Performance-Based Health Monitoring of Large Civil Structures

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Abstract

Rapid urbanization and economic development have resulted in many large civil structures such as tall buildings, large spatial structures and long span bridges throughout the world. Safety and functionality of these structures play a vital role in sustaining and promoting the current economic prosperity. Most of these structures are, however, exposed to natural and man-made hazards including typhoon, earthquake and fire over their long service life. Performance-based health monitoring and assessment of large civil structures present a substantial potential for academic research and for development into a prosperous multi-disciplinary industry to ensure these structures service properly at all specified performance levels and to prevent them from damage and collapse. A comprehensive research program with input from experts of different disciplines has been thus initiated and conducted by the four departments of The Hong Kong Polytechnic University since July 2007. The background, scopes, objectives, and milestones of the research program are briefly presented in this paper. The problems encountered and the future investigations are also highlighted.

Key words: Performance-based structural health monitoring; sensing technology

1. Background

Large civil structures, including tall buildings, long span bridges, large spatial structures, dams, and many others, provide very fundamental services to a modern society. Safety and serviceability of these large civil structures are therefore crucial elements of a civilized society and a productive economy, and also the ultimate goals of engineering, academic, and management communities.

However, many large civil structures in-service are in fact deficient owing to many factors. They deteriorate due to environmental corrosion and long term fatigue after many years in service. They may be degraded due to strong winds, severe earthquakes, terrorist attacks, and other abnormal events. American Society of Civil Engineers estimated in 2005 that nearly 1/3 to 1/2 infrastructures in the United States are structurally deficient, and the investment needs about US$1.6 trillion in five years period. Due to economic booming, a huge number of large-scale and complex civil structures have been constructed in China during the past twenty years. However, according to other countries' experience, the enormous cost and effort will be required for maintenance of these structures and for preventing them from damage in next twenty years(1). It is crucial that a concerted effort be made to identify practical and effective methods for the monitoring, evaluation, and maintenance of large civil structures.

The recently developed structural health monitoring (SHM) technology provides an appealing solution to the problems concerned. The SHM technology is based on a comprehensive sensory system and a sophisticated data processing system implemented with advanced information technology and structural analysis algorithms. The main objectives of the SHM are to monitor the loading conditions of a structure, to assess its performance under various service loads, to verify or update the rules used in its design stage, to detect its damage or deterioration, and to guide its inspection and maintenance with the ultimate goals of ensuring the functionality and safety of the landmark structures(2),(3),(4),(5),(6).

Many researchers and engineers are now working in the area of SHM around the world for both academic and practical values, but there are many key scientific problems to be solved before this cutting-edge technology can be accepted by engineering professions. These key problems include: (1) sensing technology for SHM; (2) performance-based design of SHM system; (3) real-time structural damage detection method and structural rating system; and (4) real-time loading simulation and structural performance assessment.

The Hong Kong Polytechnic University has a strong team of experts in sensing technology, spatial information technology, and civil and structural engineering, which offers a favorable combination to interdisciplinary research and application of this cutting-edge technology. Hong Kong is also a uniquely suitable place to pioneer this advanced technology because there are many tall buildings and long span bridges. Hong Kong's strong infrastructure development program provides an ideal "laboratory" for experimenting with new technologies of this kind. In this connection, a comprehensive research program entitled "Performance-based health monitoring of large civil structures" was launched by the Hong Kong Polytechnic University as one of its Niche Area Programs in July 2007 with experts with different disciplinary backgrounds from its four departments to bring this technology into a reality.

2. Scopes of Research Program

The research program consists of four tasks. Brief descriptions of the scopes of the research program in terms of the 4 closely-linked tasks and their coherences are given below.

2.1 Sensing Technology for SHM (Task 1)

Different from mechanical systems, long span bridges and tall buildings are of huge sizes and complex structural systems exposed to very harsh environment. Therefore, special sensing technology is required for health monitoring of large civil structures. The feasibility and performance of optical fiber-based sensors, global positioning system (GPS), and wireless sensors will be evaluated with the focus on their reliability, sensitivity, integrity and robustness. The evaluation and further development of these sensors together with other sensors will lead to the best configuration of performance-based SHM system for the measurements of environmental status, external loading and structural responses, such as wind, traffic, structural displacement, structural acceleration and member stress as envisaged in Task 2.

2.2 Performance-based Design of SHM System (Task 2)

Current design of a SHM system is mainly based on engineering experience without a scientific approach. The scale of SHM system is also decided by owner rather than objective criteria. A rational design method of SHM systems should be performance-based so that the system can check the performance of the structure at all the levels specified. The optimization of types, number and locations of sensors shall be conducted to satisfy the requirements of both economy and performance. The SHM system will encompass optical fiber sensors, GPS and wireless sensors and an advanced sensing network with optimal configuration. The Internet-GIS technology will be adopted as the platform to provide an efficient computerized spatial database management system for capture, retrieval, fusion, analysis and display of measurement data. Data acquired from the monitoring system will provide information for the structural rating system and structural assessment systems envisaged in Tasks 3 and 4.

2.3 Real-time Structural Damage Detection Method and Structural Rating System (Task 3)

Although many structural damage detection methods have been proposed in recent years, they are hardly applied to large civil structures because of the special features of these structures and the complex environment surrounding these structures. Furthermore, large civil structures are lacking an effective structural rating system to provide a rational basis for rating risk of major structural components and for selecting types and frequencies of inspection and maintenance. In this research program, new system identification and damage detection methods based on both local and global measurement data will be developed and uncertainties involved in measurement and modeling will be addressed. SHM system-based structural rating systems incorporating with new system identification and damaged detection methods will be developed to replace the experience-based structural rating systems being currently used.

