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Performance of Multi-Storied Irregular Steel Buildings: A Comprehensive Review of Dampers and Base Isolation Systems

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Abstract:
The increasing demand for multi-storied steel buildings in urban environments has led to significant challenges in ensuring seismic resilience, particularly for irregular structures. This study provides a comprehensive review of seismic control strategies, focusing on base isolation and damping systems to mitigate the effects of structural irregularities. Various classifications of irregularities, including plan, vertical, stiffness, and torsional irregularities, are analyzed to understand their impact on dynamic response and stress distribution. The effectiveness of passive, active, and semi-active seismic control systems is assessed through experimental and numerical studies, including shake table tests, finite element analysis, and nonlinear time history analysis. Case studies of real-world applications and past earthquake failures highlight the critical role of seismic mitigation strategies. Furthermore, the study explores emerging innovations such as AI-based adaptive control systems and sustainable damping materials to enhance future seismic resilience. Key challenges, including economic feasibility, maintenance concerns, and regulatory limitations, are discussed to identify pathways for improving seismic design codes and practical implementation. The findings emphasize the necessity for hybrid control systems and interdisciplinary collaboration to advance seismic engineering for irregular steel buildings. This review aims to bridge existing knowledge gaps and provide a foundation for future research in optimizing seismic control techniques for complex structural configurations.

Keywords: Seismic resilience, irregular steel buildings, base isolation, damping systems, structural irregularities, AI-based seismic control.

1. Introduction

The rapid growth of urbanization and the increasing demand for high-rise buildings have led to the widespread use of multi-storied steel structures. These buildings offer high strength, durability, and flexibility, making them an ideal choice for seismic-prone regions (Patil & Patil, 2024). However, many urban developments feature irregular configurations due to architectural and functional requirements, leading to structures with geometric, mass, or stiffness irregularities (Das et al., 2021). While these irregular buildings provide innovative design solutions, their complex dynamic behavior under seismic loading necessitates advanced engineering strategies to ensure their resilience (Keer et al., 2024).

Structural resilience is a critical concern for buildings located in seismic zones, as earthquakes impose severe lateral forces that can lead to catastrophic failures if not properly addressed (Poudel & Chaulagain, 2024). Unlike regular structures, irregular buildings exhibit unexpected stress concentrations, torsional effects, and amplified vibrations, making them more susceptible to seismic damage (Maharjan et al., 2022). Ensuring the resilience of these structures involves implementing innovative design techniques, seismic-resistant materials, and effective energy dissipation systems such as base isolators and dampers (Patil & Sutar, 2024).

Irregularities in multi-storied steel buildings can be broadly categorized into plan irregularities (asymmetrical shapes, setbacks, re-entrant corners), vertical irregularities (soft stories, sudden stiffness changes), mass irregularities (unequal floor weight distribution), stiffness irregularities, and torsional irregularities (Das et al., 2021). These irregularities alter the dynamic response of structures by shifting the center of mass and stiffness, resulting in torsional vibrations, differential displacement, and localized damage during seismic events (Keer et al., 2024). Studies have shown that irregular buildings experience higher inter-story drifts, base shear forces, and stress concentrations compared to regular structures, making them more challenging to design for seismic safety (Rathi et al., 2023).

To enhance the seismic performance of irregular buildings, researchers have developed seismic control techniques, including base isolation systems and damping devices. Base isolation involves installing flexible bearings at the building's foundation to decouple it from ground motion, significantly reducing seismic forces transmitted to the superstructure (Patil & Patil, 2024). Common base isolators include lead rubber bearings (LRB), high damping rubber bearings (HDRB), and friction pendulum systems (FPS). Alternatively, damping systems—such as viscous dampers, tuned mass dampers (TMDs), friction dampers, and viscoelastic dampers—dissipate earthquake-induced energy and mitigate excessive vibrations in irregular buildings (Vishwanath et al., 2025). These techniques have been successfully implemented in various high-rise buildings, demonstrating improved structural resilience and reduced damage during earthquakes.

