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

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ABSTRACT: New generation of tall and complex buildings system are now introduced that are reflective of the latest development in of materials, design, sustainability, construction, and IT technologies. While the complexity in design is being overcome by the availability and advances in structural analysis, the design of these building is still reliant on minimum code requirements and 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 at the world tallest manmade structure to validate all the fundamental assumptions in the design and construction planning of the tower.

The Burj Dubai Project is the tallest structure ever built by man; the tower is 828 meters tall and compromise 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. This paper provides a brief description of the tower structural systems and behavior and the key issues considered in integrating structural design concepts that are considered paramount to the development and execution of a state-of-the-art survey and structural health monitoring (SHM) programs. The focus of this paper is to discuss the implementation of the survey and structural health real time 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) foundation settlement, 3) Strain Measurements of the tower vertical elements, 4) wall and column vertical shortening due to elastic, shrinkage and creep effects, 5) lateral displacement of the tower under eccentric gravity load distribution resulting from elastic and creep effects, 6) temporary Real Time Monitoring Program to monitor the building displacement and dynamic response under lateral loads during construction, 7) permanent Real Time Monitoring Program to monitor the building displacement and dynamic behavior and response under lateral forces, and 8) monitoring the Pinnacle dynamic behavior and fatigue characteristics. This extensive monitoring 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 structural health monitoring programs developed for the Burj Khalifa will no doubt will 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 structural health monitoring programs for all critical and essential facilities, but with much improved devices and technologies, which is now being considered by the author for a tall and complex building development that is presently under construction.

1 INTRODUCTION

The Burj Dubai Project is the tallest structure ever built by man; the tower is 828 meters tall and compromise 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 is generally difficult to manage in supertall buildings.

Figure 1. Photo of the Completed Burj Khalifa

The structure of Burj Khalifa was designed to behave like a giant column with cross sectional shape that is a 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 systems and the key issues considered in integrating structural design concepts and construction planning into the architectural design concept; 2) a detailed understanding the overall structural behavior of the tower, which is paramount to the development of the structural health monitoring (SHM) and survey programs for the tower; 3) and a detailed description of the comprehensive SHM and survey programs developed for the Burj Khalifa.

The development of the SHM program for Burj Khalifa, at the time of the system installation, is probably one of the most comprehensive survey and real time structural health monitoring programs in the history of supertall buildings that will track the structural behavior and response 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.
- Continuous 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.
- Continuous Monitoring 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 of the building, including its natural mode of vibration, estimate of damping, measuring the building displacement and acceleration, immediate diagnose on the change on the building structural behavior, predicting behavior fatigue of critical elements that are susceptible severe and sustained wind induced vibration at different wind speed and profiles, and most importantly in providing ongoing feedback on the performance of the building structure and immediate assistance in their day-to-day operations, etc.
- Continuous monitoring and predicting the fatigue 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 and the predicted behavior of the tower.

This extensive SHM and survey monitoring program has, since its inception, resulted already in an extensive feedback and insight into the actual is-situ material properties, the tower's 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 with real time data 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 Y-shaped 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 building's 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 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 an 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.

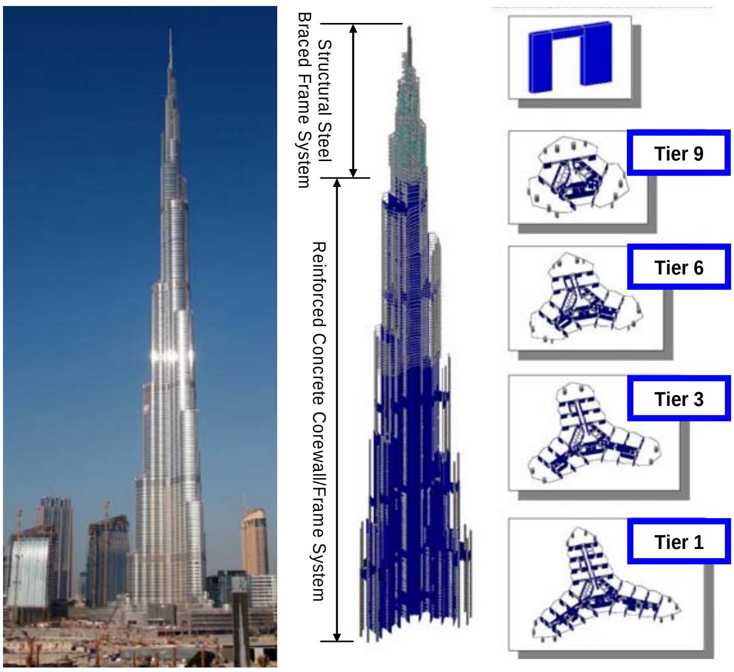

Figure 2. Lateral Load Resisting System and photo of the completed tower

2.2.1 Lateral load Resisting System

The tower's 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.
The core walls vary in thickness from 1300mm to 500mm. The core walls are typically linked through a series of 800mm to 1100mm deep reinforced concrete or composite link beams at every level. Due to the limitation on the link beam depth, ductile composite link beams are provided in certain areas of the core wall system. These composite ductile link beams typically consist of steel shear plates, or structural steel built-up I-shaped beams, with shear studs embedded in the concrete section. 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 2100mm diameter x 60mm thick at the base to 1200mm diameter x 30mm thick at the top (828m).

2.2.2 Gravity Load Management & Structural System Optimization

While the wind behavior of supertall buildings is one on the most important design criteria to be considered, gravity load management is also as critical as it has direct impact 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 complexities and construction complexities. The balance between the gravity load management and the gravity load smooth flow redistribution in concrete structure is a structural engineering art that requires in depth understanding of materials and the structural system behavior from the early design concept. 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.

