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EARTHQUAKE-RESISTANT BUILDING DESIGN: INNOVATIONS AND CHALLENGES

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ABSTRACT

This study provides a comprehensive systematic review of innovations in earthquake-resistant building design, focusing on advancements in materials, technologies, and methodologies aimed at enhancing structural resilience. A total of 32 peer-reviewed articles were analyzed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The findings highlight the critical role of advanced materials such as fiber-reinforced polymers (FRPs) and shape memory alloys (SMAs) in improving seismic performance, particularly through enhanced energy dissipation and structural flexibility. Technological integrations like Building Information Modeling (BIM), artificial intelligence (AI), and structural health monitoring (SHM) systems were identified as transformative tools that optimize design processes, predict structural vulnerabilities, and enable real-time risk management. Advanced simulation techniques, including finite element analysis (FEA) and computational fluid dynamics (CFD), were shown to significantly improve the accuracy and efficiency of seismic design. Despite these innovations, challenges related to cost, regulatory inconsistencies, and limited access to cutting-edge technologies persist, particularly in developing regions. The study concludes that while these advancements have revolutionized earthquake-resistant design, further efforts are needed to address these barriers and promote global resilience to seismic hazards.

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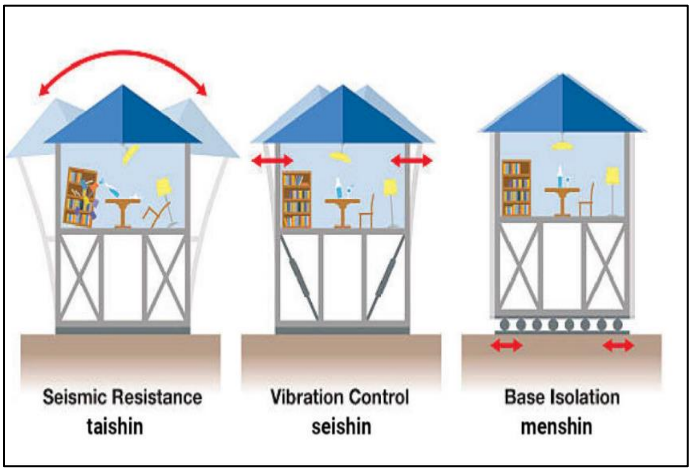
1 Introduction

Earthquakes pose a significant threat to both human lives and infrastructure, making earthquake-resistant building design a critical focus in the field of civil engineering. Over the past century, seismic events have caused widespread destruction, demonstrating the need for resilient infrastructure capable of withstanding ground shaking. The evolution of earthquake engineering has been driven by the desire to mitigate the devastating effects of earthquakes on buildings and communities. According to Rahgozar et al. (2016), the increasing frequency and intensity of seismic activities worldwide underscore the necessity for continued innovation in this area. From the early adoption of basic reinforcement techniques to the integration of advanced materials and technologies, the field of earthquake-resistant design has witnessed remarkable progress, yet challenges persist in creating structures that can adapt to varied seismic forces across different geographical regions. Thus, the exploration of seismic engineering principles remains crucial as urbanization and population density in high-risk areas increase globally (Qureshi & Warnitchai, 2016).

The importance of earthquake-resistant building design extends beyond protecting human life, as it also has substantial economic implications. The collapse of infrastructure during earthquakes can lead to massive economic losses, as was demonstrated by events such as the 1994 Northridge earthquake in California and the 2011 Great East Japan earthquake. According to Moradi and Burton (2018), the economic impact of seismic events can be staggering, with recovery costs often reaching billions of dollars. Investing in resilient infrastructure not only reduces the immediate loss of life but also decreases long-term economic disruptions. Buildings designed with seismic forces in mind employ features such as reinforced concrete, flexible steel frames, and base isolation systems, all of which play a critical role in minimizing damage and maintaining structural integrity (Rosenboom & Kowalsky, 2004). By ensuring the longevity and resilience of buildings, especially in earthquake-prone areas, communities can significantly reduce the financial burden of reconstruction and recovery, thus fostering economic stability.

Figure 1: Seismic Resistance, Vibration Control, and Base Isolation Techniques



In addition to economic benefits, earthquake-resistant building design contributes to societal well-being by safeguarding critical infrastructure. Hospitals, schools, emergency response centers, and transportation networks are vital during and after seismic events. According to Lagomarsino (2014), protecting these essential services ensures the continuity of operations and facilitates rapid response and recovery efforts. In regions such as California and Japan, where earthquakes are frequent, the adoption of resilient building standards has been instrumental in reducing casualties and maintaining functional public services during crises (Khanmohammadi & Heydari, 2015). Moreover, as Rosenboom and Kowalsky (2004) highlight, resilient infrastructure can help alleviate social instability by providing safe spaces for displaced populations and reducing the societal stress associated with post-disaster recovery. Therefore, the importance of earthquake-resistant design extends beyond individual buildings to the overall resilience and functionality of entire cities and regions.

The role of materials and construction techniques in earthquake-resistant design is a significant area of focus within the field. Advances in materials science have led to the development of new building materials that offer enhanced strength, flexibility, and energy dissipation properties. For instance, shape memory alloys and high-

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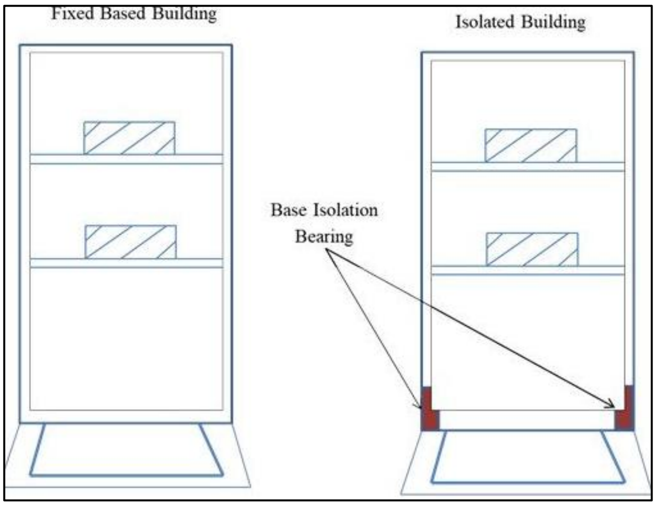
performance fiber-reinforced concrete (HPFRC) have been shown to improve the structural performance of buildings during seismic events (Ajrab et al., 2004). According to Khanmohammadi and Heydari (2015), such materials provide a combination of rigidity and flexibility that allows structures to absorb and dissipate seismic energy effectively. In tandem with advanced materials, modern construction techniques like modular construction and precast systems are being used to enhance building resilience while maintaining cost efficiency (Hu & Wang, 2021). These innovations in materials and construction techniques are key to meeting the increasing demand for earthquake-resistant buildings in seismic zones across the globe.

Figure 2: Comparison of Fixed-Base and Base-Isolated Buildings



The integration of emerging technologies is also reshaping the future of earthquake-resistant building design. Building Information Modeling (BIM) and structural health monitoring systems have been instrumental in improving the design, construction, and maintenance of resilient structures. According to Marzok and Lavan, (2021), BIM allows for detailed simulation and analysis of how buildings will respond to seismic forces, enabling engineers to optimize designs before construction begins. Structural health monitoring systems, on the other hand, provide real-time data on the performance of buildings during earthquakes, allowing for immediate post-event assessments and facilitating timely repairs (Perez et al., 2004). These technologies not only enhance the resilience of new structures but also support the retrofitting of existing buildings to meet modern seismic standards. As engineers continue to refine these tools, the future of earthquake-resistant building design will likely see even greater levels of integration between advanced materials, innovative construction techniques, and cutting-edge technologies.

The primary objective of this paper is to systematically explore the principles, innovations, and challenges associated with earthquake-resistant building design. It seeks to highlight the significance of resilient infrastructure in mitigating the impacts of seismic events on both human life and property. To achieve this, the paper aims to assess key components of seismic engineering, including the analysis of seismic forces and the structural responses they induce. A thorough evaluation of construction materials such as reinforced concrete, steel, and advanced composites will be conducted, along with a review of innovative construction techniques like precast systems and modular design. Furthermore, the paper will investigate design strategies that enhance resilience, such as energy dissipation mechanisms, redundancy, and ductility, through the lens of performance-based design approaches. Case studies of existing earthquake-resistant structures will be analyzed to identify best practices and lessons learned. In addition, the integration of emerging technologies like Building Information Modeling (BIM) and structural health monitoring systems will be examined to understand their contributions to seismic resilience. Ultimately, this paper seeks to provide insights into current trends, identify areas for improvement, and contribute to the advancement of best practices in earthquake-resistant building design.

2 Literature Review

The design of earthquake-resistant buildings has evolved significantly over the past decades, driven by advancements in engineering, materials science, and technology. This literature review aims to provide a comprehensive examination of the existing body of research on earthquake-resistant building design, focusing on key principles, materials, and design strategies. The review draws on a wide range of studies

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that explore the theoretical foundations of seismic engineering, innovations in construction materials, and the implementation of modern techniques to improve structural resilience. Furthermore, the review highlights emerging trends in the integration of technology, such as Building Information Modeling (BIM) and structural health monitoring systems, which are reshaping the field. By examining both historical developments and contemporary research, this section aims to synthesize the current state of knowledge, identify gaps, and provide insights into the challenges and opportunities that lie ahead in advancing earthquake-resistant building practices.

