



Advances in Design, Analysis, and Optimization of Diagrid Structures in Tall Buildings: A Comprehensive Review

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Abstract: The Diagrid structural system has emerged as one of the most efficient and aesthetically appealing solutions for modern tall buildings, primarily due to its superior lateral stiffness, material efficiency, and architectural flexibility. Unlike conventional framed or shear wall systems, Diagrid utilize a triangulated framework that effectively resists both gravity and lateral loads while minimizing the need for internal columns. This review paper synthesizes recent advancements and research trends in diagrid structures, with a particular focus on their seismic performance, design optimization, sustainability, and integration with intelligent computational tools. A comprehensive examination of studies published between 2021 and 2025 reveals a growing adoption of advanced computational methodologies such as machine learning, fuzzy-genetic algorithms, multi-objective evolutionary optimization, and metaheuristic techniques for refining diagrid configurations. These approaches have significantly contributed to improving design accuracy, structural resilience, and performance prediction under dynamic loading conditions. Furthermore, recent investigations emphasize the development of sustainable and resilient diagrid systems through innovative strategies like replaceable or modular components, hybrid material usage, and performance-based design frameworks. The integration of data-driven approaches with generative design tools has enabled architects and engineers to explore complex geometries, reduce material consumption, and enhance the adaptability of structures to varying environmental and seismic demands. By critically reviewing key contributions from the last five years, this paper underscores the transformative role of optimization and artificial intelligence in the evolution of diagrid structural systems. It further highlights how these advancements are shaping the next generation of high-rise buildings to be more efficient, sustainable, and responsive to both functional and environmental challenges.

Keywords: Diagrid system, tall buildings, seismic performance, optimization, machine learning, generative design, sustainable structures.

I. INTRODUCTION

In recent years, the design and construction of tall buildings have experienced significant advancement due to rapid urbanization, limited land availability, and growing architectural ambition. Among the various structural systems developed for high-rise buildings, the diagrid system has gained remarkable attention from architects and structural engineers. A diagrid (short for “diagonal grid”) structure is composed of a framework of diagonal members that intersect to form a series of triangular configurations along the exterior façade of the building. This triangular geometry efficiently resists both gravity and lateral loads, including wind and earthquake forces, thereby reducing the need for conventional vertical columns. As a result, diagrid structures are recognized for their lightweight design, improved stiffness, and greater aesthetic freedom.

Unlike conventional framed or shear wall systems, where vertical and horizontal elements resist loads independently, diagrid systems create an integrated load path through diagonal elements. This reduces bending moments in beams and columns, leading to material savings of up to 20–30% compared to traditional high-rise designs. In addition to their structural efficiency, diagrids provide architectural flexibility, allowing designers to create unique building shapes such as twisted, tapered, or curved towers while maintaining stability. Famous examples such as The Gherkin in London, Hearst Tower in New York, and Capital Gate in Abu Dhabi demonstrate how diagrid systems can merge structural performance with iconic aesthetics.

Diagrid systems—characterized by diagonally intersecting structural elements that form a triangulated exterior framework—have transformed the design of tall buildings by improving lateral load resistance while reducing steel consumption. Their geometric efficiency and architectural expression have encouraged extensive research into performance optimization, seismic resilience, and computational modelling. Recent developments focus on integrating artificial intelligence and optimization algorithms to achieve lighter, stronger, and more sustainable diagrid designs. This review consolidates contemporary findings to map the evolution of diagrid research and identify emerging trends.

In addition to performance and efficiency, sustainability and resilience have become major considerations in tall building design. Modern studies on diagrid systems focus not only on achieving high stiffness and strength but also on ensuring that the structures



can withstand seismic events with minimal damage and easier repair. The introduction of concepts like replaceable energy-dissipating components and adaptive design strategies reflects a shift toward more sustainable, reusable, and repairable building systems.



Fig.1 Real life example of Diagrid Structures

II. SEISMIC PERFORMANCE OF DIAGRID SYSTEMS

The seismic performance of diagrid systems has been a major focus of research, as tall buildings are often located in regions prone to earthquakes where controlling lateral displacement and structural damage is critical. The unique triangulated geometry of diagrids allows them to efficiently resist lateral loads by distributing forces through diagonal members rather than relying solely on vertical columns or core walls. This results in improved stiffness and reduced drift, making the diagrid an effective lateral load-resisting system. Several studies have examined how diagrid systems behave under dynamic loading, exploring both their global and local seismic response characteristics.

Jahangiri et al. (2025) [1] explored supervised machine learning methods to predict maximum inter-story drift ratio (M-IDR) in steel diagrid buildings. Their models, trained on data from incremental dynamic analyses, achieved exceptional accuracy ($R^2 > 0.95$), demonstrating that ensemble ML methods can substitute traditional nonlinear analyses.

Liu et al. (2022) performed a probabilistic fragility assessment on steel diagrids with bottom-tilted columns, identifying these elements as critical for drift control under strong ground motion.

