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The Evolution of Structural Systems in Tall Buildings: From Ancient Skyscrapers to Future Megatowers of the Future

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Abstract

Tall buildings have undergone significant structural evolution throughout history, driven by advancements in engineering, materials, and design concepts. The construction and operation of tall buildings pose challenges related to safety, transportation, and infrastructure. The development of seismic-resistant structural systems for tall buildings, especially in earthquake-prone regions, is a critical aspect of ensuring the safety and stability of structures during seismic events. The integration of these structural systems and design strategies is crucial for creating safe and resilient tall buildings in regions vulnerable to earthquakes. This paper focuses on the historical development of structural systems in tall buildings, from ancient skyscrapers to the design and construction of sustainable and eco-friendly innovative megatowers of the future. This review will highlight the diverse ways in which tall buildings can integrate sustainability-focused structural systems, contributing to environmental conservation and energy efficiency.

Key words: Tall buildings, sustainable, energy efficient, structural systems, seismic resistant

INTRODUCTION

Tall buildings, also known as high-rise structures or skyscrapers, are architectural marvels that rise above their urban surroundings. These buildings have become iconic symbols of modern cities and have been built for various purposes, including residential, commercial, and mixed use. In densely populated urban areas, the vertical expansion of buildings allows for efficient land use and helps alleviate space constraints. Mixed-use tall buildings often feature a combination of residential, commercial, and recreational spaces, creating a vertical community within a single structure.

Tall buildings are defined by its height and there is no universally agreed threshold for the construction of a building. However, buildings with a considerable number of floors or those exceeding a certain height are commonly referred to as tall or high-rise. High rise is insufficiently characterized by height alone: it must be higher than all others, at least for a time. The Council of Tall Buildings and Urban Habitat (CTBUH) is an organization that classifies buildings based on three categories: height to the architectural top, height to the highest occupied floor, and height to the tip.

The construction of tall buildings involves innovative engineering, advanced materials, and a deep understanding of structural design. Designing tall buildings requires careful consideration of structural stability, wind resistance, and other environmental factors. Engineers use materials such as reinforced concrete and steel to ensure the strength and integrity of the structure. Advanced construction techniques, such as the use of tuned mass dampers or outrigger systems, are employed to mitigate the impact of seismic and wind forces on tall buildings.

Tall buildings often highlight architectural innovation and unique designs. Architects strive to create aesthetically pleasing structures while addressing practical considerations such as space utilization, energy efficiency, and sustainability.

The construction and operation of tall buildings pose challenges related to safety, transportation, and infrastructure. Fire safety, evacuation procedures, and elevator systems are crucial aspects of tall building design.
Sustainable practices are increasingly incorporated into the construction and operation of tall buildings, considering energy efficiency, waste reduction, and environmental impact.

Mega tall and Supertall Structures

The terms "mega tall" and "supertall" are classifications used to categorize exceptionally tall buildings. These classifications are based on the height of the buildings and are generally defined by different organizations and industry standards.

The term "supertall" is commonly used to describe buildings that exceed a certain height threshold, typically 300 meters (984 feet) or more. This classification is widely accepted within the architecture and construction industry. The term "mega tall" is a more recent classification used for buildings that exceed an even greater height threshold, typically 600 meters (1,969 feet) or more. Exceptionally tall structures that surpass traditional height limits. They represent some of the tallest buildings globally and challenges the limits of architectural and engineering prowess.

Burj Khalifa, Dubai is currently the world's tallest building, standing at 828 meters (2,717 feet).
Shanghai Tower, China is 632-meter (2,073 feet) tall skyscraper in Shanghai.
One World Trade Centre, New York stands at 541 meters (1,776 feet) in Lower Manhattan.
Jeddah Tower (formerly Kingdom Tower), Saudi Arabia was planned to surpass the Burj Khalifa, with a proposed height of over 1,000 meters (3,280 feet).

EVOLUTION OF TALL BUILDING: ANCIENT TO CONTEMPORARY ARCHITECTURE

The evolution of tall building structural systems has been a fascinating journey, progressing through various civilizations and technological advancements.