2.1 Historical Development of Earthquake-Resistant Building Design

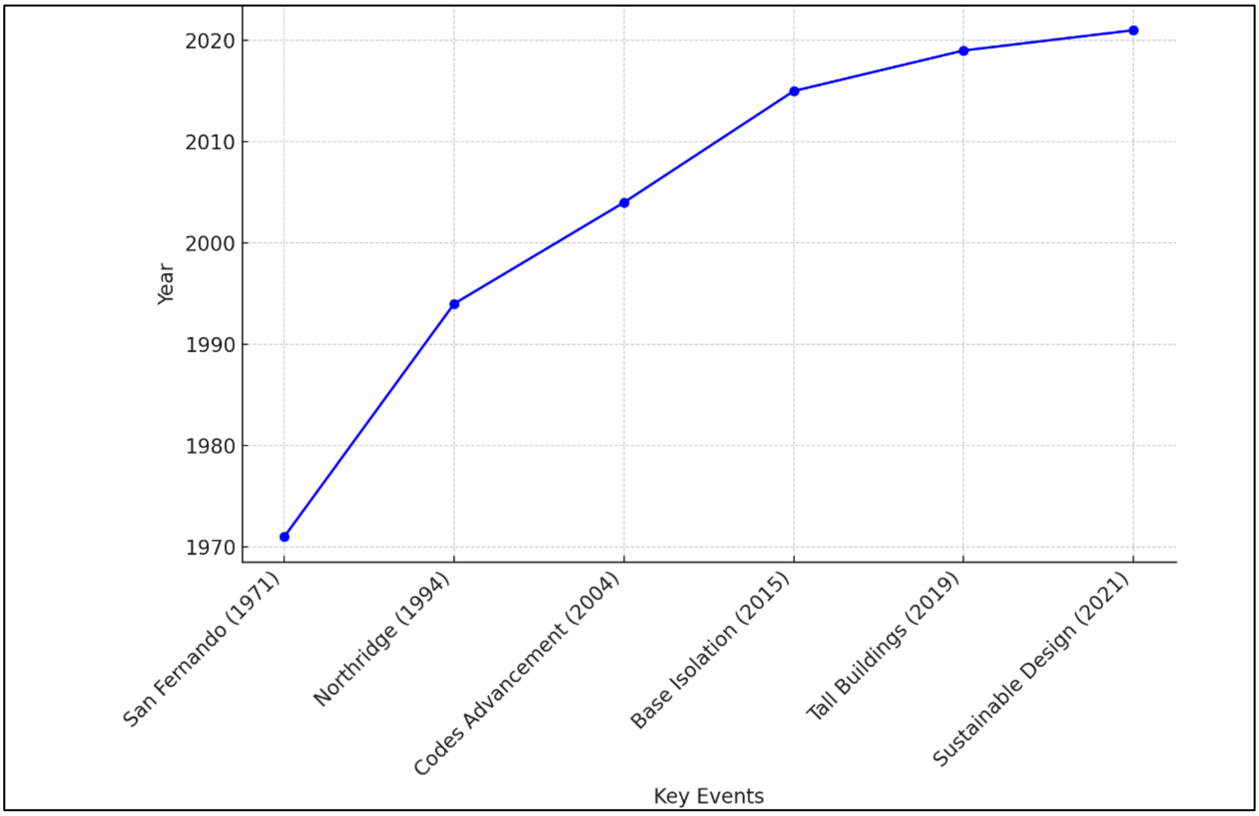
The historical development of earthquake-resistant building design has been significantly shaped by catastrophic seismic events throughout history. Early records of major earthquakes, such as the 1556 Shaanxi earthquake in China and the 79 AD eruption of Mount Vesuvius, highlight the vulnerability of human settlements to seismic activity (Hu et al., 2020). Despite these early events, modern seismic engineering did not emerge until the early 20th century, following major disasters such as the 1906 San Francisco earthquake and the 1923 Great Kanto earthquake in Japan. These events caused widespread destruction and triggered the formal study of seismic forces on structures, laying the groundwork for the development of seismic-resistant building codes and standards (Hu & Wang, 2021). The increased understanding of seismic behavior and structural responses initiated a shift from basic reinforcement practices to more sophisticated engineering approaches that could withstand dynamic loads (Perez et al., 2004).

The evolution of seismic engineering practices in the mid-to-late 20th century was largely driven by disasters such as the 1971 San Fernando earthquake and the 1994 Northridge earthquake in California. These events exposed weaknesses in existing building practices and provided engineers with crucial data on the performance of different structural designs under seismic stress (Roh & Cimellaro, 2011). According to Di Egidio et al. (2020), these earthquakes catalyzed the development of more robust building codes that emphasized the importance of ductility, redundancy, and energy dissipation in resisting seismic forces. Techniques such as base isolation and energy dissipation systems, which had been theorized but rarely implemented, became more widespread in seismic-resistant building design after these events (Holden et al., 2003). The incorporation of structural dynamics and soil-structure interaction into seismic design further advanced the field, making it a specialized area of study that integrates multiple engineering disciplines (Guo et al., 2017).

As seismic engineering evolved, innovations in materials science played a critical role in improving the resilience of buildings. The use of high-strength materials like steel and reinforced concrete became standard practice, allowing for greater flexibility and strength in structural designs (Aghagholizadeh & Makris, 2018). The development of new materials, such as high-performance fiber-reinforced concrete (HPFRC) and shape memory alloys, has further enhanced the ability of buildings to withstand seismic forces by providing both rigidity and flexibility (Mottier et al., 2017). Base isolation systems and damping technologies, such as tuned mass dampers and viscous dampers, have been increasingly incorporated into modern building designs to absorb and dissipate seismic energy, reducing the forces transmitted to the structure (Priestley & Macrase, 1996). According to Blebo and Roke (2018), these technological advancements have been critical in improving the performance of tall buildings and critical infrastructure during seismic events.

In recent years, the integration of emerging technologies has reshaped earthquake-resistant building design. Building Information Modeling (BIM) has become an essential tool in the design and analysis of earthquake-resistant structures, allowing engineers to simulate and optimize the performance of buildings under seismic loads before construction begins (Zhong & Christopoulos, 2021). Structural health monitoring systems, which provide real-time data on the performance of buildings during and after seismic events, have also become more prevalent, enabling timely assessments and repairs (Wight et al., 2007). Furthermore, performance-based seismic design, which focuses on designing structures to meet specific performance objectives during seismic events, has gained traction as a more flexible and effective approach than traditional code-based methods (Xiangmin et al., 2021). As climate change and urbanization increase the risk of seismic events in certain regions, future research will likely focus on enhancing these technologies and materials, as well as developing more sustainable and cost-effective solutions for earthquake-resistant infrastructure (Hayashi et al., 2018).

Figure 3: Dot Plot with Line of Recent Advancements in Earthquake-Resistant Building Design



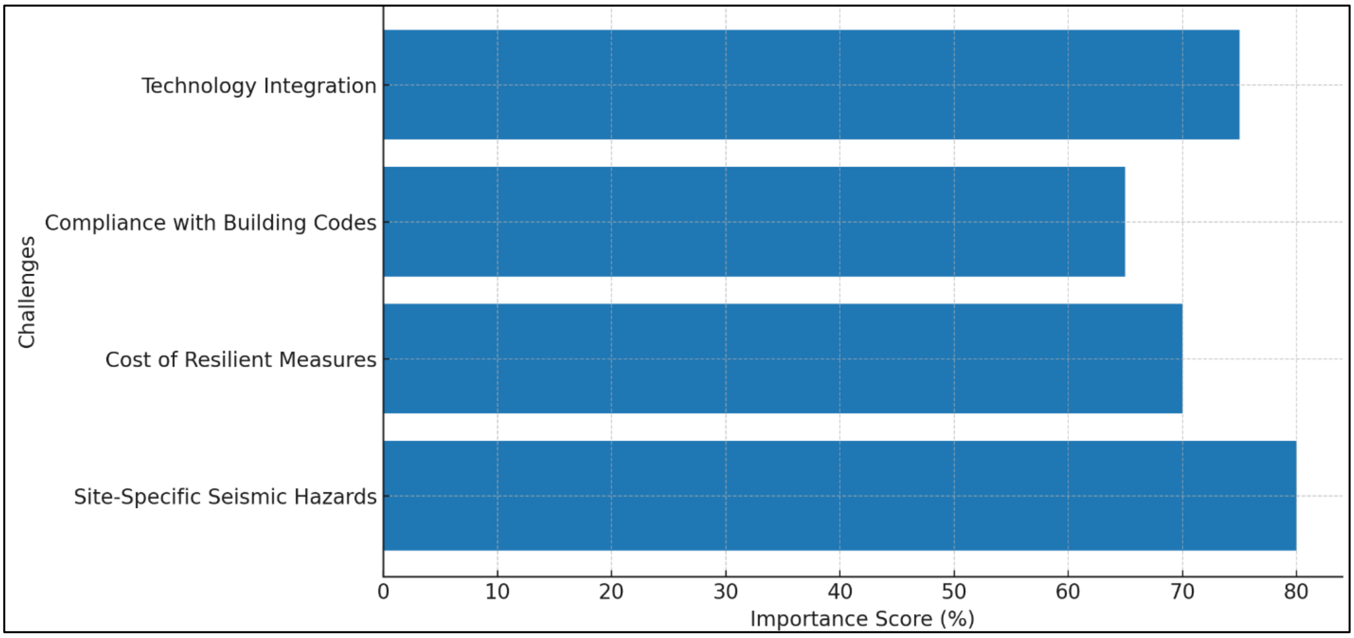
2.2 Site-Specific Seismic Hazards and Geotechnical Challenges

