Subject: Structural Engineering – Construction

Paper Title: **Validating the Dynamics of the Burj Khalifa**

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Publication Date: 2011

Original Publication: CTBUH Journal 2011 Issue II

Paper Type:

1. Book chapter/Part chapter
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Validating the Dynamics of the Burj Khalifa

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Since joining Samsung in 2004, Mr. Abdelrazaq has been involved in the construction planning and structural design of several international projects, including Burj Khalifa in Dubai, the Samsung Seocho project in Seoul, and currently the Y22 Project, also in Seoul. Prior to joining Samsung, he was an Associate Partner and Senior Project Structural Engineer with Skidmore, Owings & Merrill in Chicago. Mr. Abdelrazaq currently serves as a lecturer at the Seoul National University, where he teaches a high-rise building design course for graduate students. He also served as an adjunct professor at the Illinois Institute of Technology's School of Architecture in Chicago.

Since 2008, Mr. Abdelrazaq has been involved with the CTBUH in various positions, such as the Advisory Group, the Awards Committee and the Editorial Board of the CTBUH Journal. He has also been a speaker at CTBUH conferences and congresses in New York City (2005), Dubai (2008) and Mumbai (2010).

…free-market

"Basically, it is a free-market experiment… We needed to test densities, scale, and the feeling of material… For us, a pedestrian city is the first measure of sustainability."

KPF's principal James von Klemperer commenting on New Songdo City, South Korea. From "New Songdo City," Architectural Record, October 2010.

"The survey and Survey Health Monitoring programs developed for Burj Khalifa have pioneered the use of these concepts as part of the fundamental design concept of building structures and will be benchmarked as a model for future monitoring programs for all critical and essential facilities."

Historically, tall building design and construction relied solely on minimum building code requirements, fundamental mechanics, scaled models, research and experience. While many research and monitoring programs have been implemented before, these programs are yet to be systematically validated and/or holistically integrated. Involvement in the planning, design and construction of Burj Khalifa, from its inception to completion, prompted the author to conceptually develop an extensive survey and real-time structural health monitoring (SHM) program in order to validate the fundamental assumptions made for the design and construction planning of the tower. This strategy included the monitoring of reinforced concrete bored piles and load dissipation, foundation settlement, core walls and columns vertical shortening, the lateral displacements of the tower and vertical element strain and stresses. Additionally, temporary and permanent real time monitoring programs were installed. These programs have already resulted in extensive feedback and insights into the actual in-situ material properties, the tower's structural behavior and its responses under wind and seismic excitations.

Structural Overview

The Burj Khalifa Project is the tallest structure ever built by man (see Figure 1). The massing of the 828-meter (2,717-foot) tall Burj Khalifa is organized around a central core with three wings, each consisting of four bays (see Figure 2). At every seventh floor, one outer bay retracts a little as the structure spirals into the sky. This tapered massing introduces natural wind spoilers to manage wind engineering aspects by reducing dynamic wind excitation. Integrating these principals into the architectural design of the tower resulted in a stable dynamic response which tames the powerful wind forces.

To maximize the overall structural depth of the tower, the lateral load resisting system consists of high performance reinforced concrete core walls, which are linked to the exterior columns though a series of shear wall panels at the mechanical levels. The core walls vary in thickness from 500 to1,300 millimeters (19.69 to 51.18 inches). The core walls are

Figure 1. Burj Khalifa completed © SOM|Nick Merrick/ Hedrich Blessing

typically linked through a series of 800 to1,100-millimeter (31.50 to 43.31-inch) deep reinforced concrete or composite link beams at every level. Due to the limitation on the link beam depths, 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.

Gravity Load Management and Structural System Optimization

While wind behavior of supertall buildings is one of the most important design criteria to be considered, gravity load management is also critical as it has direct impact on the overall efficiency and performance of the tower. The means and methods of mobilizing and redistributing gravity load could have its own inefficiencies and demands. If not addressed early and managed properly, it could result in design and construction complexities.

