Health Checks through Landmark Bridges to Sky-high Structures

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Health Checks through Landmark Bridges to Sky-high Structures

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Abstract: Massive infrastructure projects developed in Hong Kong make for big challenges and unique opportunities for engineers and researchers. The construction of the cables-stayed Stonecutters Bridge sets up a new landmark in the bridge engineering community, with its main span exceeding 1,000 m as well as its sophisticated instrumentation system comprising more than 1,500 sensors. The development of structural health monitoring (SHM) technology has evolved for over 10 years in Hong Kong since the implementation of the so-called "Wind And Structural Health Monitoring System (WASHMS)" on the suspension Tsing Ma Bridge in 1997. The successful engineering paradigms of implementing and operating SHM systems for five cable-supported bridges and experiences gained by practice and research in the past decade have promoted the applications of this technology beyond Hong Kong and extending from long-span bridges to high-rise structures. In this paper, the evolution in the design methodology for SHM systems, the advancement in several aspects of SHM technology, and a performance comparison between the early implemented and lately developed SHM systems for large-scale bridges are first outlined. Subsequently, the concept of the so-called "life-cycle structural health monitoring (LSHM)" is addressed by exploring the integration of in-construction monitoring and in-service monitoring and by realizing such an integrated system to a super-tall tower structure. The issue on how an SHM system benefits structural vibration control is also discussed.

Key words: life-cycle structural health monitoring, long-span bridges, high-rise structures, integration of health monitoring and vibration control.

1. INTRODUCTION

Large-scale structures such as long-span bridges and high-rise towers are vital civil infrastructure. Maintaining their safe and reliable operation is critical in securing the well being of people, protecting the vast investments, and supporting the vitality of the economy. However, civil engineering structures cannot last forever; they begin to deteriorate as soon as they are built. As a result, it is of paramount importance to diagnose and prognose the safety of large-scale civil engineering structures throughout their entire life cycle. The significance of implementing long-term SHM systems to secure structural and operational safety and to issue early warnings on damage or deterioration prior to costly repair or even catastrophic collapse has been increasingly recognized (Ko and Ni 2005).

In the past decade, five long-span cable-supported bridges, namely the Tsing Ma Bridge, the Kap Shui Mun Bridge, the Ting Kau Bridge, the Western Corridor Bridge, and the Stonecutters Bridge, have been built in Hong Kong. All five bridges have been instrumented with a sophisticated on-line SHM system, named "Wind And Structural Health Monitoring System (WASHMS)" (Wong 2004, 2007). The WASHMS has also been periodically updated in order to effectively execute the functions of structural condition monitoring under in-service condition and structural degradation evaluation as it occurs. The successful engineering paradigms of

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implementing and operating SHM systems for these bridges and experiences gained by practice and research in the past decade have promoted the applications of this technology beyond Hong Kong and extending from long-span bridges to high-rise structures.

2. SHM SYSTEMS FOR BRIDGES IN HONG KONG

Figure 1 illustrates the SHM systems deployed on the Tsing Ma Bridge (a suspension bridge with a main span of 1,377 m), the Kap Shui Mun Bridge (a cable-stayed bridge with a main span of 430 m), the Ting Kau Bridge (a cable-stayed bridge with two main spans of 475 m and 448 m respectively), the Western Corridor Bridge (a single-tower cable-stayed bridge with a main span of 210 m), and the Stonecutters Bridge (a cable-stayed bridge with a main span of 1,018 m). The recently deployed SHM system for the Stonecutters Bridge consists of a total of 1,505 sensors, making it the most heavily instrumented bridge in the world. The SHM

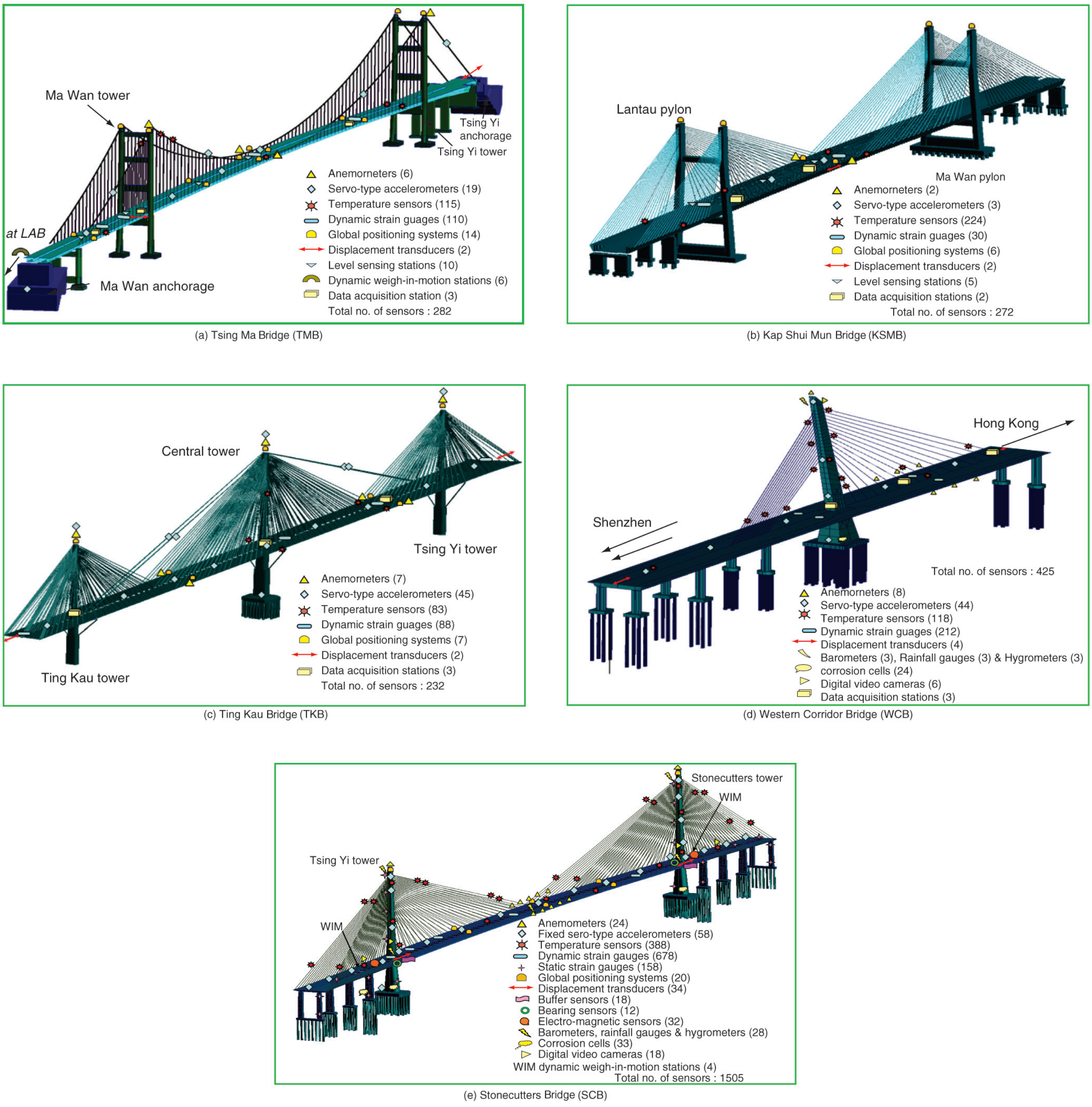


Figure 1. SHM systems for cable-supported bridges in Hong Kong

systems for bridges in Hong Kong were devised for the following purposes:

- To validate design assumptions and parameters with the potential benefit of improving design specifications and guidelines for future similar structures;
- To detect anomalies in loading and response and possible damage/deterioration at an early stage to ensure structural and operational safety;
- To provide real-time information for health and safety assessment immediately after disasters and extreme events;
- To provide evidence and instructions for planning and prioritizing structural inspection, maintenance, rehabilitation, and repair;
- To monitor repairs and reconstruction with the view of evaluating the effectiveness of maintenance, retrofit and repair works; and
- To obtain massive amounts of in-situ data for cutting-edge research.

