Implementation of the SmartSync Concept on the Burj Khalifa: An Application of Structural Identification for Tall Buildings

Tracy Kijewski-Correa[1], Dae Kun Kwon[2], Andrew Bartolini[3], Ahsan Kareem[4], and Ahmad Abdelrazaq[5]

[1]Linbeck Associate Professor, Dept. of Civil & Environmental Engineering & Earth Sciences, Univ. of Notre Dame, Notre Dame, IN, tkijewsk@nd.edu
[2]Research Assistant Professor, Dept. of Civil & Environmental Engineering & Earth Sciences, Univ. of Notre Dame, Notre Dame, IN, USA
[3]Graduate Student, Dept. of Civil & Environmental Engineering & Earth Sciences, Univ. of Notre Dame, Notre Dame, IN, USA
[4]Moran Professor, Dept. of Civil & Environmental Engineering & Earth Sciences, Univ. of Notre Dame, Notre Dame, IN, USA
[5]Executive Vice President, Highrise and Complex Building Division, Samsung C&T Corp., Seoul, South Korea

ABSTRACT: The SmartSync concept, which utilizes the local area network of a building for the transmission of data, provides a flexible, cost-efficient system for the full-scale monitoring of tall buildings. Data collected through this system has been used to validate underlying wind tunnel and finite element models used for the design of this building and provide deeper insights into their dynamic response and effect on the comfort of their occupants. This information is then used guide long-term maintenance and management. The SmartSync concept was initially demonstrated on the Burj Khalifa and has been used for its long-term monitoring since 2009.

Test Structure and Measured Data

Since the inception of the profession, structural engineers have been tasked with the design of projects of immense size, cost and ever-increasing complexity for which full-scale prototyping is not possible. This forces reliance on scaled physical models and computational models fraught with approximations and assumptions and requiring considerable conservatism. Moreover, as designers push the limits of conventional structures, there are legitimate questions surrounding the extensibility of established design and construction techniques. This is especially true for tall buildings, which are lighter, more flexible and less damped than conventional buildings, resulting in dynamically sensitive structures that have complex interactions with the surrounding urban environment and their occupants. In recent decades, full-scale monitoring has provided the only source of feedback to the design of these complex and expensive structures. Regrettably, post-commissioning monitoring programs have not been widely adopted for buildings outside of earthquake zones, primarily due to concerns over liability and reputational harm to these high value properties. This trend must be reversed in order to take advantage of the insights monitoring can provide and that begins with providing owners with low-cost, low-intrusion, flexible monitoring systems.

Much as conventional design methods cannot be extended readily for tall buildings, traditional approaches to instrumentation fall short as well. These approaches historically relied on centralized systems networking sensors with shielded cables. The wired system addressed the problems of synchronization and loss of data in transmission, but running cables vertically over highly partitioned tall buildings is frankly infeasible. Therefore, significant research was invested into wireless arrays using multi-hop wireless transmission of the data. While this system enables distributed sensing at a reasonable expense, wireless sensing has added complexities of ensuring all sensor data is synchronized and that there is no loss of data in the wireless transmission, which can be challenging on mechanical levels, generally the only levels where sensor installations are permitted in these buildings [1].

Seeking to find a new solution that allowed for distributed sensing in a cost-efficient manner and that did not result in synchronization or data loss problems, the authors created the SmartSync system. In this concept, the structure's internet backbone replaces the cables in a wired system to connect the sensors to a central server located within the structure. Self-contained sensor modules, measuring multi-axis accelerations, global displacements or meteorological data, can be installed anywhere throughout the building, provided nearby access to power and a network connection. This feature of the SmartSync system provides the flexibility to easily deploy, relocate and expand the sensor array over time. Given the sampling rates and sensor density required when monitoring tall buildings, the use of local area networks is completely feasible for synchronizing data streaming across such arrays [1].

The SmartSync system was first implemented on the Burj Khalifa, which is located in Dubai, United Arab Emirates. An image of the Burj Khalifa is shown in Figure 1. At 828 meters in height, the Burj Khalifa is the tallest building in the world. Its 160 floors have a number of uses including residential units, office spaces and hotel rooms. The Burj Khalifa's lateral system is a buttressed core that is 606 meters in height. The remaining height of the building is composed of a diagonally braced steel space frame. The structure's three wings, which form the shape of a Y, connect back to the core, which is hexagonal in shape. The buttressed core effect is augmented by wing walls that extend from the core down each leg of the structure. These wing walls are connected to hammerhead walls, which increase the lateral resistance and result in a structure that is extremely torsionally stiff. Finally, outriggers are used to link the core and the perimeter concrete columns to further increase the system's lateral resistance. These outriggers occur at the mechanical levels of the building [2].

