The Design of an Integrated Structural Monitoring System for a High-Rise Building Based on Tiltmeters and GNSS

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ABSTRACT:

The use of GNSS sensors in structural health monitoring has become increasingly important. GNSS technology has advanced to the stage where structural parameters can be obtained often without the need for supplementary information from other instrumentation. This paper discusses the design of a structural health monitoring system where the main structural parameters will be gathered from GNSS sensors and tiltmeters installed on a building under construction. This paper also discusses the use of low-cost MEMS accelerometers to complement the GNSS sensors.

The structural health monitoring system will be employed in-construction and post-construction and uses 8 GNSS sensors, 7 tiltmeters and several MEMS accelerometers at critical locations. The system will be operational for approximately 12 months. Results from the system will eventually be used to infer the influence of non-structural members on overall structural stiffness.

1. INTRODUCTION

This research is part of an Australian Research Council (ARC) Linkage project 'A new approach to structural design that incorporates the effect of non-structural components'. This project brings together researchers from the University of Melbourne and the University of New South Wales, along with industry partners C.R. Kennedy Pty Ltd, Leica Geosystems and Vekta Pty Ltd. The project will use full-scale structural measurements acquired from a variety of sensors to determine the impact of non-structural components on the lateral strength and stiffness of high-rise buildings.

The concept is to install measuring sensors on a high-rise building to determine how the structural and non-structural components interact. This interaction will be assessed by an evaluation of derived structural parameters, such as the structure's fundamental frequencies and damping.

Unique features of the monitoring system include the collection and analysis of long-term, full-scale measurements, the integration of data from a diverse array of sensors and the steps taken towards the design of a management- and user-based automated monitoring and analysis system.

2. HARDWARE & SYSTEM ARCHITECTURE

2.1 Available sensors

Measuring structural behaviour at full-scale requires use of a large range of hardware. GNSS sensors have proven capable of monitoring deformation (Li et al., 2006; Park et al., 2008) and the advantage of them returning a 3D position is of particular note. Additionally, the research of Raziq, 2008 has shown that reliable absolute positions from GNSS can be obtained at "mid-height" points (i.e. not only on the roof of the structure). For these reasons GNSS sensors will be the main sensors used in obtaining structural parameters for this project.

Additional to the GNSS sensors, tiltmeters and accelerometers will be employed. Dual-axis tiltmeters are able to measure changes in inclination of an individual structural member relative to the horizontal and vertical planes. Integration with GNSS can determine absolute 3D position. Low cost, three-axis MEMS accelerometers will be used in a proof-of-concept setting for high-frequency measurements and can eventually be used as a complement the GNSS results (Li et al., 2006). Their importance in obtaining structural responses is minimal. The accelerometers are primarily to be installed for comparison against the structural data obtained from the GNSS sensors.

Besides monitoring the structure itself, external influences such as wind speed and temperature need to be measured. For this purpose several temperature sensors will be installed throughout the building. The top of the building will have an anemometer for direct wind speed measurement and weather data from nearby stations will be obtained for a more comprehensive overview of wind and thermal loading.

In summary, the following sensors will be used in the complete monitoring system:

1. 8 Leica GMX902 GNSS receivers
2. 7 Leica Nivel 220 tiltmeters
3. 1 Anemometer
4. 8+ ST Microelectronics LIS344ALH 3-axis MEMS accelerometers
5. 8+ Microchip MCP9801 temperature sensors

The main data will be gathered from the GNSS receivers, which obtain 3D location from both GPS and GLONASS

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constellations. Real-time 3D positions from these instruments will satisfy a nominal horizontal precision of ±5 mm (1 std. dev.), and a vertical precision of ±10 mm (1 std. dev.). Data will be acquired at a frequency of 20 Hz, allowing simultaneous measurement of deformation and the fundamental frequencies of the structure.

In the installation, each of the GNSS receivers will be coupled with an accelerometer and temperature sensor. The accelerometers chosen for this project can measure up to a frequency of 1.5 kHz and will be used to complement the GNSS data and for measuring the higher order (> 10 Hz) fundamental frequencies.

The tiltmeters allow for monitoring within the building where GNSS receivers cannot be used. Each tiltmeter can measure inclination to an accuracy of ±0.005 mm/meter (±0.005 mrad). Wherever a tiltmeter is not installed together with a GNSS receiver, it will be coupled with an accelerometer and temperature sensor.

