Structural Engineering International

ISSN: 1016-8664 (Print) 1683-0350 (Online) Journal homepage: https://www.tandfonline.com/loi/tsei20

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To cite this article: Bill Baker (Partner) & James Pawlikowski (Associate Director) (2015) The Design and Construction of the World's Tallest Building: The Burj Khalifa, Dubai, Structural Engineering International, 25:4, 389-394, DOI: 10.2749/101686615X14355644770857

To link to this article: https://doi.org/10.2749/101686615X14355644770857

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The Design and Construction of the World's Tallest Building: The Burj Khalifa, Dubai

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DOI: 10.2749/101686615X14355644770857

Abstract

The design of the Burj Khalifa represents a truly collaborative effort between all members of the design team. A tower of such height required interaction and input from all parties to create a system and form that responds efficiently to wind and gravity loads, while also facilitating construction and enhancing building function. This paper will focus on the challenges faced by the design team, as well as the lessons learned during the design and construction phases, and how they can be applied to the next generation of supertall buildings.

Keywords: wind engineering; buttressed core; high-performance concrete; tall buildings.

Introduction

The challenge of the Burj Khalifa was not only to create the world's tallest building, but it was to do so utilizing conventional systems, materials, and construction methods, albeit modified and utilized in new capacities. A tower of this height had never before been seen, which required much innovation, both in terms of new ideas, and in developing new ways to use and advance current technologies. To achieve this, the design required intensive and constant collaboration between architects, engineers, and specialty consultants to develop a building form that addressed structural efficiency, constructability, building aesthetics, and function simultaneously.

At the height of 828 m, Burj Khalifa eclipsed the previous record holder by over 300 m (Taipei 101 at 508 m) (*Fig. 1*). From the outset of the project, the owner—Emaar Properties PJSC of Dubai—intended that the Tower be the world's tallest building. It currently holds the record for height in all three categories as defined by the Council on Tall Buildings and Urban Habitat (CTBUH): height to architectural top (828 m); height to tip (830 m); and highest occupied floor (585 m). The Makkah Royal Clock Tower Hotel is currently the second tallest in all three categories at 601, 601 and 559 m, respectively (ctbuh.org).

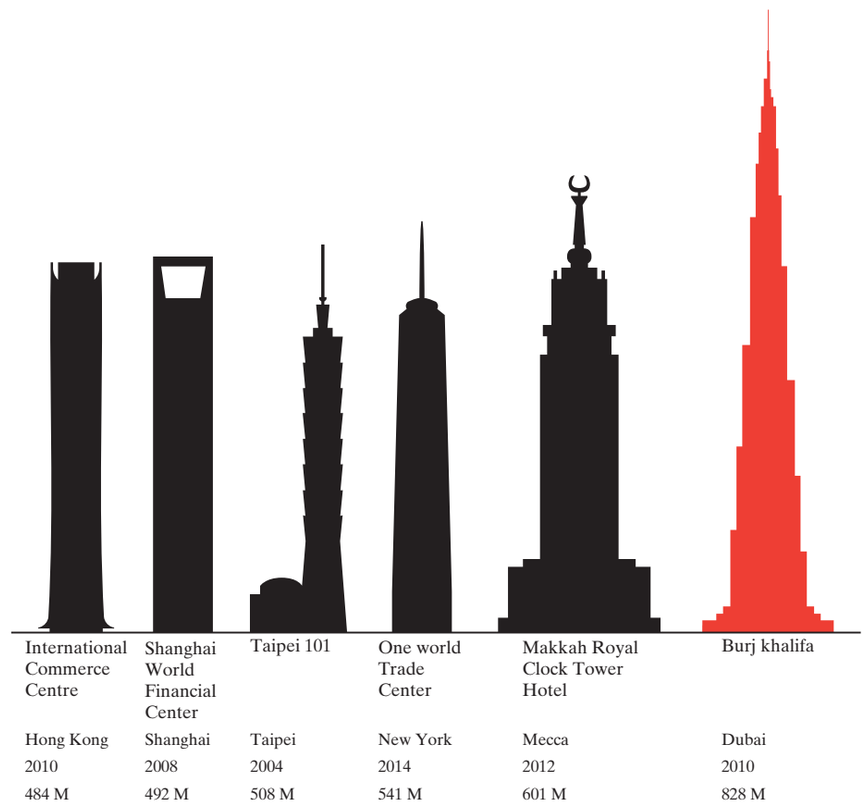


Fig. 1: World's tallest buildings

The 163 story Tower is the centerpiece of a USD20+ billion development located just outside of downtown Dubai. It is a mixed-use building, consisting primarily of residential and office usage, as well as an Armani hotel and retail outlets. The project included the Tower, an adjacent podium structure, and low-rise office and pool annex buildings. The total area for the project is 465 000 m^2, with the Tower portion being 280 000 m^2. Construction for the preliminary works and foundations began in January 2004. After a hiatus in work on the site, the construction of the superstructure started in April 2005 and was completed in January 2009. The Tower was opened in January 2010.

