The state-of-the-art and practice of structural health monitoring for civil infrastructures in the mainland of China

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ABSTRACT: Structural health monitoring (SHM), as a useful technique for ensuring the health and safety of civil infrastructures due to the damage accumulation or disaster evolvement of civil infrastructures, has more and more attract great considerations in research and engineering communities in the mainland of China since a great number of civil infrastructures are being planned and constructed each year. In this paper, the state-of-the-art and practice of structural health monitoring for civil infrastructures in the mainland of China are summarized. These contents in this paper include the development of advanced smart sensors, wireless sensors and sensor networks, data acquisition system, approach of damage detection, model updating and safety evaluation, implementations of integrated systems in practical infrastructures of long-span bridges, offshore platform structures, hydraulic engineering structures, tall buildings and large space structures in the past few years of the mainland of China. SHM systems of two cable-stayed bridges are presented in detail as examples to demonstrate the development of SHM technology in the mainland of China.

1 INTRODUCTION

Civil infrastructures, such as long-span bridges, offshore structures, large dams and other hydraulic engineering, nuclear power stations, tall buildings, large space structures and geotechnical engineering, often service for a long period of several decades or even over one hundred years. During the service time they are inevitable to suffer from environmental corrosion, material aging, fatigue and the coupling effects with long-term loads and extreme loads. The induced damage accumulates and performance degenerates due to the above factors would inevitably reduce the resisting capacity of the civil infrastructures against the disaster actions, even result in collapse with the structural failure under extreme loads. Due to those reasons the intelligent health monitoring has more and more attracted great research and development interests of scientists and engineers in the whole world because of the ability to ensure the safety and study the damage evolving characteristics of the structures.

In the mainland of China, a great number of civil infrastructures are being planned and constructed each year, such as the hydraulic engineering of the Three Gorges Project in Yangtze river, Sutong Cable-stayed Bridge with a main span of 1088m, a lot of offshore structures and seabed pipe lines for Bohai Ocean oil field exploitation, and many large-space structures for 2008 Olympic Games. The durability and safety of these civil infrastructures in the following long-term service periods then become the most important issues, which are so urgent and extensive in the mainland of China in current. To solve those problems, Chinese scientists and engineers have worked closely with others engaged in this field around the world to promote the research and development of intelligent SHM for civil infrastructures.

In the past decade, Chinese researchers have made great progress and gained fruitful achievements in all aspects of structural health monitoring, including advanced smart sensor, wireless sensors and sensor networks, data acquisition and processing system, signal transmission system, approach of damage detection, model updating and safety evaluation, data management, system integration techniques, design method of SHM system, and implementations for practical civil infrastructure, decision-making techniques of health status of structure based on measured data. In this paper, the state-of-the-art and practice of structural health monitoring for civil infrastructures in the mainland of China are summarized.

2 SMART SENSORS

A variety of advanced smart sensors have been developed with the development of health monitoring technique, such as optical fiber sensor, piezoelectric and polivinylidene fluoride (PVDF) sensors, fatigue life gauges, shape memory alloy (SMA)-based displacement transducers, strain self-sensing cement and carbon fiber reinforced polymer (CFRP)-based strain sensors.

2.1 *Optical fiber sensors*

Durability is one of the most important factors for the sensors in long-term SHM system of civil infrastructures. Among the several kinds of sensors optical fiber sensor is just the ideal and suitable one for SHM systems of civil infrastructures with long-term service period due to their distinguishing advantages of electro-magnetic resistance, small size, resistance to corrosion, convenience for multiplexing a large number of sensors along a single fiber, etc. There are four kinds of advanced optical fiber sensors have been developed and applied in practical infrastructures recently, such as OTDR (BOTDR) (Shi 2003a, 2003b), F-P sensors, white-light interferometers and optical fiber Bragg grating (FBG) sensor (Ou & Zhou 2002, 2003, 2004, 2005; Li 2004; Jiang 2003).

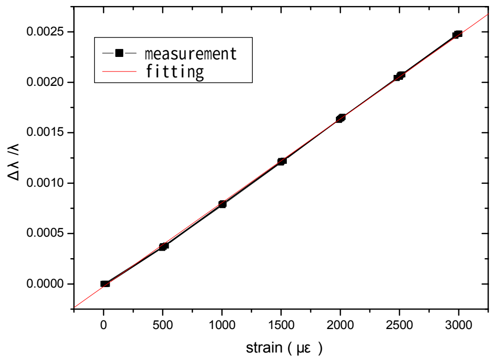
Aiming at the practical requirements of the SHM systems for civil infrastructures, Harbin Institute of Technology (HIT) breaks through the durability problem of the package of FBG sensors, and develops some efficient methods for the FBG sensor fabrication based on the basic theories of creep, strain-transfer error modification and optimization design. Various FBG sensors including direct FBG sensors, indirect FBG sensors and smart structures based on FBG are developed. The integrated monitoring system based on FBG sensors has also been developed and applied in many practical civil infrastructures.

2.1.1 *Direct FBG strain sensors*

Due to the fragility of the FBG, bare FBG without package is not appropriate to be directly applied in practical civil infrastructures. Moreover, if the FBG is only packaged by glue, the performance of the FBG sensors is also limited with the problem of "short life" because of the defection of creep and aging of the glue. To solve the "short life" problem of the sensors, HIT has developed various FBG strain sensors with good strain sensing properties and long-term durability by embedded the FBG sensors into fiber reinforced polymer (FRP) without using any short-life materials.

Six kinds of FRP-packaged FBG strain sensors are introduced herein, depicted from Figure1 to Figure 6. More details about these sensors can be available at the website www.tider.com.cn. The common measure range of these sensors is about 5000με, even to 10000με; Accuracy is about 1~2με depending on the interrogator; Repeatability error is less than 0.5%; Linearity error is less than 0.8%; Sensitivity coefficient is about 7.8×10^{-7} and the hysteresis error is less than 0.5%; Fatigue life is higher than 1,000,000 times at 1000με level. Moreover, convenient device to calibrate the FBG strain sensors for all these FBG strain sensors is also developed by HIT, as shown in Figure 7.

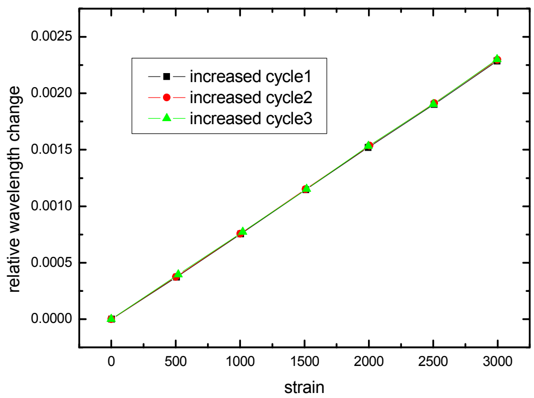
(a) Photo of the sensor



(b) Sensing properties

Figure 1. GFRP-packaged embeddable strain sensor with 80-100 mm calibration length

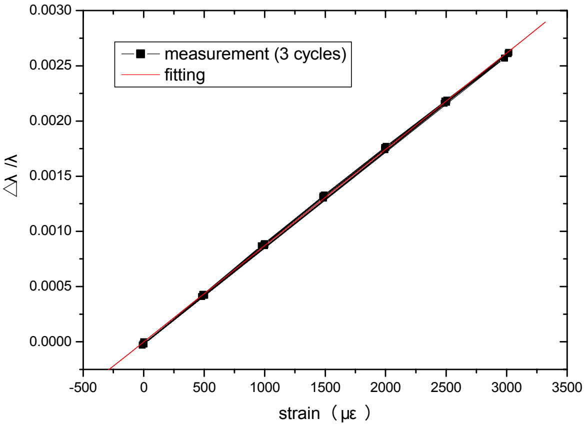
(a) Photo of the sensor



(b) Sensing properties

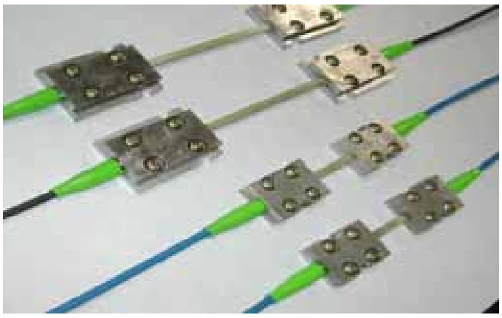
Figure 2. GFRP-packaged embeddable strain sensor

(a) Photo of the sensor

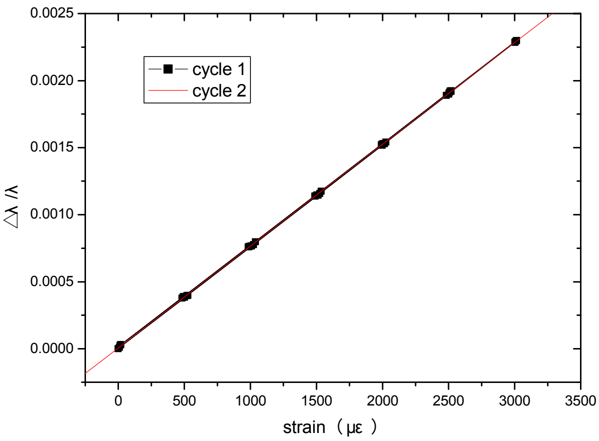


(b) Sensing properties

Figure 3. FRP-packaged embeddable FBG strain sensor with enlarged end

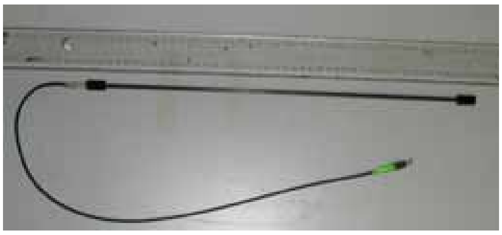


(a) Photo of sensor family

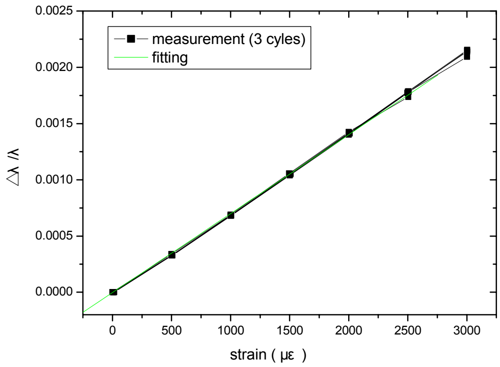


(b) Sensing properties

Figure 4. GFRP/CFRP-packaged weldable strain sensor with 20-40 mm calibration length