Ancient Civilizations

Among the earliest attempts at vertical construction, ziggurats were massive, stepped structures built with mud bricks. They served as religious temples and administrative centres, displaying the ability to stack materials to create height.
The Egyptian Pyramids (Egypt, 27th century BCE onward particularly the Great Pyramid of Giza, are iconic examples of early tall structures, constructed using limestone and granite blocks, these pyramids employed a step-like design, gradually reducing the footprint as they rose.

Roman and Greek Influence

Ancient Roman and Greek architecture employed columns, arches, and vaults to distribute weight and provide structural support to buildings like the Colosseum and the Parthenon that highlight the use of classical orders and load-bearing structures.

Medieval and Renaissance Periods: Gothic cathedrals in medieval Europe, such as the Notre-Dame Cathedral, featured innovative structural systems like flying buttresses and pointed arches. Towers like the Leaning Tower of Pisa (12th century) also demonstrated early attempts at vertical construction.

Industrial Revolution

The Industrial Revolution *(19th century)* marked a significant shift with the use of iron and later steel in construction. The Eiffel Tower (1889) in Paris, designed by Gustave Eiffel, is an early example of a tall structure using iron. The skeletal frame allowed for both strength and reduced material usage.

Steel Frame and Elevators

The development of the steel frame led to the construction of taller buildings. The Home Insurance Building in Chicago (1885) is often considered the first skyscraper, utilizing a steel skeleton for support. Elevator technology also played a crucial role in vertical expansion.

The Home Insurance Building, constructed in 1885 at the intersection of Adams and LaSalle streets in Chicago, Illinois. The Home Insurance Building holds the distinction of being the world's first modern skyscraper. Crafted by engineer William Le Baron Jenny, this groundbreaking structure pioneered the use of a revolutionary steel frame, enabling unprecedented height and stability without the traditional weight associated with masonry construction. The Home Insurance Building remained a historic symbol until 1931 when it was dismantled to make room for the Field Building of another skyscraper.

The first building to incorporate structural steel into its frame, the Home Insurance Building predominantly utilized cast and wrought iron in its construction. It is celebrated for being the initial tall building supported by a fireproof metal frame, both internally and externally, marking its status as the world's inaugural skyscraper. Originally standing at 10 stories and reaching a height of 138 feet (42 meters), it later underwent expansion in 1890 with the addition of two extra floors atop the original decadelong structure.

Structural intricacies of the Home Insurance Building involved a combination of steel framing technology and foundational support from granite piers at the base and a rear brick wall weighing significantly less than a stone building, it halted construction temporarily due to safety apprehensions.

The frame incorporated cast iron columns supporting wrought iron beams, complemented by two floors of rolled steel beams substituted during construction—marking an early and prominent use of steel in large-scale building construction. To ensure fire protection, the metal framing was entirely enclosed in brick or clay-tile cladding, a precautionary measure against the loss of strength in iron and steel when exposed to temperatures exceedingly approximately 400 °C (750 °F). [1]–[3]

The Empire State Building, an iconic symbol of New York City and one of the most famous skyscrapers in the world, has a rich history and stands as a testament to architectural and engineering prowess. The Empire State Building was designed by architectural firm Shreve, Lamb & Harmon. Construction began in 1930 and was completed in 1931 during the Great Depression. At the time of its completion, the Empire State Building stood as the tallest building in the world, soaring to a height of 1,454 feet (443.2 meters) with its iconic spire. The Empire State Building is renowned for its Art Deco architectural style, characterized by setbacks, decorative motifs, and a sleek, modern appearance. The building features two observation decks—one on the 86th floor and another on the 102nd floor—which offer panoramic views of New York City. The original design included a mooring mast for airships, although it was never used. Today, the mast functions as a broadcast tower. The building has undergone various energy-efficient upgrades to reduce its environmental impact, including the installation of energy-efficient windows and lighting systems.[4]

The Monadnock Building is a historic skyscraper located in the South Loop neighbourhood of Chicago, Illinois, USA. It is known for its distinctive architectural features and significance in the history of tall building construction. The Monadnock Building consists of two separate structures: the original southern portion (Monadnock I) and the later northern addition (Monadnock II). Completed in 1893, Monadnock I was designed by the architectural firm Burnham and Root. It stands as an early example of the Chicago School of Architecture, featuring masonry construction and large bay windows. Completed in 1896, Monadnock II was designed by Holabird & Roche. It incorporates a steel frame, representing a transition from the masonry construction of the original building. [5], [6]