The first installation of the SmartSync system on the Burj Khalifa was in 2008 during construction. Two accelerometer modules were installed at the 137th floor, along with a meteorological module and a global displacement module using GPS technology. A second global displacement module was also installed on a low-rise structure as part of the building podium to serve as a reference point for the GPS. All communication with the sensors, which sample at rates varying from 1 Hz (meteorological data) to 10 Hz (global displacement data) to 20 Hz (acceleration data), used a local fiber optic network and TCP/IP protocol. This installation demonstrated the viability of the SmartSync software to sample at high rates from distributed sensors over local area networks with negligible latency and no loss of data. This proof-of-concept provided immediate feedback on the dynamic properties of the building during the construction phase, as well as on the viability of this Smart Sync concept and the ability of the hardware to operate in the harsh extremes of high-elevation desert climates.

Fig. 1. Burj Khalifa, UAE

In 2010 the system was expanded through a joint venture with Cermak Peterka Petersen (CPP). The expanded array of sensors included a total of nine acceleration modules installed at seven different locations ranging from the three units at the wings of the basement of the structure all the way to the pinnacle. The accelerometer, global displacement and meteorological modules from the previous installation on the 137th floor were moved up to the 160th floor. All the data was managed through the SmartSync concept executed by a pair of local severs: one dedicated to processing GPS data from the global displacement modules to estimate building positions on-the-fly and then pushing this data to second server that synchronized it along with the data streaming from all other modules up the height of the building.

Later in 2016, this sensor array will once again be expanded to include five bi-axial, high-precision tilt meter modules at various elevations to improve the capacity for real-time mean and quasi-static drift evaluation over the height of the building. Inclination data from the tilt meters is converted into displacements along the height of the building. As a number of the building's modes are under 1 Hz, tilt meter displacements can be algorithmically processed along with dynamic displacements from accelerometer modules and global displacements from GPS to yield derived total displacements. These tilt meter modules will also use the TCP/IP protocol to communicate with the aforementioned severs at a rate of 1 Hz. These servers will manage these and the existing modules as well as an array of existing sonimometers monitoring wind speeds over the height. The unification of all these sensors into one system will be accompanied by an expanded web-based data management and interactive visualization environment allowing authorized users to evaluate both the real-time performance of the structure and retrieve archived historical data for structural identification. Figure 2 provides a schematic of the expanded sensor array.

