The Challenges in Designing the World’s Tallest Structure: 
The Burj Dubai Tower

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ABSTRACT

The design of supertall buildings is typically governed by their interaction with lateral winds and gravity loads. Selection of the building shaping and structural system can greatly affect the wind and gravity behavior of the structure. The following case study will demonstrate the design process and philosophy utilized in the design of supertall buildings, by highlighting specific challenges faced by the design team, and by explaining how the latest material, construction, and analysis technologies assisted in successfully overcoming these challenges.

INTRODUCTION

The goal of the Burj Dubai Tower is not simply to be the world’s highest building; it’s to embody the world’s highest aspirations (Figure 1). Such a project goal by necessity requires pushing current analysis, material, and construction technologies to literally new heights. However, as such a building height has never before been attempted, it is also necessary to ensure all technologies and methods utilized are of sound development and practice. As such, the designers sought to be able to use conventional systems, materials, and construction methods, modified and utilized in new capacities, to achieve such a lofty goal.

The superstructure is currently under construction and as of June 2008 had reached over 160 stories, capturing the title of the tallest manmade structure, eclipsing the KVLY-TV antenna mast in North Dakota at 628m. The final height of the building is a “well-guarded secret”. The height of the multi-use skyscraper will “comfortably” exceed the current building record holder, the 509 meter (1671 ft) tall Taipei 101.
The Burj Dubai Tower is the centerpiece of a $20 billion development located just outside of downtown Dubai. The project consists of the Tower itself, as well as an adjacent Podium structure, and separate 6-story Office Annex and 2-story Pool Annex. The 280,000 m² (3,000,000 ft²) reinforced concrete multi-use Tower is predominantly a residential and office usage, and also contains retail and a Giorgio Armani Hotel. The Tower and Podium structures (combined 465,000 m²) are currently under construction, and the project is scheduled for completion in 2009.

**WORLD’S TALLEST BUILDING**

From the outset, it has been intended that the Burj Dubai be the World’s Tallest Building. The official arbiter of height is the Council on Tall Buildings and Urban Habitat (CTBUH) founded at Lehigh University in Bethlehem, Pennsylvania, and currently housed at the Illinois Institute of Technology in Chicago, Illinois. The CTBUH measures the height of buildings using four categories. These categories and their current record holders are as follows (Figure 2):

<table>
<thead>
<tr>
<th>Category</th>
<th>Building Name</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of Structure</td>
<td>Taipei 101</td>
<td>509m</td>
</tr>
<tr>
<td>Top of Roof</td>
<td>Shanghai World Financial Center</td>
<td>487m</td>
</tr>
<tr>
<td>Highest Occupied Floor</td>
<td>Shanghai World Financial Center</td>
<td>474m</td>
</tr>
<tr>
<td>Top of Pinnacle, Mast, Antenna</td>
<td>Sears Tower</td>
<td>527m</td>
</tr>
</tbody>
</table>

Although the final height of the Tower is a well-guarded secret, Burj Dubai will be the tallest by a significant amount in all four categories.

**FIGURE 2** – Lineup Diagram of Several of the World’s Tallest Buildings
ARCHITECTURAL DESIGN

The primary design concept of the Tower is the form of an indigenous desert flower, an organic form with tri-axial geometry and spiraling growth that can be easily seen in the final design. Additionally, traditional Islamic forms were also utilized to enrich the Tower’s design, and to incorporate visual references to the culture and history of the surrounding region. As such, 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 (Figure 3). As the Tower rises, one wing at each tier sets back in a spiraling pattern, further emphasizing its height (Figure 4). The Y-shape plan is ideal for residential and hotel usage, in that it allows the 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 elevating and mechanical closets. Additionally, the Tower is serviced by five separate mechanical zones, located approximately 30 floors apart over the height of the building. Located above the occupied reinforced concrete portion of the building is the structural steel spire, housing communication and mechanical floors, completing the architectural form of the Tower. The architects and engineers worked closely together from the beginning of the project to determine the shape of the Tower, in order to provide an efficient building in terms of its structural system and in its response to wind, while still maintaining the integrity of the initial design concept.

