M35-grade concrete. The combination of 20% CWP and 10% RHA demonstrated superior performance, increasing compressive, tensile, and flexural strength by 14%, 28%, and 19%, respectively, compared to the control concrete. Lisantono & Pratama (2020) found out that 10% silica fume is optimal in concrete. In addition to enhancing mechanical properties, pozzolans contribute to sustainability. However, few studies have examined how sustainable pozzolanic materials influence seismic response at both structural and member levels.

Earthquakes present a serious risk to buildings and infrastructure, especially in regions prone to seismic activity. The performance of concrete structures during such events is critical; however, traditional construction methods often lack the necessary resilience. Pozzolanic additives, particularly Rice Husk Ash (RHA) and Silica Fume (SF), have been selected for this study because of their proven reactivity, widespread availability, and ability to enhance strength and durability while lowering the carbon footprint of cement-based materials (Obam, et al., 2013; Olaiya et al., 2025). RHA is abundant in Nigeria and other rice-producing regions, offering a low-cost, sustainable solution, while SF has been widely recognized for its exceptional fineness and capacity to refine pore structure, improving both mechanical and durability performance (Akeke et al., 2016; Nazeer & Kapoor et al., 2023; Olaiya et al. 2025; Onsongo et al. 2025). Despite their advantages, the specific influence of RHA and SF on the seismic performance of structural members such as beams, columns, and slabs remain under-researched. Existing studies have focused primarily on conventional reinforced concrete, leaving a gap in understanding how sustainable pozzolanic concretes behave under seismic loading. The problem this research seeks to solve is the lack of knowledge on how RHA- and SF-modified concretes affect seismic performance in multi-story buildings, particularly in at-risk communities like Nigeria where seismic preparedness remains limited. The innovation of this work lies in systematically modelling and comparing normal concrete (NC), RHA concrete (RHAC), and SF concrete (SFC) in a 20-story high-rise structure, assessing their influence on displacement, drift, modal periods, and foundation reactions under Eurocode 8 seismic provisions. This approach allows us to not only evaluate compliance with international seismic codes but also explore the practical feasibility of integrating sustainable pozzolans into real-world earthquake-resistant design. Table 1 presents the historical seismic occurrence in Nigeria.

Table 1: Historical Seismic Events in Nigeria

Year	Location(s)	Reported Magnitude / Intensity	Notes
1933	Warri (Biu region)	Tremor (no magnitude recorded)	Nigeria’s first documented tremor (Akpan and Yakubu 2010)
1939	Lagos, Ibadan, Ile-Ife	6.5 Mr and 5.3 Ms	Strongest historically recorded tremor (Alaneme and Okotete 2018)
1984	Ijebu-Ode region	MMI V–VI	One of the most widely felt tremors (Alaneme and Okotete 2018)
1990	Ibadan / Ijebu-Ode	3.7 MI	Moderate intensity event (Alaneme and Okotete 2018)
2000	Ibadan, Akure, Abeokuta	4.5 Mb / 3.9 Ms	Multi-city tremor (Alaneme and Okotete 2018)
2009	Abeokuta vicinity	3.9 MI	Felt in parts of Ogun State (Akpan et al. 2014)
2016	Saki (Oyo State)	Tremor (no magnitude recorded)	Shows persistent seismic susceptibility (Alaneme and Okotete 2018)

- ML = Local (Richter-type) magnitude
- Mb = Body-wave magnitude
- Ms = Surface-wave magnitude
- Mr = Richter-type (general) magnitude
- MMI = Modified Mercalli Intensity (observational scale)

## 2. Methodology

This section outlined a comprehensive methodology for conducting seismic analysis on a 20-story high-rise building. A hypothetical 20-story high-rise was chosen due to its structural complexity, susceptibility to seismic forces, and relevance to modern urban construction (Fu, 2018). This height also allows for a meaningful assessment of pozzolanic materials in enhancing seismic resilience. The seismic analysis of multi-story buildings, was performed using ETABS following Eurocode 8, involving several key steps to ensure a thorough assessment. The process followed a structured approach to modelling, analysing, and evaluating the seismic performance of buildings constructed with pozzolanic materials.

### 2.1 Modelling the building in ETABS

**Building Type and Dimensions:** The building model is a typical high-rise structure ranging of 20 stories, with floor heights and column spacing designed according to architectural plans. This height range also aligns with real-world urban construction trends, where taller structures are increasingly common in earthquake-prone regions (Fu, 2018). This height allows capturing key dynamic responses, including modal periods, displacements, and drifts, while maintaining computational feasibility for multi-scenario analysis. Figure 1 shows the structural plan of the building (All dimensions in mm). Figure 2 shows three-dimensional (3D) view of the building.