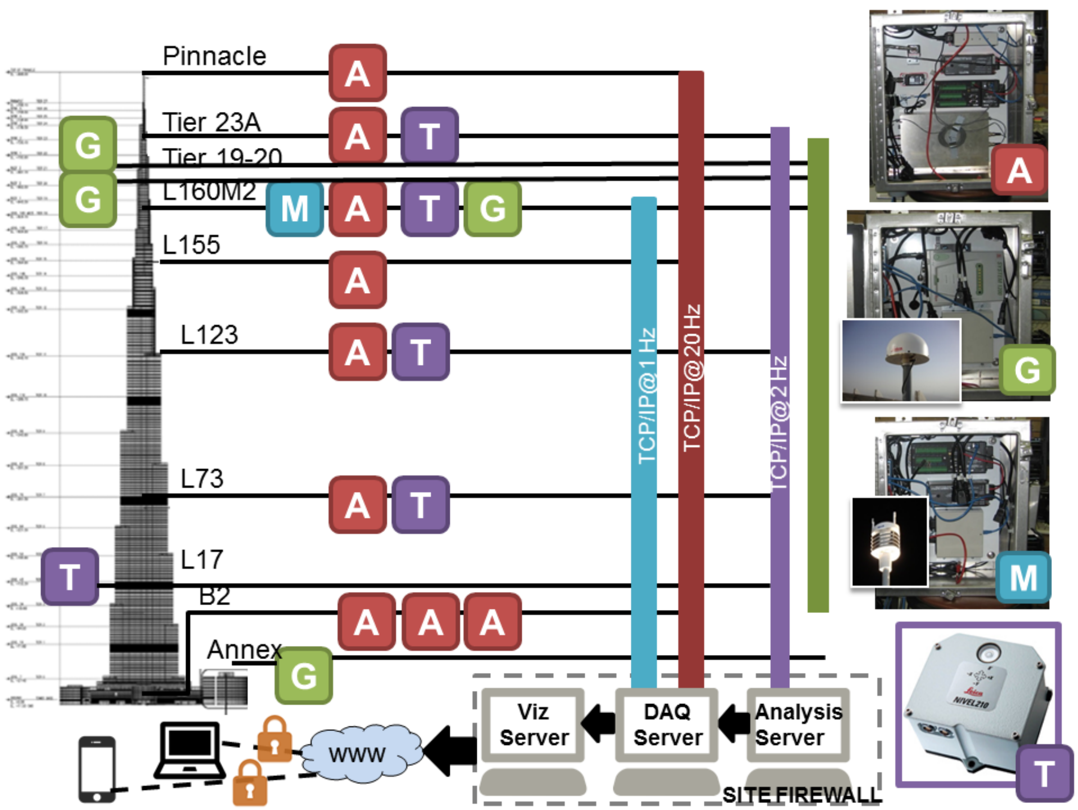

Fig. 2. Schematic of existing and future expansions of sensors on Burj Khalifa

SHM Methodology and Results

The SmartSync application on the Burj Khalifa provides authorized users with direct access to observe the current and archived performance of the structure. The full-scale monitoring system on the Burj Khalifa is a trigger-based system, which means that not all data is retained [1]. Data is buffered for ten minutes, conditioned, and statistics extracted. These are written to the SmartSync database. If the RMS acceleration statistics at a defined master module (selected to trigger under either wind or seismic events) surpasses this threshold, the next 50 minutes of buffered data is also retained and the outputs of all modules are written as a set of time-stamped 1 hour time histories to the database. This process continues until ten minute RMS statistics slip below the threshold. In this way, continuous data is only retained during events of interest (earthquakes and wind storms), minimizing the data management demands and clearly tagging significant events to ease querying and subsequent analysis. This results in a more efficient data management system.

The data can be visualized using several different web-environments by authorized users. A range of displays including statistical summaries, time histories, response loci, and power spectra are available. Additional on-demand system identification modules are included in the system to process triggered time histories and report natural frequencies, damping ratios and mode shapes [1]. Figure 3 shows a sample of one of these web interfaces. A variety of secondary analyses have been created for additional decision support, e.g., mapping acceleration amplitude and frequency to generate maps of human comfort levels [3]. Updated finite element models and acquired data have also been used to evaluate the performance of the structure under wind storms and far-field earthquakes [2].

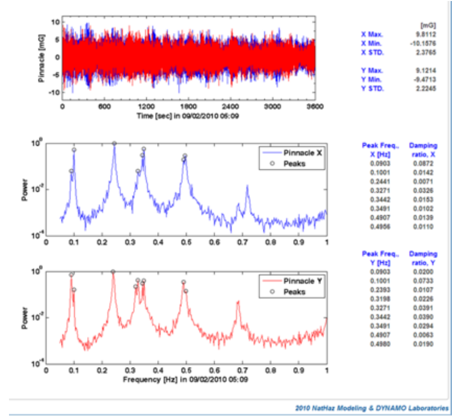

Fig. 3. Visualization Environment [2]

Lessons Learned

It is critical that the structural engineering community have feedback on the performance of structures, particularly those that push the boundaries of complexity, cost and scale. Full-scale monitoring provides such an opportunity. In this application, it is the only means to obtain feedback on the scale-model wind tunnel tests that are the basis for their load and response predictions, as well as on the validity of the assumptions used in the finite element modeling process. The SmartSync system provided a flexible, cost-efficient monitoring architecture for tall buildings like Burj Khalifa, exploiting existing building infrastructure to overcome the limitations of traditional sensor networks. The system has performed well over extended periods of time in harsh environments and verified that sampling as high as 20 Hz can be accommodated on modern local area networks of buildings. The system has continued to demonstrate value to its clients (building owner and engineers of record) and motivated their investment in expansions over time. This emphasizes the importance of (1) creating systems that are affordable, non-intrusive and easy to install and (2) then delivering true value added, including web-based interfaces that increase client awareness and participation in these monitoring efforts so they can become advocates for monitoring.

Acknowledgements

The authors acknowledge the financial support of the National Science Foundation Grant No. CMMI 06-01143, Samsung Corporation and Emaar Properties. The authors also thank former graduate students Jennifer Cycon and Jeffrey Loftus for their efforts on this project and CPP for their collaboration on the permanent monitoring system.

References

[1] Kijewski-Correa, T., Kwon, D.K., Kareem, A., Bentz, A., Guo, Y., Bobby, S., Abdelrazaq, A., SmartSync: An Integrated Real-Time Structural Health Monitoring and Structural Identification System for Tall Buildings, *Journal of Structural Engineering*. 139(10) (2013) 1675-1687.

[2] Abdelrazaq, A., Validating the Structural Behavior and Response of Burj Khalifa, *International Journal of High-Rise Buildings*. (2012) 37-51.

[3] Weigand, T., Kijewski-Correa, T. (2015) “Automated Habitability Assessment and Performance Based Design of Tall Buildings,” *Proceedings of ICWE 14, 14th International Conference on Wind Engineering*, Porto Alegre, Brazil, June 21-26.