Monadnock I is known for its load-bearing masonry construction, which was a prevalent method in the late 19th century. Monadnock I rises to a height of 197 feet (60 meters), and Monadnock II reaches a height of 215 feet (66 meters). The building has a Romanesque Revival style, and Monadnock I has a more pronounced Victorian aesthetic, while Monadnock II exhibits a more classical design. The Monadnock Building is considered a significant structure in the history of skyscraper design, showcasing the evolution from masonry to steel-framed construction.

Tubular and Diagrid Structures

Tubular and diagrid structures are innovative architectural and engineering designs used in the construction of buildings, particularly skyscrapers. They represent two distinct approaches to achieving structural stability and efficiency in tall structures.

Tubular Structures

Tubular structures refer to buildings that utilize a framework of closely spaced vertical and horizontal elements, forming a tubular or cylindrical shape. This design distributes the structural load throughout the perimeter, enhancing the building's stability. Tubular structures feature columns positioned along the building's perimeter, creating a tubular or box-like appearance. The load-bearing capacity is distributed among the exterior columns, which helps in resisting lateral forces such as wind and seismic activity. The John Hancock Centre and the Burj Khalifa are examples of buildings utilizing tubular structures.

The Willis Tower (formerly Sears Tower) in Chicago is a classic example of a tubular structure. It was one of the first skyscrapers to employ this design, with a bundled tube system that enhances structural strength. Tubular structures provide a high degree of structural efficiency, allowing for the construction of tall buildings. The exterior columns contribute to the building's ability to withstand *lateral forces, making it suitable for seismic-prone areas.* The exterior column placement can limit the flexibility of interior spaces, affecting floor layout.

Diagrid Structures

A diagrid structure involves a framework of diagonal members that form a geometric pattern across the building's façade. This design provides both structural support and an aesthetically distinctive appearance. Diagrid structures employ diagonal members that traverse the building's exterior, forming a grid-like pattern. The diagonal members form triangles, which are inherently stable geometric shapes, contributing to the building's overall stability.

The Gherkin in London and *The CCTV Headquarters* in Beijing are examples of buildings utilizing diagrid structures. The Gherkin employs a diagonal lattice of structural steel, while the CCTV Headquarters features a continuous diagonal grid of interconnected steel members.

Diagrid structures often provide a distinctive and visually appealing architectural design. The triangulated pattern enhances structural efficiency and stability. The construction of diagrid structures can be more complex than traditional designs, requiring precision in fabrication and assembly. The implementation of a diagrid structure may involve higher construction costs compared to conventional methods.
Tubular structures rely on an external framework of closely spaced columns, providing stability through the building's perimeter while on the other hand diagrid structures use a diagonal grid pattern to distribute loads, creating an aesthetically unique design.

The Gherkin, officially known as 30 St Mary Axe, is a distinctive skyscraper in the heart of London's financial district. The 'Diagrid Structure,' initially introduced by V. Shukhov as early as 1896, features a hyperboloid form. The Gherkin was designed by the architectural firm Foster and Partners, with Norman Foster as the lead architect. The Gherkin is characterized by its unique, cylindrical shape with a distinctive glass facade. Its design is energy-efficient and maximizes natural light while minimizing solar gain. It stands at a height of 180 meters (591 feet) and has 41 floors. The building's exterior is covered in diamond-shaped glass panels, providing a striking and iconic appearance. The interior features a spiral atrium that runs the full height of the building, creating an open and dynamic space. The Gherkin incorporates several sustainable design features, including energy-efficient systems and methods for natural ventilation. The building's distinctive exterior is partly attributed to the helical exoskeleton, a diagrid structural system that provides stability. This diagrid configuration and doubly curved shape, demonstrates superior lateral strength, rigidity, and efficiency compared to a rectangular frame system. This innovative design not only reduces the necessary material but also facilitates prefabrication and seamless assembly.[7]

Outrigger Structural system

An outrigger structural system is a lateral load-resisting system used in the design of tall buildings, particularly skyscrapers. This system enhances the building's stability and resistance to lateral forces such as wind or seismic loads. The outrigger system involves the use of horizontal structures, known as outriggers, which connect the core of the building to exterior columns or walls. This system is designed to distribute and transfer lateral forces more efficiently, reducing the building's sway and improving overall structural performance. The building typically has a central core that houses elevators, stairwells, and other services. Horizontal outriggers are attached to the core and extend to the building's perimeter or exterior columns.