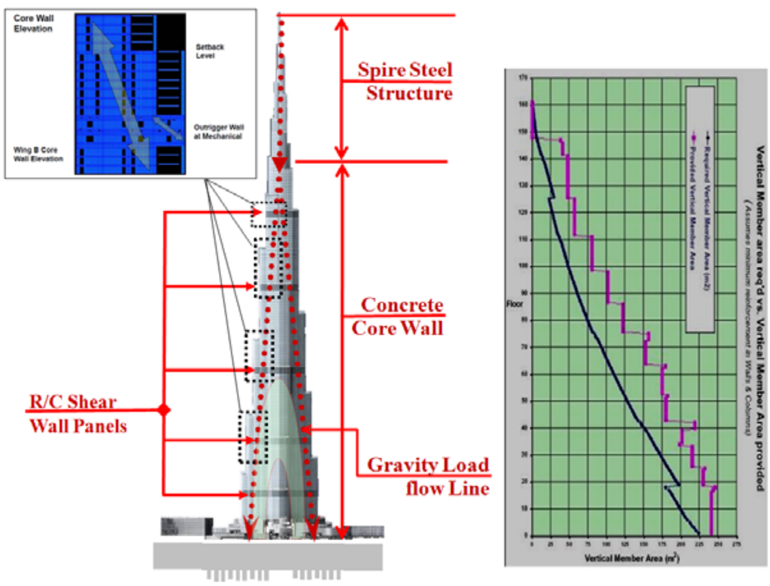

Figure 3. Lateral Load Resisting System and photo of the completed tower

Figures 3 shows that the selected structural system is efficient, and the only additional material needed is due to the required minimum members sizes and the additional materials (through link beams) needed to re-distribute the loads to the oversized members at the hammer heads walls (no penalty) and the nose columns (major penalty) though outrigger trusses. 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 (500-600mm) of the center core and the wing walls thickness (600mm) allowed, art of working with concrete, the gravity load to flow freely into the center corridor Spine web walls (650mm) 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. Special analysis, wind tunnel testing, design, and detailing were also considered for the structural design concept of the spire/pinnacle steel structure.

2.2.3 Wind Engineering Management

Wind engineering is one of the primary concerns in the design of tall building design and planning. The shape of the Burj Khalifa project is the result of direct strong and successful collaboration between SOM's architects and engineers to vary the shape of the building along its height from the early development of the design concept (competition stage), thereby 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 as shown in Figure 4.

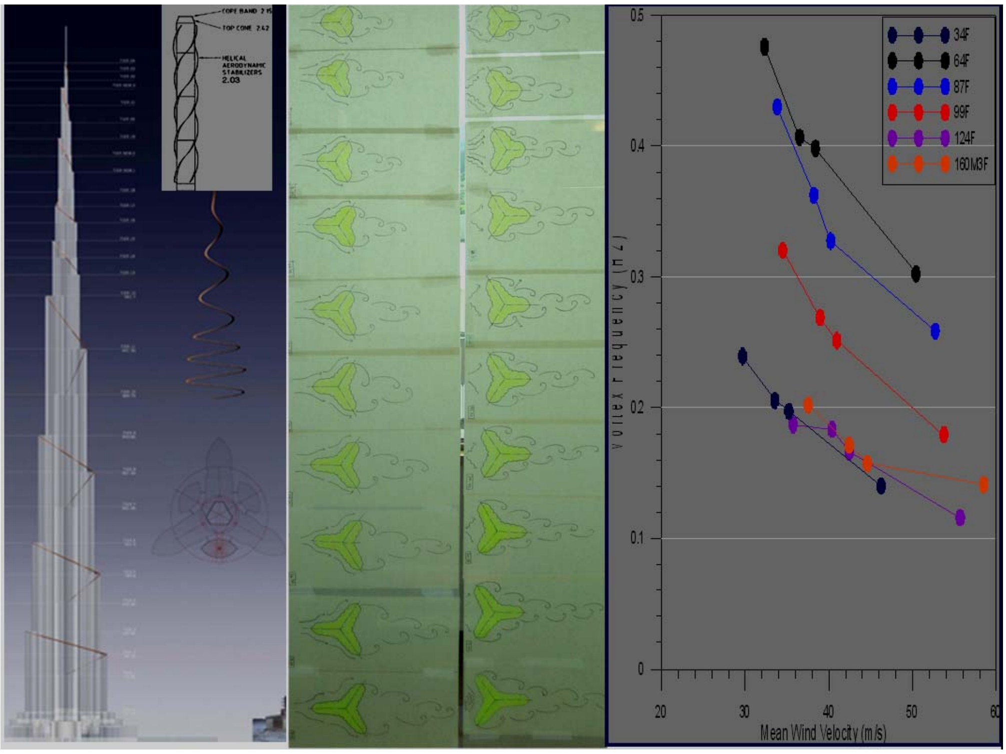

Figure 4. Vortex shedding formation, with different resonance frequencies, along the building height; (scanned copies of original sketches/concepts developed by the author while working at SOM)

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. Based on these extensive studies, target building periods and mode shapes were established to optimize the building dynamic response to the dynamic wind action.

2.2.4 Floor Framing System

The residential and hotel floor framing system of the Tower consists of 200mm to 300mm two-way reinforced concrete flat plate slabs spanning approximately 9 meters between the exterior columns and the interior core wall. The floor framing system at the tips of the tower floor consists of a 225mm to 250mm two-way reinforced concrete flat plate system. The floor framing system within the interior core consists of a two way reinforced concrete flat plate system with beams. See Figure 5 for typical floor framing system at typical residential and mechanical levels.

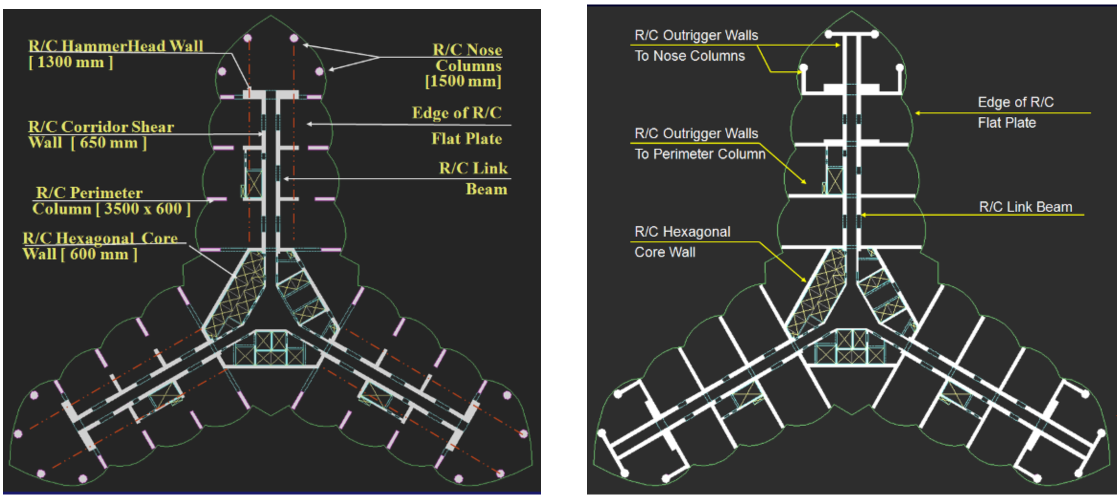

Figure 5. Typical Floor Framing Plans at a) typical hotel level and at b) Typical Mechanical Level