One of the primary challenges in earthquake-resistant building design is the site-specific nature of seismic hazards. The geological and geotechnical characteristics of a location play a crucial role in determining how structures respond to seismic forces (Kamperidis et al., 2018). Soil type, for example, can amplify seismic waves and increase the risk of structural damage. Studies by Wight et al. (2007) have shown that soft soils tend to amplify ground motion, leading to greater forces on buildings, while rocky soils may attenuate seismic waves, offering better protection. Additionally, proximity to fault lines can pose significant risks, as demonstrated by the 1999 İzmit earthquake in Turkey, where buildings near fault ruptures experienced catastrophic failures (Xiangmin et al., 2021). Addressing these geotechnical challenges requires engineers to conduct detailed site assessments and incorporate site-specific design strategies, such as soil stabilization techniques or foundation improvements, to ensure structural resilience in varying ground conditions (Midorikawa et al., 2006).

Another critical challenge in earthquake-resistant building design is the cost associated with implementing resilient measures. The incorporation of advanced materials, technologies, and design strategies often increases the overall cost of construction, which can be prohibitive, particularly in developing regions (Javanmardi et al., 2019). Balancing safety with budget constraints is a persistent issue in the field. According to East et al. (2024), investing in seismic-resistant designs upfront can save significant amounts in post-earthquake recovery costs, but many projects still prioritize short-term savings over long-term resilience. However, innovative construction techniques, such as modular and prefabricated systems, have emerged as cost-effective alternatives that offer both seismic resilience and economic efficiency (Hassanli et al., 2015). The challenge lies in adopting these techniques on a wider scale while ensuring that cost-saving measures do not compromise structural integrity or safety.

Navigating regulatory frameworks and ensuring compliance with building codes is another significant challenge in earthquake-resistant design. Different countries have varying seismic design codes, and even within a single country, regional variations may exist based on the local seismicity and risk (Tannert et al., 2024). For instance, in the United States, building codes differ between seismic zones, with more stringent requirements in high-risk areas like California compared to regions with lower seismic activity. Ensuring that structures meet the minimum standards set by these codes is critical for public safety, but the complexity of multi-layered regulations can lead to compliance issues, particularly in large, multi-regional projects (Laursen & Ingham, 2004). Furthermore, evolving standards, such as the move towards performance-based design, present challenges for architects and engineers who must stay up to date with the latest regulations (Mugabo et al., 2021). Collaboration between regulatory bodies, engineers, and architects is essential to ensure that building designs are both compliant and resilient.

Figure 4: Challenges in Earthquake-Resistant Building Design



The increasing complexity of modern building designs, combined with the need for resilience in earthquake-prone areas, has led to a growing reliance on advanced technologies. However, the integration of these technologies into the design process presents its own set of challenges. Building Information Modeling (BIM) and structural health monitoring systems have emerged as critical tools in seismic design, allowing for the real-time monitoring and assessment of buildings during and after seismic events (Chou & Chen, 2010). While these technologies offer valuable data and insights, their implementation requires significant investment in both hardware and skilled personnel, which can be a barrier for smaller projects or projects in developing regions (Kalliontzis et al., 2022; Shamim, 2022). Additionally, the integration of new materials, such as high-performance fiber-reinforced concrete (HPFRC) and shape memory alloys, presents challenges related to their practical application in large-scale construction (Li et al., 2019). Despite these obstacles, continued innovation in both materials and technologies is essential to overcoming the challenges of earthquake-resistant building design.

2.3 Innovations in Materials for Earthquake-Resistant Building Design

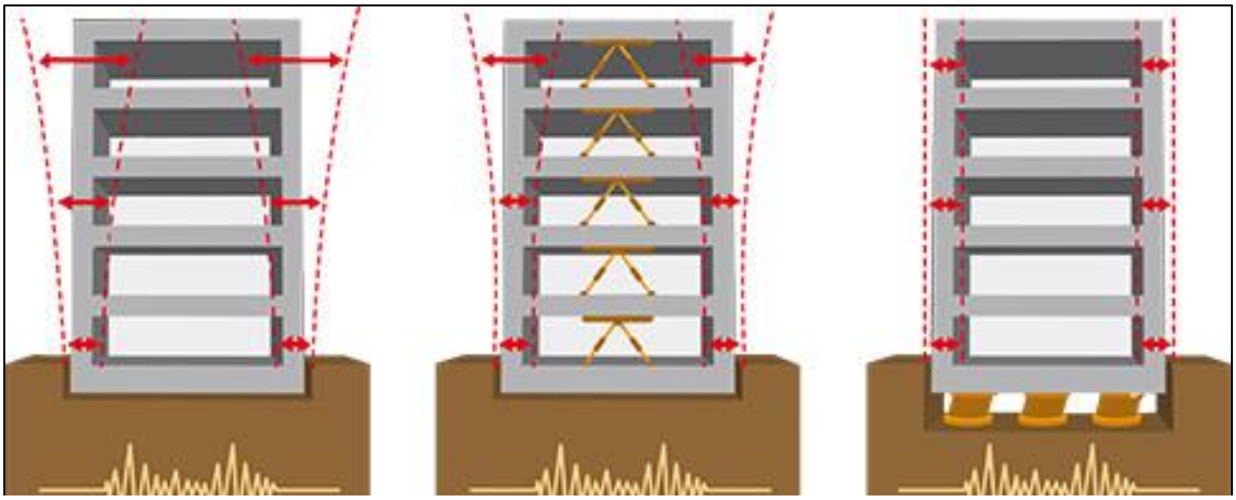
Recent advancements in earthquake-resistant building design have been largely driven by innovations in materials science, offering new possibilities for creating more resilient structures. High-performance composites, fiber-reinforced polymers (FRPs), and shape memory alloys have emerged as key materials that enhance a building's ability to withstand seismic forces. These materials offer superior strength, flexibility, and durability, enabling the construction of lighter yet more robust structures that can absorb and dissipate seismic energy more effectively than traditional materials like concrete and steel (Laursen & Ingham, 2004). For instance, shape memory alloys can recover their original shape after deformation, which is particularly useful in reducing residual structural damage after an earthquake (Yun & Chao, 2021). Additionally, fiber-reinforced polymers are widely used in retrofitting existing structures, offering a cost-effective solution to improve seismic resilience without requiring a complete overhaul of the building (Grigorian & Grigorian, 2018). The use of these advanced materials represents a significant leap in enhancing the performance of earthquake-resistant designs, allowing buildings to maintain structural integrity under extreme seismic conditions.

The advent of advanced simulation technologies and computational modeling has revolutionized the design of earthquake-resistant structures, allowing engineers to predict and optimize the behavior of buildings under seismic forces with unprecedented precision. Computational modeling tools such as finite element analysis (FEA) have become integral in evaluating the dynamic response of structures to various seismic scenarios (Wight & Ingham, 2008). These tools enable the virtual testing of different design configurations, materials, and structural systems, reducing the need for costly physical prototypes and accelerating the design process. Performance-based design approaches, which assess the performance of a building under expected seismic loads, have become increasingly common, as they provide engineers with the flexibility to optimize resilience while adhering to specific safety and performance goals (Li & Koetaka, 2022; Shamim, 2024). These innovations in simulation and modeling not only improve design accuracy but also contribute to the development of safer and more cost-efficient earthquake-resistant structures (Hu et al., 2022).

Among the most significant innovations in earthquake-resistant design are base isolation and damping mechanisms, which have proven to be highly effective in mitigating the effects of seismic forces on buildings. Base isolation is a passive seismic mitigation technique that decouples the building from ground motion through the use of flexible isolation bearings, such as elastomeric or sliding bearings, placed between the foundation and the superstructure (Chou & Chen, 2010). These isolators absorb seismic energy, reducing the transfer of forces to the building and minimizing structural damage. Studies have shown that base isolation systems can significantly improve the safety and performance of buildings during earthquakes, particularly in regions with frequent seismic activity (Nazari et al., 2016). Additionally, damping systems, both passive and active, are designed to dissipate seismic energy and reduce building vibrations. Passive systems, such as viscous dampers and friction pendulum bearings (FPB), work by absorbing energy through friction or viscous movement, while active systems use sensors and actuators to control structural vibrations in real time (Jin et al., 2019). These systems have been instrumental in increasing the overall resilience of buildings by limiting structural deformation and reducing the risk of collapse during seismic events (Javanmardi et al., 2019).

