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Technology innovation in developing the structural health monitoring system for Guangzhou New TV Tower

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SUMMARY

The Guangzhou New TV Tower (GNTVT), currently being constructed in Guangzhou, China, is a supertall structure with a height of 610 m. This tube-in-tube structure comprises a reinforced concrete inner tube and a steel outer tube adopting concrete-filled-tube columns. A sophisticated structural health monitoring (SHM) system consisting of over 600 sensors has been designed and is being implemented by The Hong Kong Polytechnic University to GNTVT for both in-construction and in-service real-time monitoring. This paper outlines the technology innovation in developing and implementing this SHM system, which includes (i) modular design of the SHM system, (ii) integration of the in-construction monitoring system and the in-service monitoring system, (iii) wireless-based data acquisition and Internet-based remote data transmission, (iv) design and implementation of a fiber Bragg grating sensing system, (v) structural health and condition assessment using static and dynamic monitoring data, (vi) verification of the effectiveness of vibration control devices by the SHM system, and (vii) development of an SHM benchmark problem by taking GNTVT as a test bed and using real-world measurement data. Preliminary monitoring data including those obtained during the Wenchuan earthquake and recent typhoons are also presented. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: supertall structure; structural health monitoring (SHM); benchmark problem

1. INTRODUCTION

Structural health monitoring (SHM) refers to the process of measurement of the operating and loading environment and the critical responses of a structure to track and evaluate the

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symptoms of operational incidents, anomalies, and/or deterioration or damage indicators that may affect operation, serviceability, or safety reliability [1]. Successful implementation and operation of SHM systems for bridges have been widely reported [2]. The applications of SHM to building structures are not as widespread as its applications to bridge structures. Since 1993, a long-term monitoring program on a 280 m 65-story office tower has been accomplished by Brownjohn and his co-investigators, aiming to monitor the structural dynamic responses and to track any variations in the structural performance [3,4]. With the intention to identify wind-induced structural response characteristics, Li and his co-investigators have made full-scale measurements on a number of high-rise structures under strong wind conditions [5–7]. In U.S.A., a monitoring program was initiated by the University of Notre Dame in collaboration with design and consultancy firms to monitor the full-scale responses of three tall buildings in Chicago and compare them with the predicated responses from wind tunnel test and finite element analysis [8,9]. It was reported that more than 150 buildings in California, U.S.A., more than 100 buildings in Japan, and more than 40 buildings in Taiwan have been instrumented with strong motion monitoring systems for seismic excitation/response measurement and post-earthquake damage assessment [10–12].

(a) (b)

Figure 1. Guangzhou New TV Tower (GNTVT): (a) bird's eye view of GNTVT and (b) GNTVT under construction.

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The Guangzhou New TV Tower (GNTVT), currently being constructed in Guangzhou, China, is a supertall tube-in-tube structure with a height of 610 m. As illustrated in Figure 1, this structure comprises a reinforced concrete inner tube and a steel outer tube with concrete-filled-tube (CFT) columns. There are 37 floors connecting the inner tube and the outer tube, which serve for offices, entertainment, catering, tour, and mainly emission of television signal. The outer tube consists of 24 CFT columns, uniformly spaced in an oval while inclined in the vertical direction. The oval decreases from $50\,m \times 80\,m$ at the ground to the minimum of $20.65\,m \times 27.5\,m$ at the height of 280 m, and then increases to $41\,m \times 55\,m$ at the top of the tube (454 m). The columns are interconnected transversely by steel ring beams and bracings. The inner tube is an oval shape as well with a constant dimension of $14\,m \times 17\,m$ in plan, but its centroid differs from the centroid of the outer tube. This hyperbolic shape makes the structure vital and attractive in aesthetics while complex in mechanics. A sophisticated long-term SHM system consisting of more than 600 sensors has been designed and is being implemented by The Hong Kong Polytechnic University to monitor GNTVT in both construction and service stages. Up to the end of September 2008, the tower has been erected to the height of 450 m, and more than 560 sensors have been installed in parallel with the construction progress. This paper describes key technological issues in developing and implementing the SHM system, and presents preliminary monitoring data including those obtained during the Wenchuan (Sichuan) earthquake and recent typhoons.

2. MODULAR DESIGN OF SHM SYSTEM

The SHM system for GNTVT has been devised on the basis of a modular design concept, which was first practiced in Hong Kong for long-span bridges [13]. In accordance with the modular design concept, the SHM system devised for GNTVT consists of six modules, namely, Module 1—Sensory System (SS), Module 2—Data Acquisition and Transmission System (DATS), Module 3—Data Processing and Control System (DPCS), Module 4—Data Management System (DMS), Module 5—Structural Health Evaluation System (SHES), and Module 6—Inspection and Maintenance System (IMS). The integration of these six modules is shown in Figure 2. The SS and the DATS are located in the structure, the DPCS, the DMS, and the SHES are inside the monitoring center room, and the IMS is a portable system.

The SS is composed of 16 types of sensors, as listed in Table I, for in-construction and in-service monitoring of GNTVT. These sensors are deployed for monitoring of three categories of parameters: (i) loading sources (wind, seismic, and thermal loading), (ii) structural responses (strain, displacement, inclination, acceleration, and geometric configuration), and (iii) environmental effects (temperature, humidity, rain, air pressure, and corrosion). The DATS consists of 13 stand-alone data acquisition units (DAUs) (sub-stations) for in-construction monitoring and 6 stand-alone DAUs (sub-stations) for in-service monitoring. DAUs or sub-stations are indispensable to SHM systems for large-scale structures such as GNTVT. They are assigned at several cross-sections of the tower to collect the signals from surrounding sensors, digitize the analog signals, and transmit the data into a central room in either wired or wireless manner. An appropriate deployment of DAUs plays a significant role in assuring the quality and fidelity of the acquired data. The DPCS comprises high-performance servers located in the central room and data-processing software. It is devised to control the on-structure DAUs regarding data acquisition and pre-processing, data transmission and filing, and display of the data. The DMS

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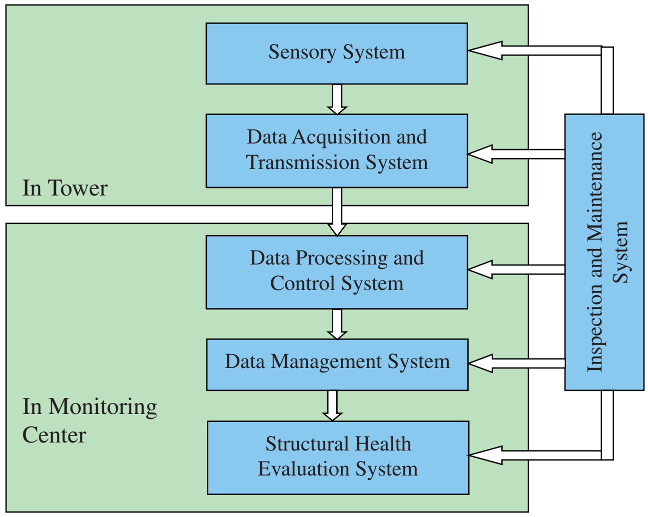

Figure 2. Modules of the SHM system for GNTVT.

comprises an Oracle-driven database system for non-spatial temporal data management and a Geographic Information System (GIS) software system for spatial data management. The database system adopts a relational database approach, while the GIS utilizes a node-arc-polygon structure. The web-based GIS software is supplied with built-in functions to perform queries, check spatial relationships or patterns among multiple data sets, and combine with external software. It also integrates the spatial data in its own database and the non-spatial data in Oracle. The SHES is composed of 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 used to compare the static and dynamic measurement data with the design values, finite element (FEM) analysis results, and pre-determined thresholds and patterns to provide a prompt evaluation on the structural condition. The off-line structural health and safety assessment system incorporates varieties of model-based and data-driven damage diagnostic and prognostic algorithms, which mostly require both historical and current monitoring data. The IMS is a laptop-computer-aided portable system for inspecting and maintaining sensors, DAUs, and cabling networks.

The quality of monitoring data is essential to evaluate the structural condition and detect the structural damage reliably, which relies to a great extent on the appropriate selection and placement of sensors. In developing the SHM system for GNTVT, the sensors were selected according to the following criteria: (i) the SS should have the ability to capture all important information about the structural static and dynamic properties; (ii) the SS should have the function to combine multiple types of sensors so as to achieve an accurate measurement for specific structural response/parameter; and (iii) different types of sensors should be collocated at crucial locations for cross-calibration. An example of illustrating criterion 1 is the selection of accelerometers. As the tallest TV tower structure in the world, GNTVT has the fundamental modal frequency of 0.11 Hz predicted by finite element analysis. The experience in similar buildings shows that the vibration amplitude under normal ambient excitation is in the order of cm/s^2. However, the overwhelming majority of the commercially available accelerometers used

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Table I. Sensors deployed for in-construction and in-service monitoring.

