International Journal of High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

International Journal of High-Rise Buildings
September 2022, Vol 11, No 3, 221-226
https://doi.org/10.21022/IJHRB.2022.11.3.221

Application of Strcutral Health Monitoring in Structual Engineering for Buildings

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Abstract Installation of Structural Health Monitoring (SHM) system is a legal obligation for high-rise buildings over 200 m or 50-floor high in South Korea. CNP Dongyang has developed key technologies for SHM system design, installation, and data analyzing. Also, CNP Dongyang has applied SHM technology to a plenty of South Korea's representative high-rise buildings. The SHM technology, also, could be used in safety management of construction phase, evaluation of structural performance, etc. In this paper, state of the art SHM technologies and their application examples are introduced to give insight for future research and practical use of SHM.

Keywords CNP Dongyang, high-rise building, field measurement, SHM

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1. Introduction

The Structural Health Monitoring (SHM) is one of reliable methods to check structural performance and safety based on measured data of structural responses to external loads. The SHM system, therefore, has been an indispensable management system in operating long span bridges and has been legislated to be obligatory for high-rise buildings in South Korea.

Structures in construction phase of tall buildings could be unstable before being completely assembled. A typical example of the instability is the delayed joint construction method of an outrigger system in high-rise construction. The SHM technology could be used in monitoring responses to wind velocities during construction to adjust gaps of outrigger joints.

A temporary SHM system could be installed on a building in operation to check performance of the building when unexpected vibrations or shakes are detected. The SHM system could help minimize the interruption of building operation because it could expedite check of building safety by interpreting quantitative response data.

The SHM system requires cutting-edge technologies in various fields of engineering such as structural analysis, remote sensing, signal processing, system identification, etc. to check building safety and give alarm signals. Recently AI technology enables the SHM system make autonomous diagnosis of a building condition by analyzing measured data.

In this paper, current technologies used in the SHM and corresponding applications are introduced to give some insight for future researches and use of the SHM system. Especially, presented application cases could give better understand of using the SHM system in structural engineering for buildings.

2. SHM system and its benefits

The SHM system is developed to provide information on structural serviceability and safety using sensing, analyzing, and alarming systems. The sensing system measures external load levels and corresponding building responses using anemometers, accelerometers, GNSS, etc. Time of measured data are generally synchronized to analyze correlations of loads and responses. Also, noises and trends in data are removed using signal processing methods.

Levels of building responses such as displacement and acceleration responses to wind excitations or ground motions are evaluated using the analyzing system. Also, inherent building properties such as natural frequencies, mode shapes, and damping ratios are identified from acceleration data. All of the analyzed results are compared with design results and triggering levels of alarm.

The alarming system is generally designed to give only warning signal of an emergency situation. It, however, has to give corresponding emergency action procedures with warning signals. The objectives, therefore, of the SHM system operation should be proposed in advance and emergency action plans should be prepared according