The modular concept has been developed in designing the SHM systems that are purposed to monitor structural condition and evaluate structural degradation as it occurs rather than to detect structural failure. As shown in Figure 2, the modular architecture of the devised SHM systems is composed of six integrated modules (Wong and Ni 2009a), namely Module 1 – sensory system (SS); Module 2 – data acquisition and transmission system (DATS); Module 3 – data processing and control system (DPCS); Module 4 – structural health evaluation system (SHES); Module 5 – structural health data management system (SHDMS); and Module 6 – inspection and maintenance system (IMS).

The SS comprises a variety of sensors and their interfacing units for the measurement of physical parameters of a bridge and its surrounding environment. There are four types of measuramds, namely environment, operation load, structural feature, and structural response. The DATS comprises two categories of equipment, namely data acquisition units (a package of software-controlled instruments) and network systems (either tethered or wireless) for the acquisition, processing, temporary storage, and transmission of signals. The DPCS refers to the hardware and software of a high-performance computer system for the execution of system control, system operation display, bridge operation display, and processing and analysis of data. The SHES, which is the core of an SHM system, is a high-performance

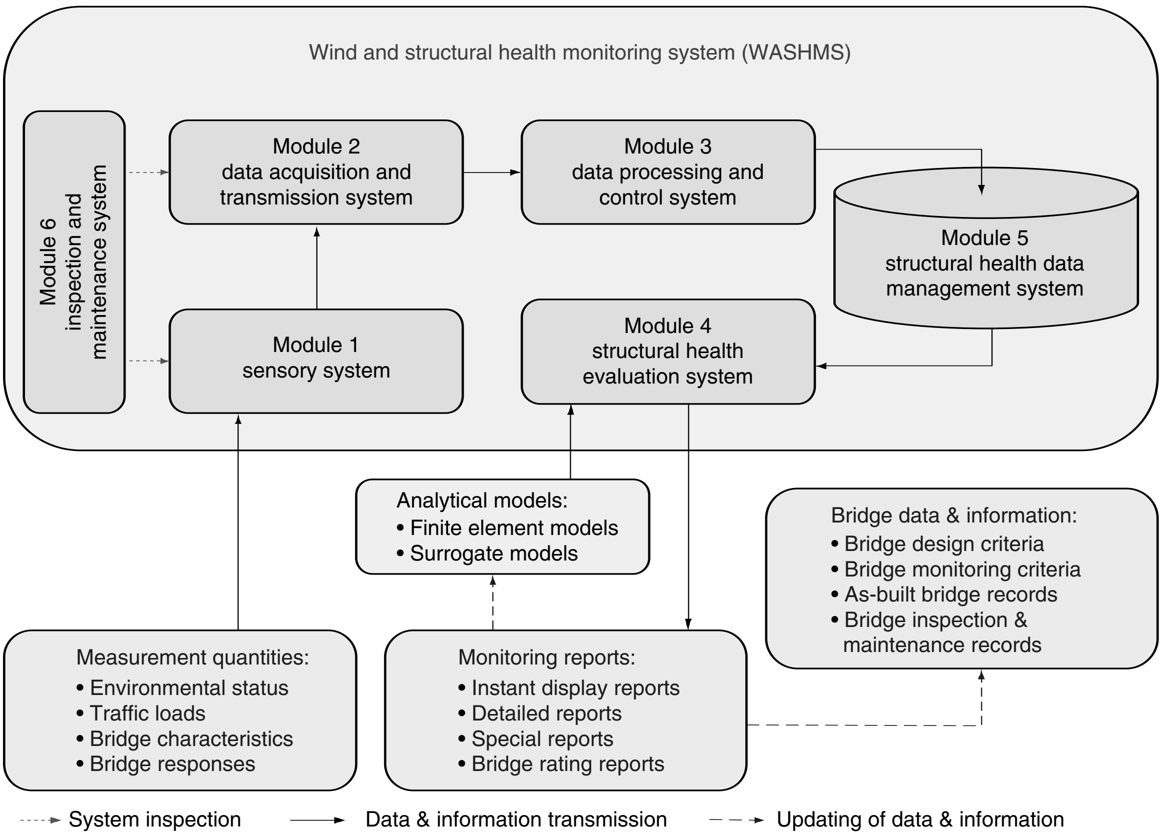


Figure 2. Modular architecture of SHM systems for bridges in Hong Kong

computer system equipped with appropriate software tools for the execution of inter-solver finite element analysis, sensitivity analysis and model updating, bridge feature and response analysis, diagnostic and prognostic analysis, and visualization of analyzed results. It includes an on-line structural condition evaluation system and an off-line structural health and safety assessment system. The on-line structural condition evaluation system is mainly to compare the static and dynamic measurement data with the design values, finite element analysis results, and pre-determined thresholds and patterns to provide a prompt evaluation on the structural condition; while the off-line structural health and safety assessment system incorporates a variety of model-based and data-driven diagnostic and prognostic algorithms which mostly require both historical and current monitoring data. The SHDMS is composed of a high-performance computer system, a data repository system, and a data warehouse management system for the storage and retrieval of monitoring data and analysis results. The IMS is a laptop-computer-aided portable system for the inspection and maintenance of sensors, data acquisition units, data transmission networks, and display facilities.

To facilitate the bridge inspection and the bridge maintenance prioritization, three operational strategies have been defined for each of the SHM systems (Wong and Ni 2009b). Operation Strategy I is normal structural condition monitoring. It refers to the measurement values of the physical quantities ($\sigma_{Measured}$) which are less than 75% of the designated monitoring values (σ_{SLS}). Here the designated values σ_{SLS} are the bridge design loads and responses at the serviceability limit state. Under such a condition, only routine statistical analysis and reports of measurement results are required. Operation Strategy II is critical structural condition monitoring. It refers to the values of $\sigma_{Measured}$ which are in between 75% and 100% of those of σ_{SLS}. Under such a condition, the structural evaluation of measurement results from finite element and/or surrogate models are required to check any over-displaced or over-stressed phenomenon occurring in non-instrumented or key locations/components. If so, inform the bridge maintenance team to carry out a detailed inspection on problematic locations/components. Operation Strategy III is structural degradation evaluation. It refers to the values of $\sigma_{Measured}$ which are equal to or greater than 100% of those of σ_{SLS}. Under such a condition, the detailed the structural evaluation based on measurement data and analytical results from finite element and/or surrogate models are required to check any damage induced and assess the adverse effects of such damage on global bridge performance. If so, inform the bridge maintenance team to carry out a detailed inspection and assess the scope and time of remedial action, where necessary.

3. EXPERIENCES AND LESSONS LEARNED

Table 1 lists the type and number of sensors installed on the five bridges in Hong Kong. The SHM system for the Tsing Ma Bridge (TMB) was implemented in 1997 when the bridge construction was completed, while the SHM system for the Stonecutters Bridge (SCB) has just completed its implementation. A comparison between these two systems can be made: (i) the sensors for TMB were mainly deployed on the half span in Ma Wan side in consideration of symmetry, whereas the sensors for SCB were distributed along the entire span; (ii) the anemometers for TMB were deployed only for vertical correlation, while the anemometers for SCB were deployed for both vertical and horizontal correlations; (iii) the SHM for TMB excludes durability monitoring, whereas the SHM system for SCB includes corrosion sensors, rainfall gauges, barometers, hygrometers to monitor durability; and (iv) the SHM for TMB originally adopted a file-based data management system, while the SHM system for SCB uses a data repository system together with a data warehouse system. The experience gained in the past decade indicates that durability may govern the condition and health of a sea-crossing bridge over its service life cycle; and therefore durability monitoring has currently become an important part of SHM systems for sea-crossing bridges, especially for those located in north China regions with heavy freezing-thawing cycling and severe saline concentration (Shao *et al*. 2010).