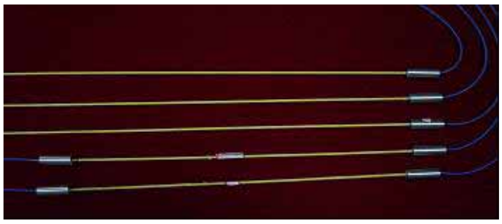


(a) Photo of the sensor

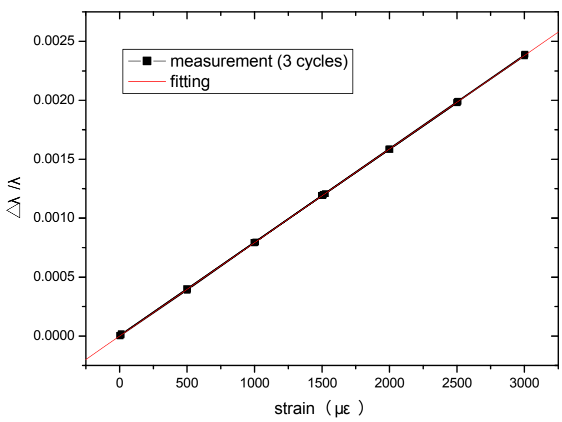


(b) Sensing properties

Figure 5. FRP-packaged embeddable long-gauge FBG strain sensor



(a) Photo of the sensor



(b) Sensing properties

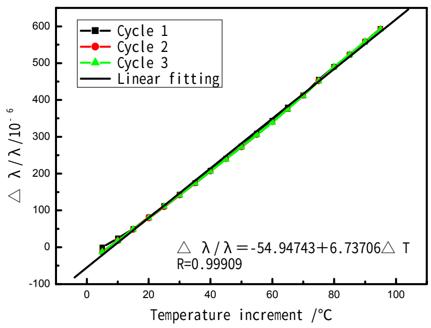
Figure 6. GFRP/CFRP-packaged embeddable long-gauge FBG strain sensor

Figure 7. Calibration device for the FBG strain sensors

2.1.2 *Direct packaged FBG temperature sensors*

The accuracy of the common packaged FBG temperature sensor is easily affected by external loads. To solve this problem, new prototype package and sensitivity-increasing package techniques for FBG temperature sensors eliminating loads influence are developed, respectively. The linearity of the packaged FBG temperature sensors is better than that of the common one with the correlation coefficient above 0.999. The sensitivity coefficients of the prototype-packaged FBG temperature sensor and sensitivity-increasing packaged FBG temperature sensor are 1 and 2.86 times to that of the bare FBG, respectively. Moreover, the wavelength of the packaged FBG temperature sensor does not change under loads of 80N when the environment temperature keeps the same. It can be seen that the developed package techniques are appropriate for FBG temperature sensors with loads effects. The developed sensors and their sensing properties are respectively shown in Figures 8 and 9, and some test result considering the loads effects is also given in Figure 10.

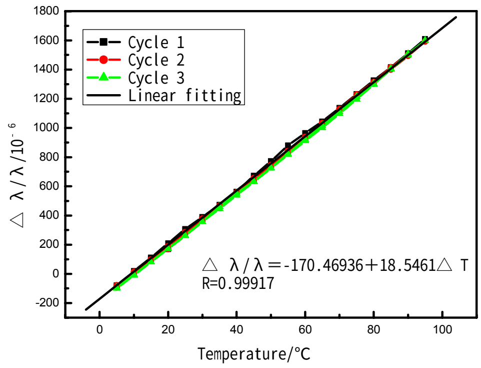
(a) Photo of the sensor



(b) Sensing properties

Figure 8. Prototype-packaged FBG temperature sensors eliminating external loads influence

(a) Photo of the sensor



(b) Sensing properties

Figure 9. Sensitivity-increasing packaged FBG temperature sensor eliminating external loads influence

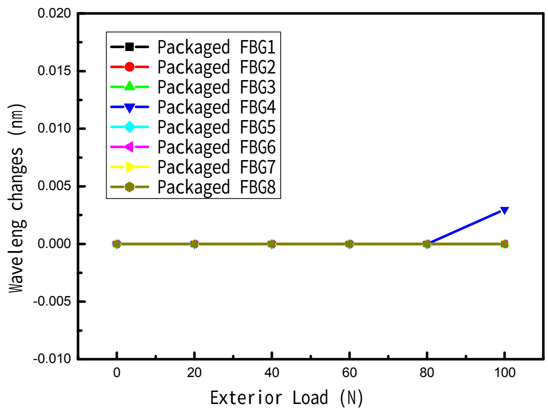


Figure 10. Test results of the effects of external loads on packaged FBG temperature sensor

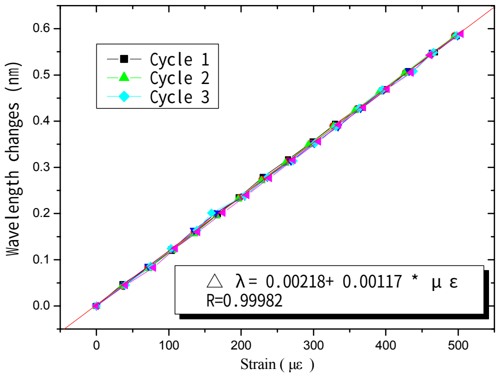
2.1.3 *Indirect FBG sensors*

HIT also develops various indirect FBG sensors, such as FBG steel-rebar meter, FBG crack meter, FBG displacement transducer, ice pressure load cell and cable load cell.

(1) *High durable packaged FBG steel-rebar meter*

The FBG steel-rebar meter is developed based on the technique of strain isolation. The photo of the sensor and the corresponding sensing properties are shown in Figure 11.

(a) Photo of the sensor family



(b) Sensing properties

Figure 11. High durable packaged FBG steel-rebar meter

(2) *FBG crack meter (large strain sensor)*

Generally, the bare FBG can only measure 3000-5000με such that it can not be directly used to detect crack and large strain of the structure. Based on the technique of sensitivity-decreasing of FBG, HIT develops the large FBG strain sensor to measure the large strain up to 100,000με and crack up to 20mm with the calibration length of 20cm. The accuracy of this sensor can reach 0.002mm, as shown in Figure 12.

Figure 12. FBG crack meter (large strain sensor)

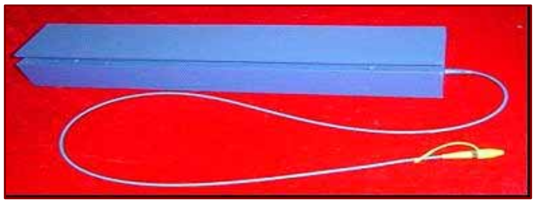
(3) *FBG displacement transducer*

The FBG displacement transducer, as shown in Figure13, developed by HIT can sense 0.01mm deformation with the calibration length of 10-20 cm.

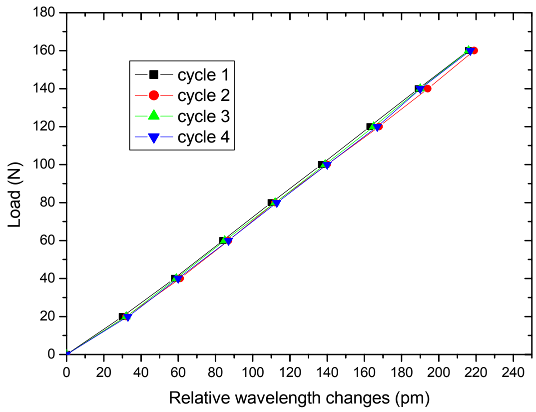
Figure 13. FBG displacement transducer

(4) *Novel ice pressure load cell based on dual FBGs*

Ice pressure is one of the critical loads applied on the offshore platforms and bridges in the high-latitude area. To evaluate the safety of those structures, it is important to obtain the long-term information of ice pressure on structure by SHM system. Traditional ice pressure load cell based on electrical strain gauge cannot meet the long-term monitoring requirement due to bad durability. Therefore, it is an urgent issue to develop the more reliable sensors for measuring ice pressure. A novel ice pressure load cell by utilizing dual FBGs has been developed at HIT, as shown in Figure 14.



(a) Photo of the sensor



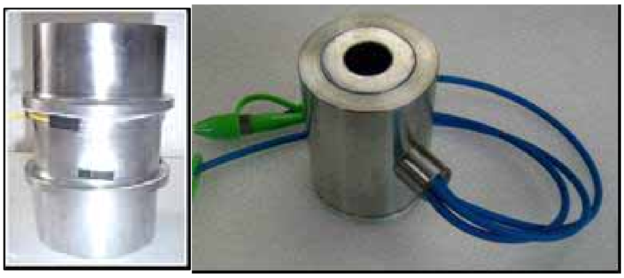
(b) Sensing properties

Figure 14. Novel ice pressure load cell based on dual FBGs

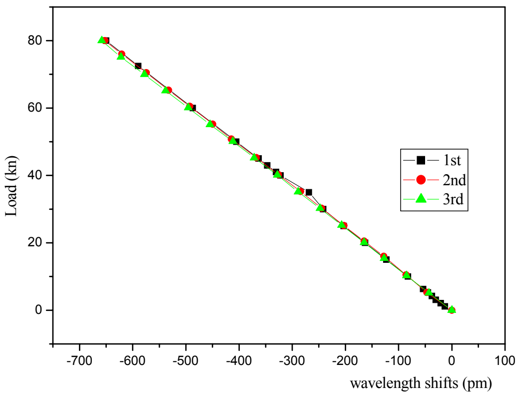
The novel FBG-based ice pressure load cell is independent from load position and temperature variation, and has good linearity and repeatability. Moreover, the resolution and accuracy can be adjusted according to the practical engineering requirements.

(5) *FBG-based cable load cell*

Stay cable is one of the most critical load-carrying components of cable-stayed bridge. Unfortunately, cables are susceptible to the environment corrosion, fatigue, materials aging, stress redistribution etc.. Whatever damage is, the stress status of cables is directly associated with the bridge safety. A FBG-based cable load cell has been developed at HIT, which is made up of a bushing elastic supporting body, four FBGs uniformly-spaced attached outside the bushing supporting body, and a temperature compensation FBG for other four FBGs. The pressure load cell has excellent linearity to applied force and FBG wavelength shifts.



(a) Photo of the sensor



(b) Sensing properties

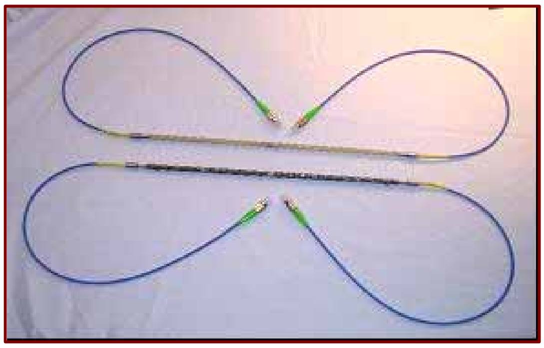
Figure 15. FBG-based cable load cell

2.1.4 *FBG-based smart sensing products*

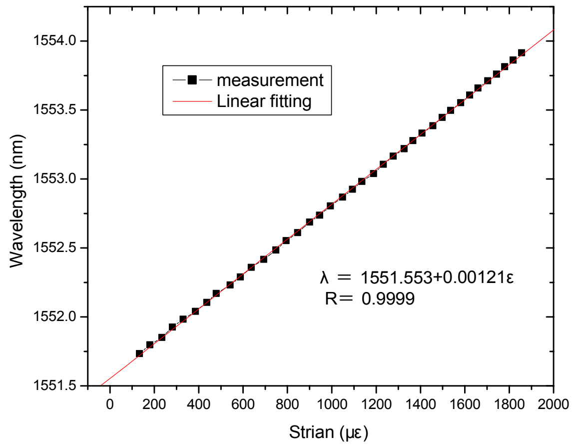
Combined FBG with other components or special materials, novel smart sensing products with better sensing properties can be developed. Aiming at the possible practical application, HIT developed several smart productions based on FBG, such as FRP-OFBG rebar, plate, tube and sheet, smart cables and smart weighbridge based on FBG.

