A Comparative Review of Diagrid Systems, Moment Frame Systems, And Shear Wall Systems in Seismic-Resistant Design

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Abstract

Design for seismic resistance is crucial for the safety and elasticity of the structures in seismic zones. This paper aims at providing a detailed comparison of three major structural systems: Diagrid, moment frame, and shear wall system to determine their seismic behavior, material consumption, economy, constructability and sustainability. Diagrids excel in lateral load distribution and offer great architectural freedom, but are costly and complex. Moment frames are ductile and have a relatively flexible design approach; however, they are susceptible to joint failure during very strong earthquake motions. Shear walls provide excellent stiffness and drift control but need special detailing to prevent stress concentrations and improve ductility. The study also found that hybrid structural systems such as base isolated diagrid and damper integrated shear wall are better than single system approaches to improve seismic resilience. Based on more than 50 peer reviewed articles, the review stresses the significance of context specific design, interprofessional practice, and sustainable approaches to addressing the varied seismic risks. The reviews are expected to assist engineers, architects, and policy makers in selecting and developing optimal structural systems that consider safety, cost, and environmental friendliness simultaneously.

Keywords: *Seismic loads, Diagrid systems, Moment frame systems, Shear wall systems, Hybrid structural systems*

1 Introduction

It has become essential to design the structures to resist the increasing frequency and intensity of seismic forces worldwide. Seismic resistant design is not only a technical issue but, in many cases, it is also a moral issue for ensuring the safety and durability of buildings and people in them. Numerous systems to build up the seismic recital of buildings, including diagrid, moment frame, and shear wall systems, which are three of the most broadly studied and prompted solutions, have been developed by structural engineers and researchers. As each of these systems contains exceptional features (advantages and challenges), in-depth comparative analysis is essential for informed decision making in earthquake resistant design.

Diagrid systems, characterized by their unique diagonal grid patterns, have gained popularity in contemporary architecture due to their efficiency in uniform load distributions and remarkable stiffness. The geometric configuration of the diagrid system facilitates even stress distribution, diminishing the necessity for internal columns and allowing innovative architectural concepts. The diagonal angle of diagrid systems is crucial, as it significantly affects both structural efficiency and material utilization. Reports suggest that adjusting the angle of the diagonal members—typically ranging from63° to 79°, based on a building's height and slenderness ratio—can significantly decrease the building's overall weight (Ashtari et al., 2021). Even though diagrid systems have exhibited efficient performances under moderate seismic activities, alarming concerns remain regarding their exposure to large deformations. Studies have shown that diagonal members of diagrid structures play a crucial role in energy dissipation, which helps diagrid systems to withstand significant deformations during rare seismic events (Heshmati et al., 2020). Conversely, moment frame systems depend on the rigid beam-column connections, are flexible and easy to construct, and for this reason, they have been a requirement in seismic-resistant design for a long time. Moment frames provide adjustable architectural design and are often more cost-effective, which makes them a preferred choice for low- to mid-rise structures. Inconclusion, seismic resilience of a diagrid system depends on the angle of the diagonal members and the overall construction of the diagrid framework.

Shear wall systems, recognized for their exceptional stiffness and strengths, exhibit superior performance in resisting lateral earthquake forces. These systems consist vertical walls engineered to counteract shear forces, rendering them a prevalent solution for high-rise buildings and areas prone to seismically active regions. However, while the effectiveness of shear walls in mitigating seismic risks is well recognized, and their rigidity can limit architectural flexibility and may lead to stress concentrations in specific areas (Junda et al., 2018).

Selecting a suitable structural system for seismic-resistant design hinges on multiple considerations, often competing factors. Building height alone can make a design approach, while geographic location, function, budget all weigh heavily. Advancements in construction technology have further broadened the possibilities for developing these systems; the integrating high-performance materials like fiber-reinforced polymers (FRPs) and shape memory alloys (SMAs), has shown potential for enhancing the seismic resilience of diagrid and moment-frame systems (Shariyat & Jahangiri, 2020). Likewise, the incorporation of advance damping devices and base isolation techniques can improve the behavior of shear wall systems during notable seismic events (Li et al. 2020).

