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Evolution and Performance of Structural Systems in Skyscrapers under Lateral Loads

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Abstract: The growth of population and rapid urbanization has significantly led to the development of high-rise buildings that provide more occupants over a limited plot size, which is a critical requirement today. The primary challenges faced by these structures are wind and seismic loads, which cause swaying and structural failure. This paper critically analyzes the evolution and lateral load performance of skyscraper structural systems with respect to their efficiency under various lateral loadings. Latest structural systems like outrigger and belt truss systems provide adequate lateral stiffness as well as reduce storey drift. On the other hand, tube-based systems, e.g., tube in tube or bundled tubes, resist overturning moments and lateral displacement. Diagrid Structural systems are not only efficient in resisting lateral loads but also provide opportunities for architectural treatments. Emerging structural systems lean towards Hybrid systems that mainly focus on improved lateral resistance with advanced materials such as fiber-reinforced plastics (FRP) for optimized efficiency. Vibrations are also one of the key challenges for these types of structures, for which damping systems are introduced, such as tuned mass dampers (TMD) and tuned liquid dampers (TLD) to reduce vibrations and improve occupant comfort. Recent advancements in structural systems indicate a strong shift towards performance-based structural design and analysis aimed at improving lateral resistance, material efficiency, and occupant comfort.

I. INTRODUCTION

From an early age, human settlement has always been challenging due to rapid urbanization and the continuous growth of the population. The demand for housing and infrastructure has led cities to develop horizontally rather than vertically, which has led to inefficient land use. Residential Structures that house a large population in a restricted area are the main objective for modern urban development. This necessity has led to the emergence and evolution of skyscrapers as an excellent solution for accommodating large populations in a dearth of land scenarios. However, the increased scale of the structures has also given birth to challenges in terms of safety and stability. Thereby making it necessary for developing healthy structures that can resist numerous loads acting on tall buildings.

II. PROBLEM STATEMENT

As the height of the structure increases, lateral loads and seismic forces become governing factors for the design. The forces induced by winds can cause lateral displacements, while the seismic forces may lead to inertial forces that affect the structural integrity and may result in excessive storey drifts as well as increased floor acceleration. Conventional structural systems (MRF's, simple rigid frames without bracing and braced frames) for resisting gravitational loads were not found to be efficient, lacking the required stiffness also the energy dissipation capacity, in order to control lateral displacements in tall structures. Consequently, their use in high-rise buildings is not considered a good option, leading to advanced structural systems for compensating lateral load resistance and overall performance.

III. EVOLUTION OF STRUCTURAL SYSTEMS

The evolution of structural systems in skyscrapers has always been driven by the lateral loads as well as architectural treatment. During the early days of designing the skyscrapers, Moment Resisting Frames (MRF) were usually considered, but today, they are inefficient for very large buildings due to inefficiency for lateral displacements and vibrations. This led to the design of more adequate systems like Frame tubes, bundled tubes, and tube-in-tube techniques. To distribute the loads efficiently to the substructure and improve drift control, outrigger and belt truss systems have been developed. The Diagrid systems, which are also a newer technique for skyscrapers, have been proven to be successful in structural efficiency as well as architectural settings. Hence, this progression shows a strong jump for performance-based design (neutralizing lateral displacements and occupant comfort) rather than just strength.

IV. RESEARCH GAPS

There are many studies regarding the structural systems for high-rise buildings, but most of this research was on isolated systems and does not provide a comprehensive comparison of different forces acting on the structure. Therefore, it is not clear how the structure will respond to various threats like drifts, earthquakes, as well as stiffness. Conversely, there is a requirement for a thorough review that compares the response of the structure to these threats and guides the engineers and architects about design principles.

V. AIMS AND OBJECTIVES

From the above observations, this review paper critically evaluates the performance of structural systems that are being utilized in structural systems and determines their reliability and sustainability under different loading conditions (Jain & Maru, 2025; Comparative Study of Seismic Performance, 2025; Al Kodmany, 2025). This consolidated review was required because individual studies focus on isolated structural systems without evaluating the performance of the building under various parameters, most prominently wind and seismic actions.

VI. LATERAL LOADS IN SKYSCRAPERS

A. Wind loads

Wind actions are a major challenge to the design and engineering of skyscrapers. Wind loading is directly proportional to the height of the building, which means high-rise buildings will experience significant wind forces and cause sway of the building. Winds act in a more complex manner on these structures by creating pressure differences between the windward side and the leeward side of the building. Wind forces are generated mainly due to flow separation and vortex shedding, eventually leading to lateral displacements, torsions, and dynamic vibrations.

