Structural Health Monitoring and Real-Time System Identification Analysis of the World's Tallest Sculptured Skyscraper

JAFARALI PAROL, JAMAL AL QAZWEENI, HASAN KAMAL and EROL KALKAN

ABSTRACT

With the rapid increase in the construction of tall buildings around the world, ensuring their safety and structural integrity has become of paramount importance. This paper focuses on the Al-Hamra Tower, a remarkable skyscraper standing at an impressive height of 412.6 meters (1,353'-6") in Kuwait City in Kuwait, and explores the role of Structural Health Monitoring (SHM) as a powerful tool for assessing building conditions, detecting damage following extreme events, and optimizing cost-saving strategies. Among the various factors that can lead to building failures, extreme events such as earthquakes in the Gulf Region pose the greatest threat. If damage conditions are not promptly identified, they can leave the structure vulnerable to further deterioration. Early diagnosis of damage is not only crucial for the safety of occupants but also proves to be cost-effective, as repairing minor damage is generally more affordable than addressing major structural failures. This paper presents an advanced AI-powered SHM system specifically developed for the Al-Hamra Tower. The study delves into the implementation of a dense array of instrumentation strategically placed throughout the tower to capture and measure its structural response under different loadings, including wind, seismic activity, and thermal effects. The SHM system incorporates an automated triggering mechanism that responds to predefined events, such as earthquakes, and promptly sends text and email notifications to alert relevant authorities. By highlighting the case study of the Al-Hamra Tower, this research underscores the critical importance of SHM for tall and critical buildings, offering invaluable insights into the design and implementation of effective SHM systems for future skyscrapers.

Keywords: AI, SHM, machine-learning, earthquake, tall-building, multi-sensing, big-data, analytics, early-warning, seismic-design, neural-network

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INTRODUCTION

In recent years, the global landscape has witnessed the emergence of ever-taller buildings, transforming city skylines and pushing the boundaries of architectural achievements. As these impressive structures continue to reach unprecedented heights, ensuring their safety and structural integrity becomes a matter of paramount importance. One notable example of this trend is the Al-Hamra Tower, standing majestically at a towering height of 412.6 meters (1,353’-6”) (**Error! Reference source not found.**) in Kuwait City, Kuwait. The unique challenges posed by such immense structures necessitate the implementation of innovative approaches to monitor their health and mitigate potential risks.

Structural Health Monitoring (SHM) has emerged as a powerful tool in assessing building conditions, detecting damage after extreme events, and optimizing maintenance strategies. The ability to rapidly identify and evaluate the extent of damage following events such as earthquakes is crucial in safeguarding structures and preventing catastrophic failures. Furthermore, early detection of damage offers significant cost advantages, as addressing minor issues is generally more economical than dealing with major structural deficiencies.

This paper focuses on revolutionizing building safety through the case study of the Al-Hamra Tower and highlights the application of SHM as a pioneering solution. It explores the implementation of an advanced AI-powered SHM system specifically tailored for this iconic structure. The system utilizes a dense array of instrumentation strategically placed throughout the tower to capture and measure its response to various loadings, including wind, seismic activities, and thermal effects.

Moreover, this study emphasizes the role of SHM in triggering timely alerts during predefined events, such as earthquakes, through automated mechanisms. Authorities receive immediate text and email notifications, enabling them to swiftly respond to potential threats and ensure the safety of occupants and surrounding areas. The integration of AI algorithms enables effective data analysis, facilitating accurate assessments of the structure's health and performance.

Figure 1. Al-Hamra Tower in Kuwait (https://www.som.com/projects/al-hamra-tower/).

Through the Al-Hamra Tower case study, this paper sheds light on the critical importance of SHM for tall and critical buildings. It showcases the significance of implementing advanced monitoring systems to detect anomalies, mitigate risks, and optimize maintenance strategies. The findings and insights gained from this study can serve as valuable guidance for the design and implementation of effective SHM systems for future skyscrapers, contributing to enhanced building safety and the preservation of invaluable architectural assets.

