The State-of-the-Art and the State-of-the-Practice of Structural Health Monitoring for Civil Infrastructure in the Mainland of China

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ABSTRACT:

In this paper, the state-of-the-art and the state-of-the-practice of structural health monitoring for civil infrastructures in the mainland of China are summarized. The contents include advanced smart sensors, such as optical fibre Bragg-grating (OFBG) sensors, OFBG-based sensors, piezoelectric ceramic arrays and PVDF sensors, smart cement-based strain sensors; wireless accelerometers and wireless strain gauge, and the wireless sensor networks, the design approaches of structural health monitoring system for long-span bridge, and implementations of integrated systems in practical infrastructures, such as long-span bridges, offshore platforms, dome structures in the past few years of the mainland of China.

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 resisting capacity of the 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

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and constructed each year. The durability and safety of these 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. 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 SHM for civil infrastructures.

In the past decades, great achievements in SHM have been made in mainland China. This paper only introduces the recent advances in this research areas.

OPTIC BRAGG-GRATING-BASED SENSORS

Durability is one of the most important factors for sensors in long-term SHM system of civil infra structures. 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), F-P sensors, white-light interferometers and optical fiber Bragg grating (FBG) sensor (Ou, 2003; Ou et al, 2005)

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 methods for the FBG sensor fabrication. Various FBG sensors are developed. The integrated monitoring system based on FBG sensors has also been developed and applied in many practical civil infrastructures. Fig.1 shows the various optic fiber Bragg-grating based sensors. Fig.2 shows the performance of the sensors. It can be seen from Fig.2 that the wavelength increases linearly with increasing strain and temperature even optic fiber sensor is wrapped by the other fibers.

Additionally, the common measure range of these sensors is about 5000 microstrain, even to 20000 microstrain; Accuracy is about 1~2 microstrain 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 1000 microstrain level.

Cable is a very critical member in bridge, offshore platform and dome structure. However, it is so readily corrosion in service. Fiber-reinforced polymer (FRP) bar has good corrosion resistant and provides a potential way to extend the life of cable. The cable made by FRP bars with OFBG has self-diagnostic function, as shown in Fig.3.

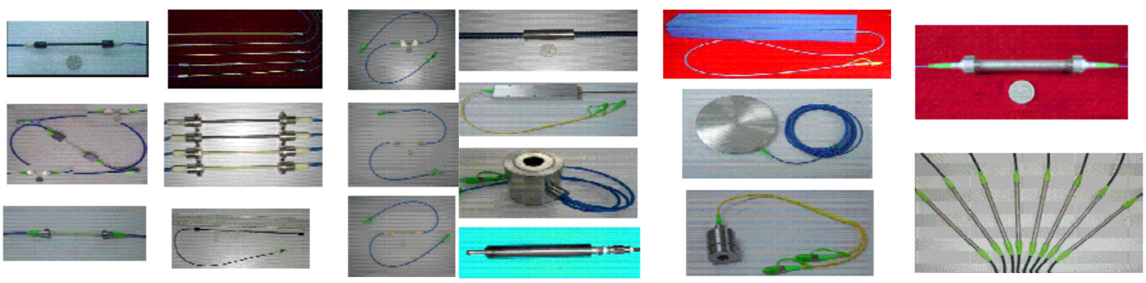

Figure 1 Optic fiber Bragg-grating -based sensors

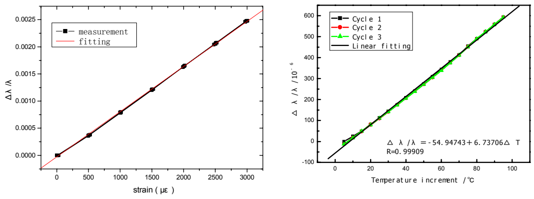

Figure 2 Performance of the OFBG-based sensors

Vehicle is one of most critical loads on bridges. Weigh-in-motion is frequently used to measure the weight and flow of vehicle. However, durability of the sensor used in weigh-in-motion is not enough, which results in a frequent replacement. A novel weigh-in-motion attached with OFBG sensor is developed by HIT, as shown in Fig. 4.

Figure 3 Smart cables with OFGB sensors Figure 4 Weigh-in-motion with OFGB sensors

PVDF AND PZT- BASED 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.

Ju et al. (2004）has utilized the sensing advantages of area sensing and fast response to study its strain sensing properties and crack monitoring abilities in civil infrastructures. Fig. 5 shows the experimental results of PVDF strain sensing properties and the crack monitoring results by PVDF. From the monitoring results, one can find that the strain sensing coefficient can reach 1mv per microstrain, 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.