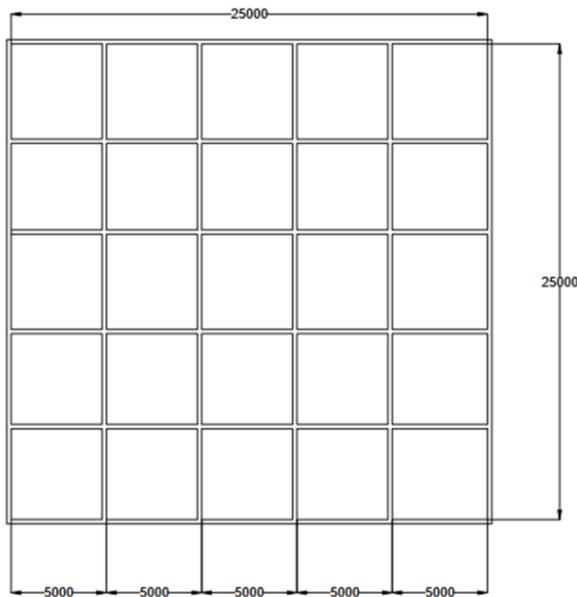


Figure 1: Plan of building

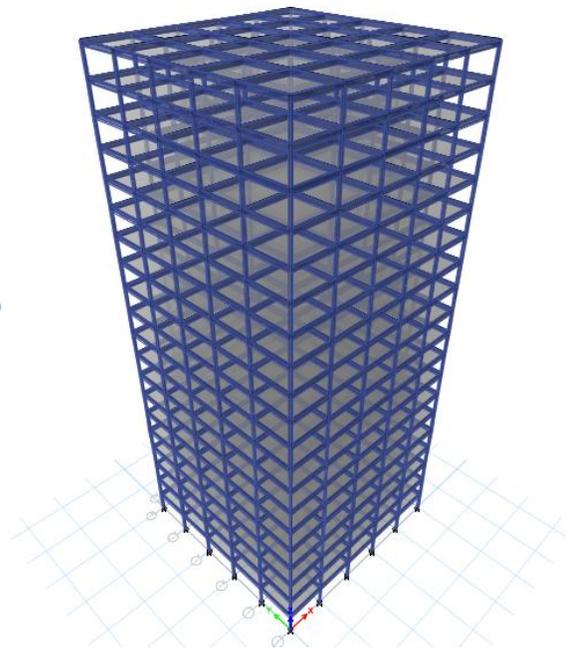


Figure 2: 3D view of building

## 2.2 Material Properties

The summarized values for the conventional concrete mix, rice husk ash concrete, silica fume concrete, including compressive strength, modulus of elasticity, Poisson's ratio, and density, are presented in Table 2 respectively. These values were selected and adjusted based on literature to reflect the influence of pozzolanic materials. The compressive strength and density incorporate this modification, while the modulus of elasticity and Poisson's ratio remain generally consistent with, or slightly lower than, reported for conventional concrete. The replacement levels of 10% RHA and 10% SF were adopted because multiple experimental studies identify these percentages as the optimum levels, achieving the best balance of strength gain, durability, and workability without adverse effects such as excessive brittleness, reduced setting time, or loss of cohesiveness (Li et al., 2025; Yang et al., 2025). The properties of the optimal pozzolan blend were utilized to model individual structural components, such as beams, columns, and slabs. To ensure an accurate representation of the structure, the building's geometry—including beams, columns, slabs, and walls—was modeled in ETABS. The optimal pozzolan properties were applied to both individual elements and the entire building, and then the results were compared with a nominal building model that uses conventional materials. Cross-sectional properties were assigned to structural elements as shown in Table 3. Seismic load cases followed Eurocode 8, incorporating dead, live, wind, and seismic loads (Table 4 and 5). Equivalent Static Analysis assessed lateral displacement, story drift, and internal forces in beams and columns. Table 6 categorizes Normal concrete (NC), Rice Husk ash concrete (RHAC), and Silica fume concrete (SFC) in structural elements.

Table 2: Material properties used for ETABS modelling

Mix ID	Mix description / SCM (%)	28-day fck (MPa)	E (GPa)	Density (kg/m <sup>3</sup> )	$\nu$ (Poisson)	Source / Note
C-RE F	Conventional concrete (0% SCM)	25	31.5 (EC2)	2480	0.2	Day (2021); Neville (2010); Qasim (2019)
RH A-10	RHA replacement	10% 41.2	35.5 (EC2)	2017	0.2	Amran et al. (2021); Salas (2023); Nguyen and Ludwig (2014); Ephraim et al. (2012)
SF-10	Silica fume replacement	10% 50.98	37.5 (EC2)	2830	0.2	Lisantono & Pratama (2020); Gražulytė et al. (2020); Enein et al. (2014)

Table 3: Structural Elements and Properties

Element	Dimension/Specification
Beam	225 x 450 mm
Column	225 x 225 mm
Slab Thickness	150 mm
Reinforcement Type	S355

Table 4: Seismic Design Parameters Table

Parameter	Value
Seismic Zone	Zone 3 (High hazard)
Soil Type	Type C (Stiff soil)
Importance Factor	1 (Essential use)
Terrain category	II
Ground Motion	0.15 g
Wind speed (Eurocode 8)	50 m/s



Although the silica fume and rice husk ash concretes exhibit different strength levels, literature indicates that these variations have minimal influence on concrete density, which remains within the typical 23–25 kN/m<sup>3</sup> range for normal-weight concrete. For example, RHA substitutions of up to 10% lower density slightly (to ~2340–2350 kg/m<sup>3</sup>) but still remain well within structural norms (Jing et al., 2025; Oyejobi & Ajibola, 2014). Consequently, applying a uniform dead load of 25 kN/m<sup>3</sup> across all mix types is justifiable and does not significantly affect modelling outcomes, as shown in Table 5.