Outriggers act as horizontal braces that link the core to the building's periphery. They play a crucial role in resisting lateral forces and preventing excessive swaying of the building during wind or seismic events. The outrigger system provides a damping effect, reducing the amplitude of vibrations caused by lateral loads. This is particularly important in tall buildings, where wind-induced or seismic-induced swaying can affect occupant comfort.[8]

The placement and configuration of outriggers depend on the building's design, height, and intended use. They may be located at different levels, and their spacing can vary based on structural requirements. The outrigger system benefit in reducing the building acceleration at higher floors by decreasing lateral displacements through reduced overturning moment. Outriggers and belt trusses can reduce differential vertical shortening between columns or a column and the core. The outrigger system enhances the overall structural efficiency of tall buildings.[9] By distributing lateral forces, outriggers help minimize lateral drift, providing stability and comfort for occupants. The system contributes to the building's ability to withstand dynamic forces, such as wind and seismic loads.

Types of Outriggers system: Belt Truss Outrigger is a horizontal truss system connecting the core to exterior columns. Floor Truss Outrigger has horizontal trusses at each floor level connecting the core to perimeter columns. Exterior Column Outrigger are horizontal beams connecting the core to exterior columns.

Sustainable and Eco-Friendly Structural Systems

Sustainable and Eco-Friendly Structural Systems involves integrating innovative structural systems that minimize environmental impact, conserve resources, and prioritize energy efficiency. Utilizing environmentally friendly green building materials with a lower carbon footprint is crucial. Examples include recycled steel, engineered wood, and sustainable concrete mixes incorporating fly ash or slag.

Mass timber, such as cross-laminated timber (CLT) and laminated veneer lumber (LVL), offers a sustainable alternative to traditional building materials. Timber is renewable, sequesters carbon, and has a lighter environmental footprint compared to steel or concrete.

Adopting modular construction is another technique reduces construction waste, minimizes site disruption, and enhances efficiency. Prefabricated components can be manufactured off-site with precision, reducing the need for excessive on-site resources.

High-performance facades with double-glazed windows, thermal insulation, and shading devices contribute to energy efficiency by optimizing natural light and reducing the need for artificial lighting and heating, ventilation, and air conditioning (HVAC) systems.

Integrating renewable energy sources, such as wind turbines and solar panels, into the building's design helps generate clean energy on-site, reducing dependence on non-renewable energy sources.

Green roofs and vertical gardens contribute to energy efficiency by providing insulation, reducing the urban heat island effect, and promoting biodiversity. They also absorb rainwater, mitigating stormwater runoff.

Employing passive design principles, such as proper orientation, natural ventilation, and thermal mass, reduces reliance on mechanical systems for heating and cooling, leading to energy savings over the building's lifecycle.
Implementing high-efficiency HVAC systems, smart controls, and energy recovery systems helps minimize energy consumption and optimize indoor environmental quality.

Integrating smart technologies for building management, including sensors, automation, and data analytics, enables real-time monitoring and control of energy usage, enhancing overall building performance.
Implementing water-efficient fixtures, rainwater harvesting systems, and water recycling technologies contributes to sustainable water management in tall buildings.

Conducting a life cycle assessment helps evaluate the environmental impact of a building from construction to demolition. This holistic approach informs design decisions to minimize the overall environmental footprint.
Opting for adaptive reuse of existing structures or retrofitting older buildings with sustainable technologies extends their lifespan, reduces waste, and conserves embodied energy.