Despite advancements in seismic engineering, the seismic behavior of irregular steel buildings remains a complex challenge due to their unpredictable response to earthquake forces (Das et al., 2021). One of the major concerns is the differential stiffness and mass distribution, which amplifies local stress concentrations and increases the risk of failure (Keer et al., 2024). Additionally, existing seismic codes and design guidelines primarily focus on regular structures, leaving gaps in standardizing approaches for irregular configurations (Maharjan et al., 2022). Another critical issue is the economic feasibility of seismic mitigation strategies. While base isolation and damping devices significantly enhance structural performance, their implementation in irregular steel buildings often involves high costs and maintenance challenges (Bhaskar, 2024). Therefore, developing cost-effective, high-performance seismic control techniques tailored to irregular buildings is a pressing need in structural engineering research.

The unique dynamic characteristics of irregular buildings necessitate customized energy dissipation mechanisms to address their complex behavior under seismic loads. Studies indicate that conventional seismic-resistant measures, such as shear walls and bracing systems, may not be sufficient for highly irregular structures (Patil & Sutar, 2024). Instead, advanced damping systems and hybrid seismic control strategies are required to optimize the distribution of seismic forces and reduce torsional responses in irregular buildings (Poudel & Chaulagain, 2024).

To bridge the existing knowledge gaps, this review aims to:

- Analyze the effectiveness of dampers and base isolation systems in mitigating seismic forces in multi-storied irregular steel buildings.
- Compare different seismic control techniques to determine the most suitable approaches for various irregular configurations.
- Provide insights into future research directions and structural design improvements, focusing on cost-effective and sustainable seismic mitigation strategies.

By systematically evaluating recent advancements in seismic control technologies, this study seeks to contribute to the development of more resilient urban infrastructure, minimizing earthquake-induced damage in irregular steel buildings.

2. Literature Review

2.1 Structural Irregularities in Multi-Storied Steel Buildings

Irregularities in multi-storied steel buildings significantly impact their seismic performance by altering load distribution and dynamic response. According to seismic design standards, irregularities in buildings can be categorized as vertical, plan, mass, stiffness, strength, and torsional irregularities, often leading to higher vulnerability in earthquake-prone regions (Ramesh & Swathi, 2021). The classification of these irregularities is essential for understanding their effects on structural behavior.

Vertical irregularities refer to abrupt changes in a building's height, stiffness, or mass, such as soft-story construction, setbacks, or discontinuities in vertical load transfer (Al-Zuhairi & Al-Ahmed, 2021). Soft-story buildings, where a particular story has significantly lower stiffness than adjacent stories, have been frequently reported to collapse in major earthquakes due to excessive inter-story drift (Omkar & Padmakar, 2019). Similarly, plan irregularities arise when a structure has asymmetrical layouts, including L-, T-, or U-shaped floor plans, leading to uneven force distribution and torsional effects (Mourya & Vyas, 2020). Plan irregularities tend to amplify seismic loads in certain areas, causing localized stress concentration and potential failure.

Mass irregularity occurs when the distribution of mass varies significantly across different floors, affecting the natural frequency and dynamic response of the structure (Haque et al., 2016). For instance, irregular mass distributions due to heavy equipment placement, penthouses, or sudden floor slab changes lead to differential inertial forces that create additional moments on the structure (Satyanarayana & Abhilash, 2017). Studies have shown that mass irregularities lead to an increase in base shear and lateral displacement, making seismic control systems necessary to counteract these effects (Reddy & Reddy, 2017).

Variations in stiffness and strength occur when certain parts of a building exhibit significantly different resistance to lateral loads, leading to excessive drift and uneven force distribution. Stiffness irregularities are often observed in buildings with open ground floors, large window openings, or irregular bracing arrangements (Omkar & Padmakar, 2019). Strength irregularities, on the other hand, arise when different structural components exhibit varying load-bearing capacities, leading to progressive collapse or localized failures in seismic conditions (Haque et al., 2025).

