
Engineering the World's Tallest – Burj Dubai

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William Baker

Bill Baker is the partner in charge of Structural and Civil Engineering for the Chicago and London offices of Skidmore, Owings & Merrill LLP (SOM). Since he joined the firm in 1981, his work has encompassed a wide range of engineering projects, from the structural systems of some of the world's tallest buildings--including the world's tallest, the Burj Dubai, currently under construction--to long span roofs, such as the 180-meter column-free KAL Hangar in Seoul, to small, specialized structures such as the new entry pavilion for the General Motors World Headquarters.

Bill contributed his extensive knowledge of high-rise structural systems as one of the lead investigators of the FEMA assessment of the collapse of the World Trade Center. He and his team of SOM structural engineers also assisted in the search, rescue, and recovery efforts at Ground Zero. He also assisted the National Institute of Standards and Technology in the detailed investigation of the WTC collapse.

In addition to his work at SOM, Bill is an adjunct professor at IIT and lectures frequently both domestically and abroad. He was elected a partner in 1997.

Lawrence Novak

Since joining Skidmore, Owings & Merrill LLP (SOM) in 1986, Lawrence Novak has collaborated on the design (from conceptual design through construction) of several high-rise, mid-rise and special use structures throughout the world. He has also undertaken numerous tenant work projects on completed buildings, providing him with a unique perspective on incorporating flexibility into the structural systems to accommodate the needs of current and future tenants and to ensure the long-term success of a project.

As an Associate Director with SOM, Mr. Novak has worked to develop the entire structural design for a project. His responsibilities include overseeing the complete structural engineering documents from conceptual design through construction, including solving complex engineering challenges and interacting with Architects, Engineers, Contractors and Clients. He was the Senior Project Engineer responsible for the structural design of the Burj Dubai Tower.

Mr. Novak is active on several structural committees, serves on the Board of Directors for engineering institutions and has co-authored several papers on structural engineering.

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Abstract

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. The superstructure is currently under construction and as of fall 2007 has reached over 150 stories. The final height of the building is a "well-guarded secret". The height of the multi-use skyscraper will "comfortably" exceed the current record holder, the 509 meter (1671 ft) tall Taipei 101. The 280,000 m² (3,000,000 ft²) reinforced concrete multi-use Burj Dubai tower is utilized for retail, a Giorgio Armani Hotel, residential and office.

As with all super-tall projects, difficult structural engineering problems needed to be addressed and resolved. This paper presents the structural system for the Burj Dubai Tower.

Keywords: Burj Dubai, Structure, World's Tallest, Tower, Skyscraper

Structural System Description

Designers purposely shaped the structural concrete Burj Dubai – "Y" shaped in plan – 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 (Figures 1, 2 and 3). Each wing, with its own high performance concrete corridor walls and perimeter columns, buttresses the others via a six-sided central core, or hexagonal hub. The result is a tower that is extremely stiff laterally and torsionally. SOM applied a rigorous geometry to the tower that aligned all the common central core, wall, and column elements.

Each tier of the building sets back in a spiral stepping pattern up the building. 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. This allows the construction to proceed without the normal difficulties associated with column transfers.

The setbacks are organized such that the Tower's width changes at each setback. The advantage of the stepping and shaping is to "confuse the wind". The wind vortices never get organized because at each new tier the wind encounters a different building shape.

The Tower and Podium structures are currently under construction (Figure 3) and the project is scheduled for topping out in 2008.