2.2 MEMS accelerometers

The use of MEMS accelerometers in structural monitoring applications is not new. A comparison of MEMS against more conventional accelerometer technology was performed on the Geumdang Bridge in Icheon, Korea (Kim et al., 2009). In this study a MEMS accelerometer and a high-accuracy piezo-electric accelerometer were interfaced together to obtain the structural response of a highway bridge. The authors found that the MEMS accelerometer was just as accurate as the piezo-electric accelerometer. They also instrumented the Yeondae Bridge, but only with a MEMS accelerometer and of a different brand, obtaining worthwhile results.

MEMS accelerometers are much cheaper than their piezo-electric equivalents and the accelerometers chosen for this research outperform the ones used in the above studies. A comparison is shown in table 1. Due to the lower noise density, a higher resolution can be obtained in this research. Kim et al., 2009 reported a price of about US$250 per accelerometer while in this research a single accelerometer will cost about US$25. As the accelerometer is bought directly as an integrated circuit chip, any measuring and digitizing interface has to be separately designed and implemented.

	Geumdang Bridge	**Yeondae Bridge**	**This research**
Sensor name	PCB Piezotronics 3801D1FB3G	Crossbow CXL02	ST Microelectronics LIS344ALH
Range	±3 g	± 2 g	± 2 g
Sensitivity	700 mV/g	1000 mV/g	660 mV/g
Noise density	140 μg/Hz	140 μg/Hz	50 μg/Hz
Resolution	5.55 mg	5.55 mg	1.98 mg

Table 1. Comparison of MEMS accelerometers

2.3 Installation on the building

As shown in Figure 1, the structure available for monitoring has a main core on the south side, a triangular central core and two rows each of 5 columns for structural support on the east and west sides. The structural components consist of a reinforced concrete frame and a structural steel 'jumpstart' construction up to level 5. The building is currently under construction and when finished will consist of 50 floors and reach a height of 190 metres.

The monitoring system's goal in this case is solely to benefit the research community[1] by evaluating the differences in measured and modelled structural parameters to infer the influence of non-structural elements on structural stiffness, and to showcase the capability of a comprehensive structural monitoring system.

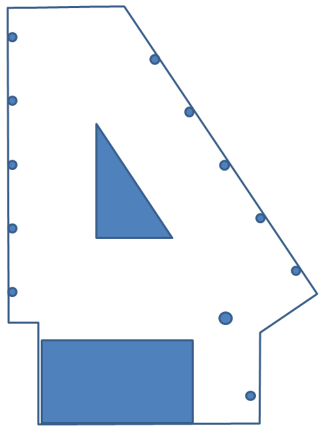

Figure 1. Structural elements of the building

The GNSS receivers will be installed at the locations shown in figure 2. Six of the receivers will be placed on the top of the structure to avoid obstructions and multipath problems. The remaining two will be installed on adjacent corners of the building at equal heights, to allow the mid-height approach of Raziq, 2009 to be proven in practice and its value demonstrated in a real structural monitoring situation. The dotted circles in figure 2 represent the mid-height GNSS receivers (north-west and south-west corners).

GNSS receivers installed at mid-height typically have only about 50% of the sky visible for tracking satellites. Additionally, as they are placed next to the building, multipath can be a significant problem. Data from two receivers on opposite sides of a building can be combined to create a single valid GNSS observation set. Due to the two receivers being only a few metres to a few hundred metres apart, errors from satellite clock, satellite orbits and propagation medium can be considered equal in both receivers. The only errors that demand special attention are the receiver based errors, especially the receiver clocks. Raziq, 2009 has developed an algorithm which combines data from two GPS receivers into one, with the assumption that they are placed on a rigid platform with a known distance between them. Raziq's algorithm takes into account the visible azimuth range from each receiver and rejects any satellite measurements outside this range, as these measurements have to be a result of multipath. The algorithm also deals with the synchronisation of the two receiver clocks.

[1] The monitoring system is not a requirement for the construction or future operation of the building.

