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BURJ KHALIFA, WORLD'S TALLEST STRUCTURE

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The world's tallest building Burj Khalifa, which was under construction for six years, was inaugurated on 4th Jan 2010 (see Fig. 1). The construction of this 828 m tall, reinforced concrete tower structure, broke several records during its construction. As it is the first time a tower of this height is attempted, a combination of several important technological concepts and innovative structural design methods were utilized in its construction. This article describes some of the features of this world's tallest tower.

Fig. 1 A view of Burj Khalifa Project

The Burj Khalifa project

The Burj Khalifa project located near down-town Dubai, United Arab Emirates, consists of the following:

- 160+ storey tower
- Adjacent podium structure
- Separate six storey office annex
- Two-storey pool annex

The tower has 280,000 m^2 of area which will be utilized predominantly for 700 residential apartments in floors 45 through 108, and corporate offices, in the remaining space up to the 160th floor. In addition the Giorgio Armani hotel is also situated in this tower (will occupy the first 37 floors). The total project cost is estimated to be around US$20 billion, out of which the tower itself will cost $ 4.2 billion. The height and the number of stories were kept as a secret till the opening of the tower.

Burj Khalifa: By Numbers

- Height: 828 m; Number of floors: 160+
- Area of Tower: 280,000 sq.m residential and office space and a Giorgio Armani hotel
- Total area: Tower+ Podium: 465,000 sq.m area
- Concrete used : 250,000 cu.m (weight of 110,000 elephants)
- Steel rebars: 39,000 tonnes (laid end to end this would extend over a quarter of the way around the world)
- Curtain walls: 83,600 sq.m of glass and 27,900 sq.m of metal (equivalent of 17 soccer fields)
- The total weight of aluminium used on Burj Khalifa is equivalent to that of five A380 aircraft and the total length of stainless steel bull nose fins is 293 times the height of Eiffel Tower in Paris.
- Taken 22 million man-hours to construct.

Shape of the tower

The architectural and structural design for the Burj Khalifa was performed by Adrian Smith and his team of ninety designers at the Chicago office of Skidmore, Owings and Merrill (SOM). (Adrian Smith worked with the company till 2006.) SOM also designed the Willis Tower (formerly known as Sears Tower) in Chicago, Illinois and 1 World Trade Center in New York City. The Burj Khalifa resembles the bundled tube form of the Willis Tower, but is not a tube structure. The design is based on the 73-floor Tower Palace Three, an all-residential building in Seoul, South Korea (Ref. 3).

SOM modified the original concept made by an Australian company. The basic structure of the Burj Khalifa is a central hexagonal core with three lobes (wings) clustered around it, as shown in Fig. 2. Fig. 2 and Fig. 3 compare the concept, shape, and height of other well-known super-tall high rise towers. As the tower rises, one wing at each tier sets back in an upward spiraling pattern, decreasing the cross section of the tower as it reaches toward the sky in twenty-six helical levels. There are 26 terraces. This concept gives the visual impression of a series of towers, each having different heights (see Fig.1). At the top, the central core emerges and is sculpted to form a finishing steel spire. Viewed from above or from the base, this form also evokes the Onion domes of Islamic architecture.