Torsional irregularities develop when the center of mass does not align with the center of rigidity, causing the building to twist under seismic excitation (Mourya & Vyas, 2020). This effect is prevalent in asymmetrical floor layouts or buildings with significant eccentricity, where one side of the structure experiences higher deformation than the other. Torsional irregularities amplify the differential drift and rotational motion of buildings, often leading to localized damage in earthquake events (Verma, 2023).

Many real-world buildings exhibit multiple irregularities simultaneously, exacerbating the structural response under seismic loading (Ramesh & Swathi, 2021). For example, a soft-story building with mass eccentricity will experience both excessive drift and torsional effects, increasing its seismic vulnerability (Jayakrishna et al., 2018). The interaction between plan, vertical, and stiffness irregularities creates complex dynamic behaviors that make standard seismic-resistant designs inadequate, necessitating advanced analysis techniques and mitigation strategies (Haque et al., 2016).

Understanding the influence of irregularities on seismic performance is crucial for ensuring structural safety in earthquake-prone regions. Studies indicate that irregular buildings suffer from increased base shear, higher lateral displacement, and greater risk of failure due to unbalanced force distribution (Al-Zuhairi & Al-Ahmed, 2021).

Irregularities significantly affect a building's dynamic response, altering natural frequency, modal participation, and stress distribution (Haque et al., 2016). The introduction of irregularities leads to localized stress concentrations, especially at points of sudden stiffness or mass changes, increasing the likelihood of material failure (Verma, 2023). Studies have demonstrated that torsional irregularities cause stress amplifications at extreme corners of structures, making them more prone to seismic damage (Mourya & Vyas, 2020).

The natural frequency of irregular buildings is affected by mass, stiffness, and geometric configurations. Unlike regular structures, where modal shapes are predictable, irregular buildings exhibit complex and unpredictable vibration modes (Omkar & Padmakar, 2019). These variations lead to unexpected resonance effects during earthquakes, where certain floors experience magnified oscillations, increasing the chances of failure (Jayakrishna et al., 2018).

Several earthquake disasters have highlighted the vulnerabilities of irregular structures. The 1994 Northridge earthquake in California and the 2011 Christchurch earthquake in New Zealand caused widespread damage to buildings with soft stories, mass irregularities, and torsional effects (Mourya & Vyas, 2020). Many failures were attributed to poorly designed vertical discontinuities and asymmetrical mass distribution, reinforcing the importance of seismic retrofitting and advanced damping techniques (Al-Zuhairi & Al-Ahmed, 2021).

International building codes provide guidelines to mitigate the adverse effects of irregularities:

- ASCE 7-22 (American Society of Civil Engineers): Specifies lateral force distribution requirements and torsional irregularity limitations.
- IS 1893:2016 (Indian Standard for Earthquake-Resistant Design): Defines seismic zone factors and performance-based design criteria.
- Eurocode 8 (European Standard for Seismic Design): Emphasizes ductile detailing and drift limitations for irregular structures.
- BNBC 2020 (Bangladesh National Building Code): Introduces performance-based analysis for irregular multi-storied buildings (Haque et al., 2025).

Despite these standards, practical implementation remains a challenge, as existing buildings often do not comply with updated seismic regulations. Therefore, advanced computational analysis, retrofitting techniques, and hybrid damping systems are required to enhance the seismic resilience of irregular buildings (Ramesh & Swathi, 2021).

2.2. Seismic Control Strategies for Irregular Steel Buildings

Base isolation is a passive seismic control strategy designed to decouple the structure from ground motion, significantly reducing seismic forces transmitted to the building. This system employs flexible bearings or sliding mechanisms that absorb seismic energy before it reaches the superstructure, allowing the building to move independently from the ground (Di Sarno et al., 2011).