Figure 5 Strain sensing properties and crack monitored by PVDF

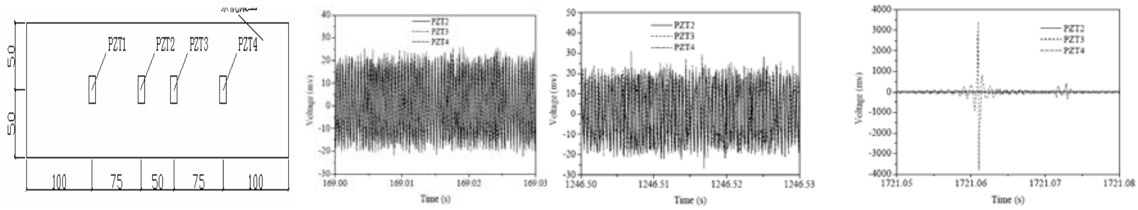

Figure 6 Multiple PZT sensors to localize and detect fatigue damage propagation

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. Li et al (2006) use multiple PZT sensors and wavelets transform method to localize and identify the fatigue damage of nano-concrete beams. The results are shown in Fig.6.

CEMENT-BASED STRAIN GAUGE

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) and Ou et al (2005). Ou et al (2005) have investigated the self-sensing properties of cement containing various kinds of nano-materials, and some results are shown in Fig. 7. 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.

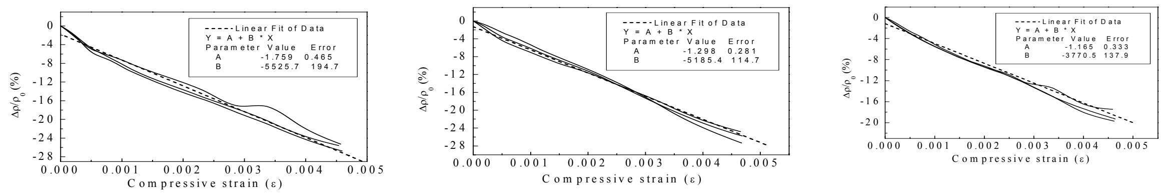

Figure 7 Self-sensing properties of cement containing carbon black

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 Fig.8. 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. 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 Fig.8. 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 (2004) investigated the performance of the CSG to monitor strain of structure through a number of tests of concrete members embedded with the sensors, respectively. The results indicate 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.

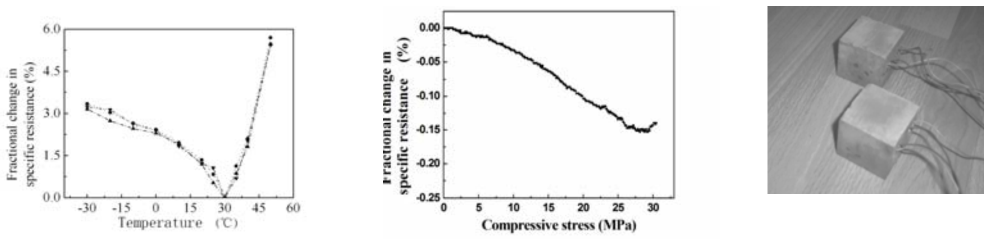

Figure 8 Self-sensing properties of smart cement and strain gauge

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 wire-less 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 Fig.9. It can be seen from Fig.9 that the wireless strain sensor unit consists of a traditional strain gauge and a wireless transceiver board, which consists of signal collection unit, microprocessor unit, wireless transceiver unit and energy unit. 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 Fig.10. It can be seen that the strain measured by wireless strain unit agrees well with that measured by wired strain gauge.

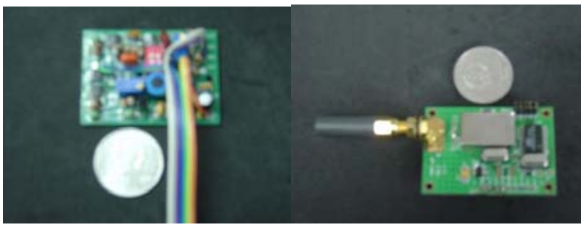

Figure 9 Photo of the wireless sensor

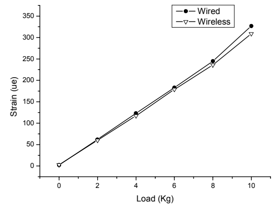

Figure 10 Test results of wireless strain sensor

Li 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 Fig.11.

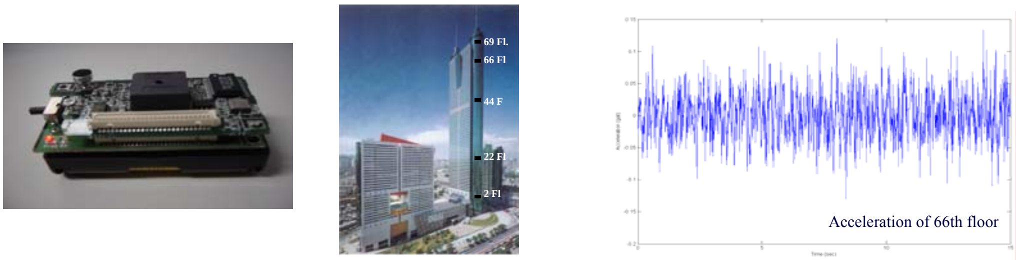

Figure 11 Vibration of the tall building measured by wireless accelerometers

PRACTICAL IMPLEMENTATIONS

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 (2006a, 2006b) 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 the mainland of China are briefly introduced.