Seismic design strategies that incorporate redundancy, ductility, and energy dissipation mechanisms are fundamental to enhancing the resilience of earthquake-resistant buildings. Redundancy refers to the inclusion of multiple load paths and structural elements that provide alternative load-bearing capacity in the event of localized damage, ensuring the overall stability of the structure during seismic events (Toranzo et al., 2009). Ductility, on the other hand, allows structures to undergo significant deformations without losing their strength, enabling buildings to absorb and redistribute seismic energy (Cui et al., 2020). This is particularly important in high-rise buildings, where large lateral displacements are common during earthquakes. Energy dissipation mechanisms, such as the yielding of structural components or the use of frictional damping devices, help to further mitigate the effects of ground motion by reducing the energy transmitted to the building (Xiangmin et al., 2021). These design strategies have been widely adopted in earthquake-prone regions and have been shown to significantly reduce damage and improve the safety of buildings during seismic events.

Figure 5: Seismic Forces and Structural Response



Source: https://constrofacilitator.com (2024)

2.4 Reinforced Concrete and Its Role in Seismic Resilience

Reinforced concrete is one of the most commonly used materials in earthquake-resistant construction due to its superior strength and durability. When reinforced with steel bars, concrete gains the ability to withstand both tensile and compressive forces, making it an ideal material for structures exposed to seismic forces (Midorikawa et al., 2006). High-strength concrete mixes, combined with advanced techniques such as post-tensioning and shotcrete application, provide enhanced ductility and load-bearing capacity, which are critical for resisting seismic stresses (Wight et al., 2007). The use of post-tensioning allows for tighter control over cracks and structural deformations during seismic events, reducing the potential for catastrophic failure (Zhong & Christopoulos, 2021). Reinforced concrete structures are widely favored in earthquake-prone regions because they can absorb and redistribute seismic energy, ensuring the building's integrity during ground shaking (Hayashi et al., 2018). These features make reinforced concrete a staple material in seismic design, contributing to the overall resilience of buildings during earthquakes.

Steel is another essential material in earthquake-resistant construction, known for its high strength-to-weight ratio and flexibility. Its inherent ability to withstand tensile stresses makes it a critical component in structures designed to resist lateral forces induced by seismic events (Blebo & Roke, 2018). Steel framing systems, such as moment-resisting frames, braced frames, and eccentrically braced frames, have been widely adopted to enhance the seismic performance of buildings (Hayashi et al., 2018). These systems allow for significant design flexibility while maintaining high levels of resistance to dynamic seismic forces. Moment-

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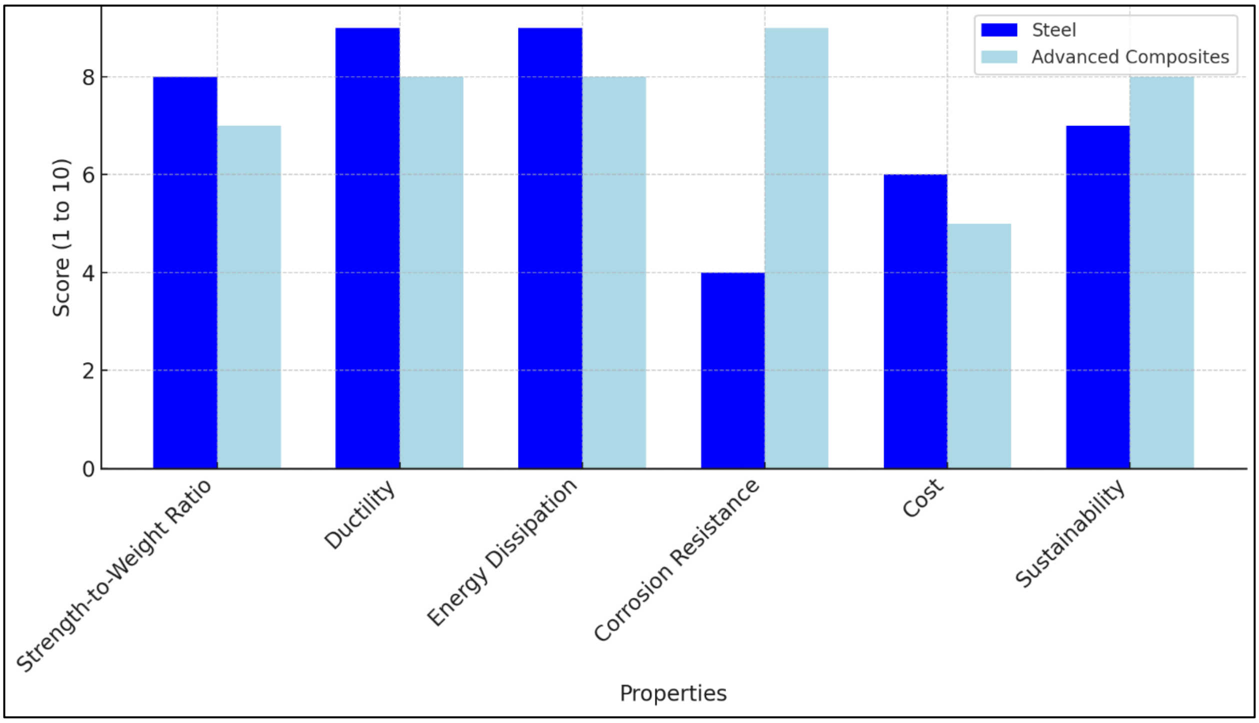
resisting frames, for example, provide the necessary flexibility to dissipate energy through large deformations, while braced frames offer enhanced stiffness and reduce lateral displacements (Wight et al., 2007). Eccentrically braced frames, which combine elements of both, improve energy dissipation by allowing controlled yielding of structural components during seismic activity (C & Goel, 2007). The adaptability and strength of steel make it a preferred material for earthquake-resistant buildings, particularly in regions with frequent seismic activity.

The use of advanced composites, particularly fiber-reinforced polymers (FRPs) and carbon fiber composites, has revolutionized the field of earthquake-resistant design. FRPs, used as wraps or overlays, are increasingly being applied to existing structures to enhance their seismic resilience (Blebo & Roke, 2018). These composites provide additional strength and ductility to concrete and masonry buildings, allowing them to better withstand the dynamic loads of earthquakes (Hu et al., 2021). Carbon fiber composites, known for their high tensile strength and lightweight properties, are used in tension ties and other critical structural components, particularly in retrofitting applications (Majumerd et al., 2022). FRP and carbon fiber retrofitting systems are especially valuable in enhancing the seismic performance of older structures that were not originally designed to withstand seismic forces. Studies have shown that the application of these materials significantly improves the ability of structures to dissipate energy and avoid collapse during seismic events (Jafari et al., 2021). As a result, advanced composites are becoming increasingly common in both new construction and retrofitting projects aimed at improving earthquake resilience.

In addition to advanced materials, innovative construction techniques have played a critical role in improving the seismic resilience of buildings. Precast construction, where structural elements are fabricated off-site and then assembled on-site, has gained popularity due to its efficiency and quality control (Mottier et al., 2020). Precast systems allow for precise fabrication under controlled conditions, which improves the quality and consistency of the structural components. This technique also reduces construction time and labor costs, as the prefabricated elements can be quickly assembled into the final structure (Majumerd et al., 2022). Precast systems are particularly effective

Figure 6: Comparison Between Steel and Advanced Composites in Seismic Design



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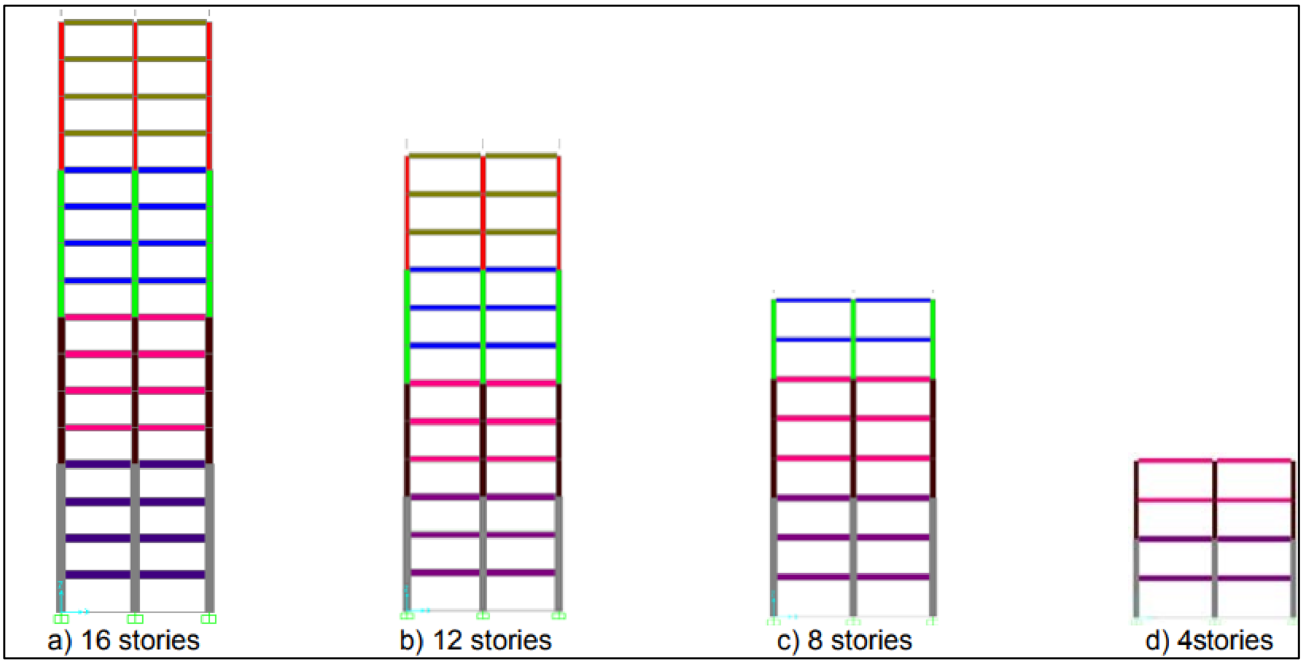
in earthquake-resistant construction because they offer high levels of seismic performance, especially when combined with advanced materials like steel and reinforced concrete. Additionally, modular construction techniques, where building components are designed to be easily replaced or repaired following seismic events, are gaining traction as an efficient way to enhance post-earthquake recovery and resilience (Xiang et al., 2022). These innovative techniques not only improve the seismic performance of buildings but also contribute to sustainable and cost-effective construction practices.