OVERVIEW OF MONITORING SYSTEM OF THE TOWER

The SHM system implemented at the Al-Hamra Tower comprises a comprehensive solution that utilizes a network of strategically placed high-precision sensors throughout the entire building. These sensors play a critical role in measuring and monitoring various vital structural parameters, including accelerations, inclinations, temperature variations, and displacements. This extensive sensor network provides a detailed understanding of the building's structural behavior under different loading conditions, facilitating effective performance evaluation and damage detection.

The sensor installation plan was meticulously executed, resulting in the placement of sensors across nine floors of the tower. The configuration includes a total of 24 biaxial accelerometers, two triaxial accelerometers, and two uniaxial accelerometers [1]. All sensors are force balance accelerometers (FBAs) with low noise levels. The uniaxial and triaxial sensors are strategically positioned on the third basement floor to capture essential data reflecting the tower's behavior across different dimensions.

Figure 2 provides a summary of the sensors installed on various floors. On a typical floor, three accelerometers are installed, with one positioned on the west wing corner, another in the center, and the third on the east wing corner. Additionally, a tilt sensor is installed in conjunction with the center accelerometer (Figure 3). For the basement floors, specifically B2 and B3, accelerometers are installed without inclinometers.

The multi-channel centralized data loggers are installed in the upper level of the tower to collect and digitize the sensor data. All the sensors are connected to the data loggers directly by the cables. These data cables are passed through horizontal ducts within various floors and one vertical shaft in the building. The sensors are synchronized by a GPS installed on the top of the roof. In the telemetry network configuration, data is continuously transmitted to the server in the Kuwait Scientific Institute of Research (KISR) via 5G/4G private VPN. The data are monitored in real-time at the SHM Centre at KISR (Figure 5).

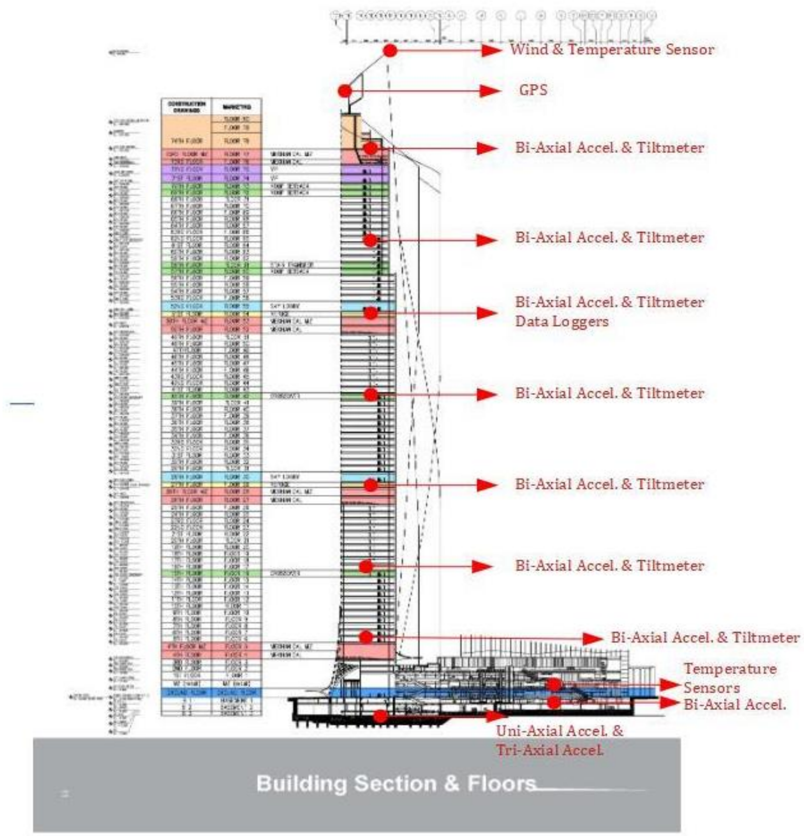

Figure 2. Instrumented floors and layout of the Al-Hamra Tower.