2.2.5 Foundation System

The Tower is founded on a 3700mm 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 100mm blinding slab over waterproofing membrane, over at least 50mm blinding slab. The raft foundation bottom and all sides are protected with waterproofing membrane. See Figure 6 for the Raft Foundation System.

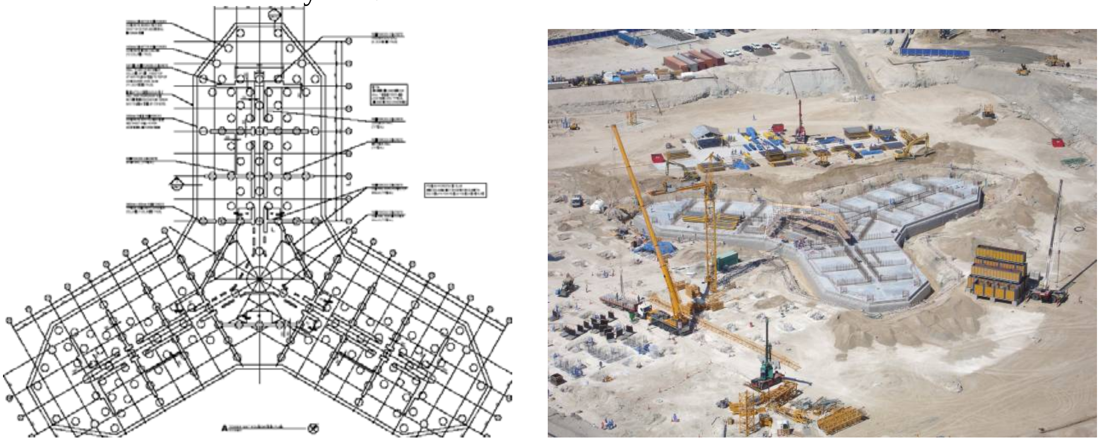

Figure 6. Tower raft foundation plan and photo of raft construction

The piles are 1500mm diameter, 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 3000Tonnes.

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 one, the construction of the tower in itself was very challenging in every aspect. The design and construction planning of the tower utilized the latest technological advances in materials and construction methods build the tower with high degree of tolerances that is similar or better than that of steel construction.

The monitoring program of the tower is comprised

- Extensive Survey Monitoring Program to measure the foundation settlement, column shortening, and lateral building movement during construction,
- Installation of Strain gages measurement to measure the total strains from the pile foundation to the top of concrete elements (level 155), including bored piles, raft foundation, walls, and columns.
- Installation of the temporary real-time health monitoring program to measure the building lateral displacement and acceleration during construction, and to confirm the building dynamic characteristics 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 due to wind, seismic, and any their unexpected lateral loads. This SHM program was also is installed at several levels along the building height and it provides in essence a full scale aeroelastic model that provide full detail information on the building dynamic characteristics, fatigue behavior of the steel structure in general and the pinnacle in particular, wind speed and distribution along the building height, and most importantly feedback on the building behavioral response that can allows for an opportunity to the building facility and operation management team to have better understanding of the building response to dynamic excitation.

3.1 Brief Description of the Survey Monitoring Programs:

A detailed survey programs was developed for the construction of the tower that involves the utilization of the latest development in geodetic electro-optical total stations, these instruments must refer to fixed reference points with known coordinates, which are critical to the precision of the entire surveying procedure and to 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 become too small.

In addition, the precision of the survey system is further complicated by the increasing height and slenderness of the tower and the movement of the tower during construction resulting from 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 150mm change in building height at the top of the concrete and 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, 8) building construction sequence, and 9) mix concrete (from foundation to level 156) and steel construction (from level 156 to the top of the pinnacle at 828m). Thus these movements create 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.

Overcoming 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, 2) the development of extensive 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.