No.	Sensor type	Monitoring items	Number of sensors: In-construction monitoring	Number of sensors: In-service monitoring	Manufacturer/model
1	Weather station	Temperature, humidity, rain, air pressure	1	1	VAISALA/WXT510
2	Anemometer	Wind speed and direction	2	2	R M YOUNG/05103L
3	Wind pressure sensor	Wind pressure	—	4	KANGYU/KYB11
4	Total station	Inclination, leveling, elevation	1	—	LEICA Geosystems/ TCA1800
5	Zenithal telescope	Inclination of tower	2	—	LAT LASER/JZC-G
6	Tiltmeter	Inclination of tower	—	2	LEICA Geosystems/Nivel210
7	Level sensor	Leveling of floors	2	—	LEICA Geosystems/Sprinter200
8	Theodolite	Elevation	2	—	KOLIDA/ET-02
9	GPS	Displacement	2	2	LEICA Geosystems/GPS1230
10	Vibrating wire gauge	Strain, shrinkage, and creep	416	60	GEOKON/GK4000, GK4200
11	Thermometer	Temperature of structure	96	60	FUMIN Measurements/ PT100
12	Digital video camera	Displacement	3	3	PROSILICA/GE2040C
13	Seismograph	Earthquake motion	—	1	TOKYO SOKUSHIN/SPC-51C
14	Corrosion sensor	Corrosion of reinforcement	—	3	S + R/Anode Ladder
15	Accelerometer	Acceleration	—	22	TOKYO SOKUSHIN/ AS-2000C, AS-2000S
16	Fiber optic sensor	Strain and temperature	—	120	MICRON OPTICS/OS310s, sm130-200
Total			527	280	

in structural engineering, although their measurable frequency range is declared from DC in specifications, fail to capture the waveforms of structural tremors accurately when the vibration frequency is lower than 0.2 Hz and the vibration magnitude is around 1 cm/s^2. A comprehensive shaking table calibration has been carried out by the authors on various accelerometers from different manufacturers. Figure 3 shows the measured waveforms by an accelerometer during the controlled shaking table testing in the presence of environmental noise. It has a frequency range of DC to 50 Hz, a scale range of ± 20 m/s^2, a sensitivity of 125 mV/m/s^2, and an operating temperature of -20 to $+70$°C. This type of uni-axial servo accelerometers was finally selected to install on GNTVT. As a practice of criterion 2, both global positioning system (GPS) and digital video cameras are deployed for the measurement of horizontal deflection at various construction stages as illustrated in Figure 4, while a combination of GPS, accelerometers, and digital video cameras is adopted to achieve a reliable measurement of dynamic displacement at long-term service stage. In accordance with criterion 3, both total station and zenithal

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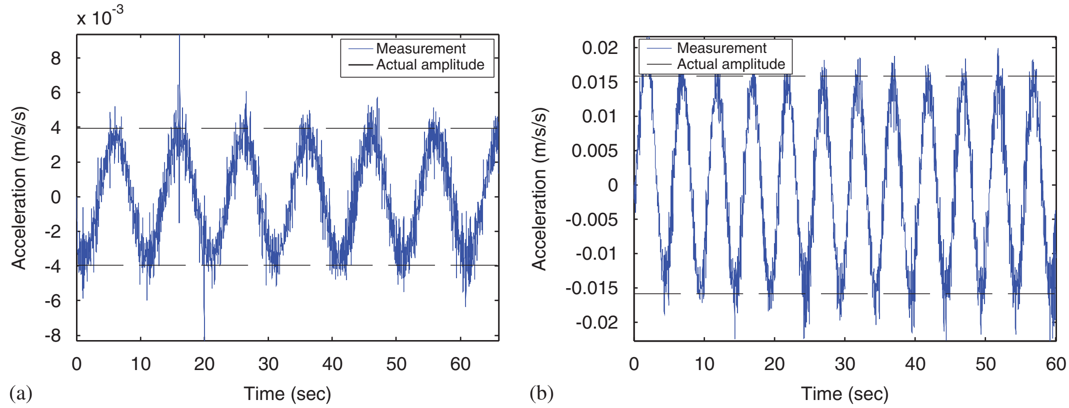

Figure 3. Calibration of accelerometers on shaking table: (a) frequency = 0.1 Hz and amplitude = 1 cm and (b) frequency = 0.2 Hz and amplitude = 1 cm.

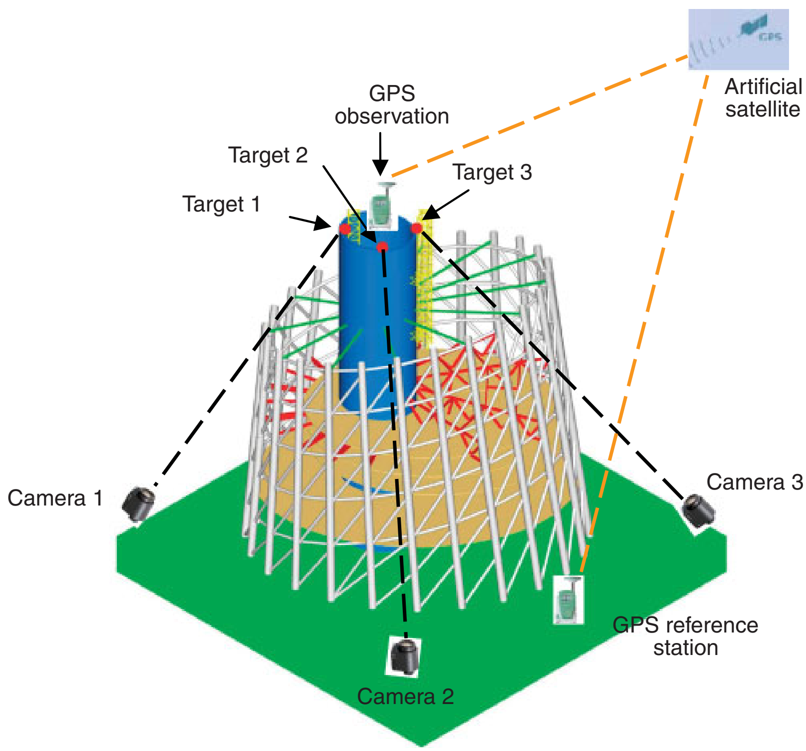

Figure 4. Combination of GPS and digital video camera for deflection measurement.

telescope are adopted for in-construction monitoring of inclination, and both strain gauges and fiber optic sensors are installed for in-service monitoring of strain. As discussed in the following section, the deployment locations of sensors are determined according to the finite element

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analysis results of the partially constructed structures at critical construction stages and the completed structure.

3. INTEGRATION OF IN-CONSTRUCTION AND IN-SERVICE MONITORING

The monitoring system for GNTVT exercises a pioneering SHM practice that integrates in-construction monitoring and in-service monitoring. Besides detecting anomalies during construction, the motivation to design and implement such an integrated monitoring system also lies in (i) facilitating the deployment of sensors devised for in-service monitoring, (ii) being able to track complete data histories from the onset of construction, and (iii) enabling life-cycle monitoring and assessment of the structure from its 'birth'. For embedment-type sensors, such as corrosion sensors and embedded gauges for measuring strain inside concrete, it is necessary to install them in synchronism with the construction progress. For high-rise structures such as GNTVT, most of surface-type sensors also have to be installed during the construction stage due to inaccessibility when the scaffolds have been dismantled. As the steel-tube columns of GNTVT are prefabricated and painted at workshop, sensor fixers must be welded to the columns at the workshop as shown in Figure 5 so that the painting will not be destroyed during the *in situ* installation of surface-type strain gauges on the columns. The majority of existent SHM systems currently in operation are only able to monitor dynamic strain rather than the total (cumulative) strain. The integrated monitoring system enables the measurement of cumulative strain, which is necessary for evaluating the real safety index of structural components and the impact of extreme events (hurricanes, earthquakes, man-made disasters, etc.) on the structural performance. When the measurement data at different construction stages are obtained by the integrated monitoring system, it is possible to update the structural finite element model stage by stage and extract environmental effect models (e.g. the correlation between strain and temperature) using the measured data. As a result, an SHM-oriented baseline model can be established at the completion of construction. One benefit of the stage-by-stage model updating lies in the fact that only the newly constructed structural portions need to be adjusted and those constructed in the previous stage remain unchanged. Consequently, substructure techniques can be employed to reduce the computational amount.

Figures 6 and 7 show the deployment of sensors and DAUs for in-construction monitoring and in-service monitoring of GNTVT, respectively. The in-construction monitoring system

(a) (b)

Figure 5. Sensor fixers for installing surface-type strain gauges: (a) welding of sensor fixers at workshop and (b) sensor fixers on erected column.

