Title:	**Validating the Structural Behavior and Response of Burj Khalifa**
Author:	Ahmad Abdelrazaq, Samsung C&T Corporation
Subjects:	Building Case Study Construction
Keywords:	Construction Foundation Seismic Structural Health Monitoring Wind
Publication Date:	2012
Original Publication:	International Journal of High-Rise Buildings Volume 1 Number 1
Paper Type:	1. Book chapter/Part chapter 2. **Journal paper** 3. Conference proceeding 4. Unpublished conference paper 5. Magazine article 6. Unpublished

International Journal of High-Rise Buildings
March 2012, Vol 1, No 1, 37-51

International Journal of
High-Rise Buildings
www.ctbuh.org

Validating the Structural Behavior and Response of Burj Khalifa: Synopsis of the Full Scale Structural Health Monitoring Programs

Ahmad Abdelrazaq†

Headg, Highrise & Complex Building, Samsung C&T, Seoul, Korea

Abstract

New generation of tall and complex buildings systems are now introduced that are reflective of the latest development in materials, design, sustainability, construction, and IT technologies. While the complexity in design is being overcome by the availability and advances in structural analysis tools and readily advanced software, the design of these buildings are still reliant on minimum code requirements that yet to be validated in full scale. The involvement of the author in the design and construction planning of Burj Khalifa since its inception until its completion prompted the author to conceptually develop an extensive survey and real-time structural health monitoring program to validate all the fundamental assumptions mad for the design and construction planning of the tower.

The Burj Khalifa Project is the tallest structure ever built by man; the tower is 828 meters tall and comprises of 162 floors above grade and 3 basement levels. Early integration of aerodynamic shaping and wind engineering played a major role in the architectural massing and design of this multi-use tower, where mitigating and taming the dynamic wind effects was one of the most important design criteria established at the onset of the project design. Understanding the structural and foundation system behaviors of the tower are the key fundamental drivers for the development and execution of a state-of-the-art survey and structural health monitoring (SHM) programs. Therefore, the focus of this paper is to discuss the execution of the survey and real-time structural health monitoring programs to confirm the structural behavioral response of the tower during construction stage and during its service life; the monitoring programs included 1) monitoring the tower's foundation system, 2) monitoring the foundation settlement, 3) measuring the strains of the tower vertical elements, 4) measuring the wall and column vertical shortening due to elastic, shrinkage and creep effects, 5) measuring the lateral displacement of the tower under its own gravity loads (including asymmetrical effects) resulting from immediate elastic and long term creep effects, 6) measuring the building lateral movements and dynamic characteristic in real time during construction, 7) measuring the building displacements, accelerations, dynamic characteristics, and structural behavior in real time under building permanent conditions, 8) and monitoring the Pinnacle dynamic behavior and fatigue characteristics. This extensive SHM program has resulted in extensive insight into the structural response of the tower, allowed control the construction process, allowed for the evaluation of the structural response in effective and immediate manner and it allowed for immediate correlation between the measured and the predicted behavior.

The survey and SHM programs developed for Burj Khalifa will with no doubt pioneer the use of new survey techniques and the execution of new SHM program concepts as part of the fundamental design of building structures. Moreover, this survey and SHM programs will be benchmarked as a model for the development of future generation of SHM programs for all critical and essential facilities, however, but with much improved devices and technologies, which are now being considered by the author for another tall and complex building development, that is presently under construction.

Keywords: Realtime-structural health monitoring program, Construction sequence analysis, Survey monitoring programs, cloumn shortening, Gravity load management, wind seismic engineering management, Foundation settlement

1. Introduction

The Burj Khalifa Project is the tallest structure ever built by man, Figure 1, that rises 828 meters into Dubai skyline tall and it consists of 162 floors above grade and 3 basement levels. While integrating wind engineering principles and aerodynamic shaping into the architectural design concept was an important consideration in mitigating and taming the dynamic wind effects, managing the gravity load flow to the building extremities was equally significant in overcoming the overturning moment due to extreme lateral loads. Most of the tower overturning resistance is managed mostly by the tower's own gravity loads. In addition, all the vertical members are proportioned to resist gravity loads on equal stress basis to overcome the differential column shortening issues that are generally difficult to manage in supertall buildings.

The structure of Burj Khalifa was designed to behave like a giant column with cross sectional shape that is a

---

†Corresponding author : Ahmad Abdelrazaq
Tel: +82-2-2145-5190, Fax: +82-2-2145-6631
E-mail: Abdelrazaq1@samsung.com

Figure 1. Photo of the Completed Burj Khalifa.

reflection of the building massing and profile. The story of structural system selection and the structural system optimization is a novel one and cannot be covered here in details, however, this paper will provide 1) a brief on the key issues that led to the structural system selection and the key issues considered in integrating structural design concepts and construction planning into the architectural design concept, 2) a detailed understanding of the overall structural and foundation system behaviors of the tower that are considered critical to the development of the survey and structural health monitoring (SHM) programs for the tower; 3) and a detailed description of the comprehensive real-time SHM and survey programs developed for Burj Khalifa.

The development of the survey and SHM program for Burj Khalifa, at the time of the system installation, is probably one of the most comprehensive survey and real-time SHM programs in the history of supertall buildings that will track the structural behaviors and responses of the tower during construction and during its lifetime and it included:

- Monitoring the reinforced concrete bored piles and their load dissipation into the soil.
- Survey and monitoring of the tower foundation settlement, corewalls and column vertical shortening, and the lateral displacements of the tower resulting from its asymmetrical geometric shape and structural system asymmetry.
- Monitoring of the tower vertical element strains and stresses due to gravity load effects.
- Installation of a Temporary Real Time Monitoring Program to monitor the building displacement and dynamic response under lateral loads (wind and seismic) during construction.
- Installation of Permanent Real Time Monitoring Program to monitor the building displacement and dynamic response under lateral loads (wind and seismic in particular). The intent of this monitoring program is to confirm the actual dynamic characteristics and response of the building, including its natural mode of vibration, estimate of damping, measuring the building displacement and acceleration, immediate diagnose of the change in building structural behavior, identify potential of fatigue at structural elements that are considered fatigue sensitive and that could be subjected to severe and sustained wind induced vibration at different wind speeds and profiles, and most importantly in providing real-time feedback on the performance of the building structure and immediate assistance in their day-to-day operations, etc.
- Providing sufficient data to predict the fatigue behavior of the pinnacle under low/moderate/severe wind and seismic excitations.
- Tracking the wind speed profile along the building height in an urban, but semi open field setting considering the scale of the project relative to its surroundings.
- Correlating the building measured responses with the predicted behavior of the tower.

These extensive survey and SHM programs have, since their inception, resulted already in an extensive feedback and insight into the actual *in-situ* material properties, the towers structural behavior and response under wind and seismic excitations, and continuous change in the building characteristics during construction. In addition and most importantly, the SHM program will provide the building owner ongoing and continuous feedback on the performance of the structure and other buildings systems in real-time to better assist them in their day-to-day operations and facility management. Comparison between the measured responses and the predicted behavior of the tower will also be discussed.