Tower Form

A primary concern in the engineering of tall buildings is the effect of wind on the buildings' structure. The form of the Burj Khalifa is the result of collaboration between the architects and engineers to vary the shape of the building along its height, thereby minimizing wind forces on the building, while also keeping the structure simple and fostering constructability (*Fig. 2*). The floor plan of the Tower consists of a tri-axial, Y-shaped plan, formed by having three separate wings connected to a central core. As the Tower rises in height, one wing at each tier "sets back" in a spiraling pattern, further emphasizing its height. The result is 24 different primary floor plates (plus some less major variations), creating a stepping geometry that presents multiple building widths

Fig. 2: Tower photo (Units: [–])

over the height of the building, providing an environment that "confuses the wind"—the wind vortices never get organized, because at each new tier the wind encounters a different building shape. The Y-shaped plan is ideal for residential and hotel usage, in that it allows maximum views outward, without overlooking a neighboring unit. The wings contain the residential units and hotel guest rooms, with the central core housing all of the elevator and mechanical closets. Additionally, the Tower is serviced by five separate mechanical zones, located approximately 30 floors apart over the height of the building. Above the occupied portion of the Tower is a largely open spire, which houses mechanical functions and future communications usages at its base. The overall shape is an extremely efficient solution to the potentially conflicting structural requirements of a supertall residential tower. Starting from a slender top, the building spreads out as the gravity and wind forces accumulate. As a result, even though the global forces are large, the forces in the individual members are not.

Tower Superstructure—The Buttressed Core

The structural system for the Tower has been termed a "buttressed core" system. The buttressed core represents a new type of system, a conceptual change in structural design whose evolutionary development began with an earlier design for Tower Palace III in Seoul. The system allows for a dramatic increase in height, using conventional materials and construction techniques. Its essence is a three-winged structure in which a strong hexagonal central core anchors three building wings. It is an inherently stable system in that each wing is buttressed by the other two (*Fig. 3*).

Within the wings, corridor walls extend from the central core to near the end of the wing, terminating in thickened cross walls referred to as hammerhead walls. The central core provides the torsional resistance for the building, while the wings provide the shear resistance and increased moment of inertia. Perimeter columns and flat plate floor construction complete the system. At the mechanical floors, outrigger walls are provided to tie all the walls and columns together allowing the perimeter columns to participate in the lateral load resisting system. In this manner, the Burj Khalifa acts as one giant concrete beam cantilevering out of the ground with the system working together as a single unit. Every piece of vertical concrete (and thereby every gravitational force) is part of this giant beam, used to resist the wind. The gravitational load then helps stabilize the structure by utilizing the weight of the building to resist the wind. The result is a very efficient tower, which is also extremely stiff laterally and torsionally. In fact, because of the shape of the building and the harmonics of the structure, the forces and motions were greatly reduced, and the motion and acceleration criteria could be satisfied without the use of supplemental damping devices.