Engaging with the local community and stakeholders throughout the design and construction process ensures that the building meets the specific needs of its users and aligns with sustainable development goals. By incorporating these sustainability-focused structural systems and design strategies, tall buildings can contribute positively to the environment, enhance occupant well-being, and set new standards for eco-friendly urban development.

One Central Park, Sydney, Australia
One Central Park features extensive *green walls and rooftop gardens*, promoting biodiversity and reducing the urban heat island effect. *Integrated solar panels* generate renewable energy for the building. A series of *heliostats* mounted on the towers redirect sunlight to the landscaped areas, maximizing natural light and reducing the need for artificial lighting.

Bosco Verticale (Vertical Forest), Milan, Italy
Bosco Verticale is renowned for its *forested balconies*, providing shade, oxygen, and habitat for birds. The building incorporates *energy-efficient technologies and insulation*. The trees and plants contribute to *air purification* and reduce the carbon footprint.

The Edge, Amsterdam, Netherlands
The Edge has a large *green roof* that enhances insulation and reduces energy consumption. The building collects rainwater (rainwater harvesting) for reuse in irrigation and plumbing. The Edge employs *advanced sensors and automation for optimal energy efficiency*, adapting to user needs and environmental conditions.

Pearl River Tower, Guangzhou, China
The building's *double-skin facade* enhances insulation and reduces solar heat gain. Pearl River Tower features *wind turbines* that harness wind energy for on-site power generation. Extensive use of *photovoltaic panels* contributes to the building's energy self-sufficiency.

The Crystal, London, United Kingdom

The Crystal is one of the most sustainable buildings globally, achieving *BREEAM Outstanding certification*. *Rainwater is harvested* for reuse, reducing the demand on the municipal water supply. The building incorporates *solar panels* to generate renewable energy.

Manitoba Hydro Place, Winnipeg, Canada
The building features *triple-glazed windows* for enhanced insulation and energy efficiency. Manitoba Hydro Place utilizes a *geothermal heating* and cooling system, reducing reliance on traditional HVAC systems. The building has achieved *LEED Platinum certification* for its sustainable design and construction practices.

Taipei 101 seamlessly integrates environmental and economic advantages through its thoughtful material choices. The structure is upheld by an immense foundation, comprising 37,000 cubic yards and 5m thick fly-ash concrete mat, supported by 1.5m diameter concrete piles. These piles are fortified with high-strength concrete and extend over 380m into the bedrock. Above ground, the building features eight blocks, each with eight floors resembling opening flowers. The floor plan adopts a square shape with saw-tooth corners, incorporating recycled steel floor framing, a square braced frame central core, and robust outrigger columns on each face.

The elevation comprises a six-story, 21.5m deep basement, a 25-storey truncated pyramidal base, and an eight-story flared module, culminating in an observation deck and spire. The structural elements include a braced core, lower multi-storey outriggers, and single-storey outriggers at the base of each module, all constructed with recycled steel. Taipei prioritizes health and comfort through its innovative structural design, incorporating saw-tooth corners into its perimeter design. This design minimizes vortex shedding, reducing wind sway and consequently diminishing the acceleration and inter-story drifts experienced by the building.

These examples highlight the diverse ways in which tall buildings can integrate sustainable and eco-friendly structural systems, contributing to environmental conservation and energy efficiency. Each project demonstrates a commitment to green building principles and serves as a model for future sustainable urban development.[10]

Innovative Materials used in the construction of Tall Buildings

High-Performance Concrete (HPC) is a specialized mix designed to exhibit exceptional strength, durability, and workability. It is ued to enhance structural integrity and reduce the need for excessive material. Ultra-High-Performance Concrete (UHPC) is an advanced form of concrete with superior strength, ductility, and durability, employed in components like slender columns and precast elements, contributing to structural resilience.

Carbon Fiber Reinforced Polymers (CFRP) materials consist of carbon fibres embedded in a polymer matrix, providing high strength and lightweight properties, used for strengthening and reinforcing structural elements, such as beams and columns, to improve load-bearing capacity.

Mass Timber Construction includes engineered wood products like cross-laminated timber (CLT) and laminated veneer lumber (LVL) for tall building construction. It is used for its sustainability, lighter environmental footprint, and versatility in creating tall wooden structures.