(1) *FRP-OFBG rebar/plate/ tube/ sheet*

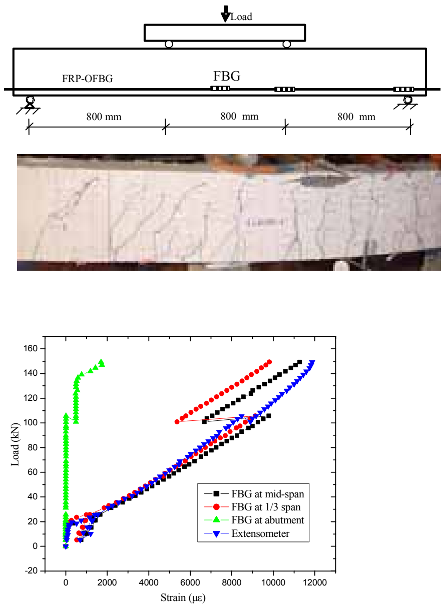
The test results have demonstrated that FRP owns the inherent advantages of corrosion resistance, high strength, nonmagnetic, fatigue resistance. Combined the FRP with OFBG, novel smart FRP-OFBG composite rebar/plate/ tube/sheet have been developed. The FRP-OFBG products conveniently used in reinforced concrete structures play both roles of sensors as well as reinforcing components at the same time. The FRP-OFBG rebar can detect slip between RC and itself.



(a) Photo of the sensor



(b) Sensing properties



(c) Test of RC beams embedded with FRP-OFBG rebars

Figure 16. FRP-OFBG reinforced bars

(2) *Smart FBG cables*

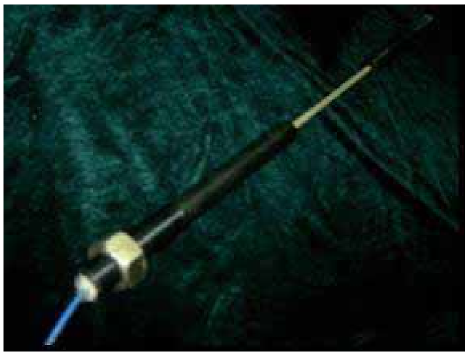
Cable is the one of the key components of cable-stayed bridges, suspension bridges, arch bridges and so on. However, the cables are susceptible to the environment corrosion, fatigue, materials aging, stress redistribution etc.

Three types of smart FBG cables have been developed at HIT, which are FRP cables, common steel-wire cable and extruded-anchor cable, respectively. In order to conveniently embed FBG sensors in the cable, a novel simple smart cable is developed using FRP-OFBG bars instead of a few of steel reinforced bars. The research results show that the FRP-OFBG bar not only acts as one component carrying load but also protects the sensors within it. The deformability of the FRP-OFBG bars in the smart cables can reach the terminal and show good accuracy.

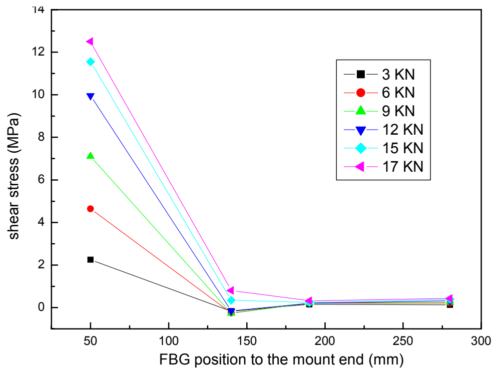
Figure 17. FBG-based smart cables

(3) *FBG-based smart FRP anchor*

FRP material has become one of popular materials to substitute the steel in civil engineering. However, from practical application view, the anchor for FRP cable is the most important issue that should be the first consideration to be solved. The real condition of the strain distribution between the FRP cables and anchor is still not yet comprehensively understood due to the shortcoming of the measurement technique. HIT develops FBG smart anchor, as shown in Figure 18, which can supply some important information for FRP anchor design and also becomes an efficient monitoring technique for FRP anchor.



(a) Photo of the Sensor

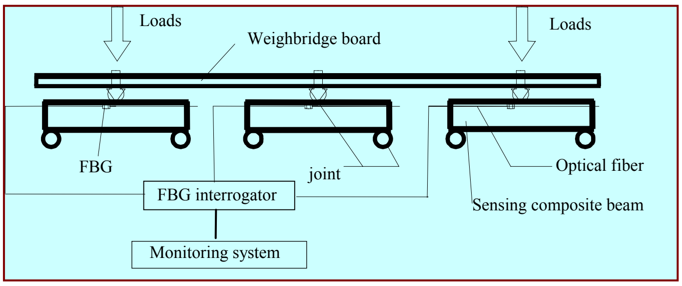


(b) Sensing properties

Figure 18. FBG-based smart FRP anchor

(4) *High durable traffic weighbridge based on FBG sensors*

Durability is one of barriers of traditional traffic weighbridge based on electrical gauges. A new kind of high durable traffic weighbridge based on FBG sensors has been studied and developed, which consists of several sensing beams and a face-board. FBG sensors are embedded in the beams. The total weigh of a vehicle is evaluated by summation of all loads on the several sensing beams, which can be derived from the relationship between the strain and the load. The strain is measured by the FBG sensors in the sensing beams. The results from the tests and calibration analysis show that this kind of weighbridge features high durability, simplicity, convenience, low cost with possible to replace the traditional traffic weighbridge for long-term monitoring of traffic loads.



(a) Configuration and mechanism of the weighbridge system

(b) Photo of the weighbridge system

Figure 19. High durable traffic weighbridge based on FBG sensors

2.2 *PVDF and PZT sensors*

The information of the germinating and developing of structural crack is the direct and most useful data for structural safety evaluation and damage location. As a sensing polymer material, PVDF shows good properties of toughness, compatibility, area sensing, adaptive to complex surface, high sensitivity coefficient and fast response (>10^5Hz), etc. Recently, PVDF has been using as strain sensors in the SHM systems for civil infrastructures.

Liu and Wang (2002) has used PVDF as vibration sensor to monitor the cable loads, and the test results show that PVDF is a good material for manufacturing sensors. Ju et al. (2004a, 2004b) has made full use of the sensing advantages of area sensing and fast response to study its strain sensing properties and crack monitoring abilities in civil infrastructures. Figures 20 and 21 show the experimental results of PVDF strain sensing properties, whereas Figure 21 gives the crack monitoring results by PVDF. From the monitoring results, one can find that the strain sensing coefficient can reach 1mv/με, and PVDF can be conveniently used as crack sensors. However, it should also be noted that the performance of PVDF is still not good enough to give accurate quantitive information of the crack at present.

PZT is one of the most important piezoelectric materials. The basic principles for PZT to be used in SHM for civil engineering are based on active sensing, impedance and wave propagation methods. PZT can be also directly used to sense dynamic strain. Using PZT patches, Shi (2002) et al monitored the dynamic strain of Hongcaofang Bridge and set up a remote monitoring system based on the public switch telephone network. According to time domain approach, Li (2003) bonded multiple PZT sensors and actuators on structure to investigate the location of damage and validate the accuracy of this method. Sun (2004) bonded two PZT patches on the surface of the concrete beam to detected the dynamic mechanical constants of concrete, and found that the dynamic modulus of elasticity and Poisson ratio can be calculated after obtaining the velocity of P waves and Rayleigh waves.

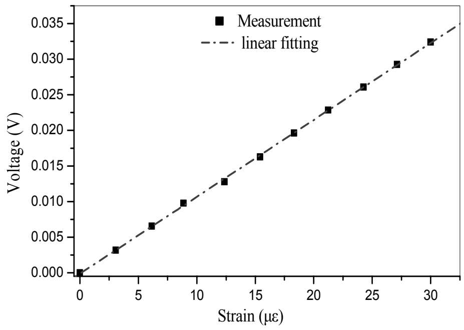


Figure 20. Strain sensing properties of PVDF

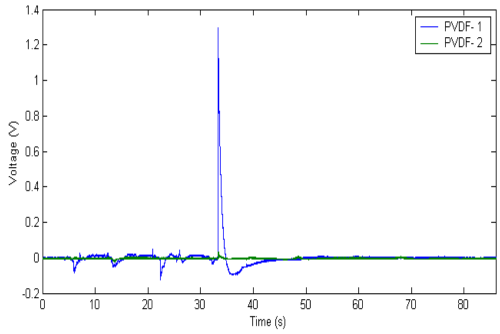
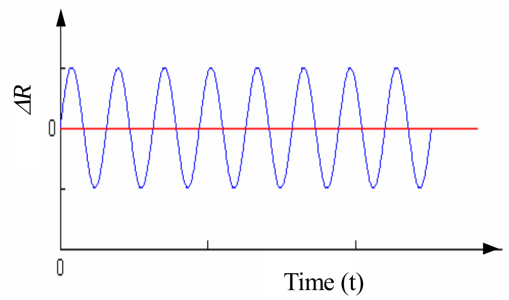


Figure 21. Crack developing monitored by PVDF

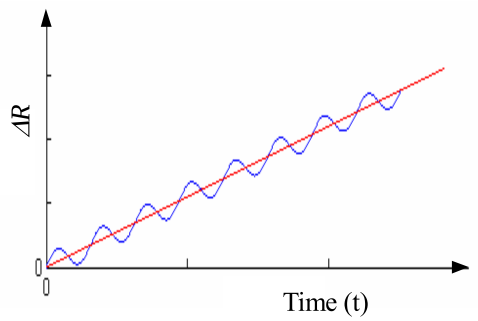
2.3 *Fatigue life gauge*

Structural fatigue life prediction, especially for the structures in service, is still a difficult problem around the whole world. Generally speaking, there is no choice except relying on the strain-time process to give statistical prediction of structural fatigue life. Although the theory of structural damage accumulation is fruitful, they are still halting at the level of research, and can not be conveniently applied in structures in-service due to lacking of reliable monitoring data. Researchers engage to develop a new kind of smart sensor which can memorize the fatigue accumulation damage just as the annual rings can tell us a tree's growth course. Smart fatigue life gauge is such a kind of sensor (Hu 2000, Zhou et al 2002, 2004).

Fatigue life gauge is a kind of accumulation senor, whose electric resistance can be accumulated according to the strain levels and cycles of the structures, and the resistance of the sensors are also withhold after the cycle loads is released. The idea of accumulation sensor for fatigue life was brought forward in 1960s. Figure 22 shows the difference between common strain gauge and smart fatigue life gauge. The resistance of common strain gauge changes with the strain courses, but it returns to its original value as soon as the external load is removed. Whereas, not only the resistance of the smart fatigue life gauge can change along with the strain cycles but also its average resistance increases with the strain amplitude and cycles, and will be kept after the loads released, as shown in Figure 22b.