Wind loading also affects the lateral deflections and inter-storey drift, which further leads to serviceability issues. The accelerations produced by winds effects occupant comfort, which further magnifies with the height and affects the building's functioning. Flexible structural systems are affected more by these dynamic forces due to resonance when the frequency of the structure matches the wind excitation frequency.

The effects of wind actions are not static; they are highly dynamic and time dependent. This necessitates the consideration of wind effects in the design of the structure as conventional structural systems are not found adequate for responding to wind-induced forces. Hence, advanced structural systems are required that focus on dynamic considerations, controlling drift, and occupant comfort.

B. Seismic Loads

Seismic load is also one of the key factors that governs the design of the structure particularly in areas prone to earthquakes. Unlike wind loads that create problems to serviceability, seismic forces create inertial forces throughout the building due to ground motion. These forces depend on the mass and dynamic characteristics of the building often resulting in complex responses by tall structures.

When an earthquake occurs the ground acceleration causes the mass of structure to resist the motion which results in the base shear, overturning moments and inter-storey drift. The response of the building to this seismic force is not static rather uniform and significantly increases with the height. These seismic forces cause major threats to structural and nonstructural components and in some cases may lead to a collapse. The earthquake or seismic forces causes backward and forward motion to the building making it necessary for the structure to have adequate energy dissipation capacities which the conventional systems usually lack making the building vulnerable to brittle failure. Therefore, modern high-rise buildings acquire systems capable of controlling drifts enhancing ductility and adequate energy dissipation.

C. Serviceability and Performance Criteria

Structural performance of a skyscraper is not only dependent on strength but also on serviceability criteria that ensure functional usability and occupant comfort. Even if the building is safe structurally, the lateral displacements, inter-storey drift, and floor acceleration may affect its serviceability. Hence, serviceability is also a major criterion while developing a skyscraper.

Inter-storey drift is a critical parameter for performance, as excessive drift can cause damage to both structural and non-structural components such as partitions, cladding, and facade systems. Design codes provide the drift limits, ensuring the safety of the structure during lateral loading scenarios. With inter-storey drifts, floor accelerations are also considered, as over-limit accelerations can cause motion sickness and discomfort to the occupants.

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These limitations have led to a transition towards performance-based design methodologies in modern high-rise construction. Performance-based design focuses on predefined objectives like acceptable storey drifts, controlled damage, and enhanced occupant comfort under different loadings. This led to the evolution of modern techniques like damping devices and material innovations to achieve efficient lateral load responses. Therefore, serviceability plays an essential role in performance and the selection of structural systems.

VII. STRUCTURAL SYSTEMS FOR LATERAL LOAD RESISTANCE

A. Moment Resisting Frames

Moment resisting frames are among the earliest systems adopted for skyscrapers due to their simplicity, which is adequate to resist lateral and gravity loads with the help of rigid beam connections. The wind and seismic forces are resisted through the flexural stiffness of the beams and columns, and the frame acts as a continuous load-resisting mechanism. These systems were primarily used for low- and medium-height buildings and in some early high-rise buildings.

But for today, as the height of buildings has reached a significant height, these systems cannot be applied as their lateral stiffness is not adequate. Skyscrapers designed with MRFs experience significant lateral displacements, inter-storey drifts, and wind-induced vibrations. Another alternative is using extremely large beams and columns to control these responses, but it leads to excessive material consumption and handling issues. However, Moment Resisting Frames have many advantages as well, especially in areas that are prone to earthquakes. They have adequate ductility and the ability to undergo inelastic deformations, enabling healthy energy dissipation during earthquakes. MRFs are also integrated with other structural systems like shear walls and braced frames to improve lateral stiffness. Hence, moment resisting frames are not alone enough for handling very tall buildings; they need other structural system supports, leading to improved efficiency.

B. Tube Systems

Tube systems were designed to overcome the inefficiencies of moment-resisting frames in tall structures. These systems work by utilizing the perimeter of the structure as a stiff, hollow, continuous tube and distributing the lateral loads to axial forces in closely spaced columns and deep spandrel beams. By moving the lateral load resisting mechanism to the exterior of the building, tube systems enhance the lateral stiffness and reduce overall structural deformation. The tube system consists of closely spaced columns connected together by spandrel beams. Forming a frame that effectively resists the wind and seismic forces. Likewise, this system provides enough resistance to overturning moments. To further increase the height of a skyscraper, tube systems were introduced that incorporate multiple tube frames for resisting lateral loads. Another variation in this system is the tube-in-tube system that combines the exterior frame with the interior core tube. Hence, the load is efficiently shared between the core and perimeter, leading to efficient stiffness. Nevertheless, tube systems have their limitations as well, such as closely spaced columns may restrain window as well as façade design, while structural efficiency may decrease for extremely irregular building geometries.