Gravity load analysis compares the concrete area required to support the tower gravity loads, without considerations to minimum member sizes, to the actual concrete area provided for the tower final design (see Figure 3). It shows that the total material needed to support the gravity load and the material required to resist the combined effect of gravity and lateral loads is one and the same. The only additional material needed for Burj Khalifa was caused by the rounding of member sizes and the additional materials required to redistribute the loads to the building extremities at the hammer head walls (no penalty) and the nose columns (major penalty) through the link beams at every floor and at the outrigger levels. The hammer walls and the nose columns, located at the extremities of the building, add significant contributions to the moment of inertia of the tower and its overall resistance to the overturning moment due to lateral loads. The limitations on the wall thicknesses (500–600 millimeters/19.69–23.62 inches) of the center core and the wing wall's thickness (600 millimeters/23.62 inches) allowed the gravity load to flow freely into the center corridor spine web walls (650 millimeters/25.59 inches) to the hammer head walls and nose columns for maximum resistance to lateral loads. These continuous load flows illustrate the art of the concrete material. Along these load flow lines the strain gages are installed to track the gravity load flow.

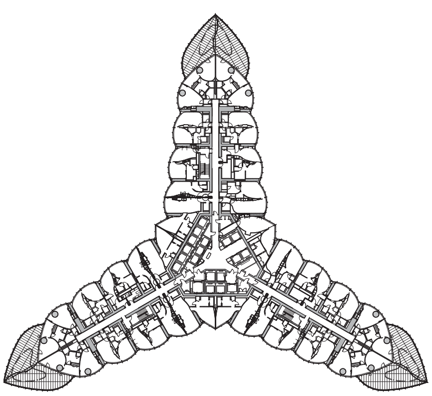

Figure 2. Typical hotel floor plan © SOM

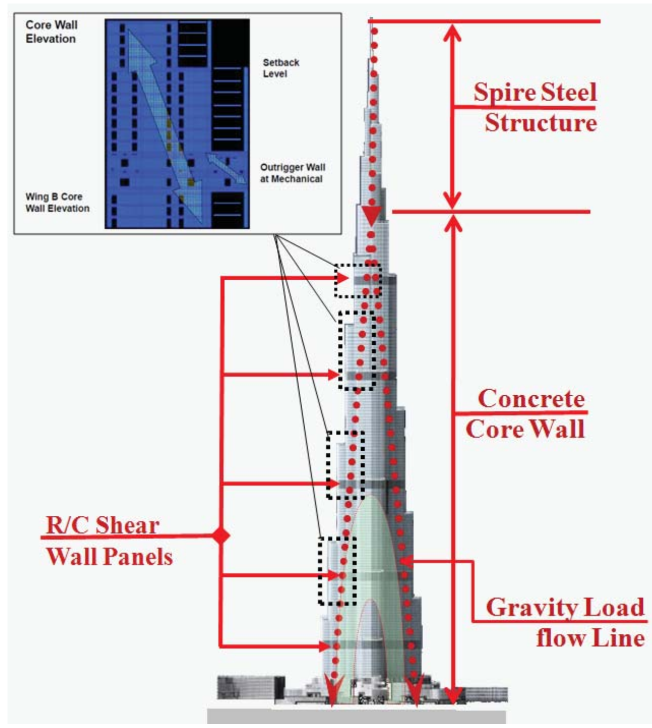

Figure 3. Lateral Load Resisting System © Samsung C&T

Wind Engineering Management

Several wind engineering techniques were employed into the design of the tower to control its dynamic response due to wind effects. These include disorganizing the vortex shedding formation along the building height (spoiler concept used in chimneys) and tuning the dynamic characteristics of the building to improve its behavior to prevent lock-in vibration.

Floor Framing System

The residential and hotel floor framing system consists of two-way reinforced concrete flat plate or flat slab systems, 200 to 300 millimeters (7.87 to 11.81 inches) thick, with additional 50 millimeters (19.7 inches) hunches at the end, which spans approximately 9 meters (29.5 feet) between the exterior columns and the interior core wall. The floor framing system near the top of the tower consists of a 225 to 250-millimeter (8.89 to 9.84-inch) two-way reinforced concrete flat slab system with 150-millimeter (5.91-inch) drop panels. The floor framing system within the interior core consists of a two way reinforced concrete slab with beams. Figure 4 shows a typical floor framing system at the typical residential and mechanical levels. Note that at the mechanical level, all the vertical elements are tied to equalize the load and stress distribution between vertical supports (walls and columns).

