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Real-time structural health monitoring of a supertall building under construction based on visual modal identification strategy

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ABSTRACT

This paper presents a real-time structural health monitoring technique for a supertall building under construction, Lotte World Tower (LWT), the tallest building in Korea. To evaluate the state and safety of the supertall building under construction, this study presents a visual modal identification method to identify mode shape and damping ratio based on modal responses from the monitoring system. In the method, mode shape and damping are visually identified from the time history plotting of well-filtered modal responses in real time. Since the presented method does not include a kind of complex calculation for measured data required in the previous SI methods, it can avoid time consuming in system identification (SI) as well as variation in value of modal parameter extracted from measurement. An ambient vibration test on the LWT under construction was performed in 2015. Using the test data, the presented method identified the mode shapes and damping of the LWT visually with small variations without any complicated computations. Further, this study presents a model updating method with a simplified pseudo frame model to construct a baseline model for the LWT under construction using measured modal responses. The validity of the updated model for the LWT was verified through estimations of mode shape and structural responses.

1. Introduction

From the late 20th century, a number of supertall buildings that are over 300 m have been built around the world, specifically in Asia. The supertall building is regarded as very important one considering scale, use, number of occupant, and function as landmark of the city. Thus, for supertall building, the structural health monitoring (SHM) system, which is a technology identifying the current state of the structure and evaluating the safety and serviceability of the structure [1–10], has been thoroughly considered in the design phase and applied to the building under construction and in service phase. Since researches on a long-term SHM for a 280 m high 65-story building in Singapore [11] and a monitoring program [12] for three tall buildings in Chicago, USA, had been started, SHM has been widely adopted to various supertall buildings constructed in 21st century and relevant researches have been actively carried out [13–23].

A SHM system with 600 sensors was implemented to a 610 m high Guangzhou New TV Tower (Canton Tower, hereafter) in China [14]. A variety of sensors such as global position system, strain sensors, accelerometer, inclinometer, and anemometer etc., were installed throughout the building and used to assess the conditions of the building under construction and in service. 632 m high and 101-story Shanghai World Financial Center is a supertall building constructed in Shanghai, China. A complicated and sophisticated SHM system was applied to the building measured diverse global and local structural responses [21] at the initial construction phase. In Burj Khalifa, the tallest building in the world, a number of advanced sensor techniques were implemented. A web-based SHM program [24] was developed for near real-time monitoring of the building and has provided accelerations, displacements, wind speed and direction, and modal parameters of the building.

As an indicator for evaluating overall state of the structure, modal parameters are usually used and extracted by system identification (SI) method. As an artificial excitation of the building, especially large-scaled building such supertall building, is a difficult matter and even impossible, modal parameters are extracted and analyzed from vibrations measured in the building randomly excited by various causes around the building. The method using ambient vibration measured in random excitation condition is called operational modal analysis (OMA). A variety of OMA methods have been developed [1,25–31] and applied [18,22,24,32–34] to the OMA of the buildings.

Values for modal parameters from those OMA methods showed

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Fig. 1. The LWT: (a) Perspective view of the LWT, (b) the LWT under construction (February 2015).

some variations according to 1) environmental conditions during measurements and 2) type of methods and configurations in the methods. At first, environmental conditions include characteristics of excitation inducing vibration of building as well as external condition such as temperature and humidity. Various researches [18,19,24,35,36] have investigated the influences of the excitations on the variations of the extracted modal parameters from high-rise buildings. From these researches, generally, natural frequency decreases and damping increases according to increase of amplitude of measured data. In addition, some literatures [33,37,38] have examined that natural frequency and damping of tall buildings are influenced by temperature and humidity. Especially, large variations for damping ratio have been shown with variations of amplitude. The amplitude dependent characteristics of damping including structural and aerodynamic damping can be explained by the nonlinear energy dissipation of the tall building. As the phenomenon for the damping of tall building is instinct characteristic, the variation or range of damping ratio by environmental conditions is unavoidable and should be provided as one of the results of the OMA.

In contrast to the variations by external condition, those induced from application of the OMA methods are regarded as targets to be reduced. Several studies [19,32,33,37] on the OMA of the tall buildings showed variations of modal parameters, natural frequency and damping ratio, according to type of selected OMA method among various OMA methods such as frequency domain decomposition (FDD), Stochastic subspace identification (SSI), Hilbert-Huang transform (HHT), random decrement technique (RDT), etc. All of the methods extracted natural frequency with less discrepancy and in a reliable manner. However, the researches presented that damping ratio from each method had relatively larger variations. Furthermore, even if an identical method is applied to extract modal parameters of tall building, its variable set up determined in the method affects the results. To implement a method and obtain reliable results, appropriate establishment of specific variables inducing variations of modal parameters is required but there are no robust rules for setting up the variables in the OMA method. In a research [32], different number of data segment in frequency domain was used for the modal identification of the Shanghai World Financial Center and variations of damping ratios according to data lengths were observed. In other research [24] using SSI-based OMA scheme, covariance-driven SSI (SSI-COV), numerical simulations for a simple model were conducted to determine window length in data correlation which leads to uncertainty of damping estimations. From the simulation studies, a window length with less error was chosen and applied to the OMA for Burj Khalifa. In a study [34] on the OMA of the Canton Tower, a SSI-COV based method was employed to extract modal parameters. In this SSI-based framework, preliminary analyses were conducted to determine the best values of parameters required in data correlation and singular value decomposition (SVD). In other research [19] on the OMA of the Canton Tower, the number of data segments in constructing power spectrum density (PSD) functions in frequency domain was chosen based on the frequency resolution inducing acceptable errors in calculating PSD. In most OMA methods, various parameters required in the complicated calculation for correlation and decomposition of the measured vibrations data induce variation in the extraction of modal parameters.

In this study, to achieve real-time and precise modal identification for supertall buildings under construction, a SHM technique, which does not require a kind of complex computations of huge matrices constructed from measured vibrations and thus, establishment of variables in the process of correlation and decomposition, is presented and applied to the OMA for Lotte World Tower (LWT) under construction. The presented method is based on the modal responses from the vibration measurements. To extract modal response for each mode, natural frequency is firstly identified through comparative analyses in frequency domain between individual vibration data considering locations and directions of sensors. Based on the identified natural frequency, modal responses are extracted through a band-pass filtering and then, through the plotting the time history of modal responses considering measured locations, mode shapes can be visually obtained. In addition, sequential implementation of FFT and inverse-FFT for the extracted modal responses provides damping ratio. Using vibrations measured from an ambient vibration test in April 2015 for the LWT under construction, the proposed method extracted mode shape and damping ratio stably and in near real-time. The performance of the presented method was compared with a previous SI method in terms of computation time reductions and variations of extracted SI results. Further, a model updating for the LWT using a three dimensional pseudo frame only considering measured location was presented based on the modal responses to establish a reference model for the building under construction. The validity of the updated model was confirmed by identifying mode shape and estimating global responses.