2. Structural System Brief Description

2.1. General

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

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

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

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

2.2. Strategy for structural system selection

From onset of the design process, the structural design of the tower was formulated based on the objectives of integrating the structural and architectural design concept and included the following structural strategy:

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

While several structural options were considered (including composite system), high performance concrete of its mass, stiffness, high strength, moldability, continuity, pumping ability, and speed of construction, local availability of high performance concrete and advanced formwork systems, and most importantly the residential use of the building, was selected as the primary structural material for the tower.

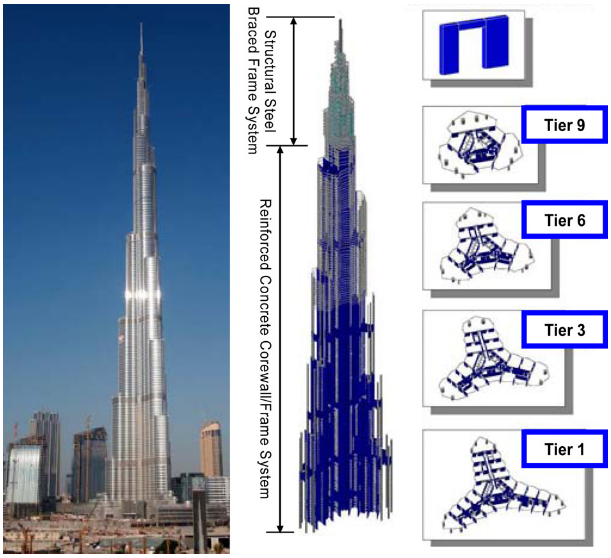

Figure 2. Lateral load resisting system and photo of the completed tower.

2.2.1. Lateral load resisting system

The towers lateral load resisting system consists of high performance, reinforced concrete ductile core walls linked to the exterior reinforced concrete columns through a series of reinforced concrete shear wall panels at the mechanical levels. See Figure 2.

The core walls vary in thickness from 1300 mm to 500 mm. The core walls are typically linked through a series of 800 mm to 1100 mm 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.

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

2.2.2. Gravity load management & structural system optimization

While the 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 and it should be addressed at the early design stage, during the development and integration of the architectural and structural design concept. The means and methods of mobilizing and redistributing gravity load could have its own inefficiencies and demands; if it is not managed properly it could result in its own design and construction complexities. The balance between the gravity load management and the smooth gravity load flow in concrete structure is a structural engineering art that requires in depth understanding of materials and the structural system behavior at the early design concept.

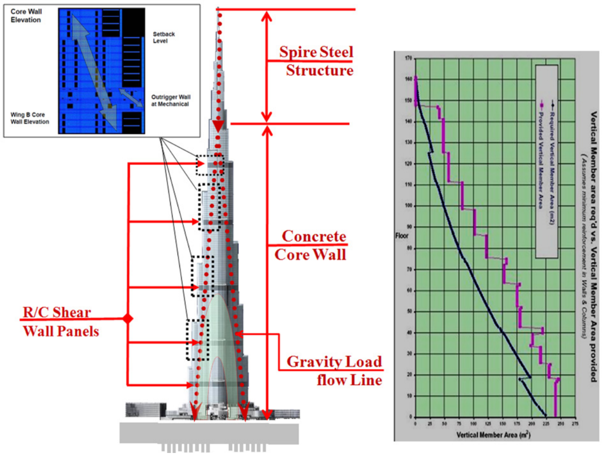

Figure 3. Lateral load resisting system and photo of the completed tower.

Figure 3 provides the gravity load analysis, performed by the author while at SOM, that compares the concrete area required to support the tower gravity loads, without considerations to minim member sizes, to the actual concrete are provided for the tower final design. Figure 3 shows that the total material needed to support the gravity load and that required to resist the combined effect of gravity and lateral loads is one and the same, which testify to the efficacy of the structural system. The only additional material needed for Burj Khalifa was only due to the rounding of members sizes and the additional materials needed to re-distribute the loads to the building extremities at the hammer heads walls (no penalty) and the nose columns (major penalty) though the link beams at every floor and at the outrigger levels. The hammer walls and the nose columns, located at the extremities of the buildings, resulted in significant contribution to the moment of inertia of the tower and its resistance to the overturning moment of the tower due to lateral loads. Figures 3 and 5 also depict the gravity load flow management along the height of the buildings. The limitations on the wall thicknesses (500~600 mm) of the center core and the wing walls thickness (600 mm) allowed, art of working with concrete, the gravity load to flow freely into the center corridor Spine web walls (650 mm) to the hammer head walls and nose columns for maximum resistance to lateral loads. Along these load flow lines the strain gages are installed to track the gravity load flow. As discussed previously, the load flow to the hammer head wall resulted in very little penalty as it occurs naturally in concrete structure, however, forcing the load into the nose columns results in structural system design complexities that I believe could be avoided all together in future system development. The reinforced concrete center core wall at level 156 provides the base support for the spire and pinnacle structure.

2.2.3. Wind engineering management

Wind engineering is one of the primary concerns in the design of tall building design planning. The shape of the Burj Khalifa project is the result of collaboration between SOMs architects and structural engineers. Several wind engineering techniques were employed into the design of the tower to control the dynamic response of the tower under wind loading by disorganizing the vortex shedding formation (frequency and direction) along the building height and tuning the dynamic characteristics of the building to improve its dynamic behavior and to prevent lock-in vibration. The wind engineering management of the tower was achieved by:

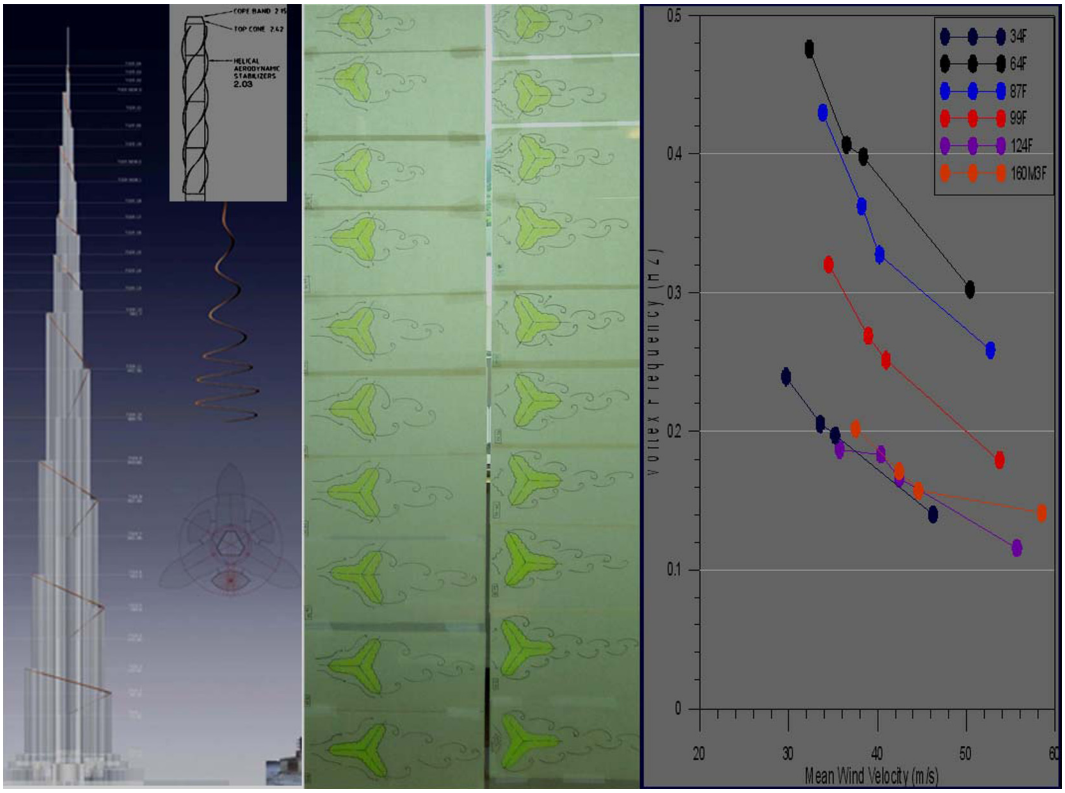

Figure 4. Vortex shedding formation, with different reson-ance frequencies, along the building height; (scanned copies of original sketches/concepts developed by the author while working at SOM).

- Varying the building shape along the height while continuing, without interruption, the building gravity and lateral load resisting system;
- Reducing the floor plan along the height, thus effectively tapering the building profile;
- Using the building shapes to introduce spoiler type of effects along the entire height of the tower, including the pinnacle, to reduce the dynamic wind excitations.
- Change the orientation of the tower in response to wind directionality, thus stiffening the structure normal to the worst wind direction.

Figure 4 depicts early conceptual sketches made by the author to demonstrate the impact of varying the shape of the building along its height from the early development of the design concept (conceptual stage), to minimizing the wind forces on the tower. The variation of the tower shape, and width, resulted in wind vortices around the perimeter of the tower that behaved differently for different shapes at different frequencies, thus disorganizing the interaction of the tower structure with the wind.

From the beginning of the project, an extensive wind tunnel studies and testing regimes were established to develop a full understanding of the building wind behavior and response and to confirm the wind engineering management strategies described above, including the tuning of the building natural frequencies and mode shape to optimize the building dynamic response against wind excitations.

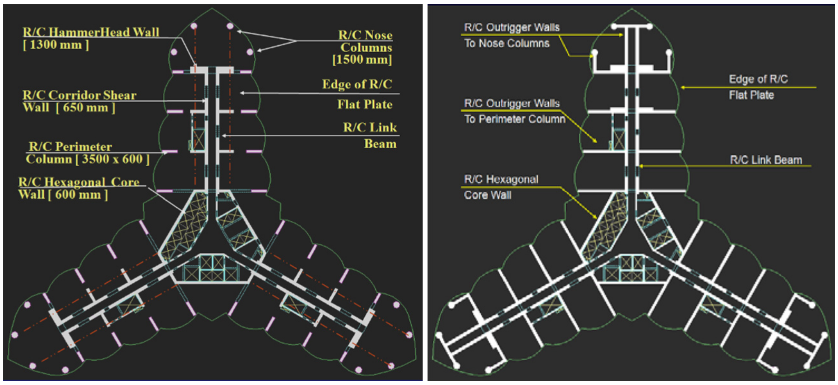

Figure 5. Typical Floor Framing Plans at a) typical hotel level and at b) Typical Mechanical Level.

Figure 6. Tower raft foundation plan and photo of raft construction.

2.2.4. Floor framing system

The residential and hotel floor framing system of the Tower consists of 200 mm to 300 mm two-way reinforced concrete flat plate slab spanning approximately 9 meters between the exterior columns and the interior core wall, which later modified to flat plate construction with 50 mm additional taperd at the supports. The floor framing system at the tips of the tower floor consists of a 225 mm to 250 mm two-way reinforced concrete flat slab system with 150 mm droppanels. The floor framing system within the interior core consists of a two way reinforced concrete slab with beams. See Figure 5 for typical floor framing system at typical residential and mechanical levels. At the mechnical level, note that all the vertical elements are tied to equalize the stress ditribution at all vertical elements (walls & columns).

2.2.5. Foundation system

The Tower is founded on 3700 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 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 Figure 6.

The tower is founded on 192~150 mm dimater high performance reinforced concrete bored piles, extending approximately 45 meters below the base of the raft. All piles utilize self compacting concrete (SCC) with w/c ratio not exceeding 0.30, placed in one continuous concrete pour using the tremie method. The final pile elevations are founded at −55 DMD to achieve the assumed pile capacities of 3000 Tonnes.

In addition to providing high performance, high durability concrete for the tower foundation systems, a complete waterproofing memebrane and cathodic protection systems were provided to protect agains the corresive soil conditions at the tower site.

3. Structural Health Monitoring System Description

The Burj Khalifa Project is now the tallest building in the world and the tallest manmade structure. 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 and it required the utilization of the latest technological advances in construction methods and techniques to build the tower to high degree of accuracy, similar or better than that used for steel construction; thus requiring the implementation of state-of-the art survey and structural health monitoring program that comprised of:

- Extensive Survey Monitoring Program to measure the foundation settlement, column shortening, and lateral building movement during construction,
- 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.
- Installation of the temporary real-time health monitoring program to measure the building lateral displacement and acceleration during construction, and to identify the building dynamic characteristics (frequencies, damping, etc) during construction. This system included bi-directional accelerometers, GPS system, and weather station (wind speed, wind direction, humidity, and temperature).
- Installation of a permanent real-time structural health monitoring (SHM) program to measure the building motions (acceleration, displacement) due to lateral loads (wind, and seismic in particular), and any other unexpected lateral loads. In addition to the installation of GPS System, bi-directional accelerometers and sonimometers were installed at several levels along the building height to provide real time building accelerations and wind data. The installation of these devices in essence resulted in 1) the

development of full scale aeroelastic model of the tower while providing full feedback and details on the dynamic characteristics of the tower, 2) sufficient data to assess the fatigue behavior of the steel structure in general and at the pinnacle in particular, 3) wind speed and distribution along the building height, and 4) most importantly providing the building facility and management team real-time information on the building movements and characteristics to allow them make better and almost instant management decision about any issues that may rise during the lifetime of the tower.

3.1. Brief description of the survey monitoring programs:

Several detailed survey program were developed for the construction of the tower that involves the utilization of the latest development in geodetic electro-optical total stations. These instruments refer to fixed reference points with known coordinates, which are critical to the precision of the entire surveying procedure and serve as fixed point to the total station. However, the use of fixed points, with the constantly increasing height of Burj Khalifa, made it difficult to use the ground level fixed points since the distance between these fixed points and the total station at the uppermost construction level became excessive for exact referencing of the total station and the relative distance between the fixed points became too small.

