Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 14 (2011) 753–760

Procedia Engineering

www.elsevier.com/locate/procedia

The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction

# Structural Health Monitoring: From Sensing Technology Stepping to Health Diagnosis

LI Hui[a*], OU Jinping[a,b]

[a]School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
[b]School of Civil & Hydraulic Engineering, Dalian University of Technology, Dalian116024, China

**Abstract**

Structural health monitoring (SHM) takes a breakthrough of civil engineering by integrating electrical, magnetic, photic, acoustic, thermal and other physical variables, chemical variables, information technology, computer science and technology as well as communication technology into a civil structure to make the structure have self-sensing and self-diagnostic abilities. The SHM is also a basis of smart earth, which may take a profound impact on the behavior and lifestyle of society. The SHM includes sensing technology, data acquisition, transmission and management, and health diagnosis. In this paper, the sensing technologies are developed for monitoring of fatigue, corrosion, score and seismic damages by using integrating piezo-electric ceramic array with optical fiber Bragg Grating sensor array and ultrasonic monitoring technology. The approaches of health diagnosis for civil structures have been proposed by authors and their group. The damage detection approaches considering the uncertainties of civil structures and environmental factors are proposed, such as probabilistic damage identification approach based on dynamic sensitivity analysis and damage detection approach by using information fusion techniques. A multi-scale finite element model (FEM) updating approach is presented for conducting safety evaluation. The modeling approaches for various loads and responses using SHM data are proposed and the framework of SHM-based structure safety evaluation is established. Finally, the role of SHM in developing smart earth in the future is also put forwarded.


Selection

*Keywords:* Structural health monitoring, sensing technology, data, health diagnosis, smart earth

* Corresponding author and Presenter
*Email*: lihui@hit.edu.cn

1877–7058 © 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
doi:10.1016/j.proeng.2011.07.095

## 1. Introduction

A structure should meet the requirement of safety, durability, serviceability and sustainability for a long-term operation. During its long term service, the structure may be deteriorated in its performance slowly, or be damaged severely and even collapse, when subjected to natural disasters, such as earthquake and strong wind. The SHM technology provides a way to evaluate the safety and durability of a structure during its service life, to ensure its serviceability and sustainability. A structure installed with a SHM system can be considered as a full-scale experimental model and system (OU 2005). The loads and response of the structure are recorded directly, from which the performance of the structure is identified. Once the life-cycle performance, the total cost of the initial investment and maintenance of a structure have been collected, the life-cycle performance-based design can be conducted accordingly. Therefore, the SHM technology is the basis of the life-cycle performance-based design approach.

A SHM system consists of sensors, data acquisition and transmission systems, database for effective data management and health diagnosis (including data processing, data mining, damage detection, model updating, safety evaluation and reliability analysis). Most of academic researches are focused on the development of advanced sensing technology and sensors, and health diagnosis approaches. Wind and earthquake bring in two dominant loads for civil structures, which may results in severe damage and even collapse of structures. In view of this, the SHM system is strongly recommended to be employed for these two natural disasters.

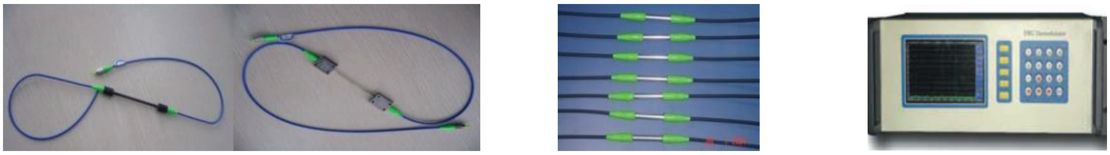
In mainland China, up to date, a number of SHM systems have been implemented in various structures, such as offshore structures, bridges structures, building structures, high-speed railway infrastructure, petroleum industry, and so on. This paper summarizes the progresses of the sensing technology and sensors, and approaches for health diagnosis in mainland China in the past decade. The challenge issues are presented for future research.

## 2. Advanced Sensing Technology and Sensors

To meet the requirement of safety, durability, serviceability and sustainability during its long-term service for a structure, the loads, environmental factors, and its behaviors are needed to monitor. In the past decade, the optic fiber sensors, PZT sensors, cement-based strain gauge, corrosion sensors, nano material-based sensors, and wireless sensors, etc., have been developed in mainland China.