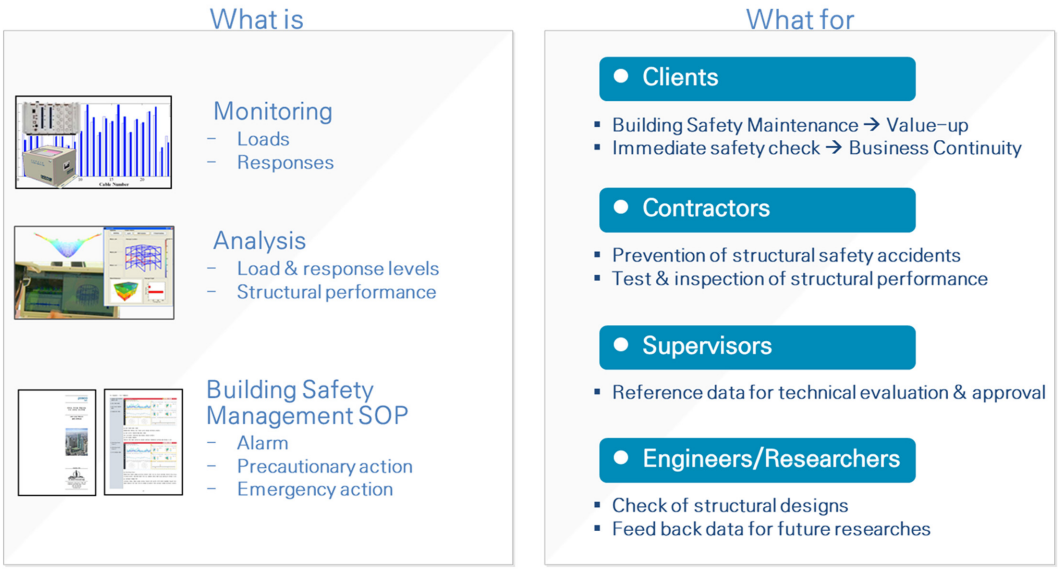


Figure 1. Objectives and Benefits of the SHM System.

to emergency situations.

The SHM system could increase asset and intangible values of a building by providing building safety and maintenance information. Building operation could be interrupted when a safety problem such as unexpected vibrations occur. The interruption period, however, could be minimized by prompt check of building safety using measured data by the SHM system.

Contractors could prevent structural accidents beforehand by monitoring behaviors of unstable structures or unexpected external events such as strong winds, earthquakes, etc. during construction period. In addition, the quality and performance of a newly developed structural system method could be checked using field measurement data. Supervisors could approve construction quality and safety based on quantitative data.

Structural designers and researchers could use the SHM data to investigate quality and performance of newly developed technologies. The SHM system could provide information on improvement points and further research items.

3. Field vibration Monitoring

Vibration is one of import factors influencing structural plan of building structures. Especially, excessive wind-induced vibration leads to serviceability problems in high-rise buildings. The wind-induced motion of vibration is evaluated through a wind tunnel test. Wind forces are usually measured by High Frequency Force Balance Test (HFFBT) and the wind-induced motions are analyzed using the measured wind forces and dynamic properties such as natural frequencies, mode shapes, and damping ratios of the building in consideration.

The dynamic properties are usually evaluated through the modal analysis. The analytical model, however, could be somewhat different with on-site structures because it is simplified for efficient design works and design purposes. These assumptions could lead to under-estimate building stiffness and over-estimate building responses.

The analytical model could be calibrated for its dynamic properties to match measured ones. Real dynamic properties of a building could be evaluated through on-site acceleration measurements and system identification methods. Field measurements of accelerations and system identifications were performed for a tall building after completion of structures using Frequency Domain Decomposition (FDD) method (J. Y. Kim, et. al., 2009). The analytical model of the building was calibrated to match the real natural frequencies of it by considering in-situ material properties, flexural rigidity of floors, beam-end-offset, non-structural walls, and podium.

The dynamic properties of the building were expected by modal analysis of the calibrated analytical model. Using the expected natural frequencies and mode shapes, acceleration responses of the building were evaluated by analyzing the wind tunnel test data and compared with real acceleration responses which were measured during a typhoon event. Real damping ratio was used in the acceleration analysis. Evaluated and measured wind velocities and corresponding accelerations at the roof floor of the building were compared and it showed that the expected results closely followed the measured acceleration responses.

Field measurement of a building under construction could be practically used to predict real responses and structural performance of it after completion. Optimal structural design could be possible through calibration of an analytical model and prediction of real responses.