STRUCTURAL SYSTEM DESCRIPTION

In addition to its aesthetic and functional advantages, the spiraling “Y” shaped plan was also utilized to shape the structural concrete Burj Dubai to reduce the wind forces on the tower, as well as to keep the structure simple and foster constructability. The structural system can be described as a “buttressed” core, and consists of high performance concrete wall construction. Each of the wings buttress the others via a six-sided central core, or hexagonal hub. This central core provides the torsional resistance of the structure, similar to a closed pipe or axle. Corridor walls extend from the central core to near the end of each wing, terminating in thickened hammer head walls. These corridor walls and hammerhead walls behave similar to the webs and flanges of a beam to resist the wind shears and moments. Perimeter columns and flat plate floor construction complete the system. At mechanical floors, outrigger walls are provided to link the perimeter columns to the interior wall system, allowing the perimeter columns to participate in the lateral load.
resistance of the structure; hence, all of the vertical concrete is utilized to support both gravity and lateral loads. The result is a tower that is extremely stiff laterally and torsionally. It is also a very efficient structure in that the gravity load resisting system has been utilized so as to maximize its use in resisting lateral loads.

As the building spirals in height, the wings set back to provide many different floor plates. The setbacks are organized with the tower’s grid, such that the building stepping is accomplished by aligning columns above with walls below to provide a smooth load path. As such, the tower does not contain any structural transfers. These setbacks also have the advantage of providing a different width to the tower for each differing floor plate. This stepping and shaping of the tower has the effect of “confusing the wind”: wind vortices never get organized over the height of the building because at each new tier the wind encounters a different building shape.

**Structural Analysis and Superstructure Design**

The reinforced concrete structure was designed in accordance with the requirements of ACI 318-02 *Building Code Requirements for Structural Concrete*. Wall and column concrete strengths range from C80 to C60 cube strength, and utilize Portland cement, fly ash, and local aggregates. The C80 concrete has a maximum specified Young’s Elastic Modulus of 43,800 N/mm² at 90 days. Wall and column sizes were optimized using virtual work / LaGrange multiplier methods, resulting in a very efficient structure. Wall thickness and column sizes were also fine-tuned to reduce the effects of creep and shrinkage on the structure. To reduce the effects of differential column shortening due to creep between the perimeter columns and interior walls, the perimeter columns were sized such that the self-weight gravity stress on the perimeter columns was equal to the stress on the interior corridor walls. The outriggers at the five mechanical floors tie all the vertical load carrying elements together, further ensuring uniform gravity stress by essentially allowing the structure to redistribute gravity loads at five locations along the building’s height, thereby reducing differential creep movements. With respect to concrete shrinkage, the perimeter columns and corridor walls were given matching thicknesses of 600mm, which provided them with similar volume to surface ratios. This measure allows the columns and walls to generally shorten at the same rate due to concrete shrinkage.

The majority of the Tower is a reinforced concrete structure. However, the top of the Tower consists of a structural steel spire utilizing a diagonally braced lateral system. The spire houses several mechanical and communication floors, open void space, and culminates in a pinnacle element. The structural steel spire was designed for gravity, wind, seismic and fatigue in accordance with the requirements of AISC Load and Resistance Factor Design Specification for Structural Steel Buildings (1999).

The entire building structure was analyzed for gravity (including P-Delta analysis), wind, and seismic loadings utilizing ETABS version 8.4 (Figure 5). The three-dimensional analysis model consisted of the reinforced concrete walls, link beams, slabs, raft, piles, and the spire structural steel system. The full analysis model consisted of over 73,500 shells and 75,000 nodes. Under lateral wind loading, the building deflections are well below commonly used criteria. The dynamic analysis indicated the first mode is lateral sidesway with a period of 11.3 seconds. The second mode is a perpendicular lateral sidesway with a period of 10.2 seconds. Torsion is the fifth mode with a period of 4.3 seconds.
The Dubai Municipality (DM) specifies Dubai as a UBC97 Zone 2a seismic region (with a seismic zone factor $Z = 0.15$ and soil profile Sc). The seismic analysis consisted of a site specific response spectra analysis. Seismic loading typically did not govern the design of the reinforced concrete Tower structure. However, seismic loading did govern the design of the reinforced concrete Podium buildings and the Tower structural steel spire. Site specific seismic reports were developed for the project including a seismic hazard analysis. The potential for liquefaction was investigated based on several accepted methods; it was determined that liquefaction is not considered to have any structural implications for the deep-seated Tower foundations.

