



EPiC Series in Built Environment

Volume 7, 2026, Pages 1102–1111

Proceedings of Associated Schools of Construction 62nd Annual International Conference



Vertical Construction: Skyscrapers as the Future of Urban Development

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Vertical construction has emerged as a solution to optimize limited space in areas with minimal territorial expansion. This methodology emphasizes maximizing land use efficiency by constructing upwards, rendering skyscrapers as the epitome of human innovation, architectural brilliance, and engineering complexity. These structures not only redefine city skylines but also address urban challenges, including sustainability, population density, and resource management. This research paper employs a qualitative methodology, primarily utilizing case studies to examine the architectural innovations, environmental impacts, and construction challenges associated with the three tallest skyscrapers in the world: the Burj Khalifa in Dubai, Merdeka 118 in Kuala Lumpur, and the Shanghai Tower in Shanghai. Through detailed case analyses, this study examines how each of these monumental structures utilizes cutting-edge design strategies and sustainable technologies, thereby contributing to the evolution of modern urban landscapes. The case studies provide valuable insights into engineering solutions and innovative design approaches that set new standards for future high-rise construction worldwide. This paper highlights the importance of vertical buildings in shaping future urban environments by examining their integration of complex architectural designs and their responses to contemporary urban needs.

Keywords: Tall Buildings, Skyscrapers, Mega Tall, Construction, Development.

Introduction

Origins of Skyscrapers

The emergence of skyscrapers dates to the late 19th century in Chicago, driven by rapid urban growth and the need to overcome constraints in height, width, and building capacity (d'Eramo, 2003) and (Ahlfeldt & Barr, 2022). The Home Insurance Building, completed in 1885, is widely regarded as the first modern skyscraper. Originally standing 10 stories tall and later expanded to 12, it revolutionized architecture with its steel-frame construction, advanced foundation techniques, and innovative elevator systems (Condit, 1968). These breakthroughs set the foundation for future skyscraper development, prompting both public and private sectors to envision and plan ambitious high-rise projects. Architects embraced the challenge of designing structures that would capture global attention, while engineers tackled the complexities of constructing taller, more resilient buildings (Ray & Roy, 2018).

Advancements in Vertical Construction

Over the decades, vertical construction has undergone significant evolution due to advancements in engineering and materials technology. Improvements in structural integrity, heat resistance, wind dynamics, seismic resilience, and evacuation systems have enabled the rise of taller and more efficient skyscrapers. Various case studies highlight how engineers have continuously pushed height limits, integrating cutting-edge technologies to create iconic megastructures (Ray & Roy, 2018).

At the 2016 China Conference, the research project *Vertical Futures: Technologies That Will Shape the World* forecasted the future of construction, emphasizing how tall buildings will define urban landscapes worldwide (Malott et al., 2016).

Defining Tall Buildings: Super-Tall and Mega-Tall Structures

The Council on Tall Buildings and Urban Habitat (CTBUH) has established standardized classifications for skyscrapers. Buildings exceeding 300 meters are categorized as super-tall, while those surpassing 600 meters fall into the mega-tall category (Yıldız & Avinç, 2024). According to this classification, three of the world's tallest buildings include:

- Burj Khalifa (828 m) – Dubai
- Merdeka 118 (678 m) – Malaysia
- Shanghai Tower (632 m) – China

Methodology

The methodology of this research is based on a qualitative approach, utilizing case studies as the principal method of investigation. Given the intricate nature of architectural and structural advancements in skyscraper construction, a qualitative approach enables an in-depth exploration of real-world examples, providing contextual richness and comprehensive insights that purely quantitative methods may not fully capture. By focusing on three of the tallest and most innovative skyscrapers—Burj Khalifa, Merdeka 118, and Shanghai Tower—this study examines their architectural design, engineering strategies, and environmental sustainability measures. Through a detailed analysis of these structures, the research aims to uncover key design principles, technological breakthroughs, and construction challenges that have contributed to the evolution of modern high-rise buildings.