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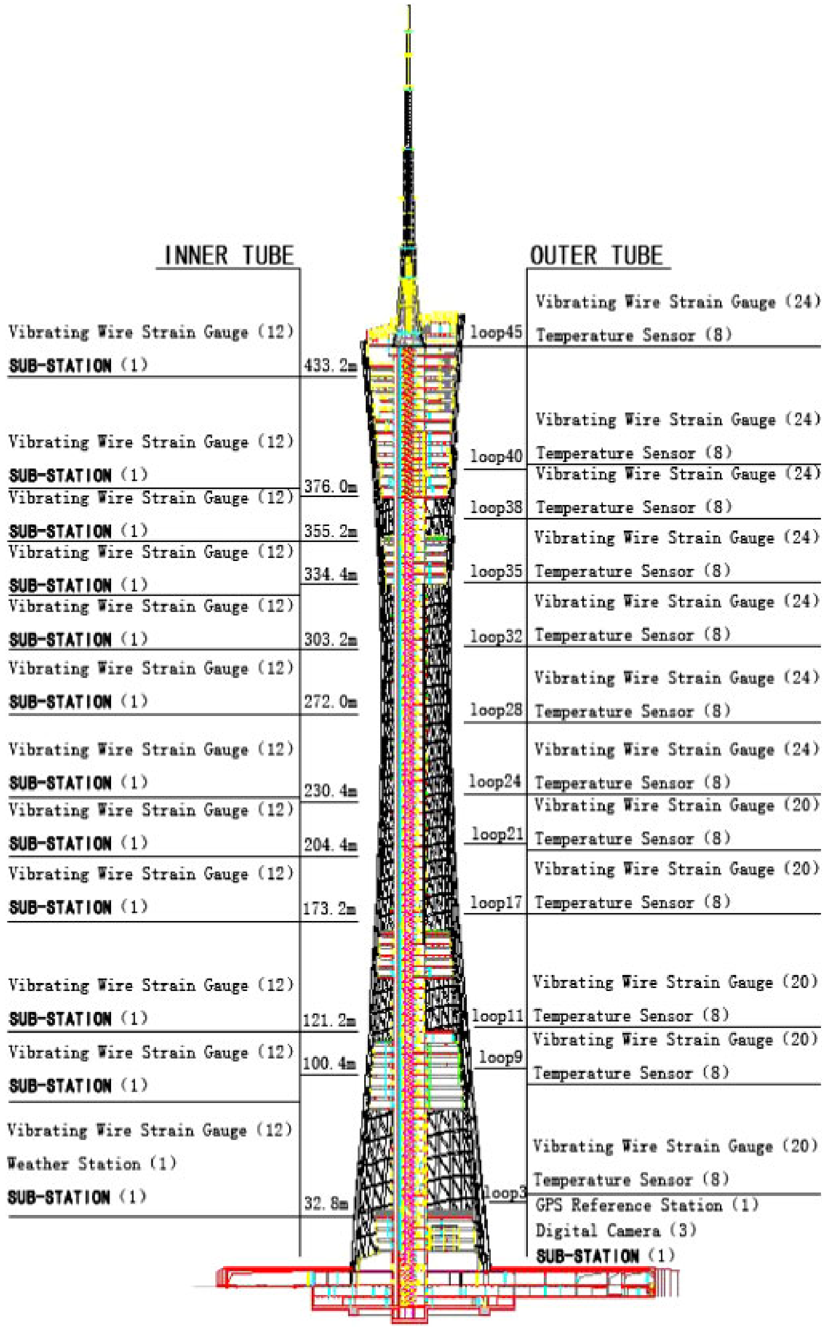

Figure 6. Deployment of sensors and sub-stations (DAUs) for in-construction monitoring.

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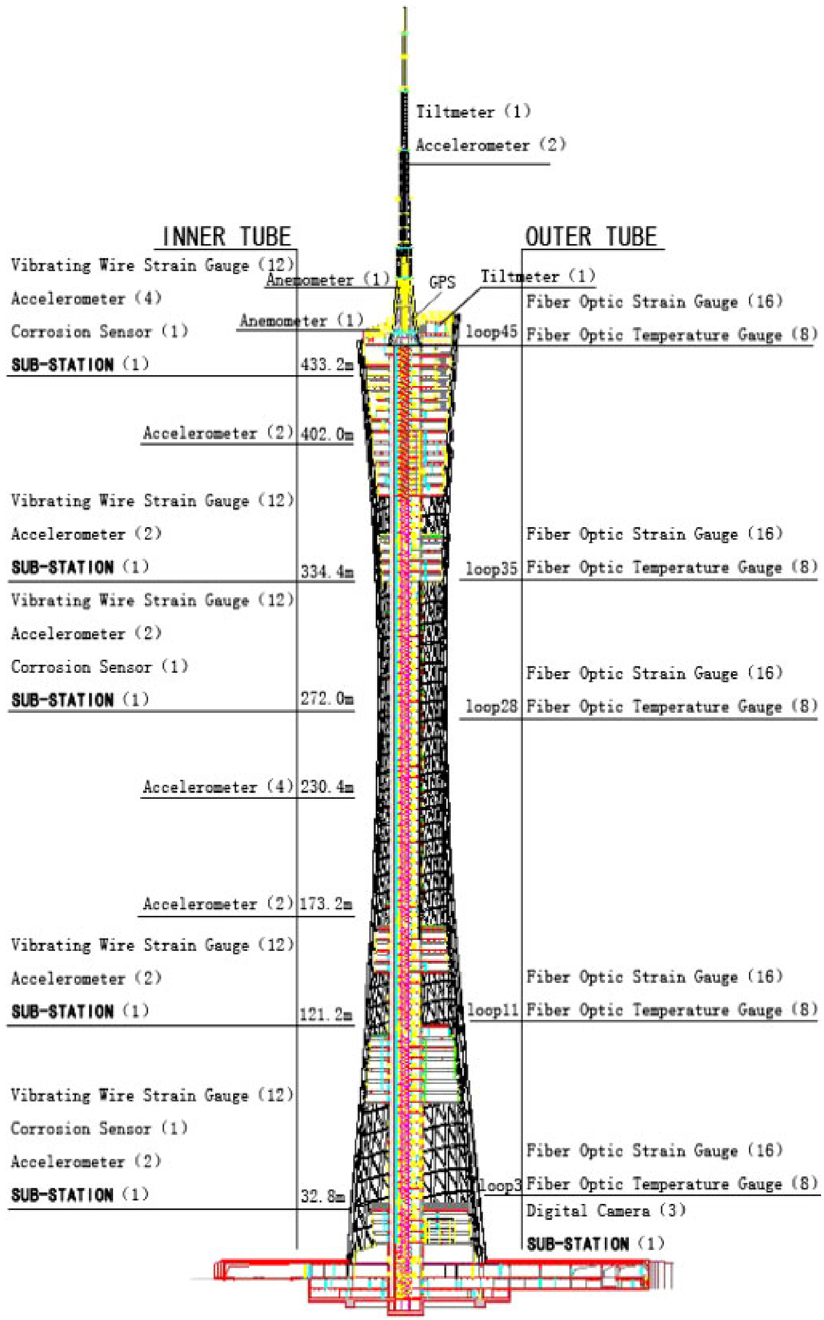

Figure 7. Deployment of sensors and sub-stations (DAUs) for in-service monitoring.

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includes 527 sensors, while the in-service monitoring system involves 280 sensors. A total of 12 cross-sections have been selected for in-construction monitoring and a total of 5 cross-sections have been selected for in-service monitoring (each cross-section is allocated one DAU and one additional DAU is located at the ground floor). These critical cross-sections are those suffering large stresses under construction and/or in-service loadings and experiencing abrupt change in lateral stiffness of the structure. They were determined through finite element analyses on the structure at critical construction stages and the completed stage. It is worth mentioning that all the five cross-sections identified for in-service monitoring have been included into the monitoring sections at the construction stage. Consequently, complete monitoring data for these cross-sections from construction to service stages could be acquired. This reflects again the merit of the integrated monitoring system. Accelerometers are positioned at more cross-sections to capture complete modal shapes and verify the effectiveness of vibration control devices, as discussed later. All the sensors (including fiber optic sensors) for in-service monitoring and their cabling networks (protected by steel tubes) are deployed in synchronism with construction progress. As shown in Table I, a considerable number of sensors are shared by in-construction monitoring and in-service monitoring.

4. WIRELESS-BASED DATA ACQUISITION AND INTERNET-BASED REMOTE DATA TRANSMISSION

A wireless system, as shown in Figure 8, is being operated for synchronous acquisition of strain and temperature data and real-time data transmission from the sub-stations to the site office

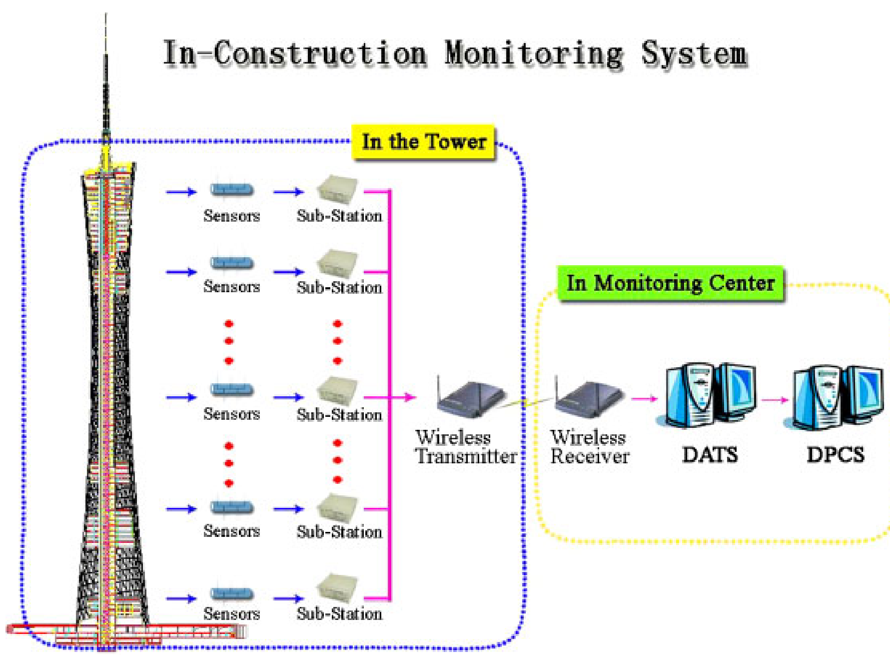

Figure 8. Wireless system for in-construction monitoring of strain and temperature.

during the construction monitoring. This system was devised by a collaborative team from The Hong Kong Polytechnic University and Intelligent Monitoring Technology System Corporation, Taiwan. It consists of three parts: WiFi router, wireless bridge, and antenna. The system can transmit the data at a speed of up to 100 Mbps and enables the maximum transmission distance of 2 km. It is also capable of being integrated with the fiber optic data transmission system via the installation of electro-optic converters. In this system, 12 static and 9 dynamic data loggers are connected under a wireless network structure, and a Network Time Protocol (NTP) server is adopted for the synchronization of data loggers over packet-switched, variable-latency data networks. The NTP is able to synchronize clocks of hosts and routers in the Internet, providing accuracies of low tens of milliseconds on wide area networks (WANs), submilliseconds on local area networks (LANs), and submicroseconds using a precision time source such as a cesium oscillator or GPS receiver [14,15]. It uses a symmetric architecture in which a distributed subnet of time servers operating in a self-organizing, hierarchical configuration synchronizes local clocks within the subnet and to national time standards via wire, radio, or calibrated atomic clock. As the NTP is designed particularly to resist the effects of variable latency, a consistent timekeeping can be kept precisely among the clock-dependent data loggers within LANs so that the data loggers can operate in consistent time.