Regardless of the extensive research on individual structural systems, there remains a need for a comprehensive comparative review evaluating the seismic-performance, material-efficiency, cost-effectiveness, and constructability. Such an analysis is essential for guiding engineers and architects for selecting the most suitable system for a specific project, particularly in earthquake-prone regions. We hope to offer valuable insights into the strengths and limitations of each system, and eventually contribute to advancements in seismic-resistant design methodologies. Beyond just academic research, implications of this review also have real-world applications in the policy-making and construction industry. Choosing the right structural system in terms of public safety, economic stability, and environmental considerations, has significant consequences in seismic-prone regions. For example, diagrid systems can help to reduce the carbon footprint of tall buildings due to their material efficiency. On the other hand, moment-frame systems are more appealing due to their cost-effectiveness and can also offer seismic-resistant construction in developing countries (Tian et al., 2020). Likewise, effectiveness of shear wall systems can enhance the structural integrity of critical infrastructure, such as hospitals and emergency response centers, during earthquakes (Salgueiro & Tarrazon-Rodon, 2021).

Along with the technical and economic factors, the architectural and functional aspects of these systems should also be considered. The prominent configuration of diagrid systems has redefined the architectural options of high-rise structures, facilitating iconic structures like the Guangzhou International Finance Centre in China and the Hearst Tower in New York City (Han et al., 2017). Moment-frame systems, with their open and flexible layouts, have enhanced the design of many commercial and residential buildings by offering greater utilization of spaces (Song et al., 2017). The placements of shear walls affect a building's seismic performance significantly. A study of a G+15 reinforced concrete building in Dhaka, Bangladesh, revealed that shear walls positioned along shorter span and symmetrically can reduce lateral drift and displacement compared to the other coordination (Zahid et al., 2023).

As the urban populations continue to grow and the demand for resilient high-rise buildings increases globally, the need for innovative and efficient seismic-resistant design solutions becomes more persistent. We seek to assist in this initiative by providing a thorough and balanced comparison of these systems in this review. By comparing their seismic performance, material usage, cost, and constructability, we hope to assist engineers, architects, and policy makers in choosing the right seismic-resistant structural solution and decision making. It is crucial to note the importance of the above aspects as well as the need for interdisciplinary collaboration and ongoing research in order to ensure that future structures not only safe and strong but also environmentally friendly and beautiful.

2 Overview of Structural Systems

Building seismic-resistant structures relies significantly on choosing and implementing suitable structural systems. Diagrid, moment frame, and shear wall system each have special features, benefits, and drawbacks that make them suitable for distinctive architectural and engineering needs. Also, these are among the most widely studied and used systems. Based on the findings from over 50 peer-reviewed analyses, we tried to provide a deeper overview of these systems, highlighting how they behave structurally, their applications, and how they perform under seismic loading.

2.1 Diagrid systems

Diagrid systems, known for their distinctive diagonal grid patterns, have revolutionized the structural design mostly for high-rise and architecturally striking structures. The term "diagrid" comes from "diagonal grid," describing how the interconnected diagonal members of the system form triangular networks. This layout of diagrid system helps in efficiently distributing both gravity and lateral loads, and thereby reducing the need for internal columns and allowing design flexibility (Nehdi et al., 2015).

One of the notable benefits of diagrid system is their incomparable rigidity and strength, which is made possible by the geometric function of triangular units. These triangular units work together to counteract lateral forces, such as those caused by wind or earthquakes, by transferring loads diagonally down to the foundation. This load distribution mechanism of these systems shows more even stress distribution and efficient material usage, due to reduced bending moments in structural components (Aslani et al., 2016). Buildings like The Hearst Tower in New York City and the CCTV Headquarters in Beijing showcase how the diagrid system eliminates the need of vertical columns in the exterior frame and allowed for innovative architectural designs and marking a major advancement (Han et al., 2017).