The SHM for TMB originally adopted a file-based data management system, which has the limitations of (i) separation and isolation of data – difficult to access files for data processing and impossible for synchronizing processing of more than two data-files, (ii) duplication of data – loss of data integrity or consistence, (iii) data dependence – creation of one-off programs, (iv) incompatible file formats – difficult for joint processing of multiple data-files, and (v) fixed queries or proliferation of application programs. Such limitations result in two major drawbacks: (i) long duration of operation for data retrieval, processing and analysis, and (ii) very difficult or even impossible to carry out three or more dimensional correlation and regression analysis. In order to overcome such limitations, a data repository system and a data warehouse system have been introduced in the updated SHDMS to realize: (i) standardization and normalization of data, (ii) semi-automatic operation of retrieval, processing and analysis of measured data, (iii)

Table 1. Sensors deployed on cable-supported bridges in Hong Kong

Type of Sensors	TMB	KSM	TKB	WCB	SCB
Anemometer	6	2	7	8	24
Servo-type accelerometer	19	3	45	44	58
Dynamic and static strain gauge	110	30	88	212	836
Displacement transducer	2	2	2	4	34
Temperature sensor	115	224	83	118	388
Global positioning system (GPS)	14	6	7	—	20
Level sensing station	10	5	—	—	—
Dynamic weigh-in-motion station	6	—	6	—	4
Barometer, Rainfall gauge & Hygrometer	—	—	—	9	28
Corrosion cell	—	—	—	24	33
Digital video camera	—	—	—	6	18
Elasto-magnetic sensor	—	—	—	—	32
Buffer sensor	—	—	—	—	18
Bearing sensor	—	—	—	—	12
Data acquisition station	3	2	2	3	8
Total number of sensors	282	272	238	425	1,505

multi-dimensional analysis of data through manipulation of appropriate software analysis tools such as on-line analytic processing (OLAP) and data mining tools, and (iv) integration of all the historical and current measured/analyzed/derived data and information for real-time monitoring, off-time evaluation, report generation and decision recommendation.

Lessons learned from the SHM practice in Hong Kong tell the importance of appropriate SHM strategies associated with software systems and appropriate analysis tools to link the SHM data with bridge inspection and maintenance action. The SHM systems in Hong Kong have been updated to operate in three strategies and to achieve (i) confirmation of existence of overstress or damage, (ii) determination of overstressed/damaged location, (iii) identification of type and cause of overstress or damage, (iv) quantification of the amount of overstress or damage, and (v) estimation of adverse effects on global structural performance or prediction of remaining service life. The software systems associated with the above tasks are detailed in Wong and Ni (2009b). Some structural condition and damage assessment methods validated using real-world monitoring data are also summarized in Ni (2010a). In order to bridge the gap between the SHM system and the bridge inspection and maintenance system, an SHM-based bridge rating system has been developed for each instrumented bridge and integrated with the SHM system to determine the priorities of bridge inspection and maintenance activities. The rating system involves the categorization of structural components, formation of criticality and vulnerability rating matrix, load resistance strength analysis, and correlation between rating indices and bridge maintenance prioritization (Wong 2006).

Collaboration between the government/owner and institutions has been shown to be important for good operation and management of the SHM systems. A number of collaborative research projects related to the development, operation and management of the SHM systems were conducted between the Highways Department of Hong Kong SAR Government and the tertiary institutions, and some projects are still underway. Technology synergy and resource leveraging between the government, tertiary institutions, and industry has been well practiced, and coordinated multi-disciplinary research has been pursued to provide technological supports for successful implementation and operation of the SHM systems. The fruitful real-world monitoring data acquired from the SHM systems not only benefit the scholars in conducting cutting-edge research, and also benefit the government (or investors) in planning and supervising the design of new bridges. For instance, the Highways Department of Hong Kong SAR Government was benefiting greatly from the long-term monitoring data of the Tsing Ma Bridge in the planning and design of the Stonecutters Bridge, and this in turn came to a more advanced SHM system for the Stonecutters Bridge. The development of the advanced SHM systems enhances the visibility of Hong Kong in bridge engineering community while showcasing new technologies to the public.

The ten years' bridge SHM practice in Hong Kong highlights the following technical issues for successful SHM engineering paradigms:

- Quality of sensors and measurement data;
- Optimization of intensity and location of sensor deployment;
- Integration of SHM in both construction and service stages;

- Integration of SHM system with bridge inspection, maintenance and management; and
- Maintenance and management of SHM system itself.

Optimal sensor placement (OSP) is an important issue in practicing SHM. While a number of theoretical investigations on this topic have been made, the existent OSP methods are not practical for instructing the optimal placement of dense sensors of different types on a large-scale bridge. The research envisaged in the following may direct OSP methods to be more applicable: (i) performance-based OPS by taking into account both structural information aspect and communication/networking constraints (e.g., analog signal transmission deterioration), (ii) simultaneous optimization of sensor placement and data acquisition station placement, and (iii) multi-scale or multi-objective optimization inclusive of both static-type sensors and dynamic-type sensors.

4. EXTENSION OF SHM PRACTICE FROM BRIDGES TO SKYSCRAPERS

The bridge SHM practice and experiences gained in the past decade have been extended to develop long-term SHM systems for high-rise structures. The SHM system for the Guangzhou New TV Tower (GNTVT) is such an example. Being the landmark of the Guangzhou city in China, the GNTVT is a supertall tube-in-tube structure with a total height of 610 m. The main tower of 454 m high is composed of a reinforced concrete inner structure with an ellipse cross-section of 14 m × 17 m and a steel lattice outer structure with its cross-section being a varying oval which decreases from 50 m × 80 m at the ground to the minimum of 20.65 m × 27.5 m at the height of 280 m (waist level), and then increases to 41 m × 55 m at the top of the main tower. There are 37 floors connecting the inner and outer structures. The antenna mast of 156 m high, founded on the top of the main tower, is a steel spatial structure with an octagonal cross-section of 14 m in the maximum diagonal. The GNTVT serves for multiple functions of TV and radio transmission, sightseeing, cultural entertainment, and accommodating an orbital Ferris wheel, a ceremony hall, observatory decks, 4D cinemas, revolving restaurants, skywalk, etc. The structural construction of GNTVT was completed in May 2009.

To ensure safety and serviceability of this landmark structure during and after its construction, a sophisticated long-term SHM system has been designed and implemented by The Hong Kong Polytechnic University in collaboration with Sun Yat-Sen University for real-time monitoring of GNTVT at both in-construction and in-service stages (Ni *et al*. 2009b). In synchronism with the construction progress, more than 600 sensors of sixteen types have been deployed on the main tower, and over 100 sensors (including anemometers and accelerometers positioned up to the height of 578 m) have been installed on the antenna mast. As illustrated in Figure 3, this integrated SHM system has been devised to possess the following features (Ni 2010b):

- Modular architecture for easy maintenance and upgrade;
- Life-cycle SHM with the integration of in-construction monitoring and in-service monitoring;
- Dual function of on-line health monitoring and real-time feedback control with the integration of SHM and vibration control;
- Integration with renewable energy technology (solar photovoltaic and wind turbine systems) to monitor the power generation efficiency and operational condition;
- Innovative sensors and customized design fit for special circumstances;
- Hybrid tethered and wireless data transmission network customized for harsh operational conditions;
- User-friendly graphical user interface (GUI) for easy operation;
- Innovative structural health evaluation methodologies catering for structural maintenance and management purposes;
- All-round protection customized for severe surrounding environment;
- Remote expert service through the web-based data collection around the world; and
- Popularization of scientific knowledge through a virtual reality system integrated with sightseeing.