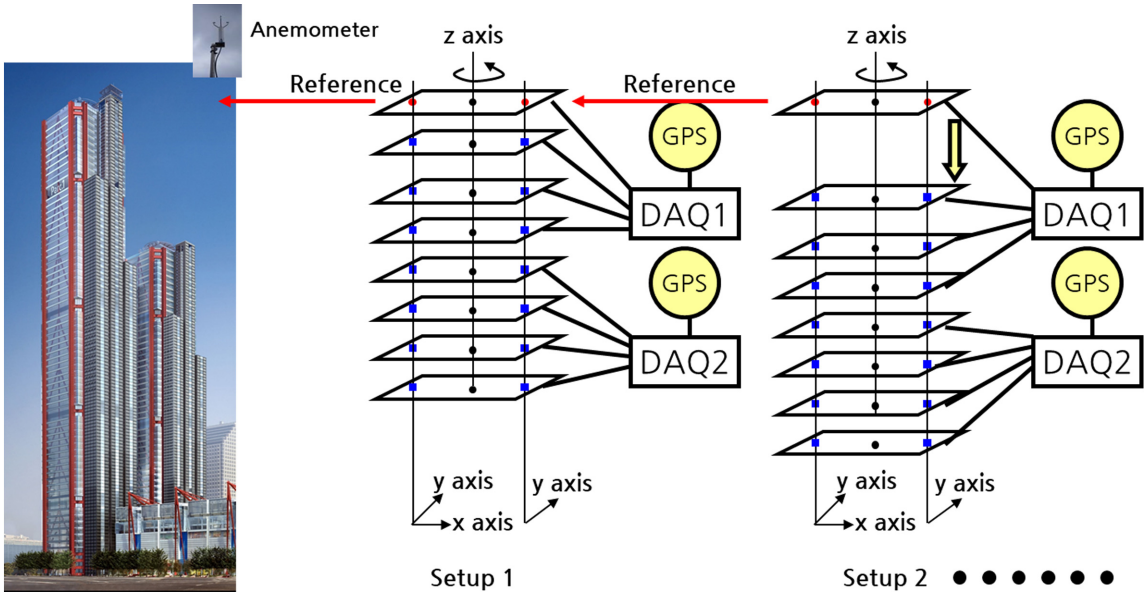


Figure 2. Field Measurement Scheme for Building Accelerations.

4. AI-driven Damage location

Damage detection and location are one of main functions in the SHM system. In most cases, damage of a structure or a member is regarded to occur in case that measured data exceed limit levels set in the SHM system. The damage detection based on limit levels could produce false alarm due to error signals from sensors. Also, it is complicated to determine whether an overall structure is unstable or not with exceeding alarm levels of some sensor measurements.

Damage location methods have been developed to overcome shortcomings of the limit level method. Most of damage location methods were developed using optimization techniques to update analytical models. An initial FE model is created to match current structural properties. The initial FE model is updated periodically or after an unexpected event, for example, earthquake. Then, Damages in the structure are identified by comparing the initial and updated FE models.

Damage location methods of FE model updating requires analysis tools integrated in the SHM system and long computational time. Recently, Artificial Intelligence become popular in various part of industry to solve com-

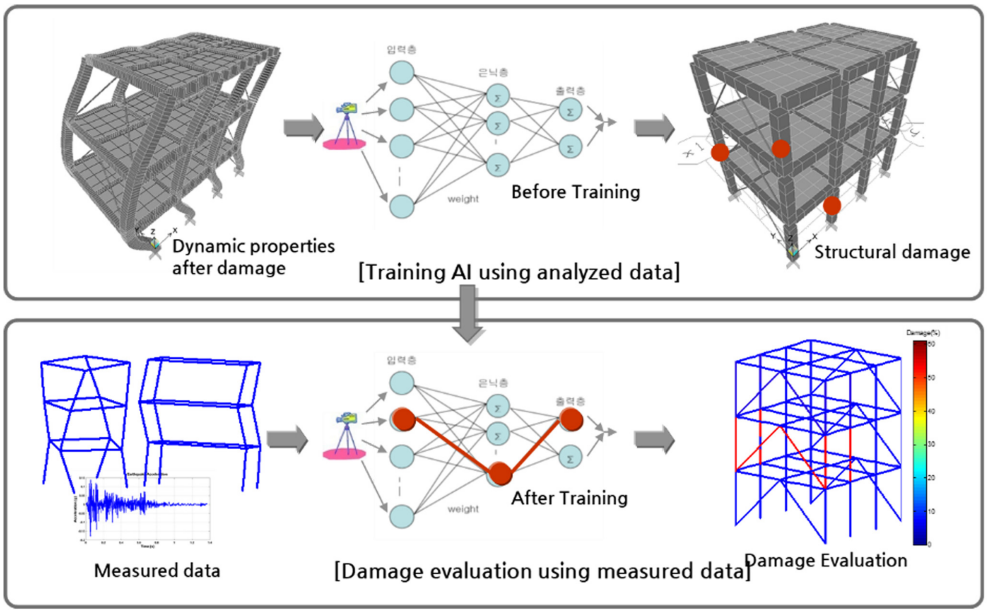


Figure 3. AI-driven Damage Location and Verification Test.

plicated problems. AI monitoring of credit card fraud is widely known as a representative example of autonomous surveillance. Such AI-driven anomaly detection could be applied to monitor abnormal event detections of building structures.