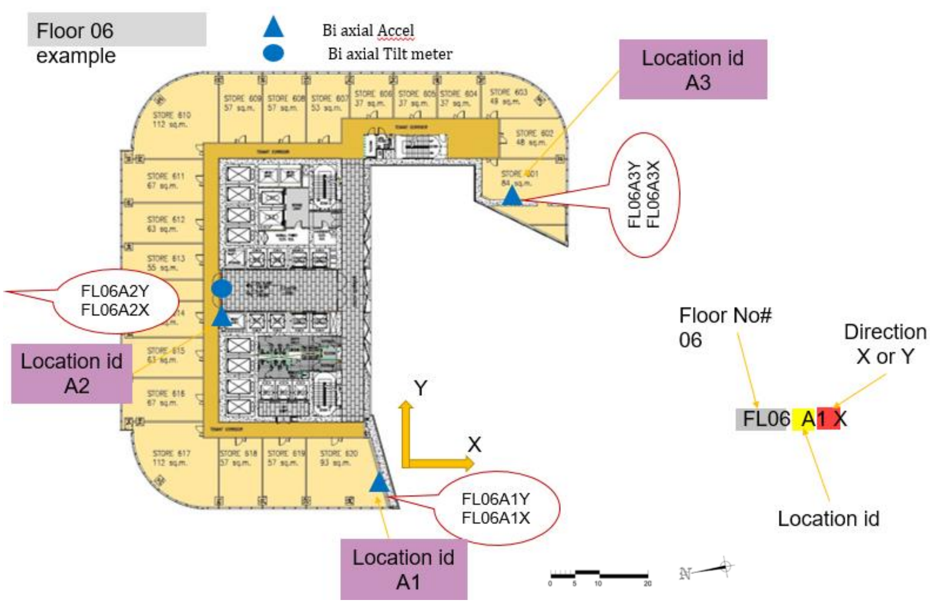

Figure 3. Typical instrumentation in a given floor of the Al-Hamra Tower.

Figure 4. Data loggers of the Al-Hamra Tower’s Structural Health Monitoring system.

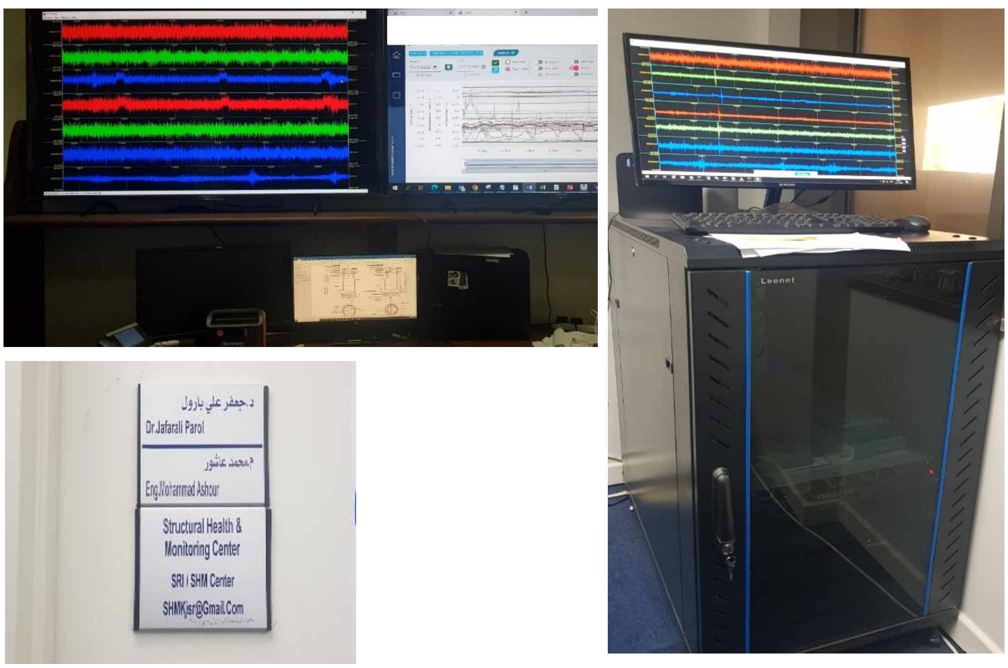

Figure 5. Integrated Structural Health Monitoring center of the Kuwait Scientific Institute of Research **(**KISR).

