버즈 두바이 콘크리트 건물의 설계와 시공

Design and Construction of the Burj Dubai Concrete Building Project

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1. Introduction

A century ago reinforced concrete was invented. At the first half of the twentieth century concrete had a lot of limitation for tall building because of its limited strength, large mass, and valuable rentable space it takes, and its impact on the overall construction program. However, the latest technological advances in high performance concrete, and concrete construction methods made concrete to become very cost effective competitive with structural steel and its use is only limited by its users.

Today, concrete has become composite materials with strength equivalent to low strength steel used at the turn of the century, and with concrete technologies that overcome all of its limitations. Present concrete technologies is not only limited to material technologies such as High Performance Concrete(HPC), but to the high speed construction cycles it offers, which include but limited to advanced formwork systems, concrete pumping technologies, and simplicity in construction planning and design. The use of Concrete on Burj Dubai Project demonstrates another beginning of new era for concrete use in supertall building structures. This paper will focus on the structural concrete use and planning works for the Burj Dubai Project.

The Burj Dubai Project is a multi-use development tower with a total floor area of 465,000 square meters that includes residential, hotel, commercial, office, entertainment, shopping, leisure, and parking facilities. The Burj Dubai project is designed to be the center piece of the large scale Burj Dubai Development that rises into the sky to an unprecedented height that exceeds 700 meters and that consists of more than 160 floors<Fig. 1>.

The Client of Burj Dubai Tower, Emaar Properties, is a globally acknowledged as one of the finest developers of lifestyle real estate in the Middle East Region. Turner International has been designated by the owner as the Construction Manager, and Samsung Joint Venture(consisting of Besix, Belgium Base Contractor, and Arabtec, Dubai base), as the General Contractor.

The design of Burj Dubai Tower is derived from

Fig. 1 Burj Dubai artist's rendering

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geometries of the desert flower, which is indigenous to the region, and the patterning systems embodied in Islamic architecture.

The tower massing is organized about the central core with three wings, with four bays, that peels off by one bay from each wing at every seven floors in a spiral as it rises into the sky. Unlike many super-highrise buildings, with deep floor plates, the Y-shape floor plans of Burj Dubai maximize the views of the Persian Gulf and provide plenty of natural light for its tenants. The modular Y-shaped building, with setback of the three wings, every 7 floors, was part of the original design concept that allowed Skidmore, Owings and Merrill to won the invited design competition.

The tower superstructure of Burj Dubai is designed as an all reinforced concrete building with high performance concrete from the foundation level to level 156 and is topped with an all structural steel braced frame structure from level 156 to the tip of the pinnacle. The tower massing is also driven by the wind engineering requirements to reduce the dynamic wind excitation of the tower by reducing the building width and shape as the tower spirals up into the sky, thus reducing wind dynamic effects, movement, and acceleration. Integrating the wind engineering principals and requirements into the architectural design of tower resulted in very stable dynamic response of the structure against the strong wind effects, thus taming the powerful wind forces.

2. Structural system brief description

2.1 Lateral load resisting system

The lateral load resisting system of the tower provides resistance to wind and seismic forces and consists of high performance, reinforced concrete ductile core walls from the foundation to the roof that are linked to the exterior high performance reinforced concrete columns through a series of high performance reinforced concrete shear wall panels at the mechanical levels<Fig. 2>.

The core walls vary in thickness from 1,300 mm to 500 mm. The core walls are typically linked through a series of 800 mm to 1,100 mm deep reinforced concrete or composite link beams at every level. Due to the

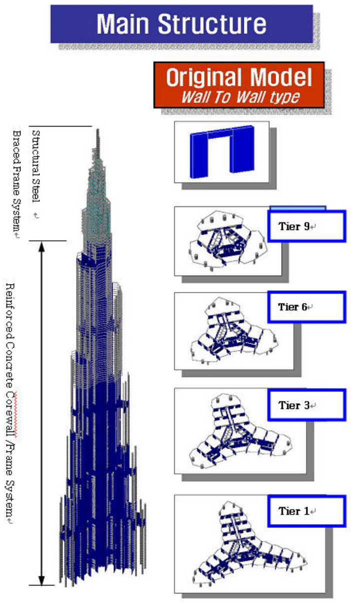


Fig. 2 Lateral load resisting system

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 and provides for the majority of the shear and moment resistance. The link beam width typically matches the adjacent core wall thickness.