AI could be trained to locate damages and to evaluate damage degrees in a structure based on measured signals. Firstly, an analytical model is created to match properties of a real structure in consideration. Sets of responses and corresponding damages are analyzed using the calibrated analytical model. The selected responses and corresponding damages are used for training input and target data, respectively. Finally, Damage locations and degrees are instantly evaluated when measured response data are input to the trained AI. Dynamic properties, peak acceleration responses, etc. are used for AI input data. Stiffness reductions of members are generally used for the target data (J. Y. Kim, et. al. 2015).

The AI-driven damage location requires no analytical model and analysis tools in the SHM system because it requires only an AI which is trained using simulated data. Also, it takes short time for AI computation so that damages could be more instantly evaluated than the FE model updating method.

The AI-driven damage location method was used for a floating structure lauching into Han-gang river. The floating structure was constructed at the riverside, then launched into the river using the airbag launching method. The responses of the floating structure to impact loading of launching were simulated using an analytical model. AI was trained using sets of damage patterns and corresponding responses levels. Accelerations, tilts, strains, etc. were monitored during towing and launching process of the floating structure. Damages were instantly evaluated by input response data into the trained AI during the launching process.

5. Permenant Monitoring system for high-rise buildings

A permanent monitoring system shall be installed in high-rise buildings over 200 m high or 50-story for disaster management purpose in south Korea. CNP Dongyang has developed key technologies for the SHM system and applied it to landmark high-rise buildings as follows.

5.1 Design and Installation Process

Firstly, structural performance of the building in consideration is evaluated through structural analysis. In general, nonlinear analysis is performed to investigate structural behaviors of each serviceability, operation, and collapse prevention level. Limit levels of responses and external loads are determined according to the analysis results. The limit levels are used to design a warning process in the SHM system. Modal analysis, also, is performed for each serviceability, operation, and collapse prevention levels to investigate change of dynamic properties. Alarming process and emergency action plan corresponding to the limits levels are planned to design an operating scenario of the SHM system.

Items and locations of measurements are planned by referring to the analysis results. Structural stability design of high-rise buildings is mainly determined by lateral loads such as wind and earthquakes. Anemometers and seismometers, therefore, are generally utilized to measure external loads. Lateral drifts and translational accelerations are commonly monitored as global behaviors to the lateral loads. In some cases, local strains are measured at structural members which initiate collapse of overall structures according to analyzed collapse mechanism.

Sensors and monitoring system are installed according to the sensor network design of the SHM system. Sensors