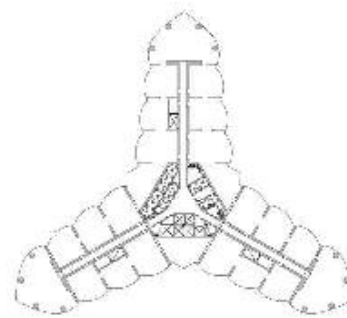


Figure 1 – Typical Floor Plan



Figure 2 – Rendering



Figure 3 – Construction Photo

Definition of Worlds' Tallest

From the outset, it has been intended that the Burj Dubai be the Worlds' 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 (measured from sidewalk at the main entrance). The categories and current record holders are as follows:

1. Highest Occupied Floor:
Taipei 101 439m
2. Top of Roof:
Taipei 101 449m
3. Top of Structure:
Taipei 101 509m
4. Top of Pinnacle, Mast, Antenna or Flagpole:
Sears Tower 527m

Although not considered to be a “building” the Tallest Freestanding Structure is:
CN Tower 553m

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

Architectural Design

The context of the Burj Dubai being located in the city of Dubai, UAE, drove the inspiration for the building form to incorporate cultural and historical particular to the region. The influences of the Middle Eastern domes and pointed arches in traditional buildings, spiral imagery in Middle Eastern architecture, resulted in the tri-axial

geometry of the Burj Dubai and the tower's spiral reduction with height (Figure 4).

The Y-shaped plan is ideal for residential and hotel usage, with the wings allowing maximum outward views and inward natural light.



Figure 4 – Construction Photo

Structural Analysis and Design

The center hexagonal reinforced concrete core walls provide the torsional resistance of the structure similar to a closed tube or axle. The center hexagonal walls are buttressed by the wing walls and hammer head walls which behave as the webs and flanges of a beam to resist the wind shears and moments. Outriggers at the mechanical floors allow the 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 wall concrete specified strengths ranged from C80 to C60 cube strength and utilized Portland cement and fly ash. Local aggregates were utilized for the concrete mix design. The C80 concrete for the lower portion of the structure had a specified Young's Elastic Modulus of $43,800 \text{ N/mm}^2$ (6,350ksi) at 90 days. The wall and column sizes were optimized using virtual work / LaGrange multiplier methodology which results in a very efficient structure (Baker et al., 2000).

The wall thicknesses and column sizes were fine-tuned to reduce the effects of creep and shrinkage on the individual elements which compose 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 matched the stress on the interior corridor walls. The five (5) sets of outriggers, distributed up the building, tie all the vertical load carrying elements together, further ensuring uniform gravity stresses; hence, reducing differential creep movements. Since the shrinkage in concrete occurs more quickly in thinner walls or columns, the perimeter column thickness of 600mm (24") matched the typical corridor wall thickness (similar volume to surface ratios) (Figure 5) to ensure the columns and walls will generally shorten at the same rate due to concrete shrinkage.

The top section of the Tower consists of a structural steel spire utilizing a diagonally braced lateral system. 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 exterior exposed steel is protected with a flame applied aluminum finish.

The structure was analyzed for gravity (including P-Delta analysis), wind, and seismic loadings by ETABS version 8.4 (Figure 6). The three-dimensional analysis model consisted of the reinforced concrete walls, link beams, slabs, raft, piles, and the spire structural steel system. The full 3D 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 (Figure 7). 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.



Figure 5 – Three Dimensional Analysis Model
(3D View of a Single Story)

The ACI 318-02 (American Concrete Institute) *Building Code Requirements for Structural Concrete* (ACI, 2002) was accepted by the Dubai Municipality (DM) as the basis of design for the reinforced concrete structure (Figure 8) for the Burj Dubai project.