(a) Resistance variaiton of common strain gauge



(b) Resistance variaiton of smart fatigue life gauge

Figure 22. Difference between common strain gauge and smart fatigue life gauge

The accumulative resistance of the fatigue life gauge is the function of strain amplitude and fatigue cycles, which can be expressed as

$$\Delta R / R \times 100\% = K(\varepsilon_a - \varepsilon_0) N^h \qquad (1)$$

where R, K, ε_a, ε_0, N and h is resistance, coefficient, strain amplitude, threshold, cycles and index respectively. The remaining life can be gotten by

$$n_{remaining} = N \times [1 - (\frac{\Delta R}{\Delta R_c})^{\frac{1}{h}}] \qquad (2)$$

where ΔR_c is the ultimate resistance for the sensor and ΔR is the measured value. Under variable amplitude loads, the equation can be rewritten as

$$n_{remaining} = \sum N_i \times [1 - (\frac{\Delta R_i}{\Delta R_{ci}})^{\frac{1}{h_i}}] \qquad (3)$$

Recently, the fatigue life gauges is investigated in the mainland of China. A new type of fatigue life gauge with good sensing properties of high electric accumulation (6% or so), long fatigue life (10^6 cycles under 1800με), low scatter sensing properties is developed. Based on this sensor, a new set of fatigue damage evaluation system is set up at HIT, and used in the fatigue monitoring of a steel-tube jacket offshore platform. Of course, the fatigue life gauges is still under developed, but it has brought us a bright solution to evaluate fatigue accumulated damage for infrastructures.

2.4 *SMA displacement transducers*

SMA is a kind of multi-functional materials with shape memory effect, pseudo-dynamic property and sensing property (the electric resistance is linearly increased with applied strain, as shown in Figure 23). The independency of SMA sensing property on load frequency is investigated and confirmed by Li et al (2005). An integrated actuator and displacement transducer of SMA by utilizing its shape memory effect and sensing property simultaneously, and an integrated damper and displacement transducer of SMA by utilizing its pseudo-dynamic property and sensing property simultaneously are developed by Li et al (2005). The integrated SMA damper/ displacement transducer, as an example, is shown in Figure 24, and the drift of a building model recorded in the series of shaking table tests is shown in Figure 25. For comparison, the drift recorded by LVDT is also shown in Figure 25. It is clear that the SMA damper/displacement transducer can accurately measure the drift of the building, which provides a potential to assess the safety or detect the damage of a building post-earthquake events.

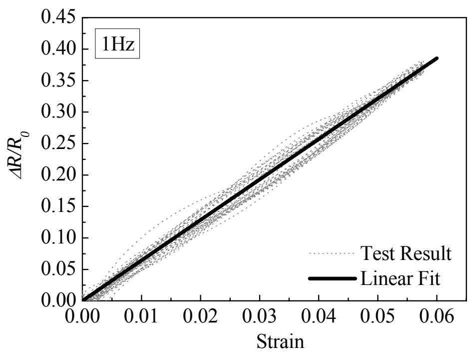


Figure 23. Sensing property of SMA materials

Figure 24. Integrated SMA damper/displacement transducer

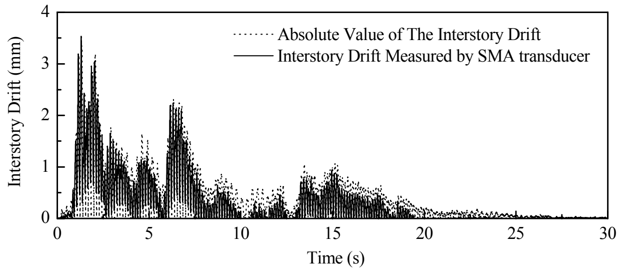
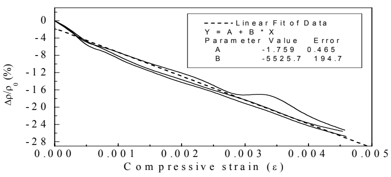


Figure 25. Interstory drift measured by the LVDT and SMA displacement transducer

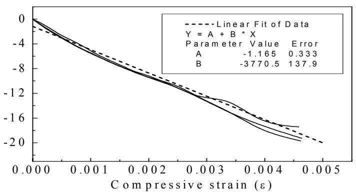
2.5 *Cement-based strain gauge (CSG)*

Usually, the durability of sensors can not match with the life of the civil infrastructures, which becomes a barrier issue of applications of SHM. The electric resistance of the cement containing nano-partciles, or short reinforced carbon fibers, or their mixture is regularly changed with applied strain, and thus the cement can sense its own strain, namely strain self-sensing cement.

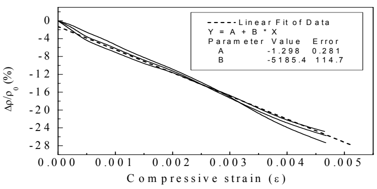
Series of tests have been carried out to investigate the property of strain self-sensing cement by Han (2005), Li et al (2004a, 2004b) and Sun et al (1998). Li et al (2004a, 2004b) have investigated the self-sensing properties of cement containing various kinds of nano-materials, and some results are shown in Figure 26. It can be observed that the electric resistance of cement containing nano-carbon black linearly decreases with applied strain up to failure. Additionally, it is found that cement with 20% carbon black achieves the best sensing property of repeatability and sensitivity.



(a) 15%



(b) 20%



(c) 25%

Figure 26. Self-sensing properties of cement containing carbon black

It is well known that cement mixed with reinforced carbon fibers has the ability of sensing its own strain and damage (Chung 2000; Han 2005). Han (2005) found that the sensing property can be improved by mixing carbon fibers and carbon black into cement at the same time. The proportion of the cement mixed with carbon fibers and carbon black was proposed. The influence of ambient temperature and moisture on the sensing property has also been investigated. Some typical results are shown in Figure 27. It can be observed that more stable sensing property of cement containing carbon fibers and carbon black is obtained than that of only containing carbon fibers.

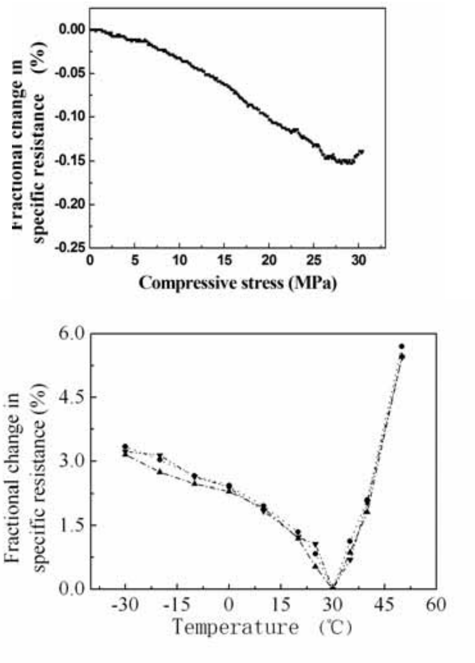


Figure 27. Self-sensing properties of cement mixed with carbon fibers and carbon black

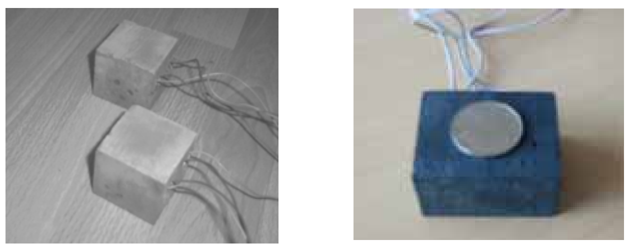


Figure 28. Photo of CSG sensor

It is impractical to use self-sensing cement as structural materials to construct infrastructure so far. Smart cement-based strain gauge (CSG) is proposed, as shown in Figure 28. Han (2005) systematically studied the properties of the CSG, such as accuracy, linearity, repeatability and so on. Han (2005) also developed a DC circuit to measure electric resistivity of the CSG with decreasing impact of polarization on electric resistivity. Han (2005) and Li et al (2005) investigated the performance of the

CSG to monitor strain of structure through a number of tests of concrete members embedded with the sensors, respectively. Some results are shown in Figure 29. It can be seen that the sensors can monitor strain of concrete columns and beams. Recently, the CSGs have been embedded into the girders of the Chongqing Guangyang Island Bridge, as shown in Figure 30. It can be seen that the strain measured by CSG agrees well with that measured by FBG-FRP.

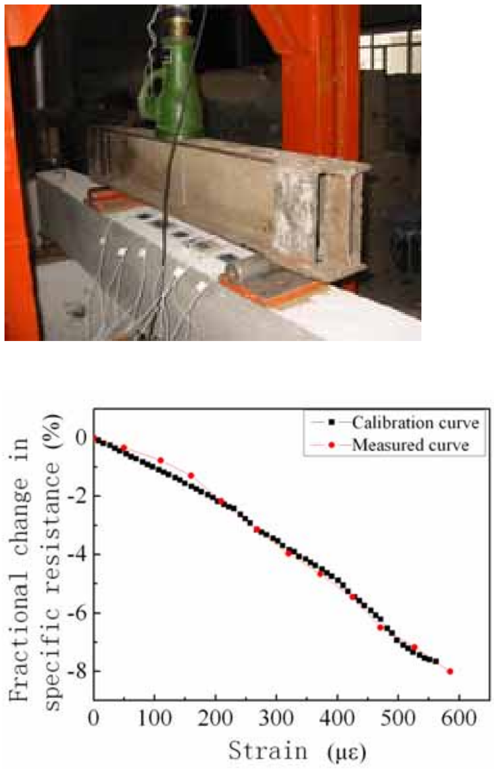


Figure 29. Strain sensing property of CSG in RC specimens

Figure 30. CSG embedded in Chongqing Guangyang Island Bridge

3 WIRELESS SENSORS AND SENSOR NETWORKS

A good SHM system requires the sensor to have the following merits of cheap, durable, easy and simple to install and maintain, wireless, no battery replacement needed for operation, smart with individual or a set of individual sensors sensing data and directly outputting the information regarding the health or damage status of the structure. To reach those aims, a task effort has been made towards to developing wireless sensors, wireless sensor networks and wireless monitoring systems in mainland China.

Yu and Ou (2005) developed a kind of wireless strain sensor unit based on MEMS technology. The photo of the wireless strain sensor unit is shown in Figure 31. It can be seen from Figure 31 that the wireless strain sensor unit consists of a traditional strain gauge and a wireless transceiver board. The wireless transceiver board consists of signal collection unit, microprocessor unit, wireless transceiver unit and energy unit, as shown in Figure 32. The wired connection technique between the traditional strain gauge and wireless transceiver board is used. The strain signal can be transmitted automatically in real time to a computer by the wireless transceiver without any wires. The calibration test of the wireless strain sensor unit was carried out through a standard steel beam and the result is shown in Figure 33. It can be seen from Figure 33 that the strain measured by wireless strain unit agrees well with that measured by wired strain gauge.

Additionally, Pei and Guo (2005) developed a wireless unit for real-time structural response measurements. The wireless sensor unit consists of data acquisition unit, CPU control unit, data memory unit, wireless transmitting-incepting control unit and computer communication unit, as shown in Figure 34. This system can be used in the prudent allocation of emergency response resources after earthquakes and for damage identification of structures under long-term deterioration and excessive loads. The validity of the unit is verified through shaking table test of a 2-story model, as shown in Figure 35. Li et al (2005) and Shao et al (2005) developed a kind of wireless monitoring system by using GPRS module. Additionally, Li (2005) has systematically studied the applications of wireless accelerometers and acoustic sensors developed by UC Berkeley in the mainland of China. The vibration of a tall building has been recorded in in-situ test by Li (2005) and part of results is shown in Figure 36. Recently, Li (2005) has developed another kind of wireless accelerometers, as shown in Figure 37. The wireless accelerometers have been applied that in a bridge health monitoring system, the detailed information can be found in the section of PRACTICAL IMPLEMENTATIONS in this paper.

