

Design and Construction Planning of the Burj Khalifa, Dubai, UAE

Ahmad Abdelrazaq, SE¹

¹ EVP, Samsung C&T Corp, Seoul, Korea, Ahmad.abdelrazaq1@samsung.com

ABSTRACT

The Burj Khalifa Project is the tallest structure ever built by man; the tower is 828 meters tall and comprise of 162 floors above grade and 3 basement levels. Early integration of aerodynamic shaping and wind engineering played a major role in the architectural massing and design of this multi-use tower, where mitigating and taming the dynamic wind effects was one of the most important design criteria set forth at the onset of the project design. This paper provides brief description of the tower structural systems, focuses on the key issues considered in construction planning of the key structural components, and briefly outlines the execution of one of the most comprehensive structural health monitoring program in tall buildings.

INTRODUCTION

The Burj Khalifa project is a multi-use development tower with a total floor area of 460,000 square meters that includes residential, hotel, commercial, office, entertainment, shopping, leisure, and parking facilities. The Burj Khalifa is designed to be the centerpiece of the large scale Burj Khalifa Development that rises 828 meters into the and consists of more than 160 floors.

The Client of Burj Khalifa Tower, Emaar Properties, is a major developer of lifestyle real estate in the Middle East. Turner International has been designated by the owner as the Construction Manager, and Samsung Joint Venture (consisting of Samsung, Korea base contractor; Besix, Belgium base contractor; and Arabtec, Dubai base contractor) as the General Contractor.

The design of Burj Khalifa is derived from geometries of the desert flower, which is indigenous to the region, and the patterning systems embodied in Islamic architecture. The tower massing is organized around a central core with three wings. Each wing consists of four bays. At every seventh floor, one outer bay peels away as the structure spirals into the sky. Unlike many super-highrise buildings with deep floor plates, the Y-shape floor plans of Burj Khalifa maximize views and provide tenants with plenty of natural light. The modular Y-shaped building, with a setback at every seventh floor, was part of the original design concept that allowed Skidmore, Owings and Merrill to win the invited design competition.

The tower superstructure of Burj Khalifa is designed as an all reinforced concrete building with high performance concrete from the foundation level to level 156, and is topped with a structural steel braced frame from level 156 to the highest point of the tower.

The tower massing is also driven by wind engineering requirements to reduce dynamic wind excitation. As the tower spirals into the sky, the building's width and shape diminish, thus reducing wind dynamic effects, movement, and acceleration. Integrating wind engineering principals and requirements into the architectural design of the tower results in a stable dynamic response, taming the powerful wind forces.

STRUCTURAL SYSTEM BRIEF DESCRIPTION

Lateral Load Resisting System

The tower's lateral load resisting system consists of high performance, reinforced concrete ductile core walls linked to the exterior reinforced concrete columns through a series of reinforced concrete shear wall panels at the mechanical levels.

The core walls vary in thickness from 1300mm to 500mm. The core walls are typically linked through a series of 800mm to 1100mm deep reinforced concrete or composite link beams at every level. Due to the limitation on the link beam depth, ductile composite link beams are provided in certain areas of the core wall system. These composite ductile link beams typically consist of steel shear plates, or structural steel built-up I-shaped beams, with shear studs embedded in the concrete section. The link beam width typically matches the adjacent core wall thickness.

At the top of the center reinforced concrete core wall, a very tall spire tops the building, making it the tallest tower in the world for all categories. The lateral load resisting system of the spire consists of a diagonal structural steel bracing system from level 156 to the top of the spire at approximately 750 meter above the ground. The pinnacle consists of structural steel pipe section varying from 2100mm diameter x 60mm thick at the base to 1200mm diameter x 30mm thick at the top (828m).