A comprehensive construction sequence analysis incorporating the effects of creep and shrinkage was performed to study the time-dependant behavior of the structure (Figure 6). Since the vertical concrete elements tend to be of similar compression stress, the building performs well under the effects of creep and shrinkage. The results of this analysis were utilized to determine the horizontal and vertical compensation programs. For horizontal compensation, the building is being “re-centered” with each successive center core jump, correcting for gravity induced sidesway effects which occur up to the casting of each story. For vertical compensation, additional height is added by increasing floor-to-floor height, offsetting the predicted vertical shortening of the column and wall elements.
TOWER FOUNDATIONS AND SITE CONDITIONS

The Tower foundations consist of a pile supported raft (Figure 7). The solid reinforced concrete raft is 3.7 meters thick and was poured utilizing 12,500 cubic meters of C50 (cube strength) self consolidating concrete (SCC). The raft was constructed in four (4) separate pours (three wings and the center core). Each raft pour occurred over at least a 24 hour period. Reinforcement was typically spaced at 300mm in the raft, and arranged such that every 10th bar in each direction was omitted, resulting in a series of “pour enhancement strips” throughout the raft; the intersections of these strips created 600mm x 600mm openings at regular intervals, facilitating access and concrete placement.

Due to the thickness of the Tower raft, limiting the peak and differential temperatures due to the heat of hydration was an important consideration in determining the raft concrete mix design and placement methods. The 50 MPa raft mix incorporated 40% fly ash and a water cement ratio of 0.34. Large scale test cubes of the concrete mix, 3.7m on a side, were poured prior to the raft construction so as to verify the concrete placement procedures and monitor the concrete temperature performance.

The Tower raft is supported by 194 bored cast-in-place piles. The piles are 1.5 meter in diameter and approximately 43 meters long, with a capacity of 3,000 tonnes each (pile load tested to 6000 tonnes). The diameter and length of the piles represent the largest and longest piles conventionally available in the region. Additionally, the 6000 tonne pile load test represented the largest magnitude pile load test performed to date within the region (Figure 8). The C60 (cube strength) SCC concrete was placed by the tremie method utilizing polymer slurry. The friction piles are supported in the naturally cemented calcisiltite / conglomeritic calcisiltite formations, developing an ultimate pile skin friction of 250 to 350 kPa. When the rebar cage was placed in the piles special attention was paid 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.

FIGURE 7 – Tower Raft under Construction

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FIGURE 8 – Tower Pile Load Test
A unique situation for this scale of project arose from the existing site conditions: the ground water, which is quite high at approximately 2m below the surface, is extremely corrosive, containing approximately three times the sulfates and chlorides as sea water. As such, a rigorous program of anti-corrosion measures was followed to ensure the long-term integrity of the Tower’s foundation system. Measures instituted included implementation of specialized waterproofing systems, increased concrete cover to reinforcement, addition of corrosion inhibitors to the concrete mix, applying a stringent crack control raft design criteria, and the implementation of an impressed current cathodic protection system utilizing titanium mesh (Figure 9). Additionally, a controlled permeability formwork liner was utilized for the tower raft which results in a higher strength / lower permeable concrete cover to the rebar. The concrete mix for the piles was also enhanced, designed as a fully self consolidating concrete to limit the possibility of defects during construction.

**WIND ENGINEERING**

For a building of this height and slenderness, wind forces and the resulting motions in the upper levels become dominant factors in the structural design. An extensive program of wind tunnel tests and other studies were undertaken in RWDI’s 2.4m x 1.9m, and 4.9m x 2.4m boundary layer wind tunnels in Guelph, Ontario. The wind tunnel testing program included rigid-model force balance tests, a full aeroelastic model study, measurements of localized pressures, and pedestrian wind environment studies (Figure 10). These studies used models mostly at 1:500 scale; however, the pedestrian wind studies utilized a larger scale of 1:250 for the development of aerodynamic solutions aimed at reducing wind speeds. Since some Reynolds number dependency (scale effect) was seen in the aeroelastic model and force balance results, high Reynolds number tests were also undertaken on a much larger rigid model, at 1:50 scale, of the upper part of the tower in the 9m x 9m wind tunnel at the National Research Council facility in

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**FIGURE 9** – Cathodic Protection below Raft

**FIGURE 10** – Aeroelastic Wind Tunnel Model

**FIGURE 11** – Reynolds Number Testing
Ottawa (Figure 11). Wind speeds up to 55 m/s could be obtained in the 9 m x 9 m wind tunnel. Wind statistics played an important role in relating the predicted levels of response to return period. Extensive use was made of ground based wind data, balloon data and computer simulations employing Regional Atmospheric Modeling techniques in order to establish the wind regime at the upper levels.