Several types of base isolators have been developed to enhance seismic resilience:

- Lead Rubber Bearings (LRB): These isolators consist of rubber layers with a lead core that provides both damping and elasticity. The lead core yields under seismic loads, dissipating energy while maintaining structural stiffness under normal loads (Stanizkai et al., 2019).
- High Damping Rubber Bearings (HDRB): Made of rubber composites with enhanced damping properties, HDRBs provide better energy dissipation and increased deformation capacity (Soto & Adeli, 2018).
- Friction Pendulum Bearings (FPB): This system utilizes a concave sliding mechanism, allowing the structure to shift laterally while maintaining stability through restoring forces. FPBs are highly

effective in reducing torsional irregularities and are commonly used in high-rise steel buildings (Akbari et al., 2024).

Research has shown that base isolation significantly reduces base shear and inter-story drift, thereby enhancing the seismic resilience of irregular structures. Studies by Kangda & Bakre (2020) indicate that base-isolated buildings experience up to 60% lower base shear forces than fixed-base counterparts, with substantial reductions in structural deformation. Moreover, computational analysis by Zafarani & Halabian (2020) demonstrated that isolators minimize torsional effects in asymmetrical buildings, making them particularly beneficial for irregular configurations.Several real-world applications of base isolation validate its efficiency. The Kobe Earthquake (1995) provided a significant case study, where base-isolated structures suffered minimal damage compared to conventional buildings (Talukdar et al., 2024). Similarly, the Christchurch Earthquake (2011) demonstrated that base-isolated buildings maintained operational functionality post-earthquake, proving their resilience against severe ground motions (Higashino & Okamoto, 2006).

Damping systems work by absorbing and dissipating seismic energy, thereby reducing structural vibrations. Various dampers are used in irregular steel buildings to enhance seismic resilience:

- Viscous Dampers: These fluid-based dampers convert seismic energy into heat via controlled fluid motion. Studies by Hu et al. (2017) show that viscous dampers reduce peak inter-story drift by up to 50%, making them particularly effective in multi-storied irregular buildings.
- Friction Dampers: These dampers operate on the principle of slip-based energy dissipation, where friction elements slide to absorb seismic forces. Research by Soto & Adeli (2018) indicates that friction dampers are highly effective in retrofitting existing irregular steel structures, offering enhanced damping without significant modifications.
- Tuned Mass Dampers (TMDs): These counter-vibrational mass systems consist of a secondary mass attached to the structure, which oscillates out of phase with the primary structure, reducing resonant vibrations. Studies by Stanizkai et al. (2019) confirm that TMDs significantly reduce torsional irregularities in asymmetrical buildings.
- Viscoelastic and Yielding Dampers: These deformation-based dampers utilize elastic and yielding materials to dissipate seismic energy through hysteretic behavior. Research by Talukdar et al. (2024) demonstrates that yielding dampers enhance energy dissipation in steel moment-resisting frames, mitigating structural damage.

The effectiveness of damping systems depends on the irregularity type and building configuration. Studies by Kangda & Bakre (2020) indicate that viscous dampers outperform friction dampers in structures with mass irregularities, whereas friction dampers are more effective in plan-irregular buildings. Meanwhile, research by Hu et al. (2017) suggests that TMDs provide superior performance in torsionally irregular steel buildings, reducing rotational movements during seismic events.A comparative analysis by Patil & Patil (2024) on irregular steel buildings subjected to nonlinear seismic simulations found that combining base isolation with dampers provides optimal seismic performance, effectively controlling both translational and torsional motions.

Unlike passive systems, active and semi-active control systems use real-time feedback mechanisms to adjust structural response dynamically. These systems include:

- Active Mass Dampers (AMD): These dampers employ motor-driven counterweights that shift in real-time to counteract seismic forces. Research by Akbari et al. (2024) found that AMD systems reduce peak acceleration in high-rise irregular buildings.
- Semi-Active Dampers: Unlike AMDs, semi-active dampers adjust their damping properties without requiring large external power sources. Studies by Zafarani & Halabian (2020) demonstrated that

semi-active Magnetorheological (MR) dampers adapt damping properties during seismic events, improving structural stability.

Recent advancements in machine learning and AI-driven algorithms have led to the development of adaptive seismic control mechanisms. AI-based control systems process real-time seismic data and dynamically adjust damping forces, significantly improving structural performance (Stanizkai et al., 2019). Hu et al. (2017) demonstrated that AI-assisted MR dampers optimize seismic response based on predictive algorithms, reducing damage risk.