FIGURE 1 – BURJ KHALIFA RENDERING
COMPLETED PROJECT PHOTO

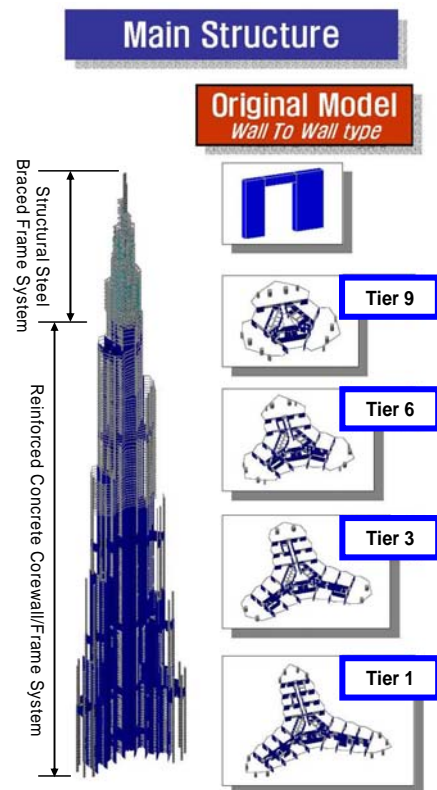


FIGURE 2 – LATERAL LOAD SYSTEM

Structural System Selection Approach

From onset of the design process, the structural design of the tower was formulated based on the following objectives in coordination and integration within the architectural design concept:

- ◆ Select and optimize the tower structural system for strength, stiffness, cost effectiveness, redundancy, and speed of construction.
- ◆ Utilize the latest technological advances in structural materials that is available in the local market, consideration for the local skilled labor, and construction method.
- ◆ Manage and locate the gravity load resisting system so as to maximize its use in resisting the lateral loads while harmonizing with the architectural planning of a luxury residential and hotel tower.
- ◆ Incorporate the latest innovations in analysis, design, materials, and construction methods.
- ◆ Limit the building Movement (drift, acceleration, torsional velocity, etc.) to within the international accepted design criteria and standards.
- ◆ Control the relative displacement between the vertical members
- ◆ Control the dynamic response of the tower under wind loading by tuning the structural characteristics of the building to improve its dynamic behavior and to prevent lock-in vibration due to the vortex shedding. Favorable dynamic behavior of the tower was achieved by:
 - ✓ Varying the building shape along the height while continuing, without interruption, the building gravity and lateral load resisting system;
 - ✓ reducing the floor plan along the height, thus effectively tapering the building profile;
 - ✓ Using the building shapes to introduce spoiler type of effects along the entire height of the tower, including the pinnacle, to reduce the dynamic wind excitations.

Therefore, concrete of its mass, stiffness, high strength and performance concrete, moldability, continuity, pumping ability, speed of construction because of the local availability of advanced formwork systems, and most importantly the residential use of the building, concrete was selected as the primary structural material for the tower.

Wind Engineering

Wind engineering is one of the primary concerns in the design of tall building design and planning. The shape of the Burj Khalifa project is the result of direct strong and successful collaboration between SOM's architects and engineers to vary the shape of the building along its height from the early development of the design concept (competition stage), thereby minimizing the wind forces on the tower. The variation of the tower shape, and width, resulted in wind vortices around the perimeter of the tower that behaved differently for different shapes at different frequencies, thus disorganizing the interaction of the tower structure with the wind as shown in Figure 3.

From the beginning of the project, an extensive wind tunnel studies and testing regimes were established to develop a full understanding of the building wind behavior and response. Based on these extensive studies, target building periods and mode shapes were established to optimize the building dynamic response to the dynamic wind action.



FIGURE 3- WIND FLOW VARIATION AROUND AND ALONG THE HEIGHT OF THE TOWER

Floor Framing System

The residential and hotel floor framing system of the Tower consists of 200mm to 300mm two-way reinforced concrete flat plate slabs spanning approximately 9 meters between the exterior columns and the interior core wall. The floor framing system at the tips of the tower floor consists of a 225mm to 250mm two-way reinforced concrete flat plate system. The floor framing system within the interior core consists of a two way reinforced concrete flat plate system with beams. See Figure 4 for typical floor framing system at typical residential and mechanical levels. See Figure 3 also for other floor framing system configuration.