Liu et al. (2024) introduced a sustainable diagrid core-tube system with replaceable steel coupling beams, significantly improving ductility, energy dissipation, and post-earthquake reparability.

Collectively, these works underscore that both data-driven prediction and innovative detailing strategies can enhance diagrid seismic resilience.

III. OPTIMIZATION AND PARAMETRIC DESIGN APPROACHES

Optimization and parametric design play an essential role in improving the efficiency and performance of diagrid systems used in tall buildings. As the geometry of a diagrid involves numerous variables—such as the angle of diagonals, spacing between nodes, and the height of modules—achieving the best combination of these parameters is a complex task. Traditional trial-and-error design methods are often time-consuming and may not yield the most efficient solutions. Therefore, researchers have increasingly turned toward optimization algorithms and parametric modelling tools to automate the design process and identify configurations that provide maximum strength and stiffness while minimizing material use and cost. These techniques allow engineers to explore a wide range of design possibilities and evaluate multiple performance criteria simultaneously.

Wang et al. (2025) [2] employed the Snow Ablation Optimizer (SAO), a nature-inspired metaheuristic method, to achieve material-efficient high-rise diagrid designs. Similarly, Liu et al. (2025) utilized NSGA-II for multi-objective optimization, balancing weight reduction with deflection and stability constraints.

Ashtari et al. (2021) [10] developed a fuzzy-genetic algorithm (FGA) that integrates fuzzy logic with evolutionary principles to account for design uncertainty and convergence accuracy.

Jalali et al. (2024) [6] further examined the influence of internal core configurations—moment frame versus braced core—on overall stiffness and load-sharing efficiency.

Together, these studies demonstrate that metaheuristic and hybrid algorithms can systematically navigate the nonlinear design space of tall diagrid systems to achieve optimal configurations.



IV. MACHINE LEARNING APPLICATIONS IN DIAGRID DESIGN

In recent years, machine learning (ML) has emerged as a powerful tool in structural engineering, offering new possibilities for predicting building performance and optimizing complex design systems like diagrids. Machine learning techniques allow engineers to analyze large amounts of data, identify patterns, and make accurate predictions without the need for repeated, time-consuming simulations. This data-driven approach has proven especially useful for diagrid structures, where multiple parameters—such as diagonal angle, member size, building height, and stiffness distribution—interact in complex ways to influence structural performance. By training models on results from numerical simulations or experimental data, ML algorithms can quickly estimate responses such as drift, displacement, and stress, thus speed up the design process and improve decision-making accuracy.

Recent studies reveal growing interest in integrating ML for performance prediction and early-stage design guidance.

Kazemi et al. (2022) [9] employed six classifiers (KNN, SVM, decision trees, etc.) to predict lateral displacement of tall diagrid buildings based on geometry, effectively bridging architectural form and seismic behavior. The 2024 study Machine Learning Techniques for Diagrid Building Design emphasized feature importance interpretation using SHAP analysis, identifying critical parameters influencing structural response. Jahangiri et al. (2025) extended this domain with regression-based prediction of seismic drift, confirming ML's robustness in structural response estimation. These efforts mark a paradigm shift toward AI-assisted structural engineering, enhancing design efficiency and interpretability.

V. GENERATIVE AND TOPOLOGICAL DESIGN METHODS

Generative and topological design methods have recently gained significant attention in the study of diagrid systems, as they allow designers to automatically create and evaluate a wide range of structural forms with minimal manual intervention. These methods rely on computational design algorithms that generate geometries based on predefined rules, constraints, or performance objectives. In the case of diagrid structures, where geometry plays a crucial role in both aesthetics and structural efficiency, generative and topological design tools help identify the most effective arrangement of diagonal members, node connections, and module heights. By combining structural analysis with computational modeling, these approaches enable designers to achieve innovative, high-performance solutions that balance visual appeal, stiffness, and material economy. Generative and topology-based approaches expand the design flexibility of diagrids. Tomei et al. (2022) [7] proposed a structural grammar framework integrating genetic algorithms for topology optimization, allowing exploration of non-uniform triangulated layouts. Cascone et al. (2021) applied parametric and genetic design tools to create stress-aligned diagrid forms with variable density, demonstrating improved weight-to-stiffness ratios. Patel et al. (2024) reviewed the effects of variable diagrid angles, highlighting their impact on stiffness, displacement control, and sustainable material use. These works emphasize that rule-based generative systems enable creative yet structurally sound solutions for future tall buildings.