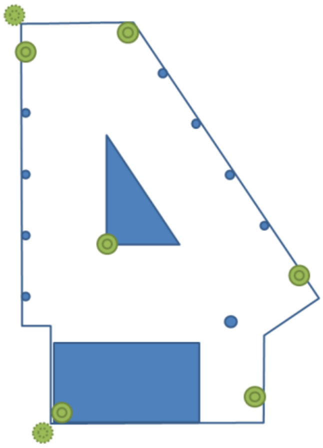

Figure 2. Locations of GNSS receivers on the building

Having six GNSS receivers on the top of the structure will not only allow for accurate displacement and frequency measurements, it will also allow distinguishing local torsion effects. The mid-height GNSS receivers will allow the same information to be gathered at a different height, albeit to a lesser degree of detail.

Tiltmeters will be installed in tandem with the two mid-height GNSS receivers and with three of the roof-top receivers. Of the remaining two tiltmeters, one will be placed at ground level and the other in the central core at approximately mid-height. These two tiltmeters will also be installed together with an accelerometer and temperature sensor. A west side view of the building with the installation locations of the tiltmeters is shown in figure 3.

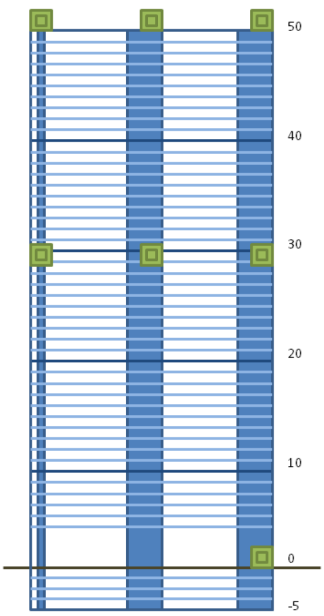

Figure 3. Locations of tiltmeters on the building

The mid-height locations are determined by calculating the different modal responses of the structure and placing the sensors according to the locations with the highest amplitude response. Although the response of a high-rise building can be determined by a cantilevered Timoshenko beam (Boutin et al., 2005), the parameters required for the Timoshenko equations for this structure are unknown. Instead, a simple Euler-Bernoulli cantilevered beam model has been used. Its eigenvalues (λ) can be determined by equation 1.

$$1+\cos(\lambda)\cosh(\lambda)=0 \tag{1}$$

The node positions, meaning the locations where, for a specific mode, no displacement takes place, can be found by using equation 2. In this equation $\bar{x}=x/h$ with h the building's total height, x the position along the building's height, and $0<\bar{x}<1$. Any amplitude effects, such as the mass per unit length are omitted.

$$\phi_r(\bar{x})=\cosh(\lambda_r\bar{x})-\cos(\lambda_r\bar{x})-\sigma_r(\sinh(\lambda_r\bar{x})-\sin(\lambda_r\bar{x}))=0 \tag{2}$$

where

$$\sigma_r=\frac{\sinh(\lambda_r)-\sin(\lambda_r)}{\cosh(\lambda_r)+\cos(\lambda_r)} \tag{3}$$

r is the mode number.

Table 2 represents the node positions for the first 5 modes and figure 4 is the graphical representation of the normalized displacement. From the graphical representation, the highest amplitude of all first five modes is positioned between 0.55 and 0.6 times the building height. The tiltmeter, in combination with the accelerometers and temperature sensors, will therefore be installed at a height of around 110 metres.

Mode	**Eigenvalue (λ_r)**	**Node positions on x-axis ($\bar{x}$)**			
1	1.87510407				
2	4.69409113	0.7834			
3	7.85475744	0.5035	0.8677		
4	10.9955407	0.3583	0.6441	0.9056	
5	14.1371684	0.2788	0.4999	0.7232	0.9265

Table 2. Eigenvalues and dimensionless node positions for the first five fundamental modes

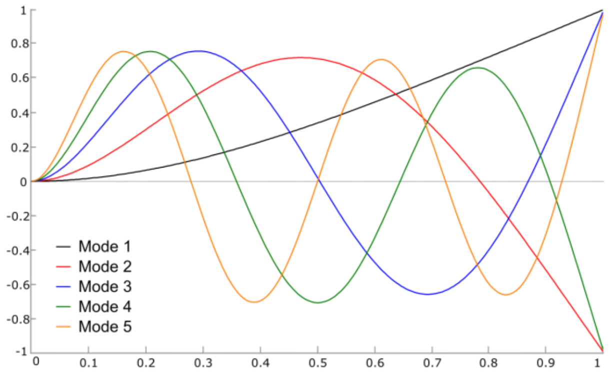

Figure 4. Normalized displacement for the first five fundamental modes of vibration following the Euler-Bernoulli cantilever beam model

2.4 System architecture

The communication between sensors and the local computer system is generally done by installing a wired system, where a central computer gathers and stores all data. The larger the structure, the more wires need to be run and installation can become very complicated and costly. In most newly constructed high-rise buildings a complete communication network is part of the design and this network may be used as the communication interface for the sensors. This type of architecture has been described by Kwon et al., 2010 in their SmartSync system. Every sensor in the SmartSync system requires control electronics to interface with the building's network, commonly a LAN.