2.4 Real-time Loading Simulation and Structural Performance Assessment (Task 4)

Real-time loading and structural performance simulation and assessment are the most important component in the performance-based SHM. It can be divided into three levels. The first level is initial loading simulation and structural performance assessment for Task 2, that is, the performance-based design of a SHM system for a given structure. The second level is real-time loading simulation and structural performance assessment based on real-time information obtained by the SHM system in operation. This level of work includes the updating of various analytical models of both loading and structure. This level of work is also closely related to Task 3 for the establishment of SHM system-based structural rating systems. The last but not least level is the performance simulation and assessment of a structure under extreme events to understand structural nonlinear behavior and collapse mechanism. The findings from this level of work will guide the operation of the SHM system to provide early warning of structural failure and detect structural deterioration and damage.

Because of the nature of this research program, an multidisciplinary research team of academic staff members from the four departments of the Hong Kong Polytechnic University is formed. The departments involved are Department of Civil and Structural Engineering (CSE), Department of Land Surveying and Geo-informatics (LSGI), Department of Electrical Engineering (EE), and Department of Computing (COMP).

3. Ten Research Projects

With the existing expertise in the four departments, a total of 10 specific projects are developed to fulfill the four tasks. Each project has its own objectives but some coherence with other projects to fulfill the four tasks. These objectives are achievable, interdependent, interpenetrative, and integrative. Their titles are listed as follows: (1) fiber Bragg sensor networks for SHM; (2) GPS technology for SHM; (3) wireless sensor networks for SHM; (4) performance-based design of SHM system; (5) advanced data acquisition, transmission and management systems; (6) new modeling technologies and model updating methods; (7) novel damage detection algorithms with consideration of uncertainties and operation conditions; (8) SHM-based bridge rating system; (9) SHM-based life-cycle deterioration models; and (10) performance simulation and assessment of structures under extreme loadings.

The names, departments, areas of expertise and projects of team members are listed in Table 1. The objectives of each project are given in the following.

Table 1. Role and expertise of major investigators

Name	Department	Area of Expertise	Project
Y.L.Xu	*CSE*	*Structural Dynamics* *Structural Health Monitoring* *Wind Engineering*	(8) (10)
X.L. Ding	*LSGI*	*GPS Technique* *Monitoring of Building Structures* *Interferometric Synthetic*	(2)
H.Y. Tam	*EE*	*Fibre-Optics Sensors* *Photonics Sensor Networks* *Optical Fibre Communication*	(1)
J.N. Cao	*COMP*	*Wireless Sensors* *Computer Networks* *Parallel and Distributed Computing*	(3)
S.S. Law	*CSE*	*Structural Dynamics* *Structural Damage Detection* *System Identification*	(6)
Y.Q. Ni	*CSE*	*Structural Dynamics* *Sensing Technology* *Structural Health Monitoring*	(4) (5)
Y. Xia	*CSE*	*Structural Damage Detection* *Structural Health Monitoring*	(7)

3.1 Fiber Bragg Sensor Networks for SHM (Project 1)

This research project is set with 6 objectives. They are (1) to review and study the long-term reliability of fiber Bragg grating sensors; (2) to design and fabricate FBG sensors for the instrumentation of the Tsing Ma bridge model for validation of simulation model; (3) to design and build FBG strain and temperature sensors for Guangzhou New TV Tower; (4) to investigate, design, construct and test FBG-based tilt sensors; (5) to design and construct FBG-based accelerometers suitable for civil structure applications; and (6) to multiplex FBG sensors and FBG-based transducers and software development to integrate the multi-functionality of FBG-based sensors.

3.2 GPS Technology for SHM (Project 2)

There are 5 objectives in this research project: (1) to study the site specific GPS errors in SHM such as the multipath and diffraction effects; (2) to develop algorithms for tightly integrating accelerometers, tilt-meters and GPS to form an integrated monitoring system; (3) to study methods for modeling and correcting tropospheric effects on GPS signals when GPS is used for monitoring tall structures; (4) to develop software packages to incorporate the algorithms developed; and (5) to carry out extensive tests of the algorithms, hardware and software developed in simulated environments and on selected super structures.

3.3 Wireless Sensor Networks for SHM (Project 3)

This research project targets 6 objectives, which are (1) to review and analyze the design issues of wireless sensor network (WSN)-based SHM; (2) to design heterogeneous WSN architecture for SHM; (3) to develop distributed processing models and algorithms for SHM ; (4) to develop reliable mechanisms for WSN- based SHM; (5) to provide middleware support for WSN application in the SHM-domain; and (6) to evaluate the results by simulation, laboratory testing and in-field deployment.

3.4 Performance-based Design of SHM System (Project 4)

Based on the results obtained from Task 1-Task 3, this research project is set with 3 objectives: (1) to develop philosophy, principles and procedure for performance-based design of SHM systems; (2) to develop an optimal sensor placement methodology based on the maximization of modal and damage-sensitive information; and (3) to develop a design methodology for integrated SHM at both construction and service stages.

3.5 Advanced Data Acquisition, Transmission and Management Systems (Project 5)

In line with Project 4, this research project is set with 3 objectives: (1) to develop an optimal design method of advanced sensor network incorporating both wired and wireless sensors; (2) to develop an integrated data fusion and knowledge discovery framework for SHM; and (3) to develop an integrated SHM data management and bridge rating system.

The above 5 projects belong to Task 1 and Task 2, focusing on sensors, sensing technology, and performance-based design of SHM systems. The rest 5 projects under Task 3 and Task 4 aim at structural damage detection, structural rating system, and structural assessment.