In addition, the precision of the survey system is further complicated by the increasing height, slenderness, and the 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 150 mm change in building height at the top of the concrete, over 6 hour period, 6) uneven solar effects that 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 sequence, and 9) mix of concrete (from foundation to level 156) and steel construction (from level 156 to the top of the pinnacle at 828 m). Rationalizing these movements created a number of challenges to consider in setting 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 position relative to its vertical axis at any instant of time required 1) the full understanding of the survey team of the building movements and behavior throughout its construction period, which discussed with the author in details since the beginning of the project and on regular basis with the survey team, 2) the development of exten-

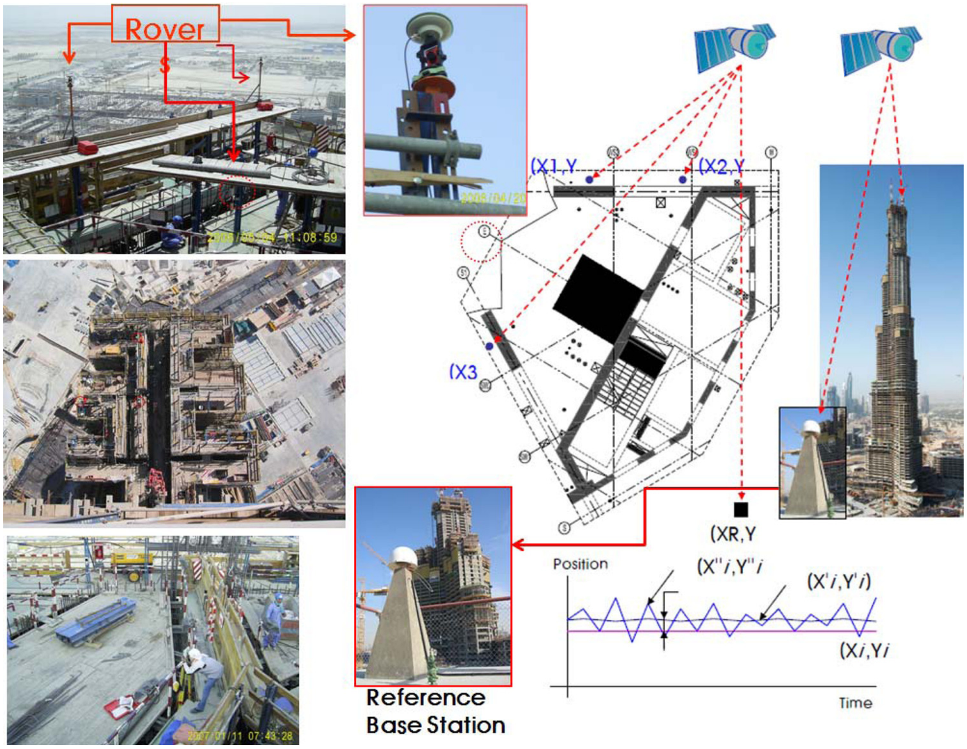

Figure 7. Measurement system: (3)GPS control points, total station, reference base station.

sive monitoring program of all building elements that affect the building movement, and 3) most importantly the installation of new "measurement system" that uses the latest development in GPS technology, the "Leica Geosystem", in combination with precision inclination sensors, clinometers, to provide a reliable position of the building at the highest construction level almost immediately, even when the building is moving.

Moreover, the complexity and the size of the auto climbing formwork system (ACS), due to the shape of the structure, required very large number of control points at each level that added to the complexity of the survey method. Therefore, it was necessary to simplify the survey procedure and system so that the control points, even when the building is moving, can be measured only once. The "measurement system" was developed for use at every level and comprised of 1) three (3)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 (3) tiltable circular prisms placed under each of the GPS antennas, and 3) a "Total Station" instruments (TPS) that were set on top of the concrete and visible to all GPS stations. See Figure 7 for an overall view of the "measurement system".

The "measurement system" at every floor is integrated with the installation of eight (8) clinometers, Leica NIVEL 200 dual-axis precise clinometers, at approximately every 20 floors from the foundation level, to track immediately 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 building verticality and to keep the building within the required tolerance at every level (within 15 mm).

The Eight (8) Leica NIVEL200 dual-axis precise clinometers are also used to immediately determine the rotation of the tower, and to compute the displacement/alignment of the tower in the x and y direction relative to the raft foundation. The clinometers are mounted on the

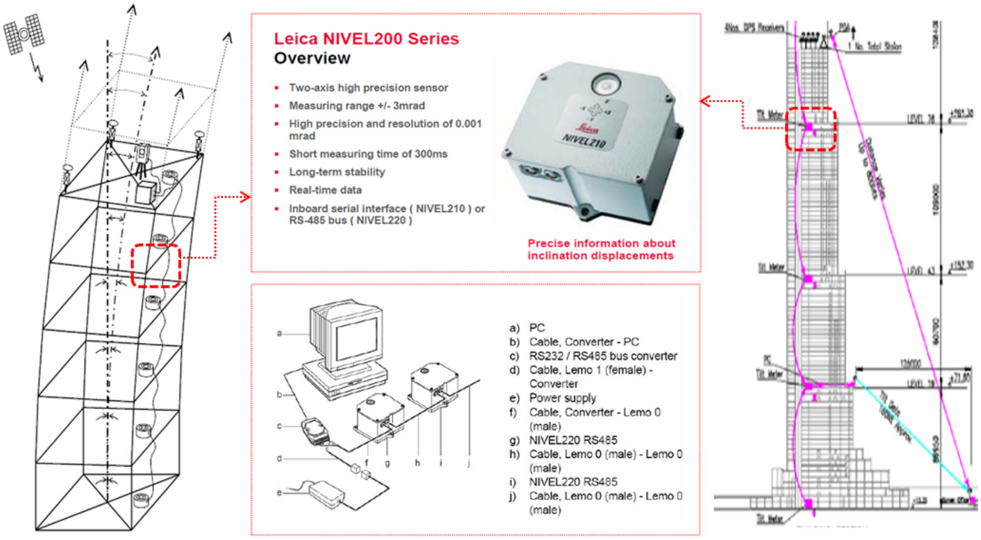

Figure 8. Schemtic for integrated measurement system with clinometers.

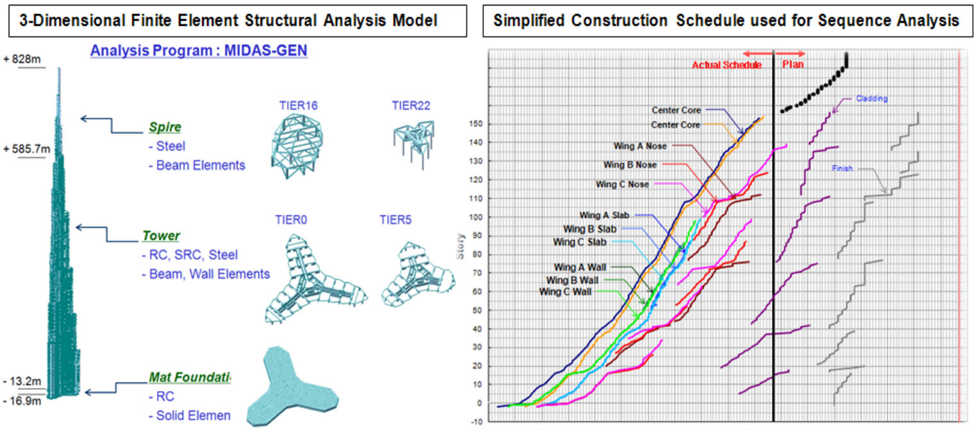

Figure 9. 3-D FEA model and Simplified Construction Schedule used for Sequence Analysis.

center corewall in areas with no disturbances and connected to RS-485 single bus cable to the LAN port dedicated PC with the Leica GeoMos software located at the survey office. See Figure 8 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 tiltmeter at that time and that 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 ACS formwork system.