The vibration of GNTVT is monitored mainly using accelerometers and wired cabling networks. Two wireless systems are also adopted *in situ* for complementary vibration monitoring aiming to (i) provide extended measurements so as to capture complete modal shapes, (ii) measure local vibration of structural components and identify local modes, (iii) enable the measurement of some positions that are inaccessible by the cabling system, and (iv) provide extra measurement data that are required by specific damage detection algorithms. The first wireless system, which is based on the Stanford Unit [16], comprises a central server and wireless sensing units. The central server is a PC or a laptop computer with a radio frequency (RF) modem for storing raw data received from sensing units. The wireless sensing unit is designed with three functional modules: the sensing interface, the computational core, and the wireless communication channel. The sensing interface converts analog sensor signals into a digital format usable by the computational core. The digitized data are then transferred to the computational core through a high-speed Serial Peripheral Interface (SPI) port. Besides a low-power 8-bit Atmel ATmega128 microcontroller with 128 kB of in-system reprogrammable flash read-only memory (ROM), an additional 128 kB of external static random access memory (SRAM) is integrated with the computational core to accommodate local data storage and analysis. Through a Universal Asynchronous Receiver and Transmitter Interface, the computational core communicates with the MaxStream 24XStream wireless transceiver, which provides a wireless connection between the units and the central server. The 24XStream operates on the unlicensed 2.4 GHz RF spectrum and can achieve long communication ranges of several hundred meters depending on the antenna and the environment. The system is also empowered with embedded data analysis capability by programming data analysis algorithms (e.g. damage detection routines) in ROM.

The second wireless system, which is based on the Imote2 [17], consists of eight ITS400 sensor boards, nine IPR2400 processor boards, and one IIB2400 interface debugging board. In this system, the IIB2400 interface debugging board and an IPR2400 processor board are coupled together by a dedicated connector, and act as a server unit after being connected to a PC or a laptop. A mixed architecture of an ITS400 sensor board and an IPR2400 processor board performs as a distributed sensing unit. In each sensing unit, the sensor board converts analog

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sensor signals into digital data, which are then transferred to the processor board. The IPR2400 processor board acts as the sensing controller with Intel PXA271 Xscale CPU, 256 kB SRAM cache memory, 32 MB FLASH program memory, and 32 MB synchronous dynamic random access memory (SDRAM) storage memory. Through a high-speed SPI port interface, the processor in a sensing unit communicates with a TI Chipcon 2420 radio transceiver, which provides a wireless connection between the sensing unit and the server unit. The TI Chipcon 2420 transceiver operates on the unlicensed 2.4 GHz RF spectrum and can achieve communication ranges of 300 m in the open space and 100 m in an indoor environment. The Imote2 network employs the time-stamp technology and possesses a synchronization precision of 10^{-6} s. The Imote2 software platform is open source on the Application Programming Interface level and is programmable under the support of Crossbow's Software Development Kit. The above two wireless systems have been adopted mainly due to their capability of embedding algorithms into the sensing units. The authors are already programming an artificial neural network-based damage alarming algorithm with built-in environmental effect filter into the wireless sensing units, targeting to achieve on-line and decentralized structural damage detection for GNTVT. Taking GNTVT as a test bed, the performance of these two wireless systems will be compared in the following aspects: capacity to collect and process low-frequency tremor signals, signal synchronization, and wireless communication range.

An Internet-based remote data transmission system, as shown in Figure 9, has been developed for video image signal and monitoring data communication between the site office (Guangzhou, China) and the SHM Laboratory of The Hong Kong Polytechnic University (Hong Kong). Both point-to-point and point-to-multipoint modes are provided in the system. The former mode provides a continuous real-time data and image signal transmission. It is a higher permission management in the system. The host computer users either at the site office or in the SHM Laboratory of The Hong Kong Polytechnic University are able to manage the data transmitted between the two ends and remotely control the angle of view of the video cameras. The latter mode works as a browser. Authorized users worldwide can access the monitoring database via the web browser. Figure 10 shows interfaces of the remote data transmission system. As shown in Figure 10(a), the users can access the video image and click on the control panel to achieve some functions, which include rotation and shift of the angle of view, auto pan, aperture adjustment, and zoom. Figure 10(b) shows the remote display and acquisition of real-time moniotirng data. With the use of built-in functions, the users can transfer the data into text and/or graphic formats for further analysis.

5. DESIGN AND IMPLEMENTATION OF FBG SENSING SYSTEM

A fiber optic sensing system based on fiber Bragg gratings (FBGs) is being implemented on GNTVT to provide long-term, real-time strain and temperature monitoring. In comparison with the conventional electrical sensors, FBG sensors offer several unique advantages: (i) FBGs are immune to electromagnetic interference as the FBG signals are optic, (ii) many FBGs could be multiplexed by wavelength division multiplexing along a single fiber, (iii) remote sensing up to 100 km is possible with an appropriate sensing network design [18,19], (iv) signal fidelity is extremely high as wavelength is an absolute parameter, which is not related to the signal power level; and (v) the wavelength of an FBG is a signature of that particular FBG and it is also an absolute reference for measurement.

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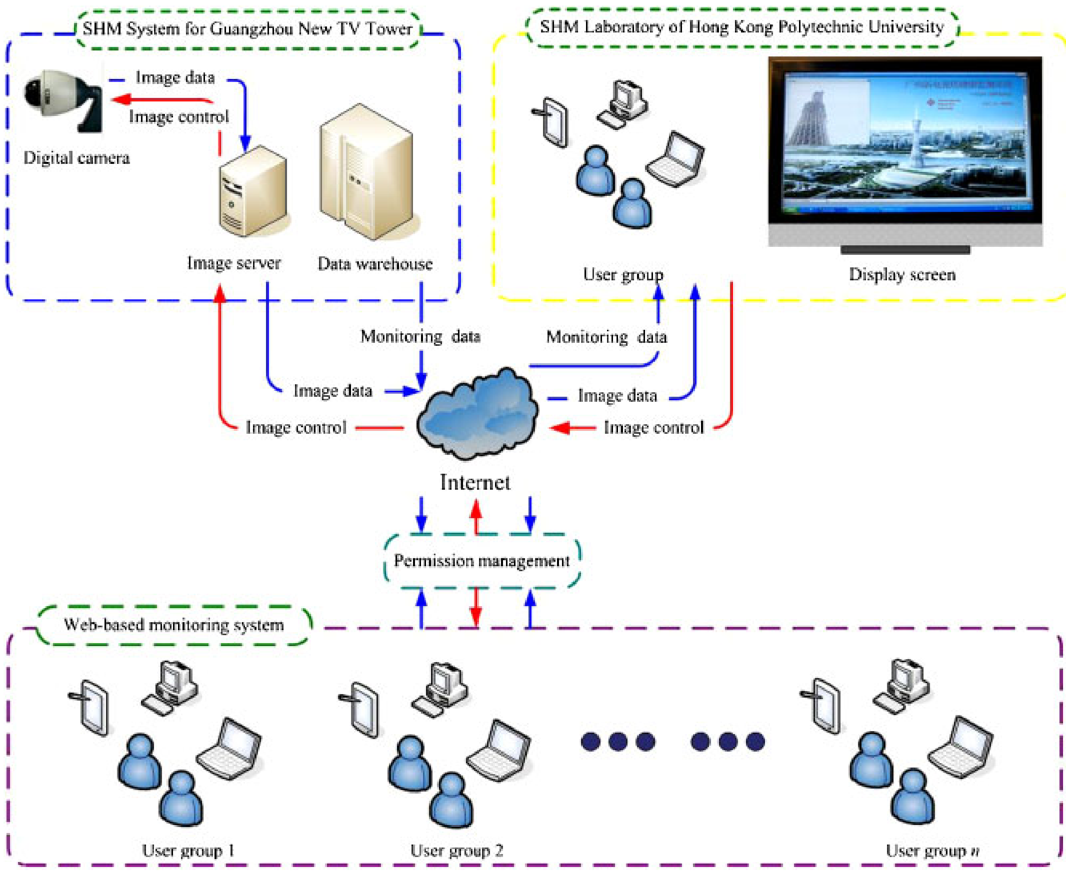

Figure 9. Internet-based remote data transmission system.

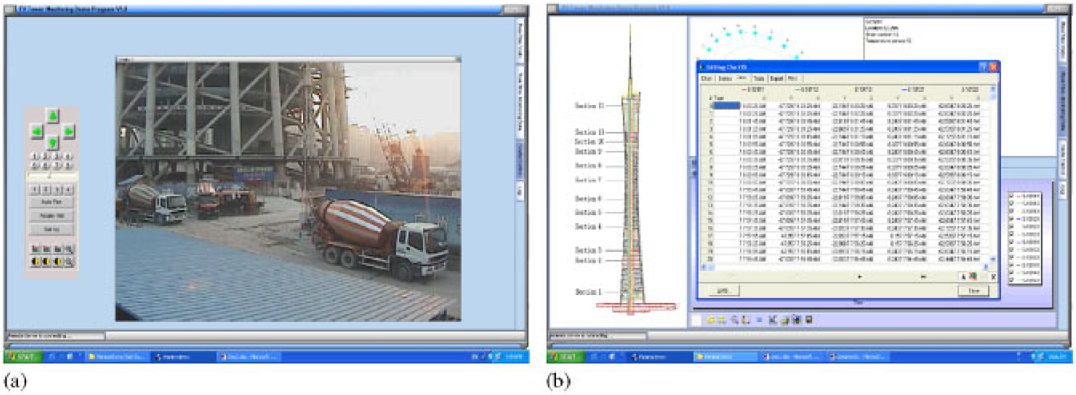

Figure 10. Interfaces of remote data transmission system: (a) remote video image monitoring and (b) remote data display and acquisition.