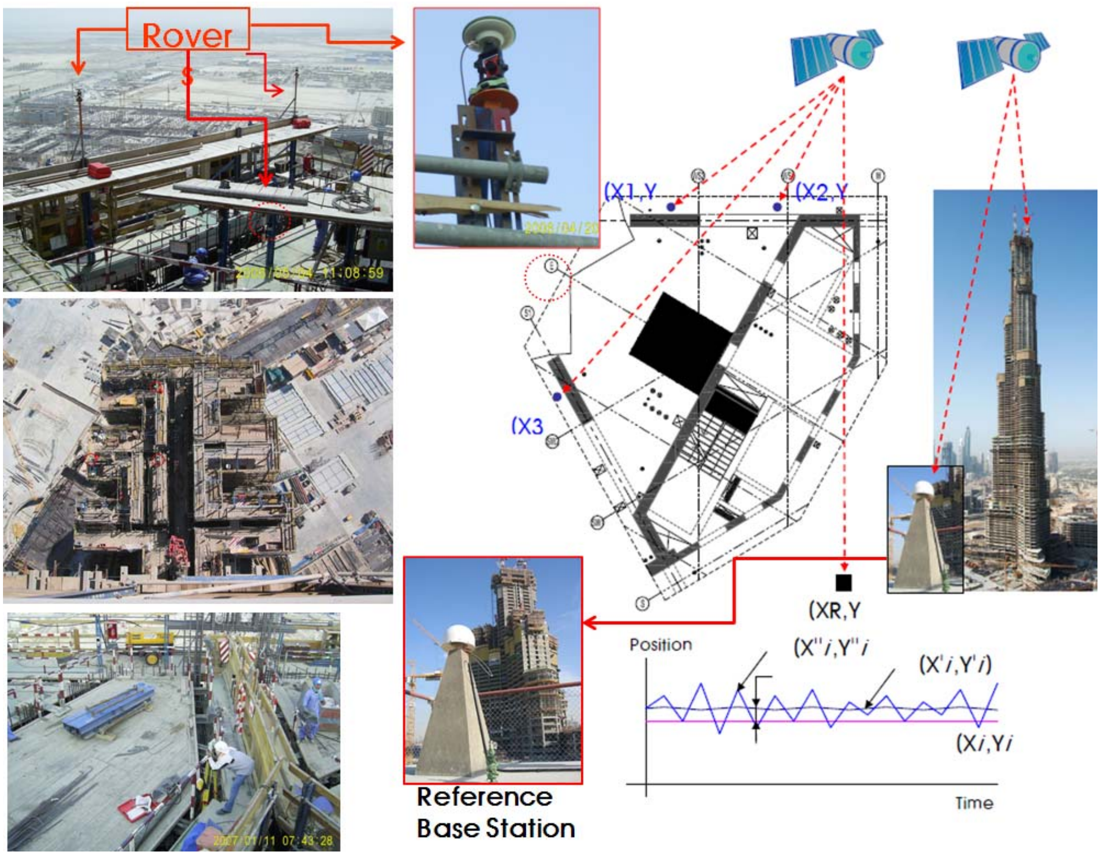

Figure 7. "Measurement System" : (3)GPS Control points, Total Station, Reference Base Station,

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 complicated the survey method further. Therefore, it was necessary to simplify survey procedure and system that can provide control points when the building is moving and that can be measured only once.

Therefore, a “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 the tower’s lateral movements due to the loads and movement described above immediately and to make the necessary correction to bring the ACS formwork system to its geometric center at every level in order to maintain the building verticality within the required tolerance at every level (within 15mm)

The Eight (8) Leica NIVEL200 dual-axis precise clinometers are used to 1) immediately determine the rotation of the tower, and 2) compute the displacement/alignment of the tower in the x and y direction relative to the raft foundation. The clinometers are mounted on the 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 observation will provide the mean x and y displacements for that tiltmeter at that time and that will be used for all future 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.

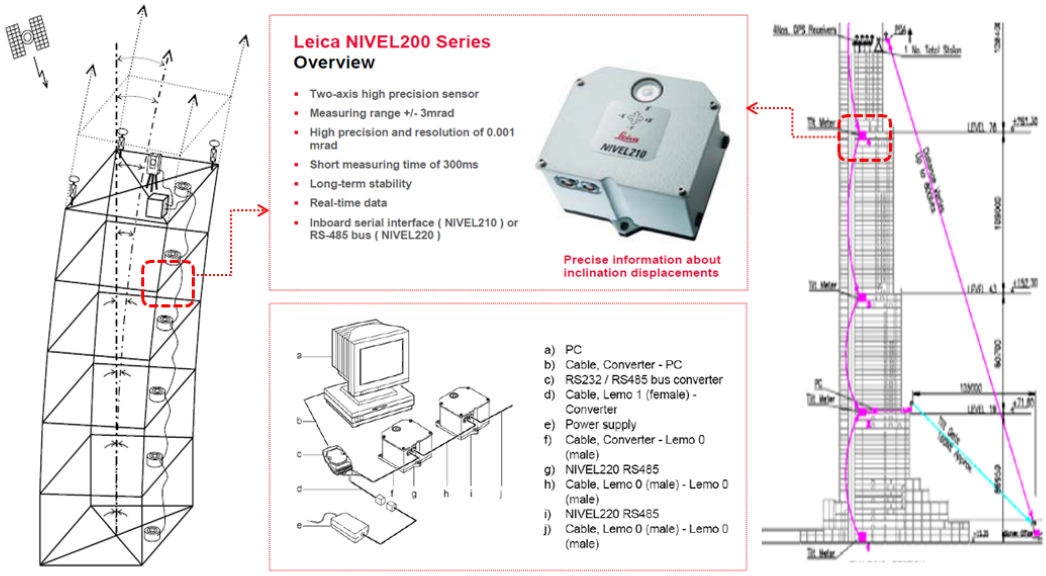

Figure 8. Schemtic for Integrated measurement system“ with clinometers

While fully describing the execution of the survey system of the tower is novel one, 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 includes 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 and when the cranes are shutdown and when the differential solar effects are minimal.

.General Description of the calibrated Finite Element Structural Analysis Model

Comparing the actual measured movements (x,y,z) to the predicted displacements from the calibrated finite element structural analysis model, a three dimensional finite element analysis program was developed for Burj Khalifa that takes 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 execution of all trades as function of time and shown in Figure 9. The intent of this analysis model is to predict 1) the foundation settlement, 2) the tower lateral displacement (x&y) from foundation to top of the pinnacle, 3) the column/wall shortening due to elastic/creep/shrinkage effects, 4) the dynamic building characteristics, 5) the strength design check of the critical elements, specially at outriggers and link beams, 6) and the lateral displacement (x,y,&z) due to any seismic events during construction and after the completion of the tower.

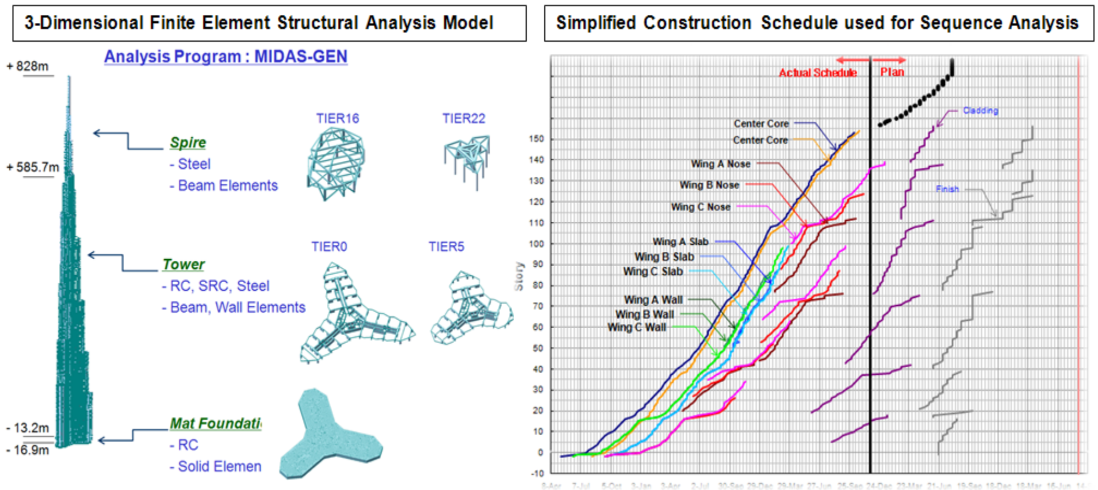

Figure 9. 3-D FEA model and Simplified Construction Schedule used for Sequence Analysis.