STRUCTURAL HEALTH MONITORING SYSTEM

The sensors deployed within the Al-Hamra Tower are seamlessly integrated into a centralized server at KSIR, which operates QuakeLogic's **SMART**BUILDING SHM software. This integrated technology platform represents a cutting-edge solution for effective disaster and risk management in high-rise buildings. By leveraging the capabilities of the SHM system, critical real-time information on the tower's structural performance is readily accessible, empowering decision-makers to make informed choices and prioritize response options based on detailed assessments. This integrated technology platform encompasses several essential systems, including:

- Structural Health Monitoring (SHM): The SHM system functions in real-time, continuously collecting, processing, and analyzing vast amounts of sensor data around the clock. By employing advanced data processing techniques and cutting-edge analytics, the system extracts valuable insights and delivers accurate information to the building management team. A visual representation of the architectural structure of the SHM system can be observed in Figure 6.
- Mobile-friendly Dashboard: The platform incorporates a user-friendly dashboard that is optimized for mobile devices. This intuitive interface allows stakeholders to access real-time data, monitor structural performance, and gain valuable insights on the go (Figure 7).
- System Watchdog: The **SMART**BUILDING platform includes a robust system watchdog mechanism that ensures continuous and reliable operation. It actively monitors the health and performance of the entire SHM system, detecting and addressing any anomalies or potential data gab and hardware issues promptly.

The SHM software utilized for the Al-Hamra Tower incorporates a wide range of technical features to enhance its monitoring capabilities. These features include the computation of velocity, displacement, and inter-story drift, as well as torsion and rocking analysis. The software also facilitates the analysis of acceleration and displacement response spectra, generation of spectrograms, and frequency response analysis. In addition, it provides tools for coherence, cross-spectrum phase, and cross-correlation analysis, Fourier amplitude spectra evaluation, and power spectral density assessment. The software supports polarization analysis, statistical analysis including regression, and the calculation of various intensity measures such as PGA, PGV, Arias intensity, CAV, RMS acceleration, duration interval, and cumulative Arias intensity. These technical features contribute to a comprehensive and sophisticated SHM system for the Al-Hamra Tower, enabling accurate and detailed structural assessment and monitoring.

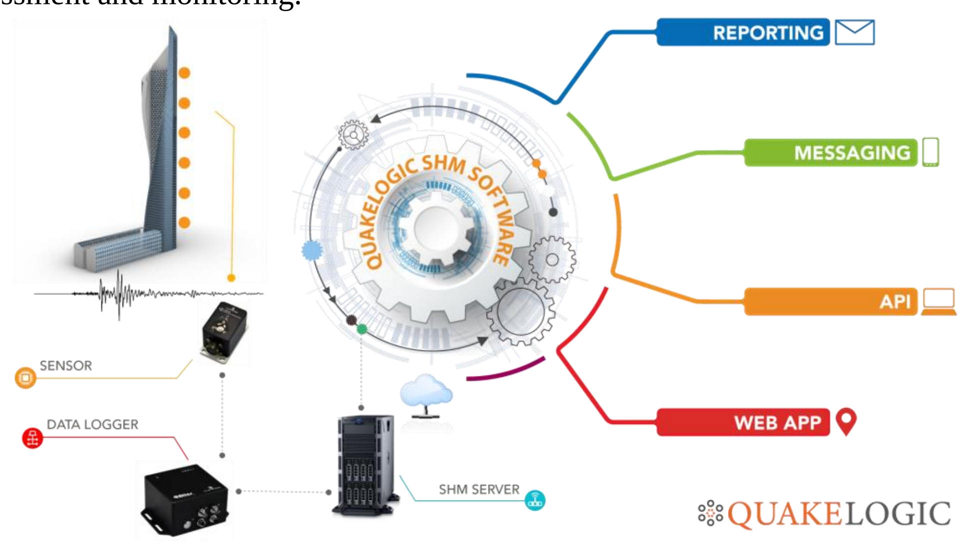

Figure 6. The **SMART**BUILDING structural health monitoring software platform for the Al-Hamra Tower.