To determine the wind loading on the main structure, wind tunnel tests were undertaken early in the design using the high-frequency-force-balance technique. The wind tunnel data were then combined with the dynamic properties of the tower in order to compute the tower’s dynamic response and the overall effective wind force distributions at full scale. For the Burj Dubai, the results of the force balance tests were used as early input for the structural design and allowed parametric studies to be undertaken on the effects of varying the tower’s stiffness and mass distribution.

The building has essentially six important wind directions (Figure 12). Three of the directions are when the wind blows directly into a wing - the wind is blowing into the “nose” or cutwater effect of each wing (Nose A, Nose B and Nose C). The other three directions are when the wind blows in between two wings, termed as the “tail” directions (Tail A, Tail B and Tail C). It was noticed that the force spectra for different wind directions showed less excitation in the important frequency range for winds impacting the pointed or nose end of a wing than from the opposite direction (tail). This was kept in mind when selecting the orientation of the tower relative to the most frequent strong wind directions for Dubai: northwest, south and east.

Several rounds of force balance tests were undertaken as the geometry of the Tower evolved, and as the Tower was refined architecturally. The three wings set back in a clockwise sequence with the A wing setting back first. After each round of wind tunnel testing, the data was analyzed and the building was reshaped to minimize wind effects and accommodate unrelated changes in the Client’s program. In general, the number and spacing of the setbacks changed as did the shape of wings. This process resulted in a substantial reduction in wind forces on the tower by “confusing” the wind, by encouraging disorganized vortex shedding over the height of the Tower (Figure 13).
Towards the end of design more accurate aeroelastic model tests were initiated. An aeroelastic model is flexible in the same manner as the real building, with properly scaled stiffness, mass and damping. The aeroelastic tests were able to model several of the higher translational modes of vibration. These higher modes dominated the structural response and design of the Tower except at the very base where the fundamental modes controlled. Based on these results, the predicted building motions are within the ISO standard recommended values without the need for auxiliary damping.

**Superstructure Concrete Technology**

High performance concrete is utilized for the Tower, with high modulus concrete specified for the columns and walls. The concrete mix was designed to provide low permeability / high durability concrete. One of the most challenging concrete design issues was ensuring the pumpability of this concrete to reach the world record heights of the Tower, which necessitated that concrete be pumped in a single stage well over 600m. Four separate basic mixes were developed to enable reduced pumping pressure as the building gets higher. The maximum allowable aggregate size decreased with building height, requiring no more than 10mm aggregate above level 127. A horizontal pumping trial was conducted prior to the start of the superstructure construction in order to ensure the pumpability of the concrete mixes (Figure 14). This trial consisted of a long length of pipe with several 180 degree bends to simulate the pressure loss in pumping to heights over 600m in a single stage. The final pumping system utilized on site employs Putzmeister pumps, including two of the largest in the world, capable of concrete pumping pressure up to a massive 350 bars through high pressure 150mm pipeline.

**Construction Methods**

The Burj Dubai Tower utilizes the latest advancements in construction techniques and material technology. The walls are formed using Doka’s SKE 100 automatic self-climbing formwork system. The circular nose columns are formed with circular steel forms, and the floor slabs are poured on MevaDec panel formwork. Wall reinforcement is prefabricated on the ground in 8m sections to allow for fast placement. Three primary tower cranes are located adjacent to the central core, with each continuing to various heights as required. High-speed, high-capacity construction hoists are utilized to transport workers and materials to the required heights. A specialized GPS monitoring system has been developed to monitor the verticality of the structure, due to the limitations of conventional surveying techniques.
The construction sequence for the structure has the central core and slabs being cast first, in three sections; the wing walls and slabs follow behind; and the wing nose columns and slabs follow behind these (Figure 15). Concrete is distributed to each wing utilizing concrete booms which are attached to the jump form system.

**CONCLUSION**

When completed, the Burj Dubai Tower will be the world’s tallest structure. It is an excellent example of a successful collaboration between the requirements of structural systems, wind engineering, and architectural aesthetics and function, which is essential for a supertall project. Additionally, the Tower represents a significant achievement in terms of utilizing the latest design, material, and construction technology and methods, in order to provide an efficient, rational structure, to rise to heights never before seen.

**PROJECT TEAM**

Owner: Emaar Properties PJSC, Dubai
Project Manager: Turner Construction International
Architect / Structural Engineers / MEP Engineers: Skidmore, Owings & Merrill LLP
Adopting Architect & Engineer / Field Supervision: Hyder Consulting Ltd.
General Contractor: Samsung / BeSix / Arabtec
Foundation Contractor: NASA Multiplex

**REFERENCES**