More and more researchers are paying their attention on the development of wireless sensors in the mainland of China.

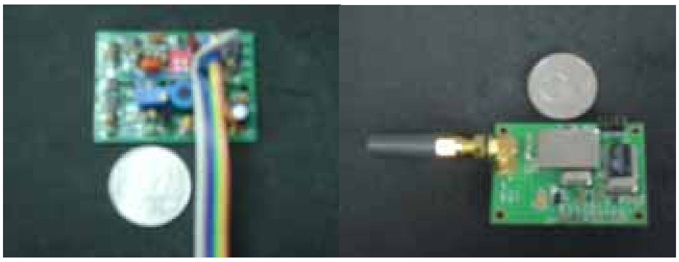


Figure 31. Photo of the wireless sensor

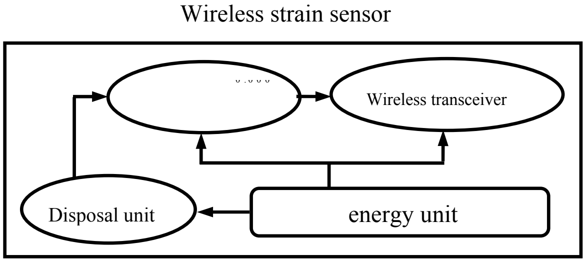


Figure 32. Main components of the wireless strain sensor

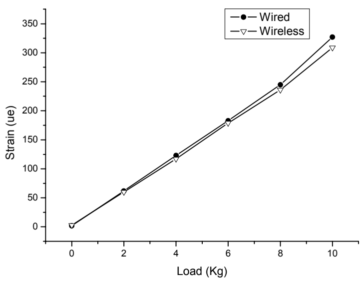


Figure 33. Calibration test results of the wireless strain sensor

Figure 34. Top view of finished prototype wireless sensing unit

Figure 35. Photo of two-story steel frame structure model

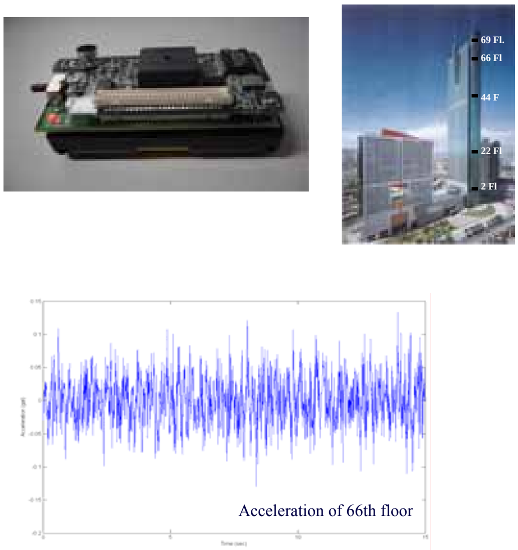


Figure 36. Vibration of the tall building measured by wireless accelerometers

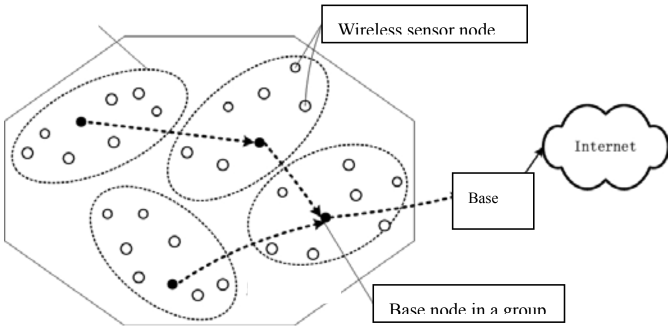


Figure 37 Wireless accelerometers developed by Li (2005)

4 DATA ACQUSITION AND PROCESSING SYSTEMS

Data acquisition software package of SHM system applied in civil infrastructures has been developed by Chinese researchers (He and Ou 2005; Zhou et al 2006). In the development of the data acquisition system, the Labview software package is widely used. As for layout of data acquisition modules in one SHM system, it is designed in accordance with the configuration of the monitored structure. For example, for moderate span bridge, one data collection station is enough, which is integrated with the industrial computer or server directly (Zhou, et al, 2006). However, for long- and super long-span bridge, distributed data collection stations are needed and signal in each collection station is transmitted to center computer or server. For the latter case, data acquired synchronously from different data collection station is the most challenge issue. He and Ou (2005) have developed distributed data acquisition system based on industrial CAN-bus technology to meet this requirement.

Great amount of data will be obtained from the sensors installed on the structure to monitor the health status of the structure, it is absolutely necessary to process the data with much more efficiency and accuracy. Pei and Guo (2005) integrated a new data acquisition system (DAQ-PI-32) used for vibration measurement in SHM, and an efficient and convenient software package (VIBAN 2.40) for data processing and analysis is also developed. The program of VIBAN 2.40 includes the following functions: FFT spectrum analysis, adding window functions analysis, filtering analysis, power spectrum analysis, transfer function analysis, cross interfere function analysis, correlation function analysis as well as H/V(Microtremor spectral ratio of soil site). With 16 or 32 single-ended channels and 16 Bit-resolution, DAQ-PI-32 can achieve dynamic range of 83 dB.

The standardized commercial data acquisition and processing system for SHM will be further developed in the future.

5 DAMAGE DETECTION AND MODEL UPDATING

How to using the collected data in the SHM systems to evaluate the safety of the structures is still a challenge issue for the development and application of SHM system until now.

Defining a sensitive and efficient damage indicator is the first issue that should be solved for structural damage detection and localization. Generally, modal parameters as natural frequencies, mode shapes and its derivatives are the common used damage indicators. Although it has demonstrated that those damage indicators are various degrees of success in numerical and experimental investigations, there are still several confounding factors that hinder their practical application. Recently, signal-energy-based damage index (Chen & Li 2005) used for damage detection is investigated by decomposing the signal energy of structural response using empirical mode decomposition (EMD) method.

Wavelet transform, as a signal processing method that can show the local character of the signal in both time and frequency domain, has been widely investigated recently for damage identification recently (Li & Sun 2003). Furthermore, eigensystem realization algorithm (ERA), Homotopy continuation algorithm, EMD, stochastic analysis method and some other analysis approaches are also adopted and investigated for identifying the structural damage.

Data infusion is another method to increase the reliability of damage detection and location. Guo and Zhang (2005) used the Dempster-Shafter fusion theory and genetic algorithm to identify multiple damaged locations of a 2-D steel truss structures. The results indicate that this method can more effectively identify multiple damage locations to compare with other methods based on modal analysis. Jiang et al (2005) developed a data fusion damage detection technique based on wavelet-probabilistic neural network by utilizing different time-space multi-sensors information resources. Li and Bao (2005) proposed a damage detection method by using data fusion technique, in which various damage detection methods are regarded as variable to be fusion. The results indicate that the data fusion technique can increase the reliability of damage detection and localization.

Combined with the finite element analysis technology, model updating method is also studied and applied to analyze the safety of the Nanjing Yangtze River Bridge (He et al 2005), Runyang Suspension Bridge (Wang et al 2005) and Binzhou Yellow River Highway Bridge (Li et al 2005, Zhou, 2005)

6 PRACTICAL IMPLENMENTATIONS

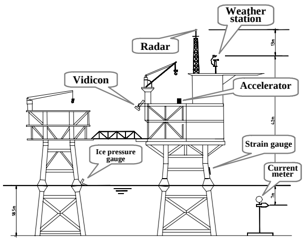
A great number of civil infrastructures are planned and constructed each year in the mainland of China, which provide better chances to develop SHM. Many SHM systems have been implemented in actual civil infrastructure. Based on the experience of full implementation of SHM systems, Li and Ou (2005a, 2005b) have systematically proposed the design method and installation procedure of SHM systems for bridges, and this method will be adopted in the compiling national guideline of SHM system for bridge.

Next, typical SHM systems implemented in actual civil infrastructures in mainland China are briefly introduced.

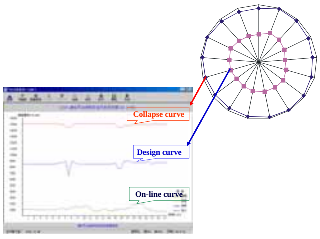
6.1 *Offshore platforms*

Bohai Ocean Oil Field is one of the important ocean oil fields in China, in which the ice pressure is the main environmental load to offshore platforms in winter. In 1960’s and 1970’s, there have respectively two platforms be destroyed by heavy ice force action. Since 1980’s, the ice conditions, ice pressure acted on the platforms in Bohai ocean have being monitored under the support of China Ocean Oil Company. Based on these facilities and systems, Ou et al (2001) developed an on-line health monitoring system, running from 1999, for one of typical platform structures, JZ20-2MUQ steel jacket platform, as shown in Figure 38a. The platform with the total height of 55.4m was built in 1991 and located in the heavy ice region of Bohai ocean with design water depth of 15.5m. The system includes the following three subsystems: environmental condition and structural response monitoring subsystem in which the sensors are shown in Figure 38b, safety evaluation subsystem in which the total base shear force under environmental loads compares in real time with the ultimate base shear force of structure in the same direction as shown as Figure 38c, and database subsystem which report form is shown in Figure 38d.

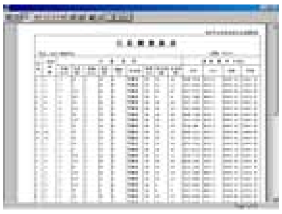
(a) Bohai JZ20-2MUQ platform to be monitored



(b) Sensors in the system



(c) Interface of safety evaluation subsystem



(d) Report form of database

Figure 38. Health monitoring system of Bohai JZ20-2MUQ Platform

Another health monitoring system have being developed by Ou and his research group for CB32A steel jacket platform in Bohai ocean under the project support by the National Hi-tech Research and Development Program of China. The Platform with jacket height of 24.7m was built in 2003 and located in water with depth of 18.2m. The SHM system includes 259 OFBG sensors, 178 PVDF sensors, 56 fatigue life meters, 16 acceleration sensors, a set of environmental condition monitoring system. The signal transmission wire of this system is reach about 27, 000m. Figure 39a shows the steel jacket and the scene that the sensors are installed on the jacket and Figure 39b shows the fabricated jacket and the jacket built in the ocean.

A SHM system is being installed on the Steel Jacket of NB35-2WHPB platform to monitor the stress and sedimentation under construction and in service. The Steel Jacket of NB35-2 WHPB platform is also located in Bohai Ocean Bay.

Figure39. Health monitoring system for CB32A platform

6.2 *Long-span bridges*

Many long span bridges have been constructed or are being planed to be constructed in China, such as the Hangzhou Bay Bridge with the total length of 36km, the Eastern Ocean Bridge with the total length of 32km, the Qingdao Bay Bridge with the total length of 26km, the Sutong Bridge with the main span of 1080m that ranks No. 1 over the world, and so on.

Public sector concerns the safety status of the bridges, and thus promotes the development of SHM. Most of long span bridges are implemented with SHM systems in mainland China as well as Hong Kong. The information of SHM systems for the bridges in the mainland of China and Hong Kong in details is listed in Table 1.