Table 5: Load Types for Structural Design

Load Type	Description	Value
<b>Dead Loads (DL)</b>	Permanent, static loads due to structure's weight	Concrete: 25 kN/m <sup>3</sup>
<b>Live Loads (LL)</b>	Temporary, variable loads due to occupancy	2.5 kN/m <sup>3</sup>
<b>Seismic Loads (EQ)</b>	Forces due to ground motion during an earthquake	0.15 g
<b>Wind Loads (WL)</b>	Forces exerted by wind on the structure	50 m/s
<b>Seismic load combination</b>	1.0 × DL + 1.0 × LL + 0.3 × EQ (Eurocode 8)	
<b>Wind Load combo</b>	1.0 × G <sub>k</sub> +1.0 × Q <sub>k</sub> + 1.0 × EQ (Eurocode 8)	

Table 6: Scenario Type

Scenario No.	Description
1	All structural members cast with Normal concrete (NC)
2	All structural members cast with Rice Husk Ash Concrete (RHAC)
3	All structural members cast with Silica Fume Concrete (SFC)
4	Columns RHAC, Others NC
5	Columns SFC, Others NC
6	Beams RHAC, Others NC
7	Beams SFC, Others NC
8	Slab RHAC, Others NC
9	Slab SFC, Others NC

### 3. Results and Discussions

The section presents the results of the effect of pozzolanic materials on structural members.

#### 3.1 Modal period

The modal period is shown in Figure 3. For normal concrete, modal periods range from 0.626 s (Mode 12) to 5.012 s (Modes 1 and 2), reflecting moderate stiffness and balanced seismic performance with moderate displacement and forces. RHA concrete exhibits shorter modal periods, from 0.606 s to 4.86 s, indicating higher stiffness. This reduction in modal period implies an increase in overall stiffness, as a stiffer structure oscillates at a higher frequency (shorter period). Studies show that properly calcined and milled RHA yields stronger and stiffer mixes both statically and dynamically—when used at optimal levels with suitable curing (Li et al., 2025; Yang et al., 2025).

While higher stiffness leads to reduced lateral displacement under seismic excitation, it also increases the seismic forces acting on the structure due to a higher acceleration response. This makes the structure more resistant to deformation but also raises the demand for stronger reinforcement to withstand the higher internal forces. Silica fume concrete, with longer modal periods from 0.822 s to 6.598 s, is less stiff and more flexible. This arises mainly from the higher density assigned to SFC case: added mass lengthens periods even when stiffness increases. This reduces seismic forces but increases lateral displacement, potentially causing greater deformation under seismic loads.

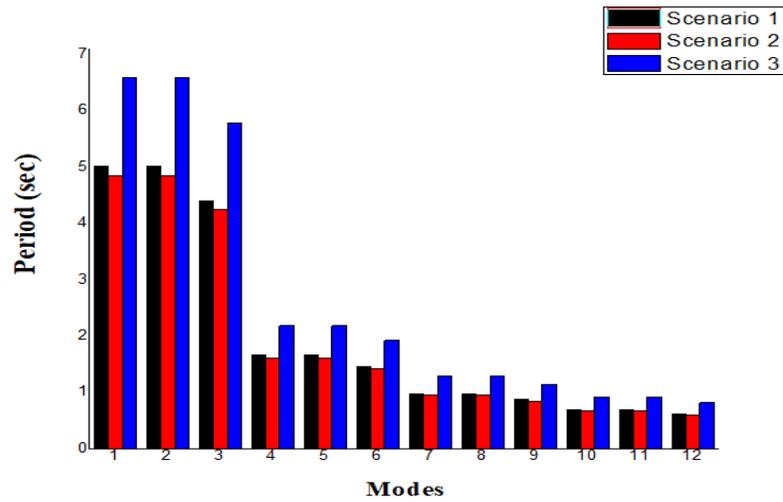


Figure 3: Modal time period of building

Scenario 5 (SFC columns) has higher modal periods than Scenario 1 (NC) and Scenario 4 (RHAC columns), indicating increased flexibility. Mode 1 reaches 5.665 s (vs. 5.012 s and 5.021 s), and Mode 12 hits 0.709 s (vs. 0.626 s and 0.627 s). SF in columns increases deformability, while RHAC behaves similarly to NC.

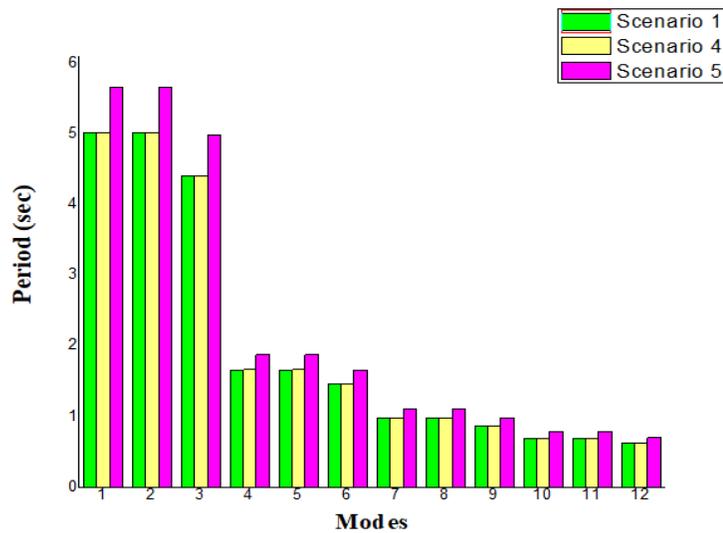


Figure 4: Modal period for columns

Scenario 7 (SFC beams) has the highest modal periods, indicating greater flexibility, while Scenario 6 (RHAC beams) has the lowest, suggesting increased stiffness. Mode 1 reaches 5.267 s (vs. 5.012 s and 4.905 s), and Mode 12 hits 0.659 s (vs. 0.626 s and 0.612 s). SF in beams increases deformability, while RHA enhances rigidity.