However, tube systems allowed advancements in the design of skyscrapers with improved lateral load performance. This development shows a critical step in the evolution of skyscraper structural systems, making the way for further advanced systems like diagrid and outrigger systems.

C. Outrigger and Belt-Truss Systems

Outrigger and belt truss systems evolved to improve the lateral stiffness to an extent that could not be achieved by MRFs and Tube Systems. In this system, horizontal elements known as outriggers are connected to the central core of the building and exterior columns. While belt truss systems are provided around the building perimeter at the same level. This configuration allows the lateral load and overturning moments to be redistributed more efficiently throughout the structural system.

Under lateral loading, the outrigger system restrains the rotation of the core by engaging the perimeter columns that develop axial tension and compressional forces. This system helps to reduce the lateral displacements and inter-storey drifts, especially for upper floors. As a result, outrigger and belt-truss systems are highly effective in improving both strength and serviceability performance under wind and seismic actions. The efficiency can be boosted by placing the outriggers more strategically at one or more levels, and optimized drift control can be achieved without the use of excessive material. Despite their structural advances, they also offer critical challenges to the designers. The presence of outriggers may interfere with architectural planning and mechanical floors; the connectivity is much more complex and requires careful design to ensure proper transfer of the load. However, these limitations are outweighed when compared to the advantages they provide in lateral performance. Therefore, Outrigger and Belt Truss systems are widely used today in skyscrapers where drift control and stability are required.

D. Diagrid Systems

Diagrid systems are the modern innovations that eliminate the need for conventional vertical columns and consist of a network of diagonal structural members along the perimeter of the building. These members resist lateral load through axial forces rather than bending, making the system highly efficient for tall buildings subjected to wind and seismic actions. This axial load-carrying mechanism offers more lateral stiffness and reduces material utilization as compared to other structural systems.

The configuration of structural members is usually triangular, which provides enhanced resistance to the torsional effects, leading to very low storey drift and building sway. This makes diagrid systems applicable for complex designing scenarios, where conventional systems may not be alone sufficient. With the absence of interior columns, the diagrid systems are always open for architectural opportunities for the building. Despite their advantages, these systems require more advanced and careful design techniques for complex load paths and joint detailing. However, with progress in computational modeling, these challenges can be overcome easily. As a result, diagrid systems are commonly used today for tall buildings as an effective solution that balances structural performance, material efficiency, and architectural expression.

VIII. COMPARATIVE PERFORMANCE OF STRUCTURAL SYSTEMS UNDER LATERAL LOADS

The performance of the structural systems depends upon their resistance to the seismic and wind forces. All structural systems have different amplitudes of efficiency for stiffness, drift control, and energy dissipation. Hence, a comparative analysis is required to understand the sustainability of each system for skyscrapers under different loading effects.

A. Moment Resisting Frames

This system provides variations for architectural treatment; its lateral stiffness is relatively low for high-rise buildings. With increasing building height, the vibrations and storey drift increase as well, making MRFs not applicable for high-rise buildings. Furthermore, their response to winds is also limited due to bending-dominated behavior and inadequate energy dissipation capacity.

B. Tube-based Systems

Tube-base systems containing Bundled tubes, Framed tubes, and Tube in Tube systems improve the lateral performance of the structure by utilizing the perimeter columns and spandrel beams that help to reduce the overturning moments. They provide higher stiffness and drift control when compared to conventional frames. Bundled tube systems also add to the performance by distributing the lateral forces among multiple interconnected tubes, making them relatively efficient for tall buildings.

C. Outrigger and Belt Truss Systems

These systems enhanced the performance of the structures by utilizing exterior columns to resist lateral loads. This allows the appreciable reduction in storey drift and base moments and increases the overall stiffness of the structure. Outrigger and belt truss systems are particularly required for controlling the lateral displacements, especially for slender high-rise buildings subjected to wind loads. Their efficiency depends upon the number and placements of outriggers, as well as the height of the structure.