At the top of the center reinforced concrete core wall, a very tall structural steel spire structure rises to the sky to make the building the tallest tower in the world for all categories. The lateral load resisting system of the spire consists of diagonalized structural steel bracing system that is founded at the top of the central reinforced concrete core wall system at level 156.

The vertical members of the core walls were designed in accordance with the ACI Building Code with due consideration to other international building codes, especially as it relates to the high strength concrete. Every vertical member in the core wall was treated as column, especially at the bottom of the building where the vertical reinforcement exceeded 0.5%. While the very large nose columns at the tip of the building where also designed in accordance with the ACI Building Code, other model codes were considered in relation to tie spacing of these mega columns. Spiral ties were used for the majority of the columns at 100 mm spacing.

The reinforced concrete link beams were designed in accordance with the ACI Building Codes for both shear and bending moments. The shear design for the link beam considered also the strut and tie model for their design. The ACI Building Code does not address well the design of composite link beams and essentially there are no design provisions on how to detail the anchorage zones of the structural steel section. Several options were considered for the design of the anchorage of the structural steel elements; however, a more conservative approach was taken in designing such members using the cantilever bracket type of approach in accordance with a recommended design methodology. Special Analysis(using ABAQUS) was also performed at the UI, Urban Champaign to confirm the design strength and ductility of the composite members. All the structural steel members embedded in the link were designed in accordance with the latest AISC-LRFD specifications.

2.2 Floor framing system

The typical residential and hotel floor framing system of the Tower consists typically of 200 mm to 300 mm 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 225 mm to 250 mm two-way reinforced concrete flat plate system. The floor framing system within the interior core consists also of two way reinforced concrete flat plate system with beams.

The reinforced concrete framing were design in accordance with the ACI Building Codes provisions for flat plate construction. 3-dimensional finite element analysis program was used to confirm the deflection of the slab. The extensive finite element analysis model was done iteratively and that took into account the effect of cracking, load redistribution, effect of construction sequence, and immediate/long term deformation. The concrete strength in the slab was increase to avoid concrete puddle at the column locations. The floor slabs and their behavior was extensively monitored to confirm their behavior during and after construction, which is a subject of great interest to many professional(practical and in academia) and it cannot be covered extensively in this article.

2.3 Foundation system

The tower is founded on a 3,700 mm 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 of 100 mm blinding slab over waterproofing membrane, over at least 50 mm blinding slab. The raft foundation bottom and all sides are protected with waterproofing membrane. See Fig. 3 for the raft foundation system.

The piles are typically 1,500 mm diameter, high performance reinforced concrete bored piles, extending approximately 45 meters below the base of the raft. All piles utilized self compacting concrete(SCC) with w/c ratio not exceeding 0.30, and 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 3,000tons.

The piles were design and test programs were performed in accordance with the IBC 2003 and in accordance with the Dubai Municipality(DM) requirements. An extensive pile testing program was also

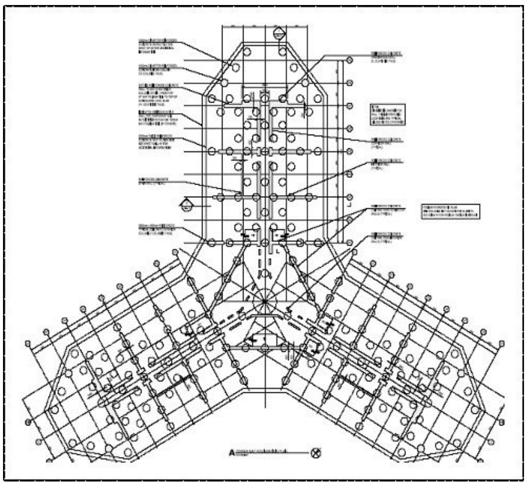


Fig. 3 Raft foundation system

performed to confirm the pile capacity under different construction methods, and under vertical and lateral loading conditions. The pile testing program was carried to get the capacity of the apparatus setup since the piles actual capacity significantly exceeded those predicted. The safety factor for the piles was significantly more than 2.