Figure 6 - 3D View of Analysis Model

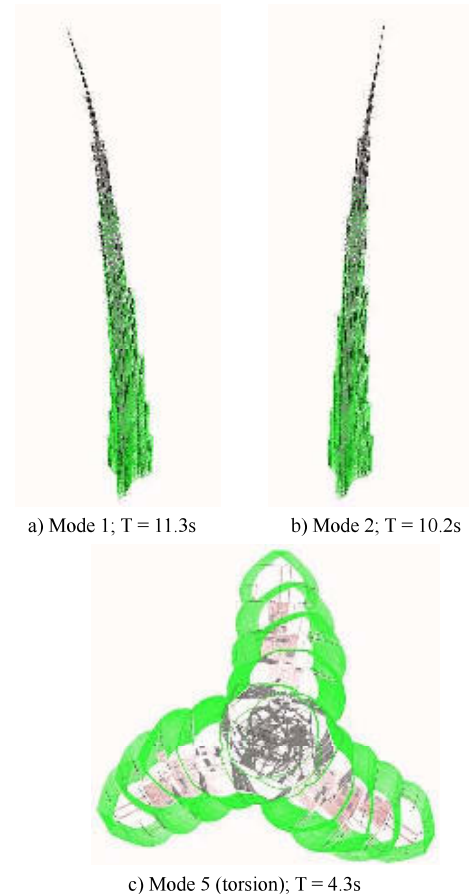


Figure 7 - Dynamic Mode Shapes

The Dubai Municipality (DM) specifies Dubai as a UBC97 Zone 2a seismic region with a seismic zone factor $Z = 0.15$ and soil profile S_c . 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. Seismic loading did

govern the design of the reinforced concrete Podium buildings and the Tower structural steel spire.



Figure 8 - Reinforced Concrete Structure

Dr. Max Irvine (with Structural Mechanics & Dynamics Consulting Engineers located in Sydney Australia) developed site specific seismic reports 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.

Foundations and Site Conditions

The Tower foundations consist of a pile supported raft. The solid reinforced concrete raft is 3.7 meters (12 ft) thick and was poured utilizing 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 at 300mm spacing 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 at which 600mm x 600mm openings at regular intervals facilitated access and concrete placement (Figure 9).



Figure 9 - Reinforced Concrete Raft Pour

In addition to the standard cube tests, the raft concrete was field tested prior to placement by flow table (Figure 10), L-box, V-Box and temperature.



Figure 10 – SCC Conc. Flow Table Testing

As the Tower raft is 3.7m (12 ft) thick, therefore, in addition to durability, limiting peak temperature was an important consideration. The 50 MPa raft mix incorporated 40% fly ash and a water cement ratio of 0.34. Giant placement test cubes of the raft concrete, 3.7m (12 ft) on a side, (Figure 11) were test poured to verify the placement procedures and monitor the concrete temperature rise utilizing thermal couples in the test cubes and later checked by petrographic analysis.



Figure 11 – Raft Conc. Placement Test Cubes

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 design capacity of 3,000 tonnes each. The Tower pile load test supported over 6,000 tonnes (Figure 12). 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 (2.6 to 3.6 tons / ft²). 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.

The site geotechnical investigation consisted of the following Phases:

Phase 1: 23 Boreholes (three with pressuremeter testing) with depths up to 90m.

Phase 2: 3 Boreholes drilled with cross-hole geophysics.
 Phase 3: 6 Boreholes (two with pressuremeter testing) with depths up to 60m.
 Phase 4: 1 Borehole with cross-hole and down-hole geophysics; depth = 140m



Figure 12 – Test Pile (6,000 tonnes)

A detailed 3D foundation settlement analysis was carried out (by Hyder Consulting Ltd., UK) based on the results of the geotechnical investigation and the pile load test results. It was determined the maximum long-term settlement over time would be about a maximum of 80mm (3.1"). This settlement would be a gradual curvature of the top of grade over the entire large site. When the construction was at Level 135, the average foundation settlement was 30mm (1.2"). The geotechnical studies were peer reviewed by both Mr. Clyde Baker of STS Consultants, Ltd. (Chicago, IL, USA) and by Dr. Harry Poulos of Coffey Geosciences (Sydney, Australia).

The groundwater in which the Burj Dubai substructure is constructed is particularly severe, with chloride concentrations of up to 4.5%, and sulfates of up to 0.6%. The chloride and sulfate concentrations found in the groundwater are even higher than the concentrations in sea water. Due to the aggressive conditions present due to the extremely corrosive ground water, a rigorous program of measures was required to ensure the durability of the foundations. Measures implemented include specialized waterproofing systems, increased concrete cover, the addition of corrosion inhibitors to the concrete mix, stringent crack control design criteria and an impressed current cathodic protection system utilizing titanium mesh (Figure 13). A controlled permeability formwork liner was utilized for the Tower raft which results in a higher strength / lower permeable concrete cover to the rebar. Furthermore, a specially designed concrete mix was formulated to resist attack from the ground water. The concrete mix for the piles was a 60 MPa mix based on a triple blend with 25% fly ash, 7% silica fume, and a water to cement ratio of 0.32. The concrete was also designed as a fully self consolidating concrete, incorporating a viscosity modifying admixture with a slump flow of 675 +/- 75mm to limit the possibility of defects during construction.