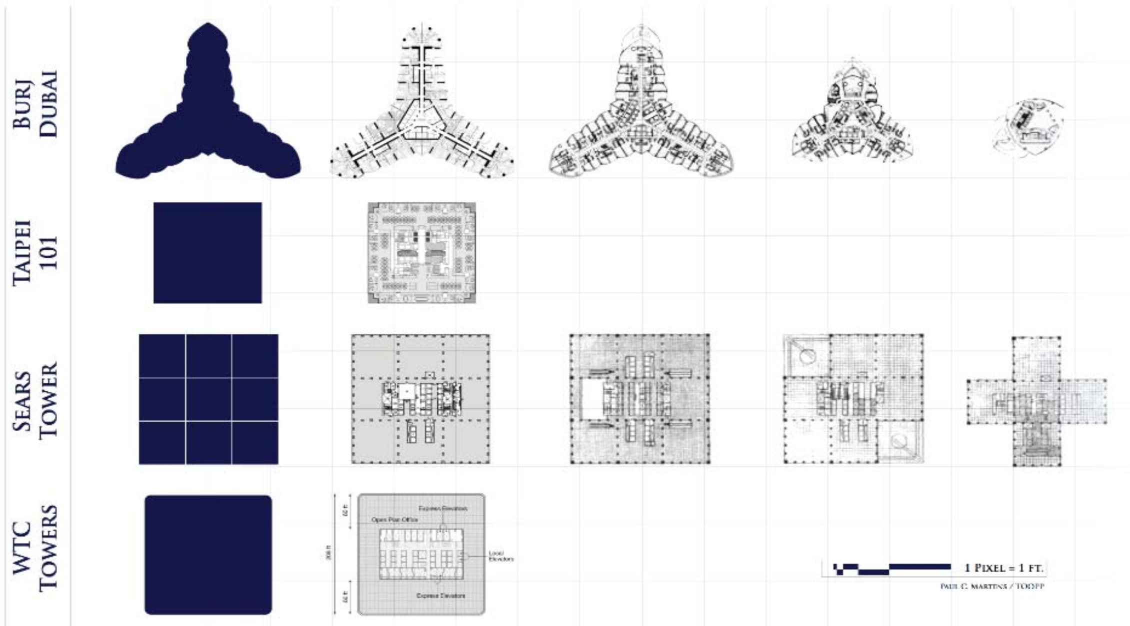

Fig. 2 Comparison of cross-section of super-tall skyscrapers (Source: Ref. 3)

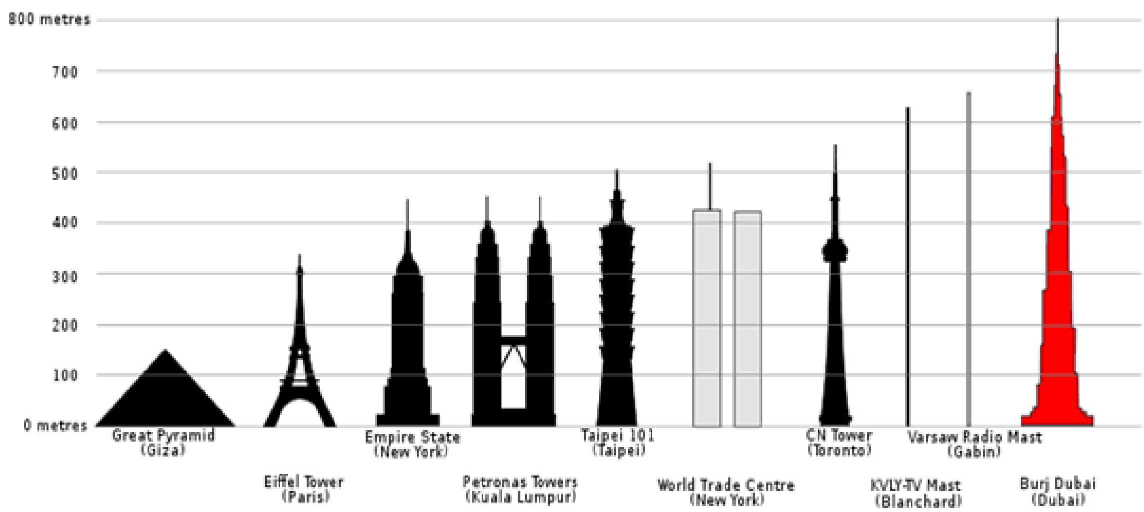

Fig. 3 Comparison of height of other well-known structures (Source: Ref. 3)

Structural System

The "Y" shaped floor plan provides high-performance and maximizes views of the Persian Gulf. This shape along with the upward spiraling pattern of setbacks in the wings, helped to reduce the wind forces on the tower (the shape was determined based on extensive wind tunnel tests). The structural system can be described as a "buttressed core", and consists of high performance concrete (HPC) wall construction. Each of the wings buttresses the others via a hexagonal central core (See Fog. 2). This central core provides the torsional resistance for the structure similar to a closed pipe or axle (Ref.5,6).

The corridor walls extend from the central core up to the end of wing, where they have thickened with hammer head walls. These walls behave like the web and flanges of a beam to resist the wind shears and moments. There are also a few perimeter columns supporting flat plates at the ends (see Fig.2). The perimeter columns are connected at mechanical floors, through outrigger walls, thus allowing the perimeter columns also to resist lateral wind loads. The three storey height outriggers tie the tower at different heights periodically. The tower does not contain any structural transfers.

The Burj Khalifa tower is crowned with a 4,000 tonnes structural steel telescopic spire, which houses communications equipment. The spire was constructed from inside the building and jacked to its full height of over 200 metres using a hydraulic pump.