### *2.1. Optic Fiber Sensing Technology*

In the past decades, the optic fiber Bragg-grating (FBG) strain and temperature sensors as well as FBG demodulators have been developed and extensively applied in civil infrastructures in mainland China (Ou 2005). The FBG sensor is embedded into a fiber reinforced polymer (FRP) composite to protect the brittle optic fiber against breakage (Ou 2005). The FBG-FRP strain and temperature sensors, as shown in Figure 1(a) and (b), can be conveniently embedded into reinforced concrete and FRP composite structures, or welded to steel structures to monitor the variation of the strain. The sensitivity coefficient, measurement range, stability for a long-term service, linearization, working temperature, fatigue life and corrosion resistance of the FBG-FRP sensors have been comprehensively investigated (Zhou 2003). Three types of FBG demodulators have been developed in a Chinese company (see in: www.tider.com.cn). The demodulators can have 64 channels, with the sampling frequency of 300 Hz, strain resolution of 1pm and wavelength range of 1520-1570nm.



(a) FBG strain sensor (b) FBG temperature sensor (c) FBG demodulator

Figure 1: Various FBG-FRP strain and temperature sensors and a demodulator.

The FBG sensors can be integrated into structural members when fabricated, and the member will be endowed with a self-sensing function. As shown in Figure 2, several FBG-FRP rebar sensors (with light color in Figure 2) can be inserted into the steel rebar hollows and fixed with the steel rebars together to form a self-sensing smart stay cable. The FBG-FRP rebar sensors can consistently deform with the other steel rebars. Thus, the strain of the stay cable can be monitored with the FBG sensors. With the recorded strain data, the fatigue accumulative damage of the cable can be assessed.

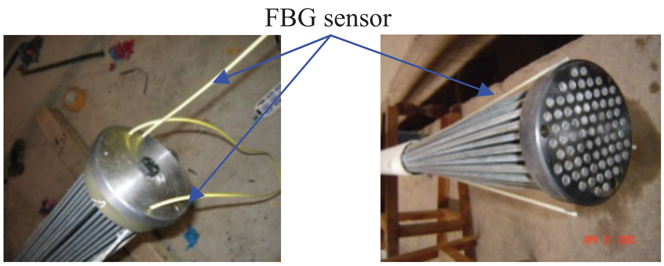



Figure 2: Smart cables

The FBG sensors as commercial products have been extensively used in bridges, buildings, highway, offshore platforms, hydraulic engineering, and petroleum industries in mainland China.

### 2.2. Piezo-electric Ceramics Sensors

PZT-based active and passive damage detection technologies have already been extensively studied in mainland China. The damage detection technique using PZT patches was developed (Zhu 2009). On the other hand, the PZT patch can be used as an acoustic emission (AE) sensor, which receives the stress wave signal generated by occurring of damage in a structure. The AE signal has fractal dimension (FD) features and the damage index is defined as (Li et al. 2009):

$$J_i = \sum_i \frac{\sigma_{b_i}}{\overline{b}_i} + \sum_i \frac{\sigma_{\mathrm{FD}_i}}{\overline{\mathrm{FD}}_i} \tag{1}$$

where $J_i$ is the damage index, $i$ denotes stage *i* in the whole event, the standard deviations $\sigma_{b_i}$ , $\sigma_{\mathrm{FD}_i}$ and mean values $\overline{b}_i$ as well as $\overline{\mathrm{FD}}_i$ are obtained for the stage *i* of the signal.

### 2.3. Cement-based Strain Sensors

Cement-based strain sensor is developed as one appropriate candidate to solve the incompatibility issue. Incorporated with short carbon fiber, conductive nano-particles, conductive metals, PZT, or combination of two or more the above components, cement can possess some sensing functions. Comprehensive investigations on the mixture proportion, fabrication procedure, sensing properties and measurement methods of the sensors have been conducted (Han et al. 2008; Li et al. 2008; Ou and Han 2009). Figure 3 shows the sketch of mechanism of electromechanical property of smart cement mixed with short carbon fibers and nano-particles.

*2.4. Corrosion Sensors*

Corrosion will cause serious deterioration in structural performance. It is critical to accurately monitor the corrosion damage of a structure. A corrosion sensor with a high accuracy and long life has been developed and experimentally verified, as shown in Figure 4 (Qiao and Ou 2007). The time-frequency analysis approach (wavelet transform) is used to diagnose the occurrence of corrosion. For the electrochemical corrosion, the electric power generated due to the electrochemical reaction can be gathered and then used as the battery power of wireless corrosion sensors, this kind of sensor namely the "self-harvesting wireless corrosion sensor".