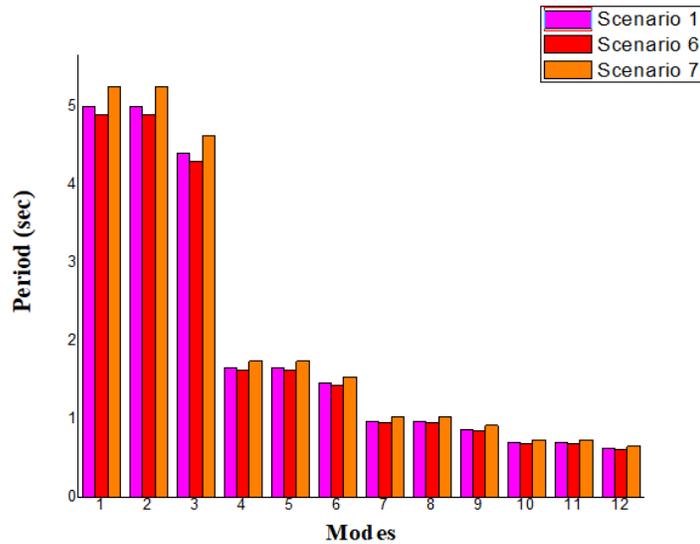


Figure 5: Modal period for beams

Figure 6 shows the modal period for slabs. Scenario 9 (Slab SFC) is the most flexible, while Scenario 8 (Slab RHAC) is the stiffest. In Mode 1, Scenario 9 records 5.23 s, exceeding Scenario 1 (5.012 s) and Scenario 8 (4.89 s). Mode 6 shows Scenario 9 and 1 at 1.467 s, while Scenario 8 registers 1.257 s. Mode 12 confirms Scenario 8's stiffness at 0.526 s. SF increases flexibility, while RHA enhances stiffness, impacting vibration response.

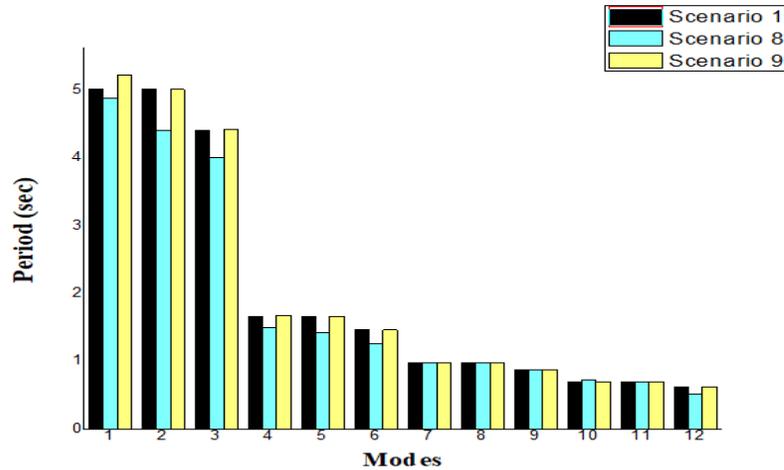


Figure 6: Modal period for Slabs

### 3.2 Mode Shapes

The mode shapes for the building, displaying all the 9 scenarios, with Figure 7 (a)-(i) displaying the mode shapes of building with different scenarios. The figures show the deformability among the structure with different members of pozzolanic materials.