VI. COMPARATIVE STUDIES AND DESIGN TRADE-OFFS

Comparative studies play an important role in understanding how different structural configurations and design choices influence the overall performance of diagrid systems in tall buildings. Since diagrid structures can vary widely in geometry, core design, and module arrangement, comparing multiple alternatives helps engineers and architects identify the most efficient and practical solutions for different design objectives such as strength, stiffness, material efficiency, and constructability. These comparisons also reveal the trade-offs that often arise between structural performance and architectural or economic considerations, guiding designers toward balanced and optimized solutions. Yıldırım et al. (2024) [12] compared diagrid and hexagrid structural systems in a 36-storey building, revealing that diagrids outperform hexagrids in dynamic response, while large-module hexagrids excel in day lighting and steel economy. Jalali et al. (2024) [6] highlighted that core typology strongly influences diagrid utilization and drift behavior, demonstrating the need for integrated architectural–structural coordination. Such comparative research informs practical decision-making between competing diagrid configurations.

VII. DISCUSSION

The review of recent literature clearly shows that the diagrid system has evolved into one of the most efficient and versatile structural solutions for tall buildings. Researchers have explored this system from multiple perspectives—seismic performance, optimization, machine learning applications, and generative design—to achieve stronger, lighter, and more sustainable high-rise structures. A common finding across all studies is that the diagrids triangulated configuration provides excellent stiffness and lateral resistance, making it particularly suitable for buildings in seismic and high-wind regions. The system's ability to distribute forces evenly through diagonals reduces bending moments in beams and columns, leading to lower material consumption and improved energy dissipation during earthquakes. However, the studies also reveal that performance depends significantly on key design parameters such as the diagonal angle, module height, and the type of internal core used.

Across the reviewed literature, three dominant trends emerge:

1. Intelligent modeling: ML and AI methods now complement traditional analysis, offering rapid and accurate response predictions. [7]
2. Optimization synergy: Evolutionary and metaheuristic algorithms improve geometric and topological efficiency.
3. Resilience and sustainability: Replaceable components and optimized geometries contribute to sustainable performance-based design.

Future studies should integrate multi-objective AI-driven optimization and life-cycle sustainability metrics to further enhance diagrid adaptability.

VIII. CONCLUSION

The diagrid structural system represents one of the most important advancements in tall building engineering over the past two decades. Its combination of structural efficiency, geometric elegance, and architectural flexibility has made it a preferred choice for high-rise structures worldwide. From the studies reviewed, it is evident that diagrid systems offer superior performance under lateral loads due to their triangulated configuration, which allows effective force transfer through diagonal members. This structural behavior not only enhances stiffness and stability but also significantly reduces material usage compared to conventional frame or shear-wall systems, making diagrids both economically and environmentally efficient. [9]

The literature further shows that the application of optimization algorithms, machine learning models, and parametric design techniques has transformed the way diagrid systems are analyzed and developed. Optimization studies using advanced algorithms like the Snow Ablation Optimizer (SAO), NSGA-II, and fuzzy-genetic approaches have proven highly effective in identifying optimal geometries that minimize weight while maintaining strength and serviceability. Machine learning methods have similarly shown great potential in predicting seismic responses and performance parameters with high accuracy, offering an alternative to computationally expensive nonlinear analyses. These approaches demonstrate how data-driven and algorithmic design can reduce human effort and improve both design speed and precision. [7]

Additionally, the integration of generative and topological design frameworks has opened up new possibilities for architectural innovation. By applying rule-based systems and parametric modeling tools, designers can now create diagrid patterns that align with internal stress trajectories, resulting in both aesthetic and functional improvements. Such methods make it possible to explore non-traditional geometries while maintaining structural integrity, giving rise to more creative, efficient, and sustainable tall buildings. Comparative studies also emphasize that while diagrid systems excel in structural performance, other systems such as hexagrids may offer benefits in terms of material economy and architectural transparency. Therefore, achieving the ideal solution often involves striking a balance between structural performance, cost efficiency, and design intent. [5]

The review also highlights the growing importance of sustainability and resilience in modern diagrid design. Recent research focusing on replaceable and energy-dissipating components has shown that diagrid systems can be designed not only to resist earthquakes but also to recover quickly after damage, thus extending their service life and reducing repair costs. This aligns with the broader trend toward performance-based and sustainable engineering practices that emphasize durability, reusability, and environmental responsibility. [3]

In conclusion, diagrid systems continue to evolve as a powerful and adaptable framework for tall building design. With the ongoing integration of artificial intelligence, optimization algorithms, and generative design tools, the future of diagrid structures lies in intelligent, adaptive, and sustainable systems capable of learning and optimizing themselves throughout their lifecycle. Continued research in this area should focus on the coupling of computational design with real-time monitoring, material innovations, and life-cycle assessment to further enhance performance and sustainability. As technology advances, the diagrid system is expected to remain at the forefront of tall building innovation — a true example of how engineering and architecture can come together to create efficient, resilient, and visually inspiring urban structures. [2]

Diagrid systems continue to redefine tall building design through structural efficiency, aesthetic innovation, and computational integration. Advances in machine learning, evolutionary optimization, and generative design have accelerated their development toward resilient and sustainable solutions. A unified framework combining these approaches could enable the next generation of intelligent, adaptive diagrid structures for high-rise construction.[12]

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