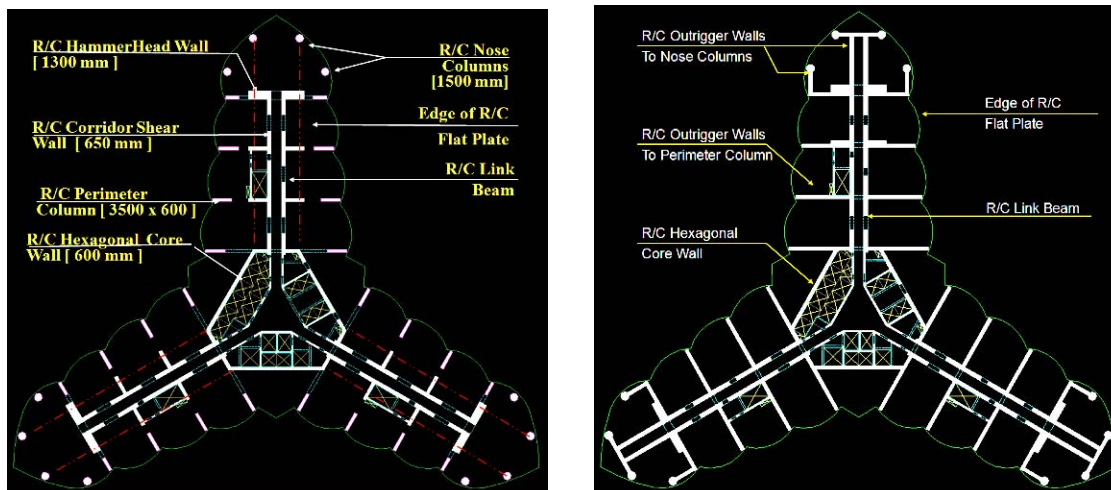


FIGURE 4 – TYPICAL FLOOR FRAMING PLANS AT RESIDENTIAL & MECHANICAL LEVELS

Foundation System

The Tower is founded on a 3700mm thick high performance reinforced concrete pile supported raft foundation at -7.55 DMD. The reinforced concrete raft foundation utilizes high performance Self Compacting Concrete (SCC) and is placed over a minimum 100mm blinding slab over waterproofing membrane, over at least 50mm blinding slab. The raft foundation bottom and all sides are protected with waterproofing membrane. See Figure 4 for the Raft Foundation System.

The piles are 1500mm diameter, high performance reinforced concrete bored piles, extending approximately 45 meters below the base of the raft. All piles utilize self compacting concrete (SCC) with w/c ratio not exceeding 0.30, placed in one continuous concrete pour using the tremie method. The final pile elevations are founded at -55 DMD to achieve the assumed pile capacities of 3000Tonnes.



FIGURE 5 – PILE SUPPORTED RAFT FOUNDATION AND COMPLETED RAFT CONSTRUCTION

A robust cathodic protection system for both the bored piles and the raft foundation system protects the foundation and the reinforced concrete raft against the severe and corrosive environment (chloride and sulfate) of the soil at the Burj Khalifa site. See Figure 5 for a summary of the pile supported raft foundation system and the completed raft construction prior to starting the supertower construction.

CONSTRUCTION OF THE TOWER SUPERSTRUCTURE

Currently the tower construction has been completed and the opening ceremony of the tower was held on the 4th of January 2010. The foundation system consisting of the piles and raft were completed in February 2005. The tower superstructure construction started in April 2005 the pinnacle was completely lifted to its final position in January 2009.

The original construction program is very tight and in order to complete the project within 48 months, Samsung, Besix, Arabtech Joint Venture (SBA-JV) established the following strategic approach:

- ◆ Achieve a three (3) day-cycle for structural works.
- ◆ Develop optimum transportation systems with large capacity high speed equipment.
- ◆ Utilize optimum formwork system to accommodate various building shapes along the building height.
- ◆ Develop organized logistic plans throughout the construction period.
- ◆ Apply all high-rise construction technologies available at the time of construction.

Since the construction planning is extensive and cannot be covered in detail in this paper, only a brief summary of the major construction planning works will be covered in this paper.