A robust cathodic protection system is also provided for both the bored piles and the raft foundation system to protect the foundation and the reinforced concrete raft against the severe and corrosive environment (chloride and sulfate) of the soil at the Burj Dubai site.

3. Construction of the tower superstructure

Currently the tower superstructure is near completion and the pinnacle structure is already assembled in the body of the spire and ready for lifting. The foundation system(pile & raft) were completed in February 2005. The tower superstructure construction started in April 2005, the concrete structure is complete, and the structural steel is being completed. Since the original construction program is very tight and is expecting the completion of more than 160 floors with very tall and slender spire/pinnacle. Samsung put forward the following strategic approach to achieve this aggressive program:

- ·Three(3) day-cycle for the structural work and reducing the risks of any structural works that is considered complex and requires careful planning works.
- ·Optimum transportation methods with large capacity & high speed equipment.
- ·Combination of optimum formwork System for various building shapes changes along the building height.
- ·Well organized logistic plans throughout the construction period.
- ·Application of all high-rise construction technologies available at the time of construction.

Since the construction planning is very extensive and cannot be covered in details in this paper, this paper will focus only on the planning and implementation of the concrete works.

4. Planning for the concrete work

High performance concrete is specified as the main structural material for the tower from the early design concept of the project with due consideration to the factors discussed above. Since Dubai is very corrosive environment and all concrete works requires high standards of care at every level and for every aspect of the concrete works. The concrete specifications for the Burj Dubai project is somewhat performance based design and required high strength, high modulus of elasticity, low shrinkage, and high demands for durability and serviceability. This type of specification allowed the contractor to take full advantage of the high performance concrete technologies available and allowed for a very innovative approach to concrete works. Table 1 below provides a comparison summary of the concrete materials specified and the actual concrete used.

4.1 Strategy for the concrete planning

Prior to the construction of the tower, an extensive concrete testing and quality control programs were put in place to ensure that all concrete works is done in agreement with the contract documents and all parties involved, including the supervision consultant(Hyder), the owner independent testing agency(IVTA), the concrete supplier(Unimix) top design and quality control team, CTL, and Samsung Engineering and

Table 1. Comparison of concrete grades

Floor Level	S.S.L.	Concrete Grade			
		Vertical Member		Horizontal Member	
		Design	Actual	Design	Actual
L154~L156	+585.700	C80	C80/14	C50	C50/14 E=37,000㎫ (28days)
L 140~L153	+569.625	C60 E=37,000㎫ (28days)	C60/14 E=39,000㎫ (28days)	C40	
L 136~L139	+502.425			C50	
L 127~L135	+488.025			C40	
L 113~L126	+452.025	C80 E=41,000㎫ (28days)	C80/14 E=43,000㎫ (56 days)	C45	C50/20 E=39,000㎫ (28days)
L 109~L112	+389.625			C50	
L 101~L108	+375.285			C45	
L 77~L100	+347.385		C80A/20 E=48,000㎫ (90days)	C45	
L73~L76	+261.215			C50	
L 44~L72	+246.885			C45	
L 40~L43	+152.225			C50	
L 27~L39	+137.885			C45	
B2 ~ L26	+ 94.485	C80A E=43,800㎫ (90days)		C50	
Foundation	- 15.350	C50/20 (SCC)			

Construction Task force team. Samsung-JV encouraged a team approach to the concrete works where the design team focuses on the design requirements and compliance, while the contractor focus is integrating all the design requirements with the means and method of designing the concrete mix and delivering to its final placement locations in full compliance of the contract documents. Some of the programs that Samsung-JV put in place from the early development of the concrete mix design until the completion of all test and verification programs included, but not limited to the following:

- ·Trial mix designs for all concrete types needed for the project.
- ·Mechanical properties, which included compressive strength, modulus of elasticity, split tensile strength.
- ·Durability tests which included initial surface absorption test, 30 minute absorption test, Water penetration tests and rapid chloride permeability test.
- ·Creep and shrinkage test program for all concrete mix design, see Fig. 4 for testing setup.
- ·Shrinkage test program for all concrete mix designs.
- ·Pump simulation test for all concrete mix design grades up to at least 600 meters. See Fig. 5 for test setup.
- ·Heat of hydration analysis and tests, which included cube analysis and tests, and full-scale heat of hydration mock tests for all the massive concrete elements that have a dimension in access 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 and through major daily and seasonal temperature fluctuations. See Fig. 6 for test setup.

Fig. 4 Creep test

4.2 Concrete mix design

Since the project required more 300,000 cubic meters of concrete, an optimum concrete mix design proportions are required to achieve high performance concrete with 1) high strength, 2) high flow rate, 3) high early strength, 4) high modulus of elasticity, 5) low heat of hydration, and 6) high pumpability. Achieving these requirements required an optimum selection of all the raw materials proportions and the verification of a

Fig. 5 Pump simulation test

Fig. 6 Heat of hydration mockup test

comprehensive concrete testing program.

In addition to achieving high durability concrete, Table 2 depicts some of the admixtures used in the mix design proportions to achieve the required properties. In addition, a comprehensive quality control program was strictly put in place at the onset of the concrete planning works, at the concrete batch plant and at the site, to warranty consistent concrete production, pumping, and placement.

4.3 Concrete pumping

Present concrete pumping technologies has made the concrete works very competitive with the structural steel construction thus allowing for fast construction cycles. In addition, concrete pumping technologies has become one of the major concrete constructions readily available for concrete, composite and steel building construction. Placing concrete nowadays is no longer dependent on the crane usage. However, the selection of optimum concrete mix design for concrete pumping requires:

- ·Selecting an optimum concrete mix design with excellent flow characteristics to minimize/avoid blockages;
- ·selecting equipment with enough capacity to deliver concrete to the highest level, more than 160 floors;
- ·selecting pipe lines for maximum output efficiency and the least friction losses;
- ·selecting equipment and pipe line systems that integrates well with the site logistic and construction planning throughout the construction period;
- ·maintaining quality control by monitoring all components of the system and concrete properties and modifications as deemed necessary;
- ·systematic coordination of all concrete works from the plant to the job site, including batching interval, delivery, discharging, pumping, placement.

4.4 Preliminary concrete pumping simulation

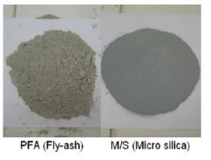
Preliminary horizontal concrete pump simulation test, Fig. 5, was performed to estimate the friction losses of the 600 m long steel pipe in order to confirm the concrete pump capacity, and the behavior of the concrete pumping system, including pumping system details, hydraulic pressure, concrete delivery pressure and number of strokes per minute. In addition, the test was performed to verify the concrete mechanical properties and flow characteristics after concrete pumping. Table 3 below provided a summary of the horizontal concrete pumping system, concrete types tested, concrete testing programs, and the expected concrete pressure.

4.5 Final concrete pumping and equipment

While the horizontal concrete pump simulation test was successful and indicative that re-pumping was not required, pumping the concrete vertically and under different environmental conditions may present itself with unexpected situation; therefore, a secondary pump was planned for emergency situation at level 124

Table 2. Key concrete technologies used for HPC

Category	Key Technology
High Strength	W/C, Binder Proportion
High Elasticity	Coarse Agg., Binder Proportion
High Flowability	Fine Agg., Binder Volume, Chemical
Early Strength	Binder, Chemical, In-situ Strength
Heat of Hydration	Binder(PFA), Mock-Up, Analysis
Drying Shrinkage	Binder / Water Weight
High-Rise Pumping	Flowability, Plastic Viscosity



PFA (Fly-ash) M/S (Micro silica)