2.5 Redundancy in Earthquake-Resistant Design

Redundancy is a critical design strategy for earthquake-resistant structures, ensuring that buildings remain stable and functional even when individual components fail during seismic events. By incorporating multiple load paths and redundant structural elements, engineers can distribute and dissipate seismic forces more effectively throughout the building (Jin et al., 2019). This strategy enhances the reliability of the structure and reduces the risk of localized failures leading to catastrophic collapse(Ahmed et al., 2024; Islam & Apu, 2024; Nahar et al., 2024). Redundant systems are particularly valuable in complex, multi-story buildings, where the failure of one structural element could otherwise trigger a chain reaction leading to significant damage. For example, moment-resisting frames and shear walls, when used in combination, create alternative pathways for load distribution, enhancing the building's capacity to withstand seismic loads (Jim et al., 2024; Abdur et al., 2024). Redundancy also contributes to occupant safety, as it ensures that critical structural components remain intact during and after seismic events, allowing time for evacuation if necessary (Yun & Chao, 2021).

Ductility is another essential principle in earthquake-resistant design, referring to a structure's ability to undergo large deformations without losing its load-bearing capacity. Ductile materials, such as steel and certain advanced composites, exhibit post-yield behavior, allowing them to absorb and dissipate seismic energy through controlled deformation (Mugabo et al., 2021). This characteristic is crucial for ensuring that buildings can endure the stresses imposed by seismic forces without collapsing. Structural systems designed for ductility typically involve careful detailing, such as the use of special moment-resisting frames or reinforced shear walls, which allow for energy dissipation during

Figure 7: Schematic representation of changes of cross sections for beams and columns for the studied models



ground shaking (Chou & Chen, 2010). Ductility also enhances the capacity of a structure to redistribute loads when one component fails, thereby preventing sudden and catastrophic structural failure (Qu et al., 2015). The incorporation of ductile materials and systems is particularly important in high-risk seismic zones, where the intensity of ground motion requires structures to accommodate large displacements without losing stability (Yun & Chao, 2021).

Energy dissipation mechanisms play a pivotal role in reducing the impact of seismic forces on buildings by absorbing and dissipating energy, thereby minimizing vibrations and structural damage. These mechanisms can be passive or active, with passive systems relying on materials and devices that dissipate energy through internal friction or damping, such as viscous dampers or friction pendulum bearings (FPB) (Mugabo et al., 2021). Active systems, in contrast, utilize sensors and actuators to monitor and control structural motion in real time, actively counteracting seismic forces (Midorikawa et al., 2006). The incorporation of energy dissipation devices into building designs has been shown to significantly enhance the overall resilience of structures, particularly in regions with high seismic activity. Studies have demonstrated that these systems can reduce the amplitude of vibrations and limit structural deformation, thereby protecting the integrity of the building during and after an earthquake (Pei et al., 2020). As a result, energy dissipation mechanisms are becoming a standard feature in modern earthquake-resistant building design, particularly for critical infrastructure and tall buildings.

Performance-based design (PBD) and probabilistic seismic hazard assessments (PSHA) are essential tools for ensuring the seismic resilience of buildings. PBD allows engineers to evaluate specific performance objectives for structures under different seismic scenarios, tailoring the design to meet defined limits of damage and ensuring life safety (Al-Subaihawi & Pessiki, 2019). Unlike prescriptive design codes, which provide generalized guidelines, PBD is flexible, enabling engineers to focus on achieving specific performance goals such as occupant comfort, functionality, and reduced post-earthquake downtime (Hassanli et al., 2015). Probabilistic seismic hazard assessments, on the other hand, provide engineers with a detailed understanding of the likelihood and severity of seismic events in a given region, taking into account historical seismic activity, geological conditions, and fault lines (Hu et al., 2022). By using PSHA to quantify seismic risks, engineers can make informed decisions about structural design and material selection, leading to more resilient and cost-effective designs (Laursen & Ingham, 2004). Together, PBD and PSHA represent a comprehensive approach to seismic design, ensuring that buildings are not only safe but also functional and economically viable in the aftermath of an earthquake.

3 Method

This study employs a systematic review approach following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and rigor in the research process. The methodology is structured in several steps, from the identification of sources to data synthesis and risk assessment.

3.1 Identification of Sources

The first step involved identifying relevant sources from multiple academic databases, including Google Scholar, Scopus, and Web of Science. A comprehensive search was conducted using specific keywords such as "earthquake-resistant design," "seismic resilience," "Building Information Modeling (BIM)," "structural health monitoring (SHM)," and "artificial intelligence (AI) in structural engineering." The search focused on peer-reviewed journal articles, conference papers, and reports published from 2000 to 2023 to capture the latest advancements in earthquake-resistant technologies. This initial search aimed to gather a wide range of literature on the subject.

3.2 Screening and Eligibility Criteria

After identifying potential sources, the next step was to screen the titles and abstracts of the retrieved articles. Duplicate and irrelevant studies were excluded from the dataset. The eligibility criteria required that articles specifically focus on innovations in earthquake-resistant building design, seismic resilience, and associated technologies. Only studies that provided empirical data, case studies, or detailed analysis of the subject were included. Studies that fell outside the scope of earthquake engineering or lacked rigorous methodological approaches were excluded from further consideration.

3.3 Data Extraction and Synthesis

For the selected studies, a structured data extraction process was carried out using a predefined template. Key information, including research objectives, methodologies, findings, and conclusions, was gathered from each study. The extracted data was categorized based on the type of innovations discussed, such as new materials like fiber-reinforced polymers and shape memory alloys, and technological advancements like BIM, AI, and SHM. This information was synthesized to present a comprehensive overview of the trends, benefits, and challenges associated with these innovations in seismic design.

3.4 Analysis of Findings

The findings from the extracted data were analyzed both quantitatively and qualitatively. Quantitative data from case studies and simulation-based analyses were used to compare the effectiveness of different materials and design strategies. Qualitative analysis focused on identifying recurring themes, such as the role of interdisciplinary collaboration, cost-effectiveness, and regulatory challenges. The analysis also aimed to highlight how these innovations are being implemented in real-world scenarios and the potential barriers to their widespread adoption.

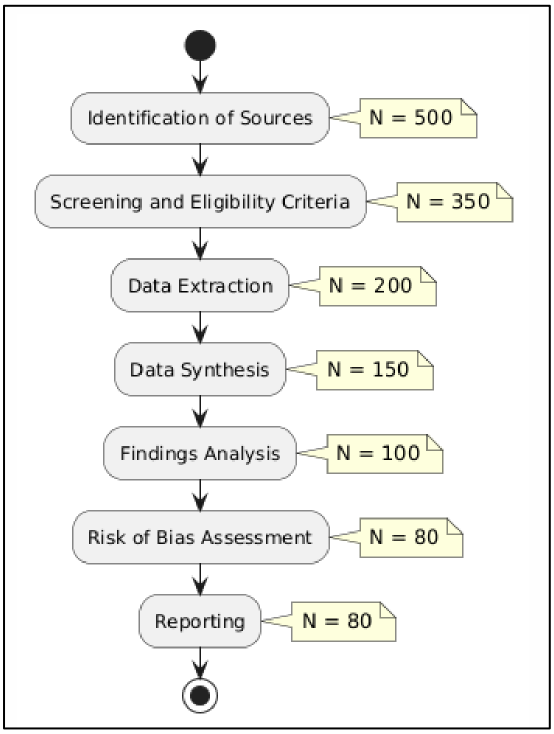
3.5 Risk of Bias Assessment

To ensure the reliability of the findings, a risk of bias assessment was conducted. This included evaluating the methodological rigor of the studies, assessing potential conflicts of interest, and verifying the reliability of the data sources. Studies with transparent methodologies and verifiable results were given higher priority in the analysis. This step helped ensure that the conclusions drawn from the review were based on reliable and objective data.

3.6 Reporting

The results of the review were organized and presented according to PRISMA guidelines, which included a flowchart outlining the selection process of the studies. The key findings related to innovations in earthquake-resistant building design were summarized, and gaps in the literature were identified to suggest future research directions. This structured approach offers a comprehensive and systematic overview of the advancements and challenges in earthquake-resistant design, based on the most reliable and up-to-date information available.