3.6 New Modeling Technologies and Model Updating Methods (Project 6)

This research project is set with 6 objectives, which are (1) to review existing techniques on modeling local anomalies and on system identification and model updating methods; (2) to develop new sub-structuring technique for large civil structures; (3) to develop new refined finite elements for modeling structural joints of large civil structures; (4) to develop wavelet finite elements for critical components of large civil structures for multi-resolution model updating; (5) to develop new model on the uncertainty propagation for model updating; and (6) to integrate the above into a new SHM-based system identification and model updating method for large civil structures.

3.7 Novel Damage Detection Algorithms with Consideration of Uncertainties and Operation conditions (Project 7)

In connection with Project 6, this research project has 5 objectives: (1) to develop a novel and practical damage detection framework to be applied to large-scale structures by integrating different types of measurement data particularly the local responses and global responses; (2) to investigate the sources of uncertainties involved in the damage detection and study the characteristics of various noise and the effect on the damage identification; (3)

to investigate the effect of operational conditions (loadings, temperature, and humidity) on the measurement data and then on the damage identification; (4) to formulate a new statistical damage detection approach by including uncertainties, and varying operational conditions; and (5) to apply the algorithms into the Tsing Ma bridge model, and one practical high-rise structure (Guangzhou Ne TV Tower).

3.8 SHM-based Bridge Rating System (Project 8)

There are 7 objectives in Project 8: (1) to review and update bridge rating criteria currently-used for long span cable-supported bridges; (2) to ascertain real-time loading and environmental conditions of a bridge using measurement data recorded by SHM systems; (3) to develop SHM-oriented bridge model; (4) to carry out criticality analysis based on the results from the first three objectives; (5) to carry out vulnerability analysis based on the results from the first three objectives; (6) to assess structural performance of the bridge; and (7) to propose a SHM-based bridge rating system for inspection and maintenance.

3.9 SHM-based Life-cycle Deterioration Models (Project 9)

This research project has 3 main objectives: (1) to establish evolutionary models for various stochastic loadings based on the monitoring data, by which long-term variation trend of each loading can be monitored and predicted through evolutionary updating of the loading models; (2) to develop SHM-based structural models with consideration of the deterioration of components over time based on the continuous monitoring of structural response; and (3) to assess the life-cycle performance deterioration of bridges in the probabilistic framework and obtain the statistical time-history profile of the reliability index in terms of serviceability and safety.

3.10 Performance Simulation and Assessment of Structures under Extreme Loadings. (Project 10)

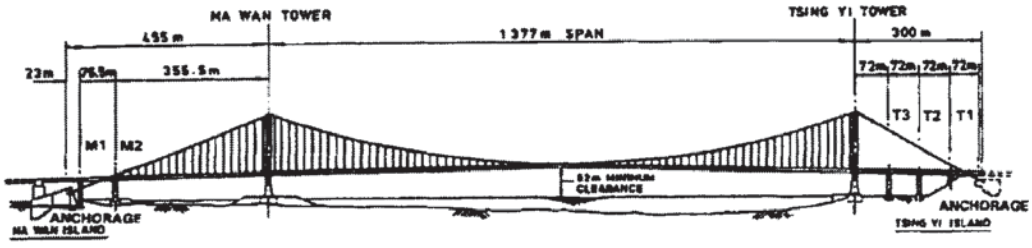
This research project is set with 5 objectives, which are (1) to develop extreme loading models (seismic loading, wind loading, impact loading and blast loading) which sufficiently utilize the real data obtained from the real-time SHM; (2) to model structures including geometric nonlinearity, material nonlinearity, and damage mechanism; (3) to conduct load path and redundancy analysis under the above mentioned extreme loadings; (4) to carry out progressive collapse analysis of structures under the above mentioned extreme loadings; and (5) to develop countermeasures to prevent the catastrophic failure and early warning system to reduce the loss under the above-mentioned extreme loadings.

4. Research Milestones

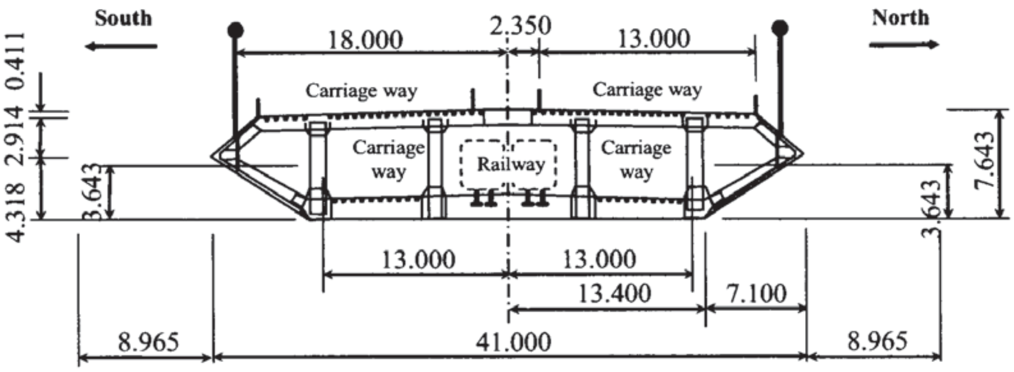
With the substantial needs of construction industry and our academic strengths and professional experience developed from this niche area project, the research team has been playing a vital role in the area of performance-based health monitoring of four large civil structures. They are (1) Tsing Ma Bridge in Hong Kong, China; (2) Stonecutters Bridge in Hong Kong, China; (3) Canton Tower in Guangzhou, China; and (4) Shanghai Tower in Shanghai, China. A summary of research and practical works performed on each structure is given as below.