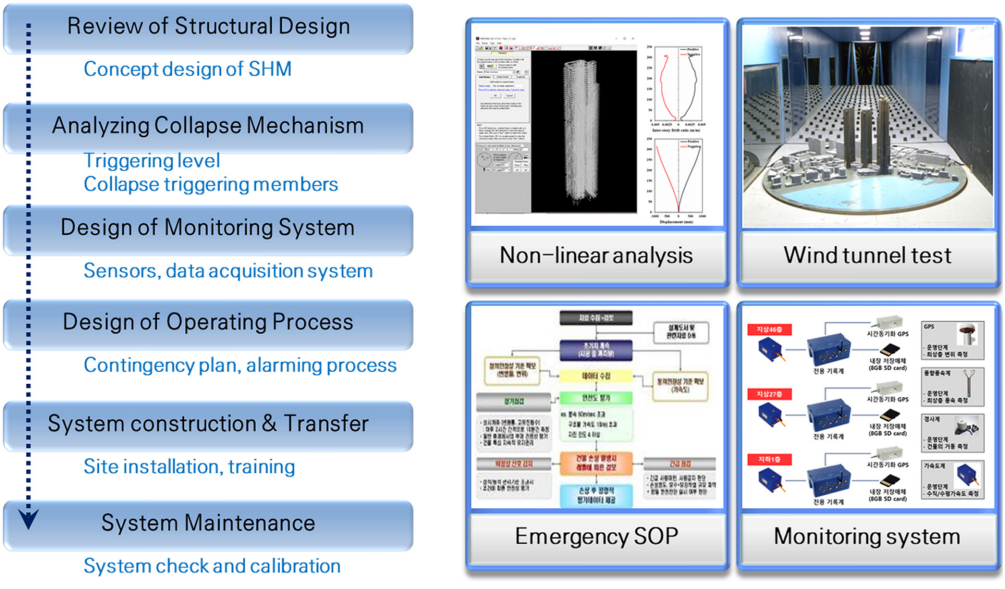


Figure 4. SHM System Design and Installing process.

are connected to local data acquisition systems and stored data in local system are transferred to a main server through optical cables, wireless transmission, etc. All of the measured data are analyzed, summarized and stored in the storage of the main server.

The management software is programmed to evaluate statistical values such as peak drifts, peak accelerations, maximum wind velocities, earthquake intensity, etc. The statistical data are visualized using charts or graphs, and summarized in tables. Signal processing and system identification algorithms are programmed to derive structural properties. The analyzed data are compared with the prescribed limit levels and send warning to building managers and residents in the building in case of emergency situations.

After test operation of the SHM system, it is delivered to building managers with operation training. Manuals are developed to provide information on equipment and software usage, maintenance method of equipment, emergency action plan and limit levels of measurements.

5.2 SHM system for Yeoui-do Parc 1

Parc 1 project has two landmark towers, a hotel, and a retail center. CNP Dongyang performed structural design and built the SHM system. Two towers are 67- and 51-storeys high, respectively. The lateral resisting system of the towers is mega tube system composed of mega columns and mega braces.

The lateral resisting system of the hotel is composed of two RC cores connected with steel moment frames and mega braces. The hotel structure is designed to transfer

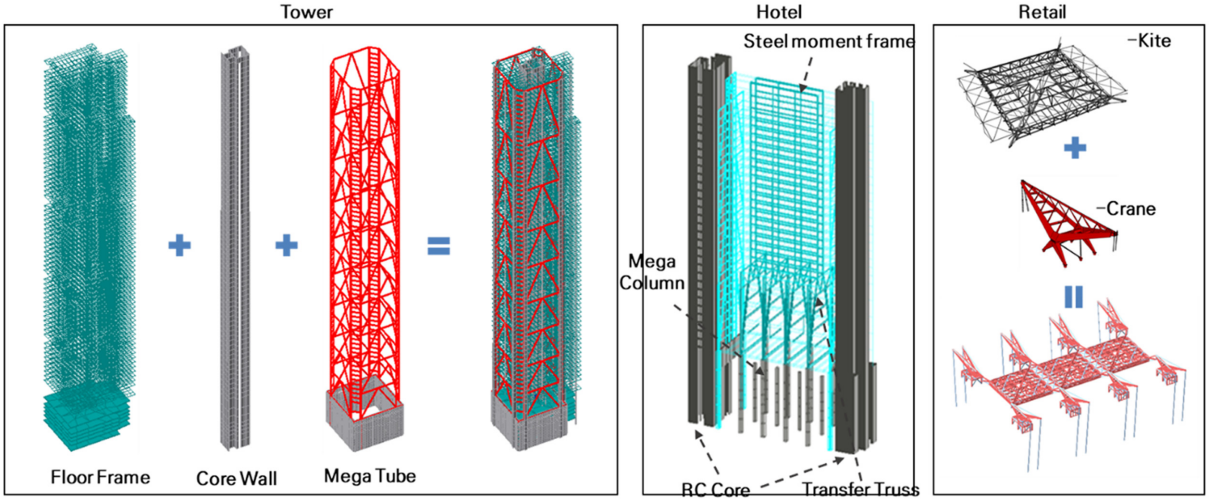


Figure 5. Structural System of Parc 1.