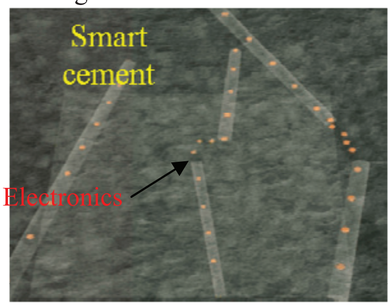


Figure 3: Smart cement-based strain sensor

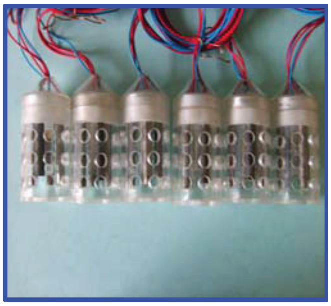


Figure 4: Corrosion sensor

**3. Long-Term Performance Monitoring of Civil Structures**

The damage of civil structures for a long-term operation may be due to large load, accident loads (not included in the design of structures), cyclic loading (fatigue damage) and environmental conditions. The degradation will deteriorate the performance of civil structures. The SHM technology can be applied to evaluate the safety of a civil structure, to make a warning and/or a decision on maintenance. The overall framework of the safety evaluation of a civil structure based on the monitoring technology is recognized as follows.

*3.1. Monitoring and analysis for live loads*

Vehicle load is one of the most important loads for bridge design and operation. But the vehicle load model used for bridge design may be quite different from the actual vehicle loads on the actual bridge. Weight in Motion (WIM) system incorporated in SHM system provides an effective tool for evaluating the real vehicle load model, which may improve the accuracy of the bridge's internal force analysis. The distributions of time intervals, vehicle weight, and total axle spacing (the axle spacing between the first and last axles of vehicle) are statistically obtained based on the acquired data. An exponential distribution is usually assigned to the time intervals between vehicles thus the stochastic process of vehicle weight and axle spacing can be approximately described by Filtered Poisson Process, where the Poisson parameter could be determined by time interval datasets. Based on the observation, several weighted normal distribution functions are employed to fit the distribution functions of vehicle weight and total axle spacing (Li et al 2010). Supposing that $\mathbf{x}_L$ indicates the vehicle weight or total axle spacing, $\mathbf{k}$

represents the logarithm of $\mathbf{x}_\mathrm{L}$, $\mathbf{k} = \ln \mathbf{x}_\mathrm{L}$. The fitting cumulative density function $F_\mathbf{k}(k)$ and $F_{\mathbf{x}_\mathrm{L}}(x_\mathrm{L})$ can be expressed as

$$F_\mathbf{k}(k) = P_1 \Phi\left(\frac{k-\mu_{k1}}{\sigma_{k1}}\right) + \cdots P_n \Phi\left(\frac{k-\mu_{ki}}{\sigma_{ki}}\right) \cdots + P_n \Phi\left(\frac{k-\mu_{kn}}{\sigma_{kn}}\right) \tag{2}$$

$$F_{\mathbf{x}_\mathrm{L}}(x_\mathrm{L}) = P(\mathbf{x}_\mathrm{L} \le x_\mathrm{L}) = P(\mathbf{k} \le \ln x_\mathrm{L}) = F_\mathbf{k}(\ln x_\mathrm{L}) \tag{3}$$

where $P_1 + \cdots P_i \cdots + P_n = 1$, $P_i > 0$ ( $i = 1,2,\cdots n$ ), $\Phi(\cdot)$ indicates the cumulative probability function of standard normal distribution. The parameters in Eq. (1) can be estimated by the nonlinear least square method or maximum likelihood method. The models and their parameters can be updated on line using Bayesian theorem. Obviously, the last type is the most important for maximum value distribution of structural responses. The maximum value distribution $F_\mathbf{M}(x)$ of the vehicle load effects can be expressed as the following formulation

$$F_\mathbf{M}(x) = \exp\left\{-\lambda p_n \mathrm{Ts}\left[1-\Phi\left(\frac{\ln x-\mu_\mathrm{Mn}}{\sigma_\mathrm{Mn}}\right)\right]\right\} \tag{4}$$

where $\lambda$ represents the Poisson parameter; $p_n$, $\mu_\mathrm{Mn}$ and $\sigma_\mathrm{Mn}$ are parameters associated with vehicle load model in the above equation. $\mathrm{Ts}$ indicates the service period.