4.1 Establishment of Bridge Rating System for Tsing Ma Bridge

The Tsing Ma Bridge is a suspension bridge with a main span of 1377 m and a total span of 2160 m that carries a dual three-lane highway on the upper level of the bridge deck and two railway tracks and two carriageways on the lower level within the bridge deck (Figure 1). The Tsing Ma Bridge is a key component of the transportation network system in the west of Hong Kong and it is situated in one of the most active typhoon regions in the world. The functionality and safety of the bridge are of critical importance to economical growth and social development of Hong Kong. To ensure safety and functionality of the bridge, a Wind and Structural Health Monitoring System (WASHMS) was designed and installed in the Tsing Ma Bridge by the Hong Kong Highways Department (HyD) and started to work since1997.



(a) Elevation



(b) Cross section of bridge deck

Fig. 1 Configuration of Tsing Ma Bridge.

The WASHMS in the Tsing Ma Bridge is composed of five sub-systems, namely, sensory system, data acquisition system, data processing and analysis system, computers for system operation and control, and fiber optic cabling network system(7). The sensory system consists of about 300 sensors and the associated interfacing units installed at different locations of the bridge (see Figure 2). They include anemometers, temperature sensors, accelerometers, strain gauges, level sensing stations, displacement transducers, weigh-in-motion sensors, signal amplifiers, and interfacing equipment. The data acquisition system refers to the computer controlled data acquisition outstation units with appropriate data acquisition interfaces and the software for parameter configuration. The data acquisition outstation units are installed on/inside the bridge and their major functions are to collect and digitize signals received from the sensory system and to deliver them to the data processing and analysis system through the fiber optical cabling network system installed along the bridge alignment. The data processing and analysis system is located at the Tsing Yi administrative building and it is a workstation for overall data collection, transmission, storage, control, and post-processing. The computer for system operation and control is also a workstation located at the Tsing Yi administrative building and is equipped with appropriate software for graphical inputs and outputs of structural modeling and analysis works.

On the other hand, to ensure safety and functionality of the bridge, a bridge rating method is currently used by the Hong Kong bridge management authority as guidance in determining the time intervals for inspection and the actions to be taken when defects are identified(8). This bridge rating method is based partly on engineering analyses and partly on practical experience acquired from similar structures elsewhere. The observations and measurement results obtained in the past ten years from the WASHMS indicate that there are some drawbacks in the existing rating method. There is insufficient link between the existing bridge rating method and the SHM system installed in the bridge.

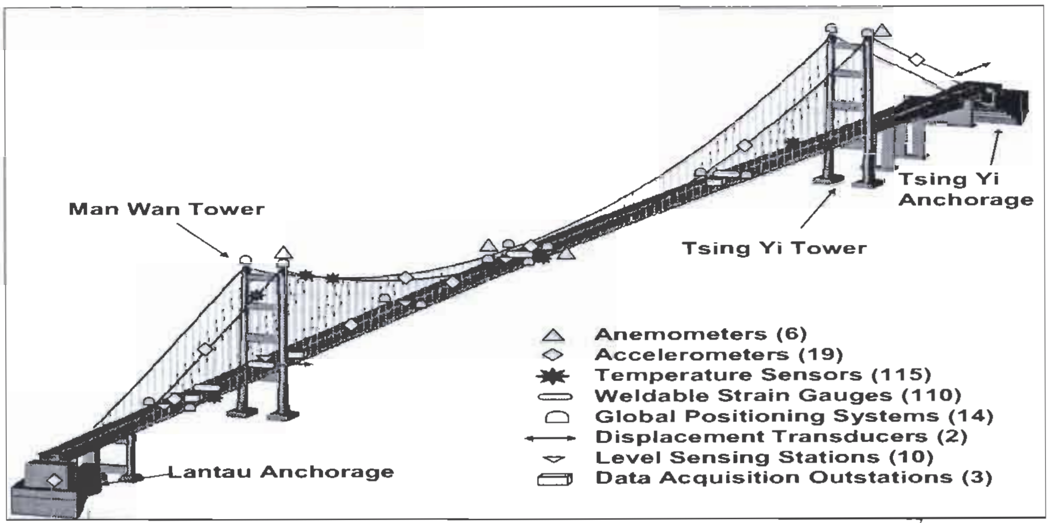


Fig. 2 Layout of Sensory Systems and Data Acquisition Units in Tsing Ma Bridge[7]

The Hong Kong Highways Department thus initiated a collaborative research project with the research team of The Hong Kong Polytechnic University to establish an effective bridge rating system for the Tsing Ma Bridge in 2006. The project has been completed in 2010. A total of 12 research reports have been submitted to the Hong Kong Highways Department. Significant results achieved are summarized as follows:

(1) In Report No.1, the details of establishment of full 3D finite element models (FEMs) for local components of the Tsing Ma Bridge have been presented. The FEMs of local bridge components include:(1) the two bridge towers; (2) the five bridge deck modules respectively in the main span, the two approach spans and the embedded decks at the two towers; (3) the five bridge piers in the two side spans (4) the cable system composed of two main cables, 95 suspender units and 95 cable bands; and (5) the cable fixture components including four tower saddles, two pier saddles and two anchorages.

(2) In Report No.2, the integration of all the bridge component models, the modeling of the connections among the bridge components, and the modeling of the supports (or boundary conditions) of the global bridge model are addressed. Because of the unique modeling requirement of stress/strain level for criticality analysis, more than 300,000 nodes, 450,000 elements including about 50,000 MPCs are used and 1.2 million DOFs are involved in the entire global bridge model. Its success resorts to the modern hardware and software development of computation technologies.

(3) In Report No.3, the predominating wind loading effects on the acceleration and displacement responses of the Tsing Ma Bridge have been investigated for typhoon and strong monsoon events. The measurement data of wind, temperature, vehicle, bridge displacement and bridge acceleration recorded by five types of sensors have been collected. The data pre-processing for each sensor has been proposed to obtain the quality data for the evaluation of wind effects on bridge acceleration and displacement responses. After that, the statistical details of wind loading environment recorded from the ultrasonic anemometers at the middle of main span of the bridge deck undergone by the Tsing Ma Bridge have been provided. In addition, the statistical relationships between the wind and bridge acceleration responses and between the wind and bridge displacement responses have been established.

