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Bringing to Life the World's Tallest Structure

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Intended as the centerpiece of constructional developments in Dubai, the Burj Khalifa now stands as the tallest building ever constructed. The uniquely designed foundation consists of a concrete raft supported by a cast-in-place pile system protected by waterproofing membrane to inhibit corrosion. The structural design integrates high-performance reinforced concrete and steel and incorporates an engineered "Y" shape that limits the lateral wind pressure on the building. Engineers applied the latest advancements in high-rise technology to develop an optimized construction plan that consisted of segmented tasks that promoted the staff to work at a quick yet manageable pace. This article details the innovative techniques involved in the foundation construction, overall structural design, wind engineering, and construction planning of the Burj Khalifa.

Introduction

The future has met the present in the Burj Khalifa, which stands today as the tallest building ever constructed, towering at around 830 meters (2,700 feet) tall. From the top of the Burj Khalifa's 160 floors, one can see a circumferential distance of about 855 kilometers (550 miles).¹ In comparison, the highest observation deck of the Empire State Building in New York City, once the tallest building in the world, embraces a circumferential view of about 320 kilometers (200 miles).² The 460,000-square-meter structure contains residential, hotel, commercial, office, entertainment, shopping, leisure, and parking facilities. With precise and sophisticated planning, engineers designed and built this larger-than-life structure in a relatively short time integrating some of latest construction methods of this era. The concepts used for the Burj Khalifa's foundation construction, overall structural design, wind engineering, and construction planning have revolutionized high-rise construction.

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Foundation Construction

Engineers first designed and constructed a unique foundation to accommodate the overlying massive tower (Figure 1). Ahmad Abdelrazaq, the Vice President and Executive Director of the Highrise Building and Structural Engineering Divisions at Samsung Corporation, reports that the foundation consists of 3.7-meter concrete raft supported by 1.5-meter-diameter piles, each with a design capacity of 3,000 metric tons. The 194 cast-in-place pile system extends approximately 43 meters below the raft. Special attention was given to orienting the raft system's steel reinforcement to ensure the overlying raft reinforcement could be meshed into the pile system. Additionally, the steel design for the raft called for the rebar to be spaced at 30 centimeters omitting every tenth bar to create 60-by 60-centimeter openings at regular intervals. This design allowed for efficient maneuverability and concrete placement during pours and greatly simplified the raft construction. The pile concrete is a self-compacting mix with 25% fly ash, 7% silica fume, water, and a viscosity-altering admixture, which allowed for the entire pour to occur in one step without defects.³ Meanwhile, the raft construction integrated four separate concrete pours, each lasting over 24 hours. This concrete was a special high-performance self-consolidating concrete blend. Due to the extreme temperature at the site, the concrete underwent a series of standard cube, flow table, L-box, V-Box, and temperature tests prior to placement.⁴

The geotechnical testing and analysis of the surrounding soils showed high levels of chlorides and sulfates in the groundwater of the subgrade. Because these corrosive chemicals pose a threat to the integrity of the substructure, engineers developed specific measures to assure the longevity of the foundation.⁵ William F. Baker, Partner with Skidmore, Owings & Merrill LLP, reports that these measures included specialized waterproofing systems, increased concrete cover, the addition of corrosion inhibitors to the concrete mix, stringent crack-control design criteria, and a titanium mesh protection system. Specifically, the waterproofing membrane covering the concrete raft and a cathodic titanium mesh covering both the bored piles and the raft protected the foundation from the highly corrosive moisture in the soil.⁶ Furthermore, the Dubai Municipality declared a seismic zone factor of 0.15 with a soil profile of Sc. A site-specific seismic hazard analysis revealed that the potential for liquefaction of the structure's subgrade was not a concern. The specialized design and construction methodology of the foundation paved the way for remainder of the tower construction.

Structural Design

The overall design of the tower came from the geometry of a desert flower indigenous to the region, the *Hymenocallis*, which resembles many Islamic architectural schemes.⁷ A view of the tower can be found in Figure 3. By design, this flower's "Y" shape, contributes to the tower's ability to minimize wind loads and creates a simple structural plan to follow throughout construction. The central core provides a support system against the lateral forces that act on the three outward wings. The wings are constructed with high-performance concrete corridor walls and perimeter columns that come together creating the six-sided central core.⁸ From the ground up, each wing contains four bays that setback from the structure at seven-floor intervals making the tower appear to spiral upward into the sky.⁹ In addition to aesthetics, the combination of the central core and wings strengthens the tower against lateral and torsional forces, maximizes viewing space, provides ample natural light inside, and lowers energy use.