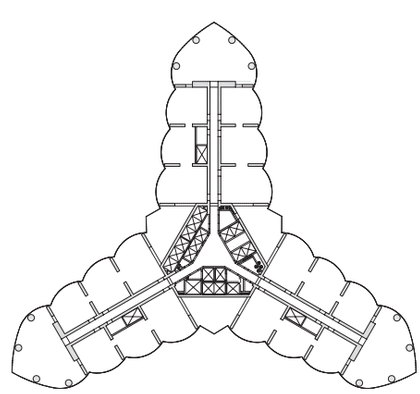


Fig. 3: Typical floor plan

The majority of the Tower is a reinforced concrete structure, with the buttressed core system extending through occupied space to Level 156. Above Level 156, a structural steel braced frame supports an approximately 230 m tall spire. Concrete strengths for the Tower's columns and walls range from C80 to C60, and utilize Portland cement, fly ash, and admixtures. The C80 concrete was specified as high-modulus concrete in order to provide increased stiffness to the system, with a minimum specified Young's Elastic Modulus of 43 800 N/mm^2 at 90 days. The contractor, however, often delivered concrete that could be classified as C100 with a Young's elastic modulus of 48 000 N/mm^2. Wall and column sizes were proportioned according to their desired contributions to the lateral load resisting system, providing efficiency by placing material where it was the most effective. The effects of creep and shrinkage on the concrete structure were also a major consideration when sizing the wall and column elements. Perimeter columns were sized to provide equal gravity stress to that seen in the interior walls, so as to minimize the differential movement between these two elements because of creep. Additionally, the outriggers that tie the columns to the core wall system are not only critical in establishing the lateral load resisting system, but they also provide an opportunity for the gravity load to distribute over the entire structure, providing for uniform gravity stress throughout the system. Further, similar volume-to-surface ratios were established for the columns and walls by providing matching thicknesses for these elements, which allowed the columns and walls to generally shorten at the same rate because of shrinkage.

Wind Engineering

The wind tunnel was an essential partner in the design process from the beginning of the project, as it was

immediately apparent that for a building of this height and slenderness, wind forces and the resulting motions in the upper levels would become dominant factors in the structural design. An extensive program of wind tunnel tests and other studies was conducted utilizing boundary layer wind tunnels. The wind tunnel program included rigid-model force balance tests, full multi-degree of freedom aeroelastic model studies, measurements of localized pressures, pedestrian wind environment studies, and wind climatic studies (*Fig. 4*). Using the wind tunnel to understand and optimize wind performance was key to the Tower's design.

Several rounds of force balance tests were undertaken as the geometry of the Tower evolved and was refined. After each round of tests, the data was analyzed and the building was reshaped to further minimize the wind effects. As a result of this effort, several revisions to the building were made. Some were related to the geometry of the Tower: the size and shape of the wings were modified, and the number and spacing of the setbacks changed throughout the process, as were their locations: the original massing had the setbacks occurring in a spiraling counter-clockwise pattern, which was revised to be in a clockwise direction. Taken together, these measures had a significant impact in encouraging disorganized vortex shedding over the height of the Tower. Another revision was related to the orientation of the building. The Tower has six important wind directions, all parallel to the major axes of the wings—three directions where wind is blowing into the "nose" of each wing, and three directions where wind is blowing into the "tail" of each wing at the center of the building (*Fig. 5*). The orientation of the Tower was then selected to better accommodate the most frequent strong wind directions for Dubai: northwest, south, and east.

The wind tunnel test results were also used to "tune" the Tower's dynamic properties, so as to further minimize wind effects. This was accomplished by first using the tests to determine the harmonic frequency of wind gusts and eddies under various wind conditions, and then using this information to set targets for the building's natural frequencies and mode shapes. The result of these efforts, coupled with the shaping and orientation refinements, had a dramatic impact by reducing wind forces and motions on the Tower. In fact, even though the Tower grew in height by 60% from the beginning of the wind tunnel testing to the final building, the wind forces for the final building were 30% less than that for the original, significantly shorter Tower (*Fig. 6*).