(4) In Report No.4, the predominating temperature loading effects on the displacement responses of the Tsing Ma Bridge have been investigated. Several data elimination criteria have been proposed for data pre-processing in order to obtain the useful data for the evaluation of temperature effects on bridge displacement responses. After that, the statistical details of ambient temperature loading environment in different seasons

undergone by the Tsing Ma Bridge and the temperature variation of the bridge components as a result have been provided. In addition, the statistical relationships between the ambient/bridge temperature and the displacement responses of the bridge have been established.

(5) In Report No.5, the highway traffic condition and the predominating highway loading effects on the Tsing Ma Bridge have been investigated. The highway traffic conditions of the Tsing Ma Bridge have been analyzed in terms of vehicle traffic volume, vehicle traffic composition, axle load spectrum and gross vehicle weight (GVW) spectrum. The measured axle load spectrum and GVW spectrum have been compared with the design spectrum and the spectrum specified in BS5400: Part 10. The strain data collected by 110 strain gauges installed at three sections of the bridge during November 2005 have been pre-processed and analyzed. A practical method in conjunction with the method proposed in BS5400: Part 10 has been used to estimate the fatigue life of the bridge due to highway loading only, railway loading only, and a combination of railway and highway loading.

(6) In Report No.6, the railway traffic condition and the predominating railway loading effects on the Tsing Ma Bridge have been investigated. The railway traffic condition of the Tsing Ma Bridge has been analyzed in terms of train traffic volume, bogie load distribution, bogie load spectrum and gross train weight spectrum. A practical method has been proposed to investigate the railway loading effects on the vertical displacement response of the bridge deck based on the GPS measured displacement data at the four bridge sections. The railway loading effects on the vertical acceleration response of the bridge deck has been compared with the traffic (both highway and railway) loading effects on the same quantity. The measured traffic-induced peak accelerations have been also compared with the design values.

(7) Report No.7 focuses on review and updating of the criticality and vulnerability rating method currently used for the Tsing Ma Bridge. A literature review concerning inspection, maintenance and condition assessment of short, medium, and long span bridges used in various regions or countries is first carried out to understand the current practice around the world. The currently used criticality and vulnerability rating method and the preliminary findings for the Tsing Ma Bridge are then introduced and reviewed for a complete understanding of the topic. After that, the criticality and vulnerability rating method used in the bridge rating system for the Tsing Ma Bridge are updated by using a more suitable mathematical framework and by integrating the WASHMS into the bridge rating system.

(8) Report No.8 is the first part of the criticality and vulnerability analysis of the Tsing Ma Bridge, focusing on the strength of the bridge under design combined loads in terms of the strength utilization factor which is one of the five criticality factors in the criticality rating of the bridge. A 3D finite element model of the Tsing Ma Bridge is first established at a stress level using the ABAQUS software package. Load types and load cases are then presented. Extensive static analyses of the Tsing Ma Bridge under dead loads, super-imposed dead loads, temperature loads, highway loads, railway loads, wind loads, seismic loads as well as load combinations are conducted. The strength utilization factors of the structural components of the bridge are computed based on the stress analysis results and the critical structural components of the bridge are finally identified.

(9) Report No.9 focuses on the criticality and vulnerability analysis of the Tsing Ma Bridge with respect to fatigue. This report estimates fatigue damage for different bridge components caused by railway and highway loadings. A traffic induced stress analysis method is first proposed based on the influence line method for the determination of stress time histories. Vehicle spectrum analysis is implemented to obtain the actual train spectrum and the actual road vehicle spectrum in terms of the measurement data of traffic loading. Fatigue-critical locations of different bridge components are then determined on the basis of

stress time histories caused by a standard train. Finally, respective fatigue damage due to train and road vehicle, and fatigue life due to both train and road vehicles at different fatigue-critical components are estimated using the vehicle spectrum method.

(10) Report No.10 focuses on the performance assessment of the Tsing Ma Bridge by integrating the computer simulation of the bridge under wind loading with the WASHMS-recorded data. The SHM-based finite element model (FEM) which replicates the geometric details of the as-built complicated bridge deck and the SHM-based buffeting analysis method are first introduced. The wind forces composed of steady-state wind loads due to mean wind, buffeting forces due to turbulent wind, and self-excited forces due to interaction between wind and bridge motion are generated and distributed over the bridge deck surface. After that, the accurateness of the SHM-based buffeting analysis method is evaluated through the comparisons between the computed displacement responses and the corresponding responses measured from the field. The statistical relationships obtained in the previous report are extended to extreme wind speeds and other locations on the bridge deck through computer simulation. The results are compared with the measurement data from wind tunnel tests and the allowable movements of the bridge under the given limit state for serviceability assessment. In addition, the SHM-based buffeting analysis method is also utilized to compute wind-induced stress in all the bridge components and identify critical steel members. The wind-induced stresses of the critical members are then linked to the wind-induced displacement response at the mid-main span through the hybrid use of the GPS measured displacements and FEM analyses. The wind-induced stresses derived at extreme wind speeds are then compared with the yield stress of the steel material to assess the safety of the bridge.

(11) Report No.11 focuses on the current and new bridge rating systems for the Tsing Ma Bridge integrated with the SHM system, which is one of the most important investigation topics for the collaborative research project "Establishment of bridge rating system for the Tsing Ma Bridge". This report integrates the results obtained in the previous studies with both the current and new bridge rating systems to assess the feasibility of the SHM-and fuzzy-based analytic hierarchy approach (F-AHP) bridge rating system.