D. Diagrid Systems

Diagrid Systems provide excellent lateral load resistance due to their axial force-dominating behavior. The members of the diagrid systems efficiently transfer the loads, making high stiffness possible with lower material consumption. When compared to Conventional frames and Tube systems, Diagrid systems have better control over lateral displacements and torsional effects, especially for high-rise buildings. Moreover, they provide architectural flexibility by eliminating the need for perimeter vertical columns.

Table 1: Comparative performance of structural systems under lateral loads.

Structural System	Lateral Stiffness	Drift Control	Seismic Performance	Wind Performance	Architectural Flexibility	Limitations
Moment Resisting Frames (MRF)	Low	Poor	Moderate	Poor	High	Excessive drift and bending behavior
Braced Frames	Moderate	Moderate	Good	Moderate	Limited	Facade and opening restrictions
Tube Systems	High	Good	Good	Very Good	Moderate	Perimeter constraints

Outrigger & Belt-Truss Systems	Very High	Excellent	Very Good	Excellent	Moderate	Construction complexity
Diagrid Systems	Very High	Excellent	Very Good	Excellent	High	Complex joint detailing
Hybrid Systems	Maximum	Excellent	Excellent	Excellent	High	Higher cost and coordination

However, no single system can be considered optimal for every type of skyscraper design. The selection process depends upon the factors such as building height, Load conditions, architectural requirements and desired performance. Hybrid systems that integrate other structural systems are being utilized to achieve the desired performance, efficiency and comfort.

IX. FUTURE TRENDS AND ADVANCED STRUCTURAL SYSTEMS

The requirement for increased building height has led the industry to more advanced and innovative structural systems. These structures enable the designers to achieve not only stiffness and strength but also serviceability, sustainability, and user comfort in the presence of lateral loads. Hence, high-rise structures in the contemporary era necessitate hybrid systems and performance-based designs in order to attain the overall efficiency in the structure.

A. Hybrid Systems

These systems incorporate different systems like diagrid, tube base, and outriggers to enjoy the benefits of all. These systems improve lateral resistance to loads by optimizing the local pathways while eliminating redundancy in structures. By combining various systems, designers will benefit from optimized control when dealing with the drift, base shear, and torsional component in super-tall structures.

B. Performance-Based Design

PBD systems emerged as a revolution for design and engineering. Unlike conventional code-based design methodology, PBD allows the designer to make calculations under realistic loading scenarios, including seismic and wind loading. Hence, it allows engineers to assess multiple performance criteria such as damage control and life safety. Furthermore, performance-based design allows for the achievement of reliability and sustainability with lower material consumption.

C. Advanced Materials

The application of technology such as fiber-reinforced polymers and high-strength concrete can be effectively employed for the design. The materials enable the engineers to achieve a strong strength-to-weight ratio. The design will enable the structure to achieve a reduced structural weight as well as provide superior seismic performance. The systems promote sustainable design in the construction of the structure. The design is also expected to improve the life of the structure.

D. Smart Damping

One of the most prominent technologies used in skyscrapers is Vibration control devices that play a crucial part in the safety aspects of design. Passive and semi-active damping systems like Tuned Mass Dampers(TMD) and Tuned Liquid Dampers(TLD) are widely used nowadays due to their efficiency in controlling wind-induced loadings, hence contributing to occupant comfort. Other technology applications include sensor-monitoring systems, which improve efficiency by effectively utilizing other parameters such as the real-time performance capabilities of high-rise structures when subjected to various loading conditions.

In general, the design for Skyscrapers is moving forward at a fast pace towards more adaptive and performance-based systems for the structure. All these developments make it possible for the sector to provide excellent solutions to the problem posed by the excessive height and harsh climatic changes.

X. CONCLUSION

The rapid growth of urbanization and exceeding populations have made tall buildings an essential part of development. However, the extreme height of a building makes lateral load, seismic, and wind act more vigorously, making an efficient structural system a critical part of the design. This review has examined the evolution of structural systems in skyscrapers with a focus on their performance under lateral loading conditions.

It is observed that conventional structural systems like MRFs and simple rigid frames can be used for low to medium-sized buildings, but are not adequate for skyscrapers due to their limited stiffness, low control over lateral displacements, and vibrations. These obstacles have led the engineers to develop advanced techniques as a solution to these challenges, like tube-based, Diagrid, and belt-truss systems. Tube-base systems are quite efficient in controlling overturning moments, while outrigger and belt truss systems significantly provide adequate stiffness as well as reduced storey drift by engaging core and exterior columns. The Diagrid system improves structural efficiency through the combination of gravity and lateral load resistance.