3.1.1 Foundation settlement Survey

As described above, a soil structure interaction finite element analysis model developed to simulate the construction sequence of the tower that also include a detailed analysis model of the raft. The foundation settlement was initially estimated based on the subgrade reaction modulus provided by the geotechnical engineering consultants; however, the foundation stiffness were adjusted, based on the actual measured settlements. See Figure 10. The soil structure interaction analysis 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.

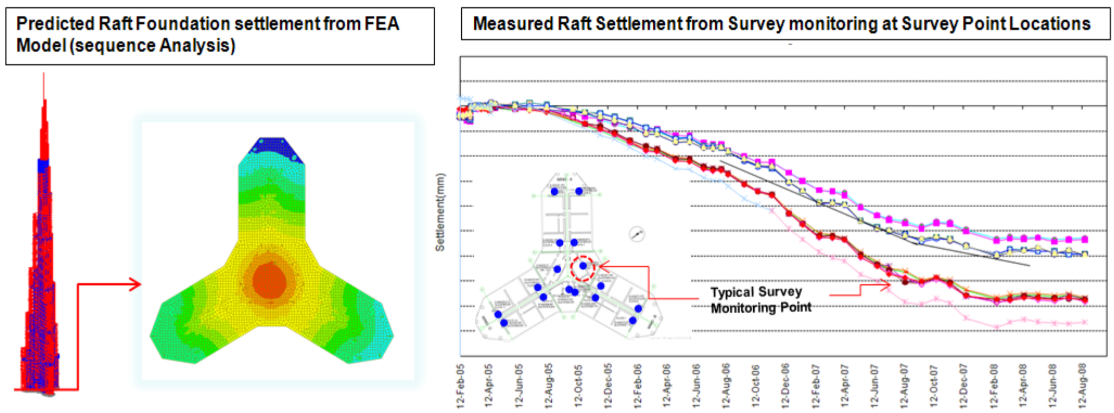

Figure 10. Foundation Survey Point and measured foundation settlement

Comparison between the predicted settlements, from the calibrated foundation settlement analysis that takes into account construction sequence, and the measured settlement values were excellent considering the complexities involved in the analysis and the geotechnical conditions. Settlement analysis took into account the soil flexibility and pile shortening.

3.1.2. Column and wall shortening Survey

Since Burj Khalifa is very tall structure, column differential shortening was considered to be one of the most critical issues to consider since the inception of the design stage and during the construction stage. The structural system was developed to overcome this issue fundamentally during the development and selection of the tower structural system by equalizing the stress and similar long term behavioral characteristics 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 engaging them into the lateral system and to allow for better gravity load and stress distribution. However, to have a better estimate of the column shortening and extensive concrete testing programs were put in place and monitor the concrete characteristics. The actual concrete test data were used in the analysis construction sequence analysis to have understanding the building movement during construction, during its lifetime, and to allow the flexibility of making adjustment to the compensation program (if needed).

An extensive survey monitoring program concept was also developed by the author 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 and compared against the predicted measurements, 2) used as a tool to keep track of the overall building structural behavioral characteristic, 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.

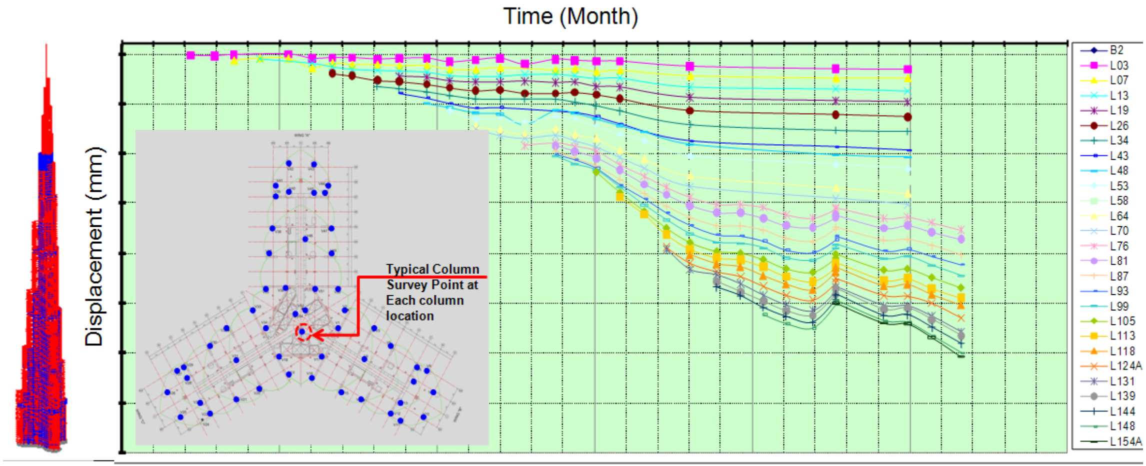

Figure 11. Location of typical survey points at all column/wall locations and center core wall shortening subsequent to survey point installation at all surveyed levels.

3.1.3. Survey of the tower lateral movement of the Tower 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 movement and to make the necessary corrections to build the tower to its geometric center, the tower lateral movement was constantly monitored, almost daily, as described in the survey section above. A detailed optical survey program was also performed monthly at every setback level to measure the lateral movement subsequent to the time of its installation. See Figure 12 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 construction sequence analysis model that took into account the foundation stiffness, actual material properties (strength/elastic modulus/creep/shrinkage), and the detailed construction program for all trades activities as a function of time. This analysis was performed on regular basis to compare the actual measured lateral movements to the predicted lateral movement during tower construction, after completion of the tower construction, and under permanent and long term building conditions.

