Research Assessment Exercise 2020
Impact Case Study

University: City University of Hong Kong
Unit of Assessment (UoA): 16 - Civil Engineering (inc. Construction Engineering & Management) and Building Technology

Title of case study: Wind loading, Structural Health Monitoring and Vibration Control of Super-tall Buildings

(1) Summary of the impact

This research project presents a combined study of wind loading, structural health monitoring (SHM) and vibration control on the 600-meter-high Ping-An Finance Centre (PAFC), the 420-meter-high Two International Finance Centre (2IFC) and the 508-meter-high Taipei 101 Tower. This study provides valuable information for the future development of SHM, enhances understanding of the wind effects on super-tall buildings, improves wind-tunnel testing techniques and promotes the application of the active control technique. The findings are of utmost importance for the wind-resistant design of super-tall buildings in typhoon-prone regions. The project was supported by two GRF grants (HK$1,391,935) and a NSFC grant (RMB590,000).

(2) Underpinning research

In order to ensuring the structural safety and serviceability, the SHM systems have been installed in PAFC, 2IFC and Taipei 101 Tower to monitor their performance. Since these skyscrapers are located in the world's most active typhoon-generating areas, the PAFC is equipped with the world's largest active tuned mass damper (ATMD) system while Taipei 101 Tower has installed the heaviest tuned mass damper (TMD) system in the world to reduce the wind-induced vibrations of the skyscrapers. We used PAFC, 2IFC and Taipei 101 Tower as research platforms to investigate several key scientific problems associated with the wind loading and structural response, SHM and vibration control of super-tall buildings. This study includes four closely related parts:

1. Structural Health Monitoring. A novel strategy, named elevation pre-adjustment, has been implemented in the design and construction of the PAFC. The effectiveness of the strategy was examined by monitoring the vertical deformations of various vertical structural members along the building height based on the records of the SHM system. In the service stage, structural health conditions are assessed using data obtained from the SHM system and the results of numerical analysis of an updated finite element (FE) model. Moreover, the SHM system is used as a test-bed to verify the effectiveness and limitations of SHM-related algorithms.

2. Wind effects monitoring. We investigate the wind loads and the wind-induced vibration characteristics and serviceability of the high-rise structures. Wind velocity information recorded atop the skyscrapers was intensively analysed to obtain statistical information on wind speed and direction, and atmospheric-turbulence properties above typical urban areas. Intensive analysis of the acceleration responses under typhoon conditions, e.g. modal analysis, spectral analysis, and serviceability evaluation was conducted. Furthermore, the amplitude-dependent damping ratios and natural frequencies of the super-tall buildings were evaluated over a wide range of response amplitudes. The mean, fluctuating and peak pressure coefficients, and the probability density, spectra and coherence of pressure fluctuations were obtained on basis of the cladding pressure monitoring.

3. Wind tunnel tests. Pressure measurement, force balance and aeroelastic model tests were performed to investigate the effects of wind on the super high-rise buildings. Through comparing the

pressures on the building models with the on-site measurements, we examined the capability of the model test for the generation of extremely high suction pressures on corners and leading edges of the buildings. Cross-comparisons of the overall wind loads from the three model tests were conducted to examine the effects of aerodynamic damping. Moreover, the wind-induced acceleration and displacement responses obtained from the three tests were compared with those from the accelerometers and Global Positioning System in the SHM systems to evaluate the accuracy of the model test results and the adequacy of the techniques used in the wind tunnel tests.

4. Structural vibration control. The effectiveness of the ATMD system installed in the PAFC and TMD system installed in Taipei 101 Tower was evaluated; the optimal control strategies for vibration mitigation of super-tall buildings were proposed through the combined study of monitoring, wind tunnel tests and numerical analysis.

(3) References to the research

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(4) Details of the impact

In accordance with the underpinning research, detailed impacts of this study are listed in four aspects:

Part 1 (Structural Health Monitoring) comprises an in-depth study of SHM and structural performance assessment based on measurements obtained by the SHM systems and the results of numerical analysis. Results showed that the elevation pre-adjustment strategy can effectively reduce the differential axial shortenings, which offered useful guidelines for elevation pre-adjustment in the design and construction of super-tall buildings. A good agreement was found between the numerical results and the field measurements of vertical deformation, which validated the finite element models of the PAFC at different construction stages. The outcomes of this study would be of interest and practical use for engineers and researchers involved in the structural design and construction of tall buildings, and will help to improve SHM-related techniques for high-rise structures.

Part 2 (Wind effects monitoring) involves a comprehensive investigation of the effects of wind on the super-tall buildings based on the data gathered by the SHM systems under harsh typhoon conditions. The wind records atop the skyscrapers provided a valuable characterization of upper-level wind properties above urban terrains. And the acceleration measurements, in conjunction with post-typhoon occupant surveys, were used to validate the existing occupant comfort criteria. Besides, the damping measurements were used to examine and validate the adequacy of current codes of practice for selection of damping values in the wind-resistant design of super-tall buildings. What's more, the cladding pressure measurements were very useful in the design of cladding and glass panels for super-tall buildings. The datasets acquired from the SHM systems can be used to improve wind tunnel test techniques and to develop design standards and guidelines for super-tall buildings. The findings of this study enhance the understanding of the wind loading and structural response characteristics of super-tall buildings, provide important validation of design procedures and assurance of acceptable behaviour.

Part 3 (Wind tunnel tests) comprises a series of wind tunnel tests, such as pressure measurement, high-frequency force balance and aeroelastic model tests, to investigate the wind loads and wind-induced responses of the high-rise structures. As is well known, boundary layer wind tunnel testing is an effective tool in wind engineering. However, it is generally difficult to reproduce exact field conditions such as incident turbulence, terrain characteristics and Reynolds number in wind tunnel tests. This may result in uncertainties in experimental results. Therefore, comparing wind tunnel test results with field measurements is very useful, not only in evaluating the accuracy of the model test results and adequacy of the techniques used in the model tests, but also in providing better understanding of the physics. Besides, the findings can aid evaluation of the ability of current design codes and wind tunnel tests to realistically predict the effects of wind on super-tall buildings.

Part 4 (Structural vibration control) involves an assessment of the performance of the ATMD system and the TMD system in the PAFC and Taipei 101 Tower as well as an exploration of the optimal control strategies for suppressing the wind-induced responses of super-tall buildings. The effectiveness of the ATMD system and the TMD system was evaluated based on the measurements from the SHM systems and numerical analysis to assess the benefits gained from the applications of the active control technique and passage control techniques in the two skyscrapers. Besides, the optimal control strategy suitable for applications to wind-excited high-rise structures was proposed. The findings provided useful information on the effectiveness of the ATMD system and TMD system and the real performance of the controlled super-tall buildings in windstorms. Such information is scarce, and will be helpful for the further development of vibration control of super-tall buildings.

In sum, the findings of this comprehensive study promote the advancement of SHM and structural control techniques, improve the wind tunnel test techniques and enhance understanding of the effects of wind on super-tall buildings. The outputs of this project are of utmost importance for the wind-resistant design of super-tall buildings in typhoon-prone regions.

(5) Sources to corroborate the impact

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