13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-195

Sustaining vertical giants: Autonomous monitoring solutions for the construction and lifecycle of tall buildings

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ABSTRACT: As urban environments increasingly shift towards vertical development, the challenges associated with constructing and maintaining tall buildings have intensified. Real-time and dynamic monitoring systems play a vital role in addressing these issues by providing accurate positioning and deformation data. The integration of diverse monitoring technologies during and after the construction of high-rise buildings is crucial for ensuring structural integrity, safety, and efficiency.

By combining geodetic and geotechnical monitoring techniques, these systems offer comprehensive insights into building behaviour. The fusion of technologies like GNSS, IoT sensors, and remote sensing, alongside traditional survey methods, ensures precise data acquisition and analysis. This hybrid approach is essential for optimising construction and maintenance processes, reducing costs, and enhancing safety. Furthermore, the ability to process and analyse large volumes of monitoring data efficiently is critical for transforming raw data into actionable insights, aiding decision-makers in understanding the magnitude and direction of structural movements.

The successful implementation of these monitoring techniques on iconic high-rise buildings, such as the Burj Khalifa and One World Trade Center, highlights their importance in modern construction and post-construction maintenance. Ultimately, the intelligent use of integrated monitoring technologies supports sustainable and resilient urban development.

KEY WORDS: Autonomous; Deformation monitoring; Verticality; Positioning; High-rise; Tall buildings.

1 INTRODUCTION

In the rapidly evolving urban landscape, the shift towards constructing tall buildings presents unique challenges that demand innovative solutions. Ensuring the structural integrity and safety of these vertical giants requires advanced positioning and deformation monitoring technologies capable of delivering real-time and precise data on buildings' behaviour.

Environmental forces such as wind and temperature variations can lead to significant deformation during construction, therefore precise measurements are required to maintain vertical alignment and correct positioning. Traditional surveying methods, while effective at lower elevations, often reach their limits as buildings rise, necessitating the adoption of advanced active survey control systems.

In the lifecycle phase, the safety and integrity of tall buildings can again be at risk in case of nearby excavations or movements caused by natural events. In such cases, deformation monitoring is essential, to provide an understanding of structural behaviour.

In both phases of the building's timeline, deformation monitoring information is crucial for decision-makers.

2 CONSTRUCTION OF TALL BUILDINGS

2.1 Surveying challenges

Constructing tall buildings introduces a range of complex and unique surveying challenges primarily due to their height and slender profiles, which significantly alter the structure's rigidity compared to low-rise buildings. As the geometry shifts from a wide base to a narrow top, resistance to deformation decreases, necessitating precise engineering surveying and monitoring systems to maintain vertical alignment and correct positioning. As depicted in Figure 1, environmental forces such as wind loads can cause deflection, varying with the stiffness of different elements and the location on the building. Temperature changes and sunlight can lead to uneven thermal expansion, causing the building to lean. Additionally, as construction progresses, the increasing mass leads to the compression of lower elements, potentially resulting in differential settlement and vertical alignment issues. This requires adjustments to the vertical datum to account for axial shortening and ensure the final height meets specifications.

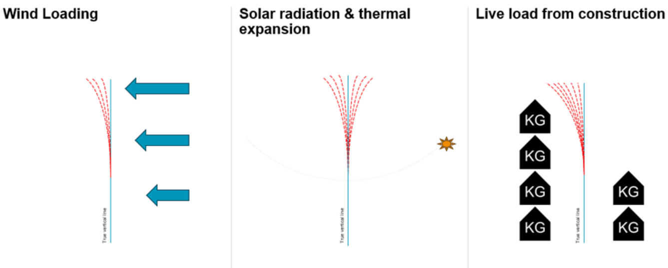

Figure 1 Environmental forces and live load impacting tall buildings [1]

Dimensional control is crucial for each floor's horizontal and vertical alignment, involving traditional survey methods like optical levelling, plumb line and total stations. These methods establish base gridlines at stable ground levels, with new references created as construction progresses. However, maintaining uninterrupted vertical lines of sight can be

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challenging and costly, slowing down the construction progress and bringing risks to the structural stability of the high-rise building. For this reason, between 100m and 200m elevation from the ground level, the traditional and passive survey methods reach their limits and must be replaced with high-rise specific active survey control positioning methods.

2.2 Active survey control and deformation monitoring

The introduction of active survey control systems marks a significant advancement in the field of structural deformation monitoring and positioning systems for tall buildings. These systems leverage the power of interoperable connectivity between survey instrumentation and Internet of Things (IoT) sensors, providing real-time data that ensures accurate positioning. By automatically resolving positions to the necessary precision, active survey control systems reduce human error and enhance efficiency. These systems employ Global Navigation Satellite Systems (GNSS) and IoT sensors to continuously monitor and report positions, compensating for dynamic structural deformation. This capability establishes survey control points and a reference frame within specified tolerances, streamlining the engineering surveying process.