During this research the above mentioned support electronics will also be developed and used. However, the structural monitoring system is designed to be modular and capable of use for in-construction monitoring. Therefore, besides the electronics supporting wired networks, it will also have a wireless capability. For this purpose, the IEEE 802.15.4 transmission standard is chosen. Wireless structural monitoring networks are a common research topic (Lynch and Loh, 2006) and have also been successfully implemented in practice (Ou et al., 2005; Kim et al., 2009).

Many structural monitoring systems are set up in a modular fashion, such as the monitoring systems on several Hong Kong bridges (Wong, 2007) and in the Canton Tower (Ni and Zhou, 2010). Their implementation allows for all objectives of this research project to be pursued and additionally allows for management of the building through the monitoring system. A similar modular structure will therefore be implemented. The architecture of the structural monitoring system for the building can be described by figure 5,where the same module names as used by Wong, 2007 and Ni and Zhou, 2010, are used.

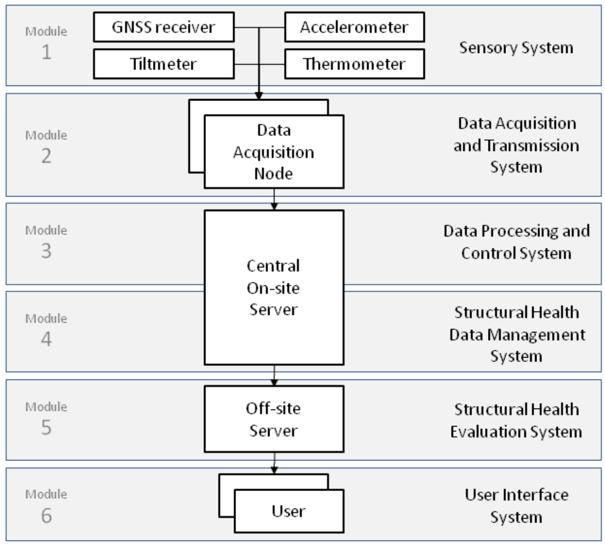

Figure 5. Schematic representation of the structural health monitoring system architecture

Independent of the choice of a traditional or wireless sensor system, the data flow of the structural monitoring system can be transformed into a schematic representation as shown in figure 6. Except for the denotation of the 'building analysis engine', this representation can be easily modified to apply to other structures, such as bridges and towers.

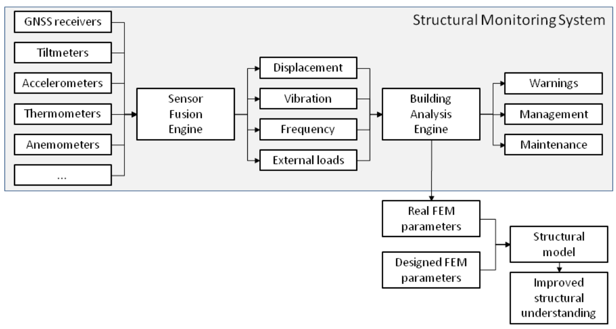

Figure 6. Schematic representation of the dataflow of the structural monitoring system

The development of the structural monitoring system is still an ongoing process and the research team is currently undertaking discussions with additional project partners for installation on the building. When the system is installed it will be active for a period of at least 12 months.

3. CONCLUSION

This paper presents the ongoing process for the development of a structural monitoring system for a high-rise building with the intention of using the data to infer the influence of non-structural elements on the building's stiffness. The structure, the sensors and the architectural representation of the monitoring system are introduced.

The installation's goals are to provide a real-world example of GNSS mid-height location retrieval and the implementation of cheap MEMS accelerometers to complement the GNSS location results. Furthermore steps are taken to implement the modular structural health monitoring system as used on several Hong Kong bridges and the Canton Tower.

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