While fully describing the execution of the survey system of the tower is novel task, it cannot be covered fully here, however, this paper will describe the execution of the survey monitoring program developed for Burj Khalifa to measure the actual building movements periodically and it included 1) foundation settlement, 2) column and wall total shortening resulting from elastic, shrinkage and creep effects, 3) overall lateral displacement of the tower at every setback level, and 4) lateral displacement of the spire/pinnacle structure during construction and lifting operation. All periodical survey and monitoring were performed early in the morning, to minimize the differential solar effects, and when the cranes are shutdown in order to reduce number of variable to be considered in the survey.

To compare the actual measured building movements (x, y, z) to the predicted displacements from, a 3-dimensional finite element structural analysis model was developed for Burj Khalifa that took into account the actual material properties (concrete strength, modulus of elasticity, coefficient of thermal expansion, etc) and the foundation flexibility (subgrade modulus). 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 and as shown in Figure 9. The intent of this analysis model is to predict 1) the foundation settlement, 2) the tower lateral displacements (x&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 4) the dynamic building characteristics, 5) the strength design check of the critical elements, especially at the outriggers and link beams, 6) and the lateral displacement (x, y, &z) due to any seismic or wind events during construction and after the completion of the tower.

3.1.1. Foundation settlement survey

As described above, a soil structure interaction three dimensional finite element analysis model (3D-FEAM) was developed to simulate the construction sequence of the tower that includes a detailed analysis model of the raft foundation system, including the foundation system flexibility. The foundation settlement was initially estimated based on the subgrade reaction modulus provided by the geotechnical engineering consultants; however, the foundation stiffness was adjusted, based on the actual *in-situ* measured settlements shown in Figure 10. The 3D-FEAM and soil structure interaction analysis model took into account the pile axial shortening, soil flexibility, and the stiffening effect of the superstructure. Sixteen (16) survey points at the top of the raft foundation were installed to measure the tower foundation settlement monthly until the completion of the structure.

Comparison between the predicted settlements, from the calibrated 3-dimensional and construction sequence analysis model, and the measured settlement values were excellent despite the complexities involved in setting the structural analysis and the assumed geotechnical engineering parameters.

3.1.2. 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 stage and construction stages. The development of the tower 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

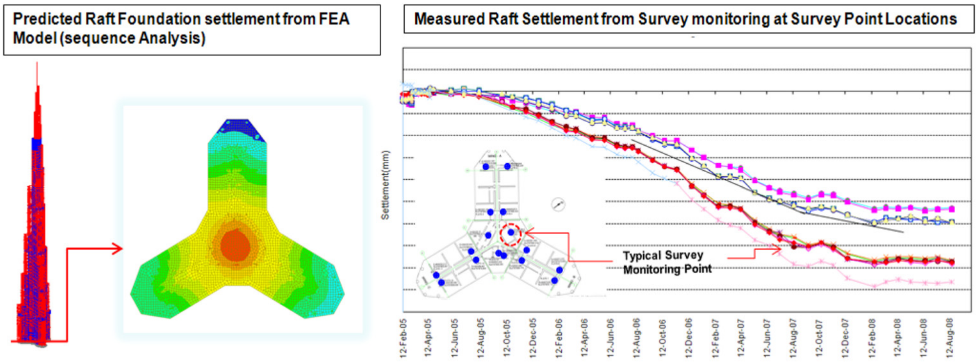

Figure 10. Foundation survey point and measured foundation settlement.

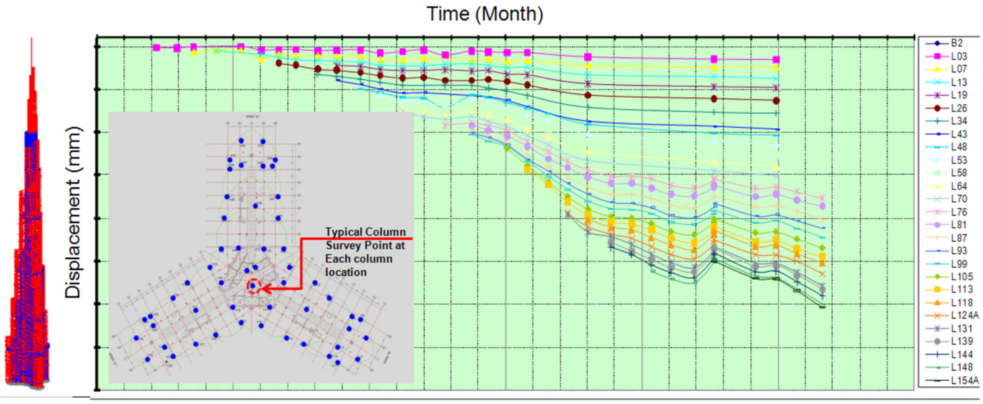

Figure 11. Location of typical survey points at all column/wall locations and center core wall shortening subsequent to survey point installation at all surveyed levels.

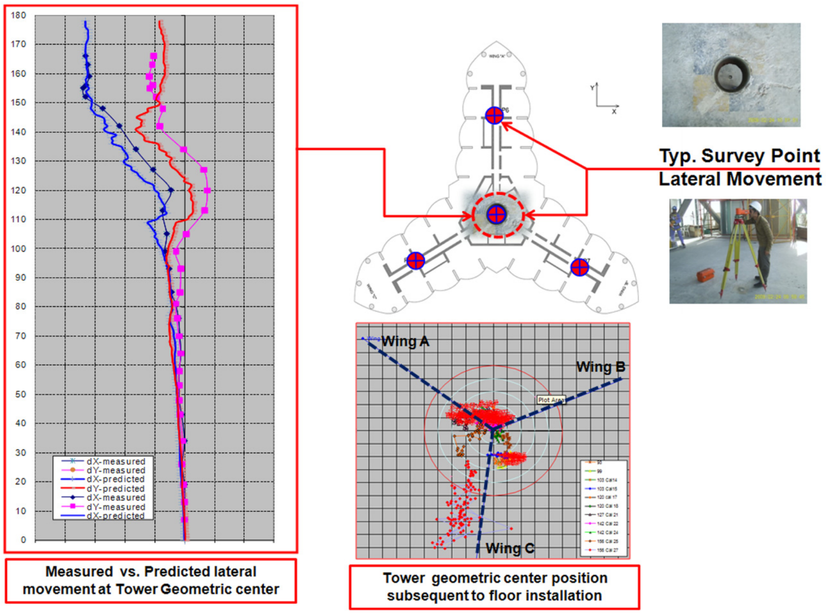

Figure 12. Measured vs. predicted tower lateral movement, at towers geometric center, at every setback level and the towers center position with time.

columns are tied together through four story shear wall panels at the mechanical levels to engaging all vertical members in the lateral system and to allow for better gravity load and stress distribution between them. For better estimation of the wall and column short term and long term shortening, an extensive concrete creep and shrinkage testing programs were developed by Samsung at the start of construction to monitor the concrete elastic/shrinkage/creep characteristics. The actual concrete test data were used in the 3D-FEAM construction sequence analysis of the tower to predict the actual column/wall strains and shortening during construction and through its lifetime. Correlation between Samsung predicted and actual column/wall total strains and shortening were excellent; thus providing better confidence in the analytical predictions and in allowing Samsung to make adjustment to the compensation program as deemed necessary.