The solution provided by Leica Geosystems, Core Wall Control System (CWCS) shown in Figures 2 and 3, specifically developed and advanced for tall building construction over 15 years since the construction of Burj Khalifa [2], combines the following components:

- Leica iCON GNSS Smart Antennas placed on the uppermost floor to provide continuous, real-time positional data collocated with 360° prisms
- Robotic total stations, such as Leica TS16/60, measuring prisms and used for establishing and verification of the survey control using positional information provided by the monitoring software
- GeoCloud Drive service responsible for data transfer and synchronization of results between the field instrumentation and monitoring software
- WiSenMeshWAN® IoT inclinometers and distance meters deliver displacement information at various levels
- GeoMoS Monitor software for GNSS and IoT data processing and publishing positioning results consumed by total stations for stakeout

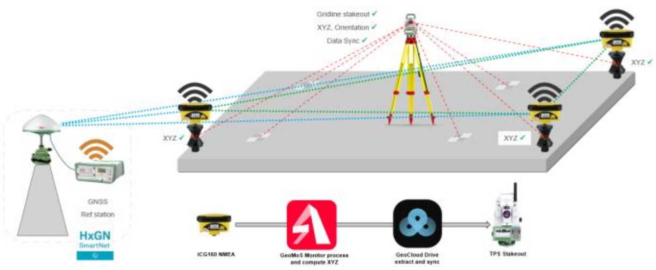

Figure 2 Leica Geosystems' CWCS solution [1]

The real-time information provided by these systems is used to determine live axial shortening values for structural compression. This is achieved through multiple vertically installed IoT distance sensors, while the rotation component from the sensors helps determine live structural tilt. Additionally, GNSS positioning data provides absolute XYZ locations at the upper working face of the building, creating a comprehensive integrated solution. By combining these data sets with traditional monitoring of foundation deformation and environmental sensors, engineers gain a thorough understanding of where to place new elements at the upper workface, ensuring that positional data is available and within tolerance when required.

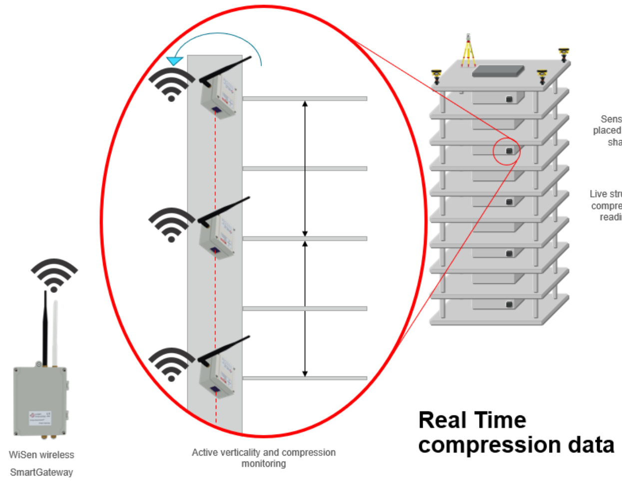

Figure 3 WiSenMeshWAN® solution for real-time compression readings [1]

Although the accuracy of live RTK GNSS positioning is around ± 3cm, averaging the results over the period of at least one hour will significantly improve the accuracy. Figure 4 displays the combination of raw and averaged 6-hour RTK GNSS data, where raw data shows horizontal consistency within ± 2cm over 24 hours, whereas averaged results filter out dynamic movements and reveal slow movements of the building influenced by cyclic environmental conditions, reaching the accuracy of ±5mm.

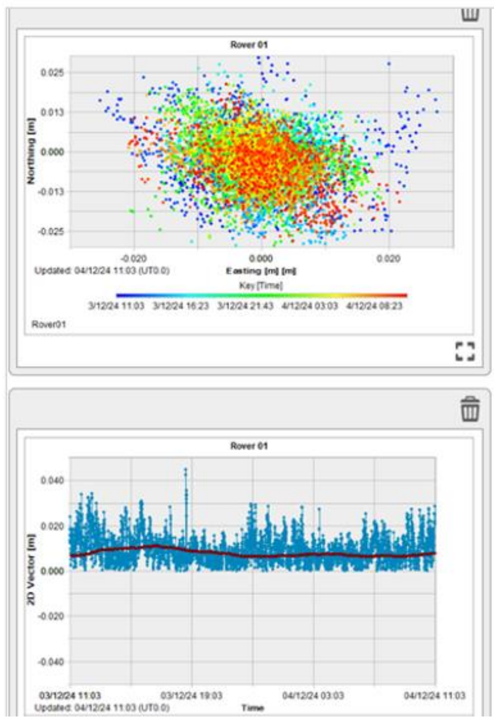

Figure 4 Raw and averaged RTK GNSS data over 6 hours

DOI: 10.3217/978-3-99161-057-1-195

Real-time monitoring systems extend beyond construction, monitoring the building's lifespan and supporting future design models.