Figure 13 – Cathodic Protection below Mat

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 under the direction of Dr. Peter Irwin of Rowan Williams Davies and Irwin Inc.'s (RWDI) boundary layer wind tunnels in Guelph, Ontario (Figure 14). The wind tunnel program included rigid-model force balance tests, a full multi degree of freedom aeroelastic model studies, measurements of localized pressures, pedestrian wind environment studies and wind climatic studies. Wind tunnel models account for the cross wind effects of wind induced vortex shedding on the building (Figure 15). The aeroelastic and force balance studies used models mostly at 1:500 scale. The RWDI wind engineering was peer reviewed by Dr. Nick Isyumov of the University of Western Ontario Boundary Layer Wind Tunnel Laboratory.

In addition to the structural loading tests, the Burj Dubai tower was studied by RWDI for cladding, pedestrian level, and stack effect (Irwin et al., 2006).



Figure 14 – Aeroelastic Wind Tunnel Model
 (Image courtesy of RWDI)

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 detailed shape of the Tower and allowed parametric studies to be undertaken on the effects of varying the tower's stiffness and mass distribution.

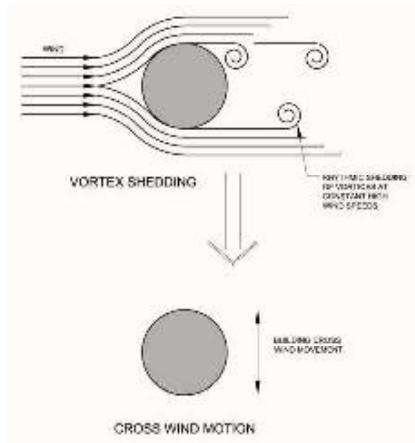


Figure 15 – Vortex Shedding Behavior

The building has essentially six important wind directions. The principal wind directions are when the wind is blowing into the “nose” / “cutwater” of each of the three wings (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 (Figure 15) 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 and the direction of the set backs.

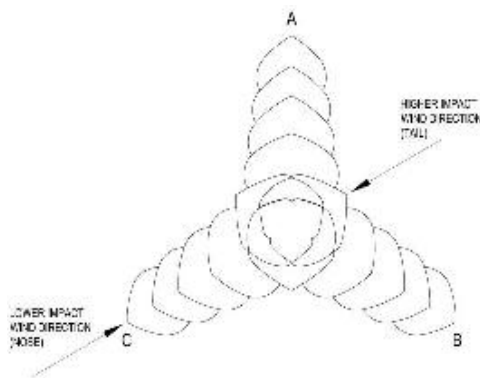


Figure 15 – Plan View of Tower

Several rounds of force balance tests were undertaken as the geometry of the tower evolved and was refined. 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 set backs changed as did the shape of wings. This process resulted in a substantial reduction in wind forces on the tower by “confusing” the wind (Figures 16 and 17) by encouraging disorganized vortex shedding over the height of the Tower.



Figure 16 – Tower Massing

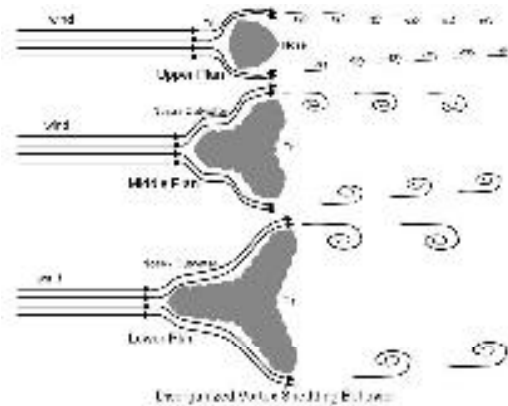


Figure 17 – Wind Behavior

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 the results of the aeroelastic models, the predicted building motions are within the ISO standard recommended values without the need for auxiliary damping.