An extensive survey monitoring program concept was also developed by the author as shown in Figure 11 to monitor the total columns shortening at every setback level, which was reported by the survey team every month. These survey measurements were 1) analyzed every month by the author and compared against the predicted measurements, 2) used as a tool to keep track of the overall building structural behavioral characteristics, and 3) allowed for better management of the actual construction sequence of the tower. Figure 11 depicts number of survey points measured at a typical level and a sample of the column shortening at the center of the core subsequent to concrete placement until the completion of the tower superstructure. Evaluation of the measured column/wall shortening at all locations indicates that the column differential shortening is within the expected predicted range.

3.1.3. Survey of the tower lateral movement during construction

Because of the tower constant changes in shape and the shift of center of gravity load relative to the center of stiffness, the tower was expected to move laterally during construction. In order to keep track of the tower movements and to make the necessary corrections for the keep of the tower verticality, building the tower at its geometric center, the tower lateral movement was monitored daily as described in the tower survey section above. A detailed optical survey program was also performed monthly at every setback level to measure its lateral movement subsequent to the time of installation. Figure 12 below depicts the survey point location at every set back level to monitor the lateral movement of the tower as a function of time.

Comparison between the measured and the predicted lateral movement, shown in Figure 12, indicated excellent correlation. The predicted movement was based on the three dimensional finite element construction sequence analysis models that took into account the foundation stiffness, actual material properties (strength/elastic modulus/creep/shrinkage), and the detailed construction program for all construction activities as a function of time. This analysis was performed by Samsung on regular basis to compare the actual measured lateral movements to the predicted lateral movement during the tower construction, after completion of the tower construction, and after 30 years of the tower construction. To compensate for this lateral movement, Samsung constructed the tower at its geometric center at every level.

3.2. Strain gage measurement during construction and for permanent building condition

In order to manage the column shortening and lateral movement issues of the tower, an extensive strain measurement program was also developed by the author as shown in Figure 13 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 13 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, and finally 5) temporary weather stations were installed at several setback levels to measure the temperature, humidity, wind velocity and direction.

The tower superstructure received 1) 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 electroni 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 gage (type 4200), three (3) gage rosettes, and two (2) gage rosettes at the load cells.

The *in-situ* strain measurements shown in Figure 13

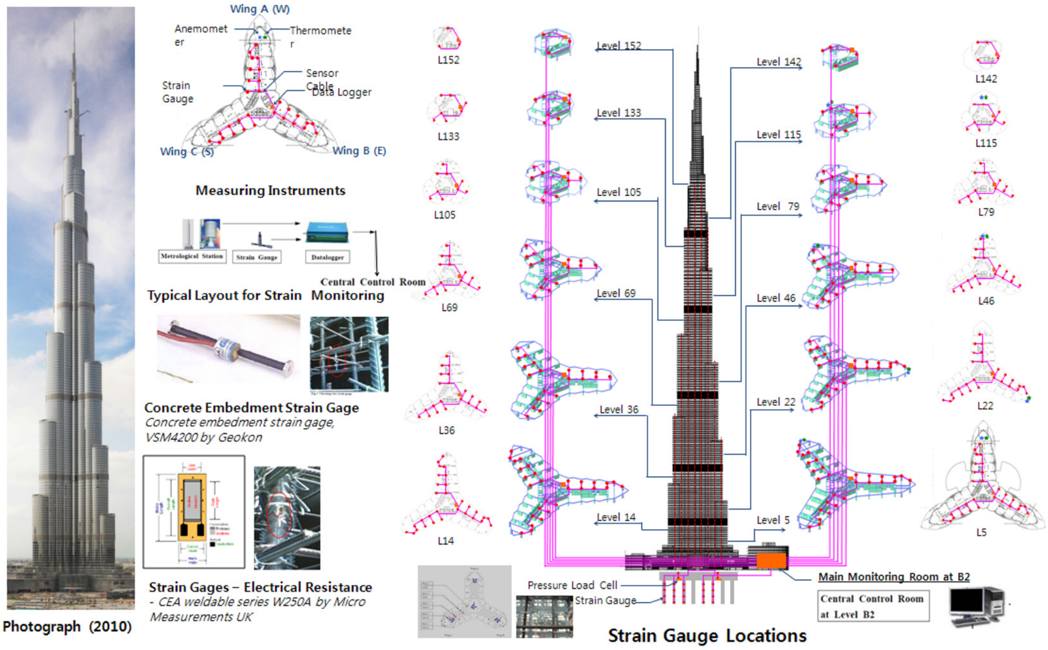

Figure 13. Typical Strain Gage Monitoring System Concept and Layout for the tower superstructure and foundation systems.

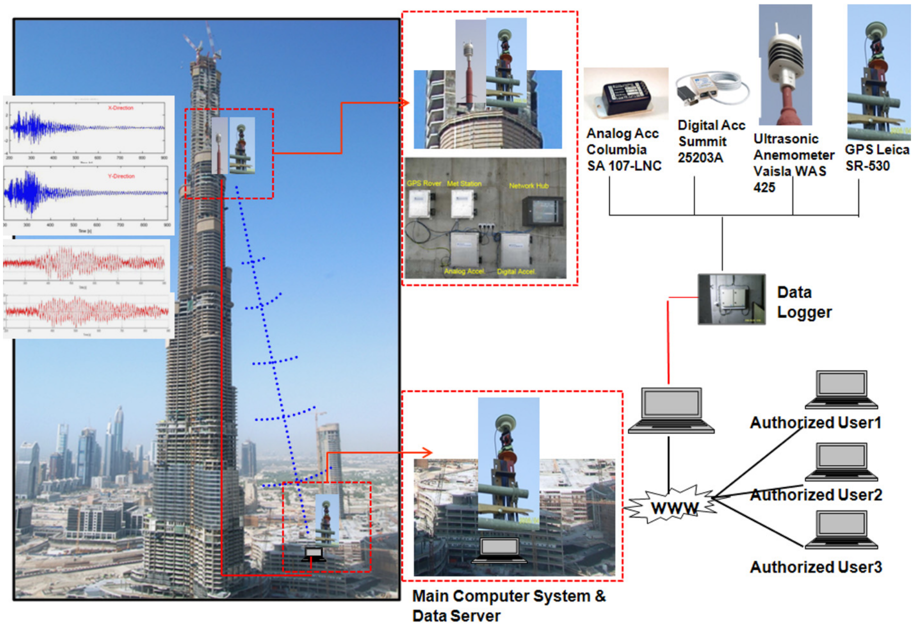

Figure 14. Detailed summary of the temporary real time monitoring program configuration and building movement during construction (due to Sept. 10 2008 earthquake in Iran).

below were compared with the tower predicted strains, from Samsung detailed 3D-FEAM and construction sequence analysis models, from the time of strain gage installation until the completion of the tower construction. Good correlation between Samsung predicted strains and measured strains were found. However, difficulties were encountered in providing continuous measurement at some location because of the site constraints during construction. The strain measurements were taken from the time concrete was cast until the completion of construction. The strain measurements directly recorder temperature rise in the large concrete element, and the time it took to bring the temperature of these element to the ambient temperature.