Table 1. List of health monitoring systems for bridge in the mainland of China and Hong Kong

No.	Name/Structural Type/Time	Span (m)	SHM system
1*	TingKau Bridge /Cable stayed/1998	127+475+448+127	7 anemometers, 83 temperature sensors, 45 accelerometers, 88 strain gauges, 2 displacement transducers, 6 weigh-in -motion systems. 5 global positioning systems. On-line monitoring system.
2*	Tsing Ma Bridge/ Suspension /1997	Main span: 1377	Anemometers, temperature sensors, strain gauges, accelerometers, displacement transducers, GPS, weigh-in-motion systems, level sensors, video cameras. On-line monitoring system.
3*	Kap Shui Mun Bridge/Cable stayed/1997	Main span: 430	Anemometers, temperature sensors, strain gauges, accelerometers, displacement transducers, GPS, weigh-in-motion systems, level sensors, video cameras. On-line monitoring system.
4*	Shenzhen Western Corridor/ Cable stayed/	Main span: 210	Anemometers, temperature sensors, strain gauges, accelerometers, displacement transducers, GPS, weigh-in-motion systems,

	Under construction		corrosion sensors, video cameras, barometers, hygrometers, pluviometers. On-line monitoring system.
5*	Stonecutters Bridge/ Under construction	Main span: 1018	Anemometers, temperature sensors, strain gauges, accelerometers, displacement transducers, GPS, weigh-in-motion systems, elasto-magnetic sensors, corrosion sensors, optic fiber sensors, tiltmeters, video cameras, barometers, hygrometers, pluviometers. On-line monitoring system.
6*	Jiangyin Bridge/ Suspension/1999	369+1385+309	Anemometers, temperature sensors, strain gauges, accelerometers, displacement transducers, GPS, optic fiber sensors. On-line monitoring system.
7*	1st Nanjing Yangtze River Bridge /Steel truss / 1968	Main span: 160	Anemometers, temperature sensors, strain gauges, accelerometers, displacement transducers, seismometers, weigh--in-motion systems. Off-line monitoring system.
8*	2nd Nanjing Yangtze River Bridge /Cable stayed /2001	Main span: 268	Anemometers, temperature sensors, strain gauges, accelerometers, displacement transducers, weigh-in-motion systems, seismometers, elasto-magnetic sensors, hygrometers. On-line monitoring system
9*	Runyang South Bridge /Suspension/ 2000	Main span: 1490	Anemometers, temperature sensors, strain gauges, accelerometers, GPS. On-line monitoring system
10*	Runyang North Bridge /Suspension /2004	Main span: 460	Anemometers, temperature sensors, strain gauges, accelerometers. On-line monitoring system
11*	Sutong Bridge /Cable stayed /Under construction	Main span: 1088	Anemometers, temperature sensors, strain gauges, accelerometers, displacement transducers, GPS, weigh-in-motion systems, corrosion sensors, elasto-magnetic sensors, optic fiber sensors, tiltmeters, hygrometers, video cameras. On-line monitoring system.
12	3rd Nanjing Yangtze River Bridge /Cable stayed/ 2005	Main span: 648	Strain gauges, displacement transducers, accelerometers. On-line monitoring system.
13*	Tongling Yangtze River Bridge /Cable stayed /1995	Main span: 432	Anemometers, temperature sensors, accelerometers, tiltmeters, strain gagues. Off-line monitoring system
14*	Wuhu Bridge /Cable stayed /2000	Main span: 312	Temperature sensors, strain gauges, accelerometers, displacement transducers, optic fiber sensors, level sensors. Off-line system
15*	Humen Bridge /Suspension /1998	Main span: 888	Strain gauges, GPS, tiltmeters, level sensor. Off-line monitoring system
16*	Zhanjiang Bay Bridge / Cable stayed /2002	Main span: 480	Anemometers, temperature sensors, strain gauges, accelerometers, displacement transducers, GPS, elasto-magnetic sensors, tiltmeters, seismometers, hygrometers. On-line monitoring system
17*	Xupu Bridge /Cable stayed /1997	Main span: 590	Temperature sensors, strain gauges, accelerometers, weigh-in-motion systems, level sensors. Off-line monitoring system
18*	Lupu Bridge / Arch /2003	Main span: 550	Temperature sensors, strain gauges, accelerometer, level sensors. Off-line monitoring system
19*	Dafosi Bridge /Cable stayed/ 2001	Main span: 450	Temperature sensors, strain gauges, accelerometers, optic fiber sensors, level sensors. On-line monitoring systems.
20	Guangyang Island Bridge /Continuous rigid /Under construction	115+200+115	FBG temperature sensors, FBG strain sensors, smart concrete strain sensors. Off-line monitoring systems.
21	Binzhou Yellow River Bridge /Cable stayed/ 2004	Main span: 300	2 anemometers, 20 temperature sensors, 39 accelerometers, 3 GPS, 96 optic fiber sensors. On-line monitoring system.
22	Dongying Yellow River Bridge /Continuous rigid/ 2005	115+210+220+210 +115	1300 FBG temperature and strain sensors. Off-line monitoring system (is updating to on-line monitoring system)
23	Maocao Street Bridge /Arch /Under construction	Main span: 368	1 Anemometers, 26 accelerometers, 20 FBG temperature sensors, 80 FBG strain sensors. Off-line monitoring system
24	Ebianxian Dadu River Bridge /Arch /1992	150	Smart FBG tied and suspender, Acoustic emission sensors. Off-line monitoring systems.
25	4th Qianjiang River Bridge /Arch/ 2004	Main span: 580	Elasto-magnetic sensors, anemometers, temperature sensors, strain gauges, accelerometers. Off-line monitoring system
26	Songhua River Bridge /Cable stayed /2004	Main span: 365	1 anemometer, 20 accelerometers, 2 GPS, 8 FBG temperature sensors, 48 FBG strain sensors. Off-line monitoring systems.
27	Hulan River Bridge /Continuous rigid /2000	Main span: 40	3 FBG temperature sensors, 12 FBG strain sensors. Off-line monitoring system.
28	Niutou Mountain Bridge /Continuous rigid /2002	Main span: 42	10 FBG strain sensors. Off-line monitoring system.

Table 2. Modal frequencies of Binzhou Yellow Highway Bridge (Hz)

Tower (Transverse direction)	Tower (Longitudinal direction)	Deck (Transverse and torsion)	Deck (Vertical)
0.274-0.281	0.259-0.278	/	0.256-0.269
/	0.492-0.501	/	0.492-0.518
/	0.595-0.596	/	0.588-0.634
/	/	/	0.698-0.712
/	0.836-0.864	0.830-0.864	0.843-0.864
/	/	0.961-1.018	0.961-1.017

Table 3. Comparison of the calculated and the measured strain

Location of section		Level 1	Maximum loads	Calculation	Measurement	Error
CB24	1	31.5565	27.4351	-4.1214	-5.0000	-17.57%
	2	15.8930	12.0853	-3.8077	-3.3333	14.23%
	3	31.5565	27.4351	-4.1214	-3.3333	23.64%
	4	19.67870	15.543784	-4.13492	-4.1667	-0.76%
	5	-18.7920	-25.87733	-7.0853	-6.6667	6.28%
HLD	2	15.8930	12.0853	-3.8077	-5.0000	-23.85%
	3	32.2026	26.6789	-5.5237	-6.6667	-17.14%
	5	-18.7920	-25.8773	-7.0853	-5.8333	21.46%
	6	36.6910	30.4624	-6.2285	-9.1666	-32.05%

The systems listed in Table 1 can be divided into three levels with regard to running mode: Level-1 refers to the SHM system which automatically run in real time and can be internet-based operated, such as Hongkong Tsingma Bridge and Shandong Binzhou Yellow River Highway Bridge; Level-2 refers to the SHM system which automatically collects data for a duration at periodical interval, after that, damage detection, model updating and safety assessment are carried out based on the measurement data offline, such as Harbin Songhua Cable-stayed Bridge; Level-3 refers to SHM system which is indeed an extension of the system for static and dynamic test before the bridge is open to traffic and an assistance of inspection for general maintenance of bridge, such as Humen Bridge.

It can be seen from Table 1 that the following sensors are frequently selected in the implemented SHM systems: anemoscope, accelerometer, strain gauge, GPS, temperature sensor, weigh-in-motion, displacement transducer, level sensor, tiltmeter, elasto-magnetic sensors, corrosion sensors, seismometer, barometers, hygrometers, pluviometers, video camera, and so on. Anemoscope is used in most of SHM systems to record wind loads including speed, direction and angle of wind. Weighbridge -in-motion is used to record the vehicle loads including weight, speed and flow. Temperature can be usually measured by thermal couple. FBG sensor provides an additional candidate for temperature measurement due to its high performance mentioned above in this paper. The humidity is recorded by hygrometer. The precipitation rain fall is recorded by pluviometer. Acceleration is the most readily acquired by various accelerometers. Consider that wireless sensors are very convenient to install and save labour resources, wireless accelerometers have been attached on Harbin Songhua River Cable-stayed Bridge (Li, 2005). The displacement can be measured by GPS or level sensor or displacement transducer. It is well-known that GPS is the first candidate from the point of view of high performance, while with fault of high cost and low accuracy in dynamic measurement at present. The inclination is frequently observed and measured by tiltmeter, level sensor or GPS. Consider that strain is the most critical related with safety of bridge, strain gauge is included in all SHM systems listed in Table 1. The durability of conventional strain gauge is very short, which becomes primary barrier of application of SHM system in bridge engineering. Optical fiber strain sensor provides more candidates for strain measurement with its high performance and long durability. More and more SHM systems have adopted optical fiber strain sensors, such as Shandong Binzhou Yellow River Highway Bridge, Harbin Songhua Stayed-cable Bridge, etc. Recently, some SHM systems have been updated by using optical fiber strain sensors instead of conventional strain gauges, such as Jiangyin Bridge and so on. The corrosion and breakage of cable are widely observed in many bridges and the deterioration rate of performance is very fast, which shorten the life of bridge in service and increase the maintenance cost. Vibration-based tension prediction is broadly used to monitor tension in cable, which acceleration of cable is recorded by accelerometer. Ou et al (2005) proposed to embed FBG strain sensor into cable to monitor strain of reinforced bars in cable, which has been adopted in Shandong Binzhou Yellow River Highway Bridge (Shandong, China), Hunan Maocao

Street Bridge (Hunan, China) and Sichuan Ebian Bridge (Sichuan, China). Wang (2003) developed elasto-magnet sensors and attached this kind of sensor round cable to monitor tension in cable, which has been implemented in Zhanjiang Bay Bridge, located in Zhanjian, Guangzhou, China. Additionally, breakage of reinforced bars in cable can also be monitored in real time by acoustic emission technique. This technique has been used to detect breakage of cables of Ebian Bridge, Sichun, China, and the feasibility and validity have been verified.

Software of data acquisition for SHM system developed by researchers in the mainland of China has been employed in the implementation of SHM systems. The software can be running in both WINDOWS and UNIX systems. For moderate span bridge, only one data collection station is enough and usually integrated with industrial computer directly. While distributed data collection stations along the span of bridge to acquire data are needed for long and super long span bridge. The data collected from the distributed stations are them transmitted to server by wire, generally using optical fiber for long and super-long span bridge. The distributed data collection station scheme has been adopted in SHM systems for the Jiangyin Bridge (Jiangsu, China) and the 3rd Nanjing Yangtze River Bridge (Jiangsu, China).