The sensing system devised for GNTVT comprises 120 FBG sensors that can be monitored at a speed of up to 50 samples/s. Figure 11 shows the system configuration where five groups of 24 FBG sensors are employed to monitor the outer tube of GNTVT 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 allocated for strain measurement and the other two for temperature measurement. Both the FBG strain and FBG temperature sensors employed are custom designed to cope with

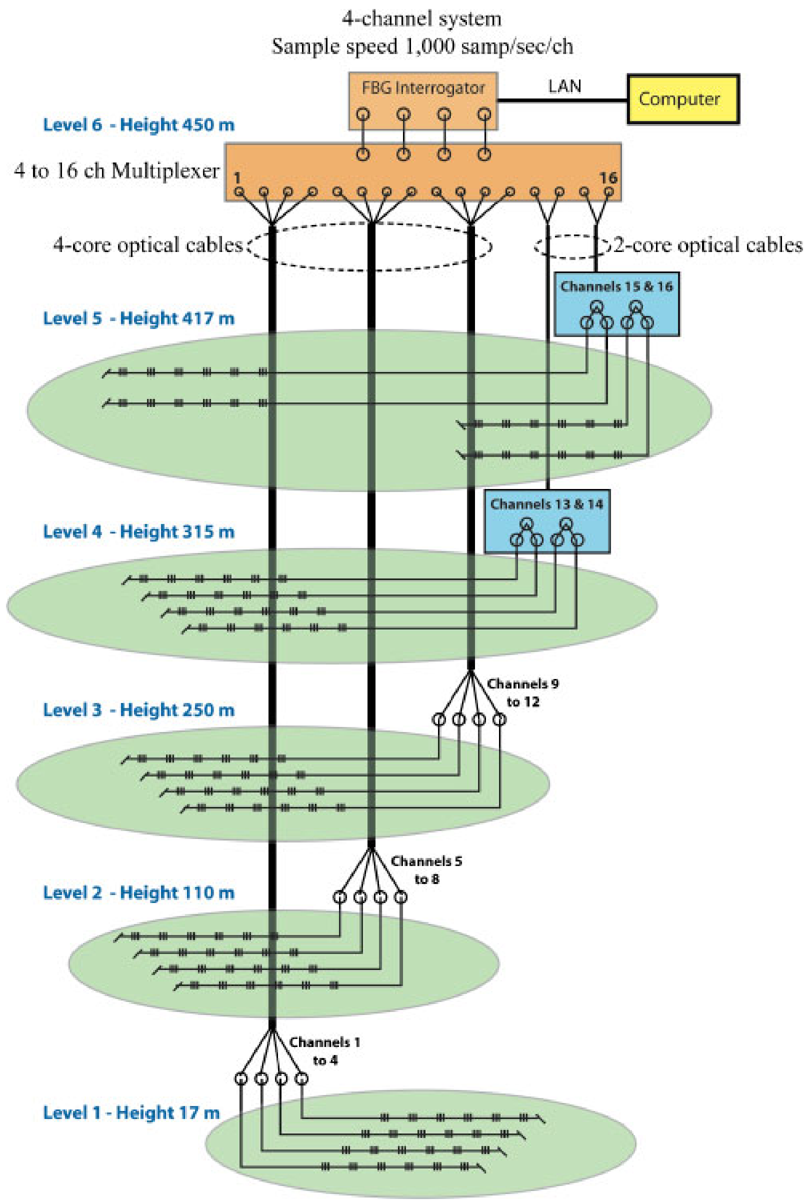

Figure 11. FBG sensing system for long-term monitoring of strain and temperature.

the hostile environment outside the tower. Each FBG sensor is attached onto a 0.8-mm thick SS302 stainless steel to protect it from handling and to ensure long-term reliability. The steel-packaged FBGs permit them to be welded directly onto the structure. Figure 12 illustrates an FBG sensor and various metal parts for installation of the FBG sensor onto the tower. The FBG sensing system is designed to measure temperature with an accuracy of 0.1°C over the temperature range of -40 to $+120$°C and strain with an accuracy of 1 $\mu\varepsilon$ and strain limits of $\pm 2500\,\mu\varepsilon$.

The FBG interrogation system employs a wavelength-tunable fiber laser whose emission wavelength can be tuned at a speed of 200 cycles per second with each cycle covering the entire reflection wavelength of the FBG sensors. The FBG interrogator is produced by Micron Optic Incorporation and has a wavelength tuning range of 80 nm. The interrogator has 4 outputs, which are increased to 16 outputs using an optic multiplexer. Each of the 16 channels covers 80 nm but operates at one-fourth the original sampling speed (namely, 50 Hz). Armored optic fibers are used to connect all the FBG sensors to the FBG interrogation system. The FBG sensors are secured onto a stainless steel tray, which also keeps the armored optic cables in position. During installation, the two metal stubs are welded onto the surface of steel structural members. Then the FBG sensor tray is placed around the metal stubs before welding the FBG package onto the structure. A metal cover measuring 10 mm $\times$ 70 mm $\times$ 140 mm for protecting the FBG sensor is screwed onto the metal stubs and sealed with a sealant to prevent water seeping into the sensor housing. Figure 13 shows the installation and protection of the FBG sensor on a CFT column.

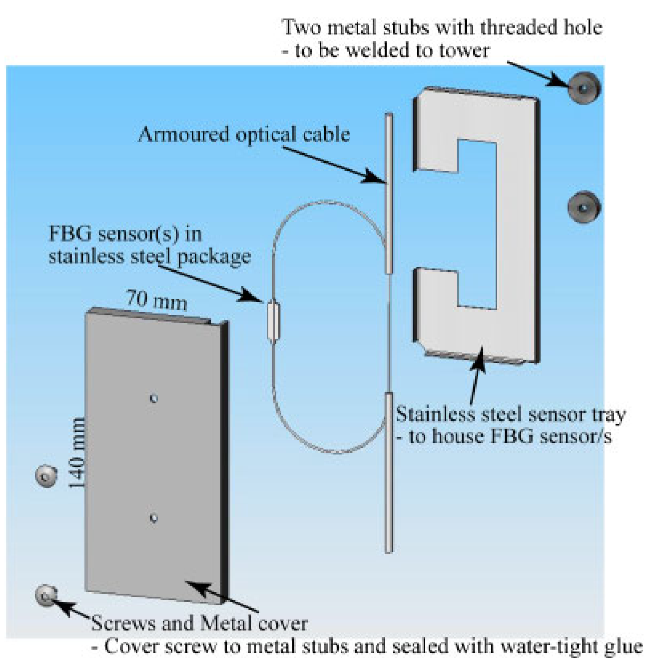

Figure 12. Components of one FBG sensor unit for welding onto the structure.

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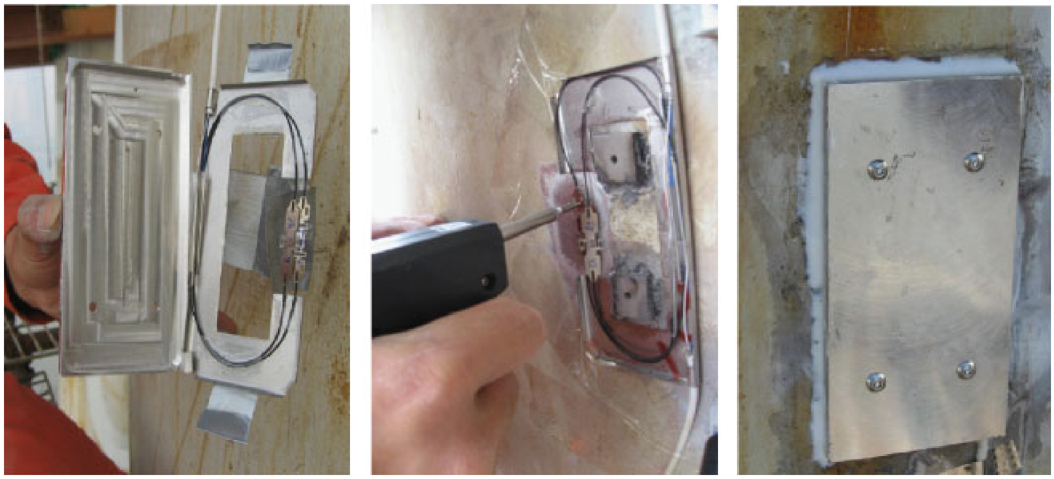

Figure 13. Installation and protection of FBG sensor.