Planning for the Concrete Work

Prior to the construction of the tower, extensive concrete testing and quality control programs were put in place to ensure that all concrete works are done in agreement with all parties involved, including the supervision consultant (Hyder), the owner independent testing agency (IVTA), the concrete supplier (Unimix) top quality team, CTL, and Samsung Engineering and Construction Task force team. These programs started from the early development of the concrete mix design until the completion of all test and verification programs. The testing regimes included, but were not limited to the following programs:

- ◆ Trial mix designs for all concrete types needed for the project.
- ◆ Mechanical properties, including compressive strength, modulus of elasticity, and split tensile strength.
- ◆ Durability tests which included initial surface absorption test and 30 minute absorption test.
- ◆ Creep and shrinkage test program for all concrete mix design (see Figure 6 for testing setup).
- ◆ Water penetration tests and rapid chloride permeability test.
- ◆ Shrinkage test program for all concrete mix designs.
- ◆ Pump simulation test for all concrete mix design grades up to at least 600 meters (see Figure 7 for test setup).
- ◆ Heat of hydration analysis and tests, which include cube analysis and tests, and full scale heat of hydration mock tests for all the massive concrete elements that have a dimension in excess of 1.0 meter. These tests are needed to confirm the construction sequence of these large elements and to develop curing plans that are appropriate for the project, considering major daily and seasonal temperature fluctuations. See Figure 8 for test setup.



FIGURE 6 – RAFT FOUNDATION SYSTEM



FIGURE 7 – PUMP SIMULATION TEST



FIGURE 8 – HEAT OF HYDRATION MOCK UP TEST

Site Logistic Plan

The Burj Khalifa site area is approximately 105,600m² and encompassing the tower, the office annex, the pool annex, and the parking areas, divided into three zones (Zone A, Zone B, and Zone C). The site logistic works and planning works are constantly evolving to reflect current construction activities, lay-down areas, site traffic circulation, etc.

Technologies used to achieve 3-day cycle

The tower consists of more than 160 floors and is expected to be completed within a very tight schedule and 3-day cycle. Hence, the following key construction technologies were incorporated to achieve the 3-day cycle set for the concrete works:

- ◆ Auto Climbing formwork system (ACS)
- ◆ Rebar pre-fabrication
- ◆ High performance concrete suitable for providing high strength, high durability requirement, high modulus, and pumping
- ◆ Advanced concrete pumping technology
- ◆ Simple drop head formwork system that can be dismantled and assembled quickly with minimum labor requirements
- ◆ Column/Wall proceeding method, part of ACS formwork system

Sequence of Construction and ACS

Figure 9 depicts the construction sequence of the tower and show the auto climbing formwork system (ACS), designed by Doka. The ACS form work is divided into four sections consisting of the center core wall that is followed by the wing wall construction along each of the three tower wings. Figure 9 also demonstrates the following construction sequence:

- ◆ the center core wall construction is followed by the center core slab construction;
- ◆ the wing wall construction is followed by the wing flat plate slab construction; and
- ◆ the nose columns are followed by flat plate and flat slab construction at the nose area.

In addition, the core walls are tied to the nose columns through a series of multi-story outrigger walls at each of the mechanical levels. The construction of these outrigger walls are complex and time consuming because of the congestion of reinforcing bars at the connection zones. Therefore, the multi-directional highly congested reinforcing bars zones at the outrigger levels were replaced with structural steel members to help resolve the design forces more effectively at the joints, eliminate the reinforcing bar congestion issues, and most importantly ensuring the joint integrity. See Figure 10 for structural steel section used. These levels were constructed at a later stage and then taken out of the critical path.