It is well known that SHM system accumulates mega-data after running for long-term period. Therefore, it is necessary to systematically manage the mega-data by using database. Both independent database and database in geographical information system (GIS) have been adopted in the implemented SHM systems, for example, software of SQL Server is used in SHM system for Shandong Binzhou Yellow River Highway bridge, while the data is managed by using database of GIS in SHM system for Tsingma Bridge. Two SHM systems of cable-stayed bridges in mainland China are introduced in detail as follow.

(1) *SHM system for the Shandong Binzhou Yellow River Bridge*

The Binzhou Yellow River Highway Bridge is a cable-stayed bridge with three towers in Shandong, China, as shown in Figure 40. It has a total length of 768m consisting of two three hundred-meter main spans and two eighty four-meter side spans. The framework of this system is shown in Figure 41. Following modules are included in this system: sensor module, data acquisition and processing module, signal transmitting module, structural analysis module including damage detection, model updating and safety evaluation, and database module. The sensor module includes 96 FBG strain and temperature sensors, 2 anemoscopes, 39 accelerometers and 4 GPS. The sensor locations are shown in Figure 42. There is only one data collection station located in control center nearby the middle tower, which is integrated into an industrial computer directly. Due to no internet available on the site of the bridge, one microwave wireless transmitting system is set up for transferring data from the control center to the server, which is located in the toll station. The toll station is 10km far from the site of the bridge. The wireless transmitting system can send out the data in real time with a 2MB/s in 15km distance range. The software package for data acquisition and transmission is edited by using Labview. A program edited in MATLAB is used to detect damage based on vibration measurement. A FE model is established using ANSYS software package. And then a program edited in MATLAB and ANSYS is employed to update the FE model. The safety of the bridge is evaluated based on both component level and whole bridge. A program edited in MATLAB is used to assess the safety of the bridge based on component level. For the safety of the whole bridge, the FE model in ANSYS is available. SQL Server 2000 database is used to efficiently manage all information of SHM system for this bridge. This system can be automatically operated at web. The system has been running since the static and dynamic test for the open to traffic of this bridge (July 18, 2004). SQL Server database is employed to manage efficiently all information of SHM system.

Since the system has been running, data have been acquired. Diagnosis of health status and decision-maker based on the measured data are the goal of SHM. Zhou (2005) analyzed the data and obtained natural frequencies and response of this bridge. The natural frequencies are obtained by picking up peak values of the power spectrum of correlation function of acceleration and listed in Table 2. The measured natural frequencies shift slightly due to measurement noise and ambient variation. The stress along the cross section of deck and strain in cables are also measured by FBG sensors and shown in Figure 43. It can be seen that the additional stress caused by live loads is very small. The acceleration of deck, towers and cables subjected wind loads and combination of vehicles with wind loads are recorded and analyzed, only some of results are shown in Figure 44. It can be observed from the records that the vehicles dominant the vertical vibration of deck, the vibration level is influenced by the speed of vehicle that is attributed to resonant frequency; the wind loads dominant the horizontal vibration of deck, tower and cables; and the cable vibration is independent from that of the joint deck and tower. Zhou (2005) observed that the tower vibrates independently in some modes. And thus a concept of sub-structure of cable-stayed bridge is proposed and model updating of cable-stayed bridge can be carried out on the sub-structure level. Li et al (2005) updated FE model of the Shandong Binzhou Yellow River Highway Bridge by utilizing sub-structure character. And then the updated FE model is calibrated by using measured static deflection of the bridge subjected to vehicles. The comparison of the calculated and measured deflection is shown in Figure 45. It can be seen that the maximum quantity of error between the calculation and measurement is about 6%. Additionally, stress along cross section of members cannot be directly obtained from the FE model of whole bridge due to the occurrence of reinforced bars, a FE model of part of component by using solid finite element was established by Li et al (2005). Stress of the cross section was then calculated and comparison of calculated and measured stress is listed in Table 3.

Figure 40. Photo of the Binzhou Yellow River Highway Bridge

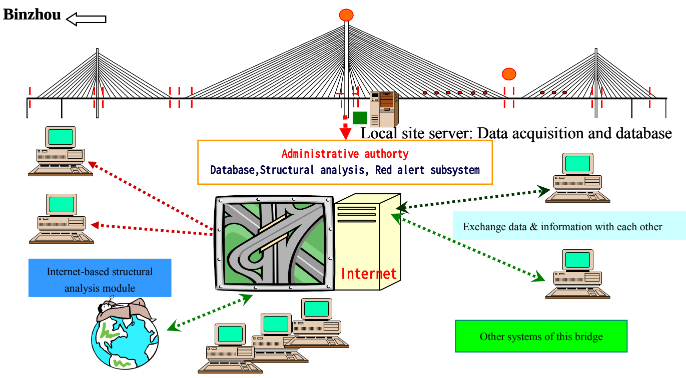
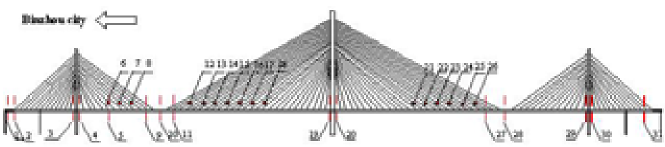
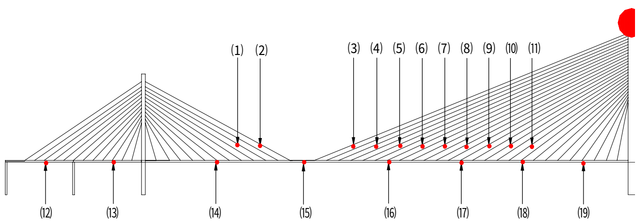


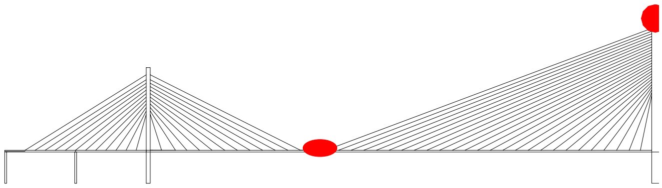
Figure 41. Framework of the SHM system



(a) FBG sensors



(b) Accelerometers



(c) Anemoscopes and GPS

Figure 42. Locations of the sensors

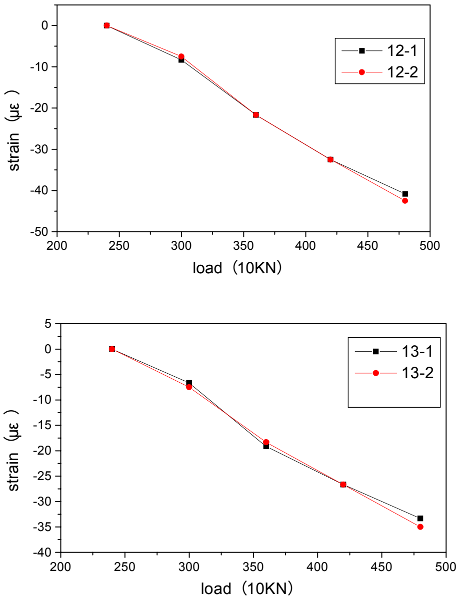
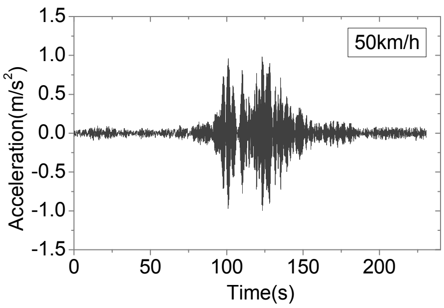
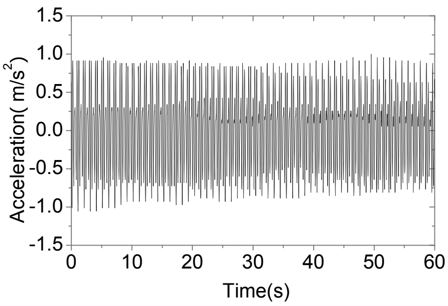


Figure 43. Strain on the top of the cross section of the girder at the foot of middle tower

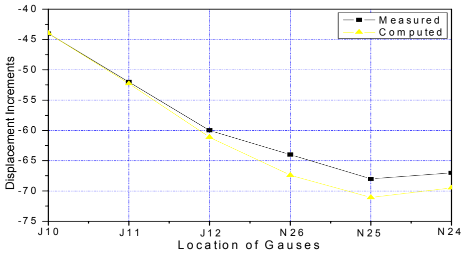


(a) Time history of acceleration of the deck along vertical direction

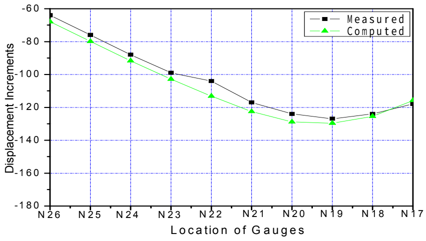


(b) Acceleration time history of a cable

Figure 44. Vibration of the Binzhou Yellow River Highway Bridge



(a) Under14th loads case



(b) Under 16th loads case

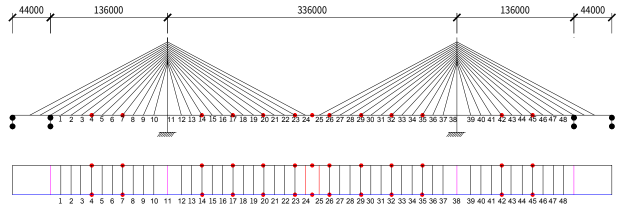
Figure 45. Comparison of the calculated and measured deflection

(2) *SHM system for the Harbin Songhua River Cable-stayed Bridge*

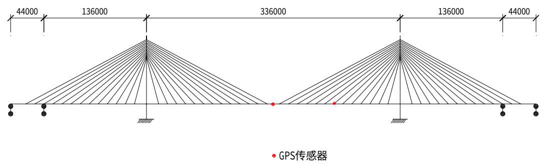
The Harbin Songhua River Cable-stayed Bridge is a bridge with a main span of 365m, as shown in Figure 46. A SHM system is implemented in this bridge before it opened to traffic on August 26, 2004. The system continuously collects data for 7 days twice time each year. After collecting data, structural analysis and health diagnosis based on measured data are conducted offline in lab, not in-situ. The SHM system consists of sensor module, data acquisition module, database and module of structural analysis and decision-making based on measured data. The sensor module includes FBG strain and temperature sensors, wireless accelerometer networks and 3 GPS. The locations of the sensors are shown in Figure 47. The wireless accelerometer networks used herein are that introduced in Figure 37. The various data acquisition systems match with the corresponding sensors, respectively. The database is the same as that of the Shandong Binzhou Yellow River Highway Bridge. In May, 2005, the in-situ test was carried out and some typical results are shown in Figure 48. The power spectrum is then further calculated based on measurement and shown in Figure 49. The natural frequencies of the bridge are listed in Table 5. The tension forces of some cables are also identified and listed in Table 5.