### *3.2. Monitoring and analysis for environmental actions*

Environmental factors including temperature, humidity, rain (rain fall, raindrop and so on), chloride, salty, acid, alkali, etc. are concerned to the long term performance of a structure. Based on the monitoring data, a zone map of environmental actions similar to the zone map of earthquake ground motion parameters can be developed, which will provide criteria to evaluate the life-cycle performance of a civil structure. Sensors for monitoring temperature, humidity and rainfall have been included in the most of monitoring systems of bridge and building structures. Other variables are still difficult to be monitored in the real time.

### *3.3. Damage detection based on SHM technology*

Once data is monitored, damage detection of a structure can be conducted. Vibration-based damage detection methodology has been comprehensively investigated in mechanical systems and civil structures. However, due to the uncertainty of the environment, loads and structure configurations, as well as the characteristics of the local damage of civil structures and strong noise contamination in the field monitoring, the vibration-based damage detection approaches cannot identify the damage of civil structures accurately. The distributed sensor networks, which can monitor the local damage directly, may be a potential solution to this problem. Advanced signal process technology provides another chance to detect the local and minor damages in civil structures, such as the fractal analysis, information fusion, and wavelet transform (Liu and Ding 2006; Ding et al 2008; Li et al 2008) and so on. The results indicate that the adverse effect of the uncertainty on the damage detection is depressed remarkably by this approach.

### 3.4. Modeling of structures based on the monitoring technology

Finite element model (FEM) is extensively used in structural analysis. Based on monitoring results, model updating technique is frequently applied to get a more accurate FEM. A number of vibration-based model updating approaches have been proposed. The objective function consists of the modal parameters, e.g. frequency, damping ratio and mode shape, referred as global FE model updating techniques. The stiffness of the structure is frequently selected as the modified parameters, related to the material properties and geometric parameters of a structural member, e.g. flexure stiffness (*EI*), elastic modulus of the material (*E*) and the inertial moment (*I*). The bending bearing capacity of a structural member can be written as $M = A_s f_y (h_0 - x)$ , $h_0$ is the effective height of the cross-section, contributing to the member stiffness, $A_s, f_y$ , the area of cross-section and yield strength of the reinforced bar, respectively, contributing to the bearing capacity and decreasing due to corrosion. These two parameters are not included in the modified parameters of global FEM. In view of this, the global updated FEM cannot reflect the detailed damage information of a member accurately, such as corrosion of reinforced bar, which is needed for capacity assessment. Multi-scale FE model updating technique may be a good solution to this problem. The model consists of global finite elements and solid finite elements. The solid finite element can account for the decrease of the cross-section area, reinforced bar area and debonding of the reinforced bar from concrete. The multi-scale FEM has the advantage on the balance between calculation cost and structural information details.

### 3.5. Monitoring for the structural response

The response of the structure subjected to external forces can be monitored, such as strain, displacement, acceleration and so on. Based on the monitored data, the model of extreme value can be statistically obtained. The fatigue accumulative damage can be evaluated through the analysis of the recorded stress time history. For the location without sensors, the extreme value of the response can be calculated using the updated FE model and the monitored load models. It should be noted that the extreme value model should be established when the structure behaves nonlinear. If the monitored data represents a linear response of the structure, the extreme value model cannot be correctly set up from the monitored data. Deduction logic from monitored linear response to extreme value model should be developed in the future.

### 3.6. Safety evaluation and reliability prediction

To evaluate the safety of a structure, the capacity and extreme value need to be compared. The safety of a structure is categorized to member level and whole structure level. Most of researches are focused on the member level. The safety evaluation of a whole structure is still difficult to reach because the real failure modes cannot be found so far. The SHM technology may provide a potential solution. The performance deterioration of materials will reduce the bearing capacity of a structure. The bearing capacity can be calculated from the updated FE model, or from the variation of the structural performance evaluated by using the monitored data, or from the durability analysis. In fact, it is still difficult to derive a deterioration evolution of a structure accurately, with the existing approaches.

Figure 5 shows the reliability evaluation based on the inspection and monitored data of a cable-stayed bridge. The FE models have been updated using the calibration test results, the inspection data (tested when the bridge was observed cracking at mid-span section of the girder in 2005), and the monitored data (tested after the bridge was repaired in 2006 and re-damaged in 2008). It can be seen from Figure 5 that the reliability index at mid-span is smallest, which is consistent with the crack at mid-span section in 2005.

