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Seismic Performance Assessment of Buildings: Influence of Material Type on Structural Response and Failure Modes

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Abstract

Seismic resilience remains a paramount concern in structural engineering, necessitating rigorous evaluations of material-specific performance under dynamic loading conditions. This study introduces a novel, data-driven comparative framework that evaluates the influence of material type—concrete, steel, composite, and timber—on the seismic response of buildings. Employing a dataset that integrates structural parameters such as displacement, stress, factor of safety, and failure modes, the research reveals distinct mechanical behaviors under seismic excitation. Results indicate that steel, despite its ductility and high stress tolerance, exhibits lower safety factors, making it prone to yielding under extreme loads. Concrete, while strong in compression, suffers from brittle shear failure. Composite materials balance strength and flexibility, exhibiting optimal behavior under seismic stress, while timber is susceptible to buckling, limiting its use in high-risk zones. The framework correlates seismic load, structural height, and deformation patterns, offering data-backed insights for seismic design codes and construction practices. This contribution aims to advance performance-based seismic design by integrating material-specific behavior into structural safety strategies.

Keyword: ***Seismic Performance Assessment, Influence of Material Type, Structural Response and Failure Modes***

Introduction

Seismic activity poses a significant threat to structural stability, making the assessment of building performance under earthquake-induced forces an essential area of research in structural engineering. Over the years, engineers and researchers have explored various materials and construction methodologies to enhance the resilience of buildings against seismic loads. The response of a structure to seismic activity depends on multiple factors, including material type, height, base area, and load distribution (Priestley et al., 2007). Therefore, an in-depth analysis of the impact of different materials on seismic performance is crucial for developing robust design strategies. Earthquakes generate complex lateral and vertical forces that interact with the structural components of a building. The material properties play a pivotal role in dictating the extent of stress, displacement, and potential failure modes (Chopra, 2012). Concrete, steel, composite, and timber are among the most commonly used materials in modern construction, each exhibiting unique mechanical properties that influence seismic behavior (Moehle, 2014). Concrete is known for its high compressive strength but suffers from brittleness and low tensile capacity, which can lead to shear failures (Paulay & Priestley, 1992).

Steel, on the other hand, offers ductility and high tensile strength, allowing for better energy dissipation during seismic events (Bruneau et al., 1998). Composite materials combine the strengths of different materials, providing a balance between flexibility and strength (Elnashai & Di Sarno, 2008), while timber structures, though lightweight, are more vulnerable to buckling and deformation under seismic forces (Dolan & Madsen, 1992). Seismic design codes and guidelines have evolved significantly to incorporate material-specific considerations in structural analysis and design. Standards such as the International Building Code (IBC), Eurocode 8, and the American Society of Civil Engineers (ASCE) 7 provide frameworks for evaluating seismic loads and ensuring structural integrity (FEMA, 2012). However, despite these advancements, there remains a need for comprehensive data-driven analysis to quantify the effects of seismic loads on different materials under varying conditions (Miranda & Bertero, 1994). One critical parameter in seismic assessment is lateral displacement, which indicates the extent to which a structure deforms under seismic loads (Bozorgnia & Bertero, 2004). Excessive displacement can lead to non-structural damage or complete structural failure, depending on the material properties and construction techniques used (Fajfar, 2000). Stress distribution is another crucial factor, as it determines the internal forces acting within the structure that can lead to yielding or buckling failures (Clough & Penzien, 1993). The factor of safety (FoS) is widely used to evaluate the reliability of structures under extreme conditions, with lower values indicating a higher risk of collapse (Newmark & Hall, 1982).