Wind Engineering Design

The entire tower structure was designed for gravity (including P-Δ analysis and creep and shrinkage), wind and seismic loading using a three-dimensional analysis model that consisted of the RC walls, link beams, slabs, mats, piles and the spire. The ETABS software developed by Computers & Structures Inc., of USA was used for the analysis and design. The model consisted of over 73,500 shell elements and 75,000 nodes. The link beams were quite stocky with a shear-span ratio (l/2h) of 0.85, a width of 650mm, and a height of 825mm. The strut-and-tie method was used to design the link beams (Ref. 6)

Since wind load is critical for the tower, over 40 wind tunnel tests were conducted on Burj Khalifa, at the Boundary layer wind tunnels at Guelph, Ontario, Canada from May 2003 to Sept 05 (see Fig.4). These tests were done to study the effects of wind on the tower and also on its occupants. The upward spiraling set back shaping, as discussed earlier, was derived based on this study, and has the effect of 'confusing' the wind. As the wind encounters a different shape at each new tier the wind vortices never gets organized. The shape of the tower resulted in much reduced wind forces. In addition to testing the building itself, wind statistics for the United Arab Emirates were also analyzed to examine local wind load effects.

Even the temporary conditions during the construction stage, with the tower cranes on the tower, were tested in the wind tunnel facility to ensure safety at all times. The 3D analysis and dynamic analysis indicated the following:

- At its tallest point, the tower sways a total of 1.5 m
- The first mode has a period of 11.3 sec, the perpendicular lateral sidesway second mode10.2 sec, and the torsional fifth mode 4.3 sec.

Fig. 4 Wind tunnel model at the Boundary layer wind tunnels at Guelph, Ontario, Canada (Source: Ref. 5)

Details of Foundation

The construction started on 21 September 2004. The primary builder is South Korean Samsung Engineering & Construction, who also built the Taipei 101 and Petronas Twin Towers. The superstructure is supported by a large reinforced concrete raft, which is in turn supported by bored reinforced concrete piles (see Fig.5) The design was based on extensive geotechnical and seismic studies (Ref. 4). The 3.7 m thick raft was constructed in four separate pours, and is made C50 grade self-consolidating concrete (SCC). The total volume of concrete in the raft is 12,500 m^3. The 194 numbers of bored cast-in-place piles, supporting the raft are 1.5 meter in diameter and 43 meter long. Capacity of each pile is 3000 tonnes. The piles were made high density, low permeability C60 grade SCC concrete placed by tremie method utilizing polymer slurry. A cathodic protection system was also installed under the mat, to minimize any detrimental effects of corrosive chemicals, which may be present in local ground water.

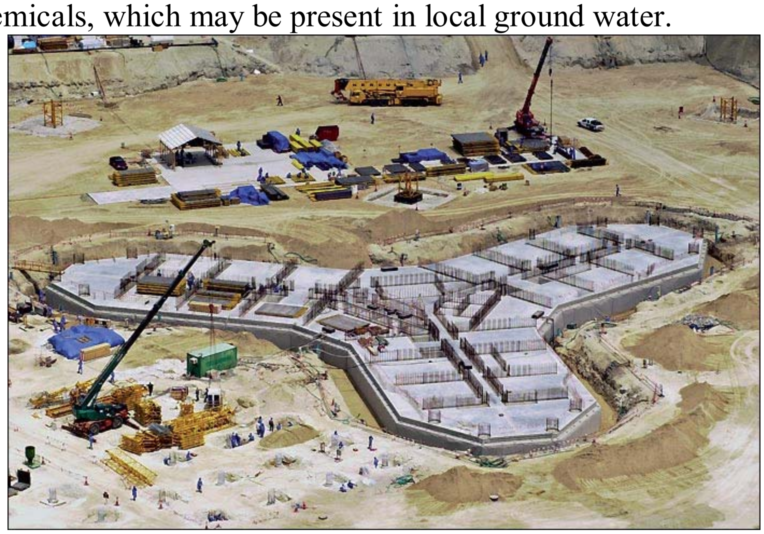

Fig. 5 The piled-raft foundation of Burj Khalifa

Breaks all Records

At the peak of construction, over 12,000 workers and contractors were on site everyday, representing more than 100 nationalities. At the upper level the Earth's curvature and rotation is detectable.