(12) Report No.12 is a summary report of all the investigations carried out in the collaborative research project "Establishment of bridge rating system for Tsing Ma Bridge" between The Hong Kong Polytechnic University and the Hong Kong Highways Department.

A book entitled" Structural health monitoring of long-span suspension bridge" was written by the research team and published by Taylor & Francis in 2011 based on their research work and practical experience acquired in the past fifteen years in the field of SHM of civil structures. The book systematically introduces the fundamentals and outlines the advanced technologies for achieving long-term monitoring. The book consists of fourteen chapters: (1) introduction; (2) long-span suspension bridges; (3) structural health monitoring systems; (4) SHM-oriented modeling; (5) monitoring of highway loading effects; (6) monitoring of railway loading effects; (7) monitoring of temperature effects; (8) monitoring of wind effects ; (9) monitoring of seismic effects; (10) monitoring of other effects; (11) structural damage detection; (12) bridge rating system; (13) establishment of test-beds; and (14) epilogue: challenges and prospects.

4.2 Development of Structural Health Prognosis Tools and Condition Rating System for Stonecutters Bridge

Stonecutters Bridge, a two-cable-plane cable-stayed bridge, has been recently built in Hong Kong. As the world's second longest cable-stayed bridge, it carries dual 3-lane highway traffic. The main/central span of Stonecutters Bridge is 1018m, and the total length including side spans is 1596m. The noteworthy structural characteristics of Stonecutters

Bridge include: (1) separated and streamlined steel twin-box girders at central span; (2) hybrid (concrete/steel) separated box girders at side spans; (3) hybrid (concrete/stainless steel) single tower leg; (4) floating deck-to-tower connections in central span and rigid deck-to-pier connections at side spans. A comprehensive SHMS, termed Structural Health Monitoring and Safety Evaluation System (SHM&SES), is going to be deployed for monitoring and evaluation of Stonecutter Bridge under in-service condition. The SHM&SES is composed of nine interrelated components, namely, sensory system, data acquisition system, cabling network system, portable data acquisition system, data processing and control system, portable inspection and maintenance system, structural health rating system, structural health evaluation system and data management system[9]. The sensory system is composed of 1571 sensors in 15 different types, namely anemometers, barometers, hygrometers, temperature sensors, corrosion cells, accelerometers, dynamic weigh–in-motion stations, video cameras, dynamic strain gauges, static strain gauges, GPSs, tiltmeters, bearing sensors, buffer sensors and tension-magnetic sensors[9]. Figure 3 shows the layout of the sensory system.

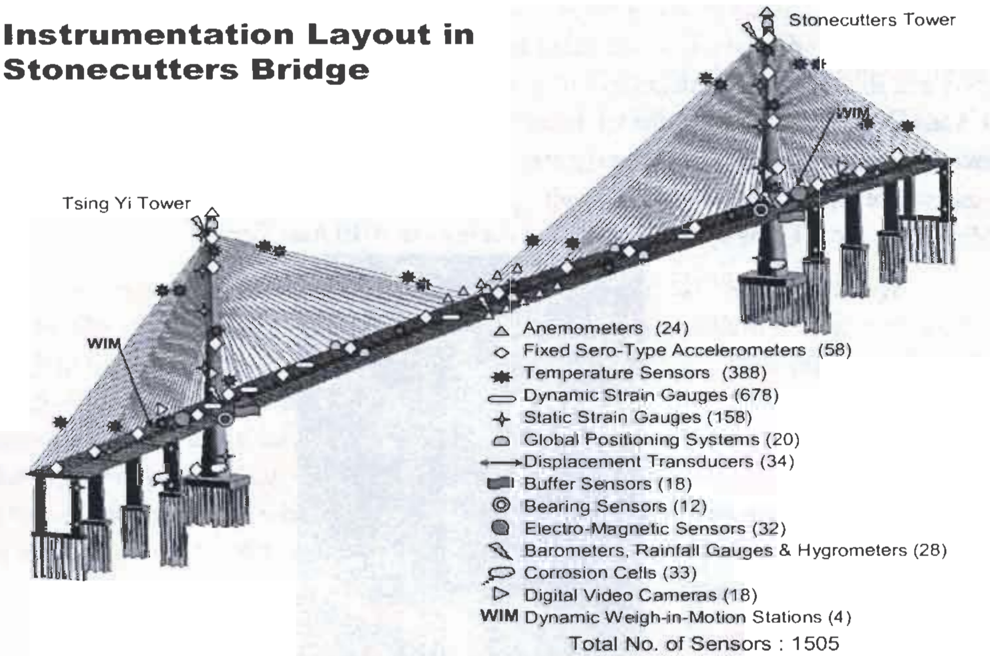


Fig. 3 Instrumentation Layout in Stonecutters Bridge[9].

The Hong Kong Polytechnic University, in collaboration with the Highways Department of Hong Kong SAR Government, has been developing Structural Health Prognosis Tools and Condition Rating System for Stonecutters Bridge since 2010. A series of structural prognosis tools are being developed for the evaluation of Stonecutters Bridge under in-service conditions. The main tasks include: (i) to customize finite element analytical tools for bridge engineers executing structural health evaluation works; (ii) to identify the critical sections and/or components under different types of loading conditions in respective the limit states of serviceability (normal), ultimate (maximum normal), and structural integrity (extreme); (iii) to quantify the stress/force distribution and status in the critical sections and/or components identified in the item (ii); (iv) to determine the failure modes (for component-level) and/or failure mechanisms (for system-level) of the bridge under different types of loading conditions in respective the limit states of serviceability (normal), ultimate (maximum normal), and structural integrity (extreme); and (v) to correlate the analyzed results with for structural component health rating, which will be used to set the priority of different types of bridge inspection and maintenance activities.