Foundation System

The tower is founded on a 3,700-millimeter (145.67-inch) thick pile supported raft. The reinforced concrete raft foundation utilizes high performance self compacting concrete (SCC), which is placed over a 100-millimeter (3.94-inch) minimum blinding slab, a waterproofing membrane and a 50-millimeter (1.97-inch) minimum blinding slab. The raft is supported on 192 to 1,500 millimeters (7.56 to 59.06 inches) diameter high-performance reinforced concrete, 3,000 metric ton

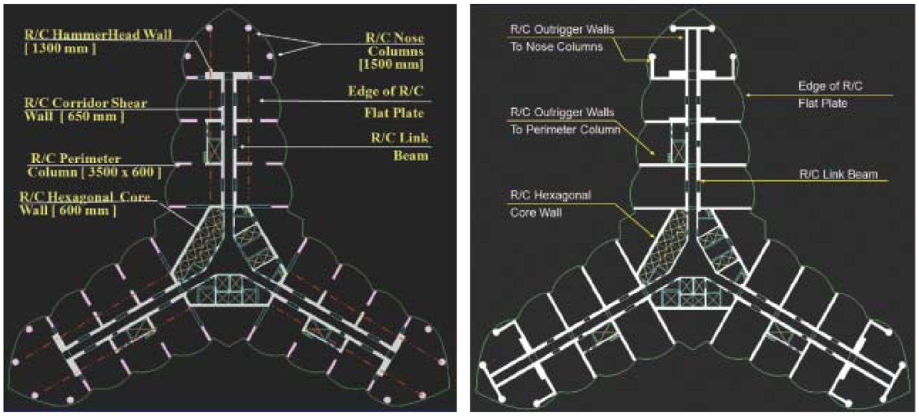

Figure 4. Typical floor framing slabs for a typical hotel level (left) and mechanical level (right) © Samsung C&T

capacity bored piles that extend 45 meters (147.6 feet) below the base of the raft. To provide high performance, high durability concrete for the tower foundation systems, a complete waterproofing membrane and cathodic protection systems were also provided to protect against the corrosive soil conditions at the tower's site (see Figure 5).

Structural Health Monitoring

While developing the structural system requirements and integrating them into the architectural design concept was a novel task, the construction planning of the tower was very challenging in every aspect. The implementation of the latest technological advances in construction methods and techniques were required to build the tower with a high degree of accuracy, similar or better than that used in steel construction. This required the use of a state-of-the art survey and Structural Health Monitoring Program, which comprised of four major components:

1. An extensive Survey Monitoring Program to measure the foundation settlement, column shortening and lateral building movement during construction.
2. Installation of strain gages to measure the total strains at the main structural members including, piles, raft foundation, walls, columns and outrigger shear wall panels.
3. Installation of a temporary real-time health monitoring program during construction to measure the building's lateral displacement and acceleration, and to identify the building's dynamic characteristics (frequencies, damping, etc).
4. Installation of a permanent real-time Structural Health Monitoring (SHM) Program to measure the post-construction building motions, such as acceleration, displacement due to lateral loads (particularly wind and seismic) and any other unexpected lateral loads.

Survey Monitoring Programs

Several detailed survey programs, which utilize the latest geodetic electro-optical equipment, were developed for the construction of the tower. The instruments used, called "total stations," refer to fixed reference points with known coordinates, which are critical to the precision of the entire surveying procedure. However, the constantly increasing height of Burj Khalifa during construction caused the distance between the fixed points and the total station at the uppermost construction level to became excessive. Exact referencing of the total station compared to the relative distances between the fixed points became too small.

The precision of the survey system is further complicated by the slenderness and movement of the tower during construction. The movement of the tower during construction is the result of:

1. Dynamic wind excitations
2. Large and concentrated crane loads at the upper most constructed level
3. Foundation settlement
4. Column shortening due to elastic, creep and shrinkage effects
5. Daily temperature fluctuation, which could result in more than a 150-millimeter (5.91-inch) change in building height at the top of the concrete during a six-hour period
6. Uneven solar effects which could result in building tilt
7. Lateral drift of the building under gravity loads due the asymmetrical load distribution relative to the tower center of rigidity
8. Building construction sequencing
9. Mix of concrete (from foundation to Level 156) and steel construction (from Level 156 to the top of the pinnacle)

Rationalizing these movements created a number of challenges to consider in locating the building at the correct theoretical design position. Therefore, the need for an extensive survey monitoring program was essential to provide the exact building position, at any particular instant in time, relative to its design position and to confirm the precise position of the total station.

To overcome the difficulties described above, and to have complete control and synthesis of the building's position relative to its vertical axis at any instant of time, the development of an extensive monitoring program of all building elements that affect movement was required. Additionally, a new measurement system was developed which uses the latest development in GPS technology (the Leica Geosystem) in combination with precision inclination sensors. The latter is also referred to as a clinometer, which is an instrument for measuring angles of slope or tilt and elevation or depression of an object with respect to gravity. It can therefore provide a reliable


Figure 5. Raft construction © Samsung C&T

position of the building at the highest construction level almost instantaneously, even when the building is moving.