Figure 8: Employed PRISMA Method



4 Findings

The systematic review identified significant advancements in materials that have greatly enhanced the resilience of buildings to seismic forces. High-performance materials such as fiber-reinforced polymers (FRPs), shape memory alloys (SMAs), and advanced composites were found to play a crucial role in modern seismic design. Studies highlight that these materials offer enhanced tensile strength, flexibility, and energy absorption properties, outperforming traditional construction materials like reinforced concrete and steel. FRPs have been particularly

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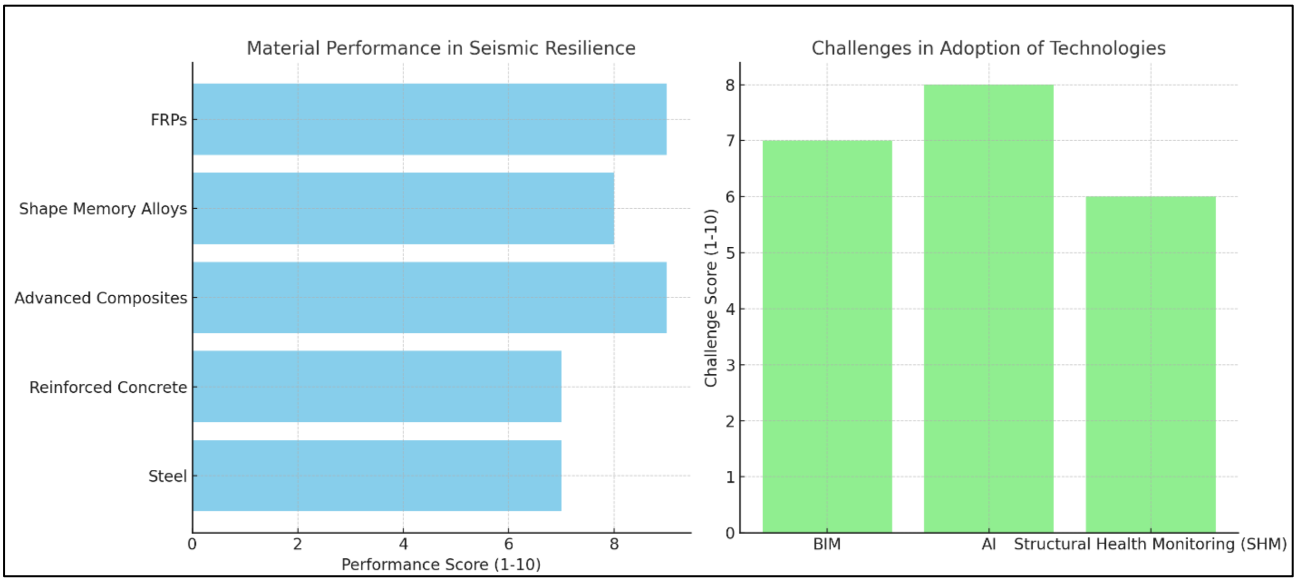
effective in retrofitting older structures, significantly improving their seismic resilience without requiring extensive reconstruction. Additionally, the ability of SMAs to revert to their original form after deformation has been pivotal in reducing residual damage following earthquakes. These material innovations represent a major leap forward in enhancing the durability and performance of structures in high-seismic-risk areas.

The integration of advanced technologies such as Building Information Modeling (BIM) and artificial intelligence (AI) has transformed earthquake-resistant building design. The findings reveal that BIM has become indispensable in optimizing the design process by facilitating real-time visualization and simulation of building behavior under seismic loads. BIM's ability to streamline collaboration among engineers, architects, and contractors has resulted in improved accuracy and efficiency, reducing the potential for errors during construction. AI and machine learning (ML) have further enhanced this by analyzing large datasets of seismic events and optimizing structural designs to mitigate weaknesses. These technologies have proven essential for the early detection of vulnerabilities in structural systems, leading to more resilient and robust earthquake-resistant designs.

The review highlights the growing use of advanced simulation techniques such as finite element analysis (FEA) and computational fluid dynamics (CFD), which have significantly optimized seismic performance in building design. FEA, in particular, enables engineers to model and evaluate the behavior of individual structural components under seismic forces with high precision, allowing for the identification and correction of potential failure points. CFD has been instrumental in assessing how environmental factors, such as wind or fluid dynamics, interact with structures during seismic events. Together, these simulation tools have reduced the need for costly physical prototypes and have enabled more efficient fine-tuning of structural design, ensuring that buildings can withstand the complex forces exerted during earthquakes. These techniques are now considered essential in modern earthquake-resistant design practices.

Significant findings also point to the crucial role of structural health monitoring (SHM) systems and real-time risk assessment technologies in improving seismic resilience. SHM systems, equipped with sensors and accelerometers, provide continuous real-time data on a building's structural integrity, allowing engineers to detect early signs of damage and intervene before serious failures occur. Real-time risk assessment technologies, which integrate seismic data, satellite imagery, and historical records, have proven essential in providing immediate insights into potential threats,

Figure 9: Challenges in Adoption of Technologies



enabling swift decision-making and preventative measures. The use of these systems has significantly enhanced the safety and operational continuity of critical infrastructure, particularly in earthquake-prone regions. The findings underscore that SHM and real-time systems are becoming a standard feature in high-value, high-risk structures to ensure timely intervention and reduce the risk of catastrophic failures. While significant technological and material advancements have been made, the review identified key challenges that limit the widespread adoption of these innovations in earthquake-resistant design. Cost remains a substantial barrier, especially in developing countries where budget constraints hinder the use of advanced materials like FRPs and SMAs. Moreover, the lack of uniform building codes and regulatory frameworks across different regions complicates the implementation of standardized seismic design strategies. The findings also revealed that the adoption of advanced technologies like BIM, AI, and SHM requires significant upfront investments in both technology and training, which poses challenges for smaller projects or under-resourced regions. Future research should focus on developing cost-effective, scalable solutions and harmonizing global building standards to make earthquake-resistant technologies more accessible. Additionally, ongoing innovation in AI-driven optimization and SHM systems holds the potential to further enhance the precision, affordability, and global applicability of seismic resilience strategies.

5 Discussion

The findings of this study demonstrate the significant advancements in materials and technologies that have reshaped earthquake-resistant building design. High-performance materials like fiber-reinforced polymers (FRPs), shape memory alloys (SMAs), and advanced composites have been shown to enhance the resilience of structures, outperforming traditional materials such as concrete and steel. This aligns with earlier studies by, who emphasized the importance of material ductility and flexibility in seismic design. However, while older studies focused primarily on the use of steel and reinforced concrete, more recent research has shifted toward innovative materials that provide superior energy dissipation and structural flexibility. The growing adoption of these advanced materials suggests a broader trend towards designing lighter yet more robust structures capable of withstanding higher seismic forces. Nevertheless, challenges remain in making these materials more cost-effective especially in developing regions where budget constraints limit their use (Pei et al., 2020).

The integration of technologies such as Building Information Modeling (BIM) and artificial intelligence (AI) has further transformed earthquake-resistant design, allowing for greater precision in structural modeling and performance optimization. This study's findings corroborate with Midorikawa et al. (2006), who noted BIM's role in improving design accuracy and collaboration among stakeholders. However, while earlier studies focused on BIM as a tool for visualization and coordination, more recent research highlights the potential of AI and machine learning (ML) in enhancing predictive capabilities and identifying structural vulnerabilities. The use of AI in optimizing designs is a notable departure from traditional manual calculations and modeling techniques discussed in earlier works. Despite these advancements, the cost and complexity of implementing such technologies pose challenges, particularly for smaller-scale projects, a concern that was also raised in past research by Mugabo et al. (2021).

The use of advanced simulation techniques like finite element analysis (FEA) and computational fluid dynamics (CFD) has proven instrumental in optimizing earthquake-resistant design, a finding that supports the conclusions of Xiangmin et al. (2021). These tools allow engineers to conduct detailed analysis of structural behavior under seismic loads, offering insights that were not previously available in earlier methods that relied heavily on physical prototypes and empirical testing. While traditional approaches emphasized prescriptive codes and static models, modern simulation techniques enable performance-based design, allowing engineers to fine-tune designs based on the specific seismic risks of a given location. However, while these technologies offer significant benefits, their high upfront costs and the need for specialized expertise limit their widespread adoption, particularly in regions with limited resources. This contrasts with earlier studies, which largely viewed prescriptive design codes as sufficient, emphasizing that current approaches offer more flexibility but at a higher complexity and cost.

Finally, the role of structural health monitoring (SHM) systems and real-time risk assessment technologies marks a significant advancement over traditional approaches to earthquake risk management. Earlier studies, such as those by Cui et al. (2020), primarily focused on the design of buildings to withstand seismic forces, with limited attention to real-time monitoring and adaptive risk management. In contrast, modern SHM systems provide continuous data on the health of structures, allowing engineers to take proactive measures before significant damage occurs (Toranzo et al., 2009). The findings from this study highlight that SHM and real-time monitoring are increasingly adopted in high-value structures, providing a level of risk mitigation that was not possible in earlier designs. However, as noted by Toranzo et al. (2009), the widespread implementation of SHM systems is still hampered by cost and technical challenges, which echoes the findings of this study. The integration of real-time risk management remains an area that requires further research to become more accessible and affordable, particularly in less-developed regions that face higher seismic risks but have limited technological infrastructure. In brief, while the advancements in materials, technology, and simulation techniques have significantly enhanced earthquake-resistant building design, there remain notable challenges in cost, accessibility, and implementation. Comparing this study's findings with earlier research highlights a shift toward more sophisticated, technology-driven approaches, though the widespread adoption of these methods is still constrained by practical limitations. Future research should focus on addressing these challenges to ensure that the benefits of modern seismic design are accessible to a broader range of regions and projects.