Despite their advantages, active and semi-active control systems face several challenges:

- High Cost: The implementation of active dampers involves substantial installation and maintenance costs, making them less feasible for widespread adoption (Talukdar et al., 2024).
- Power Dependency: Unlike passive systems, active dampers require continuous power supply, which may be unreliable during strong earthquakes (Higashino & Okamoto, 2006).
- Complexity in Retrofitting: Retrofitting existing irregular buildings with active control systems requires significant structural modifications, limiting their practical application (Patil & Patil, 2024).

2.3 Experimental and Analytical Approaches

Shake table tests and real-time hybrid simulations are widely used to assess the seismic response of irregular steel buildings equipped with dampers and base isolation systems. These tests simulate actual earthquake ground motions, enabling researchers to observe structural behavior under different seismic intensities (Öztürk et al., 2024). In a recent experimental study, rolling-type seismic base isolation was tested on a multi-story steel building model, demonstrating a significant reduction in inter-story drift and acceleration responses compared to fixed-base structures (Öztürk et al., 2024). Furthermore, scaled shake table experiments on asymmetric steel structures equipped with friction pendulums revealed enhanced lateral stability and reduced energy dissipation demand (Meral, 2021).

Finite Element Analysis (FEA) is an essential numerical method used to predict the seismic behavior of irregular steel buildings with dampers and base isolators. Studies employing FEA models have highlighted the effectiveness of different damping systems in mitigating torsional responses in asymmetrical structures (Yuan et al., 2021). A comparative analysis of various damping configurations using SAP2000 and ETABS software showed that base isolation combined with steel dampers offers superior energy dissipation efficiency, particularly for structures with stiffness irregularities (Patil & Patil, 2024). Additionally, nonlinear FEA simulations confirmed that lead rubber bearing (LRB)-based isolation systems effectively lower seismic-induced stress concentrations, making them an ideal solution for seismic retrofitting (Di Sarno et al., 2011).

Nonlinear Time History Analysis (NTHA) is widely employed to simulate dynamic responses under real earthquake excitations. This method provides insights into how energy dissipation mechanisms function during seismic events (Ozer & Inel, 2025). A study utilizing incremental dynamic analysis (IDA) on irregular steel structures demonstrated that buildings equipped with viscous dampers and base isolation systems experience significantly reduced displacement demands compared to conventional buildings (Meral, 2021). Furthermore, NTHA simulations incorporating moment-resisting steel frames with tuned mass dampers (TMDs) validated the efficacy of hybrid damping solutions in mitigating seismic-induced torsional effects (Kangda & Bakre, 2020).

3. Summary of Literature and Gap

Despite advancements in seismic engineering, challenges remain:

- Gaps in Standardized Design Codes: Most seismic design guidelines primarily focus on regular structures, leaving gaps in standardized approaches for irregular configurations.

- Cost and Feasibility Concerns: High implementation and maintenance costs of seismic control strategies hinder widespread adoption.
- Limited Research on Hybrid Control Systems: While base isolation and damping systems are effective, their integration for complex irregular buildings requires further research.
- AI-Based Seismic Control Systems: The potential of AI and real-time monitoring in seismic mitigation remains underexplored.

This review aims to address these gaps by evaluating recent advancements in seismic control technologies and proposing future research directions.

4.Results and Discussion

4.1. Comparative Performance Analysis

The comparative efficiency of base isolation and various damping techniques has been extensively studied through experimental and numerical models. A study by Manchalwar & Bakre (2020) assessed the seismic performance of U-shaped steel dampers, revealing that isolated foundations with dampers achieve up to 65% reduction in base shear forces, compared to fixed-base structures. Similarly, base isolation systems were found to extend the structural period, reducing earthquake-induced accelerations and structural damage (Di Sarno et al., 2011).