The complexity and size of the Auto Climbing Formwork System (ACS) requires a very large number of control points at each level. As a result, it was necessary to simplify both the survey procedure and the system so that the control points, even when the building is moving, needed to be measured only once. The measurement system was developed to be used at every level and consisted of the following components:

1. Three GPS antenna/receivers fixed on tall poles at the top level of the ACS formwork to establish the survey control at the uppermost level.
2. Three tiltable circular prisms placed under each of the GPS antennas.
3. Total Station instruments (TPS) that were set on top of the concrete and visible to all GPS stations (see Figure 6).

The measurement system at every floor is integrated with the installation of eight Clinometers (Leica Nivel210 Precision) at approximately every 20 floors from the foundation level. These are used to track the tower's lateral movements, due to the loads and movement described above, and to make the necessary correction to bring the ACS formwork system to its geometric center at every level. This correction program was necessary to maintain the verticality of the building and to keep the building within the required tolerance of 15 millimeters (0.59 inches) at every level.

The clinometers were also used to instantaneously determine the rotation of the tower and to compute the displacement and alignment of the tower in the x and y directions relative to the raft foundation. The clinometers are mounted on the center core wall in areas with no disturbances. to the LAN port dedicated PC with the Leica GeoMos software located at the survey office. See Figure 7 for schematic of the integrated "measurement system" with the clinometers. The clinometers are calibrated relative to the survey control at that level by verticality observations from the raft. A series of observations provided the mean x and y displacements for that tilt meter at that time, which was used for all subsequent readings. The data and observations collected from the clinometers, GPS with the prisms and the total station were analyzed and synthesized to accurately position the top level of the ACS formwork system.

To compare the actual measured building movements (*x, y, z*) to the predicted displacements, a three-dimensional finite element structural analysis model was developed that took the actual material properties (such as concrete strength, modulus of elasticity, coefficient of thermal expansion, etc) and the foundation flexibility (subgrade modulus) into account. This analysis model was also used to simulate the actual construction sequence of the tower with due considerations to actual works being performed by all trades as a function of time. The intent of this analysis model was to predict:

1. The foundation settlement
2. The tower's lateral displacements (*x* and *y*) from foundation to top of the pinnacle
3. The column/wall shortening due to elastic/creep/shrinkage effects
4. The wall and column elastic/shrinkage/creep strains as a function of time
5. The dynamic building characteristics
6. The strength design check of the critical elements, especially at the outriggers and link beams
7. The lateral displacement (*x, y, z*) due to any seismic or wind events during construction and after the completion of the tower

Foundation Settlement Survey

As described above, a soil structure interaction Three Dimensional Finite Element Analysis Model (3D-FEAM) was developed by the author to simulate the construction sequence of the tower. The model provided a detailed analysis of the raft foundation system, including the foundation system flexibility. The foundation settlement was initially

Figure 6. The measurement system, consisting of a reference base station (left) and total station (right), used to triangulate current positions © Samsung C&T

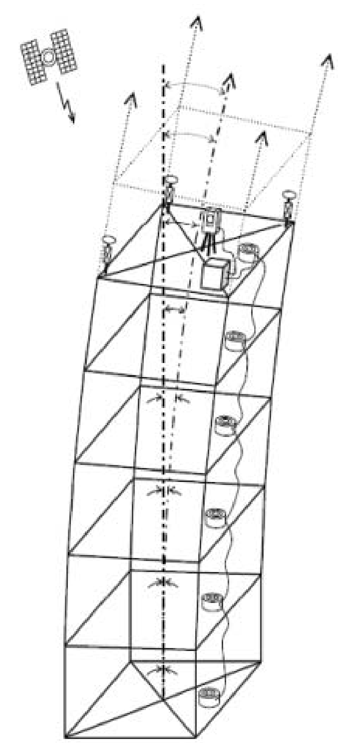

Figure 7. Schematic impression of the measurement of the lateral movement © Samsung C&T