Fig. 6 Construction stages and setting records

The Burj Khalifa created all types of records during its construction and some of them are listed below (see Fig. 6):

- February 2007: Surpasses the Sears Tower as the building with the most floors. (previous record was held by both 1 & 2 World Trade Center with 110 floors)
- 13th May 2007: Sets record for vertical concrete pumping on any building at 452 m; Previous record: 449.2 m for Taipei 101
- 21st July 2007 : Level 141 reached – becomes world's tallest building, surpassing Taipei 101, whose height is 509.2 m
- 12th September 2007: At 555.3 m became the world's tallest freestanding structure, surpassing the CN Tower in Toronto.
- 1st September 2008: With 688 m becomes the tallest man-made structure ever built, the Warsaw Radio Mast in Konstantynów, Poland
- 17th January 2009: Reaches its height of 828 m
- World's highest and fastest elevators at speed of 64 km/h or 18 m/s (previous record by Taipei 101 – 16.83 m/s)

- Highest vertical concrete pumping (for any construction): 601 m (previous record by Riva del Garda Hydroelectric Power Plant - 532 m)
- Highest occupied floor, the tallest service lift, and the world's highest observation deck - on the 124th floor.
- The world's highest mosque and swimming pool located on the 158th and 76th floors.
- It set the record in occurred expenses too: 4.2 billion Dollars.

Burj Mubarak al Kabir, Kuwait
Though Burj Khalifa has broken several records and has become the world's tallest tower at 828 m, it won't remain in this position for too long as Kuwait is planning to build the 1001 m tall tower, Burj Mubarak al Kabir, designed by the London based architect Eric Kuhne at a price tag of $7.37 billion-it is scheduled to be completed in 2016. To withstand the high winds, Eric Kuhne has designed it as three interlocked towers instead of one tower. Each tower will be twisted to 45-degrees top-to-bottom for a better stabilization. Also, the buildings' inside edges will meet in the center in order to mold a triangular shaft-like structure.

High Performance Concrete Used in the Tower

High-performance SCC concrete with a mix designed to provide a low-permeability and high-durability was used in the walls and columns of Burj Khalifa tower. The C80 to C60 cube strength concrete used Portland cement, fly ash, and local aggregates. The C80 concrete had a specified Young's Modulus of 43,800 N/mm^2 at 90 days. Two of the largest concrete pumps in the world were used to deliver concrete to heights over 600 m in a single stage. To reduce the cracks due to the high temperatures of Dubai (about 50^{o}C), the concrete was poured at night, when the air is cooler and the humidity is higher, with ice added to the mix. Special mixes of concrete were made to withstand the extreme pressures of the massive building weight; as is typical with reinforced concrete construction, each batch of concrete used was tested to ensure it could withstand certain pressures (Ref. 3).

Tower Cranes

Three primary self-climbing Favco tower cranes were located adjacent to the central core, with each continuing to various heights as required (see Fig.7). The cranes were modified to lift the extreme lengths of cables and 25 tonne payloads, at high speeds.

Fig. 7 Tower Cranes used in Burj Khalifa

Cladding of the tower

The exterior cladding of Burj Khalifa is made of reflective aluminum and textured stainless steel spandrel panels with numerous small tubular fins. This design is supposed to resist the strong desert heat and solar rays better (see Fig. 8). 28,261 glass panels, each individually hand-cut, were used in the exterior cladding. It is estimated that the exterior temperature at the top of the building will be 6 °C cooler than at its base.

The tower is provided with 18 permanently installed track and fixed telescopic, cradle equipped, building maintenance units. These track mounted units, which are hidden when not in use, will be used for both window washing and exterior façade maintenance. Using these, the exterior may be accessed from the top down to level seven of the tower. Under normal conditions, and when all building maintenance units are in operation, it will take three to four months to clean the entire exterior facade.

Fig. 8 High performance exterior cladding system was used to withstand the extreme temperatures during the summer months in Dubai (Source: Ref. 5)

Mechanical, Electrical and Plumbing

The mechanical, electrical and plumbing services for this tower were developed during the design phase itself in consultation with all the consultants, to achieve the greatest efficiencies (Ref 4).

- The tower's water system is designed to supply about of 946,000 litres of water daily.
- At peak cooling, it will require about 10,000 tons of cooling, equal to the cooling capacity provided by about 10,000 tons of melting ice.
- The building's cooling requirements, coupled with the hot and humid climate of Dubai, will result in a significant amount of condensation. This condensed water is collected and drained in a separate piping system to a holding tank in the basement car park.
- The condensate collection system provides about 15 million gallons of supplement water per year, equal to about 20 Olympic-sized swimming pools.
- The tower's peak electrical demand is 36mW, equal to about 360,000 numbers of 100 Watt bulbs operating simultaneously.