One of the primary advantages of base isolation is the elongation of the structural period, which shifts the natural frequency of the building away from predominant seismic frequencies. Studies indicate that LRB and HDRB isolation systems effectively extend the fundamental period, thereby mitigating seismic impact (Shah & Bakhaswala, 2017). However, high-rise irregular buildings with mass eccentricities may experience excessive displacement if isolation systems are not properly optimized (Deringöl & Güneyisi, 2020).

Dampers such as viscous and friction dampers are particularly effective in reducing inter-story drifts. Experimental results from shake table tests confirmed that fluid viscous dampers (FVDs) decrease inter-story drifts by approximately 50% in steel-framed irregular buildings, enhancing structural safety (Ozer & Inel, 2025). On the other hand, while base isolation reduces overall seismic forces, it may allow larger lateral displacements, necessitating the use of additional restraining mechanisms (Meral, 2021).

Comparative studies on energy dissipation mechanisms show that friction dampers and tuned mass dampers (TMDs) outperform base isolation in structures with extreme torsional irregularities (Kangda & Bakre, 2020). However, hybrid control systems integrating both base isolation and dampers provide the most comprehensive seismic resilience strategy, as demonstrated in recent nonlinear analysis models (Patil & Patil, 2024).

Numerical simulations play a crucial role in benchmarking seismic performance metrics for irregular steel buildings. Researchers have employed software such as ETABS, SAP2000, and OpenSees to conduct parametric studies on seismic response variations across different structural configurations (Yuan et al., 2021). A benchmark study using OpenSees on steel buildings with varying damping configurations demonstrated that fluid viscous dampers (FVDs) provide the most consistent performance across different seismic intensities, while friction dampers show efficiency under moderate earthquake loads but may underperform in high-intensity seismic events (Di Sarno et al., 2011).

4.2. Case Studies and Real-World Applications

The impact of past earthquakes on irregular steel buildings has been widely studied to assess their performance under real seismic conditions. For instance, the 1994 Northridge earthquake in California caused extensive damage to 19-story irregular steel moment-frame buildings, primarily due to torsional irregularities and inadequate seismic detailing (Krishnan, 2007). Similarly, a study of the L'Aquila earthquake in Italy (2009) found that hospital structures with irregular configurations experienced severe failure, emphasizing the need for advanced seismic mitigation techniques (Ferraioli, 2015). Additionally, research on seismic performance of irregular steel buildings in Seismic Zone 4 revealed that plan and vertical irregularities significantly increased base shear forces and inter-story drift, resulting in localized structural failures (Uroš et al., 2020). Such findings highlight the importance of base isolation and damping systems to mitigate seismic effects in irregular structures.

Several real-world projects have successfully integrated seismic control systems to enhance the resilience of irregular steel buildings. A notable example is the Tokyo Skytree, which employs tuned mass dampers (TMDs) and friction dampers to control dynamic response and seismic forces (Kim & Adeli, 2005). Another example is the Taipei 101 tower, which features a 660-ton TMD to counteract wind and earthquake-induced oscillations. In the San Francisco International Airport Terminal, base isolation techniques were used to decouple the structure from ground motion, significantly reducing earthquake-induced accelerations and improving operational continuity post-seismic events (De Stefano & Pintucchi, 2008). Research also indicates that the implementation of hybrid damping solutions in hospitals and emergency facilities enhances seismic resilience, ensuring structural integrity during and after earthquakes (Saedee et al., 2024).

The progressive collapse of irregular steel structures following seismic events has provided valuable lessons for seismic design improvements. A study by Repapis et al. (2006) analyzed structural failures in older steel buildings, finding that non-ductile detailing and insufficient seismic bracing were key contributors to catastrophic failures. Similarly, in the 2017 Puebla earthquake, irregular steel buildings exhibited excessive torsional behavior, leading to structural instability and localized collapses (Homaei et al., 2017). An assessment of earthquake-induced damages in Croatian hospitals with irregular geometries revealed that plan irregularities and mass eccentricities resulted in increased shear stress concentration and failure at connection points, leading to severe damage (Uroš et al., 2020). Such findings reinforce the necessity of adaptive seismic retrofitting measures to enhance the safety of irregular structures.