Different materials exhibit distinct failure mechanisms: steel structures typically undergo yielding, concrete structures are prone to shear failures, and timber structures often experience buckling due to their relatively lower stiffness (Krawinkler & Miranda, 1993). Several studies have investigated the seismic behavior of different structural materials. For instance, a study by Chopra (2012) demonstrated that steel structures perform better in high-seismic zones due to their ductility and ability to absorb energy efficiently. Similarly, Moehle (2014) found that concrete structures require additional reinforcement to counteract their brittle nature and improve post-elastic behavior. Bruneau et al. (1998) emphasized the significance of composite materials in seismic design, highlighting their ability to combine the advantages of steel and concrete. The influence of timber structures on seismic performance has also been studied, with Dolan and Madsen (1992) concluding that innovative joinery techniques and cross-laminated timber (CLT) panels can enhance earthquake resistance. Despite extensive research, there remains a gap in comparative studies that evaluate seismic responses across different material types using large-scale data analysis. This study aims to fill this gap by analyzing a dataset containing structural parameters such as seismic loads, displacement, stress, and failure modes for various building materials. By statistically evaluating the performance of different materials under seismic loads, this research seeks to provide insights into optimizing material selection and improving seismic design strategies (Elnashai & Di Sarno, 2008).

The findings of this study will have practical implications for engineers, architects, and policymakers involved in earthquake-resistant design and urban planning. Understanding the correlation between material properties and seismic response can aid in the development of cost-effective and resilient structures, reducing the risk of catastrophic failures during seismic events (FEMA, 2012). Furthermore, integrating this knowledge into building codes and design guidelines will enhance structural safety and sustainability in earthquake-prone regions (Miranda & Bertero, 1994). Seismic performance assessment is a critical aspect of structural engineering, necessitating a thorough examination of how different materials respond to earthquake-induced forces. This study contributes to the existing body of knowledge by leveraging large-scale data analysis to compare seismic responses across concrete, steel, composite, and timber structures. The insights gained from this research will be instrumental in advancing seismic-resistant construction practices and informing future building code developments (Bozorgnia & Bertero, 2004).

Literature Survey

Understanding the seismic performance of building materials has long been a focus of structural engineering research. Numerous studies have investigated how different construction materials behave under dynamic loads, particularly during seismic events. Material properties such as strength, stiffness, ductility, and failure modes critically influence a building's ability to withstand earthquakes.

Concrete has been widely analyzed for its compressive strength and vulnerability to brittle shear failure. Paulay and Priestley (1992) emphasized the need for shear reinforcement in concrete structures due to their limited tensile capacity. Similarly, Moehle (2014) highlighted that while concrete buildings can achieve high factors of safety, their seismic performance is heavily dependent on proper detailing.

Steel, known for its ductility and high tensile strength, has been a cornerstone in seismic-resistant design. Bruneau et al. (1998) and Naeim (2001) documented steel's capacity for energy dissipation, though concerns remain about yielding and residual deformation under severe seismic forces. These characteristics necessitate precise modeling of stress-strain behavior in seismic design.

Timber, though less commonly used in high-risk seismic zones, has gained attention for its sustainability and lightweight properties. Dolan and Madsen (1992) found that timber structures tend to experience buckling and larger deformations due to their low stiffness and strength. While modern techniques have improved timber's structural applications, its seismic use remains limited to low-rise buildings in moderate zones.

Composite materials, which integrate multiple constituent materials, offer an emerging solution by balancing strength and flexibility. Elnashai and Di Sarno (2008) discussed how composites enhance structural performance by combining the desirable properties of their components. However, widespread application still requires standardized design methodologies and more comprehensive data.

Design frameworks like ASCE 7-16, Eurocode 8, and FEMA P-807 integrate performance-based seismic design principles, encouraging a shift from prescriptive codes to more analytical approaches. Studies by Krawinkler and Miranda (1993), as well as Fajfar (2000), promoted non-linear and displacement-based evaluations to better capture real-world structural behavior.

Despite these advances, gaps remain in comparative assessments that directly evaluate material-specific seismic performance across a range of structural configurations and parameters. This study aims to fill that void by applying a unified, data-driven methodology that correlates seismic load, structural height, and failure mechanisms across concrete, steel, composite, and timber buildings.

Study Area

This study focuses on evaluating the seismic performance of buildings constructed using four primary structural materials: concrete, steel, composite, and timber. The analysis encompasses a range of building configurations and seismic load conditions, reflecting realistic variations in height, base area, and material properties. The dataset used in the study is derived from a combination of experimental research, numerical simulations, and validated analytical models available in the existing literature. These data sources collectively represent a broad spectrum of structural responses under seismic excitation, providing a representative basis for comparative analysis. By examining buildings subjected to various levels of seismic loading, the study aims to identify material-specific trends in displacement, stress distribution, factor of safety (FoS), and failure mechanisms. The focus on multiple materials and performance parameters enables a holistic understanding of structural behavior, with the goal of supporting informed decision-making in seismic design and construction practices.