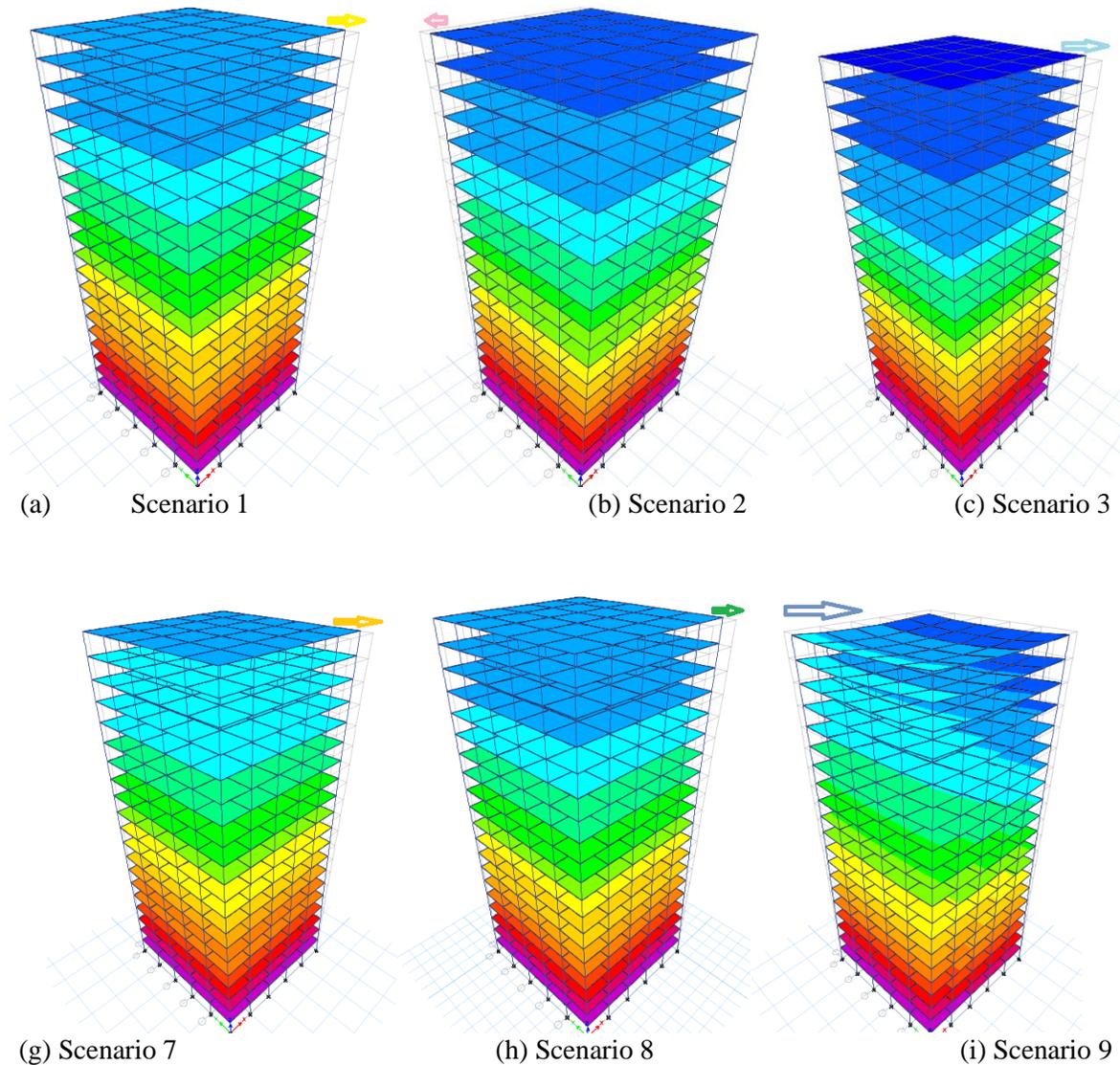


Figure 7 (a-i) : Modal shape of the building scenarios

### 3.3 Displacement

Figure 8 illustrates the variations in maximum displacement for buildings constructed with different concrete types. Normal Concrete (NC) shows balanced performance with  $E_x = 254.91$  mm and  $W_x = 267.11$  mm. RHAC exhibits slightly higher displacements ( $E_x = 256.25$  mm,  $W_x = 272.56$  mm), indicating reduced stiffness. SFC records the highest values ( $E_x = 271$  mm,  $W_x = 284.12$  mm), highlighting increased flexibility. NC resists lateral forces best, while SFC may need extra bracing. In practical seismic design, the choice between SFC and RHAC involves a trade-off: SFC may be employed in non-critical members where flexibility and energy dissipation are beneficial, while RHAC is preferred for primary structural elements (columns, critical beams) where minimizing displacement and drift is essential. The combination of both materials can provide a balanced seismic performance by simultaneously enhancing stiffness and ductility, aligning with modern performance-based design principles.

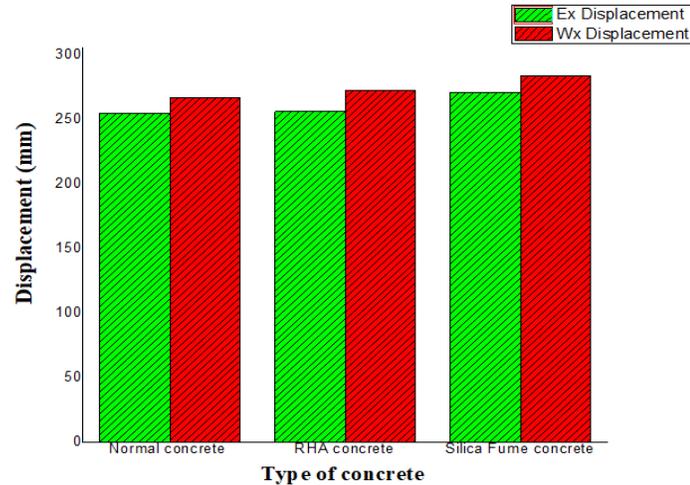


Figure 8: maximum displacement for building constructed with different concrete type

Table 7 shows displacements for building with columns made from NC, RHAC and SFC. Scenario 1 (NC) serves as the baseline (Ex: 254.91 mm, Wx: 257.14 mm). Scenario 4 (RHAC columns) shows a slight stiffness reduction, while Scenario 5 (SFC columns) records the highest displacements (Ex: 268.27 mm, Wx: 281.58 mm), indicating increased deformability and reduced lateral stability.

Table 7: Displacements for building with columns made from NC, RHAC and SFC.

Scenarios	Ex (mm)	Wx (mm)
<b>Scenario 1</b>	254.91	257.14
<b>scenario 4</b>	257.62	262.53
<b>scenario 5</b>	268.27	281.58

The results in Table 8 show variations in structural deformation across the scenarios. Scenario 1 (NC) serves as the reference (Ex: 254.91 mm, Wx: 257.14 mm). Scenario 6 (RHAC beams) shows minimal change (Ex: 255.62 mm, Wx: 274.41 mm), indicating negligible stiffness effects. Scenario 7 (SFC beams) records higher displacements (Ex: 272.13 mm, Wx: 281.2 mm), highlighting increased deformability and reduced stiffness.