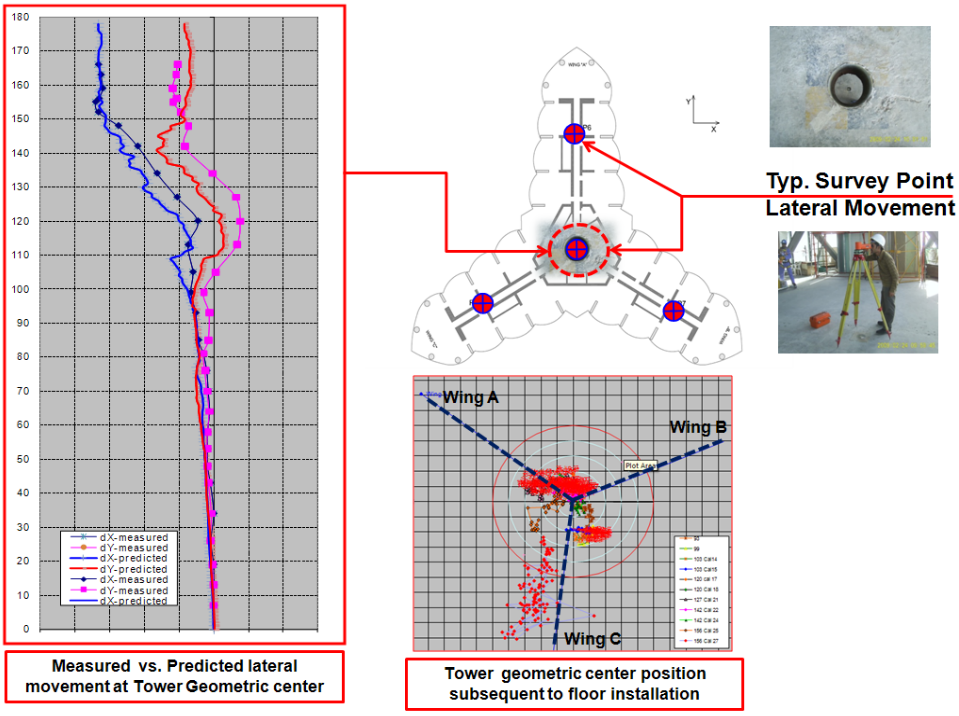

Figure 12. Measured vs, predicted tower lateral movement at tower's geometric center and lateral movement survey point locations.

3.2 Strain Gage Measurement during construction and for permanent building condition.

In order to manage column shortening and lateral movement issues of the tower, an extensive strain measurement program was also developed by the author to measure the total strain in the core wall and columns due to elastic, shrinkage, and creep strains. In addition, the intent of this strain measurement and monitoring program was to measure the actual strain in the building at typical column locations (not effected by local conditions), but to also measure the actual strain/stress distribution in areas where large load re-distribution is expected, especially in the areas above and below the outrigger levels and as shown in Figure 13. Figure 13 also shows that the strain gages and load cells are installed at the raft foundation to measure the bending strains at the bottom of the raft and the direct load transfer from the raft t the soil layers through bearing. In addition, temporary weather stations are installed at several setback level to measure the temperature, humidity, wind velocity and direction at several setback level.

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 starin gages, VSM 4200 by Geokon, were designed for direct embedemnent in the concrete. In addition, 24 Geokon embedment vibrating wire strain gage (type 4200), 3 guage rossettes at the raft and 2 rossettes at the load cells, were installed at the raft foundation.

The in-situ strain measurements shown in Figure 13 below were compared with the tower predicted strains, from Samsung detailed analysis models, from the time of installation until the completion of the tower construction. Good correlation between the predicted and measured strains was 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.

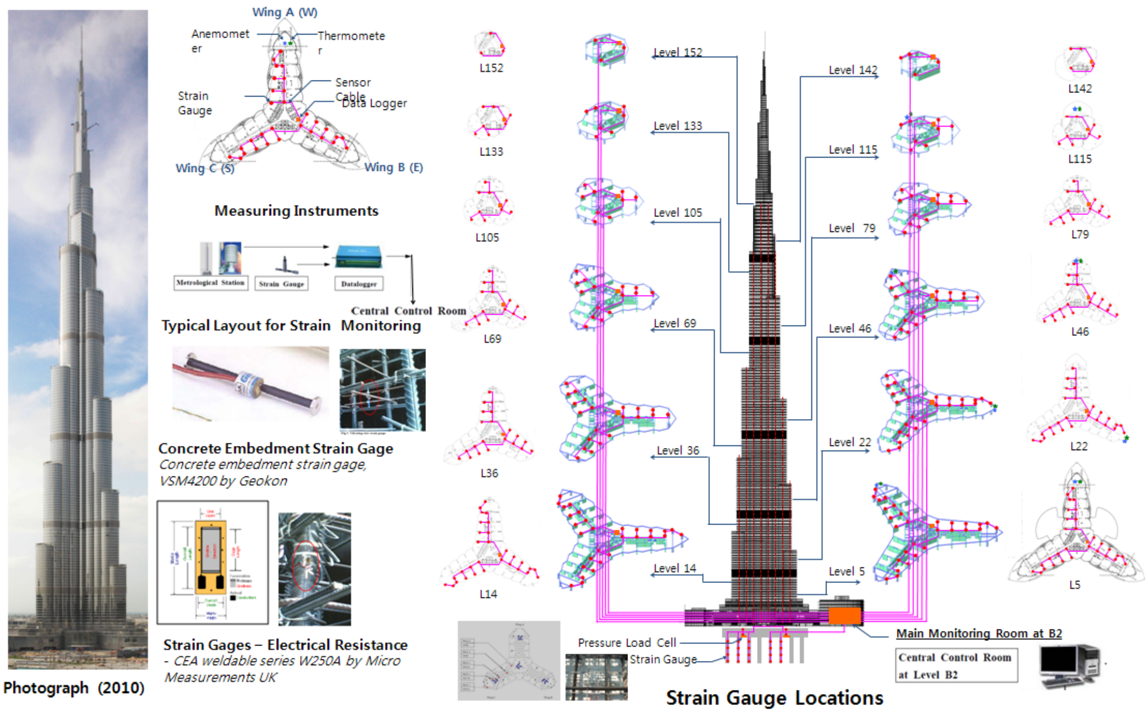

Figure 13. Typical Strain Gage Monitoring System Layout at column/walls/Pile/Raft foundation