Crushed Sand & Dune Sand

Table 3. Preliminary concrete pumping simulation and concrete testing program

Pumping Length	250m, 450m, 600m
Pipe Diameter	125mm (5-inch)
Grade of Concrete	C80A/20, C80/14, C60/14, C50/20
Pressure Measuring	Hydraulic & Delivery Pressure, Strokes
Concrete Testing	Flow, Temperature, Strength
Concrete Properties (per 100m pumping)	Flow Loss : 25~30mm Temp. increment : 0.8~1.0℃ Early Strength : 30% ↑
Expected Concrete Pressure (vertical, 6" pipe)	C80A/20 (250m) : 151bar C80/14 (450m) : 170bar C60/14 (600m) : 209bar C50/20 (600m) : 199bar

Pumping Simulation (600m horizontal)

as shown in Fig. 7.

Three major pumps are placed at the ground level that can potentially connect to any of the five (5) pump lines installed at the ground level, that can potentially connects to four (4) concrete placing booms. See Fig. 7 for Tower pump Equipment layout and major pipe lines. Pumping line 1 is placed at the center core, pumping line 2, 3 &4 were placed at the south, west, and east wings of the core wall respectively. An additional pumping line 5 was used at the center core area for emergency use. As of the time of writing this paper, the concrete was pumped directly to 600 m, which makes the highest concrete pumping.

The concrete pumping system was monitoring closely to verify that there is no unexpected behavior and to make adjustment to the pumping system or concrete types as deemed necessary. The pressure in the pumping system was monitoring every 50 m, and the concrete characteristics, including its mechanical properties, were also tested. Table 4 shows a summary of the monitoring and testing programs executed to

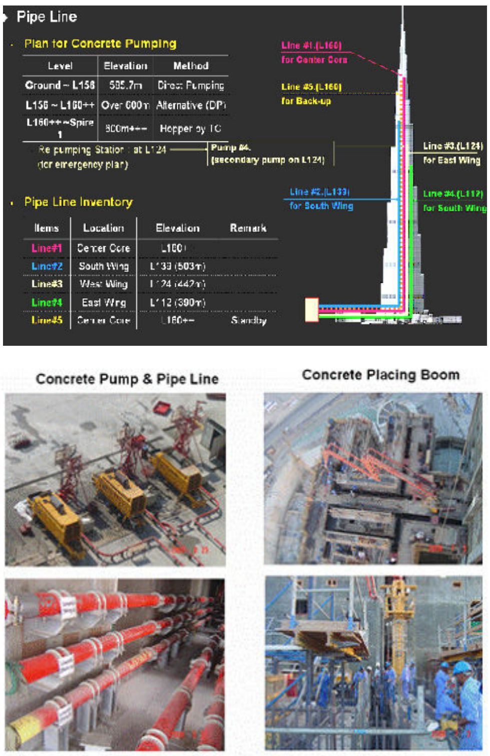


Fig. 7 Tower pump equipment & pipe lines

Table 4. Summary of pumping monitoring program and concrete testing

Pumping Height		- 150m, 200m, 250m, ... 500m, 550m, 585.7m (every 50m)
Grade of Concrete		- C80A: ~350m, C80/14: ~450m, C60/14 & C50/20: ~585.7m
Measuring Pressure	Data Measuring	- Data Logger with Brosa Sensor (~400bar)
	Measuring Items	- HY (Hydraulic Pressure), C0 (Max. Concrete delivery Pressure), C1 (Horizontal Pressure Loss), ST (strokes per min)
	Analysis	- Out-Put (M3/h), Friction Factor, Pumping Efficiency
Concrete Testing	Data Measuring	- Slump Test, Rheometer Test, Compressive Test, Air Test (Test Condition : Before Pumping & After Pumping)
	Measuring Items	- Slum Flow, Time to 500mm Flow, Temperature, Plastic Viscosity, Strength(12H, 24H, 7D, 28D), Modulus of Elasticity
	Analysis	- Flow Loss, Temperature Increment, Unit Weight Change, Plastic Viscosity Change, Early Strength increment

ensure the successful completion of the direct concrete pumping and concrete works 600 m.