The Burj Khalifa stands as a high-performance reinforced concrete system from the foundation to the 156th floor. The concrete walls of the central core resist torsional forces, much like an axle on a car, as outriggers on the mechanical levels allow all the concrete in the columns to efficiently handle both vertical and lateral loads. The concrete mix for the walls contains Portland cement and fly ash with a mixture of local aggregates, which yielded a modulus of elasticity equal to 43,800 N/mm² (6,350 ksi). Design engineers used Lagrange multiplier methods along with other enhancements to optimize the wall and column sizes and to lessen the effects of creep and shrinkage on critical elements of the structure. To avoid discrepancy in the shortening of these critical elements, the columns were designed to have a gravity induced stress equal to the induced stress on the interior walls. Five sets of outriggers located on various levels of the structure further lessen the effects of differential shortening due to creep by connecting all the vertical load bearing elements together.¹⁰ The superstructure is designed geometrically so that each wing's columnar supports lie directly above its corridors walls allowing for a smooth transition of loads all the way down the structure. This smooth grid of load transition prevents construction complications related to column transfers. The rotation of wing-to-wing bay setbacks, along with the overall shape, help prevent wind currents from developing vortexes that cause powerful lateral forces along the vertical supports.¹¹

From the 156th floor to the pinnacle, the tower consists of a structural steel, diagonally-braced framing system designed for gravity, wind, seismicity, and fatigue in agreement with the Load Resistance and Factor Design Specifications of the American Institute of Steel Construction. Workers flame-applied an aluminum finish to the exterior steel to reduce the effects of corrosion.¹² Additionally, the steel spire consists of reinforced concrete walls, link beams, slabs, rafts, and piles. Engineer's utilized full 3-D model software to analyze the effects of wind loading in the lateral, perpendicular lateral, and torsional directions on the spire's framing system and found all deflections to be well below the most commonly used sidesway criteria.¹³

Wind Engineering

Engineers extensively analyzed the dynamic wind forces that are often the design limitations for a structure of such great height and slenderness. In Guelph, Ontario, they utilized a system of rigorous wind tunnel tests and other tests to analyze the behavior of a small-scaled model of the tower gaining information on the rigid-model force balance, aeroelastic model behavior, pressure measurements, pedestrian wind environments, and wind climaxes. Aerolasticity refers to the science of studying inertial, dynamic, and aerodynamic forces. Early in the design, wind tunnel data was used in combination with behavioral properties of the model to calculate the dynamic reaction at full scale, which governed further structural, stiffness, weight distribution, and shape enhancements. Also, the wind tests revealed the tower's different responses to wind in the direction of the each wing's nose (Nose A, Nose B, Nose C) or each wing's junction (Tail A, Tail B, Tail C). The structure most effectively minimized the wind's dynamic forces with Nose A pointing in the direction of the wind current, which led to the early decision on orienting the structure relative to Dubai's predominant wind current (Figure 2). The staff continually performed force balance tests throughout the construction phases to refine the structure's geometric shape. The refining of the geometric shape and setting back of wings disallowed the wind to develop the spiraling vortexes that create significant lateral forces. Near the end of

construction, representative aerolastic models of the structure simulating scaled stiffness, mass, and damping were again analyzed to reveal that the building's predicted response fell within the International Standards Organization's recommended criteria.¹⁴

Construction Planning

The construction of such a tall and detailed structure called for a specific development plan. Project managers began by establishing a three-day-cycle plan for all the structural work that divided the construction into segments promoting the staff to work at a quick yet manageable pace. Engineers applied the latest advancements in high-rise technology involving an optimal concrete formwork system that could accommodate the various geometries of the tower. The steel reinforcement sections for the walls were prefabricated on the ground to minimize construction time and worker transportation. Also, a revolutionary automatic self-climbing formwork machine designed to be dismantled and reassembled by a small workforce quickly formed the walls.¹⁵ The central core and slab sections were cast first followed by the wing walls, nose columns, and slabs. The circular nose columns were formed with steel forms while the slabs were casted in MevaDec formwork, a versatile formwork system that can be quickly assembled to minimize work time and construction costs.