It can be seen that most natural frequencies are lower than 2Hz and vertical vibration dominant the response of the bridge. The strain amplitude of the bridge subjected to vehicles is on the order of 150 microstrain. The strain amplitude of this bridge is larger than that of Binzhou Yellow River Highway Bridge due to the effects of the steel girder bridge.

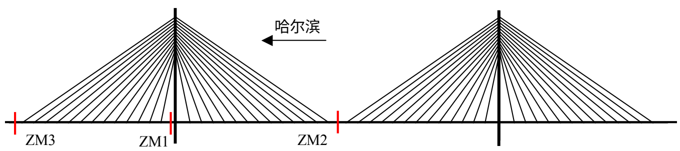
Figure 46. Photo of the Harbin Songhua River Cable-stayed Bridge



(a) Accelerometers



(b) GPS



(c) FBG strain sensors

Figure 47. Locations of sensors on the Harbin Songhua River Cable-stayed Bridge

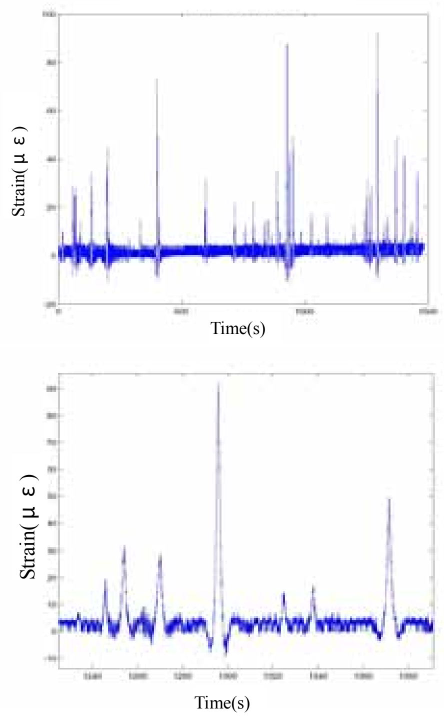


Figure 48. Strain measured by FBG sensors

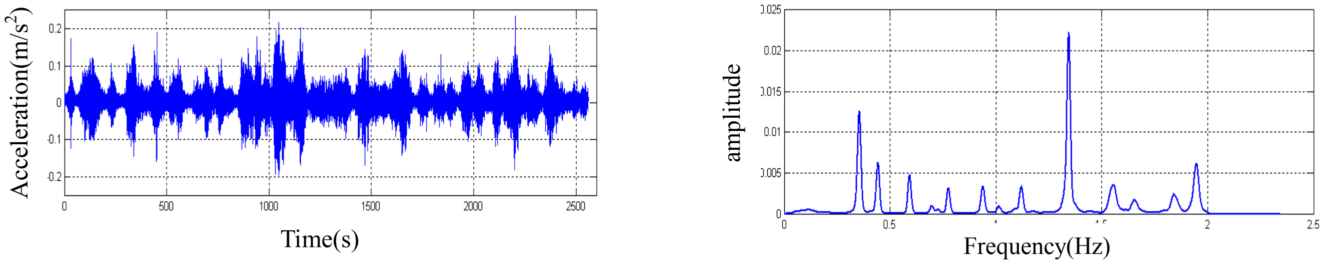


Figure 49. Time history and frequency response of acceleration of deck

Table 5. Modal frequencies of the Harbin Songhua River Cable-stayed Bridge (Hz)

Modal No.	1st	2nd	3rd	4th	5th	6th
Lognitudinal Mode	0.035					
Vertical mode	0.356	0.444	0.820	1.122	1.171	1.342
Torsion mode	0.593	0.777	1.015			
Transverse mode	0.697					

Table 6. Tension forces of some cables measured and designed (kN)

No. of cable	Measured	No. of cable	Measured	No. of cable	Measured	No. of cable	Measured	Designed
SES01	4512	SEC01	3858.9	NEC01	4343.8	NES01	4448.3	3939.6
SES02	4650.1	SEC02	3834.4	NEC02	4132.8	NES02	4172.9	3939.6
SES03	4042.3	SEC03	3681.4	NEC03	4144.8	NES03	4095.1	3939.6
SES04	4663	SEC04	4314.2	NEC04	4799.7	NES04	4540.5	4519.6
SES05	4609.2	SEC05	4344.7	NEC05	4836	NES05	4523.2	4519.6
SES06	5747.6	SEC06	5563.9	NEC06	5859.8	NES06	5673.2	5824.4
SES07	4458.1	SEC07	5387.7	NEC07	5825.1	NES07	5711.9	5824.4
SES08	5507.9	SEC08	5991.3	NEC08	6228.9	NES08	5391.6	5824.4
SES09	5878.6	SEC09	5956.0	NEC09	6010.8	NES09	5444.9	5824.4
SES10	5891.7	SEC10	6110.1	NEC10	6173.3	NES10	5478.8	6404.4
SES11	7576.4	SEC11	7367.3	NEC11	7998.6	NES11	8079.2	7274.8
SES12	7860.9	SEC12	7433.8	NEC12	7111.6	NES12	8170.4	8144.8
SES13	8753	SEC13	8644.9	NEC13	8810.9	NES13	8657.5	8869.6

6.3 *Large-space structures*

In mainland China, a lot of large space structures for 2008 Olympiad are being planed and constructed.

In 2002, Qu et al (2002) finished the health monitoring system for the large-space truss roof of Shenzhen Government Office Building. The building roof is 486m length and 156m width, in which the branch truss braced on the towers in the middle span and some other members of the truss maybe buckle while subjects to strong wind, as shown in Figure 50. The monitoring system consists of sensors measured the response of the roof-system, analysis program calculating the response and evaluating the safety of the roof-system. The signals are saved in a database and the signals in the database can be transmitted to the local network and internet by remote severs. The sensors include optic fiber strain sensors, strain gauges, accelerometers, anemoscopes and wind-pressure meters. The strain of the members can be measured by strain gauges and optic fiber strain sensors. The acceleration and displacement of the roof can be measured by the accelerometers. The wind pressure distribution can be measured by both the anemoscopes and wind-pressure meters. The program can detect the damage of the roof, update the analysis model and evaluate the safety based on the measured response and the wind loads.

SHM systems are being planned to install on National Swimming Center (Ou et al, 2005) and National Palaestra for 2008 Olympic Games. A large amount of funds have been supported for studying SHM systems for gymnasiums for 2008 Olympic Games.

Generally, since space structure consists of a great number of components and has the character of vibration modes with closely spaced frequencies, it is difficult to identify natural modal frequencies and modal shapes separate, which is the basis to detect damage. Additionally, since time consumption to assess safety of structure by using FE model is usually huge, diagnosis in real time, which is a challenge topic for this kind of structure.

Figure 50. Photo of Shenzhen Government Office Building

6.4 *Buildings*

In fact, the deterioration of performance of building is not severe compared with other types of infrastructure. Wind loads, earthquakes and their induced-vibration are the first concerned parameters to monitor.

Ou (2003) attached anemoscopes, and wireless accelerometers and sound sensors at the Shenzhen Diwang Tall Building, which is 68-story with a height of 324.95m above ground level and the first modal natural frequency is less than 0.2Hz. The anemoscopes recorded Typhoon for many times (Xiao 2004). Xiao (2004) analyzed the wind loads on this building. Wireless accelerometers recorded vibration of the building and the natural frequencies are further obtained. The noise indoor and outside is recoded by wireless sound sensor.

Recently, a SHM system is being planned to be installed on the building of CCTV (China Center Television), which is under construction. Because of the complexity of the structure of this building, wind loads, earthquakes and their induced-vibration as well as strain of some key components are needed to monitor.

6.5 *Hydraulic engineering structures*

SHM systems have been widely used in hydraulic engineering structures since 1950's in mainland China. Since 1998, the intelligent SHM systems including optical fiber sensors began to be implemented in some hydraulic engineering structures of the Three Gorges Project. Cai (1998) developed the crack monitoring systems using optical fiber sensors and implemented them respectively in a temporary ship milldam and Gudongkou concrete face rockfill dam of the Three Gorges Project. Figure 51 shows Gudongkou concrete face rockfill dam and the construction scene of optical fiber sensors to be embedded in the concrete face of dam. The dam is located in Xiangqi anabranch of Yangzhi river, Xingshan county of Hubei province, which control drainage area is 956km^2, height 120m and volume 1,880, 000m^3. The cross distributed optic fiber and optical time domain reflection was employed in the crack monitoring system for the field detection, as shown in Figure 52.

Figure 51. Gudongkou Concrete Face Rockfill Dam and construction scene of optical fiber sensors to be embedded

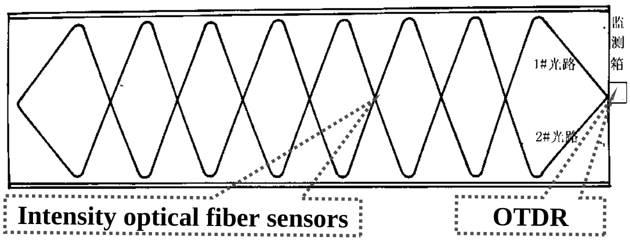


Figure 52. Optical fiber monitoring system for the crack of Gudongkou Concrete Face Rockfill Dam

7 DIAGNOSIS OF HEALTH STATUS AND DECISION-MAKER BASED ON MEASURED DATA

Although a great number of SHM systems have set up at present, it is still a challenge problem to diagnose health status and assess the safety of bridge by utilizing measured data. In the past decades, the combination of vibration-based damage detection approaches with empirical method suggested in

China Bridge Management System (CBMS) is employed to evaluate the safety status of bridge. Recent year, advanced vibration-based damage detection methods and model updating approaches are studied and integrated into SHM systems, such as a damage detection method based on wavelet and BP neuro-network has been integrated into the SHM system for Runyang Bridge, and a sub-structure model updating method has been integrated into SHM system for Shandong Binzhou Yellow River Highway Bridge.

At present, very few publications associated with structural analysis based on SHM systems can be found. Zhou (2005) systematically analyzed the dynamic properties, loads and response of Shandong Binzhou Yellow River Bridge by utilizing measured data. The natural frequencies of the bridge shift slightly day and night. The mean wind speed, direction and angle, and the turbulent intensity, spectrum of pulse wind speed and correlation function based on the measured wind loads by two anemoscopes are statistically obtained, which provides the real wind loads on the bridge. The acceleration response of the deck, tower and cables of the bridge subjected to wind loads and vehicles is also analyzed. Vibration characteristics and level of the bridge under different loads are revealed. The vibration of the bridge is very slight. The strain recorded by FBG strain sensors is also very small.

Li et al (2005) updated the FE model of Shandong Binzhou Yellow River Highway Bridge and verified the validity of the updated FE model by comparison of calculated and measured deflection and strain of the bridge subjected to vehicles.

8 CONCLUSIONS

The state-of-the-art and practice of SHM systems for civil infrastructures in recent year of mainland China is summarized in this paper. The research works and application of SHM system, including advanced smart sensors, wireless sensors and sensor networks, data acquisition system, approach of damage detection, model updating and safety evaluation, implementations of integrated systems in practical infrastructures of long-span bridges, offshore platform structures, hydraulic engineering structures, tall buildings and large space structures is brief introduced. The information introduced in this paper shows that there have gained fruitful achievement in the researches and applications of SHM systems with the social, economy and technology development in mainland China in the past few years.

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