The lessons from past earthquake failures have led to significant advancements in seismic design codes and engineering practices. For example, the development of hybrid base-isolation and damper systems has improved the seismic resilience of modern structures (De Stefano & Pintucchi, 2008). The use of advanced nonlinear time history analysis (NTHA) has further enabled accurate prediction of structural response, aiding in the design of more robust seismic mitigation strategies (Kyrkos & Anagnostopoulos, 2012). Recent seismic retrofitting techniques emphasize the integration of fluid viscous dampers (FVDs), tuned mass dampers (TMDs), and friction dampers to reduce torsional response and inter-story drift in irregular buildings (Saedee et al., 2024). Furthermore, artificial intelligence (AI)-based adaptive control systems are being explored for real-time seismic performance optimization, ensuring enhanced safety during extreme earthquake conditions (Krishnan, 2007).

5. Conclusion

The review of seismic resilience in irregular steel buildings highlights the significant vulnerabilities these structures face during earthquake events. Various irregularities, including plan, vertical, stiffness, and torsional irregularities, contribute to differential seismic responses, amplifying structural risks. Research findings emphasize the importance of implementing advanced seismic control systems, such as base isolation and energy dissipation dampers, to mitigate these challenges effectively. Shake table tests, finite element analysis, and nonlinear time history analysis have provided substantial insights into the effectiveness of these mitigation strategies, demonstrating that hybrid solutions incorporating both isolation and damping mechanisms yield the most promising results.

A major conclusion drawn from the review is that AI-driven adaptive seismic control systems present a transformative potential for enhancing the resilience of irregular steel buildings. These systems enable real-time optimization of damping and isolation mechanisms, ensuring adaptive responses to varying seismic loads. The incorporation of machine learning algorithms into structural health monitoring can facilitate predictive maintenance, allowing engineers to assess potential vulnerabilities before significant damage occurs. Furthermore, hybrid isolation-damping strategies, which combine traditional base isolation with supplemental damping devices, offer enhanced performance in addressing torsional and stiffness irregularities commonly found in modern steel structures.

Despite these advancements, several challenges hinder the widespread implementation of seismic control solutions in irregular buildings. Economic constraints remain a critical barrier, particularly in developing regions where budget limitations restrict the adoption of state-of-the-art seismic mitigation technologies. Cost-benefit analyses of various seismic control strategies indicate that while base isolation and advanced dampers significantly improve structural resilience, their initial investment and long-term maintenance costs pose challenges for large-scale application. The need for more cost-effective and modular solutions is evident, driving research towards innovative materials such as shape memory alloys and graphene-based composites, which offer high damping efficiency at a lower cost.

Another challenge lies in the long-term reliability and maintenance of seismic control devices. Fluid viscous dampers, friction pendulum bearings, and lead rubber bearings, while highly effective, require periodic maintenance and recalibration to maintain optimal performance. The environmental degradation of these materials over time further complicates their long-term usability. Advances in nano-enhanced rubber and self-healing elastomers present promising avenues for developing low-maintenance seismic control solutions that ensure sustained effectiveness without frequent intervention.

Regulatory challenges also present a significant obstacle to the integration of advanced seismic mitigation techniques in irregular steel buildings. Existing building codes, such as ASCE 7-22 and Eurocode 8, primarily cater to regular structures, leaving gaps in standardized guidelines for irregular configurations. There is a pressing need for performance-based design approaches that offer greater flexibility in addressing the complexities of irregular structures. Collaborative efforts between researchers, policymakers, and engineering professionals are essential to develop adaptable codes that facilitate the incorporation of AI-driven control systems and hybrid damping solutions into mainstream seismic design practices.

The recommendations emerging from this review emphasize the importance of multidisciplinary collaboration in advancing seismic engineering solutions for irregular buildings. Greater investment in research and development is required to explore alternative materials and hybrid structural systems that optimize energy dissipation while maintaining cost-effectiveness. AI-based monitoring and control should be integrated into seismic design frameworks to enable predictive response mechanisms, reducing the risk of catastrophic failure. Additionally, governments and industry stakeholders must work together to establish funding mechanisms that support the implementation of seismic mitigation technologies in vulnerable regions.