6. STRUCTURAL HEALTH AND CONDITION ASSESSMENT STRATEGY

A structural health and condition assessment strategy using static and dynamic monitoring data will be executed in this project. The modal properties that constitute the basic parameters for vibration-based damage detection will be identified from ambient vibration responses acquired by the accelerometers. The dynamic displacement response will also be obtained through analyzing the monitoring data from GPS, accelerometers, and digital video cameras simultaneously, and will be integrated for structural condition assessment. The authors have experimentally verified a number of damage detection methods proposed specifically for high-rise structures, including a Hilbert–Huang transform and a novelty detection technique [20], several modal-based damage index methods [21], a wavelet-based diagnosis technique [22], a time–frequency analysis method [23], and a principal component analysis-based neural network technique [24]. These methods will be adapted and refined for vibration-based structural damage detection of GNTVT. Some of the methods need a precise finite element model of the structure in healthy state as a baseline. Such a baseline model will be established through model updating using the measured modal properties at various construction stages and at the completion of the structure, and is therefore referred to as a dynamically calibrated baseline model. The extreme loadings for GNTVT are mainly due to typhoons/hurricanes and earthquakes. As a tri-axial seismograph and a number of accelerometers have been permanently deployed, both the earthquake excitation and the structural seismic response will be picked up once an earthquake occurs. The structural performance during earthquake and the impact of earthquake on the structural safety can be accurately assessed because the structural transfer functions can be evaluated from both input and output measurements. Similarly, as both anemometers and wind pressure sensors are installed to monitor wind excitation and the wind-induced structural responses are measured by accelerometers, GPS, and fiber optic sensors, it is possible to accurately identify both along-wind and across-wind effects during a typhoon or hurricane attack and evaluate the real wind-resistant capacity of this supertall slender structure.

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It is difficult to identify the local structural damage for large-scale structures by using modal properties only. A more reliable structural health evaluation is based on multilevel data fusion through combining the global modal properties and the local strain information. As the integrated monitoring system enables the measurement of static strain, dynamic strain, and total (cumulative) strain, a method based on long-term monitoring data of strain and reliability analysis will be executed to GNTVT for safety and condition evaluation of structural members and cross-sections. Following this method [25,26], the probability density function (PDF) of the load effect in a structural member or cross-section is obtained directly from continuous strain measurement, while the PDF of the resistance is determined using the material strength and its coefficient of variation prescribed in provisions or obtained by material tests, and further revised with the damage identification results if any. With the obtained PDFs of load effect and resistance, the safety indices of structural members and/or cross-sections are estimated using the first-order reliability method, which can readily be used to identify the most vulnerable structural components and quantify the real safety reserve of each component. As such an evaluation of the safety index can be done year by year with updated monitoring data, this method also gives the information on the degradation rate of the safety index. Two issues have to be taken into account in implementing this method. First, as the influence of temperature on strain is significant and the temperature-induced strain does not produce stress in most situations, the temperature effect on the measured strain must be eliminated or accommodated in evaluating the PDF of the load effect. Figure 14 shows the measured strain versus temperature for a point inside the inner tube of GNTVT during a period of 4 days. A noticeable correlation between the measured strain and temperature is observed. A wavelet method has been proposed by the authors to remove the temperature effect from the measured strain [27]. Second, for the structural members where the strain is not measured, their safety indices can only be approximately estimated with the help of a finite element model of the structure. Different from the dynamically calibrated baseline model, however, the finite element model needed for safety index estimation must be calibrated using the measured strain at various construction stages and at the completion of the structure. It is the so-called statically calibrated baseline model. Figure 15 illustrates three construction stages of GNTVT and Figure 16 shows the corresponding finite element models. A comparison of the computed and measurement-derived principal stress increments for two monitoring points at the three

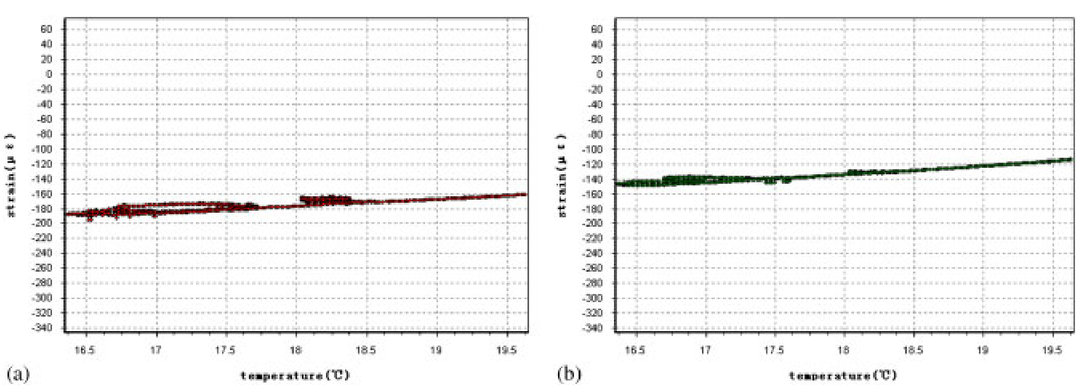

Figure 14. Correlation between measured strain and temperature: (a) vertical strain and (b) horizontal strain.

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Figure 15. Three construction stages of GNTVT: (a) Stage 1 (20 July 2007); (b) Stage 2 (15 August 2007); and (c) Stage 3 (25 October 2007).

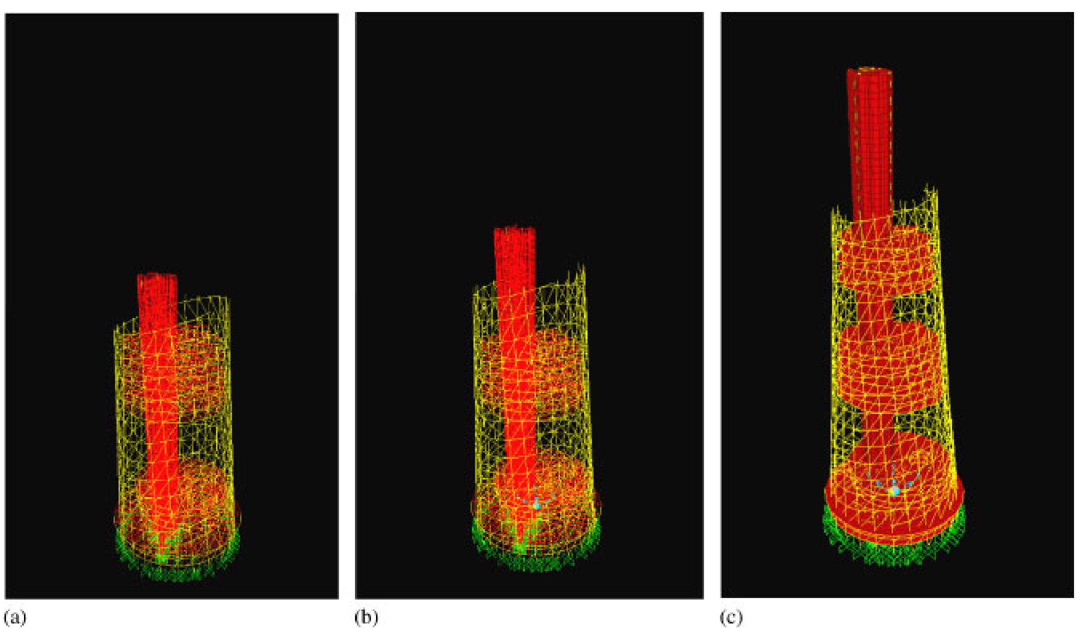

Figure 16. Finite element models corresponding to the three construction stages.

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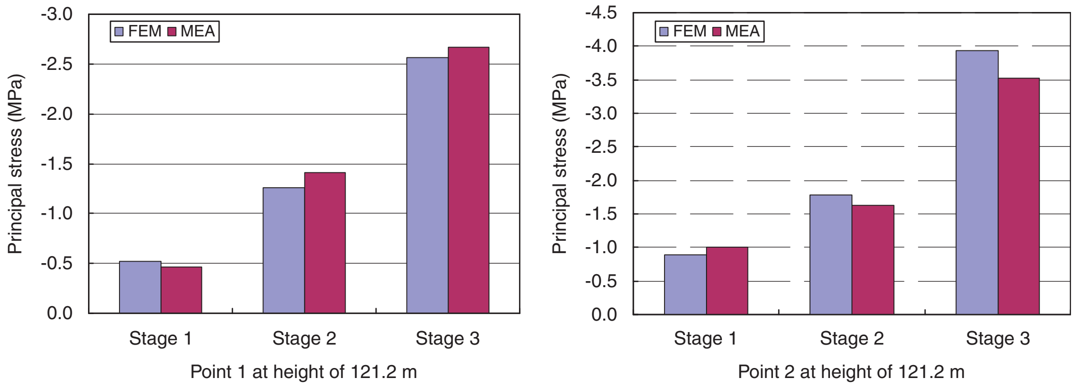

Figure 17. A comparison between calculated and measurement-derived stress increments.

construction stages is shown in Figure 17. The static finite element models are calibrated and refined using the measured strains after eliminating the temperature effect and their derived stresses.