Despite having significant benefits in structural efficiency and architectural flexibility, the adoption of diagrid systems is not free from challenges, and often stalled by the complexity of their design and construction. Complex geometry of diagrids requires advanced computational modeling, and precise fabrication techniques, which can increase both the construction costs and timeline. Additionally, reliance on high-strength materials, like steel or reinforced concrete (for diagonal members) can raise material expenses compared to conventional structural systems (O'Reilly et al., 2018).

Recent advancements in materials science, like the use of high-strength steel and fiber-reinforced polymers (FRPs), are ensuring the probability of addressing these challenges and improving the seismic performance of diagrid systems (Shariyat & Jahangiri, 2020).

2.2 Moment Frame Systems

Moment Frames, or rigid frame systems, are widely utilized in earthquake-resistant structures due to their effectiveness in load-distribution. The rigid beam-column framework allows the system to effectively distribute bending moments and shear stresses throughout the structure, lessening the sidesways movement under seismic loading and improving seismic performance (Mirza Hessabi & Mercan, 2016).

One of the major perks of moment frame systems is their flexibility in architectural design. This system is suitable for all sorts of buildings-commercial, residential, and industrial buildings due to their open and capacious floor plans, where shear walls or diagonal bracing would limit space. Additionally, many parts can be prefabricated and assembled on-site, and ease of construction can cut down construction time and labor costs (Junda et al., 2018).

However, moment-frame systems have some limitations. Under intense seismic loading, they can experience significant deformations due to their reliance on beam-column joints for support. To address this issue, researchers have explored numerous methods to improve the seismic performance of moment-frames, like incorporating energy-dissipating devices and innovative materials to enhance their seismic resilience (Wu et al., 2020). For example, integrating shape memory alloys (SMAs) in beam-column joints has been shown to improve the system's ability to recover from displacements and reduce residual shifts after seismic events (Chu et al., 2019).

2.3 Shear Wall Systems

The shear wall system relays on vertical structural walls to resist lateral forces, enhancing the building's seismic performance. These walls are positioned within the building to offer additional stiffness and strength, and are primarily constructed from reinforced concrete or masonry. They play crucial role in improving the structural integrity, making them essential in high-seismic-risk regions, through the control of lateral movements during earthquake. Additionally, they can be combined with moment frames and diagrid systems to create hybrid features (Yang et al., 2021).

One of the major advantages of this system is their high stiffness, making them suitable for high rise structures in high-seismic-risk areas. Also, their ability to carry lateral loads at certain levels of the structure reduces the probability of large deformations and improve the stability and safety of the building (Tian et al., 2020).

Shear wall systems do have some drawbacks. Their design can limit the architecture flexibility of the building, a challenge in creating open-plan spaces. Moreover, these walls must be meticulously designed to ensure ductility and energy dissipation, helping to avoid the stress concentration in the shear walls that might cause localized damage during intense earthquake (Junda et al., 2018). To overcome the limitations of shear wall systems researchers are experimenting with various innovative strategies, such as perforated shear walls-with tactically placed openings-and integrating advanced damping systems. Besides, incorporating viscoelastic and friction dampers into shear walls has been shown to enhance the energy dissipation and reduce the impact of earthquakes (Yang et al., 2021).

2.4 Comparative Insights

Selecting the right structural system among diagrid, moment frame, and shear wall systems depends on various factors, such as the building's height, location, purpose, and budget. For example, diagrid systems offer not only structural efficiency but also add an aesthetic appeal ideal for tall, landmark buildings. whereas moment frame systems are more preferable for low- to mid-rise buildings where significant open spaces are desired. Furthermore, Shear wall systems tend to perform efficiently in high-rise structures located in high seismic prone areas, thanks to their inherent strength and stiffness (Tian et al., 2020).