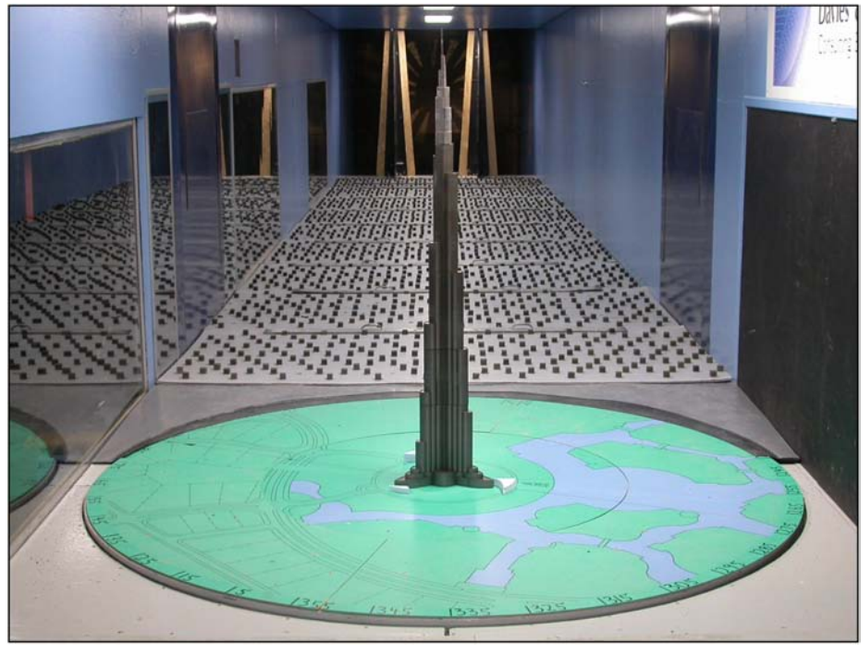


Fig. 4: Aeroelastic wind tunnel model at RWDI

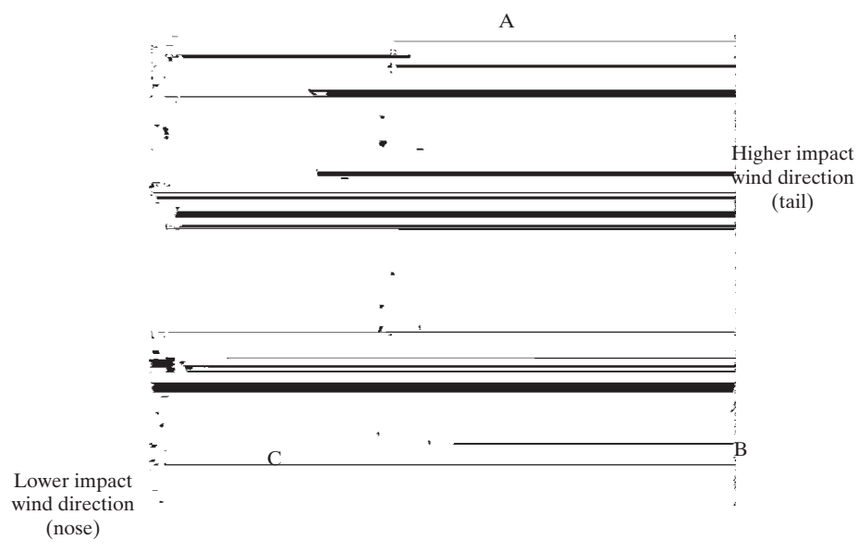


Fig. 5: Wind directions in plan

Tower Foundations

The Tower is founded on a 3.7 m thick solid reinforced concrete raft, supported by 194 bored cast-in-place piles. The piles are 1.5 m in diameter and ~43 m long, with a capacity of 3000 t. The diameter and length of the piles represented the largest and longest piles conventionally available in the region. A pile load testing program was conducted prior to production piling, whereby the 1.5 m piles were tested to more than twice the rated capacity (over 6000 t) (*Fig. 7*). The piles utilized C60 self-consolidating concrete (SCC) and were placed by the tremie method using polymer slurry.

The mat utilized 12 500 m^3 of C50 SCC concrete. Such a volume of concrete required the mat to be poured in four separate pours—first at each of the three wings, and then at the central core. Each of the raft pours occurred over at least a 24 h period. Because of the thickness of the raft, limiting the peak differential temperatures result-