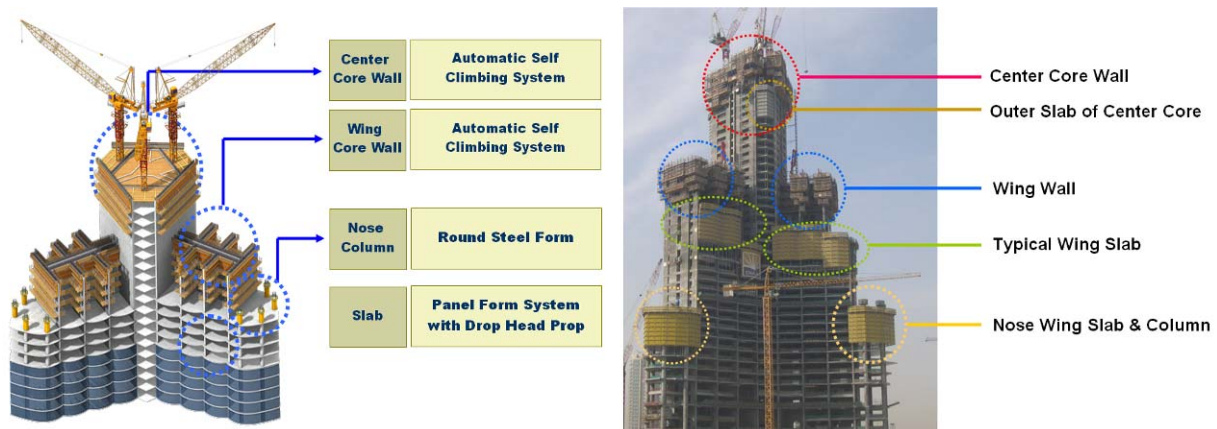


FIGURE 9 – SEQUENCE OF CONSTRUCTION



FIGURE 10 – PREFABRICATED BUILT-UP STRUCTURAL STEEL MEMBERS IN CENTER CORE WALL

Rebar Pre-fabrication

Most of the reinforcing bars for the core walls, wing walls, and the nose columns were prefabricated at the ground level as shown in Figure 11. This rebar fabrication and pre-assembly method resulted in many quality control advantages and reduced the number of workers going up and down the tower. Moreover, whenever possible, the rebar was assembled in double story modules to speed up the vertical element construction time.

Composite Link Beams

In addition to connecting the vertical core wall elements rigidly for maximum strength and stiffness for the lateral load resisting system, the link beams are also used as means of transferring and equalizing the gravity loads between the vertical members (core-wall elements and nose columns).



FIGURE 11 – REBAR PREFABRICATION FIGURE 12 – COMPOSITE LINK BEAM INSTALLATION

Downloaded from ascelibrary.org by PRINCETON UNIVERSITY LIBRARY on 10/09/13. Copyright ASCE. For personal use only; all rights reserved.

This equalizes stresses and strains between the members. Because the link beams are subject to large shears and bending moments, many of the link beams were composite members (steel members encased in high strength concrete). Thus the steel beams imposed special demands on the cranes, pre-assembly and lifting methods. Figure 12 depicts the composite link beam pre-assembly and installation method.

Slab Formwork System

Figure 13 shows a drop head system used for the slab construction. Meva Deck Drop Head slab formwork system was selected because of its installation simplicity, lightness, panel formwork material and strength, prop strength and stiffness, system flexibility and suitability for the slab hanging geometry, and allowance for cambering where needed.

The slab shoring system consists of four levels of shores and one level of re-shore to control the maximum loads in the slabs at the lowest level. However, the shoring props at the uppermost slab were left undisturbed. Figure 14 provides an outline of the slab construction methodology used.



FIGURE 13 – TYPICAL SLAB FORMWORK SYSTEM

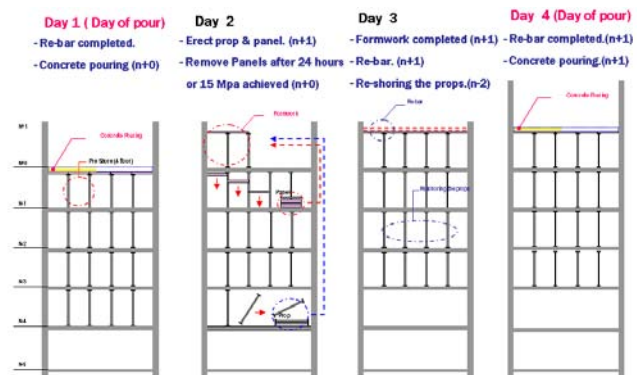


FIGURE 14 – OUTLINE OF SLAB CONSTRUCTION METHOD

Concrete Pumping

The utilization of high strength concrete and concrete pumping technologies was critical in the construction of the project. C60 and C80 grade concrete was used for vertical members, and C50 grade concrete was used for horizontal members.