Long-Term and Construction Sequence Analysis

Historically, engineers have typically determined the behavior of concrete structures using linear-elastic finite element analysis and/or summations of vertical column loads. As building height increases, the results of such conventional analysis may increasingly diverge from actual behavior. Long-term, time-dependant deformations in response to construction sequence, creep, and shrinkage can cause redistribution of forces and gravity induced sidesway that would not be detected by conventional methods. When the time-dependant effects of construction, creep, shrinkage, variation of concrete stiffness with time, sequential loading and foundation settlements are not considered, the predicted forces and deflections may be inaccurate. To account for these time-dependant concrete effects in the Burj Dubai Tower structure, a comprehensive construction sequence analysis incorporating the effects of creep and shrinkage was utilized to study the time-dependant behavior of the structure (Baker et al., 2007). The creep and shrinkage prediction approach is based on the Gardner-Lockman GL2000 model (Gardner, 2004) with additional equations to incorporate the effects of reinforcement and complex loading history.

Construction Sequence Analysis Procedures

The time-dependant effects of creep, shrinkage, the variation of concrete stiffness with time, sequential loading and foundation settlement were accounted for by analyzing 15 separate three-dimensional finite-element analysis models, each representing a discrete time during construction (Figure 18). At each point in time, for each model, only the incremental loads occurring in that particular time-step were applied. Additional time steps, after construction, were analyzed up to 50 years. The structural responses occurring at each time-step were stored and combined in a database to allow studying the predicted time-dependant response of the structure.

Long-term creep and shrinkage testing, over one year in duration, have been performed, by the CTL Group (located in Skokie, IL) under contract with Samsung, on concrete specimens to better understand the actual behavior of the concrete utilized for the project.



Figure 18 – Construction Sequence Models

Compensation Methodology

The tower is being constructed utilizing both a vertical and horizontal compensation program. For vertical compensation, each story is being constructed

incorporating a modest increase in the typical floor-to-floor height. This vertical compensation was selected to ensure the actual height of the structure, after the time-dependant shortening effects of creep and shrinkage, will be greater than the as-designed final height.

For horizontal compensation, the building is being “re-centered” with each successive center hex core jump. The re-centering compensation will correct for gravity induced sidesway effects (elastic, differential foundation settlement, creep and shrinkage) which occur up to the casting of each story.

Vertical Shortening

Based on the procedures presented above, the predicted time dependant vertical shortening of the center of the core can be determined at each floor of the Burj Dubai tower (Figure 19), not accounting for foundation settlements. The total predicted vertical shortening of the walls and columns at the top of the concrete core, subsequent to casting, is offset by the additional height added by the increased floor to floor height compensation program.

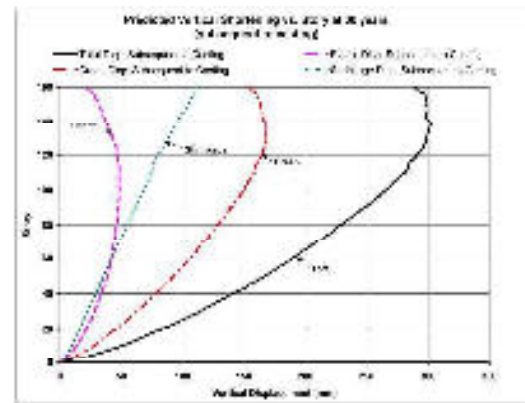


Figure 19 – Predicted Vertical Shortening vs. Story at 30 years (Subsequent to Casting)

Due to the compatibility requirements of strain between the rebar and the concrete in a reinforced concrete column, as the concrete creeps and shrinks, i.e. shortens, the rebar must attract additional compressive stress and forces to maintain the same strain as the concrete. Since the total load is the same, over time, part of the load in a reinforced concrete column is transferred from the concrete to the rebar. This un-loading of the concrete, therefore, also reduces the creep in the concrete (less load results in less creep). As per Figure 20, the rebar in the columns and walls (with a rebar to concrete area ratio of about 1%) at Level 135 support about 15% of the load at the completion of construction and the concrete supports 85%. However, after 30 years, the rebar supports 30% of the total load and the concrete supports 70%. This percent increase in force carried by the rebar increases as the steel ratio is increased and/or as the total load decreases.