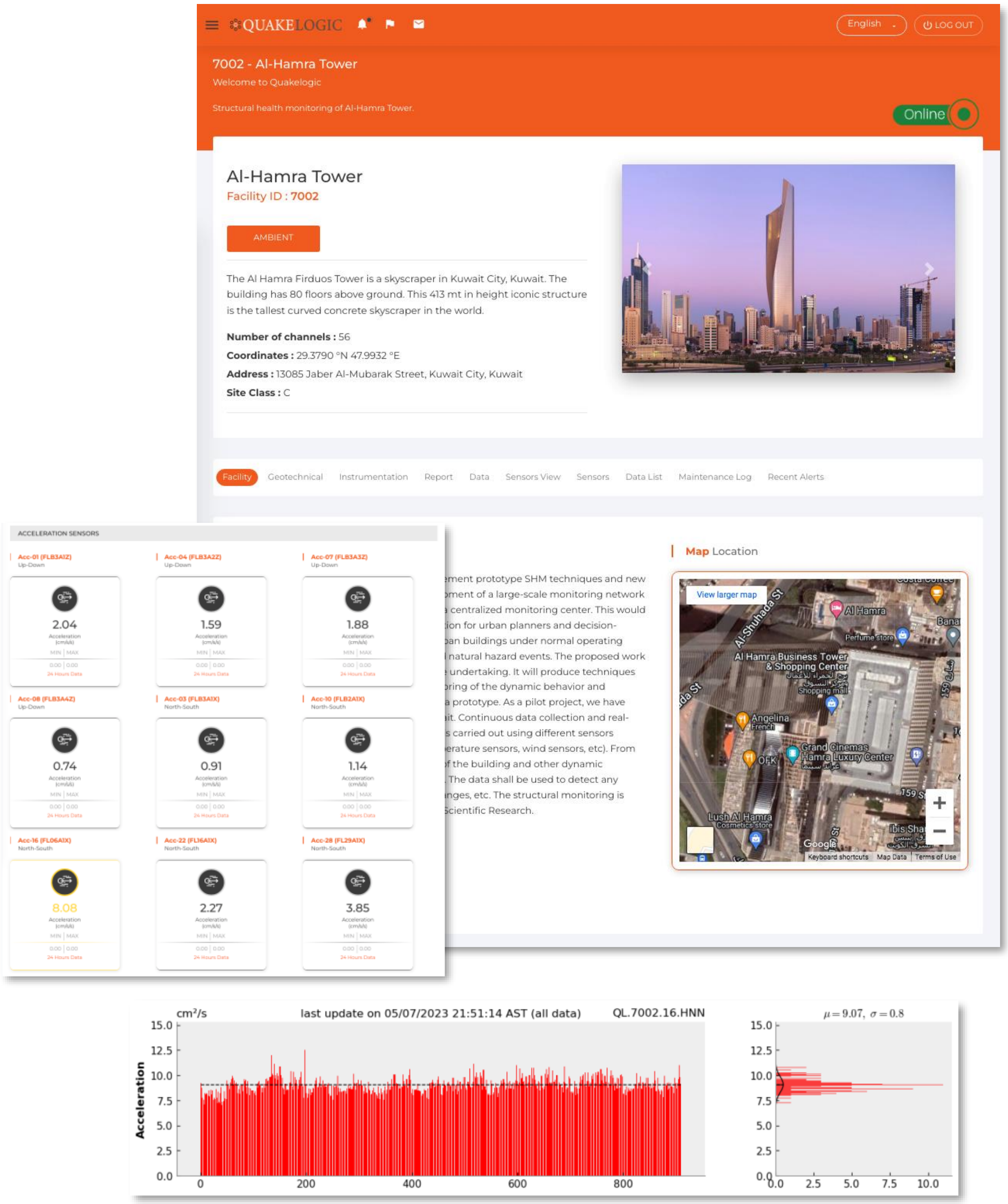

Figure 7. The **SMART**BUILDING structural health monitoring dashboard overview for the Al-Hamra Tower.