The SHM system for GNTVT has been designed to have a special function of monitoring and verifying the effectiveness of vibration control devices installed on the structure. It is a unique and interesting practice of SHM. A hybrid control system consisting of two tuned mass dampers coupled with two active mass dampers was installed at the floor of 438 m high for mitigating wind-induced vibration of the main tower, while two tuned mass dampers were suspended at the heights of 571 m and 575 m respectively for vibration suppression of the antenna mast. To on-line command the active mass dampers (made from linear motion actuator), it is necessary to establish a structural response feedback system which will provide thorough information for real-time vibration control. As illustrated in Figure 4, the SHM system of GNTVT has been devised to

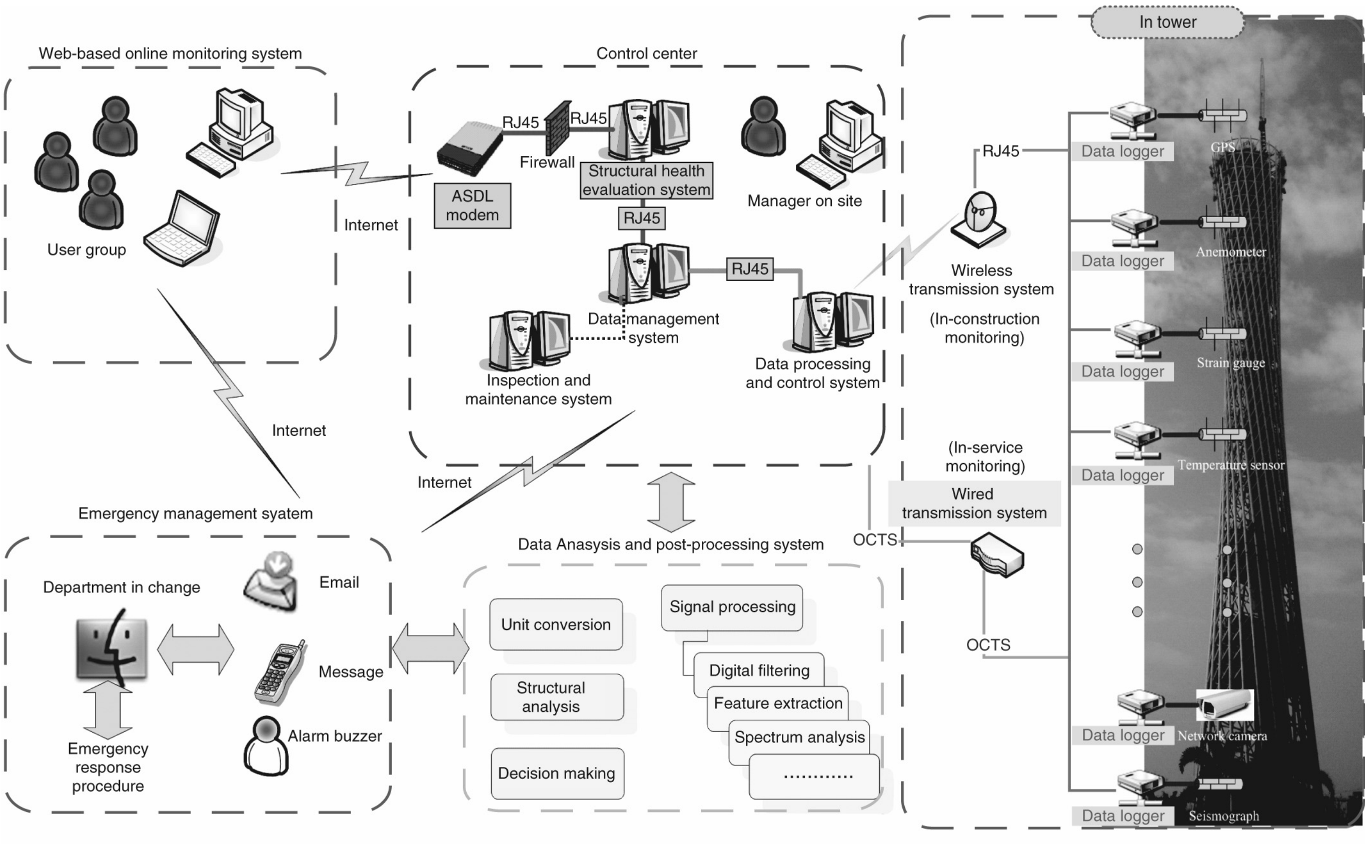


Figure 3. Integrated in-construction and in-service monitoring system for GNTVT

integrate with the vibration control system so that reliable and real-time monitoring data can be obtained for feedback vibration control, thus enhancing the control effectiveness. With such integration, the signals from the anemometers and the seismograph of the SHM system will be provided on-line to the vibration control system for making decisions on activating or locking the control system which is designed for wind-induced vibration control only. In addition, the signals from the *ad hoc* transducers which provide real-time feedback to vibration control will also be transmitted to the monitoring center and compared with the measured structural response signals by the monitoring system to detect possible fault of the control-specific transducers.

The hybrid tethered and wireless data transmission network provides a unique research platform to verify long-range communication capacity of wireless systems. As shown in Figure 5, wireless systems have been implemented in GNTVT for both static and dynamic monitoring. A wireless system is operated for synchronous acquisition of strain and temperature data and real-time data transmission from the sub-stations to the site office (Ni *et al*. 2009b). The vibration of GNTVT is monitored mainly by using a wired cabling network, while two wireless systems are also adopted in-situ for complementary vibration monitoring and for comparisons between wireless and tethered systems. The first wireless system, which is based on the Stanford Unit, consists of three functional modules: sensing interface, computational core, and wireless communication channel. The main component of the sensor signal digitization module is a 4-channel 16-bit A/D converter (Texas Instruments ADS8341). The digitized signals are transferred to the computational core through a high-speed serial peripheral interface (SPI) port. Besides a low-power 8-bit Atmel ATmega128 microcontroller, external static random access memory is integrated with the computational core to accommodate local data storage and analysis. A special low-noise signal conditioning module is designed to amplify the sensor signal prior to A/D conversion. 7.0 dBi outdoor omni-directional antennas (Buffalo AirStation Pro WLE-HG-NDC) are adopted for wireless communication. The second wireless system, which is based on the Imote2, comprises processor/communication board IPR2400, sensing board ITS400, and algorithm reprogramming board IIB2400. The IPR2400 has one 416 MHz Intel PXA271 Xscale CPU, 32 MB FLASH program memory, and 32 MB SDRAM data memory. It realizes wireless communication using TI Chipcon2420 radio transceiver, which operates on 2.4 GHz free RF