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, Z20-2MUQ steel jacket platform. 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, 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, and database subsystem which report form. Another SHM 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. Fig.12 shows the steel jacket and the scene that the sensors are installed on the jacket.

Figure 12 SHM system for CB32A platform

Long-span bridges

The Binzhou Yellow River Highway Bridge is a cable-stayed bridge with three towers in Shandong, China, as shown in Fig.13. The framework of this system is shown in Fig.13. 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. 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. 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. The data has analyzed and natural frequencies and response of this bridge have been obtained. 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, which indicates that the vehicles dominant the vertical vibration of deck, the vibration level is impacted 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.

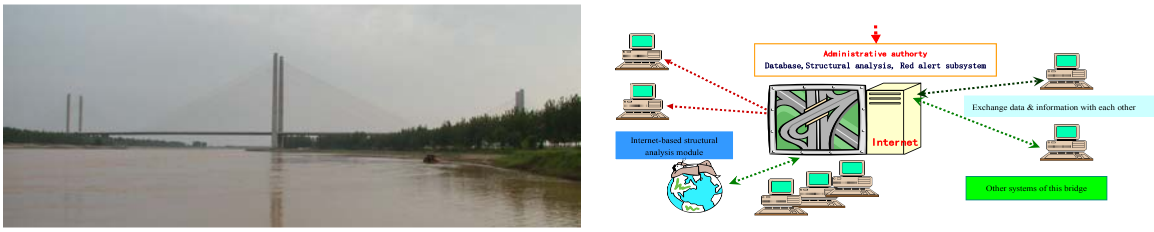

Figure 13 SHM system for the Shandong Binzhou Yellow River Highway Bridge

Large-span space structures

A health monitoring system for the large-space truss roof of Shenzhen Government Office Building was finished 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 Fig.14. 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 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. Ou and Li (2005) designed the SHM system for the National Swimming Center for 2008 Olympic Games, as shown in Fig.14.

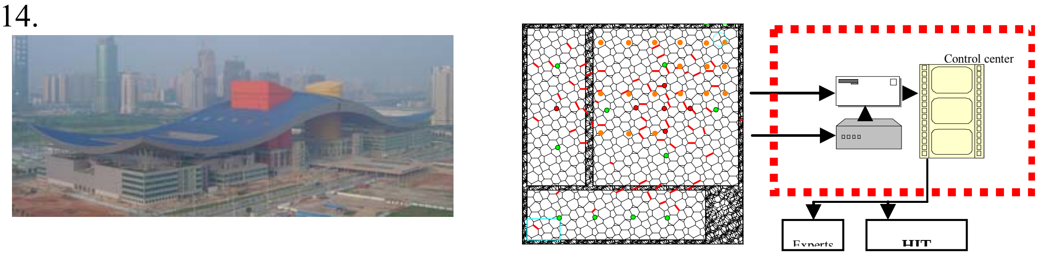

Figure 14 SHM systems for two dome strutures

CONCLUSIONS

The research and practice of sensing technologies of SHM 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, and application in practical infrastructures of long-span bridges, offshore platform 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 sensing technologies of SHM for civil engineering with the social, economy and technology development in mainland China in the past few years.

ACKNOWLEDGEMENTS

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REFERENCES

1. D.D.L Chung, Cement reinforced with short carbon fibers: A multifunctional material. *Composites: Part B* 31: 511-526 (2000)
2. B.G. Han, Properties, sensors and structures of pressure-sensitive carbon fiber cement paste. PhD Thesis, Harbin Institute of Technology (in Chinese) (2005)
3. D.S Ju, Z. Zhou, & J P Ou, Study on strain-sensing of PVDF film. Journal of Function Materials 26(3):245-248 (In Chinese) (2004)
4. H. Li and J. P. Ou Design methods and installation procedures of Health monitoring systems for cable-stayed bridges (I) and II Design methods and Installation. *Journal of Civil Engineering of China*,No.3 (in Chinese) (2006)
5. J. P. Ou, 2003, Some recent advances of intelligent health monitoring systems for infrastructures in the Mainland of China, *Proceedings of 1st International Conference on Structural Health Monitoring and Intelligent Infrastructures, Tokyo, Japan*(Keynote Lecture)
6. J P Ou, H Li and Z D Duan, Structural health monitoring and intelligent infrastructure, Taylor & Francis (Editors) (2005)
7. Ou, J. P. & Li, H. Active control force characteristics and design approaches of semi-active control systems. *Proc. of the SE04,* Osaka, Japan (2004)
8. R. Shi, R, Z. M. Li,. & S. L.Huang The research on piezoelectric sense and remote monitoring for the dynamic strain of bridge. Chinese Journal of Scientific Instrument 23 (4):369-372 (In Chinese) (2002)
9. Y. Yu & J P Ou, Integration and Test of Wireless Strain Sensor Applied to Structure local monitoring. *2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure,* Shenzhen, China.(2005)