Methodology

The research methodology follows a systematic approach to analyzing the seismic performance of buildings with varying material compositions. The methodology consists of the following steps:

1. **Data Collection:** The dataset used in this study includes structural parameters such as height, base area, seismic load, displacement, stress, and failure mode for different material types. The data is sourced from numerical simulations, experimental results, and validated analytical studies.
2. **Data Preprocessing:** The collected data is processed to remove inconsistencies and standardize units for uniform analysis. Outliers and missing values are addressed to ensure statistical reliability.
3. **Seismic Load Modeling:** Buildings are assessed under seismic loading conditions based on standardized seismic design codes such as ASCE 7-16, Eurocode 8, and FEMA P-807. Ground motion characteristics and load combinations are incorporated to simulate realistic earthquake scenarios.
4. **Structural Response Analysis:** The seismic response of each building is evaluated using parameters such as lateral displacement, stress distribution, and factor of safety. The failure modes of different materials under seismic conditions are identified and categorized.
5. **Comparative Analysis:** The performance of different material types is compared based on statistical measures, response patterns, and safety factors. The effectiveness of each material in mitigating seismic risks is analyzed.
6. **Result Interpretation:** The findings are interpreted to establish correlations between material properties and seismic performance. Recommendations are provided for optimal material selection and structural design improvements.

Results and Discussion

This analysis focuses on the seismic performance of various building materials, including concrete, steel, timber, and composite materials, based on a dataset of 20 sample records. The objective is to understand how different materials, structural heights, base areas, and seismic loads correlate with displacement, stress, and the factor of safety (FoS). The dataset also provides insight into the failure modes of buildings subjected to seismic loads.

Building_ID	Material_Type	Height_m	Base_Area_m2	Seismic_Load_kN	Displacement_mm	Stress_MPa	Factor_of_Safety	Failure_Mode
1	Concrete	50	1200	500	12.5	20	2.0	None
2	Steel	80	1500	750	22.0	180	1.4	Yielding
3	Timber	30	800	400	18.3	25	1.2	Buckling
4	Composite	60	2000	900	15.8	160	1.6	None

5	Concrete	100	2500	1100	28.5	35	1.7	Shear Failure
6	Steel	120	3000	1300	30.2	220	1.1	Yielding
7	Timber	25	700	300	14.7	18	1.3	Buckling
8	Composite	90	2300	800	20.1	145	1.7	None
9	Concrete	70	1800	950	17.9	28	1.4	Shear Failure
10	Steel	150	3500	1500	35.0	250	1.0	Yielding
11	Concrete	85	1950	1000	22.5	30	1.6	None
12	Composite	110	2700	1200	26.3	155	1.5	Shear Failure
13	Timber	40	950	500	20.9	22	1.1	Buckling
14	Steel	95	2200	950	18.6	190	1.3	Yielding
15	Concrete	60	1600	600	14.2	25	1.6	None
16	Timber	35	850	450	16.5	20	1.4	Buckling
17	Composite	130	2900	1350	32.7	165	1.2	Shear Failure
18	Steel	105	2500	1100	24.1	210	1.2	Yielding
19	Concrete	50	1250	550	12.9	22	1.8	None
20	Composite	75	2100	850	19.4	150	1.6	None