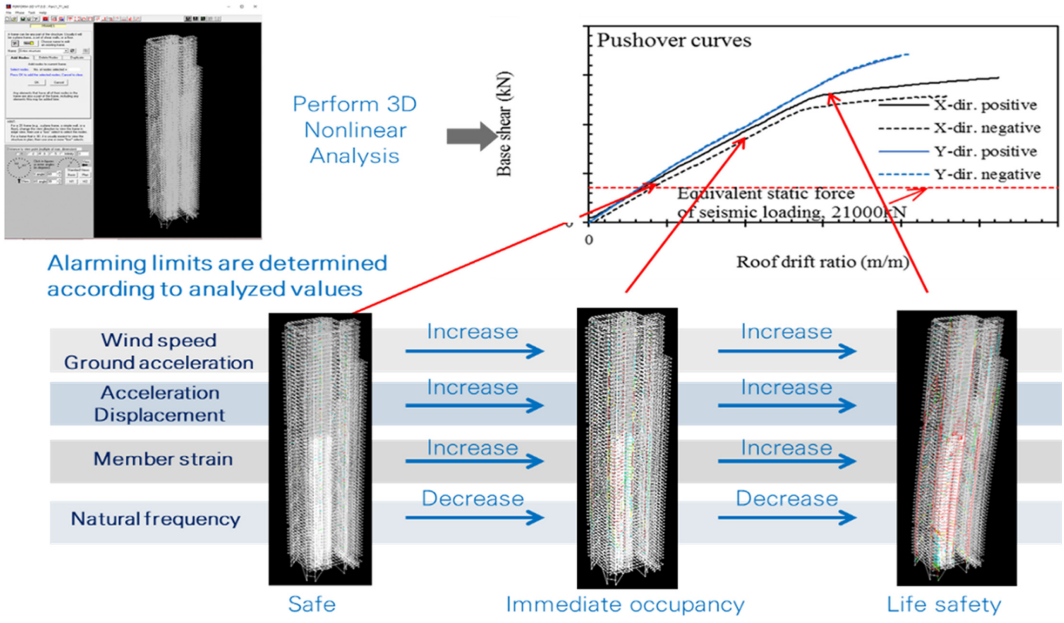


Figure 6. Nonlinear Analysis for Design of SHM System.

gravity loads from upper steel frames to lower mega columns through transfer steel truss frames. The roof of the retail has the Crane and Kite structural system which creates large courtyard.

The primary objective of the SHM system built on the two towers is to monitor behaviors of lateral resisting system to lateral loads because its performance determines structural stability of the high-rise building. Lateral displacements, inclinations, and translational accelerations are adopted to be monitored. Wind velocities and ground motions are chosen for external load monitoring. GNSS and accelerometers were installed to monitor displacement at the top and accelerations on 4 to 5 floors in each tower. Anemometers and seismometers were installed to monitor wind velocities and earthquake accelerations.

Strain monitoring is conducted on critical members which show high stresses under design loads and could initiate progressive collapse. Structural analysis shows that stress levels are considerably high in some members of the Crane and Kite system. Also, the mega columns of the hotel show high stress level in structural analysis results. Failure of mega columns leads to collapse of overall structures because they resist transferred gravity loads from upper stories. Strain sensors were installed those critical members to monitor strain levels.

Nonlinear analyses were performed to determine limit levels of responses for the two towers. Triggering levels and corresponding alarming process were designed based on the analysis results. Design codes and reports were also referred to determine the limit levels of building accelerations, wind velocities, and ground accelerations.

The SHM system for Parc 1 project was installed according to the system design results and is currently in operation. Measured data and current structural condition of the buildings could be checked in the management software. When abnormal situation occurs, the management software detects it automatically and create a warning signal for building managers to check the event.

6. Concluding remarks

CNP Dongyang has a lot of experiences applying SHM technology to high-rise landmark buildings like Parc 1. Haewundae LCT, Songdo Ijinbay City, etc. in South Korea. The SHM systems in the high-rise buildings could be used to reduce risk of natural disasters and secure business continuity. Also, the application examples of the SHM technology show that it could be used to check construction safety and building structural performance. CNP Dongyang will develop the SHM technology to be a total package for safety management during lifecycle of a building. These could be used as a smart safety system in smart city and smart nation in the future.

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