6 Conclusion

The advancements in earthquake-resistant building design, particularly through the integration of innovative materials such as fiber-reinforced polymers (FRPs) and shape memory alloys (SMAs), along with cutting-edge technologies like Building Information Modeling (BIM), artificial intelligence (AI), and structural health monitoring (SHM) systems, have significantly enhanced the resilience of modern structures against seismic forces. These innovations provide greater flexibility, precision, and adaptability in design, surpassing traditional materials and methods in terms of both performance and predictive capabilities. However, despite these technological and material advances, challenges such as high costs, complex implementation, and regional disparities in access to these technologies remain substantial barriers to their widespread adoption. While the shift towards performance-based design and real-time monitoring represents a critical evolution in earthquake-resistant engineering, future efforts must focus on making these solutions more accessible, affordable, and scalable, particularly for developing regions that are most vulnerable to seismic risks. Addressing these challenges will be crucial for advancing global resilience to earthquakes and ensuring that innovations in seismic design benefit a broader spectrum of communities.

References

Aghagholizadeh, M., & Makris, N. (2018). Seismic Response of a Yielding Structure Coupled with a Rocking Wall. *Journal of Structural Engineering*, *144*(2), 04017196-NA. https://doi.org/10.1061/(asce)st.1943-541x.0001894

Ahmed, N., Rahman, M. M., Ishrak, M. F., Joy, M. I. K., Sabuj, M. S. H., & Rahman, M. S. (2024). Comparative Performance Analysis of Transformer-Based Pre-Trained Models for Detecting Keratoconus Disease. *arXiv preprint arXiv:2408.09005*.

Ajrab, J. J., Pekcan, G., & Mander, J. B. (2004). Rocking Wall–Frame Structures with Supplemental Tendon Systems. *Journal of Structural Engineering*, *130*(6), 895-903. https://doi.org/10.1061/(asce)0733-9445(2004)130:6(895)

Al-Subaihawi, S., & Pessiki, S. (2019). Static pushover response of spring anchored unbonded post-tensioned rocking systems. *Engineering Structures*, *200*(NA), 109582-NA. https://doi.org/10.1016/j.engstruct.2019.109582

Blebo, F. C., & Roke, D. A. (2018). Seismic-resistant self-centering rocking core system with buckling restrained columns. *Engineering Structures*, *173*(NA), 372-382. https://doi.org/10.1016/j.engstruct.2018.06.117

C, D., & Goel, S. C. (2007). Seismic strengthening of rocking-critical masonry piers. *Journal of Structural Engineering*, *133*(10), 1445-1452. https://doi.org/10.1061/(asce)0733-9445(2007)133:10(1445)

Chou, C.-C., & Chen, J.-H. (2010). Tests and analyses of a full-scale post-tensioned RCS frame subassembly. *Journal of Constructional Steel Research*, *66*(11), 1354-1365. https://doi.org/10.1016/j.jcsr.2010.04.013

Cui, Y., Shu, Z., Zhou, R., Li, Z., Chen, F., & Ma, Z. (2020). Self-centering steel–timber hybrid shear wall with slip friction dampers: Theoretical analysis and experimental investigation. *The Structural Design of Tall and Special Buildings*, *29*(15), NA-NA. https://doi.org/10.1002/tal.1789

Di Egidio, A., Pagliaro, S., Fabrizio, C., & de Leo, A. M. (2020). Seismic performance of frame structures coupled with an external rocking wall. *Engineering Structures*, *224*(NA), 111207-NA. https://doi.org/10.1016/j.engstruct.2020.111207

East, M., Ezzeldin, M., & Wiebe, L. (2024). Strategies to Reduce and Quantify Seismic Damage in Controlled Rocking Masonry Walls. *Journal of Structural Engineering*, *150*(2), NA-NA. https://doi.org/10.1061/jsendh.steng-11851

Grigorian, M., & Grigorian, C. E. (2018). Sustainable Earthquake-Resisting System. *Journal of Structural Engineering*, *144*(2), 04017199-NA. https://doi.org/10.1061/(asce)st.1943-541x.0001900

Guo, T., Xu, Z., Song, L., Wang, L., & Zhang, Z. (2017). Seismic Resilience Upgrade of RC Frame Building Using Self-Centering Concrete Walls with Distributed Friction Devices. *Journal of Structural Engineering*, *143*(12), 04017160-NA. https://doi.org/10.1061/(asce)st.1943-541x.0001901

Hassanli, R., ElGawady, M. A., & Mills, J. E. (2015). Strength and Seismic Performance Factors of Posttensioned Masonry Walls. *Journal of Structural Engineering*, *141*(11), 04015038-NA. https://doi.org/10.1061/(asce)st.1943-541x.0001272

Hayashi, K., Skalomenos, K. A., Inamasu, H., & Luo, Y. (2018). Self-Centering Rocking Composite Frame Using Double-Skin Concrete-Filled Steel Tube Columns and Energy-Dissipating Fuses in Multiple Locations. *Journal of Structural Engineering*, *144*(9), 04018146-NA. https://doi.org/10.1061/(asce)st.1943-541x.0002157

Holden, T., Restrepo, J. I., & Mander, J. B. (2003). Seismic Performance of Precast Reinforced and Prestressed Concrete Walls. *Journal of Structural Engineering*, *129*(3), 286-296. https://doi.org/10.1061/(asce)0733-9445(2003)129:3(286)

Hu, S., & Wang, W. (2021). Seismic design and performance evaluation of low-rise steel buildings with self-centering energy-absorbing dual rocking core systems under far-field and near-fault ground motions. *Journal of Constructional Steel Research*, *179*(NA), 106545-NA. https://doi.org/10.1016/j.jcsr.2021.106545

Hu, S., Wang, W., & Qu, B. (2020). Seismic evaluation of low-rise steel building frames with self-centering energy-absorbing rigid cores designed using a force-based approach. *Engineering Structures*, *204*(NA), 110038-NA. https://doi.org/10.1016/j.engstruct.2019.110038

Hu, S., Wang, W., & Qu, B. (2021). Self-centering companion spines with friction spring dampers: Validation test and direct displacement-based design. *Engineering Structures*, *238*(NA), 112191-NA. https://doi.org/10.1016/j.engstruct.2021.112191

Hu, S., Zhu, S., Wang, W., & Alam, M. S. (2022). Structural and nonstructural damage assessment of steel buildings equipped with self-centering energy-absorbing rocking core systems: A comparative study. *Journal of Constructional Steel Research*, *198*(NA), 107559-107559. https://doi.org/10.1016/j.jcsr.2022.107559

Islam, S., & Apu, K. U. (2024). Decentralized vs. Centralized Database Solutions in Blockchain: Advantages, Challenges, And Use Cases. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, *3*(4), 58-68. https://doi.org/10.62304/jieet.v3i04.195

Jafari, A., Preti, M., Beheshti, M., & Dugnani, R. (2021). Self-centering walls strengthening by high-

Copyright © The Author(s)

performance concrete: a feasibility study. *Materials and Structures*, *54*(3), 1-20. https://doi.org/10.1617/s11527-021-01710-0

Javanmardi, A., Ibrahim, Z., Ghaedi, K., Ghadim, H. B., & Hanif, M. U. (2019). State-of-the-Art Review of Metallic Dampers: Testing, Development and Implementation. *Archives of Computational Methods in Engineering*, *27*(2), 455-478. https://doi.org/10.1007/s11831-019-09329-9

Jim, M. M. I., Hasan, M., Sultana, R., & Rahman, M. M. (2024). Machine Learning Techniques for Automated Query Optimization in Relational Databases. *International Journal of Advanced Engineering Technologies and Innovations*, *1*(3), 514-529.