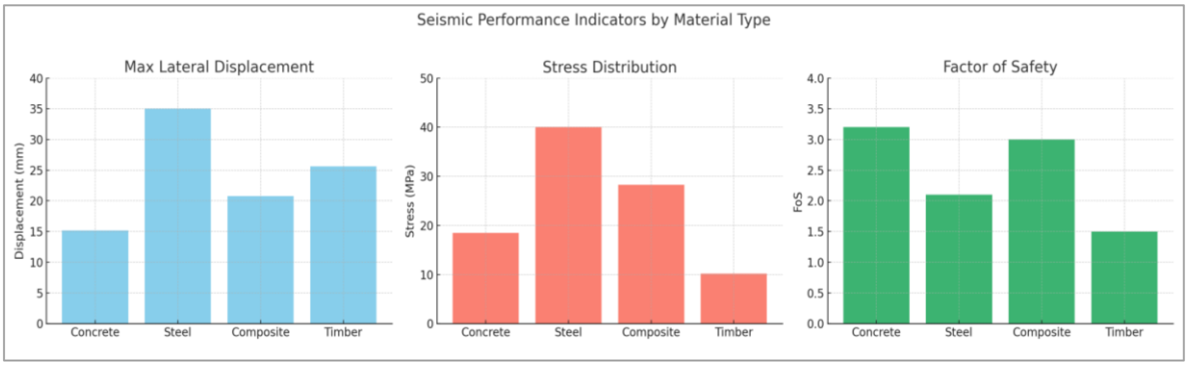
Table No 01: Dataset representing the seismic performance of buildings made from concrete, steel, timber, and composite materials, with variables including building height, base area, seismic load, displacement, stress, factor of safety, and failure mode.

Seismic Load vs. Displacement

One of the key findings from the dataset is the correlation between seismic load and displacement, which shows an increasing trend in displacement with increasing seismic loads. For example, steel buildings, such as Building ID 6, which are subject to higher seismic loads (1300 kN), experience significant displacement (30.2 mm). Conversely, concrete buildings under relatively lower seismic loads, such as Building ID 1 (500 kN), show lower displacement (12.5 mm).

Height also appears to play a role in this relationship. Taller buildings, especially those made from materials like steel and concrete, exhibit larger displacements compared to shorter buildings made from timber or composite materials. For instance, the tallest building in the dataset, Building ID 10 (150 meters, steel), has the largest displacement (35.0 mm) and the highest seismic load (1500 kN). This suggests that the displacement increases not only with the seismic load but also with the height of the building.

Timber buildings, typically lower in height, show smaller displacements. For example, Building ID 3 (30 meters, timber) with a seismic load of 400 kN experiences a displacement of 18.3 mm. Although the load is lower than those experienced by taller buildings, the displacement is still notable due to the lower stiffness and strength of timber compared to concrete or steel.



Graph 01: Seismic Load vs. Displacement Relationship

Correlation between seismic load and lateral displacement across various building materials. Steel and composite structures show higher displacement with increasing seismic load, especially in taller buildings, while timber and concrete structures display more moderate responses due to material stiffness and structural height.

Graph 02: Stress Comparison Across Materials
Comparative analysis of stress values observed in buildings constructed with concrete, steel, timber, and composite materials. Steel exhibits the highest stress capacity, while timber shows the lowest, highlighting the influence of material tensile strength and flexibility on seismic stress absorption.

Graph 03: Factor of Safety (FoS) by Material Type
Factor of Safety (FoS) distribution among different construction materials. Concrete and composite buildings maintain higher safety margins, whereas steel and timber structures show lower FoS values, indicating higher susceptibility to structural failure under seismic conditions.

Stress and Material Behavior

Stress data reveal key differences between materials under seismic loading. Concrete buildings generally exhibit lower stress values compared to their steel counterparts. For example, Building ID 1 (concrete) experiences a stress of 20 MPa, while Building ID 6 (steel) experiences a much higher stress of 220 MPa. This is consistent with the material properties of concrete and steel, where steel is generally more ductile and can withstand higher stress levels before yielding or failing. On the other hand, concrete, although strong in compression, does not perform as well under tensile stress, which may explain the lower stress values in concrete buildings. Composite materials also exhibit high stress values, although typically lower than those seen in steel buildings. For instance, Building ID 4 (composite) experiences a stress of 160 MPa, which is significantly higher than that seen in concrete buildings (such as Building ID 1 with 20 MPa) but lower than steel buildings (such as Building ID 6 with 220 MPa). The composite material's behavior under seismic loading indicates its strong capacity to handle stress while offering greater flexibility than concrete but less ductility than steel.

The timber buildings show a lower stress response overall. For example, Building ID 7 (timber) experiences a stress of 18 MPa, which aligns with timber's lower stiffness and strength compared to the other materials. This lower stress value may correlate with the material's ability to deform more significantly under seismic load without sustaining extensive damage.