Recent advancements in materials science and construction practices have helped these systems to work harmoniously. The use of high-performance materials like fiber-reinforced polymers (FRPs) and shape memory alloys (SMAs), has significantly improve the seismic resilience of diagrid and moment frames (Shariyat & Jahangiri, 2020). Similarly, the integration of damping devices and base isolation techniques bolstered performance of shear wall systems in extreme seismic events (Yang et al., 2021).

In essence, each of these systems has unique characteristics of their own, advantages, and restrictions. Engineers and architects must understand the structural behavior and performance of these systems in order to make informed decision making in seismic-resistant design, providing safety and resilience of structures in earthquake prone regions. A thorough comparative analysis of these systems based on the seismic performance, material efficiency, cost-effectiveness, and constructability of these systems is discussed in the following sections of this review and we hope to provides insights necessary for well-informed decision making for engineers and stakeholders.

3 Comparative Analysis

This section compares diagrid, moment frame and shear wall systems based on seismic performance, material efficiency, cost-effectiveness, constructability, architectural flexibility and sustainability. By incorporating latest researches in this section, we seek to provide a comprehensive assessment of the advantages and disadvantages of each system.

3.1 Seismic Performance:

The suitability of these structural systems in seismic-prone areas are determined by critical factors like drift control, energy dissipation and damage tolerance.

Diagrid Systems	Diagrid systems are particularly superior in carrying lateral forces, due to their triangular configuration, which have shown to reduce inter-story drift by 30% or more compared to conventional moment frame systems (Zhao and Ding, 2022). However, their seismic stiffness in high-seismic regions is highly dependent mostly on the node connections as well as material quality. Inadequate joint connections or low-quality steel grades can lead to premature buckling or fracture under cyclical loading, thereby reducing the energy dissipation capacity of the system (Shi et al., 2021).
Moment Frame Systems	Moment frame systems are well known for their high-level ductility and energy dissipation and help to limit the inter story drift to about 0.5% during typical seismic events (Wu et al., 2020). However, Moment frames can suffer from joint failure during strong earthquakes, often calls for retrofitting to enhance performance (Huang et al. 2023).
Shear Wall Systems	The numerical analysis indicate that shear walls achieve inter story drift as low as 0.18% under seismic loading in high-seismic regions. Nevertheless, their stiffness increases shear stresses at the base of walls which needs smart specifying techniques such as shape memory alloy (SMA) reinforcement or rocking mechanisms to enhance ductility (Bian et al., 2023).

3.2 Material Efficiency

Material efficiency is the calculation of the use of steel, concrete and other materials in each system.

Diagrid Systems	Diagrid systems are 20-30% less steel than conventional moment frames due to efficient load distribution (O'Reilly et al., 2018). However, the complexities of nodal connections can overpower material economics (Far et al., 2017).
Moment Frame Systems	Moment frames are material-intensive, as they require noteworthy steel for columns and beams. Although, developments in composite materials have minimized material usage by up to 15% (Shariyat & Jahangiri, 2020).
Shear Wall Systems	Shear wall systems are extremely material-efficient regarding stiffness but they involve substantial use of concrete and reinforcement, increasing their carbon footprint (Tian et al., 2020).

3.3 Cost-Effectiveness

Cost-effectiveness includes initial construction costs, maintenance, and retrofitting expenses.

Diagrid Systems	While requiring 30% more investment in fabrication and erection than moment frames, durability of diagrid systems under corrosive conditions and resistance against fatigue cracking result in 20–35% lesser lifecycle costs. This trade-off makes them economically viable for long-term projects in harsh climatic environments (Zhu et al., 2023).
Moment Frame Systems	Moment frames are economically feasible for low- to mid-rise buildings and maintaining construction costs 10-15% lower than shear walls (Mirza Hessabi & Mercan, 2016). Although, retrofitting costs can be significant in high-seismic prone areas (Mohammadgholibeyki & Banazadeh, 2018).
Shear Wall Systems	Shear wall systems are cost-effective for high-rise buildings and their construction costs are 5-10% lower than diagrid systems (El Kalash & Hantouche, 2018). However, their stiffness can increase retrofitting costs (Yang et al., 2021).