Looking ahead, the future of seismic engineering in irregular steel buildings is expected to witness significant technological advancements. The development of real-time AI-driven seismic monitoring systems will revolutionize how irregular structures respond to dynamic loading conditions. Further research into self-adaptive materials with inherent damping capabilities is likely to enhance the sustainability and longevity of seismic control systems. Moreover, the increasing focus on sustainable construction practices will drive the adoption of eco-friendly damping materials that minimize environmental impact while maximizing structural resilience.

The evolution of seismic mitigation strategies will also be influenced by the growing demand for resilient urban infrastructure. As cities continue to expand vertically, irregular high-rise steel buildings will become more prevalent, necessitating advanced solutions for seismic safety. The integration of modular and prefabricated damping systems will enable more efficient retrofitting of existing structures, ensuring that aging infrastructure remains compliant with evolving seismic standards. Furthermore, advancements in computational modeling and simulation techniques will enable engineers to develop highly optimized seismic mitigation solutions tailored to the specific needs of irregular buildings.

In conclusion, the review underscores the critical role of innovative seismic mitigation strategies in enhancing the resilience of irregular steel buildings. While significant progress has been made in the development of base isolation systems, energy dissipation dampers, and AI-based adaptive control mechanisms, challenges related to cost, maintenance, and regulatory compliance must be addressed to ensure widespread implementation. By fostering interdisciplinary collaboration and investing in emerging technologies, the seismic engineering community can pave the way for safer, more resilient irregular structures capable of withstanding future seismic events.

Future Scope

The integration of artificial intelligence (AI) in seismic mitigation has emerged as a promising research direction for enhancing the resilience of irregular steel buildings. AI-driven adaptive control systems leverage real-time sensor data and machine learning algorithms to dynamically adjust damping and isolation mechanisms based on seismic activity (Krishnan, 2007). Recent studies highlight that neural network-based seismic control frameworks have the potential to optimize energy dissipation in irregular structures, ensuring efficient force distribution and minimizing localized failures (Kim & Adeli, 2005).Additionally, predictive AI models can be employed to enhance the performance of tuned mass dampers (TMDs) and friction dampers, enabling real-time optimization of damping strategies for torsionally irregular buildings (Ferraioli, 2015). Future research should focus on the integration of AI with Internet of Things (IoT) technology, allowing real-time monitoring and automated response mechanisms in seismic-prone regions.

Hybrid seismic mitigation strategies that combine base isolation with various damping techniques have gained significant attention in recent years. Research indicates that hybrid lead rubber bearings (LRBs) and fluid viscous dampers (FVDs) offer superior seismic resilience compared to traditional systems, particularly for vertically irregular structures (Uroš et al., 2020).Recent experimental models have demonstrated that hybrid isolation-damping solutions significantly reduce inter-story drift and base shear, minimizing the risk of catastrophic failure during earthquakes (Saedee et al., 2024). Future studies should explore the synergistic effects of multiple dampers, such as combining friction pendulum bearings (FPB) with viscoelastic dampers, to enhance torsional stability and energy dissipation efficiency.

The development of eco-friendly and cost-effective seismic mitigation materials is an important area of research. Traditional damping systems rely on expensive materials such as high-grade rubber and steel, which pose challenges in large-scale implementation (De Stefano & Pintucchi, 2008). Emerging materials, such as shape memory alloys (SMAs) and graphene-based composites, have demonstrated promising potential for self-healing and high-damping efficiency (Repapis et al., 2006).Furthermore, recycled polymer-based elastomers and bamboo-reinforced isolation pads offer sustainable alternatives for seismic mitigation in developing countries (Kyrkos & Anagnostopoulos, 2012). Future studies should evaluate the long-term performance and durability of these materials under extreme seismic conditions, ensuring their viability for real-world applications.

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