2.3 Real-life examples

Since the first implementation of the Core Wall Control System for the construction of Burj Khalifa, CWCS has been deployed and further developed in many iconic high-rise and super high-rise buildings worldwide. Some of the examples are:

- 432 Park Avenue in New York City [3] completed in 2015 and standing at 426m
- The Central Park Tower in New York City [4] – one of the tallest residential buildings with 472m, completed in 2020
- One World Trade Center in New York City – the tallest building in North America with 541m, completed in 2014
- Millenium Tower in Boston [5] – one of the tallest residential buildings in Boston with 208m of height, completed in 2016
- 22 Bishopsgate in London [6] – the second tallest building in the UK with 278m, completed in 2020
- The Shard in London [7] – the tallest building in the UK with 306m, completed in 2013

3 STRUCTURAL HEALTH MONITORING OF TALL BUILDINGS

Every building and structure changes over time due to various environmental and structural impacts and neglecting these changes can have serious consequences. Tall buildings are particularly impacted due to their unfavourable geometry. The most common causes of movements in urban environments include nearby construction, excavations, ageing of the structure, maintenance of the building, natural hazards and seismic activity.

3.1 Choosing the right technology

No single technology can fully capture the dynamic behaviour and the entire scope of high-rise and super high-rise buildings. Also, each technology has its advantages and limitations, which should be considered when designing the deformation monitoring system. Hence, a hybrid approach is essential [8].

In the case of geodetic monitoring, prism and GNSS measurements provide a complete 3D understanding of movements but are limited to a small number of single points depending on either a clear line of sight or an open sky. Automated 3D laser scanning in monitoring [9] on the other hand captures thousands of points per second, but can only deliver information about deformations perpendicular to the scanned surface. Geotechnical sensors, such as inclinometers and extensometers, provide point-specific data in a relative, non-georeferenced context. However, due to the IoT technology, they can be installed indoors and outdoors and create a self-forming dynamic radio mesh network which sends data to a gateway.

The fusion of geodetic and geotechnical data creates a more complete picture of building deformations. By cross-analysing data from different sources, engineers can validate findings and ensure the reliability of the monitoring system. This integration allows for early detection of potential issues, enabling proactive measures to maintain structural integrity.

3.2 Edge computing, automation and autonomy

The integration of edge computing, automation, and autonomy into monitoring solutions represents a significant advancement in the field [10]. These technologies enhance the efficiency and reliability of data acquisition and processing, enabling real-time insights into structural behaviour.

GeoMoS Edge is crucial in Leica Geosystems' monitoring systems because it addresses the significant challenge of data acquisition continuity during communication outages. Traditional monitoring systems rely heavily on stable communication between sensors and a central server, which can lead to data gaps and safety risks when communication is disrupted. GeoMoS Edge mitigates this issue by embedding a data acquisition component directly on a communication device, allowing the system to operate autonomously even during periods without connection to the GeoMoS monitoring software.

This autonomy ensures that measurements continue uninterrupted, eliminating data gaps that could otherwise pose safety threats. By replicating server functionality on edge devices such as Leica ComBox60, GeoMoS Edge can perform measurement cycles, assess data quality, and trigger repeated measurements if necessary. Once communication is restored, the collected data is seamlessly delivered to the central monitoring software.

4 CONCLUSION

The integration of deformation monitoring technologies in the construction and lifecycle management of tall buildings is the key for stability and health of the structure and the people in its vicinity. The combination of GNSS, IoT sensors, and traditional survey methods provides a comprehensive understanding of structural behaviour during its construction, allowing for precise positioning as the building grows. This hybrid approach, as demonstrated by Leica Geosystems' Core Wall Control System (CWCS), has proven effective in iconic buildings worldwide, starting from Burj Khalifa in the United Arab Emirates, over 22 Bishopsgate and The Shard in the United Kingdom, to The Central Park Tower, One World Trade Center and many others in the United States of America. By leveraging real-time data from geodetic and geotechnical sensors, engineers can monitor axial shortening, structural tilt, and environmental impacts with high accuracy, enabling proactive measures to address potential issues.

The continuous development of these technologies, including edge computing and automation, further enhances the reliability and efficiency of data acquisition and processing. Solutions like GeoMoS Edge ensure persistent monitoring even during communication outages, mitigating safety risks associated with data gaps. This autonomy allows for uninterrupted measurements and seamless data integration, supporting informed decision-making throughout a building's lifecycle.

Ultimately, the adoption of integrated monitoring solutions not only optimises construction and maintenance processes but also supports sustainable urban development. As cities continue to grow vertically, the demand for precise and reliable monitoring systems will increase, driving further innovation in the field. By embracing these technologies, stakeholders can ensure the safety, efficiency, and longevity of high-rise

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buildings, contributing to resilient and sustainable urban environments.

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