Case study analysis is particularly effective in this context as it allows for a comparative evaluation of skyscrapers built in different regions with varying climatic, cultural, and regulatory influences. By assessing both commonalities and unique design solutions, the study offers a more comprehensive understanding of the factors influencing contemporary skyscraper development. Additionally, this methodology facilitates exploration of the cultural, economic, and environmental dimensions that influence the planning, construction, and functionality of these megastructures. The case studies include an examination of historical records, architectural blueprints, structural engineering reports, sustainability assessments, and scholarly literature, ensuring a holistic understanding of advancements in vertical urbanism.

Case Studies

Design: Architectural and Interior Design

The evaluation of mega tall buildings focuses on how they interact with nature through their architectural form and interior design. Information on the design elements of these structures was gathered from academic literature and online sources that document their features. This approach

highlights the ways in which these towering structures reflect natural patterns and principles, both in their external appearance and internal spaces.

Burj Khalifa (Dubai, UAE)

Officially inaugurated in January 2010, the Burj Khalifa remains the world's tallest building at 828 meters. Its foundation system employs a piled raft, an increasingly common method for supporting superstructures subjected to immense vertical loads (Baker et al., 2008). This technique efficiently distributes the weight across both deep foundation piles and a load-bearing raft, ensuring structural stability. (Russo et al., 2013)

Designed by Skidmore, Owings & Merrill, the tower's hexagonal central core is inspired by the Spider Lily (*Hymenocallis*), a desert flower known for its tri-axial symmetry and spiraling growth. The architectural form incorporates traditional Islamic motifs, with intricate geometric patterns adding to its aesthetic and cultural significance. Structurally, the tapering design minimizes wind resistance, while the curved façades and rounded edges reduce aerodynamic drag, optimizing performance against environmental forces. (CTBUH Staff, 2020)

The triaxial layout also benefits residential units by enhancing privacy and maximizing panoramic views. The interior design embraces biophilic principles, featuring indoor gardens and natural elements to foster a tranquil environment. Lobbies are adorned with perennial trees, and office spaces incorporate green rest areas to promote well-being and relaxation among occupants. (Yıldız & Avinç, 2024)

Merdeka 118

Completed in 2023, Merdeka 118 stands at 678 meters with 118 floors, making it the tallest building in Southeast Asia and the second tallest in the world. Designed by Arup, the tower functions as a hotel, residential space, and office complex (Yıldız & Avinç, 2024).

Its architectural concept is inspired by Tunku Abdul Rahman's posture during Malaysia's independence declaration in 1957, reflecting a symbolic and patriotic design. A biophilic approach is seamlessly integrated, softening the rigid aesthetic of concrete curtain walls with organic textures and landscape elements. The interior spatial composition features soft flooring materials, greenery, and natural elements, creating a welcoming and harmonious ambiance. Additionally, water features and lush vegetation enhance the landscape design, strengthening the building's interaction with nature.

Structurally, steel outriggers, belt trusses, mega columns, and concrete shear walls form the core of this innovative high-rise, ensuring both stability and aesthetic sophistication. These elements contribute to Merdeka 118's status as a landmark in engineering and architecture (See, 2019).

Shanghai Tower

Shanghai Tower, completed in 2015, stands 632 meters tall with 128 floors, making it the tallest building in China and the third tallest in the world. Located in Pudong's Lujiazui financial district, the tower is part of a "three sisters" master plan, alongside Jin Mao Tower (1999) and the Shanghai World Financial Center (SWFC) (2008) (Zhao et al., 2011).

Designed to withstand the strong winds and seismic activity of the region, its spiraling, twisting form reduces wind loads by 24%, enhancing structural efficiency. The tower features a dual-layered glass façade, which acts as an insulating buffer, reducing cooling demands while maximizing natural daylight

penetration. Additionally, the building was designed for LEED Gold certification, incorporating sustainable technologies such as rainwater harvesting, wind turbines, and geothermal energy systems to reinforce its eco-friendly approach (Yıldız & Avinç, 2024).