Elevators and Lifts

The building is expected to hold up to 35,000 people at any one time, so transportation as well as evacuation of the building is an important consideration. Otis Elevators has installed 57 elevators, and 8 escalators. The observation deck elevators and can carry 42 people at a time and travel at 10 to 18 m/sec. Fire safety and speed of evacuation were given great importance during the design phase of Burj Khalifa. Concrete surrounds all stairwells. The building has service/fireman's elevator with a capacity of 5,500 kg and will be the world's tallest service elevator. Some elevators are programmed to allow controlled evacuation during fire or emergency situations. Since it is not possible for people to walk down 160 floors in case of emergency or fire, pressurized, air-conditioned refuge areas are provided every 25 floors.

Other Details and technology

The tower is serviced by five separate mechanical zones, 30 floors apart over the height. Seven double-storey height mechanical floors, distributed around every 30 storeys, house the electrical sub-stations, water tanks and pumps, air-handling units etc, that are essential for the operation of the tower. Other details and technologies used include the following:

- Doka's SKE 100 automatic self-climbing formwork was used for the construction of walls
- High-speed (120-m/minute), high-capacity (3,200-kg) construction hoists were used to transport workers and materials to the required heights.
- A specialized GPS monitoring system has been developed to monitor the verticality of the structure
- Construction crews ran into a problem with the walkie-talkies they were using for communication when they got past the 30th floor. The communication problem was solved through the use of a wireless mesh network and using walkie-talkies with ROIP and VOIP features.
- Project managers used computer animation and graphing to make workers and subcontractors understand various stages of the construction process.
- The interior design of Burj Khalifa public areas was also done SOM and was led by award-winning designer Nada Andric. It features glass, stainless steel and polished dark stones, together with silver travertine flooring, Venetian stucco walls, handmade rugs and stone flooring.
- Over 1,000 pieces of art from prominent Middle Eastern and international artists will adorn Burj Khalifa and the surrounding Emaar Boulevard.
- Burj Khalifa's observation deck is located on level 124 and provides unprecedented views of the neighborhood (see Fig 9).

Fig. 9 A view from the tower. In fair weather a person in the Observation Deck can see as far away as 80 km! On a clear day the tip of the spire can be seen by a person 95 km away.

Musical Fountains

There is an artificial lake and a 275 m long fountain in front of the tower (see Fig.10). The fountain's jets are computer controlled and installed at a cost of US$ 220 million. This is the World's largest musical fountain, and 22,000 gallons of water will be sprayed into the air at any given time. The curtain of water can go up to 150 m high (about the height of a 50 story building) and is 250 m long.

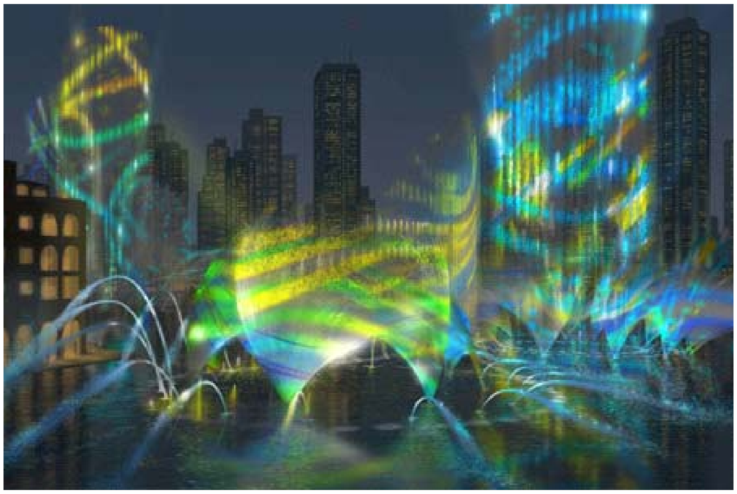

Fig.10 The water jets are illuminated by 6600 electric bulbs and 50 colored light projectors.

The following videos about Burj Khalifa tower and the musical foundation may provide more visual impact:
http://www.youtube.com/watch?v=5LjTWSKbfiU&feature=player_embedded#
http://www.youtube.com/watch?v=m7_zeMC6ZKM&feature=related

Acknowledgements

The details and photographs used in this article were culled from different sources in the Internet and the author wishes to acknowledge them. Some of these sources are listed in references.

Credits

- Architect/Structural/MEP design: Skidmore, Owings and Merrill LLP, Chicago
- Field supervision, Adopting Architect: Hyder Consulting Ltd.
- General contractor: Samsung/BeSix/Arabtec
- Foundation contractor: NASA Multiplex
- Project Management: Turner Construction Company

- Developer: Emaar Properties PJSC, Dubai

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