Table 8: Displacements for building with Beams made from NC, RHAC and SFC

Scenarios	Ex (mm)	Wx (mm)
<b>Scenario 1</b>	254.91	257.14
<b>scenario 6</b>	255.62	274.41
<b>scenario 7</b>	272.13	281.2

The results in Table 9 indicate how different slab materials affect structural deformation. Scenario 1 (NC) and Scenario 8 (RHAC slab) have identical values (Ex: 2549.091 mm, Wx: 17515.41 mm), indicating no significant stiffness change. Scenario 9 (SFC slab) shows higher displacements (Ex: 287.5 mm, Wx: 291.4 mm), suggesting increased deformability and reduced stiffness, impacting stability under lateral loads.

Table 9: Displacements for building with slabs made from NC, RHAC and SFC

Scenarios	Ex (mm)	Wx (mm)
<b>Scenario 1</b>	254.91	257.14
<b>scenario 8</b>	254.91	257.14
<b>scenario 9</b>	287.5	291.4

### 3.4 Drift

Table 10 present the maximum drift ratio values for different types of concrete in X direction. Normal Concrete has the lowest drift (0.003171), indicating higher stiffness but potential brittleness. RHA Concrete

(0.003217) shows slightly higher drift, with marginal stiffness reduction but improved durability. Silica Fume Concrete (0.004225) exhibits the highest drift, suggesting reduced stiffness but better energy dissipation and seismic performance. The drift results in Table 11 indicate significant variations in lateral deformation across the scenarios. Scenario 1 (All NC) has a drift of 0.003171. Scenario 4 (Columns RHAC) reduces it to 0.000328, enhancing stiffness. Scenario 5 (Columns SFC) increases it to 0.003011, reducing stiffness. RHA improves resistance, while SF increases flexibility, requiring drift control.

Table 10: Drift Values for scenarios

Scenarios	Drift
<b>Scenario 1</b>	0.003171
<b>Scenario 2</b>	0.003217
<b>Scenario 3</b>	0.0004225
<b>scenario 4</b>	0.000328
<b>scenario 5</b>	0.003011
<b>scenario 6</b>	0.003181
<b>scenario 7</b>	0.00338
<b>scenario 8</b>	0.000324
<b>scenario 9</b>	0.000324

Beam drift values are similar across scenarios: Scenario 1 (NC) at 0.003171, Scenario 6 (Beams RHAC) at 0.003181, and Scenario 7 (Beams SFC) at 0.00338. RHA has minimal impact, while SF slightly increases drift. Slab drift shows a significant reduction: Scenario 1 (NC) at 0.003171, while Scenarios 8 (Slab RHAC) and 9 (Slab SFC) drop to 0.000324, enhancing lateral stability. All values comply with Eurocode 8 limits (0.004–0.005), ensuring structural safety.

#### 3.4.1 Linking modal behavior to displacement and drift

The dynamic response differences observed among NC, RHAC and SFC follow the well-known relation  $T_n = 2\pi\sqrt{M_n/K_n}$ . As effective stiffness ( $K_n$ ) increases, modal periods shorten, which aligns with the shorter periods and reduced lateral displacements observed in the RHA-modified mixes (Figures 3 and 8). In contrast, the SF scenarios exhibited longer periods and larger displacements in the baseline models. Although silica fume typically enhances compressive strength and refines microstructure, modal periods are influenced by both stiffness and mass. These findings indicate that RHA mixes can improve structural stiffness, whereas SF mixes require careful modeling of both mass and dynamic modulus to ensure accurate displacement predictions.

#### 3.5 Storey shear

Storey shear analysis (Table 11) shows: Normal Concrete (17265.03 kN), RHA Concrete (17145.16 kN), and SF Concrete (17757.90 kN). RHA reduces shear due to lower density, while SF increases it, enhancing force transfer but requiring stronger foundations. Scenario 5 has the highest shear (17757.90 kN), indicating greater lateral resistance, while Scenario 8 has the lowest (17012.42 kN), suggesting reduced stiffness.

Table 11: Storey shear

Scenarios	Storey shear (kN)
<b>Scenario 1</b>	17265.0322
<b>Scenario 2</b>	17145.16
<b>Scenario 3</b>	17757.90
<b>scenario 4</b>	17251.576
<b>scenario 5</b>	17277.077
<b>scenario 6</b>	17191.809
<b>scenario 7</b>	17330.5747
<b>scenario 8</b>	17012.422
<b>scenario 9</b>	17265.0322

SFC increases storey shear, meaning higher internal forces that must be resisted by stronger foundations and member reinforcement. RHAC reduces shear, which may lead to cost savings in reinforcement and foundation design.

### 3.6 Base reactions

Table 12 compares the base reactions of beams, columns, and slabs made with normal concrete (NC), rice husk ash concrete (RHAC), and silica fume concrete (SFC). Silica fume concrete (SFC) significantly increases vertical force (Fz) compared to normal concrete (NC) and rice husk ash concrete (RHAC). In beams, SFC records 2366.86 kN, higher than NC (1063.49 kN) and RHAC (1021.42 kN). Slabs show a similar trend, with SFC at 2333.23 kN, NC at 1063.49 kN, and RHAC at 1044.22 kN. In columns, SFC reaches 1114.13 kN, surpassing NC (1063.49 kN) and RHAC (1053.24 kN).