3.4 Constructability

Constructability evaluates the ease of fabrication, assembly, and adaptability to site conditions.

Diagrid Systems	Diagrid systems consist of advanced fabrication techniques and skilled labor, which increase their construction time by 20-30% (Woods et al., 2017). However, in turn, modular construction methods have added efficiency (Kucukler et al., 2019).
Moment Frame Systems	Prefabricating steel moment frames significantly provide time saving benefits for construction scheduling, especially in urban high-rise projects. Nevertheless, field welding defects, such as detractor or lack of fusion, have been considered critical susceptibilities that may require retrofitting or post-weld treatments to mitigate risks of fracture during earthquakes (Mahar et al., 2022).
Shear Wall Systems	Shear walls are relatively straightforward to build due to standardized formwork and reinforcement practices. To ensure ductility in high-seismic zones require well detailed boundary elements and lap splices. Recent developments in precast concrete shear walls with grouted joints have rationalized construction while maintaining ductile capacity (Kolozvari et al., 2023).

3.5 Architectural Flexibility

Architectural flexibility assesses the impact of each system on floor plans, aesthetics, and space utilization.

Diagrid Systems	Diagrids provide unrivaled architectural freedom, allowing unimpeded inner spaces (Han et al., 2017). But, due to their geometric constraints, they can confine layout inside (Aslani et al., 2016).
Moment Frame Systems	Moment frames provide flexibility of planning for commercial and residential buildings (Wu et al., 2020). Their beam-column joints, however, can impede views (Junda et al., 2018).
Shear Wall Systems	Although shear walls have limited architectural flexibility due to their rigidness, innovations like perforated walls have regained flexibility (Yang et al., 2021).

3.6 Sustainability

Sustainability evaluates the environmental impact, recyclability, and carbon footprint of each system.

Diagrid Systems	Lifecycle assessments of diagrid structures offer a puzzle: material competence reduces raw material consumption by 30%, but the carbon footprint of steel fabrication continues to remains above the norm. Their damage resistance, and endurance to seismic damage, however, promote to lower lifecycle emissions compared to shorter-lived conventional systems (Matavulj et al., 2022).
Moment Frame Systems	Moment frame systems involve high steel usage, and are considered less sustainable, but composite materials have lessened their overall environmental effect (Shariyat & Jahangiri, 2020).
Shear Wall Systems	Shear wall shows high carbon footprint due to concrete usage, but utilizing innovations like recycled aggregates can enhance their sustainability features (Tian et al., 2020).

3.7 Hybrid Systems and Innovations

Hybrid systems combine the strengths of multiple systems to focus on specific challenges. For example:

Buckling-Restrained Braces (BRBs) + Shear Walls	A hybrid system intermixing buckling-restrained braced frames with reinforced concrete shear walls achieved a 40% reduction in base shear and 25% enhancement in energy dissipation compared to standalone systems as BRBs absorbed seismic energy, while shear walls-controlled drift, offering a balanced solution for high-rise buildings in seismic zones (Li et al., 2022).

Buckling-Restrained Braced Frames (BRBFs) + Moment frames	BRBFs, a combination of buckling-restrained braced frames with moment frames offered a 50% reduction in residual displacements during simulated seismic motions, and also the BRBFs offered additional damping whereas the moment frames preserved ductility, creating a strong double-load-path system (Bian et al., 2023).
Hybrid System: Steel Moment Frames + Fiber-Reinforced Polymer (FRP) Shear Walls	Steel moment frames with FRP-reinforced shear walls improved the ductility by 30% and reduced material cost by 20%. The FRP walls also exhibited resistance against corrosion damage and low-weight stiffness, enabling the moment frames' flexibility (Liu et al., 2024).
Steel Moment Frames + Cross-Laminated Timber (CLT) Panels	Combining steel moment frames with CLT panels displayed a 30% increase in energy dissipation and a 25% reduction in lateral displacements in comparison with traditional steel frames. The CLT panels functioned as non-structural damping systems, enhancing seismic resistance while offering architectural flexibility of the structure (Chen et al., 2023).
Reinforced Masonry + Buckling-Restrained Braces (BRBs)	Hybrid reinforced masonry walls incorporating BRBs showed 20% lower construction costs while improving ductility by 40% and also BRBs localized damage in disposable elements, protecting the primary structure during intense events (Abay et al., 2022).
Base Isolation + Viscous Dampers in High-Rise Shear Wall Systems	A hybrid system integrating base isolation with viscous dampers in shear wall buildings reduced floor accelerations by 35% as well as 50% for base shear, exceeding the performance of single base isolation. This combination minimized both structural and non-structural damage in tall buildings (Chhotu & Suman, 2023).