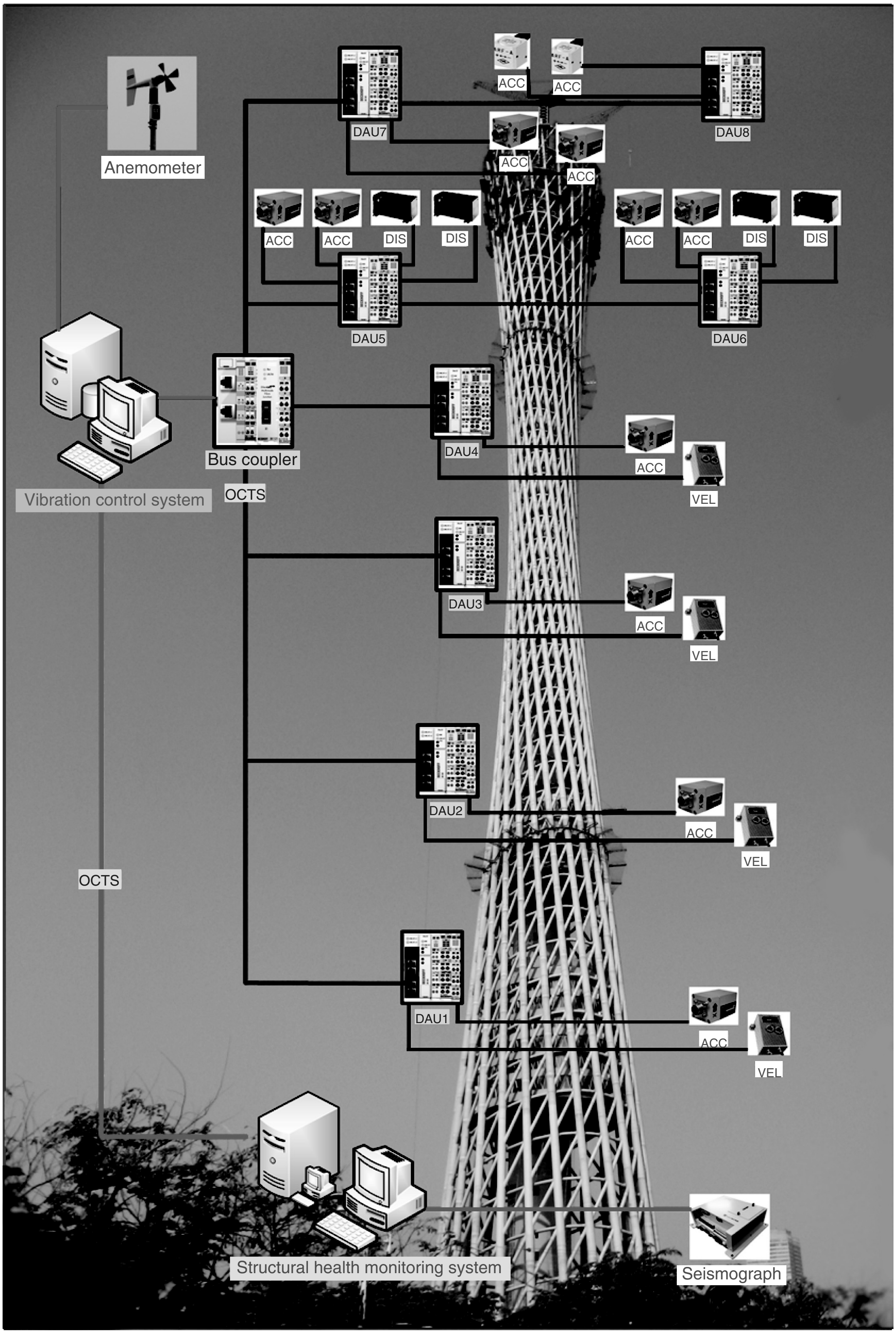


Figure 4. Integration of SHM and vibration control

spectrum and has a communication bandwidth up to 250 Kbps. The software platform based on TinyOS is open-source, and customized data analysis algorithms can be reprogrammed into the IPR2400. Taking the tethered system as a reference, the above two wireless sensing systems are currently tested in the field with the purposes: (i) to verify the systems' reliability and measurement precision by comparing the wireless and

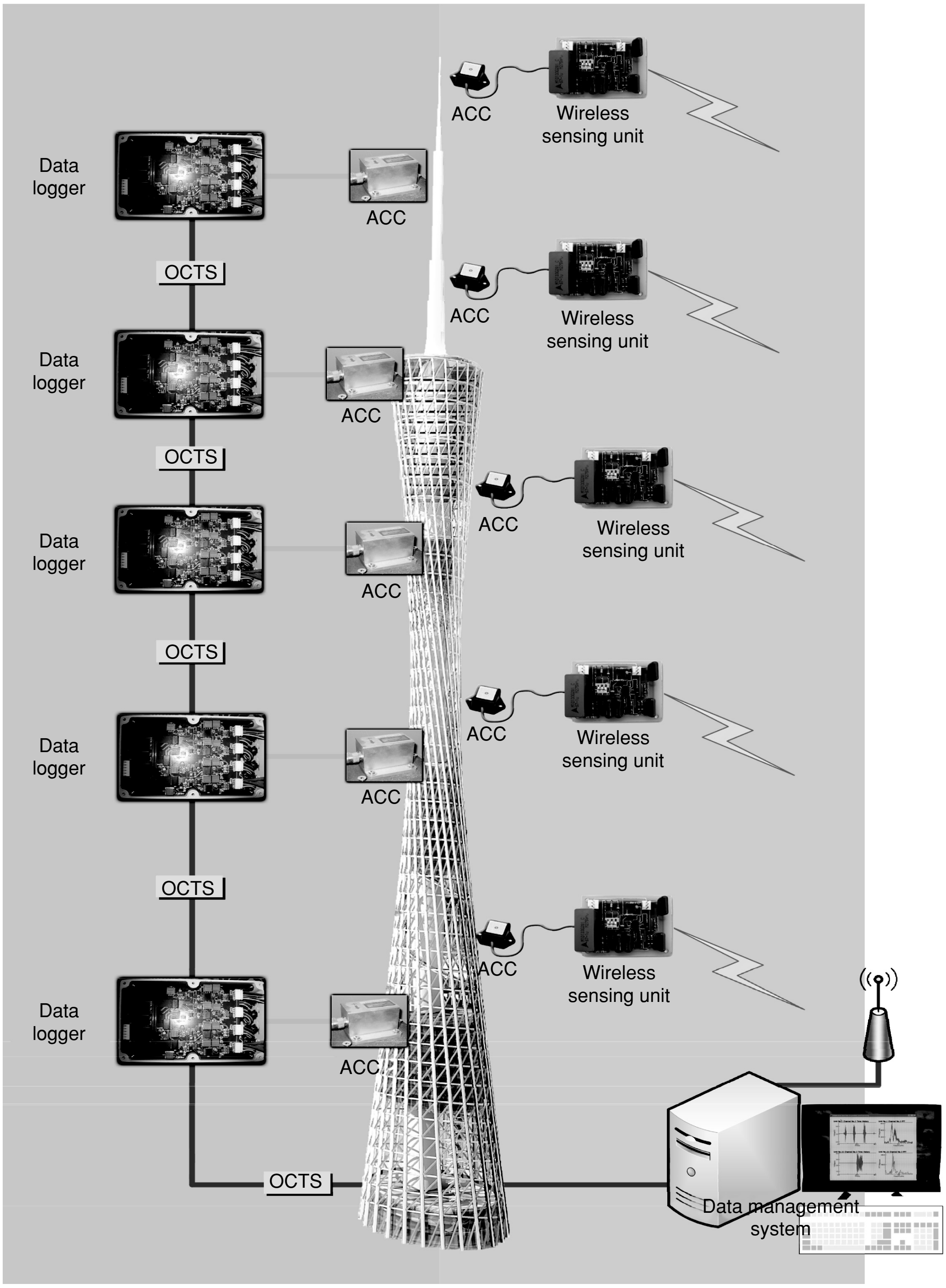


Figure 5. Wireless data transmission

tethered monitoring data, (ii) to testify the capability of synchronization of the wireless systems, (iii) to examine the long-range wireless communication capacity, and (iv) to testify the multi-hop technology for wireless signal transmission. The wireless sensing units have been placed up to the height of 448.8 m on GNTVT for data acquisition and communication with the base station being located at the ground level. Figure 6 illustrates a comparison of acceleration responses and the corresponding frequency-domain spectra obtained by the wireless and wired systems, respectively, at a location of 448.8 m high.

As shown in Figure 7, a fiber optic sensing system based on fiber Bragg gratings (FBGs) has been implemented on the steel outer structure and also the antenna mast of GNTVT to provide long-term, real-time