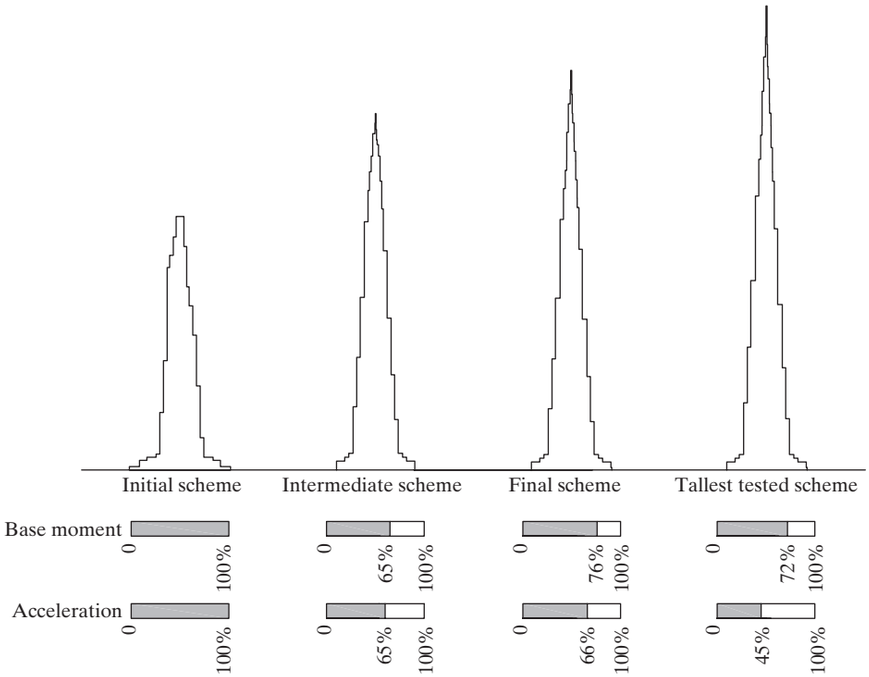


Fig. 6: Tower's improved wind behavior

Fig. 7: Pile load test

ing from the heat of hydration was an important consideration in determining the raft concrete mix design and placement methods. The C50 raft mix incorporated 40% fly ash, to slow the process, and a water-to-cement ratio of 0.34. Additionally, some water was substituted with ice to limit the heat gain. A testing program was instigated prior to the first pour whereby large-scale, 3.7 m test cubes of the concrete mix were poured to verify the concrete's temperature performance, as well as the concrete placement procedures.

Special attention was given to reinforcement detailing for the foundation elements to assist in facilitating in their construction. "Pour enhancement strips" were created throughout the raft, providing for ease of access to the bottom of the raft and allowing for simplified concrete placement. These strips were created by omitting every tenth reinforcing bar in each direction, which established a grid of 600 mm × 600 mm access points throughout the raft (raft reinforcement was typically spaced at 300 mm) (*Fig. 8*). In addition to this enhancement, pile rebar cages were placed so as to orient the rebar cage such that the raft bottom rebar could be threaded through the numerous pile rebar cages without interruption, which greatly simplified the raft construction.

Construction Methods and Concrete Technology

The latest advancements in construction techniques and material technology were used by the prime contractor to construct the Burj Khalifa. Three primary tower cranes were located adjacent to the central core, with each continuing to various heights as required. One of the keys to speed and to facilitate construction was to minimize the time these cranes were needed: automatic self-climbing formwork was employed to form the walls and perimeter blade columns: wall reinforcement was prefabricated on the ground in 8 m segments to facilitate rapid placement; and high-speed, high-capacity construction hoists were used to transport workers and materials. The nose columns were formed with circular steel forms, and the floor slabs were placed on panel formwork. A specialized GPS monitoring system was developed to ensure the verticality of the structure.

The construction sequence for the structure had the central core and slabs cast first, in three sections, followed by the wing walls and their slabs, and then the wing nose columns and slabs (*Fig. 9*). With the exception of the wing noses, the contractor used

Fig. 8: Raft reinforcement

a very rapid "up-up" system where the vertical concrete proceeded several stories above the slab concrete. Concrete was distributed to each wing utilizing concrete booms, which were attached to the formwork system. One of the most challenging construction issues was to provide a system and mix design that could support pumping the high-performance, high-modulus concrete over 600 m in a single stage. Four separate basic mix designs were created to enable reduced pumping pressure as the building grew in height. Additionally, a horizontal pumping trial prior to the start of the superstructure construction was conducted to ensure that the concrete could be pumped as needed. This trial consisted of a long length of pipe with several 180° bends to simulate the pressure loss in pumping to heights over 600 m. Putzmeister concrete pumps, including two of the world's largest, were used in the final pumping system.

Fig. 9: Tower construction

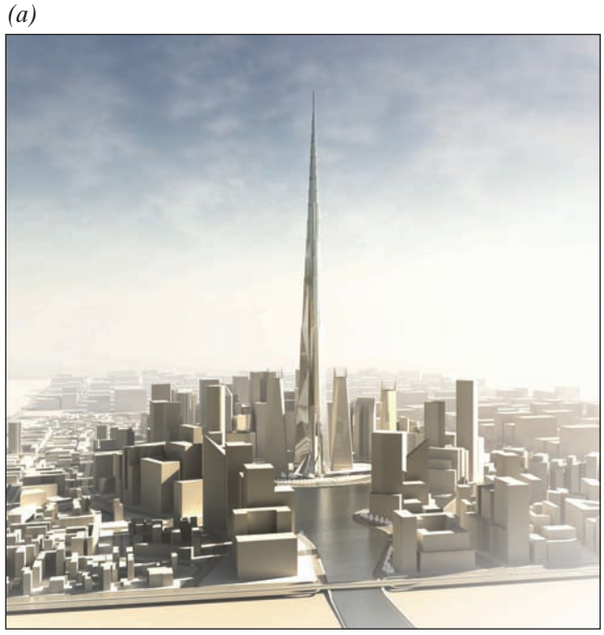
The Next Generation of Supertall Buildings—Lessons Learned from Burj Khalifa