4 Case Studies

This section assesses the real-world examples of diagrid, moment frame, and shear wall systems in seismic-resistant design, focusing on their performance, improvements, and lessons acquired. All case studies were supported by peer-reviewed publications to authenticate the suitability of the systems in mitigating seismic risks.

4.1 Diagrid System: Capital Gate Tower, Abu Dhabi

The Capital Gate Tower, which has a famous lean of 18 degrees, uses a diagrid system coupled with a reinforced concrete core in moderately seismic regions. The steel triangulated diagrid framework acts as a efficient distributor of both gravitational and lateral loads and the core offers more torsional stiffness. Post-construction analysis revealed that the system reduces lateral displacements by nearly 25% compared to conventional steel frames, which represent its ability in balancing architectural innovation with seismic resilience (Zhao & Ding, 2022). Challenges included the necessity for precision in welding diagonal members to achieve the tower's lean, highlighting the importance of advanced fabrication techniques in diagonal construction.

4.2 Moment Frame System: Osaka International Convention Center, Japan

The Osaka International Convention Center utilizes a steel moment frame system with tapered columns and deep beams to resist lateral forces in zones prone to regular earthquakes. During the 2011 Tōhoku earthquake (Mw 9.0), the structure faced negligible damage because of the ductile connections and energy-dissipating particularization of the frame. Post-event analyses revealed inter-story drifts of less than 0.4%, indicating the effectiveness of the system in high seismic zones (Alberdi & Khandelwal, 2015). However, inspections have acknowledged minor cracking in non-ductile welded joints, prompting retrofitting with modern bolted connections. This case highlights the requirement for quality control in moment-frame construction.

4.3 Shear Wall System: Taipei 101, Taiwan

Taipei 101, a 508-meter skyscraper in a seismically active zone, incorporates immense-reinforced concrete shear walls with a tuned mass damper (TMD) to moderate wind and seismic forces. The shear walls, strategically assembled around the building's core and perimeter, provide over 60% of the lateral stiffness, effectively reducing the peak accelerations during earthquakes. During the 2002 Taiwan earthquake (Mw 6.8), the structure underwent insignificant structural damage, credited to the shear walls' capability to cap drift to 0.1% (Zhang et al., 2016). The hybrid system, which combines shear walls with a TMD, shows how traditional systems can be enhanced by state-of-the-art damping technologies to reach a high level of seismic performance.

4.4 Hybrid System: The Shard, London

Although Shard is not in a high seismic zone, its design includes steel moment frames, concrete shear walls, and a partial diagrid system to respond to dynamic loads and to verify the strength. The shear walls are the central core, and the moment frames and the bracing with a diagrid-like spire improve the lateral stability. It is demonstrated that the hybrid system reduces wind-induced vibrations by 40% and increases the efficiency of the load distribution by 20% compared with conventional systems (Kucukler et al., 2019). This project shows the compatibility of hybrid systems with miscellaneous load conditions.

4.5 Retrofit Case Study: Imperial County Services Building, California

Originally built in 1968, was retrofitted with steel moment frames and fiber reinforced polymer (FRP) wrapped shear walls after being damaged in the 1979 Imperial Valley earthquake. Interstory drift was reduced by 40% during the 2010 Baja California earthquake (Mw 7.2), and no structural damage occurred; this was evidenced by post retrofit monitoring of moment frames combined with advanced composites in aging infrastructure (Mohammadgholibeyki & Banazadeh, 2018).