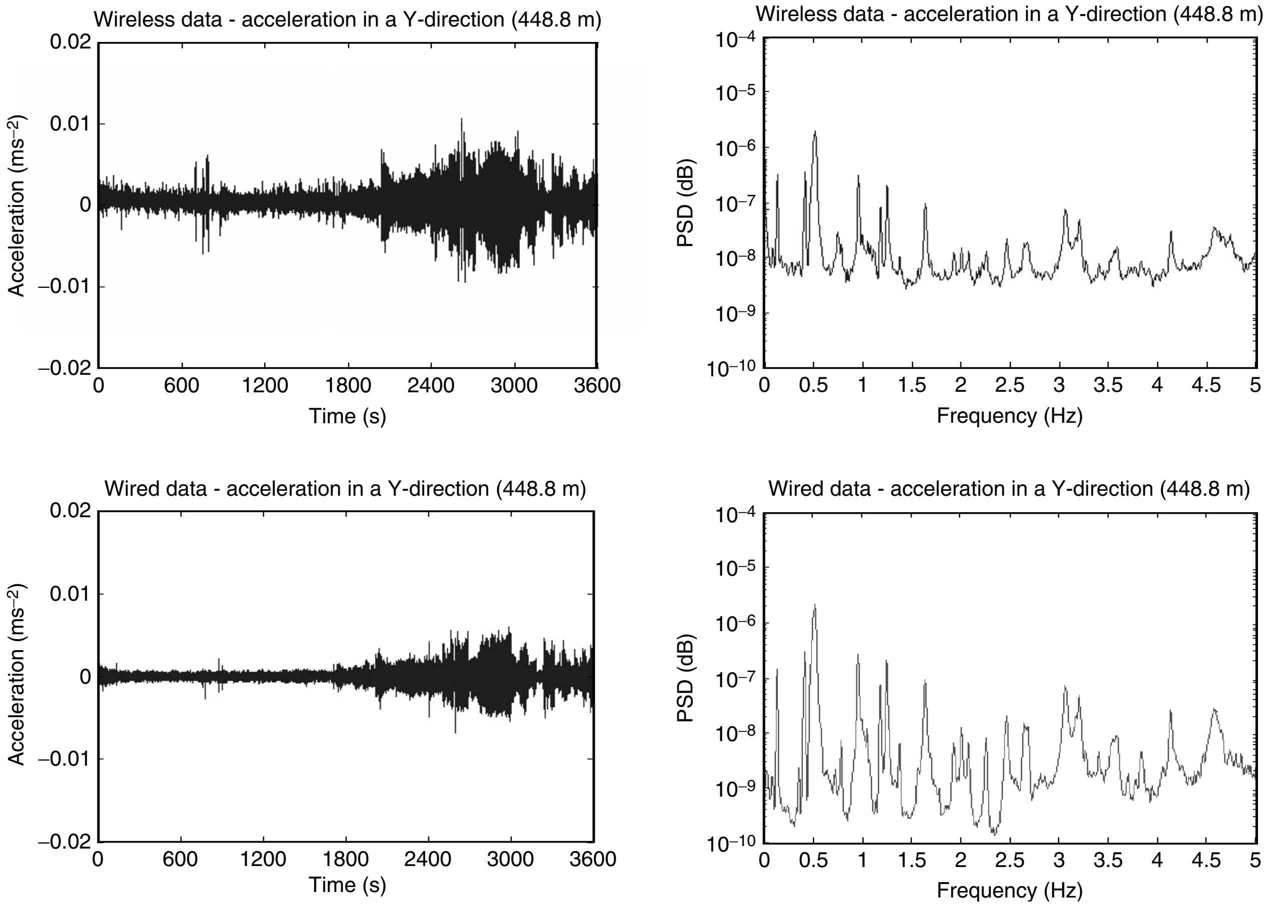
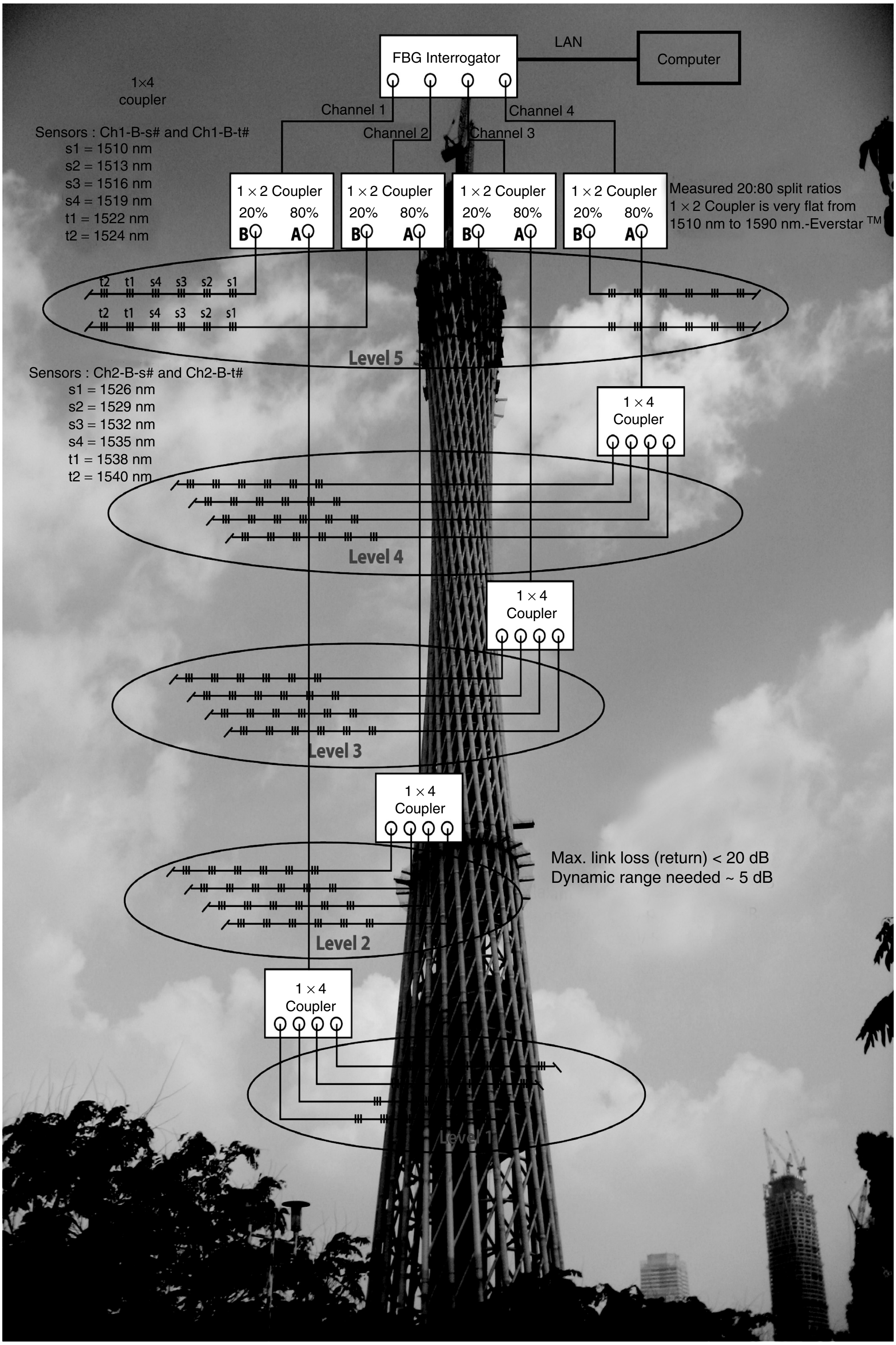


Figure 6. Accelerations measured by wireless and wired sensing systems (Height: 448.8 m)