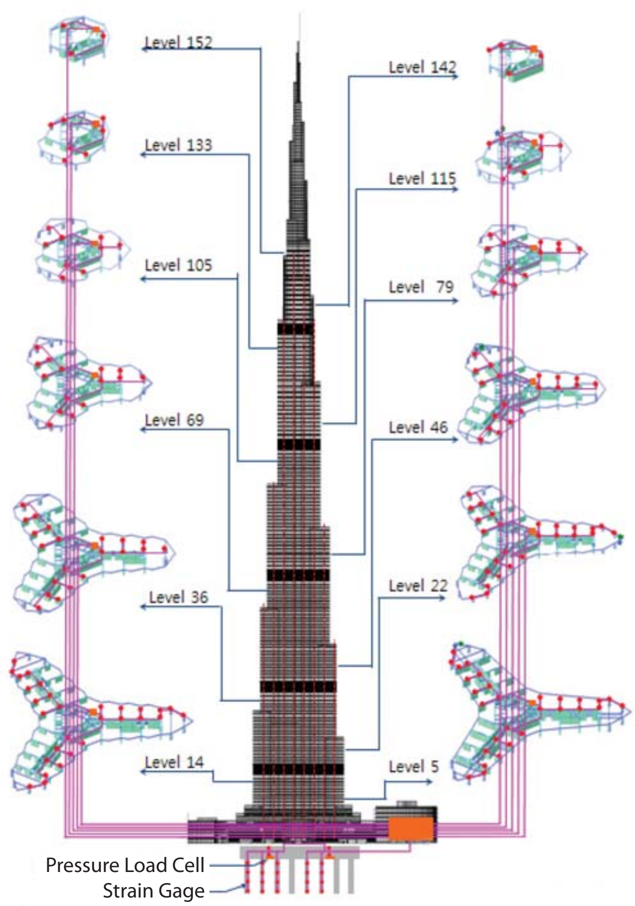

Figure 8. Strain Gage Monitoring System © Samsung C&T

estimated based on the sub grade reaction modulus provided by the geotechnical engineering consultants. However, the foundation stiffness was adjusted based on the actual in-situ measured settlements. The 3D-FEAM and soil structure interaction analysis model also took the pile axial shortening, soil flexibility and the stiffening effect of the superstructure into account. From constriction to the completion of the structure, 16 survey points at the top of the raft foundation were installed to measure the tower foundation settlement monthly. Despite the complexities involved in setting the structural analysis and the assumed geotechnical engineering parameters, a comparison between the predicted settlements from the calibrated three-dimensional and construction sequence analysis model on the one hand, and the measured settlement values on the other, showed excellent results.

Column and Wall Shortening Survey

Since Burj Khalifa is a very tall structure, column differential shortening was one of the most critical issues considered at the early design and construction stages. The development of the tower's structural system addressed this issue fundamentally by equalizing the stress level and geometry (V/S ratio) of the vertical elements. While most of the wall elements are tied together at every floor, other perimeter walls and nose columns are tied together through four story shear wall panels at the mechanical levels to engage all vertical members in the lateral system and to allow for better gravity load and stress distribution between them. For a better estimation of the wall and column short term and long term shortening, extensive concrete creep and shrinkage testing programs were developed at the start of construction to monitor the concrete elastic/shrinkage/creep characteristics. The concrete test data was used in the 3D-FEAM construction sequence analysis of the tower to predict the actual column/wall strains and shortening during construction and throughout its lifetime. Correlation between predicted and actual column/wall total strains and shortening were excellent.

An extensive survey monitoring program concept was also developed to track the total column shortening at every setback level, and was reported by the survey team every month. These survey measurements were analyzed and compared against predicted measurements and used as a tool to track the overall structural behavioral characteristics. They also allowed for better management of the actual construction sequencing of the tower. Evaluation of the measured column/wall shortening at all locations indicates that the column differential shortening is within the predicted range.

Survey of the Tower's Lateral Movement During Construction

Because the tower changes in shape as it rises, there is a shift in the center of gravity load relative to the center of stiffness. As a result, the tower was expected to move laterally during construction. In order to keep track of the tower's movements and to make necessary corrections, the tower's lateral movement was monitored daily. A detailed optical survey program was also performed monthly, at every setback level, to measure its lateral movement subsequent to the time of installation.

The predicted movement was based on the three-dimensional finite element construction sequence analysis models developed by the author, which took the foundation stiffness, actual material properties (strength/elastic modulus/creep/shrinkage), and detailed construction program for all construction activities as a function of time, into account. This analysis was performed on a regular basis to compare the actual measured lateral movements to the predicted lateral movement during the tower's construction, immediately after completion, and 30 years after completion. To compensate for this lateral movement, the tower was constructed at its geometric center at every level.