3.2.1. 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 Notre Dame University to monitor 1) the building acceleration level during construction, which was also used for the tower system identification, 2) a complete GPS system, consisting of the rover at level 138 and a fixed station at the office annex, to measure the building real time displacement with time; and 3) a weather station to measure the temperature, humidity, wind speed and direction at level 138. The detail configuration of the temporary real time monitoring system is shown in Figure 14.

While the building movement from wind load remained relatively small throughout the construction period, on September 10 2008, the tower was subjected to the influence of a remote earthquake that occurred in Bandar Abbas, Iran at approximately 850 miles south of Tehran. During this event the earthquake was observed and felt across the GCC states and many buildings were evacuated at the time of the quake. Figure 14 shows the measured motion of the tower at level 139. The peak accelerations observed were 2.76 milli-g and 3.82 milli-g in the x and y directions respectively. Since the tower did not have base accelerometer at the base, real time history analysis was not performed. During this event the tower had the highest acceleration ever recorded since the monitoring system installation.

In addition to the recorded building acceleration and displacements depicted in Figure 14, complete system identification was performed for the tower and included the estimation of the tower natural frequencies, and damping. Comparison between the predicted natural frequencies from the three-dimensional finite element analysis model performed by the author and the measured frequencies were within 2~3%, including the higher modes. The temporary real-time monitoring program that was conceptualized, funded, and installed by Samsung in cooperation with Notre Dame University (Kareem, Kijewski, and Kwon) and finally used as the seed in expanding the monitoring system into a state-of-art Full Scale Structural Health Monitoring Program, which is probably first of its kind in the history of tall buildings.

3.2.2. 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 consisting of 1) three (3) pairs of accelerometers at the foundation level of the tower to

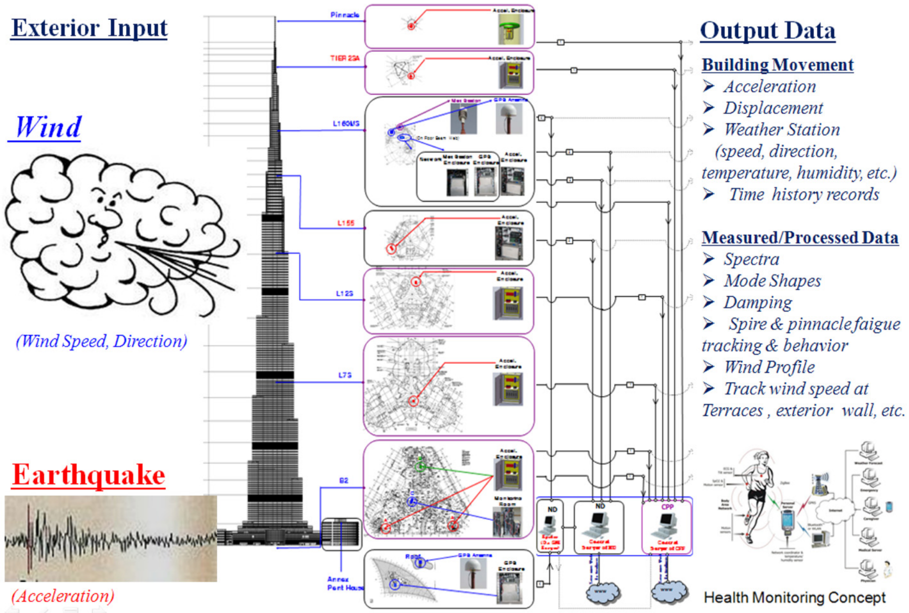

Figure 15. Detailed summary of the permanent real-time Structural Health Monitoring (SHM) program concept developed by the author for Burj Khalifa.

capture base accelerations, 2) six (6) pairs of accelerometers at levels 73, 123, 155 (top of concrete), 160M3, Tier23A, and top of the pinnacle to measure the tower acceleration simultaneously at all levels, 3) a GPS system to measure the building displacement at level 160M3, 4) twenty three (23) sonimometers at all terrace and setback levels, including the top of the pinnacle at +828 m above ground, to measure wind speed and direction, 5) and weather station at level 160M3 to measure, wind speed & direction, relative humidity, and temperature. This final SHM program was an extension to the already developed temporary SHM system developed to monitor the building behavior during construction, and developed in cooperation between Samsung C&T, The University of Notre

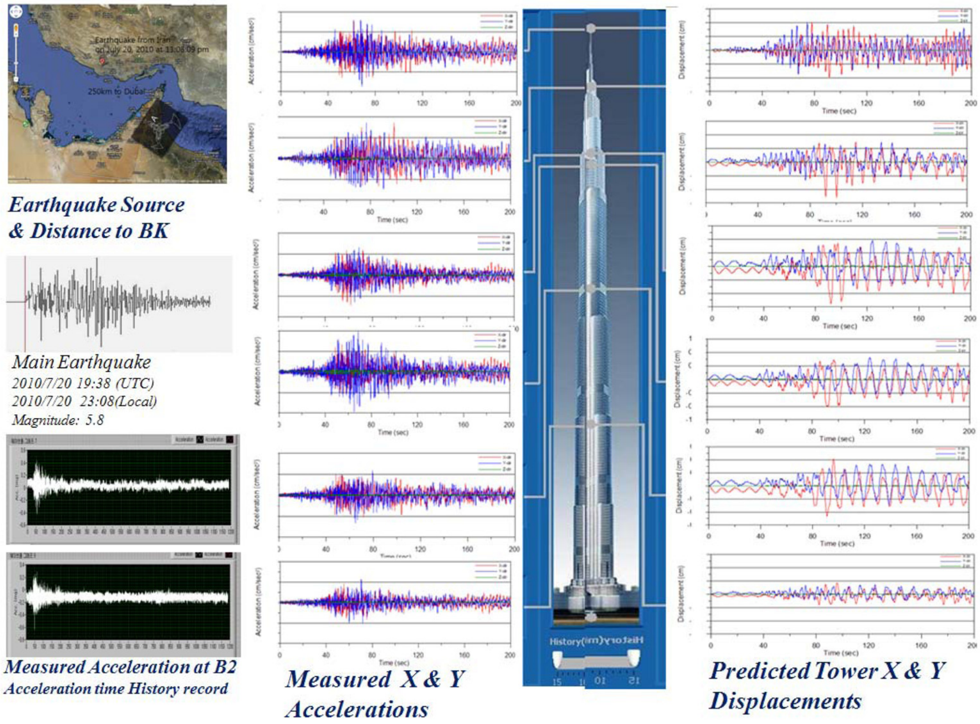

Figure 16. Sample of measured acceleration at all levels (not to scale) and predicted displacement at all levels due an earthquake event that occurred in southern Iran on July 10, 2010.