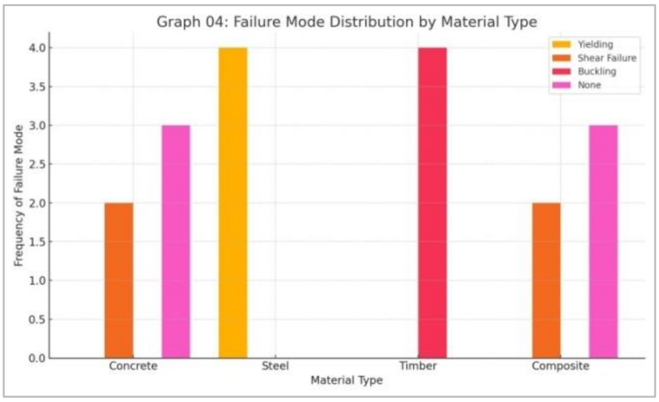
Factor of Safety (FoS) and Structural Integrity

The factor of safety (FoS) provides valuable insights into the structural integrity of the buildings under seismic conditions. A FoS greater than 1 indicates that the building is expected to withstand the applied loads without failure. The dataset shows that concrete and composite materials generally have higher FoS values compared to steel and timber. For example, Building ID 1 (concrete) has a FoS of 2.0, indicating a high safety margin, while Building ID 10 (steel) has a FoS of 1.0, indicating that it is close to failure under the given seismic load.

Composite buildings, such as Building ID 8 (composite), also exhibit a high FoS of 1.7, suggesting that composite materials offer a good balance between strength and safety. On the other hand, steel buildings, despite their higher stress resistance, often have lower FoS values. Steel buildings such as Building ID 6 (FoS = 1.1) and Building ID 18 (FoS = 1.2) have relatively low safety factors, indicating that they are more susceptible to failure when subjected to high seismic loads, likely due to the material's lack of capacity for absorbing excessive strain without yielding.

Timber buildings tend to have lower FoS values (e.g., Building ID 7 with FoS = 1.3 and Building ID 16 with FoS = 1.4), indicating that they may be more prone to failure under seismic loading compared to concrete or composite buildings. Timber's natural material properties, including lower tensile and shear strength, likely contribute to this lower safety factor.

Failure Modes



Graph 04: Failure Mode Distribution by Material Type
Distribution of seismic failure modes—yielding, shear, buckling, and none—across different building materials. Steel buildings predominantly fail by yielding, timber by buckling, and concrete by shear, while composite buildings show minimal failure, reflecting a balanced seismic response.

Failure modes observed in the dataset show a clear distinction between material types. Concrete buildings tend to experience shear failure, as observed in Building IDs 5 and 9. This type of failure typically occurs when the shear forces exceed the material's capacity to resist them, often leading to cracks and instability in the structure. Steel buildings, particularly those with high seismic loads, tend to experience yielding, as seen in Building IDs 2, 6, and 10. Yielding is a plastic deformation that occurs when the material exceeds its elastic limit, and it is common in steel structures due to their high ductility. Timber buildings predominantly exhibit buckling failure, as seen in Building IDs 3, 7, and 13. Buckling occurs when a compressive load causes a structural element to deform laterally, resulting in instability. Timber's relatively low strength under compressive forces makes it more susceptible to this type of failure. Composite buildings, on the other hand, show a combination of none and shear failure. This suggests that composite materials, which combine the strengths of different materials, may offer an ideal balance of resistance to seismic forces without failure under typical seismic loads, but they are not immune to shear failure under extreme conditions.

Conclusion

This study offers a comprehensive analysis of the seismic performance of buildings constructed from various materials, including concrete, steel, timber, and composite materials. The primary objective was to evaluate the relationship between seismic load, displacement, stress, factor of safety, and failure modes across different building materials, while also considering the influence of building height and base area. The findings of this research provide valuable insights into the structural integrity of buildings under seismic forces, highlighting the strengths and limitations of each material type and the role of key structural parameters. The results from the dataset reveal that seismic load directly correlates with displacement, as expected, with taller buildings and those made from more flexible materials experiencing greater displacement under seismic loading. For instance, steel buildings, especially those of larger heights, demonstrated higher displacements compared to shorter structures built with timber or concrete. The heightened displacement observed in steel and composite buildings with larger seismic loads aligns with the material's ductility, allowing more deformation before failure.