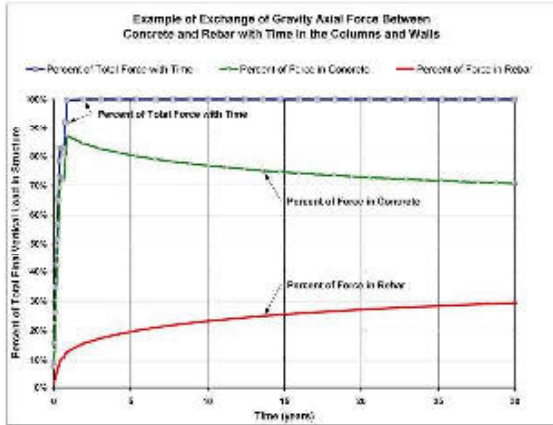


Figure 20 – Exchange of Gravity Axial Force between Concrete and Rebar vs. Time

Gravity Induced Horizontal Sidesway

Prediction of the gravity induced horizontal sidesway is more difficult than predicting the vertical shortening. Gravity induced horizontal sidesway is extremely sensitive to the following:

- Differential Foundation Settlements
- Construction Sequence
- Differential Gravity Loading
- Variations in the Concrete Material Properties

The gravity sidesway can be thought of as the difference between the vertical shortening at the extreme ends of the building causing curvature which is integrated along the height of the structure. Concrete creep and shrinkage properties are variable. Taking the difference between two variable numbers results in a value which has an even greater variability; hence, prediction of gravity induced horizontal sidesway is more of an estimate than the prediction of vertical shortening alone.

Based on the construction sequence, time step, elastic, creep, shrinkage, and foundation settlement analysis, predictions of the Burj Dubai tower gravity-induced horizontal sidesway have been made.

Reinforced Concrete Link Beam Analysis / Design

The reinforced concrete link beams transfer the gravity loads at the setbacks (Figure 21), including the effects of creep and shrinkage, and interconnect the shear walls for lateral loads.

The link beams were designed by the requirements of ACI 318-02, Appendix A, for strut and tie modeling. Strut and tie modeling permitted the typical link beams to remain relatively shallow while allowing a consistent design methodology (Novak & Sprenger, 2002). Dr. Dan Kuchma of the University of Illinois was retained to review the predicted behavior of the link beams utilizing the latest in non-linear concrete analysis. The link beams designed by strut and tie are predicted to have adequate strength and ductility (Kuchma et al., 2007) (Figure 22).