Table 12: Base reactions for beams, columns, and slabs made with pozzolanic materials

	<b>F<sub>x</sub> (kN)</b>	<b>F<sub>y</sub> (kN)</b>	<b>F<sub>z</sub> (kN)</b>
<b>Scenario 1</b>	-150.324	-11.7812	1063.491
<b>Scenario 2</b>	-147.018	-13.4443	1165.676
<b>Scenario 3</b>	-151.042	-12.826	1245.677
<b>Scenario 4</b>	-150.339	-11.8274	1053.239
<b>Scenario 5</b>	-152.684	-12.675	1114.133
<b>Scenario 6</b>	-149.741	-11.8294	1021.422
<b>Scenario 7</b>	-147.073	-20.4573	2366.855
<b>Scenario 8</b>	-151.011	-12.456	1044.221
<b>Scenario 9</b>	-149.042	-20.1526	2333.225

### 3.7 Moment distribution

Table 13 shows moment variations under seismic loading. NC records 521 kNm, RHAC lowers it to 448 kNm, while SFC increases it to 652 kNm, indicating higher stiffness. Scenario 5 (SF columns) with the highest moment (697 kNm), while Scenario 8 (RHAC slabs) has the lowest (404 kNm). Beams and slabs show minor variations, with SFC slightly increasing stiffness and RHAC reducing it.

Table 13: Moments of buildings with scenarios

<b>Scenarios</b>	<b>Moment distribution (kN-m)</b>
<b>Scenario 1</b>	521
<b>Scenario 2</b>	448
<b>Scenario 3</b>	652
<b>scenario 4</b>	534
<b>scenario 5</b>	697
<b>scenario 6</b>	559
<b>scenario 7</b>	601
<b>scenario 8</b>	404
<b>scenario 9</b>	493

Higher moments in SFC indicate the need for more robust reinforcement to resist bending. RHAC's lower moments reflect a stiffer, more stable response, reducing the risk of excessive deformation. Combining SFC and RHAC strategically can achieve both ductility and stiffness, optimizing seismic performance.

### 3.8 Overall Efficiency and Feasibility

Table 14 Summarizes Efficiency and feasibility. Table 14 shows RHAC improves stability, while SFC enhances base reactions, offering design-dependent benefits against conventional concrete. These

metrics demonstrate that RHAC improves stiffness and minimizes displacement, ideal for columns and critical beams. SFC increases ductility and energy dissipation but requires additional reinforcement and careful design to manage higher drift and storey shear. A hybrid design using RHAC for primary vertical and horizontal members, combined with SFC in secondary or non-critical members, achieves an optimal balance of seismic resistance, safety, and cost.

Table 14: Efficiency and feasibility

Parameter	RHA Concrete	Silica Fume Concrete
Displacement	+0.53%	+6.31%
Drift	+1.45 %	+ 33.25%
Storey shear	-0.69%	+2.85%
Base reactions	+9.61%	+17.13%

Based on the modal period, displacement, drift, storey shear, and base reaction results, the study identifies optimal concrete types for different structural members to enhance seismic performance:

Columns: RHA-modified concrete (RHAC) is recommended due to its higher stiffness, shorter modal periods, and lower lateral displacements. These properties improve vertical load transfer and reduce overall building sway, enhancing stability under seismic excitation.

Beams: RHA concrete also performs effectively in beams, providing increased rigidity and reduced deflection while maintaining sufficient ductility for seismic energy dissipation.

Slabs: Normal concrete (NC) or RHA concrete is suggested for slabs where stiffness is crucial to minimize diaphragm deformation. SF concrete (SFC) is less preferred for slabs if minimal lateral drift is desired, as it increases flexibility and displacement.

Full structure (integrated): A hybrid approach can optimize seismic resistance: using RHA concrete for columns and critical beams to maximize stiffness, combined with normal concrete for slabs to maintain adequate floor rigidity, while selectively incorporating SF concrete in non-critical beams or secondary elements to allow controlled flexibility and energy dissipation.

In summary, RHA concrete is favored for vertical and primary horizontal elements to enhance stiffness and minimize displacement, whereas SF concrete may be employed selectively for its ductility benefits, balancing structural resilience and energy dissipation. These recommendations align with both the numerical modeling results and literature evidence regarding pozzolanic concrete behaviour under seismic loads (Amran et al., 2021; Lisantono & Pratama, 2020; Chopra, 2012).

### 3.9 Validation

The validation of result based on literature is shown in Table 15.

Table 15: Validation Table

Source/Material	Max Drift	Max storey Shear (kN)	Remarks
Piyush Bhawsa et al. (2023)	0.001339	17304	Reference data for comparison; indicates typical structural performance.
NC	0.003171	17265	Drift is higher than reference, suggesting lower stiffness; base shear aligns closely with the reference.
RHAC	0.003217	17145.2	Slightly higher drift than normal concrete, indicating reduced stiffness; base shear is marginally lower.
SFC	0.004225	17757.9	Highest drift, indicating greater flexibility; highest base shear suggests increased stiffness and lateral force transfer.

Figures 10 and 11 show Scenario 1’s Response spectrum (RS) peaking at 0.2s–0.3s, then stabilizing, while Eurocode 8 (Soil Type C) follows a sharp rise, plateau, and gradual decay. Both align with Taiwan’s Site Class C data, peaking at  $T < 1s$ , confirming expected soil behavior with minor regional variations.