Ferro-cement involves a thin layer of cement mortar reinforced with mesh or metal lath, creating lightweight yet strong facades. It is applied as cladding material for tall buildings, offering durability, reduced weight, and ease of construction.

Nanoparticles, such as silica fume or titanium dioxide, are added to concrete mixes to enhance strength, durability, and self-cleaning properties. This improves the performance of concrete in tall buildings, especially in challenging environmental conditions.

Building Information Modelling (BIM) is a digital representation of the physical and functional characteristics of a building, facilitating collaborative and efficient design and construction processes. This is utilized for precise planning, coordination, and optimization of tall building projects, leading to improved efficiency and reduced errors.

Prefabrication and Modular Construction involves manufacturing building components off-site, while modular construction assembles prefabricated units on-site. It accelerates construction timelines, reduces waste, and enhances quality in the construction of tall buildings.

Smart Glass and Dynamic Facades can adjust its tint or transparency based on external conditions, improving energy efficiency and occupant comfort. Incorporated into dynamic facades of tall buildings to optimize natural light, reduce glare, and enhance thermal performance.

3D Printing in Construction creates three-dimensional objects layer by layer using materials like concrete or polymer, explored for the construction of complex building components, offering customization, reduced waste, and faster construction.

Self-Healing Concrete contains embedded capsules or bacteria that react to cracks by forming healing agents, restoring the material's integrity. Increases the longevity and durability of tall building structures by autonomously addressing minor cracks and damages.

Hybrid Structural Systems is one combining different materials like steel, concrete, and composites in a single structural system to optimize performance. Enables the benefits of each material to be harnessed, resulting in efficient and resilient tall building structures.

The Burj Khalifa, located in Dubai, UAE, stands as the world's tallest structure, soaring to a height of 829.8 meters. Designed and engineered by Skidmore Owings & Merrill LLP, its construction commenced in 2004 and concluded in 2010. This mixed-use marvel comprises 900 apartments, 304 hotel rooms, office spaces, retail areas, and 2,957 parking spaces.

The Y-shaped building plan draws inspiration from Dubai's local desert flower, providing enhanced ventilation, natural lighting, and reduced wind forces on the structure. The exterior is adorned with 26,000 reflective glasses, aluminium, stainless vertical tubular fins, and textured stainless steel spandrel with low E-glass for thermal insulation, catering to the region's high temperatures. The thin cladding enhances the building's slenderness.

Structurally, the Burj Khalifa primarily consists of reinforced concrete (RCC), transitioning to a steel spire at the top with diagonal braces. Its bundled tube system incorporates a central hexagonal core of RCC and three side wings, acting as buttresses for high torsional stiffness. The stepped configuration of these wings reduces mass at the top and mitigates wind load.

The foundation comprises 192 bored concrete piles supporting a 3.7m thick RCC mat, utilizing concrete with strengths ranging from $60N/mm^2$ to $80N/mm^2$ cube strength. A cathodic protection system addresses corrosive groundwater. Formwork includes Doka's SKE 100 automatic self-climbing formworks for walls and circular steel forms for nose columns.

Mechanical floors, housing water tanks, pumps, substations, and air handling units, are strategically placed every 30 floors, serving 15 floors above and below. The tower features 57 high-speed elevators, 8 escalators, and a fire service lift with a 5500kg capacity. A sky lobby system facilitates elevator transfers.

In terms of sustainability, the Burj Khalifa minimizes reliance on municipal water by collecting condensate water from air conditioning, repurposed for gardening. The tower's management system incorporates smart lighting and mechanical controls, optimizing operational costs and resource usage. Individual electric energy monitoring systems further enable energy optimization over the tower's lifetime. [11]

Seismic-Resistant Structural Systems

The development of seismic-resistant structural systems for tall buildings, especially in earthquake-prone regions, is a critical aspect of ensuring the safety and stability of structures during seismic events. Over the years, significant advancements have been made in seismic engineering and structural design to mitigate the impact of earthquakes on tall buildings.