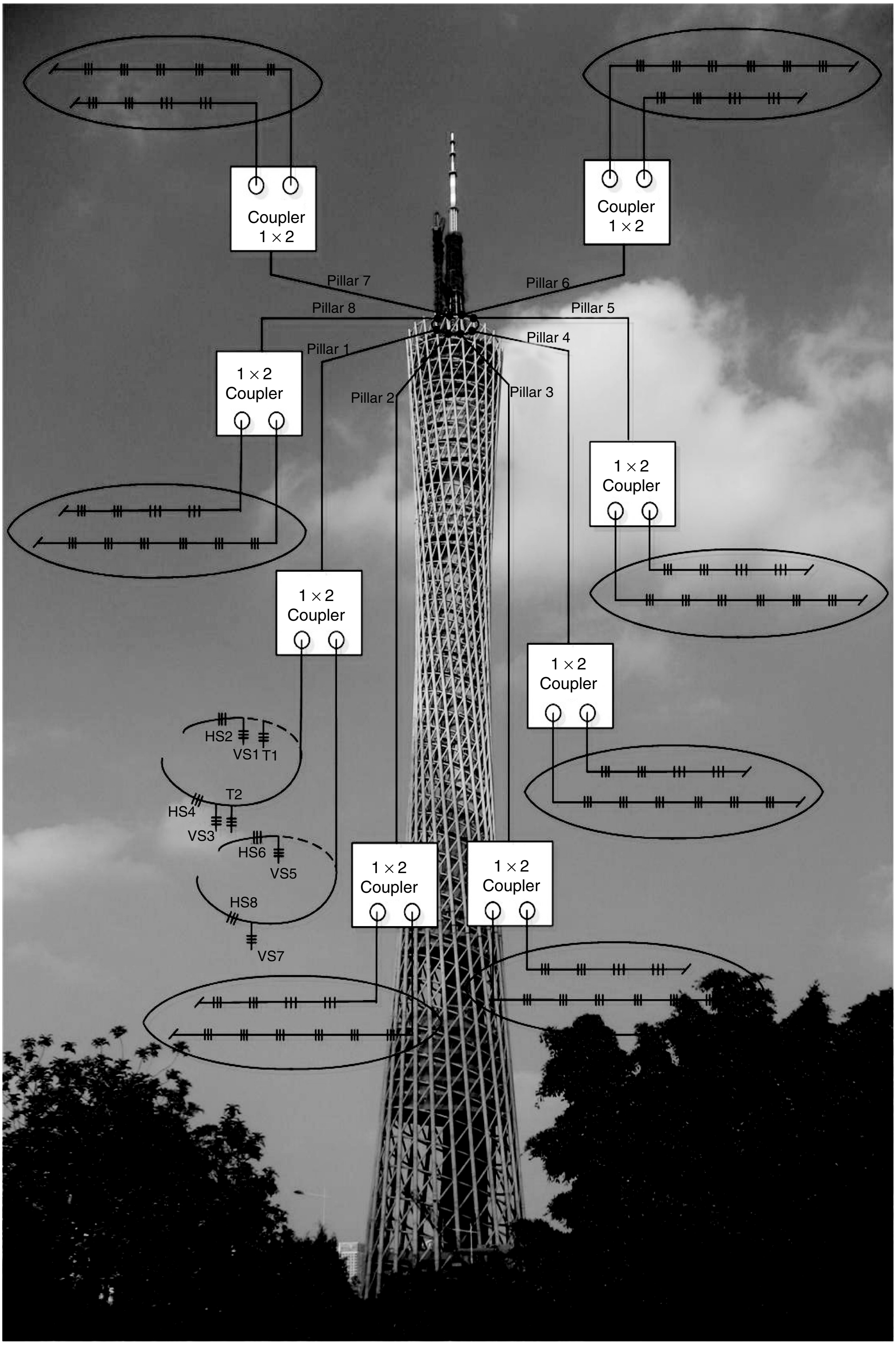
strain and temperature monitoring. The system for the main tower comprises 120 FBG sensors. As illustrated in Figure 7(a), five groups of 24 FBG sensors are deployed to monitor the outer structure at different heights. Each group of the 24 sensors is arranged into four 6-FBG sensor arrays. Four of the FBGs in each array are for dynamic strain measurement and the other two are for temperature measurement. Likewise, a total of 80 FBG sensors have been installed on the antenna mast as shown in Figure 7(b). The antenna mast is welded into the steel-tube columns of the inner structure. Two levels of the steel-tube columns are selected for instrumentation with FBG strain sensors. One is below the welding line of the steel-tube columns between the inner structure and antenna mast, and the other is above the welding line. At each level, 32 FBG strain sensors are attached to the surfaces of eight steel-tube columns with four sensors each. On each column, two FBG strain sensors are aligned longitudinally at two opposite sides of the steel-tube column. Similarly, two sensors are tangent to the surface. At the upper level, 16 FBG temperature sensors are also attached to the surfaces of the eight steel-tube columns with one sensor at each opposite side. In total, 64 FBG strain sensors and 16 FBG temperature sensors are mounted on the antenna mast. Both the FBG strain and temperature sensors are custom designed to cope with the hostile environment outside the tower. All the FBG sensors are attached onto a 0.8-mm thick SS302 stainless steel to protect them from handling and to ensure long-term reliability. The steel packaged FBGs permit them to be welded directly onto the structure. The sampling rate for GBS-based dynamic strain monitoring is set as 50 Hz.

The integrated in-construction and in-service SHM system of GNTVT is composed of sixteen types of sensors, including a weather station (air temperature, humidity, barometric pressure, and rainfall), a total station, a GPS system, a seismograph, accelerometers, anemometers, wind pressure meters, FBG strain and temperature sensors, vibrating wire strain gauges and temperature sensors, electrical resistance temperature sensors, corrosion sensors, digital video cameras (a vision-based displacement measurement system), level sensors, tiltmeters, laser zenith meters, and altazimuths, in conjunction with 13 sub-stations (data acquisition units, DAUs) during in-construction monitoring and



(a) Main tower

Figure 7. (*Continued*)



(b) Antenna mast

Figure 7. FBG sensors for dynamic strain and temperature monitoring

5 DAUs during in-service monitoring. As a result, this project offers a unique engineering paradigm to explore sensor and information fusion for SHM. It is difficult to calibrate or verify the dynamic displacement measurement results by a GPS system, and such a calibration or verification is usually conducted in an indirect way by doubly integrating the measured acceleration data. However, this approach cannot provide an accurate reference of dynamic displacement because of unknown initial displacement and numerical error. In this project, a vision-based system has been developed and used together with a GPS system for dynamic displacement measurement of GNTVT. This vision-based system is capable of remote long-distance (500 to 1,000 m) dynamic displacement measurement with a sampling frequency between 5 and 60 Hz. Figure 8 shows a comparison of dynamic displacement responses at the top of the main tower (454 m high) measured by the vision-based system and the GPS system. It is observed that while the displacement responses measured by the two systems coincide well with each other, the displacement obtained by the vision-based system is less noise-corrupted and does not exhibit spikes.

The SHM strategy for GNTVT has been defined in three levels: (i) on-line structural condition evaluation; (ii) target-oriented verification and evaluation; and (iii) off-line structural health and safety assessment. The on-line structural condition evaluation is mainly to compare the static and dynamic measurement data with the pre-determined thresholds and patterns to provide a prompt evaluation on the structural condition. The target-oriented verification and evaluation refers to monitoring-based verification/evaluation of temperature-induced deformation and thermal stress, fatigue life of welded steel connections, wind loading and wind effects below and above the gradient wind level, human comfortability during typhoons, etc. The off-line structural health and safety assessment involve a variety of model-based and data-driven damage diagnostic and prognostic algorithms including dynamic-based methods, static-based methods, and hybrid methods (Ni *et al*. 2009b).

As the data acquisition system is operated to automatically and continuously acquire monitoring data, the SHM system has detected the extreme responses of GNTVT during the Wenchuan earthquake as well as the Neroguri typhoon, Kammuri typhoon, Nuri typhoon, Hagupit typhoon, Molave typhoon, and Koppu typhoon in the past two years (Ni *et al*. 2009a). Figure 9 illustrates the recorded strain responses of GNTVT during the Wenchuan earthquake and the Neroguri typhoon. Based on these monitoring data, structural condition and health evaluation has been made for GNTVT after each of the events and the evaluation reports have been submitted to the owner of GNTVT. The city of Guangzhou is located at the edge of the most active typhoon generating area in the world. As the maximum gradient wind level stipulated in the current Chinese design code is 450 m high, the wind-resistant design parameters obtained from the specification usually fail to provide an accurate description of the fluctuating wind loads acting on supertall structures higher than 450 m. Because anemometer and accelerometers have been deployed on GNTVT up to 578 m high, we are able to investigate the wind properties and wind effects above the maximum gradient wind level by using the monitoring data of wind and structural response acquired during typhoons. It will contribute to the development of new design codes for super-tall buildings and structures.

The SHM system for GNTVT is a long-term monitoring system. Some of the sensors and sensing cables are located outside. To ensure a long-term stable system operation, all-round protection is required for all the sensors, sensing cables, and data acquisition and

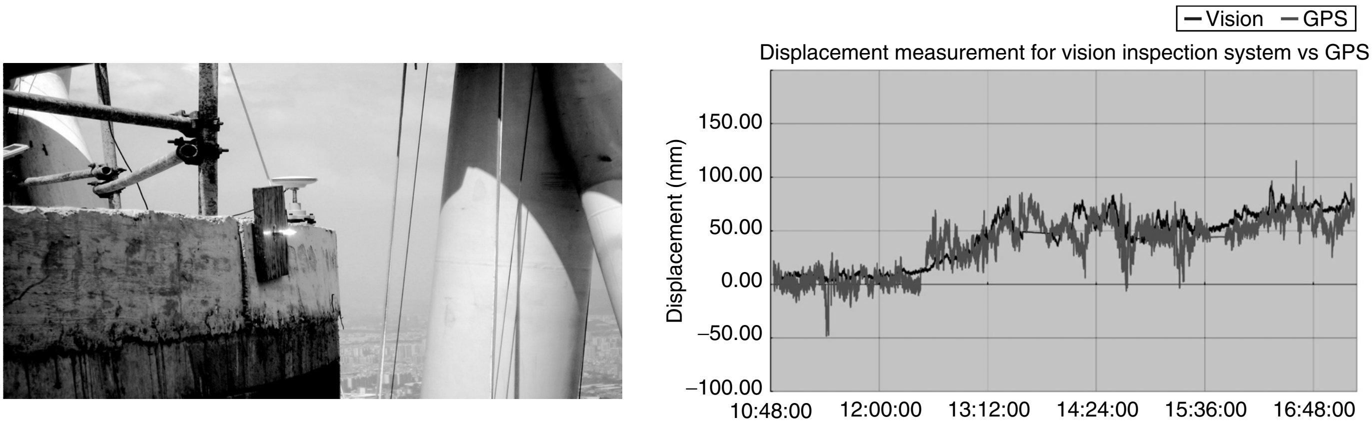


Figure 8. Comparison of dynamic displacement measured by GPS and vision-based system