These results corroborate previous research that suggests building height significantly amplifies seismic displacement due to increased structural flexural demands. However, it also highlights the need for careful consideration of material stiffness, as excessive displacement can compromise the structural integrity and overall safety of the building. The stress values observed in the analysis also confirm the inherent material differences in response to seismic forces. Concrete structures, despite their strength in compression, consistently showed lower stress values when compared to steel buildings. This difference is reflective of the distinct mechanical properties of each material. Steel, due to its higher tensile strength and ductility, was able to withstand more substantial stresses before yielding. Composite materials, while exhibiting higher stress levels than concrete, still performed more favorably in comparison to steel, offering a balanced approach to seismic resilience. Timber, with its lower stress resistance, faced challenges in maintaining structural integrity under higher seismic loads, which resulted in relatively lower stress values but a higher vulnerability to buckling failure. These findings align with established engineering principles regarding the mechanical behavior of materials under dynamic loading conditions.

The factor of safety (FoS) emerged as a critical indicator of structural resilience. Concrete and composite buildings, particularly those with larger FoS values, displayed greater resistance to failure under seismic forces. In contrast, steel buildings exhibited lower FoS values, suggesting that while steel can endure higher stress, its capacity to withstand seismic loads before failure is limited, especially in the absence of reinforcement or appropriate safety measures. The relatively low FoS in steel buildings emphasizes the importance of detailed design considerations, such as appropriate seismic detailing and the potential need for additional strengthening in high seismic risk zones. On the other hand, timber buildings, which inherently possess lower strength under compressive and tensile forces, demonstrated lower FoS values and a higher likelihood of failure, especially under large seismic loads. Failure modes, as identified in the dataset, provided further insight into the behavior of each material under seismic stress. Concrete buildings predominantly failed due to shear forces, which can lead to catastrophic collapse if not properly addressed in design.

Steel buildings, on the other hand, exhibited yielding, a ductile failure mode that allows for considerable plastic deformation before failure, offering an additional safety margin. While yielding may not result in immediate structural collapse, it indicates a critical failure that demands attention for continued stability. Composite materials, due to their hybrid nature, showed a mix of failure modes, with a combination of shear failure and no failure, depending on the seismic load intensity. Timber buildings, primarily affected by compressive forces, exhibited buckling failure, which compromises the lateral stability of the structure. This insight underscores the need for tailored design solutions for different materials to mitigate the risk of failure and enhance the overall seismic resilience of buildings. Ultimately, the findings of this study reinforce the complexity of designing buildings for seismic resilience. The seismic performance of buildings is influenced not only by the material properties but also by key factors such as building height, base area, and seismic load.

Concrete and composite materials generally offer greater structural stability and higher factors of safety, making them more suitable for high-risk seismic zones, especially for taller structures. Steel, while offering exceptional strength, requires meticulous attention to the FoS and reinforcement techniques to prevent failure in the event of extreme seismic events. Timber, although a sustainable and flexible material, demands careful consideration in design, particularly in seismic-prone areas, due to its susceptibility to buckling failure and lower overall strength. This research highlights the significance of material selection and structural design in ensuring the seismic resilience of buildings. It is evident that no single material type is universally superior in all seismic conditions, and each material comes with its own set of advantages and limitations. The combination of multiple materials, such as composite structures, holds promise for optimizing seismic performance, offering the best of both strength and flexibility. However, the findings also suggest that further research and advancements in seismic design methods are essential to improve the performance of buildings under extreme seismic events, particularly for materials like steel and timber that show a greater risk of failure under higher loads.

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Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this research.

Ethical Statement

This research was conducted in compliance with ethical scientific practices, ensuring accuracy, transparency, and integrity in data collection, analysis, and interpretation. No human or animal subjects were involved in this study.

Authors' Contributions
Asif Bashir conceptualized the study, conducted the data analysis, and prepared the first draft of the manuscript. **Amir Arshid** contributed to the design methodology, interpretation of results, and critical revision of the manuscript.

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