Dame, and the wind tunnel testing facility at Cermak Peterka, Petersen (CPP). See Figure 15 for the detailed configuration of the SHM program concept developed by the author for Burj Khalifa.

Since completion of the installation of the SHM program at Burj Khalifa, most of the structural system characteristics have been identified and included measuring the following:

1. Building acceleration at all levels
2. Building displacements at level 160M3
3. Wind profile along the building height at most balcony areas, including wind speed & 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.

Comparison between the predicted building behavior and the *in-situ* measured response has been excellent. While these findings cannot be shared fully here because of confidentiality, Figure 16 provides samples of the data measured in real time at Burj Khalifa during an earthquake of M5.8 magnitude that occurred in southern Iran on July 20, 2010. While the magnitude of this earthquake was diminished when it reached Dubai and was relatively small (less than 1 milli-g at BK site), the earthquake had frequency content the that matched the pinnacle frequencies, thus setting the pinnacle in resonance. The acceleration time history record captured at the lowest basement level was used to perform the time history analysis of tower and a summary of the measured accelerations and the predicted displacements (not to scale) of the tower is shown in Figure 16 at all monitored levels.

4. Conclusion

Historically tall buildings 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 done in tall buildings, these programs had very limited research and scope and yet to be systematically validated and or holistically integrated.

The intimate involvement of the author in 1) developing the structural and foundation systems for Burj Khalifa, while at SOM, 2) participating in the development of the construction methodology and planning of Burj Khalifa, while at Samsung, 3) pursuing the achievement of US national science and foundation grant for the “Full Scale Monitoring Program in Tall Buildings under wind”, while at SOM and in cooperation with the BLWTL and the university of Notre Dame, and finally 4) the author passion to understand and to reflect on the actual performance of Burj Khalifa structure by confirming concrete materials characteristics, design assumptions, and analytical modeling assumptions and techniques, led to the development of the detailed survey and SHM program that provided immediate and direct feedback on the actual structural performance of the tower from beginning of construction and throughout its lifetime. The development of the comprehensive SHM programs at Burj Khalifa included

- Testing all concrete grades to confirm the concrete mechanical properties and characteristic (strength, modulus of elasticity, shrinkage and creep characteristics, split cylinder, durability, heat of hydration, etc.)
- Survey monitoring programs to measure the foundation settlement, column shortening, and tower lateral movement from the early construction stage until the completion of the structure.
- Strain monitoring program to measure the actual strains in the columns, walls, and near the outrigger levels to confirm the load transfer into the exterior mega columns.
- Survey program to measure the building tilt in real time, and the utilization of GPS technology in the survey procedure.
- Temporary real time SHM program in collaboration with the university of Notre Dame to measure the building acceleration, displacement, and to provide real-time feedback on the tower dynamic characteristics and behavior during construction and before completion of the structure.
- Permanent real time SHM program in collaboration with the University of Notre Dame and CPP to measure the building acceleration, movement, dynamic characteristics (frequencies, mode shapes), acceleration time history record and tilt of the foundation at the base of the tower, wind velocity profile along the entire height, weather station, and fatigue behavior of the spire/pinnacle.

The measured data collected from the above survey and SHM programs were found in good agreement with Samsung predicted structural behavior. The survey and SHM programs developed for Burj Khalifa has:

- Validated the design assumptions and parameters used in the design, analysis, and construction techniques.
- Provided real-time information on the structural system response and allowed for potential modification to the construction techniques to ensure the expected performance during construction and though its lifetime.
- Identified anomalies at early stages and allowed for means to address them.
- Generated very large *in-situ* data for all concrete materials used for the tower
- Provided full feedback on the foundation and structural system behavior and characteristics since the start of construction.

The survey and SHM programs developed for Burj

Khalifa will with no doubt pioneer the use of survey and SHM program 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. However, 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 and it will become an integral part of the building design and Intelligent Building Management System.

Acknowledgements

The author gratefully acknowledges the support and contribution from Emaar Properties PSJ in agreeing to the implementation of the comprehensive monitoring program at Burj Khalifa, Samsung C&T for 100% funding of the temporary real time monitoring programs and partial funding of the permanent real time monitoring programs, the highrise and complex building structural engineers for their help in preparing the 3D_FEAM and construction sequence analysis models, and for the full support of the Burj Khalifa site staff in facilitating the installation of the monitoring system. The development and implementation of the temporary real time monitoring program (accelerometers, GPS, and weather station) was realized because of the full support of professors Ahsan Kareem, Tracy Kijewski, and Dr DK Kwon at the University of Notre Dame. The author wishes also to thank the University of Notre Dame team (Professors Ahsan Kareem, Tracy Kijewski, and DK Kwon) and CPP team (Roy Denoon and Tom Lawton) for their contributions to the design, assembly, and the final of the SGM programs installation.

References

Abdelrazaq, A. (2010) "Design and construction planning of the Burj Khalifa", Dubai, UAE, *Proc. ASCE Structures Congress 2010*, Orlando, USA.

Brownjohn, J. M., Pan, T. C., and Deng, X. (2000) "Correlating dynamic characteristics from field measurements and numerical analysis of a high rise building", *Earthquake Engineering & Structural Dynamics*, 29(4), pp. 523~543.

Brownjohn, J. M. and Pan, T. C. (2001) "Response of a tall building to long distance earthquakes", *Earthquake Engineering & Structural Dynamics*, 30, pp. 709~729.

Jol, V. C., Hayes, D., and Sparks, I. (2007) "GPS Network for Tallest Building".

Kijewski-Correa, T., Young, B., Baker, W. F., Sinn, R., Abdelrazaq, A. Isyumov, N., and Kareem, A. (2005) "Full-scale validation of finite element models for tall buildings", *Proc. CTBUH 2005* CD-ROM_CTBUH, Chicago, USA.

Kijewski-Correa. T., Kilpatrick, J., Kwon, D. K., Bashor, R., Young, B. S., Abdelrazaq, A., Galsworthy, J., Morrish, D., Sinn, R. C., Baker, W. F., Isyumov, N., and Kareem, A. (2005) "Full-scale validation of the wind-induced response of tall buildings: updated findings from the chicago monitoring project", *Proc. Americas Conference On Wind Engineering*, Baton Rouge, LA, USA.

Ni, Y. Q., Xia, Y., Chen, W. H., Lu, Z. R., Liao, W. Y., and Ko, J. M. (2009a) "Monitoring of wind properties and dynamic responses of a supertall structure during typhoon periods", *Proc. 4th International Conference on Structural Health Monitoring and Intelligent Infrastructure*, Zurich, Switzerland (CD-ROM).

Ni, Y. Q., Xia, Y., Liao, W. Y., and Ko, J. M. (2009b) "Technology innovation in developing the structural health monitoring system for Guangzhou New TV Tower", *Structural Control and Health Monitoring*, 16(1), pp. 73~98.

Jol, V. C., Hayes, D., and Sparks, I. (2007) "GPS Network for Tallest Building".