Direct concrete pumping and delivery methods required considerations for the following:

- ◆ selecting an optimum concrete mix design with excellent flow characteristics to minimize/avoid blockages;
- ◆ choosing equipment that has enough capacity to deliver concrete to the highest level, more than 160 floors up;
- ◆ designing a pipe line that can be installed with maximum construction efficiency;
- ◆ selecting equipment and pipe line system that work well with the site's overall logistics and planning; and
- ◆ maintaining quality control of the pumping system and placement method by monitoring all components of the system and ensuring the concrete properties required.

A horizontal pump simulation test, shown in Figure 7, was performed, using over 600m of pipe length to confirm the pump capacity and evaluate the overall pressure losses in the pipes due to friction/connections/concrete type, etc. BSA-14000-SHP-D Putzmeister was utilized for all concrete grades. Refer to Figure 17 for concrete pumping plan.

MAJOR EQUIPMENT

The process of selecting the right equipment to ensure delivery of materials and workers effectively and efficiently is an art in its own right. Selecting the optimal equipment and vertical transportation system for construction requires ongoing analysis and constant modifications due to the dynamic nature of the project during its construction life.

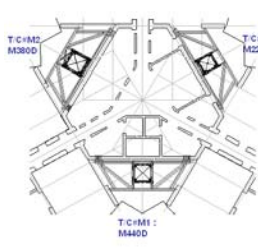
Since the project is more than 160 floors, close coordination of many overlapping activities of various trades, throughout the construction period, required careful planning, analysis, scheduling, and regular coordination. The process of selecting equipment for this project was extensive and cannot be adequately described in detail in this paper. Therefore, only a brief summary of the equipment used for the project will be provided and it includes cranes, hoists, and concrete pumping equipment.

Tower Cranes

Three high capacity self climbing luffing type tower cranes were optimally selected and located at the center core of the tower as shown in Figures 9 and 15. A summary of the tower crane specifications utilized for the project is shown in Figure 16.

Tower Main Hoist

Figure 17 depicts the location of the main hoists and the hoist specifications. The hoists were installed in three different phases following the construction sequence of the tower. Additional Jump hoists were installed in accordance with the specifications shown in figure 17.



	M1	M2	M3
Model	Favco M440D	Favco M380D	Favco M220D
Capacity	25 ton	25 ton	11 ton
Boom Length	55 m	55 m	55 m
Lifting Speed	220 m/min	220 m/min	145 m/min
Engine	600 HP	600 HP	350 HP
Erection Height	48 m (12 Masts)	48 m (12 Masts)	48 m (12 Masts)
Climbings	36 times + Telescoping	36 times	35 times
Miscellaneous	Spire Erection	Spire Erection	

	Phase 1	Phase 2	Phase 3
	H/C#1	H/C#2-#4	H/C#5-#6
Model	32/40 TD VFC HS		20/32 TD
Capacity	3.2 ton		2.0 ton
Cage Size (LxW)	4.0 m x 1.5 m		3.2 m x 1.5 m
Speed	100 m/min		45 m/min
Service Floors	B2-L112	B2-L100	L99-L139
Service Height	410 m	366 m	164 m
Location	Wing B	Wing B	Center Core

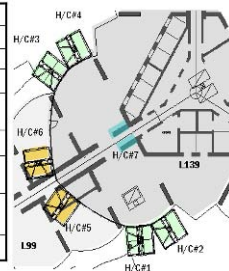


FIGURE 15 – TOWER CRANE TYPES&LOCATION FIGURE 16 – TOWER MAIN HOISTS SYSTEM

Concrete Pumping Equipment

While the horizontal concrete pump simulation test was very successful and indicative that re-pumping was not required, pumping the concrete vertically and under different environmental conditions could potentially present unexpected complications. Therefore, a secondary provisional pump at level 124 was procured for emergency as shown in Figure 17.