The development of structural health rating system aims to provide a rational basis for rating risk of essential bridge structural components utilizing the monitoring data from

SHM system and for selecting types and frequencies of inspection and maintenance. Its main tasks are therefore: (i) to develop and establish a systematic and practical approach to categorize the structural components of Stonecutters Bridge for facilitating the activities of structural health rating and bridge inspection and maintenance; (ii) to develop and establish a structural health rating system with deterministic rating indices and appropriate rating tools, which can directly reflect the realistic structural condition of the structural components under their in-service condition; and (iii) to develop software tools which are compatible with SHM&ES for Stonecutters Bridge for semi-automatic or automatic execution of the components categorization and structural health rating works.

4.3 Development of Structural Health Monitoring System for Canton Tower

The Canton Tower (CT), formerly named Guangzhou New TV Tower, located in Guangzhou, China, assures a place among the supertall structures worldwide by virtue of its total height of 600 m. As shown in Figure 4, the CT consists of a 450 m high main tower and a 150 m high antenna mast. The main tower is a tube-in-tube structure consisting of a steel lattice outer structure and a reinforced concrete inner structure. The outer structure has a hyperboloid form, which is generated by the rotation of two ellipses, one at the ground level and the other at an imaginary horizontal plan 450 m above the ground. The CT serves a variety of functions – television and radio transmission, sightseeing, catering, and entertainment embracing an orbital Ferris wheel, a ceremony hall, observatory decks, 4D cinemas, revolving restaurants, skywalk, etc. With completion of structural construction in May 2009, the CT was open for operation during the 2010 Asia Games.

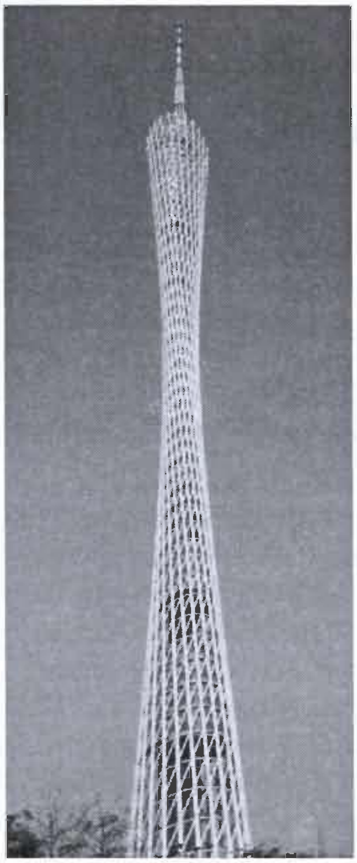


Fig. 4 Canton Tower

To ensure safety and serviceability of this landmark structure during construction and operation, a sophisticated long-term SHM system has been designed and implemented by The Hong Kong Polytechnic University for real-time monitoring of the CT at both in-construction and in-service stages(10), (11). The integrated SHM system consisting of over 600 sensors includes a weather station (air temperature, humidity, barometric pressure, rainfall), a total station, a GPS system, a seismograph, accelerometers, anemometers, wind pressure meters, FBG temperature and strain sensors, vibrating wire strain gauges and temperature sensors, electrical resistance temperature sensors, corrosion sensors, digital video cameras (a vision-based displacement measurement system), tiltmeters, level sensors, laser zenith meters, and altazimuths. A hybrid tethered and wireless data acquisition network in conjunction with 13 data acquisition units (DAUs) during in-construction monitoring and 5 DAUs during in-service monitoring has been adopted in the SHM system.

Because the data acquisition system is operated to automatically and continuously acquire monitoring data, the SHM system has monitored the structural responses of the CT during a number of typhoon and earthquake events [12]. During 2008 and 2011, the SHM system has monitored the wind properties and structural responses of the CT during eight typhoons, i.e., the Neoguri typhoon (April 18th, 2008), the Kammuri typhoon (August 6th, 2008), the Nuri typhoon (August 22nd, 2008), the Hagupit typhoon (September 24th, 2008), the Molave typhoon (July 16th, 2009), the Koppu typhoon (September 24th, 2009), the Haima typhoon (June 23rd, 2011), and the Nalgae typhoon (October 3rd, 2011). In addition, the SHM system has successfully monitored seismic responses of the CT during more than ten earthquake events in the past four years, including the Wenchuan earthquake (May 12th, 2008, Richter scale 8.0), the Japan earthquake (March 11th, 2011, Richter scale 9.0), and the Burma earthquake (March 24th, 2011, Richter scale 7.2).

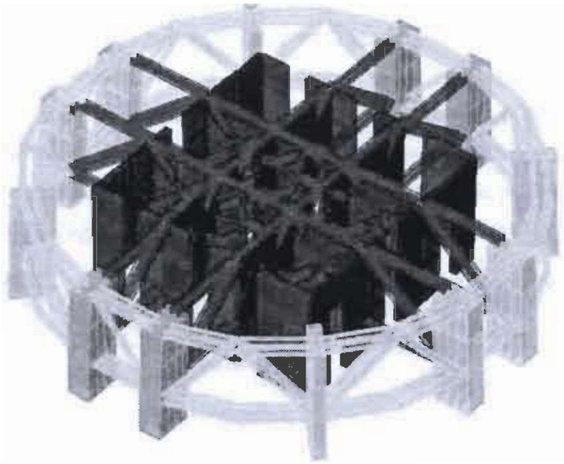
4.4 Development of Structural Health Monitoring System for Shanghai Tower

The Shanghai Tower, currently under construction, will be 632 m tall (in total) and 580 m high at the roof. Upon completion in 2014, it will be the tallest skyscraper in China. The Shanghai Tower adopts a frame-core-outrigger system, as shown in Figure 5. The outer frame consists of eight super RC columns and eight levels of two-story-high steel belt trusses. The inner core is a 30 m × 30 m square consisting of nine bundled RC tubes at the bottom of the building, which gradually decrease to five at the top. The outriggers are two-story-high steel radial trusses connecting the inner core and the outer frame at six strengthening levels. In each floor, ring beams link the super columns and diagonal columns. Radial beams connect the inner tubes to the exterior columns.