Base Isolation Technology
Base isolation involves placing a building on flexible bearings or isolators, allowing it to move independently of the ground motion during an earthquake. Reduces the transmission of seismic forces to the structure, minimizing structural damage and ensuring occupant safety. Widely used in earthquake-prone regions, especially in retrofitting of existing buildings.

Tuned Mass Dampers: Tuned mass dampers are devices installed in tall buildings to counteract the swaying caused by seismic forces. Absorbs and dissipates energy, reducing building movement and preventing structural damage. This is implemented in skyscrapers and tall structures to enhance stability during earthquakes.

The Taipei 101 skyscraper is situated in the Hsinyi District of Taipei, Taiwan, serves as a prime example of effectively mitigating vibrations in high-rise building floors exposed to strong winds. Employing a specially designed Tuned Mass Damper (TMD), the structure successfully dampens low-frequency vibrations and reduces their amplitudes, particularly during typhoons, with a specific emphasis on the upper floors.[12] The structure standing at 508 meters, consists of 101 above-ground floors and five below-ground floors features a colossal 660-metric-ton tuned mass damper, the world's largest of its kind. Notably, both the skyscraper and the tuned mass damper experienced swaying during Typhoon Fanapi on September 19, 2010. The Taipei 101 exhibits both translational and torsional vibrations, identifiable through spectral amplitudes of accelerations or rotational motions.[13]

Shear Walls and Core Structures: Reinforced concrete shear walls and core structures provide lateral stability to tall buildings. Distributes seismic forces efficiently and prevents excessive lateral movement, commonly used in the design of tall buildings, particularly those in high seismic risk zones.

Ductile Structural Systems: Ductile materials and structural systems allow for controlled deformation during an earthquake, preventing sudden failure. Enhances the building's ability to absorb and dissipate seismic energy, reducing damage. Employed in the design of earthquake-resistant tall buildings, emphasizing flexibility and ductility.

Performance-Based Design: Performance-based design considers the actual behaviour of a structure under seismic loads. This allows for more tailored and efficient seismic design, considering specific site conditions and building characteristics. This is increasingly adopted for the design of tall buildings in earthquake-prone regions to optimize seismic performance.

Advanced Computer Modelling and Simulation: The use of sophisticated computer models and simulations enables engineers to analyse and predict the behaviour of tall buildings during seismic events. It provides insights into structural responses, facilitating the design of more effective seismic-resistant systems. This is an integral part in the design and assessment of tall buildings, allowing for precise modelling of seismic forces.

Innovative Materials: Development and use of advanced materials, such as fibre-reinforced polymers, to enhance the seismic performance of structures. Improves the strength, ductility, and energy dissipation capacity of buildings integrated into seismic-resistant design strategies for tall buildings.

Stringent Building Codes: Implementation of strict building codes and standards that prescribe seismic design requirements. Ensures that tall buildings are designed and constructed to withstand seismic forces based on the latest engineering knowledge. Building codes are enforced in earthquake-prone regions to enhance overall structural resilience.

The evolution of seismic-resistant structural systems reflects a commitment to improving the resilience of tall buildings in earthquake-prone regions. Continuous research, technological advancements, and a holistic approach to design contribute to the development of structures that can withstand the complex forces associated with seismic events. The integration of these seismic-resistant strategies is crucial for creating safe and resilient tall buildings in regions vulnerable to earthquakes.

CONCLUSION

Tall buildings have undergone significant structural evolution throughout history, driven by advancements in engineering, materials, and design concepts. The construction and operation of tall buildings pose challenges related to safety, transportation, and infrastructure. The development of seismic-resistant structural systems for tall buildings, especially in earthquake-prone regions, is a critical aspect of ensuring the safety and stability of structures during seismic events. The integration of these structural systems and design strategies is crucial for creating safe and resilient tall buildings in regions vulnerable to earthquakes. This paper focuses on the historical development of structural systems in tall buildings, from ancient skyscrapers to the design and construction of sustainable and eco-friendly innovative megatowers of the future. This review will highlight the diverse ways in which tall buildings can integrate sustainability-focused structural systems, contributing to environmental conservation and energy efficiency.