The tower's structural framework consists of a reinforced concrete core, mega-frame system, and deep foundation piles, ensuring stability on the soft soil of Shanghai's landscape. The design was shaped by extensive wind and airflow analyses, resulting in an aerodynamic form that optimizes resilience against the region's challenging climate. Beyond its structural elements, Shanghai Tower functions as a mixed-use development, housing offices, a luxury hotel, and retail spaces, offering modern, high-tech environments designed for efficiency and comfort. Its open-plan layouts and warm material palette contribute to a dynamic yet welcoming atmosphere (See, 2019).

Emphasizing biophilic design, the interior integrates natural elements to counterbalance the extensive use of glass and steel. The tower features vertically displaced sky gardens, which create lush communal spaces that promote natural ventilation and enhance occupant well-being. Positioned between the double-shell façade, these landscaped atriums soften the rigid structure, offering green oases within the high-rise. The incorporation of soft textures, organic materials, and natural lighting fosters a harmonious and inviting environment, making Shanghai Tower not only an architectural landmark but also an innovative example of sustainable urban living (See, 2019).

Table 1 compares the three tallest buildings in the world. All three of the tallest buildings are in Asia, and they are mixed-use.

	Burj Khalifa	Merdeka 118	Shanghai Tower
Country	Dubai, UAE	Malaysia	China
Continent	Asia	Asia	Asia
Completed	2010	2023	2015
Height m/ (feet)	828 (2717)	678 (2224)	632 (2073)
Floors, above ground	163	118	128
Total Area m²/ (sq ft)	309,473 (3,331,100)	292,000 (3,140,000)	380,000 (4,090,300)

Design: Construction Challenges

Burj Khalifa (Dubai, UAE)

As the tallest building in the world, it faced several construction challenges including:

deep foundations. The Burj Khalifa required a remarkably robust foundation to support its weight. The foundation consists of a reinforced concrete mat 3.7 meters (12 feet) thick, supported by more than 190 bored reinforced concrete piles that reach depths of up to 50 meters (164 feet). The soil in Dubai has comparatively low strength, making a solid and stable foundation essential (Russo et al., 2013).

water table. Burj Khalifa was constructed in an area with a high water table, which posed challenges during excavation. To address this, dewatering techniques were employed to prevent groundwater from interfering with the foundation construction (Russo et al., 2013).

wind resistance. The impact of wind at such great heights posed a major challenge. The building's design needed to account for aerodynamic forces and wind-induced vibrations. To improve stability and manage lateral wind loads, engineers incorporated a buttressed core structure. Given the potential for extreme wind speeds at higher elevations, specialized construction methods were employed to ensure the structure would not experience excessive sway or vibrations. (Coast, 2018)

material transportation. The sheer scale of the project required the daily supply of vast amounts of materials. Due to the site's limitations, coordinating the transportation and distribution of materials for such a large-scale construction effort presented a major logistical challenge.

crane Operations. Lifting materials to such great heights presented another obstacle. To address this, the building used high-capacity tower cranes specifically designed to be relocated vertically as the structure expanded upward (Lee et al, 2011).

weather. In Dubai, summer temperatures can range from 40°C to 50°C (104°F to 122°F). To work effectively in such intense heat, construction teams had to implement strategies, including cooling systems for materials like concrete, to prevent it from setting too quickly. The concrete mix had to be modified to account for the high temperatures, as the curing process can be impacted by excessive heat.

concrete. High-performance concrete was a crucial material in the construction of the Burj Khalifa, specially designed to support the immense weight and height of the tower. Pumping the concrete to the upper floors presented significant challenges, requiring engineers to utilize a vertical pumping system capable of reaching considerable heights. To ensure proper curing at such extreme elevations, the concrete was pumped during cooler parts of the day, and the mix was specifically formulated to perform optimally in high temperatures, preventing issues with the curing process (Aldred, 2010).

construction budget and schedule. The Burj Khalifa, being an exceptionally ambitious project, presented significant challenges in terms of both timeline and budget management. The construction process spanned six years, from 2004 to 2010, and required considerable coordination and resource allocation to ensure that every stage progressed efficiently and without major setbacks. Given the scale and complexity of the project, it was essential to maintain a highly organized and precise approach to scheduling, with constant monitoring and adjustments to keep construction on track. The total cost of building the Burj Khalifa was estimated at approximately \$1.5 billion, and managing such a monumental financial investment required careful oversight and meticulous planning. Each phase of construction, from the foundation to the final touches, needed to adhere to strict budgetary constraints while also meeting the high standards of quality and safety. Achieving these goals required extensive collaboration among engineers, architects, contractors, and project managers, all working together to ensure that the project remained within scope and met its targeted completion date (See, 2019).