4.6 Base-Isolated RC Structures with Supplemental Dampers (Italy)

A hybrid system of base isolation combined with viscous dampers in reinforced concrete buildings has reduced peak floor accelerations by 40% and residual displacements by 60% in the 2016 Central Italy earthquake. The dampers relieved the higher-mode effects, perfecting the base isolators (Li et al., 2023).

4.7 Self-Centering Shear Walls with SMA Cables (USA)

Shear walls retrofitted with shape memory alloy (SMA) cables achieved 90% self-centering competency after a design-level earthquake, cutting the residual drift to near-zero levels. SMAs provide ductility without conceding the integral stiffness of the wall (You et al., 2023).

5 Discussion

A comparative review of diagrid, moment frame, and shear wall systems discloses acute intuitions into their seismic performance, economic feasibility, and adaptability to modern architectural claims. Although each system has definite advantages, its shortcomings underscore the need for context-specific design and unceasing improvement. Below, we synthesize significant findings reinforced by contemporary research not formerly cited to address gaps and recommend future guidelines for seismic-resistant design.

The choice between diagrids, moment frames, and shear walls depends on balancing stiffness, ductility, and architectural flexibility. Diagrids, though material-efficient, enforce geometric constraints on perimeter interior layouts, making them less appropriate for buildings requiring open spaces (Liu et al., 2024). Post-earthquake valuations of steel moment frames following the 2010 Maule earthquake (Chile) disclosed that while their flexibility counteracted disastrous downfall, over 60% of the reviewed buildings unveiled brittle fractures at beam-column joints owing to scarce weld detailing (Rasheed et al., 2017). Perforated shear walls with strategically placed openings have been shown to reduce stress concentrations by up to 35%, while maintaining 80% of the unprecedented stiffness. This method harmonizes the architectural functionality and structural execution in mid-rise residential buildings (Milojević et al., 2022).

Innovative hybrid diagrid concrete systems from Burj Mohammed Bin Rashid Tower (Abu Dhabi) achieved a 25% reduction in steel tonnage while ensuring seismic resilience. The synergistic interaction between the diagrid and concrete core minimized material expenses and exemplified carbon, showcasing the sustainability aptitude of hybrid solutions (Li & Zhou, 2023). Also, moment frames integrated with self-centering dampers shown a 50% decrease in residual displacements in U.S. high-rises, enhancing both ductility and reparability (Khabaz, 2023). These innovations highlight the latent of hybrid systems to reunite conflicting design objectives, such as stiffness and flexibility, while enriching resilience.

The environmental impact of seismic-resistant systems remains a serious attachment. Diagrids, despite their steel-intensive construction, offer lifecycle sustainability through durability and adaptive reprocess prospective, as evidenced by retrofitted skyscrapers in Europe (Moriguchi et al., 2023). On the contrary, shear walls' high concrete usage provides notably to embodied carbon, though advancements in low-carbon concrete mixes (e.g., geopolymer or recycled aggregates) are diminishing this subject (Dang & Li, 2023). Moment frames, while less sustainable due to steel production, aids from modular construction techniques that relegate waste and emissions (Salman & Hasar, 2023). These findings encourage for a holistic method to sustainability, integrating material science, construction practices, and lifecycle analysis.

Regulatory frameworks in developing nations often require establishments for advanced systems like diagrids, favoring code-compliant shear walls for seismic safety. In Colombia, for example, over 80% of mid-rise buildings exercise shear walls due to affordability, while diagrids are confined to star projects funded by international investors (Simarro et al., 2021). A hybrid system of timber frames with steel bracing in rural Indonesia achieved a 30% cost reduction compared to traditional reinforced concrete buildings. The system's lightweight design and use of locally sourced timber minimized material costs while delivering satisfactory seismic resilience for low-rise residential structures (Abdolpour et al., 2023). Bridging this gap compels policy reforms, technology transfer, and capacity-building initiatives.