7. VERIFICATION OF VIBRATION CONTROL EFFECTIVENESS BY SHM

The SHM system for GNTVT has been designed to have a special function of verifying the effectiveness of vibration control devices to be installed on the tower. 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 will be installed at the floor of 438 m height for mitigating wind-induced vibration of the primary structure, while two tuned mass dampers will be suspended at the heights of 571 and 575 m, respectively, for vibration suppression of the antenna mast. As shown in Figure 7, accelerometers are deployed at eight heights of the tower for long-term vibration monitoring. They will also measure the structural dynamic response before and after the activation of the vibration control devices, and monitor the effectiveness of the vibration control devices under strong wind and typhoon conditions. In order to verify the whipping effect predicted to occur in the 156 m high mast and its influence on the effectiveness of vibration control, two accelerometers are installed on the mast to monitor its dynamic response and modal properties, with the intention to compare them with the dynamic properties of the primary structure. As an appropriate tuning frequency of tuned mass dampers is most important for vibration control and it relies on the structural modal frequencies, ambient vibration tests will be conducted at two different construction stages (Phases I and II) and completed stage (Phase III), as shown in Figure 18. This will provide information for helping the design of the tuned mass dampers, and provide measured modal properties for SHM benchmark problem studies as described in the following section. The signals from the anemometers and the seismograph of the monitoring system will be provided on-line to the vibration control system for making decision on activating or locking the control system (it 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

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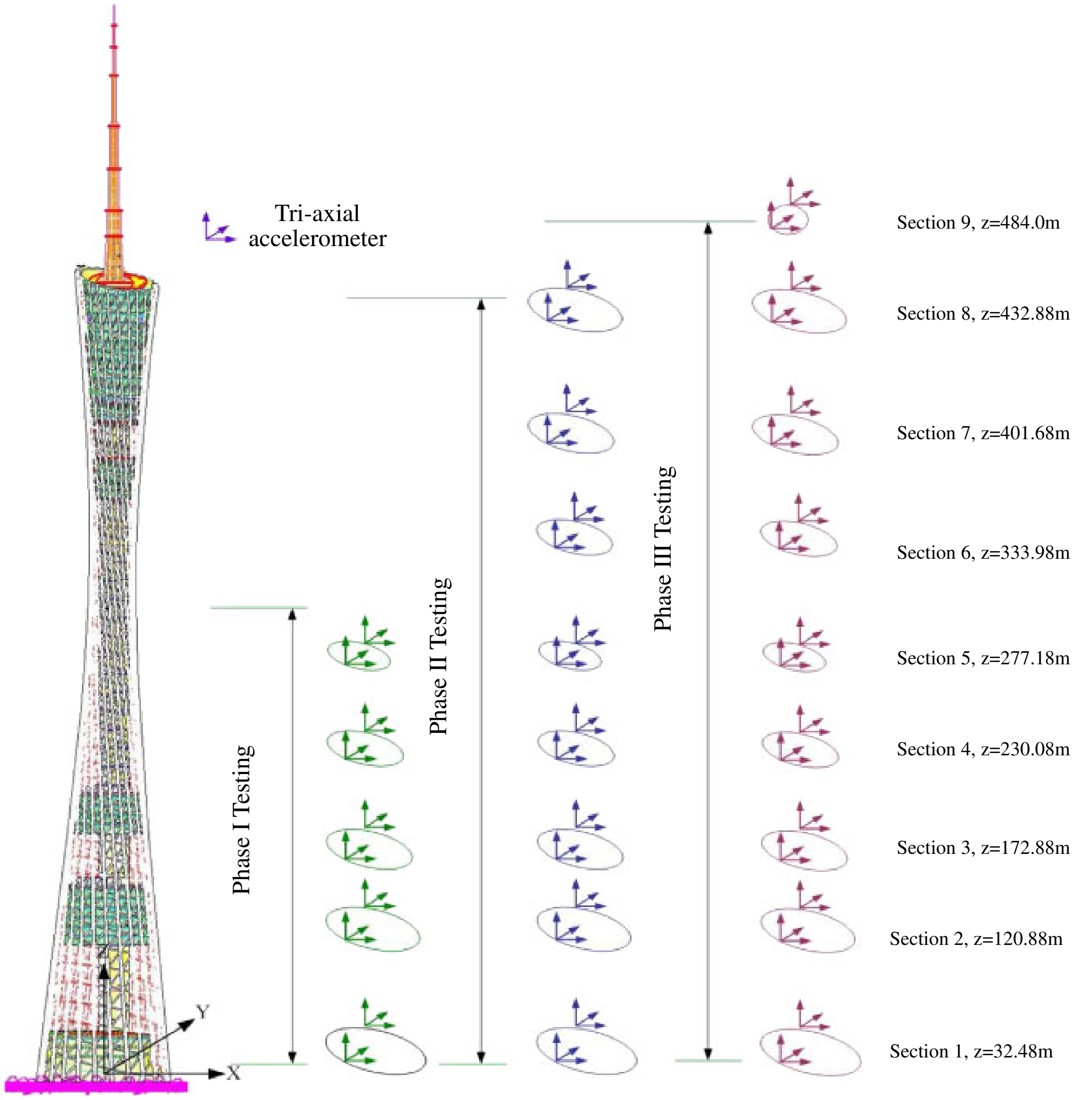

Figure 18. Three phases for ambient vibration measurement.

structural response signals by the monitoring system to detect possible fault of the control-specific transducers.

8. DEVELOPMENT OF AN SHM BENCHMARK PROBLEM

In the past two decades, a variety of damage diagnosis methods have been proposed by different investigators. However, the feasibility of these methods for real-world applications, especially

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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 therefore have opportunities to test their SHM techniques using real-world data from a full-scale structure and to recognize the obstructions in real life implementations. In recognizing this, an SHM benchmark problem for high-rise structures is currently being developed by taking the instrumented GNTVT as a test bed. The first stage of the SHM benchmark problem consists of the following four tasks:

(i) Output-only modal identification and finite element model updating. A baseline model is required for the majority of vibration-based damage detection methods. In the present study, a validated finite element model of GNTVT will be developed to serve as the baseline model. As shown in Figure 18, at least three stages of ambient vibration tests will be conducted on GNTVT during its construction period. The measurement data obtained from these ambient vibration tests will be provided through the web site to interested participants for the benchmark problem of output-only modal identification and finite element model updating.

(ii) Damage detection using model-based simulation data. With the full-order and reduced-order finite element models of GNTVT, vibration-based damage detection will be studied using the simulation data. The present study aims to evaluate the applicability and reliability of various damage detection algorithms in the case that (a) only limited modal information is available; (b) there is modeling error; and (c) the measured modal parameters are noise-polluted. The 'measured' modal properties before and after damage will be produced from the full-order finite element model, but only the reduced-order finite element model (in MATLAB format) will be provided to the participants for damage detection to incorporate the modeling error.

(iii) Performance-based optimal sensor placement for SHM. For large-scale structures such as long-span bridges and high-rise buildings, optimal sensor placement is essential to achieve cost-effective and reliable SHM. The instrumented GNTVT provides a unique paradigm for investigating the optimal sensor placement for damage detection of high-rise slender structures. The existent studies on this topic seek for the sensor locations that can best measure the structural properties. However, a standard SHM system for large-scale civil structures does not pick up the data at the individual measurement points directly; instead, the sensed analog signals are transmitted to the central computer for analog-to-digital data conversion or are first collected by on-structure DAUs (sub-stations) for analog-to-digital conversion and then transmitted to the central computer. The data quality can be heavily influenced during signal transmission. As a result, optimal or good locations for structural property monitoring do not imply that the data transmitted to the DAUs or central computer are also with high quality. In this task of the benchmark problem, performance-based optimal sensor placement will be studied by considering both structural information aspect and communication/networking constraints. Furthermore, the optimal placement problem can be addressed by exploring multi-scale sensing and data fusion for damage identification.

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(iv) Damage detection using field measurement data. In the latest phase of the benchmark problem, field measurement data of GNTVT before and after 'damage' will be acquired and provided to all interested participants for damage detection study. In this study, the tower immediately before construction of some beams connecting inner tube and outer tube at top will be treated as a 'damaged' structure, and the structure shortly after construction of the top connection beams will serve as the 'intact' state. Another damage scenario will be constructed in which the monitoring data acquired before and after the installation of the 156 m high antenna mast will serve as the field measurement data prior to and posterior to structural damage, respectively. The measured dynamic strain and displacement signals can be used in conjunction with the measured modal properties for structural damage identification.

A web site (http://www.cse.polyu.edu.hk/benchmark/) has been established for this SHM benchmark problem.

9. MONITORING DATA DURING EXTREME EVENTS

During the construction period of GNTVT, the monitoring system has detected the structural responses of GNTVT caused by several extreme events such as the Wenchuan earthquake, Neoguri typhoon, Kammuri typhoon, and Nuri typhoon. The devastating Wenchuan (Sichuan) earthquake of magnitude 8.0 occurred at 14:28 on 12 May 2008 in southwest China's Sichuan Province. All the embedded strain gauges installed at the 10 erected cross-sections of GNTVT signaled large strain variations lasting for 1–2 min on that day. Figure 19 illustrates the measured vertical strain and the measurement-derived principal stress of a measurement point at the cross-section of 121.2 m height on 12 May 2008. It is observed that the large strain variations started at 14:35, about 7 min behind the time of the earthquake occurrence at the epicenter. The distance between the earthquake epicenter (Wenchuan) and the tower site (Guangzhou) is approximately 1325 km. According to the time of the earthquake's arrival at the tower site, the seismic wave propagation velocity is estimated to be 3155 m/s. The maximum

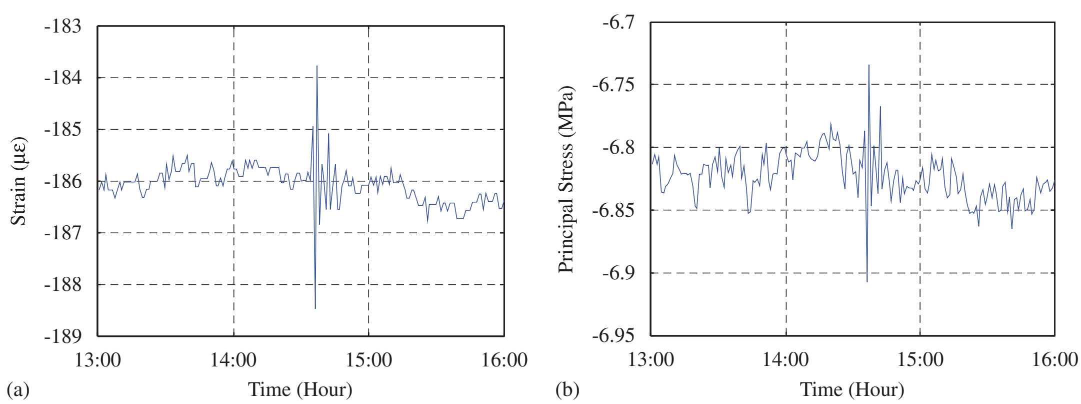

Figure 19. Measured strain and measurement-derived stress during Wenchuan earthquake: (a) vertical strain and (b) principal stress.