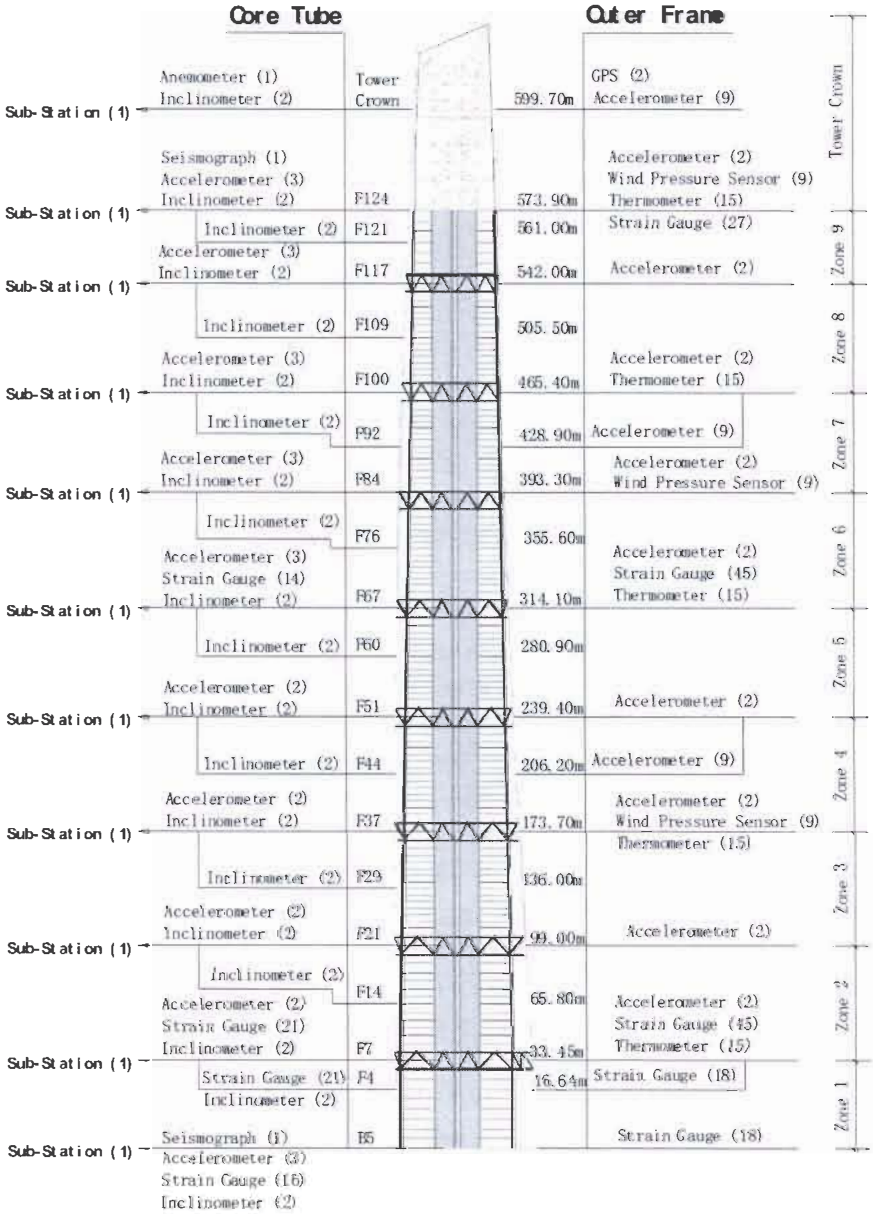
A comprehensive SHM system has been designed and is being constructed by a joint venture from the Tongji University, Hong Kong Polytechnic University, and Tongji Architectural Design (Group) Co. Ltd. This SHM system serves to monitor the performance of the structure under wind, seismic, and temperature loadings during the construction and service stages. The monitoring system consists of four modules, namely, the sensory system, the data acquisition and transmission system, the data processing and control system, and the structural performance evaluation system. The sensory system has over 400 transducers of 12 different types, including anemometers, wind pressure sensors, accelerometers, seismographs, strain gauges, thermometers, GPS, total stations, theodolites, inclinometers, digital video cameras, and crack sensors. Figure 5(b) illustrates the position of the sensors and the associated substations distributed over the structure.

5. Challenges and Prospects

SHM is a cutting-edge technology, providing better solutions for design, construction, maintenance, functionality and safety of large civil structures. While substantial progress has been made in this area, there are still some important issues not being fully discussed and some challenging issues to be solved in near future. These important and challenging issues include but not limited to (1) durability and optimization of the sensor network; (2) novel damage detection methods; (3) advanced computational simulation; and (4) structural performance assessment and life-cycle management.



(a) Frame-core-outrigger system of the Shanghai Tower



(b) Sensor layout of the SHMS

Fig. 5 Instrumentation layout in Shanghai Tower

Although there are many challenging issues ahead in SHM of large-scale civil structures, the implementation of SHM technologies for practical applications is being widely considered and is in process. Mutual respects and effectively coordinated collaborations are also established among professional engineers, academic researchers, government agencies, contractors, managers, and owners. This is because the benefits of SHM technologies are well recognized by all levels of communities for improving structural reliability and operational efficiency while reducing maintenance and operating cost. These benefits are the major incentives to drive this technology development in various aspects. The rapid development in sensing technology, information technology, computation simulation, and asset management will eventually overcome remaining challenging issues to fully realize the goals and objectives of the SHM.

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