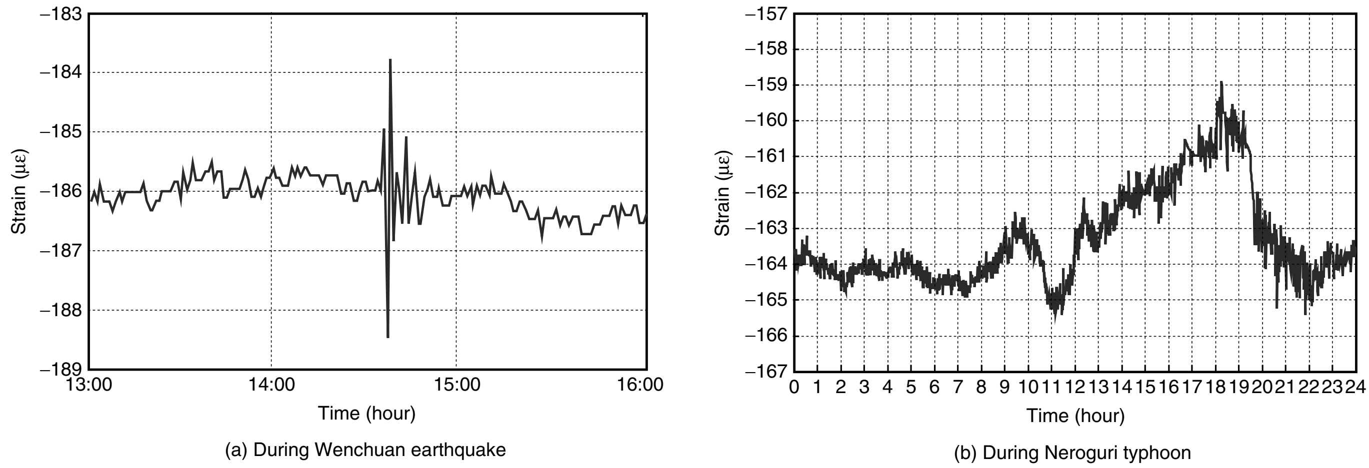


Figure 9. Strain responses of GNTVT during earthquake and typhoon

1. Installation of pre-embedded pieces in workshop;
2. Painted pre-embedded pieces;
3. Protection of sensor installed in steel column;
4. In-situ installation of fiber optic sensor;
5. Aluminum alloy protection case for fiber optic sensor;
6. Protection of fiber optic sensor;
7. Protection of vibration wire strain gauge;
8. Installation of surface-type vibrating wire strain gauge;
9. Protection of embedment-type vibrating wire strain gauge;
10. In-situ installation of embedment-type vibrating wire strain gauge;
11. Protection of accelerometer;
12. Zinc plating steel tube for protection of sensing cable in inner structure;
13. Stainless steel wire duct for protection of sensing cable in circumferential direction;
14. Stainless steel wire duct for protection of sensing cable in vertical direction;
15. Aluminum alloy wire duct for protection of sensing cable in longitudinal direction;
16. Protection of data logger.

Figure 10. All-round protection for long-term operation of SHM system

transmission systems (Figure 10). To escape from the problems of paint-off and weak weld strength, all of the pre-embedded pieces were welded on the steel members prior to installing the sensors and sensing cables on to the outer structure. Detachable stainless steel cases and wire ducts were utilized to protect the sensors and sensing cables, whilst aluminum alloy protection cases were adopted for the fiber optic sensors. Specific sealant was used to seal up the apertures. All of these adopted measures not only made the sensor system presentable in its outlook, but also made it waterproof and dustproof. Pre-protection measures for embedded sensors are necessary prior to the sensor installation to avoid damage to the sensors (e.g., vibration wire strain gauges which were embedded into the inner structure). Sensing cables to the sub-stations were safeguarded by zinc plating steel tubes. The sub-stations were protected by special industrial mainframe-boxes to ensure lightning protection, moisture-proof, electro-magnetic-interference prevention and temperature control. The aluminum alloy wire ducts were adopted to protect the sensing cables between the control center and the sub-stations.

The GNTVT, designed with the function of sightseeing and cultural entertainment, is deemed to be an ideal and unique place for tourist sightseeing and at the same time learning science. The tower allows the tourists to understand its SHM and vibration control systems' operation and the scientific principles behind, and view its real-time data. Display terminals are distributed at various popular zones such as the high-tech exhibition hall, ceremony hall, etc. The terminals are connected by local networks and are controlled by the SHM system at the control center.

5. SHM BENCHMARK PROBLEM USING REAL-WORLD DATA

In the past two decades, varieties of structural health and damage detection methods have been proposed by different investigators. However, the feasibility of these methods for real-world applications, especially for applications to large-scale structures, has been rarely examined. A gap still exists between the research and the practice in this field, which impedes broader applications of SHM techniques in civil engineering community. It is significantly meaningful to establish an SHM benchmark problem in regard to a full-scale structure with the use of field measurement data, aiming to provide an international platform for direct comparison of various algorithms and methods. The participants thus have opportunities to test their SHM techniques using real-world data from a full-scale structure and recognize the obstructions in real life implementations.

Under the auspices of Asian-Pacific Network of Centers for Research in Smart Structures Technology (ANCRiSST), an SHM benchmark problem for high-rise structures is being developed by taking the instrumented GNTVT as the host structure (Ni *et al.* 2009c; Xia *et al.* 2009). This SHM benchmark problem aims to provide an open platform to the researchers and practitioners in the field of SHM for exchanging their innovative strategies; to apply various SHM algorithms to a real high-rise structure with the purpose of examining applicability and reliability of the techniques; and to close the gap between the algorithms and the practice in SHM. As shown in Figure 11, a website for this SHM benchmark problem has been established (http://www.cse.polyu.edu.hk/benchmark/). Four phases of the benchmark study have been defined, and Phase I of the benchmark study is to address the output-only modal identification and finite element model (FEM) updating with the use of ambient vibration monitoring data from GNTVT. To serve Phase I, field monitoring data and a reduced-order FEM have been prepared and are currently available at the benchmark website. The field monitoring data include 24-hour measurement data from 20 accelerometers, one

Figure 11. Website of SHM benchmark problem for high-rise structures

anemometer and one temperature sensor. The reduced-order FEM is deduced from a validated full-scale 3D FEM consisting of 122,476 elements, 84,370 nodes and 505,164 degrees of freedom (DOFs). With a total of 185 DOFs, the reduced-order FEM comprises 37 beam elements and 37 nodes having 5 DOFs each. A good agreement between the reduced-order and full-scale FEMs has been achieved in terms of both modal frequencies and mode shapes for the first 15 modes (Lin *et al*. 2010).

6. CONCLUDING REMARKS

The evolution of designing and implementing SHM systems for large-scale bridges in Hong Kong spanning over ten years has been summarized. The bridge health monitoring systems are currently considered as an integrated part of bridge operation, inspection, and maintenance and have been included as a standard mechatronic system in the design and construction of large-scale and multidisciplinary bridge projects in Hong Kong. The experience gained in the design, installation, operation, maintenance, and upgrading of the existing SHM systems has a significant influence on the development of new SHM systems in Hong Kong and the Chinese mainland. The bridge SHM practice and experiences have been extended to the development of SHM systems for high-rise structures. As such an example, a sophisticated long-term SHM system has been designed and implemented on the Guangzhou New TV Tower (GNTVT) with a total height of 610 m. This system exercises a pioneering SHM practice that integrates in-construction monitoring and in-service monitoring, and has been designed to have a special function of verifying the effectiveness of vibration control devices installed on the tower. In addition, innovative fiber optic sensors, and vision-based sensing and wireless monitoring techniques have been practiced in this project. An SHM benchmark problem for high-rise structures has been initiated by taking the instrumented GNTVT as the host structure.

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