Three major pumps were placed at the ground level as shown in Figure 17. Pumping line 1 situated at the center core, with pumping lines 2, 3 and 4 at the south, west, and east wings of the core. An additional pumping line 5 was located at the center core area for emergency use. The secondary pump was not needed since most of the concrete was pumped directly to the highest concrete elevation 600 meters.

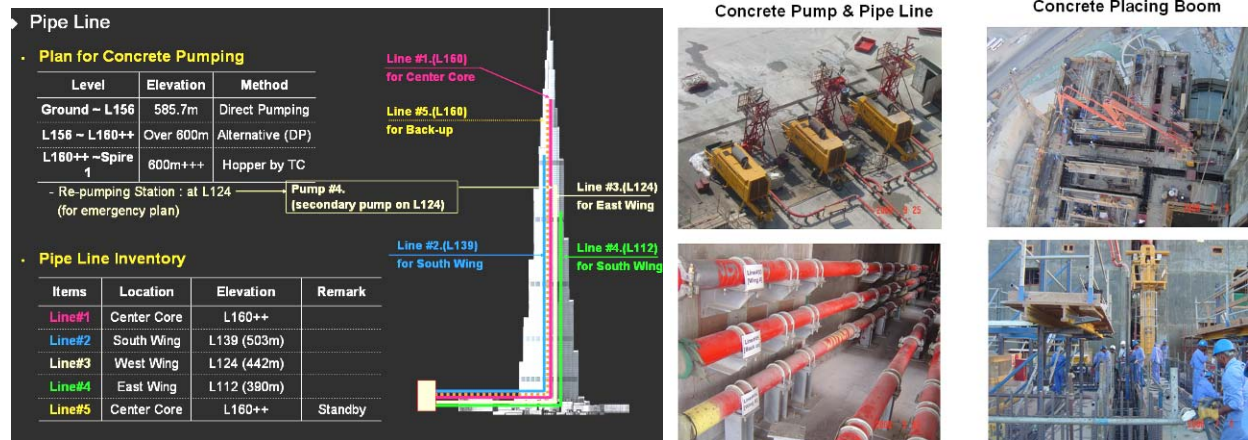


FIGURE 17 – CONCRETE PUMPING PLAN (EQUIPMENT, PIPE LINES, CPB, ETC.)

At Level 156, the reinforced concrete core wall will reach its highest point and serves as the foundation for the spire's structural steel works. The central pinnacle structure, which consists of 1200mm-2100mm diameter structural steel pipe, varies in thickness from 60mm at the lowest level to 30mm at the top.

The structural steel works above level 156 consists of the spire structure surrounding the central spine pinnacle structure, and provides the basis for its lateral support and stability. The spire structural system consists of an exterior diagonal braced frame system to provide for the lateral stability system. While the spire structural steel works is fabricated in Dubai, the pinnacle structure is procured and made in Korea and shipped to Dubai for final fabrications and assembly.

The erection of the spire and the pinnacle starts from level 156, and the erection of the spire was done in traditional steel construction method. However, the pinnacle pipe sections are stacked from level 156 and lifted to the final position from within the spire as shown in Figure 18.

The lift of the pinnacle will occur in three steps. After each lifting step, the cladding on the pinnacle will be completely installed.

- ◆ Erection of the spire structure
- ◆ Installation of the support beam
- ◆ Installation of the lifting block and assemblies
- ◆ Installation of the lifting equipment and assemblies
- ◆ Lifting the pinnacle in a three step process
- ◆ Installing cladding after each lift
- ◆ Completing lift of the pinnacle and all connection connections (gravity and lateral)
- ◆ Completion of the cladding installation