3.2.1 Selection of Temporary Real Time Monitoring Program and Network

A temporary real time monitoring program was installed at the tower 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; this system was used to measure the building real time displacement with time; and 3) a weather station was also installed 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 until wind load remained small throughout the construction period, on September 10 2008, the tower was subject 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 wewr evacuated at the time of the quake. Figure 14 shows that measured motion of the tower at level 139. The peak acceleration observed were 2.76milli-g and 3,82milli-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 the University of Notre Dame (Karem, Kejiwski, and Kwon) was used as the seed in expanding the monitoring system into the Full Scale Structural Health Monitoring Program, which is probably firs of its kind in the history of Tall Building

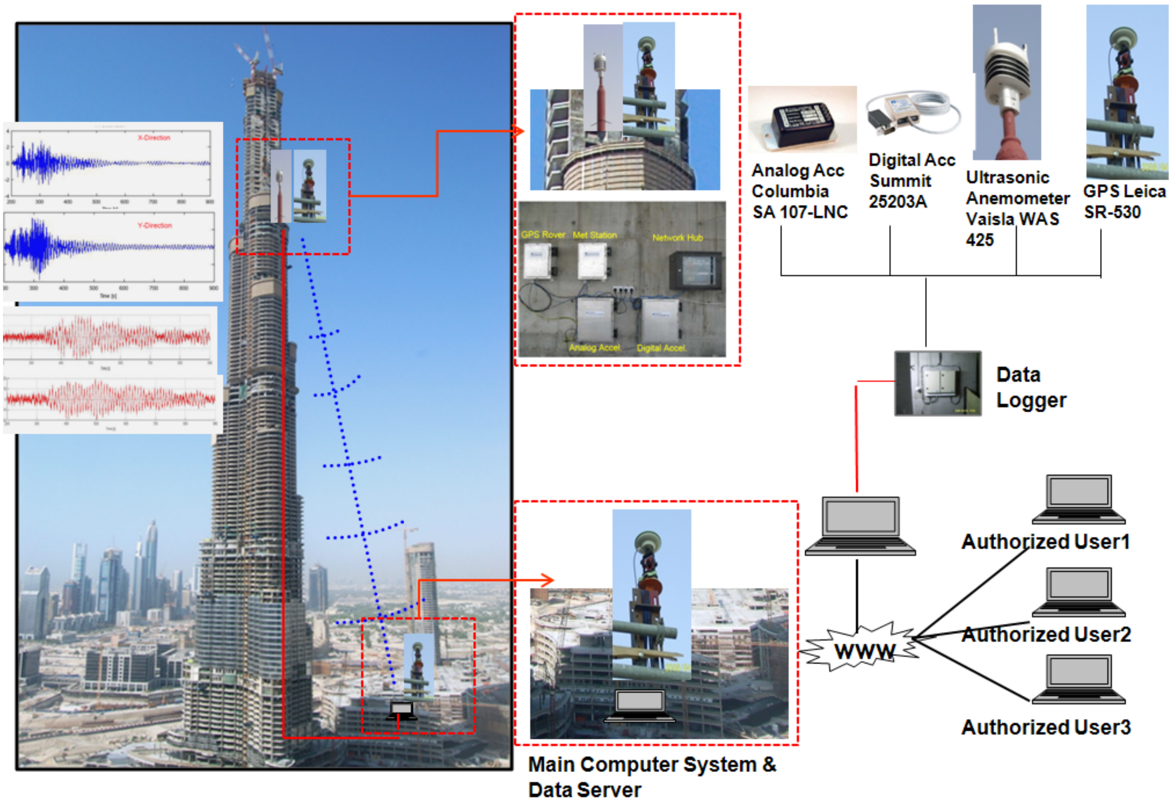

Figure 14. Detailed Summary of the temporary real time monitoring program configuration and building movement during construction (due to Sept. 10 2008 earthquake in Iran).

3.2.2 Permanent Full Scale Real Time Structural Health Monitoring Program and Network

The final chapter of the monitoring the structural system of Burj Khalifa was concluded by the development and installation of a comprehensive structural health monitoring (SHM) program consisting of 1) 3 pairs of accelerometers at the lowest basement level of the tower, 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) 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 +828m 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 was an extension to the already developed temporary SHM developed to monitor the building behavior during construction and developed in cooperation between the author at Samsung C &T, The University of Notre 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.

Since the complete 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 all 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 buildings.