Jin, Z., Pei, S., Blomgren, H.-E., & Powers, J. (2019). Simplified Mechanistic Model for Seismic Response Prediction of Coupled Cross-Laminated Timber Rocking Walls. *Journal of Structural Engineering*, *145*(2), 04018253-NA. https://doi.org/10.1061/(asce)st.1943-541x.0002265

Kalliontzis, D., Schultz, A. E., & Sritharan, S. (2022). Unbonded Post-Tensioned Structural Masonry Wall with Rubber Interface for Limited-Damage Systems. *Journal of Structural Engineering*, *148*(1), 04021223-NA. https://doi.org/10.1061/(asce)st.1943-541x.0003159

Kamperidis, V. C., Karavasilis, T. L., & Vasdravellis, G. (2018). Self-centering steel column base with metallic energy dissipation devices. *Journal of Constructional Steel Research*, *149*(NA), 14-30. https://doi.org/10.1016/j.jcsr.2018.06.027

Khanmohammadi, M., & Heydari, S. (2015). Seismic behavior improvement of reinforced concrete shear wall buildings using multiple rocking systems. *Engineering Structures*, *100*(NA), 577-589. https://doi.org/10.1016/j.engstruct.2015.06.043

Lagomarsino, S. (2014). Seismic assessment of rocking masonry structures. *Bulletin of Earthquake Engineering*, *13*(1), 97-128. https://doi.org/10.1007/s10518-014-9609-x

Laursen, P., & Ingham, J. (2004). Structural Testing of Large-Scale Posttensioned Concrete Masonry Walls. *Journal of Structural Engineering*, *130*(10), 1497-1505. https://doi.org/10.1061/(asce)0733-9445(2004)130:10(1497)

Li, Y.-W., & Koetaka, Y. (2022). Steel rocking column bases with replaceable cover plates: Cyclic loading behaviour and practical design. *Engineering Structures*, *264*(NA), 114467-114467. https://doi.org/10.1016/j.engstruct.2022.114467

Li, Y.-W., Li, G.-Q., Jiang, J., & Wang, Y.-B. (2019). Use of energy-dissipative rocking columns to enhance seismic performance of buckling-restrained braced frames. *Journal of Constructional Steel Research*, *159*(NA), 548-559. https://doi.org/10.1016/j.jcsr.2019.04.041

Majumerd, M. J. E., Dehcheshmeh, E. M., Broujerdian, V., & Moradi, S. (2022). Self-centering rocking dual-core braced frames with buckling-restrained fuses. *Journal of Constructional Steel Research*, *194*(NA), 107322-107322. https://doi.org/10.1016/j.jcsr.2022.107322

Marzok, A., & Lavan, O. (2021). Seismic design of multiple-rocking systems: A gradient-based optimization approach. *Earthquake Engineering & Structural Dynamics*, *50*(13), 3460-3482. https://doi.org/10.1002/eqe.3518

Md Abdur, R., Md Majadul Islam, J., Rahman, M. M., & Tariquzzaman, M. (2024). AI-Powered Predictive Analytics for Intellectual Property Risk Management In Supply Chain Operations: A Big Data Approach. *International Journal of Science and Engineering*, *1*(04), 32-46. https://doi.org/10.62304/ijse.v1i04.184

Midorikawa, M., Azuhata, T., Ishihara, T., & Wada, A. (2006). Shaking table tests on seismic response of steel braced frames with column uplift. *Earthquake Engineering & Structural Dynamics*, *35*(14), 1767-1785. https://doi.org/10.1002/eqe.603

Moradi, S., & Burton, H. V. (2018). Response surface analysis and optimization of controlled rocking steel braced frames. *Bulletin of Earthquake Engineering*, *16*(10), 4861-4892. https://doi.org/10.1007/s10518-018-0373-1

Mottier, P., Tremblay, R., & Rogers, C. A. (2017). Seismic retrofit of low-rise steel buildings in Canada using rocking steel braced frames. *Earthquake Engineering & Structural Dynamics*, *47*(2), 333-355. https://doi.org/10.1002/eqe.2953

Mottier, P., Tremblay, R., & Rogers, C. A. (2020). Shake table test of a two-story steel building seismically retrofitted using gravity-controlled rocking braced frame system. *Earthquake Engineering & Structural Dynamics*, *50*(6), 1576-1594. https://doi.org/10.1002/eqe.3411

Mugabo, I., Barbosa, A. R., Sinha, A., Higgins, C., Riggio, M., Pei, S., van de Lindt, J. W., & Berman, J. W.

(2021). System Identification of UCSD-NHERI Shake-Table Test of Two-Story Structure with Cross-Laminated Timber Rocking Walls. *Journal of Structural Engineering*, *147*(4), 04021018-NA. https://doi.org/10.1061/(asce)st.1943-541x.0002938

Nahar, J., Rahaman, M. A., Alauddin, M., & Rozony, F. Z. (2024). Big Data in Credit Risk Management: A Systematic Review Of Transformative Practices And Future Directions. *International Journal of Management Information Systems and Data Science*, *1*(04), 68-79. https://doi.org/10.62304/ijmisds.v1i04.196

Nazari, M., Sritharan, S., & Aaleti, S. (2016). Single precast concrete rocking walls as earthquake force-resisting elements. *Earthquake Engineering & Structural Dynamics*, *46*(5), 753-769. https://doi.org/10.1002/eqe.2829

Pei, S., Huang, D., Berman, J. W., & Wichman, S. (2020). Simplified Dynamic Model for Post-tensioned Cross-laminated Timber Rocking Walls. *Earthquake Engineering & Structural Dynamics*, *50*(3), 845-862. https://doi.org/10.1002/eqe.3378

Perez, F. J., Pessiki, S., & Sause, R. (2004). Seismic Design of Unbonded Post-Tensioned Precast Concrete Walls with Vertical Joint Connectors. *PCI Journal*, *49*(1), 58-79. https://doi.org/10.15554/pcij.01012004.58.79

Priestley, M. J. N., & Macrase, G. A. (1996). Seismic tests of precast beam-to-column joint subassemblages with unbonded tendons. *PCI Journal*, *41*(1), 64-81. https://doi.org/10.15554/pcij.01011996.64.81

Qu, B., Sanchez-Zamora, F., & Pollino, M. (2015). Transforming Seismic Performance of Deficient Steel Concentrically Braced Frames through Implementation of Rocking Cores. *Journal of Structural Engineering*, *141*(5), 04014139-NA. https://doi.org/10.1061/(asce)st.1943-541x.0001085

Qureshi, M. I., & Warnitchai, P. (2016). Reduction of inelastic seismic demands in a mid-rise rocking wall structure designed using the displacement-based design procedure. *The Structural Design of Tall and Special Buildings*, *26*(2), e1307-NA. https://doi.org/10.1002/tal.1307

Rahgozar, N., Moghadam, A. S., & Aziminejad, A. (2016). Quantification of seismic performance factors for self-centering controlled rocking special concentrically braced frame. *The Structural Design of Tall and Special Buildings*, *25*(14), 700-723. https://doi.org/10.1002/tal.1279

Roh, H., & Cimellaro, G. P. (2011). Seismic Fragility Evaluation of RC Frame Structures Retrofitted with Controlled Concrete Rocking Column and Damping Technique. *Journal of Earthquake Engineering*, *15*(7), 1069-1082. https://doi.org/10.1080/13632469.2010.551704

Rosenboom, O., & Kowalsky, M. J. (2004). Reversed In-Plane Cyclic Behavior of Posttensioned Clay Brick Masonry Walls. *Journal of Structural Engineering*, *130*(5), 787-798. https://doi.org/10.1061/(asce)0733-9445(2004)130:5(787)

Shamim, M. M. I. (2024). Artificial Intelligence in Project Management: Enhancing Efficiency and Decision-Making. *International Journal of Management Information Systems and Data Science*, *1*(1), 1-6.

Shamim, M. I. (2022). Exploring the success factors of project management. *American Journal of Economics and Business Management*, *5*(7), 64-72.

Sui, X., Liu, D., Li, L., Wang, H., & Yang, H. (2019). Virtual machin

Tannert, T., Ajibola, O. A., & Popovski, M. (2024). Structural Performance of CLT Shear Walls with Hyperelastic Hold Downs. *Journal of Structural Engineering*, *150*(1), NA-NA. https://doi.org/10.1061/jsendh.steng-12703

Toranzo, L. A., Restrepo, J. I., Mander, J. B., & Carr, A. J. (2009). Shake-Table Tests of Confined-Masonry Rocking Walls with Supplementary Hysteretic Damping. *Journal of Earthquake Engineering*, *13*(6), 882-898. https://doi.org/10.1080/13632460802715040

Wight, G., & Ingham, J. (2008). Tendon Stress in Unbonded Posttensioned Masonry Walls at Nominal In-Plane Strength. *Journal of Structural Engineering*, *134*(6), 938-946. https://doi.org/10.1061/(asce)0733-9445(2008)134:6(938)

Wight, G., Kowalsky, M. J., & Ingham, J. (2007). Shake Table Testing of Posttensioned Concrete Masonry Walls with Openings. *Journal of Structural Engineering*, *133*(11), 1551-1559. https://doi.org/10.1061/(asce)0733-9445(2007)133:11(1551)

Xiang, P., Song, G., Fan, K., Li, Z., & Jia, L.-J. (2022). Shaking table test on a low-damage controlled multiple-rocking-column steel frame. *Engineering Structures*, *254*(NA), 113896-113896. https://doi.org/10.1016/j.engstruct.2022.113896

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Xiangmin, L., Fuwen, Z., Wang, Z., Kun, T., Jinzhi, D., & Lu, J. (2021). Shaking table test of a frame structure retrofitted by externally-hung rocking wall with SMA and disc spring self-centering devices. *Engineering Structures*, *240*(NA), 112422-NA. https://doi.org/10.1016/j.engstruct.2021.112422

Yun, C., & Chao, C. (2021). Study on seismic performance of prefabricated self-centering steel frame. *Journal of Constructional Steel Research*, *182*(NA), 106684-NA. https://doi.org/10.1016/j.jcsr.2021.106684

Zhong, C., & Christopoulos, C. (2021). Self-centering seismic-resistant structures: Historical overview and state-of-the-art. *Earthquake Spectra*, *38*(2), 1321-1356. https://doi.org/10.1177/87552930211057581