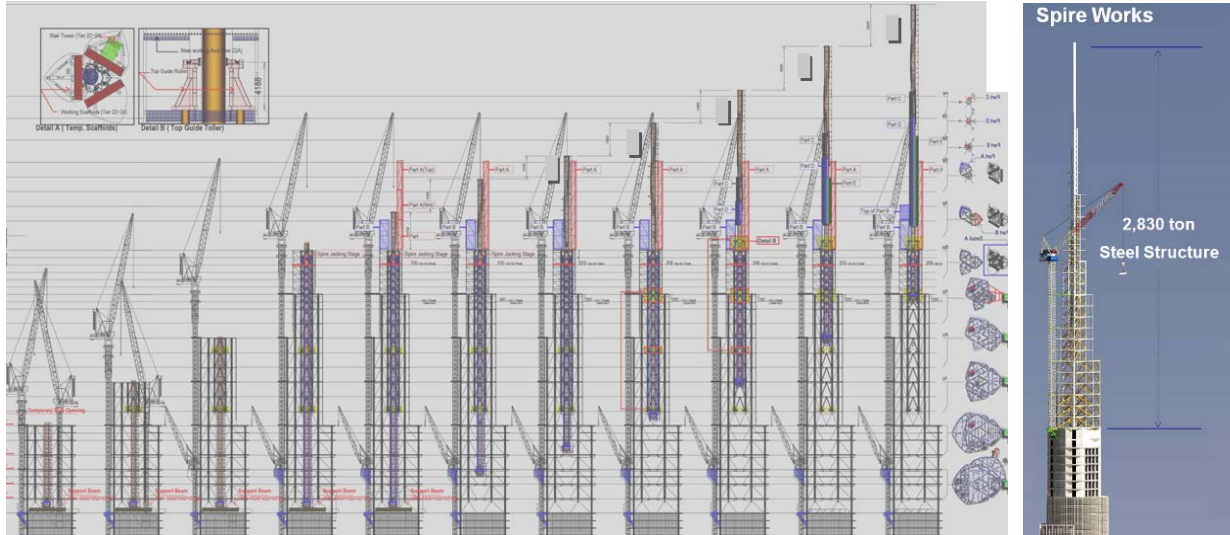


FIGURE 18 – SPIRE & PINNACLE LIFT-UP METHOD

STRUCTURAL HEALTH MONITORING & SURVEY PROGRAM

At the Burj Khalifa project, one of the most extensive structural health and survey monitoring program has been installed and it includes 1) more than 3000 strain gages at the columns, walls and beams, 2) foundation settlement survey, strain gages in the piles, horizontal and vertical survey system, accelerometers, and GPS system to monitor the dynamic behavior of the tower during construction and for permanent buildings conditions. Due to the limitation of the paper length, details of the monitoring system cannot be fully described here; however a special publication on the monitoring system of the Burj Khalifa project will follow.

CONCLUSION

On the 4th of January 2010, the opening ceremony of Burj Khalifa was held to celebrate the tallest man made structure in the world for at least the next decade. This project has made a new history in the world of architecture and engineering. At the turn of the century, concrete construction was at its infancy and nobody then could have dreamed of creating a building this tall using concrete. The Burj Khalifa project demonstrates that tall building system development is always directly related to the latest developments in material technologies, structural engineering theories, wind engineering, seismic engineering, computer technologies, and construction methods. The Burj Khalifa project capitalizes on the advancements in these technologies, and in advancing the development of supertall buildings and the art of structural engineering.

As of today, the Burj Khalifa is the tallest man made structure in the world in all categories, and it has become a catalyst for further development in highrise construction in the Middle East and throughout the world. The Burj Khalifa project is another step forward in meeting the technological challenges of future construction and it set a new stage for the future generation of supertall buildings.

REFERENCES

Abdelrazaq, A, Kim, K. J., Kim, J.H. “Brief on the Construction Planning of the Burj Dubai Project, Dubai, UAE”, 17th IABSE Congress, Creating and Renewing Urban Structures – Tall Buildings, Bridges and Infrastructure, Chicago, September 17-19, 2008.

Baker, W.F. Korista, S., Novak, L. “The Structural Design of The World's Tallest Structure: The Burj Dubai Tower”, 17th IABSE Congress, Creating and Renewing Urban Structures – Tall Buildings, Bridges and Infrastructure, Chicago, September 17-19, 2008