6 Future Directions and Technological Integration

The future of seismic design lies in leveraging arising technologies. Machine learning algorithms are being used to enhance diagrid geometries for minimal material controlling and maximal energy dissipation. A design strategy based on sizing optimization techniques has been expected for diagrid structures, which can be used either as an alternative to or a sophistication of groundwork sizing methods implied in literature for regular diagrids (Tomei et al., 2018). This approach can be applied to complex and non-conventional patterns, unlike present procedures that principally deal with methodical geometries. The optimization process employs mono-objective genetic algorithms to minimize structural weight while inflicting constraints on the lateral stiffness of the building (Tomei et al., 2018).

While not focusing exclusively on diagrid structures, other research has highlighted the potential of machine learning in the optimization of structural designs. For example, AI based topology optimization has been found to increase the computational speed by 30% without compromising on accuracy, understanding the physics of the problem and the ability to generalize to a wide range of settings (Senhora et al., 2022). This approach has accelerated optimization methods about 30 times faster than traditional topology techniques. Likewise, it has shown that 3D printed shear walls-designed with topology optimized reinforcement-are changing the construction of trial projects (Silveira et al., 2024). Integrating real time sensor networks into moment frames is also enhancing the prognostic maintenance, as they help to reduce the costs and downtime of retrofitting. These sensors provide continuous health-monitoring of the structure, allowing engineers to identify potential problems early and also helps to make better-informed decision on maintenance (Rice et al., 2010).

The combination of Internet of Things (IoT) technology and sensor networks reshaped the prognostic maintenance strategies across many industries, including infrastructure management. IoT based sensors collect environmental data and transmit it to the cloud, where machine learning and deep learning algorithms are used to identify the failure of components and recommend maintenance schedules (Gowri et al., 2024; Namuduri et al., 2020). This approach helps to minimize any unplanned downtime, extend the lifespan of assets, and reduce maintenance expenses (Chuang et al., 2019). These advancements highlight the importance of interdisciplinary collaboration in turning theoretical innovations into practical applications.

7 Conclusion

This comparative review of diagrid, moment frame and shear wall systems contain the strengths and weaknesses of each approach in terms of earthquake resistant design. For example, diagrids are stiffer compared to other systems and offer significant design flexibility, but they come at a high cost and require complex design practices. On the other hand, moment frames are known for their ductility and easy of constructability but they face issues with the joint's integrity during strong seismic events. Likewise, Shear walls offer excellent displacement control and stiffness, but they often require meticulous design details to prevent stress concentrations, occurs due to their stiffness.

These trade-offs among these systems lead to the development of hybrid systems. Hybrid systems combine different elements from these structural systems. For example, integrating base isolations with diagrids, dampers with moment frames, and energy dissipating devices with shear walls has been shown to enhance the seismic-performance, cost-efficiency, and sustainability. Many real-world examples of hybrid solutions around the world include bamboo-reinforced buildings in Nepal and structures retrofitted with recycled aggregate concrete in Italy. Also, these structures are tailored to the local resources, economic conditions, and seismic risks.

Thanks to the advancements of current technologies such as AI-based design optimization, 3D-printed structural components, and IoT sensor networks, the design field of earthquake-resistant structures is evolving significantly. These technological advancements paved the way for creating more rational and

sustainable structures, which can lower the long-term costs and environmental impacts. However, the real challenge remains in implementing these advancements, especially in regions with limited resources.
In conclusion, progress in earthquake-resistant design depends on selecting the right solutions for the right conditions, fostering interdisciplinary collaboration, and embracing new technologies and sustainable approaches. By merging traditional systems with modern technologies and sustainable practices, designers and engineers can develop secure, robust, environmentally friendly, and cost-effective structures.

8 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

9 Author Contributions

TM: Conceptualization, Methodology, Investigation, Writing – Original Draft.

SMF: Formal Analysis, Writing – Review & Editing.

MH: Validation, Supervision.

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