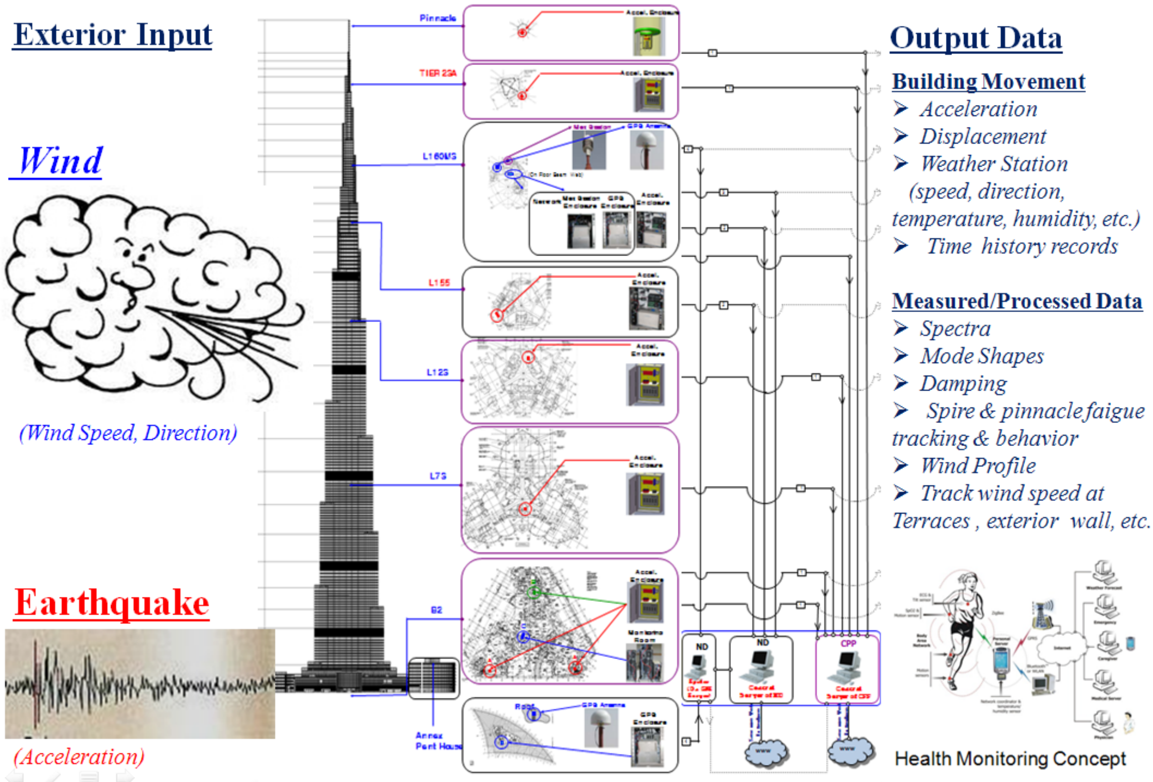

Figure 15. Detailed summary of the permanent real-time Structural Health Monitoring (SHM) program Developed Concept at Burj Khalifa by the author

Comparison between the predicted building behavior and the in-situ measured response has been excellent. While these finding cannot be shared fully here because of confidentiality, Figure 16 provide 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 reached Dubai and is relatively small (less than 1milli-g at BK site), the earthquake had frequency content 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 displacement (not to scale) of the tower is shown in Figure 16 at all monitored levels.

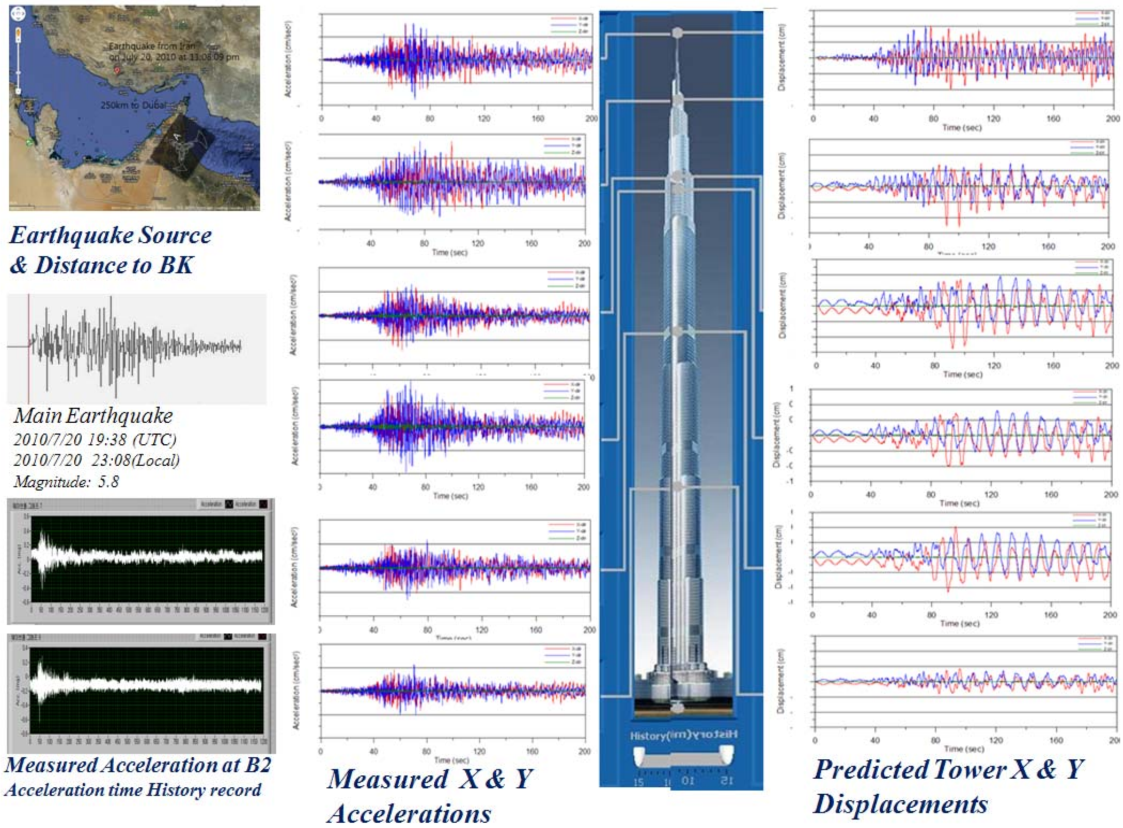

Figure 16. Sample of measured acceleration at all levels (not to scale) and predicted displacement at all levels due an earthquake event that occurred in southern Iran on July 10, 2010.

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 developing the structural and foundation systems for Burj Khalifa, while at SOM, involvement in the development of the construction methodology and planning of Burj Khalifa, at Samsung, his involvement with the “Full Scale Monitoring Program in Tall Buildings under wind”, while at SOM, and the author passion to reflect on the actual performance of the structure by confirm concrete materials characteristics, design assumptions, and analytical modeling techniques has led to the development of a 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 and included the development of comprehensive:

- Testing for 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 of the tower 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 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 the fatigue behavior of the spire/pinnacle.

The measured data collected from the above survey and monitoring program were compared with the predicted structural behavior and responses were found in good agreement. The SHM and survey and other monitoring 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 expected performance during construction and long term performance.
- Identified anomalies at early stages and allowed for means to correct them
- Generated very large in-situ data on concrete materials and structural system behavior sand characteristics for all building components.

The survey and structural health monitoring programs developed for the Burj Khalifa will no doubt will 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, after several years after the development of the survey and SHM programs of Burj Khalifa, significant 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.

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