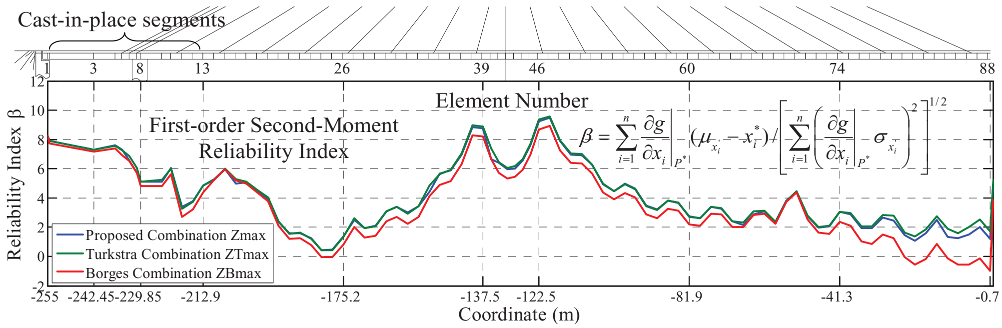



Figure 5: Reliability analysis of a bridge based on monitored data

## 4. Conclusions

This paper summarizes the recent progress in the SHM technology achieved in mainland China and put up the challenges and opportunities of the development of the SHM in the future. Advanced sensors, having promoted the development of SHM, are extensively used in SHM systems for practical structures in mainland China. Current sensing technologies, however, cannot meet the requirement of SHM for civil structures in some aspects, which needs further research and development.

The SHM technology can be used for monitoring of long-term performance of structures, and structure behaviors when subjected to natural disasters, such as wind and earthquake. The SHM system can record the real loads, environmental actions and response, act as a full-scale test model and system. The damage detection approaches based on the advanced signal process technology may be sensitive to damage and robustness against uncertainty and noise. The modeling approaches of loads, environmental factors and response, and the methods of safety evaluation of a structure based on SHM have been proposed. Considering the complication of the structures, loads, environments and coupled responses, more efforts on such directions are proposed.

## Acknowledgments

This research is financially supported by NSFC (Grant Nos. 50525823, 90815022 and 50538020) and MOST (Grant Nos. 2006BAJ02B05, 2007AA04Z435 and 2006BAJ13B03).

## References

[1] Ou JP (2005). The state-of-the art and practice of health monitoring system for civil infrastructure in the mainland of China. Proc. of the Second International Conference on Structural Health monitoring and Intelligent Infrastructure, Shenzhen, China (keynote lecture).

[2] Zhou Z (2003). Optimal fiber smart Bragg grating sensors and intelligent monitoring systems of civil infrastructures, Ph.D. Thesis, Harbin Institute of Technology, Harbin, China (in Chinese)

[3] Zhu HP (2009). Smart method of structural damage detection, China Communications Press, Beijing (in Chinese)

[4] Li H, Huang Y, Han W, and Ou JP (2009). Damage warning of fatigue test of cable based on acoustic emission and fractal theory, Proc. of the 4th International Conference on Structural Health Monitoring on Intelligent Infrastructure (SHMII-4), Zurich, Switzerland, Paper No. 332 (CD-ROM)

[5] Han BG, Yu Y, Han BZ, and Ou JP (2008). Development of a wireless stress/strain measurement system integrated with pressure-sensitive nickel powder-filled cement-based sensors. Sensors and Actuators: A physical. 147(2). pp. 536-543

[6] Li H, Xiao HG, and Ou JP (2008). Electrical property of cement-based composites filled with carbon black under long-term wet and loading condition. Composites Science and Technology, 68(9). pp. 2114-2119

[7] Ou JP and Han BG (2009). Piezoresistive cement-based strain sensors and self-sensing concrete components, Journal of Intelligent Material Systems and Structures 20(3). pp. 329-336.

[8] Qiao GF and Ou JP (2007). Corrosion Monitoring of Reinforcing Steel in Cement Mortar by EIS and ENA. Electrochimica Acta. (52). pp. 8008-8019

[9] Liu T, Li AQ, and Ding Y (2006). A damage alarming method of long-span suspension bridges based on Wavelet Packet. Proceedings of 4th China-Japan-US symposium on structural control and monitoring, Hangzhou, China (CD-ROM).

[10] Ding YL, Li AQ, and Liu T (2008). A study on the WPT-based structural damage alarming of the ASCE benchmark experiments. Advances in Structural Engineering. 11(1). pp. 121-127.

[11] Li H, Bao YQ, and Ou JP (2008). Structural damage identification based on integration of information fusion and Shannon entropy. Mechanical Systems and Signal Processing. 22. pp. 1427-1440.

[12] Li H, Li SL, Ou JP, and Li HW (2010). Reliability assessment of cable-stayed bridges based on structural health monitoring techniques. Structure and Infrastructure Engineering. First published on: 02 July 201