Merdeka 118

A skyscraper located in Kuala Lumpur, Malaysia, is currently the second-tallest building in Southeast Asia. The construction of Merdeka 118 involved a wide range of significant challenges, encompassing both engineering obstacles and logistical complexities. Due to its immense height and unique design, the project required advanced engineering solutions to ensure stability, safety, and efficiency. The deep foundations and careful consideration of geotechnical conditions in Kuala Lumpur were crucial to supporting the structure, particularly given the city's soft soil and dense urban environment. (Fender et al., 2016)

wind resistance. One of the critical challenges was managing wind resistance at such a height. The building's aerodynamic design, which included a tapered shape and curved facade, helped minimize wind shear and ensure stability in extreme weather conditions. Extensive wind tunnel testing further optimized the design to prevent dangerous sway and vibrations.

material transportation. The sheer scale of the project presented major logistical challenges as well. The height of Merdeka 118 necessitated the use of specialized high-capacity cranes to transport materials efficiently to the upper floors, as the cranes had to be repositioned as the building rose. The narrow construction floors made it challenging to place equipment and materials, while the limited space around the site, typical of a dense urban setting, demanded careful coordination to maintain construction schedules and avoid disruptions to the surrounding area (Fender et al., 2016).

concrete. Additionally, the structural design of the tower, incorporating steel and concrete, required meticulous balancing to achieve the necessary strength and flexibility for the building. One of the key challenges was pumping concrete to the higher floors, which required specialized pumps and careful management of pressures to ensure that the concrete set properly at extreme heights.

seismic resistance. It was also a consideration, despite Malaysia not being in a high seismic zone. The inclusion of damping systems and a reinforced concrete core helped ensure stability during seismic events. Similarly, the building's sustainability features, including solar panels, rainwater harvesting, and energy-efficient glass, were carefully integrated to make the building as environmentally friendly as possible.

safety. Throughout the project, worker safety was paramount, with stringent safety protocols and special provisions made for the challenging working conditions, particularly with Kuala Lumpur's extreme heat and humidity. Furthermore, the building's iconic design presented additional complexities, requiring close collaboration between architects, engineers, and construction teams to ensure that both aesthetic goals and structural integrity were achieved (Fender et al., 2016).

Overall, the construction of Merdeka 118 required meticulous planning, sophisticated technology, and innovative engineering to overcome these diverse challenges and create one of the tallest and most advanced buildings in Southeast Asia.

Shanghai Tower

The tallest building in China is a remarkable feat of modern architecture. Its construction involved overcoming a range of unique challenges due to its height, design, location, and technical specifications.

The construction of the Shanghai Tower, one of the world's most remarkable skyscrapers, presented numerous challenges that required innovative engineering, meticulous planning, and sophisticated construction techniques. One of the most critical aspects of the project was its foundation and structural support. Due to the building's colossal height, a robust foundation was essential. The tower is situated on a deep concrete mat foundation, which is supported by 980 concrete piles that extend as deep as 80 meters (262 feet) into the ground, ensuring the building's stability and preventing potential sinking. Shanghai's soil conditions, which are relatively soft, further complicate this challenge. The ground's tendency to settle required engineers to design a foundation capable of evenly distributing the immense weight of the tower to avoid any shifting or settling over time (Lianjin et al., 2015).