4.6 Concrete creep and shrinkage test

An extensive creep and shrinkage testing program was performed at CTL laboratory in the Skokie, Illinois, and USA and at Samsung Own Testing Laboratory in Seoul, Korea. The testing program was performed in accordance with ASTM C512 Creep and Shrinkage Test. The concrete was tested for both sealed and unsealed conditions, and loaded at 7 days and 28 days at 25% and 40% the tested concrete compressive strength. Because the high performance concrete mixes are designed for high strength, high durability, low water cement ratio, low shrinkage, and pumpability, most of the concrete mixes revealed very low shrinkage values and most of the shrinkage tend to occur very early. See Fig. 4 for a typical Creep and Shrinkage test setup. Analysis of the creep and shrinkage test results also revealed that the Burj Dubai creep and shrinkage characteristics were different from those predicted by international model codes. Due to the extensive nature of this issue, this topic cannot be covered in detail in this paper.

5. Conclusion

At the turn of the century, concrete construction was at its infancy and the present concrete construction technologies have made concrete a reality for supertall building design. The Burj Dubai project presents a testimony that tall building system development is always directly related to the latest development in material technologies, structural engineering theories, wind engineering, seismic engineering, advancement in computer technologies, and construction methods. The Burj Dubai Project capitalizes on these technologies to advance the development of supertall building structural system and the art of structural engineering.

As of today, the Burj Dubai project has become the tallest man made structure in all the world in all categories and it has become a catalyst to the explosive use of high performance concrete in highrise building construction in the Middle East in particular and to the whole world in general. The Burj Dubai project will also offers another beginning for new technological challenges for high performance concrete and new opportunities for tall building systems.

Fig. 8 Construction progress photos

Abstract The Burj Dubai Project will be the tallest structure ever built by man; when completed the tower will be more than 700 meter tall and more than 160 floors. While the early integration of aerodynamic shaping and wind engineering considerations played a major role in the architectural massing and design of this multi-use/residential tower, where mitigating and taming the dynamic wind effects was one of the most important design criteria, the material selection for the structural systems of the tower was also a major consideration and required detailed evaluation of the material technologies and skilled labor available in the market at the time Concrete was selected for its strength, stiffness, damping, redundancy, moldability, free fireproofing, speed of construction, and cost effectiveness. In addition, the design challenges of using concrete for the design of the structural system components will be addressed. The focus on this paper will also be on the early planning of the concrete works of the Burj Dubai Project.

Keywords Core Wall System, High Performance Concrete, self compacting/consolidating concrete, raft foundation, wind engineering integration with the architectural massing, heat of hydration analysis, pump simulation test, creep and shrinkage test & construction sequence analysis, concrete durability, ACS forming system.

요 약 700미터 이상의 높이와 160층 이상으로 설계된 버즈두바이가 완공되면 버즈두바이는 인간이 건축한 건축물 중에서 최고높이의 건축물이 될 것이다. 바람의 동적효과를 완화하고 제어시키는 것이 가장 중요한 설계요소중의 하나이며, 설계초기의 공기역학적 형상과 풍공학에 대한 고려가 이러한 주상복합건물의 건축적 형상 및 디자인에 있어 큰 역할을 하는 반면, 건물의 구조시스템을 위한 재료선택 또한 디자인의 중요한 요소이고 그 다음으로 세부적인 재료기술에 대한 평가 및 기술자 수급이 요구되어진다. 콘크리트는 콘크리트의 강도, 강성, 감쇠, 잉여력, 형틀성, 내화성, 시공성, 원가 등을 고려하여 선정된다. 이 논문은 콘크리트를 활용한 구조시스템을 적용하면서의 설계적으로 도전되었던 부분과 버즈두바이의 콘크리트공사의 초기계획에 대해 집중적으로 다룰 것이다.

핵심용어 코어월 시스템, 고성능 콘크리트, 매트 기초, 건축적 형상에 대한 풍공학의 융합, 수화열 해석, 펌프 시뮬레이션 실험, 크리프와 건조수축 실험, 시공단계 해석, 콘크리트 내구성, ACS 폼 시스템