One of the remarkable features of the SHM system is its capability to swiftly issue reports and notifications to both building management and occupants in the event of an earthquake. This crucial functionality enables immediate responses and protective measures to be taken, safeguarding the safety and well-being of individuals within the tower. Potential actions may include evacuating the premises, shutting down critical systems, and implementing emergency response protocols. The real-time nature of the SHM system provides occupants with sufficient warning time to execute appropriate measures, potentially saving lives and reducing the risk of injuries.

In addition to earthquake monitoring, the implemented SHM system performs continuous assessments of the Al-Hamra Tower's structural health. By analyzing sensor data in real-time, the system actively scans for any anomalies or indications of deterioration. This proactive approach ensures that potential issues are identified at their early stages, empowering the building management team to take prompt action and prevent them from escalating into critical problems.

AI-BASED SHM METHODOLOGY

The SHM methodology employed for the Al-Hamra Tower also incorporates an AI-based algorithm that operates in an unsupervised manner to detect changes in the building's dynamic properties resulting from external factors. By analyzing data collected from the tower's SHM sensors and processing it through unsupervised machine learning algorithms, the AI algorithm demonstrates its efficiency in real-time SHM without the need for training or manual calibration.

Evaluation of the AI algorithm's performance, as presented in [2, 3], utilized data from the Al-Hamra Tower's SHM system. The performance of this method has been evaluated and verified initially with the data simulated from the IASC-ASCE benchmark [4]. The results in [3] indicated that the proposed AI algorithm successfully detected changes in the building's dynamic behavior caused by external factors. The summary of the AI algorithm implemented is as follows:

Feature extraction: Feature extraction aims to extract damage-sensitive features for decision-making. “In the most general terms, damage can be defined as changes introduced into a system that adversely affect its current or future performance” [4–7]. Therefore, the change in acceleration response is considered as the damage-sensitive feature.

Decision-Making: The process of decision-making aims to make decisions on the structural conditions by analyzing extracted damage-sensitive features. The DSVDD (deep support vector domain description) is adopted here as the decision maker.

Evaluation Criteria: To evaluate the performance of this method on testing data, two types of evaluation criteria are used. The two criteria are MAD (mean false alarm density) and MFAD (mean false alarm density), which are for the evaluation of true-positives and false-positives respectively

The algorithm's capability to identify subtle changes that might be overlooked by human observers is a valuable advantage, enabling prompt detection and diagnosis of structural changes critical for the safety and longevity of such a complex structure.

CONCLUSIONS

The implemented SHM system at the Al-Hamra Tower showcases the power and effectiveness of real-time data monitoring and analysis. By leveraging state-of-the-art technologies and methodologies, it enables proactive measures to ensure the safety of the building and its occupants during seismic events. The integration of high-precision sensors, advanced data processing techniques, and rapid alert capabilities establishes a robust foundation for enhancing building safety and mitigating risks associated with extreme loading conditions.

The AI algorithm developed for the Al-Hamra Tower operates in an unsupervised manner, detecting changes in the building's dynamic behavior caused by external factors such as earthquakes, wind, and thermal effects. Its integration into the existing SHM system enhances real-time monitoring, ensuring the continuous assessment of the tower's structural health.

This study contributes valuable insights for the monitoring and maintenance of tall and complex buildings, emphasizing the importance of AI-driven approaches in structural health monitoring. The findings provide a framework for improving SHM systems in the future, enhancing structural safety practices, and ensuring the long-term durability and stability of iconic structures like the Al-Hamra Tower.

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