Selecting the most effective equipment for the job and logistically coordinating the delivery of materials and workers were major elements of the construction plan. Engineers had to develop a pumping system for distributing the concrete mixtures throughout the sections and levels of the structure. According to Baker and his report team, this system consisted of three specialized Putzmeister pumps with the largest having the capability of pumping concrete to heights of 600 meters in a single pump stage. These three main pumps were located at the ground level; however, project managers placed an emergency pump on the 124th level to assist in pumping during any complications. Five pump lines ran vertically through the structure with two located in the central core and one in each of the three wings. Along with the high-powered pumping system, three high capacity self-climbing tower cranes were utilized at the tower's core, and additional hoists were installed to handle other lifting duties. Furthermore, a special GPS system, instead of conventional surveying techniques, was used to constantly measure vertical data from the structure. As the geometry of the structure continually changed, managers had to continually analyze and modify these logistical plans.¹⁶

For all the structural concrete, engineers used a rigorous testing program allowing for the development of curing plans that took into account the daily and seasonal temperature variations. According to Abdelrazaq's report team, conventionally structures are examined using elastic finite-element analysis or by summing vertical loads, but since the Burj Khalifa is so tall, these conventional analysis techniques were predicted to yield inaccurate structural behavior.¹⁷ Because differential creep and shrinkage redistribute forces, analysts developed a sequential analysis system that took these time-dependent factors into account. Engineers divided the structure into fifteen different three-dimensional finite-element analysis models, which could be accurately examined for creep, shrinkage, and stiffness over a discrete period of time as incremental loads were added. To counteract the redistribution of forces, structural engineers designed each tier of the tower to be "re-centered" minimizing gravity's

horizontal sidesway as the tower was erected. Analyzing these time-dependent loading effects freed engineers to make other design modifications that included slight increases in floor heights to sustain the structural integrity. The rigorous testing procedures and complex analysis measures testified to the ingenuity of the entire construction planning process.¹⁸

Conclusion

Designed as the centerpiece of a series of construction developments in Dubai, the Burj Khalifa symbolizes some of civil engineering's highest aspirations. It exhibits the latest developments in foundation construction, structural design, wind engineering, and construction planning. Today, the structure rises into the skies over Dubai, showing how the advancements and paradigm shifts in construction methodology can bring about a new era in the engineering of super-tall buildings.

Appendix

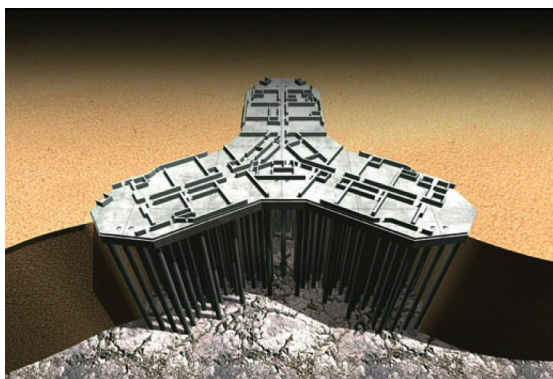


Figure 1. An elevation view of the tower's foundation system (Burj Khalifa 2010).¹⁹

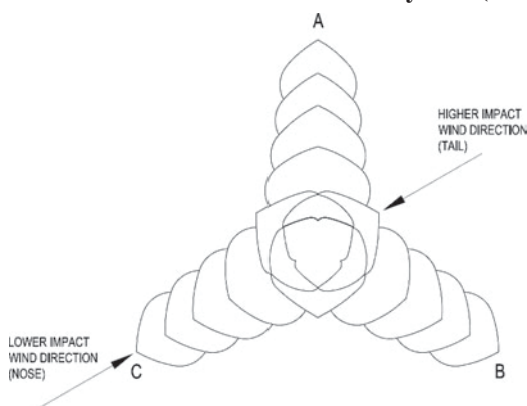


Figure 2. The orientation of the tower that most effectively minimized the wind's effect (Baker 2007).²⁰



Figure 3. A view of the Burj Khalifa rising into the sky (Burj Khalifa 2010).²¹

Endnotes

- 1 Abdelrazaq (2008)
- 2 Friedman (1930)
- 3 Abdelrazaq (2008)
- 4 Baker (2007)
- 5 Abdelrazaq (2008)
- 6 Baker (2007)
- 7 Abdelrazaq (2008)
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- 9 Abdelrazaq (2008)
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- 16 Baker (2007)
- 17 Abdelrazaq (2008)
- 18 Baker (2007)
- 19 Burj Khalifa (2010)
- 20 Baker (2007)
- 21 Burj Khalifa (2010)

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About the Author

Jonathan Weigand graduated at the top of his class from the University of Tennessee in 2012 with a degree in Civil Engineering. Jonathan is a three time winner of the John Callaway Academic Achievement award by the Department of Civil and Environmental Engineering and received recognition as a Top Collegiate Scholar in the engineering department upon graduation. This past fall, Jonathan entered the Civil Engineering master's program and has began research in the field of high fidelity modeling of structural impacts.

About the Advisor

Dr. Stephanie TerMaath is an Assistant Professor in the Department of Civil and Environmental Engineering at the University of Tennessee. She received her Bachelor's degree from Pennsylvania State University, her Master's degree from Purdue University, and her Ph.D. from Cornell University. Her research interests include computational mechanics and structural dynamics.