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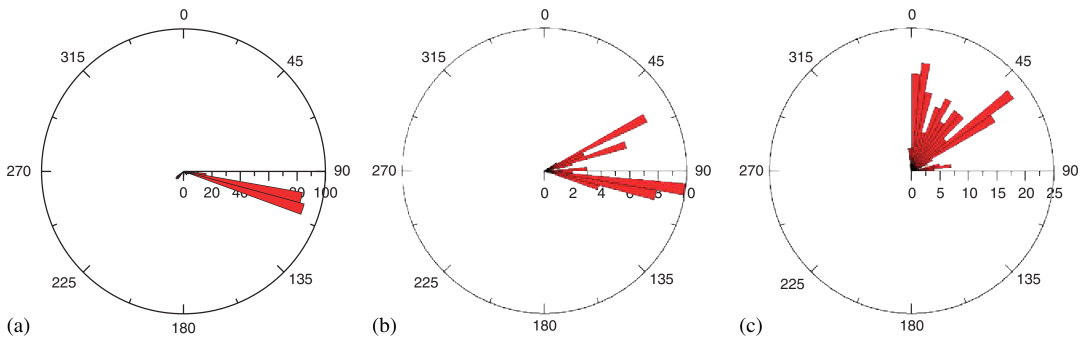

Figure 20. Wind rose diagrams during three typhoon events: (a) Neoguri typhoon; (b) Kammuri typhoon; and (c) Nuri typhoon.

stress variation in the cross-sections caused by this earthquake is 3.6 MPa, which is about 10% of the static stress produced by the self-weight of the structure at that construction stage.

Figure 20 illustrates the wind rose diagrams formulated using the data from the anemometer deployed on top of the structure during the Neoguri typhoon (18 April 2008), Kammuri typhoon (6 August 2008), and Nuri typhoon (22 August 2008). In the figure, 0° denotes due north. The measured maximum 3-s gust wind speed at the tower top is 28.1 m/s during the Neoguri typhoon, 32.3 m/s during the Kammuri typhoon, and 25.5 m/s during the Nuri typhoon. Besides wind speed and wind direction, the corresponding structural acceleration, displacement, strain, and temperature during the typhoons were also measured by the accelerometers, GPS system, and strain gauges, respectively. Figure 21 shows the measured acceleration time histories at the height of 386 m during a typhoon. The measured maximum acceleration during the three typhoons is close to $0.05\,\mathrm{m/s^2}$. Figure 22 shows the dynamic displacement measured by the GPS system during a typhoon. The maximum displacement during the three typhoons was measured to be about ± 15 cm. Figure 23 illustrates the measured vertical strain and the measurement-derived principal stress at the cross-section of 121.2 m height during a typhoon. The maximum stress variation during the three typhoons is approximately 0.5 MPa, which is about 20% of the static stress produced by the self-weight of the structure. With the measured acceleration responses during each typhoon, the modal properties (frequencies, mode shapes, and damping ratios) of GNTVT were identified using the output-only stochastic subspace identification technique. The modal properties identified using the typhoon-response data were compared with the identification results using normal ambient vibration data obtained in daytime (with construction activity) and in nighttime (without construction activity), respectively. The analysis of the influence of environmental factors (wind and temperature) on the identified modal properties and the updating of the structural models for different construction stages using the measured/identified data are currently under way.

10. CONCLUSIONS

The GNTVT is deemed to be the most heavily instrumented high-rise structure in the world with both in-construction and in-service monitoring systems being equipped. The integrated design and implementation of in-construction and in-service monitoring systems greatly facilitates the

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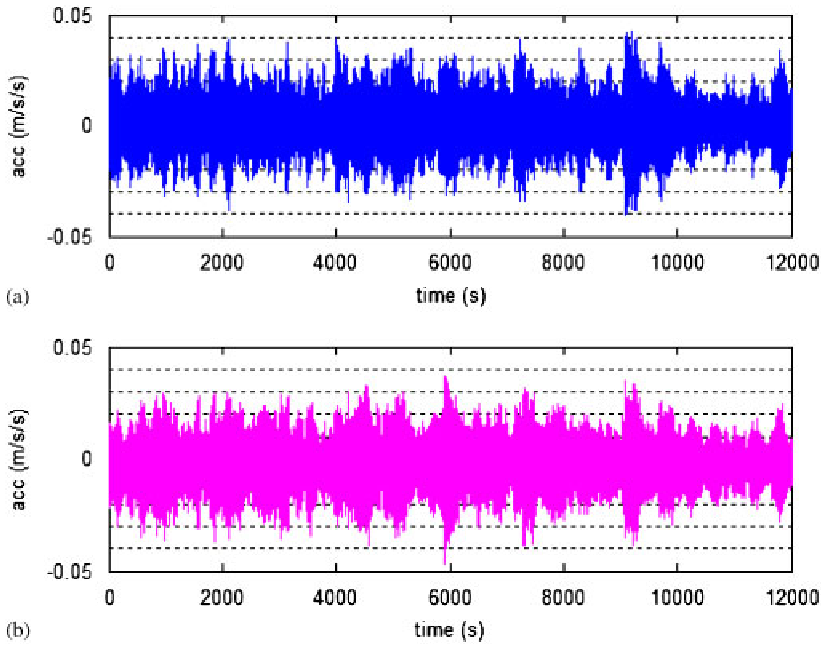

Figure 21. Measured acceleration during a typhoon: (a) acceleration in the east–west direction and (b) acceleration in the south–north direction.

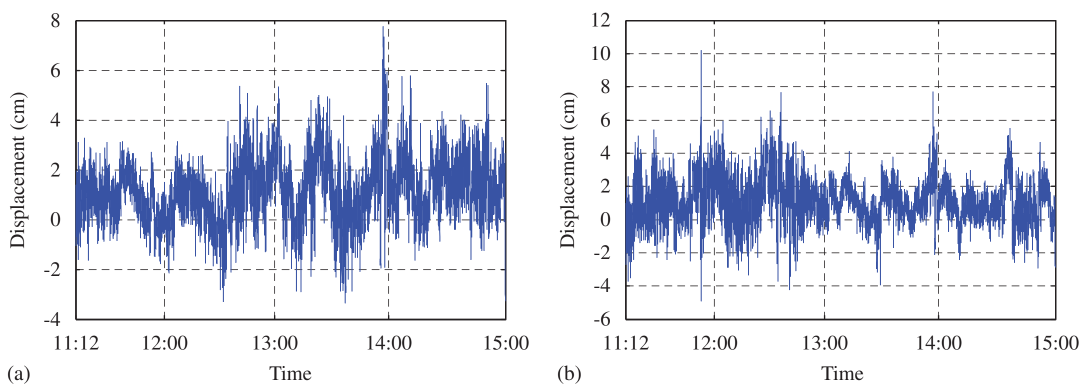

Figure 22. Measured dynamic displacement during a typhoon: (a) displacement in the east–west direction and (b) displacement in the south–north direction.

deployment of both embedment-type and surface-type sensors and enables life-cycle monitoring and assessment of the structure from its 'birth'. This also makes it possible to implement reliability-based methods for structural health and condition evaluation. Wireless monitoring technique and innovative fiber optic sensing system have been utilized in developing the SHM system for GNTVT. Taking the instrumented GNTVT as a test bed, an SHM benchmark problem for high-rise structures is being developed. Since a full-scale structure and the

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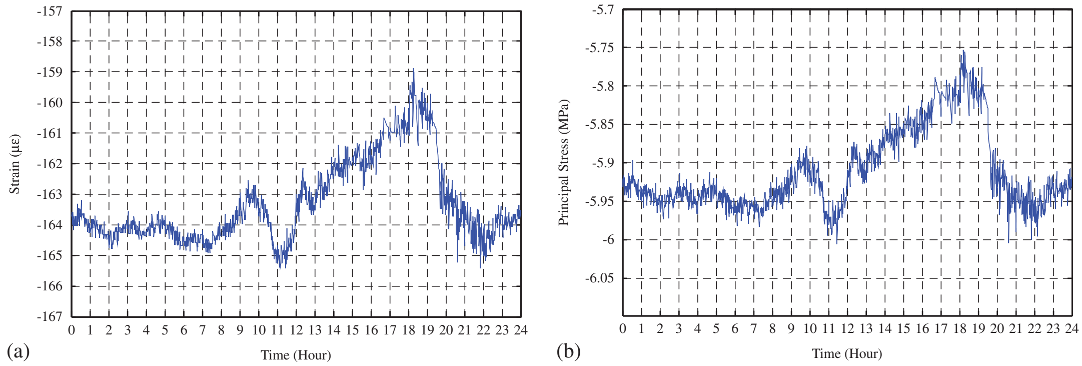

Figure 23. Measured strain and measurement-derived stress during a typhoon: (a) vertical strain and (b) principal stress.

real-world measurement data are addressed, the results from this benchmark problem shall be convincing and enable researchers to recognize the obstructions in real life implementations of their damage detection algorithms or techniques. Such a benchmark problem will help reach the most promising directions in future research of SHM, narrow the gap between research and application, and motivate international collaborations in SHM community.

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