The final design of the Burj Khalifa is an appropriate response to its many influences. However, an analysis of the design and construction of the Burj Khalifa gives an opportunity to investigate the further refinement of supertall building design and the buttressed core on subsequent project proposals. This analysis assists in the development of the next generation of structural systems, which can allow for even taller heights with greater efficiency and construction speed. One such refinement is to consider eliminating the stepping setbacks characteristic to (the) Burj, and instead provide a tapered tower. This establishes an environment in which the wind vortices never get organized due to the continuously changing building width. Additionally, the gravity load flow down the building is one smooth load path in that it is not interrupted with the addition of new structure that is seen at each setback location.

Another refinement is to consider the impact of the perimeter columns. More specifically, perimeter columns require outriggers that tie them to the central core structure, which are typically heavily reinforced members that require a significant amount of time to construct. A system that eliminates these columns and, more importantly, the outriggers can greatly simplify and accelerate construction. A review of the Burj Khalifa construction data has shown that a typical floor cycle required as little as 2.5 days; however, the outrigger zone took much longer to construct. As such, the key to accelerating construction speed is to make every floor a typical floor, whereby the construction does not need to slow down or stop in order to construct atypical elements.

The architect developed a further refined scheme as described above for the Kingdom Tower competition in 2009 (*Fig. 10*). Termed the "stayed buttressed core," it represents the next generation of the Burj Khalifa, and realizes the full potential of the buttressed core concept. The Tower has a tripod plan, and tapers to over 1000 m in height. No perimeter columns are required; instead, the floor plates cantilever off the core wall system via reinforced concrete cantilever framing. This new structural system eliminates the need for outriggers, and is easily constructed within a standardized formwork system. The result is a taller building than Burj Khalifa, using virtually the same concrete quantities per square meter.

(a)



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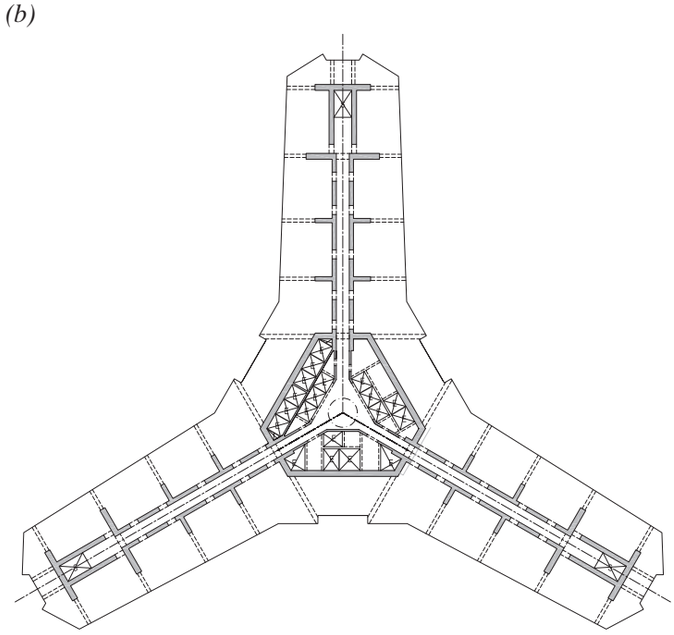

Fig. 10: Kingdom Tower proposal—rendering (a); typical plan (b)

Conclusion

The structural system and form of the Burj Khalifa are the result of close collaboration among all members of the design team. The Tower is a model of structural efficiency, wind behavior, and construction. Its development, innovations, and success have changed how tall buildings are designed and constructed, and will pave the way for the next generation of supertall buildings.

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SEI Data Block

Owner:
Emaar Properties PJSC

Architect, Structural Engineer, MEP Engineer:
Skidmore, Owings & Merrill LLP

Architect and Engineer of Record:
Hyder Consulting

Contractor:
Samsung, BeSix, and Arabtec

Estimated cost (EUR million):

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