Strain Gage Measurement during Construction and Life of the Building

In order to manage the column shortening and lateral movement issues of the tower, an extensive strain measurement program was also developed to measure the total strain in the walls and columns due to elastic, shrinkage and creep strains. This total strain monitoring program was typically located in areas that are not affected by local strain conditions, but it was also located two floors below and above the outrigger levels, where large load re-distribution is expected. Figure 8 shows:

1. The location of the strain gages throughout the tower to measure column and wall strains
2. The location of the strain gages at the piles to measure the strain distribution along the pile length
3. The location of the strain gages in the raft to measure the bending strain at the bottom of the raft
4. The location of the load cells at the raft foundation to measure the direct load transfer from the raft to the upper stiff sandstone layer by bearing
5. Temporary weather stations were installed at several setback levels to measure the temperature, humidity, and wind velocity and direction

A total of 197 Electrical Resistance Type Strain Gages (CEA weldable series W250A by Micro Measurements, UK) were attached to the rebar and a total of 197 Electronic Extensometer-vibrating Wire Strain Gages (VSM 4200 by Geokon), were embedded in the concrete. The tower's raft foundation received a total of 24 Geokon Embedment Vibrating Wire Strain Gages (Type 4200), three gage rosettes, and two gage rosettes at the load cells.

The in-situ strain measurements were compared with the tower's predicted strains through detailed 3D-FEAM and construction sequence analysis models. This was done from the time of strain gage installation until the completion of the tower. Correlation between predicted strains and measured strains was acceptable. However, difficulties were encountered in providing continuous measurements at some locations because of site constraints during construction. The strain measurements directly recorded the temperature rise in the large concrete elements and the time it took to bring the temperature of these elements to the ambient temperature.

Selection of Temporary Real Time Monitoring Program and Network

A temporary real time monitoring program was developed and installed at the tower in cooperation with the University of Notre Dame. This was installed to monitor the building's acceleration levels during construction, to assist with the tower's system identification (a complete GPS system consisting of the rover at Level 138 and a fixed station at the office annex), and to measure the building's real time displacement with time. The program also included a weather station to measure the temperature, humidity, and wind speed and direction at Level 138.

While the building's movement from wind load remained relatively small throughout the construction period, the tower was subjected to the influence of a remote earthquake on September 10, 2008. The earthquake occurred in Bandar Abbas, Iran, which is approximately 850 miles south of Tehran. The event was observed and felt across the Gulf States and many buildings were evacuated. The peak accelerations observed at Level 138 were 2.76milli-g and 3.82milli-g in the x and y directions, respectively. Since the tower did not have Accelerometers at the base, real time history analysis was not performed. This event recorded the highest acceleration since the monitoring system was installed.

In addition to the recorded building acceleration and displacements, complete system identification was performed for the tower, which included the estimation of the tower's natural frequencies and damping. A comparison between the predicted natural frequencies from the 3D-FEAM (calibrated FEAM developed by the author) and the measured frequencies were within 2–3%, including the higher modes.

Permanent Full Scale Real Time Structural Health Monitoring Program and Network

The final chapter of monitoring the structural system at Burj Khalifa was concluded by the development and installation of a comprehensive full scale Structural Health Monitoring (SHM) program. This consists of:

1. Three pairs of accelerometers at the foundation level to capture base accelerations
2. Six pairs of accelerometers at Level 73, 123, 155 (top of concrete), 160M3, Tier 23A, and on top of the pinnacle to measure the tower acceleration simultaneously at all levels
3. A GPS system to measure displacement at Level 160M3
4. Twenty three Sonimometers at all terrace and setback levels, including the top of the pinnacle, to measure wind speed and direction.
5. A weather station at Level 160M3 to measure, wind speed and direction, relative humidity, and temperature.

Since the installment of the SHM program, most of the structural system characteristics have been identified and include measuring the following:

1. Building acceleration at all levels
2. Building displacements at Level160M3
3. Wind profile along the building height at most balcony areas, including wind speed and direction, which still needs calibration to relate to the basic wind speed
4. Building dynamic frequencies, including higher modes
5. Expected building damping at low amplitude due to both wind and seismic events
6. Time history records at the base of the tower

Comparisons between the predicted building behavior and the in-situ measured responses have provided excellent results.

Conclusion

The survey and SHM programs developed for Burj Khalifa have pioneered the use of these concepts as part of the fundamental design concept of building structures and will be benchmarked as a model for future monitoring programs for all critical and essential facilities. Advancements in computer and IT technologies, innovative advancement in fiber optic sensors, nanotechnologies, dynamic monitoring devices, new GPS system technologies and wireless monitoring techniques will be used as a base for future survey and SHM programs. These elements will become integral parts of future building designs and Intelligent Building Management Systems. ■