The tubular and diagrid structures provide distinct solutions for the challenges in constructing tall and visually striking buildings. The choice between them depends on factors like architectural preferences, construction feasibility, and site/project-specific requirements. The outrigger structural system, integral to modern high-rise design, enhances stability, safety, and overall performance by addressing lateral forces. Ongoing efforts to improve tall building construction include the adoption of innovative materials and technologies, addressing sustainability, efficiency, and structural performance challenges. The future of tall buildings is anticipated to incorporate sustainable practices, smart technologies, and architectural ingenuity to meet evolving urban and societal needs. Advancements in seismic-resistant structural systems reflect a commitment to enhancing the resilience of tall buildings in earthquake-prone regions, with continuous research, technological progress, and holistic design approaches contributing to structures capable of withstanding the complex forces associated with seismic events. The integration of these seismic-resistant strategies is crucial for ensuring the safety and resilience of tall buildings in earthquake-vulnerable areas.

REFERENCES

[1] T. Turak, "Remembrances of the Home Insurance Building," *Journal of the Society of Architectural Historians*, vol. 44, no. 1, pp. 60–65, Mar. 1985, doi: 10.2307/990061.

[2] R. H. Bletter, "The Invention of the Skyscraper: Notes on Its Diverse Histories," *Assemblage*, no. 2, p. 110, Feb. 1987, doi: 10.2307/3171092.

[3] W. Weisman, "New York and the Problem of the First Skyscraper," *Journal of the Society of Architectural Historians*, vol. 12, no. 1, pp. 13–21, Mar. 1953, doi: 10.2307/987622.

[4] R. Sacks and R. Partouche, "Empire State Building Project: Archetype of 'Mass Construction,'" *J Constr Eng Manag*, vol. 136, no. 6, pp. 702–710, Jun. 2010, doi: 10.1061/(ASCE)CO.1943-7862.0000162.

[5] D. Hoffmann, "John Root's Monadnock Building," *Journal of the Society of Architectural Historians*, vol. 26, no. 4, pp. 269–277, Dec. 1967, doi: 10.2307/988453.

[6] V. Danilo Matteis, "The Monadnock Building in Chicago Un edificio-manifesto nel crocevia di sperimentazioni tecniche e costruttive," 2018.

[7] M. Küçük and H. Ibrahim Arslan, "Investigation of Diagrid Structures Over Gherkin Tower," in *Proceedings Article*, Alanya Hamdullah Emin Paşa Üniversitesi, 2020, pp. 2–22. doi: 10.38027/N12020ICCAUA316291.

[8] G. Wai-Ming Ho and G. W. M Ho, "The Evolution of Outrigger System in Tall Buildings High-Rise Buildings The Evolution of Outrigger System in Tall Buildings," 2016. [Online]. Available: www.ctbuh-korea.org/ijhrb/index.php

[9] H. S. Choi, T. Tomasetti, L. Joseph, S. Choi, ; Leonard, and J. C. Org/Papers, "Title: Outrigger System Design Considerations High-Rise Buildings Outrigger System Design Considerations," 2012. [Online]. Available: www.ctbuh.org

[10] A. Tamboli, T. Tomasetti, L. Joseph, U. Vadnere, and X. Xu, "Title: Tall Buildings: Sustainable Design Opportunities."

[11] A. Abdelrazaq, "Design and Construction Planning of the Burj Khalifa, Dubai, UAE," in *Structures Congress 2010*, Reston, VA: American Society of Civil Engineers, May 2010, pp. 2993–3005. doi: 10.1061/41130(369)270.

[12] V. Teplyshev, A. Mylnik, M. Pushkareva, M. Agakhanov, and O. Burova, "Application of tuned mass dampers in high-rise construction," in *E3S Web of Conferences*, EDP Sciences, Mar. 2018. doi: 10.1051/e3sconf/20183302016.

[13] K. C. Chen, J. H. Wang, B. S. Huang, C. C. Liu, and W. G. Huang, "Vibrations of the TAIPEI 101 skyscraper induced by typhoon Fanapi in 2010," *Terrestrial, Atmospheric and Oceanic Sciences*, vol. 24, no. 1, pp. 1–10, Feb. 2013, doi: 10.3319/TAO.2012.09.17.01(T).