The review also describes that most present studies only highlight individual structural systems without providing a detailed description of their lateral load performance. This limits the understanding of designers and engineers of a system's response under varying load conditions. Therefore, a consolidated assessment of different structural systems, as presented in this paper, is essential during the selection process.

Future advancements in skyscraper design will also likely include advancements in performance-based design methods, hybrid structures, and smart damping technologies. Therefore, it can be concluded that the above article demonstrates an integrated understanding of the evolution of structural systems in terms of addressing lateral loads. It would be an effective reference to engineers or to those working on such projects.

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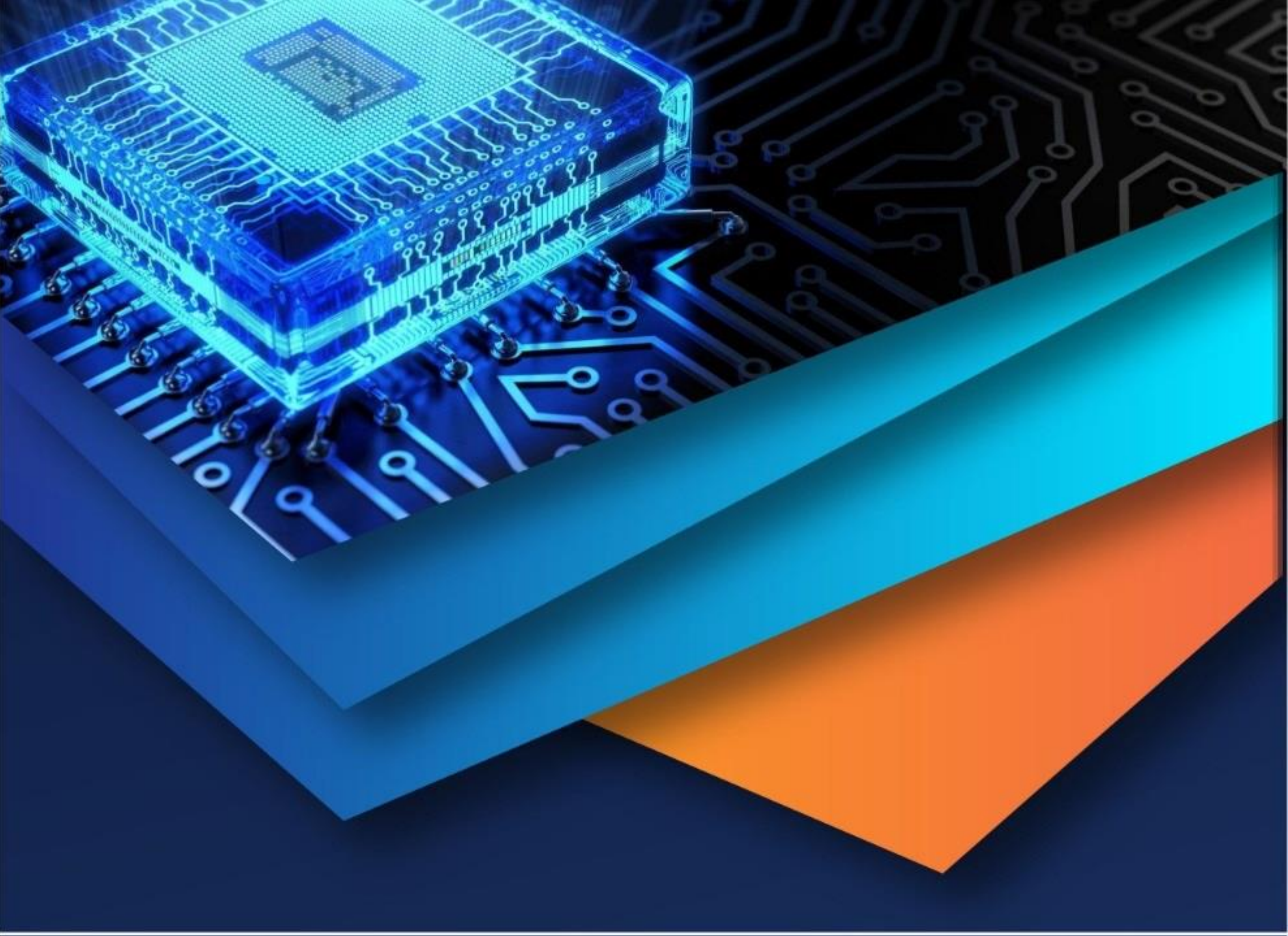

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