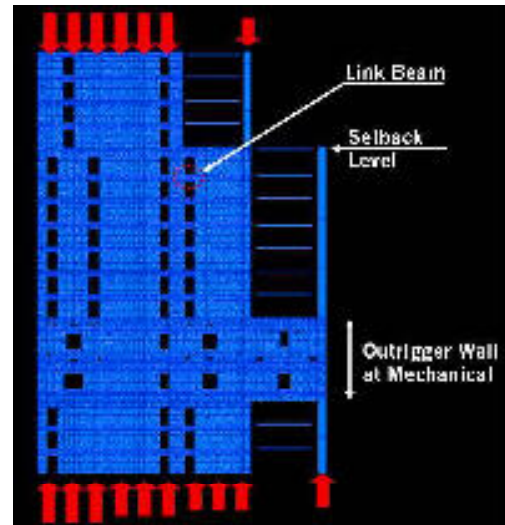


Figure 21 – Elevation of Shear Wall Setback

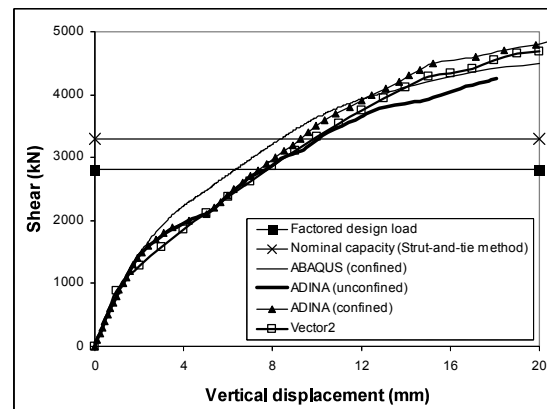


Figure 22 – Predicted Load-Deformation Response of a Strut & Tie Designed Reinforced Concrete Link Beam
(Image courtesy of Dr. Kuchma of the University of Illinois)

Superstructure Concrete Technology

The design of the concrete for the vertical elements is determined by the requirements for a compressive strength of 10 MPa at 10 hours to permit the construction cycle and a design strength / modulus of 80 MPa / 44 GPa, as well as ensuring adequate pumpability and workability. The concrete strength tests indicated the actual concrete utilized had much higher compressive strength than the specified strength requirements. The ambient conditions in Dubai vary from a cool winter to an extremely hot summer, with maximum temperatures occasionally exceeding 50° C. To accommodate the different rates of strength development and workability loss, the dosage and retardation level is adjusted for the different seasons.

Ensuring pumpability to reach the world record heights is probably the most difficult concrete design issue, particularly considering the high summer temperatures. Four separate basic mixes have been developed to enable reduced pumping pressure as the building gets higher. A horizontal pumping trial equivalent to the pressure loss in pumping to a height of

600m (1970 ft) was conducted in February 2005 to determine the pumpability of these mixes and establish the friction coefficients. The current concrete mix contains 13% fly ash and 10% silica fume with a maximum aggregate size of 20mm (3/4"). The mix is virtually self-consolidating with an average slump flow of approximately 600mm (24"), and will be used until the pumping pressure exceeds approximately 200 bar.

Above level 127, the structural requirement reduces to 60 MPa, and a mix containing 10mm maximum aggregate may be used. Extremely high levels of quality control will be required to ensure pumpability up to the highest concrete floor, particularly considering the ambient temperatures. The Putzmeister pumps utilized on site include two of the largest in the world, capable of concrete pumping pressure up to a massive 350 bars through high pressure 150mm pipeline.

Construction

The Burj Dubai utilizes the latest advancements in construction techniques and material technology. The walls are formed using Doka's SKE 100 automatic self-climbing formwork system (Figure 23). The circular nose columns are formed with steel forms, and the floor slabs are poured on MevaDec formwork. Wall reinforcement is prefabricated on the ground in 8m sections to allow for fast placement.

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 23). Concrete is distributed to each wing utilizing concrete booms which are attached to the jump form system.



Figure 23 – Self-Climbing Formwork System

Due to the limitations of conventional surveying techniques, a special GPS monitoring system has been developed to monitor the verticality of the structure. The construction survey work is being supervised by Mr. Doug Hayes, Chief Surveyor for the Burj Dubai Tower, with the Samsung BeSix Arabtech Joint Venture.

Conclusion

When completed, the Burj Dubai Tower will be the world's tallest structure. The architects and engineers worked hand in hand to develop the building form and the structural system, resulting in a tower which efficiently manages its response to the wind, while maintaining the integrity of the design concept.

It represents a significant achievement in terms of utilizing the latest design, materials, 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

Project Manager:

Turner Construction International

Architect/Structural Engineers/MEP Engineers:

Skidmore, Owings & Merrill LLP

Adopting Architect & Engineer/Field Supervision:

Hyder Consulting Ltd.

Independent Verification and Testing Agency:

GHD Global Pty. Ltd.

General Contractor:

Samsung / BeSix / Arabtec

Foundation Contractor:

NASA Multiplex

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