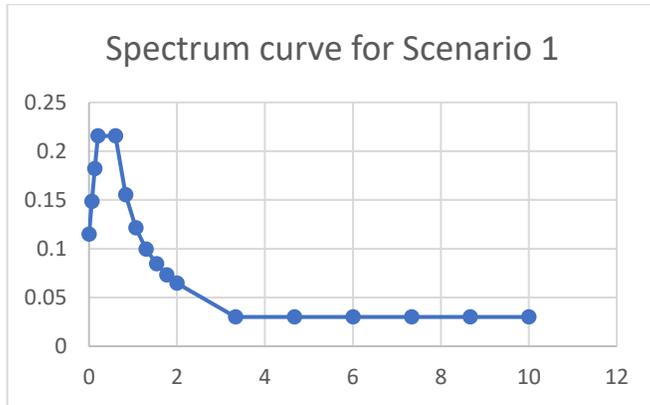


Figure 10: RS for Scenario 1

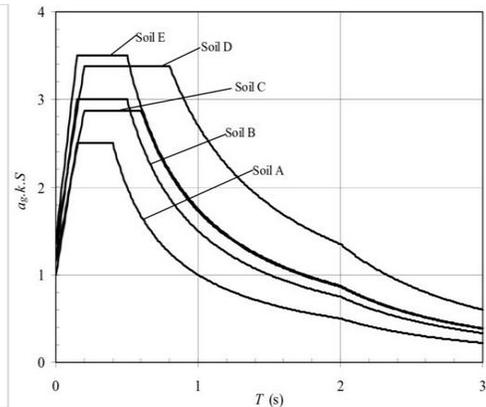


Figure 11: Eurocode 8 RS (Kappos, 2009)

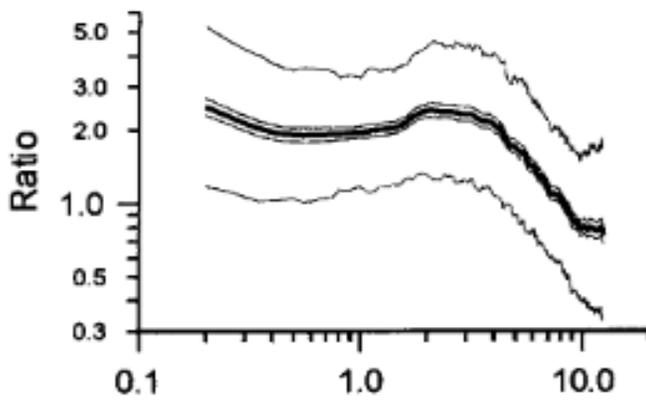


Figure 12: The characteristics of Site Class C amplification functions for the Taiwan region evaluated using the Chi-Chi earthquake data (Sokolov et al., 2004)

#### 4. Conclusion

This study investigated the seismic performance of multi-story reinforced concrete structures incorporating pozzolanic materials, specifically Rice Husk Ash (RHA) and Silica Fume (SF), through numerical simulations. The findings provide insights into the influence of these materials on modal periods, displacement, drift, storey shear, base reactions, and moment distribution under seismic loading. The following are the conclusions:

1. RHA concrete (RHAC) exhibited higher stiffness compared to normal concrete (NC) and SF concrete (SFC), as reflected by shorter modal periods (Mode 1: 4.86 s for RHAC vs. 5.012 s for NC and 6.598 s for SFC) and reduced lateral displacements (Ex: 256.25 mm for RHAC vs. 254.91 mm for NC and 271 mm for SFC). Drift ratios also indicated higher rigidity for RHAC (0.003217) compared to NC (0.003171) and SFC (0.004225). This suggests RHAC is well-suited for columns and critical beams where minimizing sway is crucial.

2. SF concrete increased flexibility, with longer modal periods and higher displacements (Ex: 271 mm, Wx: 284.12 mm), allowing greater energy dissipation. This makes SFC suitable for secondary elements or beams/slabs requiring controlled flexibility.
3. RHAC reduced storey shear slightly (17,145 kN) compared to NC (17,265 kN), while SFC increased it (17,757 kN), indicating higher force transfer. Base reactions were highest for SFC in beams (2,366 kN) and slabs (2,333 kN), while RHAC had lower vertical reactions (Beams: 1,021 kN; Slabs: 1,044 kN), consistent with stiffness trends.
4. NC recorded moments of 521 kNm, RHAC lowered moments to 448 kNm, and SFC increased them to 652 kNm, further supporting the selection of RHAC for primary structural members and SFC for members needing higher deformability.
5. For member-level recommendations, RHA concrete is preferred for columns and critical beams due to its enhanced stiffness and reduced displacement, while normal concrete or RHA concrete is suitable for slabs to maintain adequate diaphragm rigidity, with SF concrete used selectively; at the full-structure level, a hybrid approach that combines RHAC in primary elements and SFC in non-critical members provides a balanced stiffness–ductility response and improves seismic resilience.
6. Incorporating optimal pozzolanic materials improves structural performance under lateral loads, providing a sustainable, low-carbon alternative to conventional concrete without compromising safety.

#### *Limitations*

1. The study relied on simulated properties of concrete based on literature-reported optimums rather than experimental mixes prepared under controlled laboratory conditions.
2. Only two pozzolanic materials (RHA and SF) were considered; other sustainable materials may offer different performance characteristics.
3. The analysis considered a specific high-rise building model; results may vary with different building heights, geometries, and seismic zones.

#### *Future Work*

1. Experimental validation of RHA and SF concrete mixes in multi-story structures to confirm the numerical predictions.
2. Investigation of other pozzolanic or industrial by-product materials for sustainable seismic-resistant concrete.
3. Exploration of hybrid reinforcement strategies, including fiber-reinforced pozzolanic concretes, to further enhance ductility and energy dissipation.
4. Application of the methodology to buildings with diverse geometries, heights, and seismic intensities to generalize findings.

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