As the Shanghai Tower rises to 632 meters (2,073 feet), managing wind resistance and aerodynamics became another major design hurdle. At such heights, wind pressure on the building could be intense,

especially on the upper floors. To combat this, the tower's twisting form was specifically designed to reduce wind resistance and minimize vortex shedding, a wind pattern that can cause oscillations. This spiral shape aids in enhancing the building's aerodynamic performance, making it more stable against high wind speeds. Wind tunnel testing was conducted to refine the design, ensuring that the structure could withstand strong winds without excessive sway or vibration.

material transportation. Construction logistics also played a pivotal role in the tower's successful completion. Given its immense height, material transportation to the upper floors posed significant challenges. Specialized high-capacity cranes were utilized to lift materials to the upper levels, and precise scheduling and staging were crucial to maintaining construction timelines. The tower's site, surrounded by other structures, a complicated crane setup, and the cranes had to be relocated vertically as the building grew taller to maintain efficiency (Xia et al., 2010).

concrete. The choice of building materials was another crucial aspect of the project. The use of high-performance concrete was indispensable for the tower's structural integrity, particularly in its core and foundation. The concrete mix was designed to withstand cracking, shrinkage, and the effects of temperature fluctuations. Pumping concrete to such high elevations, sometimes reaching up to 600 meters (1,969 feet), required specialized pumps and equipment capable of handling the pressures involved in lifting material to such great heights.

earthquake resistance. Although earthquake resistance was not a primary concern in Shanghai due to its relatively low seismic activity, the tower was designed with seismic resistance in mind. A reinforced concrete core offers lateral stability during seismic events, while advanced dampers were incorporated into the design to absorb seismic forces, reducing building sway during tremors.

weather. The climate and temperature variability in Shanghai, characterized by hot summers and cold winters, posed further challenges. The high humidity could interfere with concrete curing, affecting its strength and setting time. To address this, the construction team employed temperature-controlled equipment and specialized techniques to ensure optimal curing, even during extreme weather conditions. Additionally, solutions were developed for working efficiently in high heat, ensuring the welfare of workers and minimizing risks during the summer months (Gao & Shi, 2014).

elevator. With 128 floors, the vertical transportation system in the Shanghai Tower had to be highly efficient. The building's elevator system, designed to transport large numbers of people quickly, includes double-decker elevators capable of speeds up to 20.5 meters per second (about 45.8 miles per hour). This system was critical in ensuring that the building's tenants could move seamlessly between floors during peak times.

sustainability. It was a central theme in the design of the Shanghai Tower. The structure incorporates high-performance glass that reduces energy consumption by controlling heat gain and improving insulation. The tower also features rainwater collection systems, solar panels, and a geothermal heating and cooling system, all of which contribute to its status as one of the world's most energy-efficient skyscrapers.

safety. Safety and worker welfare were top priorities throughout the construction process. The complexity and height of the tower necessitated stringent safety protocols to protect workers from accidents. The use of safety nets, harnesses, and scaffolding minimized risks, while systems for fire alarms, emergency evacuation, and ventilation were planned early to meet safety regulations.

design. The complex design and engineering of the Shanghai Tower required close collaboration between architects, structural engineers, and construction teams. The tower's twisting form not only reduces wind resistance but also optimizes interior space, with each floor rotated slightly to offer panoramic views and minimize wind effects. This innovative design was the result of careful coordination to ensure both aesthetic appeal and structural integrity. (Zhao et al., 2011)

schedule and budget. Finally, managing the construction schedule and budget proved to be a significant challenge. The tower was completed within a 7-year period, from 2008 to 2015, despite the complexities of such a large-scale project. The total cost of the tower was estimated at around \$2.4 billion, and maintaining the project within this budget required precise planning, constant oversight, and collaboration among all parties involved. Coordinating the efforts of contractors, engineers, and project managers was vital to keep the construction on track and on budget, ensuring that the final product met the expected standards of excellence.

Through a combination of advanced engineering, sustainable design, and effective project management, the Shanghai Tower successfully overcame numerous challenges to become an iconic symbol of modern architecture and one of the world's tallest and most innovative skyscrapers.

Design: Environmental Impacts

Burj Khalifa (Dubai, UAE)

The Burj Khalifa incorporates several energy-efficient and sustainable features. Its high-performance glass façade helps reduce heat gain from the harsh desert climate, enhancing energy savings by minimizing solar heat absorption through the use of low-emissivity glass. Additionally, the building features a condensate collection system that collects water from the air conditioning system, filters it, and repurposes it for landscape irrigation, significantly lowering water consumption. Energy-efficient LED lighting is used throughout the tower, reducing electricity usage and contributing to a decrease in carbon emissions. The construction of the Burj Khalifa also prioritized sustainability by utilizing recycled materials and adopting environmentally friendly building practices, including minimizing construction waste. Moreover, the building's air conditioning system utilizes district cooling, which utilizes chilled water piped throughout the structure, thereby reducing energy consumption compared to traditional air conditioning systems. Together, these elements contribute to the Burj Khalifa's status as a highly efficient and environmentally responsible skyscraper (Aldred, 2010).

Merdeka 118

Merdeka 118 incorporates a range of sustainable features designed to minimize its environmental impact. The building is designed with energy-efficient, high-performance glass that minimizes heat gain and enhances insulation, thereby reducing the need for air conditioning and lowering overall energy consumption. It also features a rainwater harvesting system, which collects and repurposes rainwater for landscaping and non-potable uses, significantly lowering water demand. To further enhance sustainability, the building has a green roof that helps manage stormwater, reduces the heat island effect, and promotes biodiversity. Sustainable materials were used throughout the construction, with a focus on minimizing waste and sourcing responsibly to reduce the environmental footprint. An advanced energy management system optimizes lighting and air conditioning, improving operational efficiency and reducing energy usage. Merdeka 118 is also pursuing LEED certification, ensuring it meets high sustainability and green building standards while contributing to energy savings and a smaller environmental footprint (Fender, 2016).

Shanghai Tower

The Shanghai Tower incorporates multiple sustainability features to improve its energy efficiency and reduce its environmental impact. It features a dual-layered glass façade that reduces solar heat gain and improves insulation, helping reduce the need for air conditioning and heating and ultimately leading to significant energy savings. The building also features a rainwater harvesting system, that collects and stores rainwater for use in landscape irrigation and other non-potable purposes, promoting water conservation. Additionally, wind turbines are integrated into the rooftop to generate clean energy, powering some of the building's operations and further contributing to its sustainability. The tower also utilizes geothermal energy systems for heating and cooling, reducing its reliance on fossil fuels and minimizing its carbon footprint. In recognition of its environmentally responsible design, the Shanghai Tower has achieved LEED Gold certification, ensuring it meets high standards of sustainability, energy efficiency, and eco-friendly construction practices (Xia, 2010) and (Zhao, 2011).

Conclusion

In conclusion, the construction of the Burj Khalifa, Shanghai Tower, and Merdeka 118 represents a remarkable achievement in modern engineering and architecture, each overcoming its own unique set of challenges to become a towering symbol of innovation.

The Burj Khalifa, still the tallest building in the world, faced challenges related to its extreme height, harsh environmental conditions, and intricate structural requirements. By employing cutting-edge engineering solutions and an innovative design inspired by the desert flower, the tower effectively addresses issues of wind resistance, material distribution, and environmental sustainability, while blending modern aesthetics with cultural significance.

Merdeka 118, the tallest building in Southeast Asia, fuses cutting-edge engineering with a deeply symbolic architectural concept. Inspired by Malaysia's declaration of independence, the tower incorporates both innovative structural solutions, such as steel outriggers and mega columns, and a biophilic interior that connects the structure to nature. Despite challenges from site conditions and urban constraints, the tower stands as a testament to modern engineering and architectural ingenuity.

Similarly, the Shanghai Tower, standing at 632 meters, demonstrates the power of advanced construction techniques and thoughtful urban design. With careful consideration of wind and seismic challenges, the building's twisting, aerodynamic form, reinforced concrete core, and sustainable technologies, such as rainwater harvesting and geothermal systems, highlight the balance between energy efficiency and functionality. Its biophilic design principles also promote a healthier and more inviting environment for its occupants, reflecting a growing trend of integrating nature into high-rise buildings.

Collectively, these iconic skyscrapers reflect the evolution of design and construction, showcasing how ambitious projects can redefine skylines, create new architectural standards, and stretch the boundaries of engineering. Their successful realization underscores the importance of meticulous planning, creative problem-solving, and collaboration across multiple disciplines in overcoming the challenges associated with building such monumental structures. These towers are not only defining landmarks in their cities but also milestones in the ongoing advancement of modern construction.

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