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RECENT ADVANCES IN STRUCTURAL HEALTH MONITORING FOR CIVIL STRUCTURES IN MAINLAND CHINA: TECHNOLOGIES, THEORIES AND SYSTEMS

Jinping OU
Dalian University of Technology, China
Harbin Institute of Technology, China

Hui LI
Harbin Institute of Technology, China

Abstract

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 systems, signal transmission systems, damage detection, model updating and safety evaluation, data management, system integration techniques, design methods of structural health monitoring systems, and implementations for practical civil infrastructure, strategic decision-making techniques of health status of structure based on measured data by the operation of the practical structural health monitoring systems. This paper focuses on the review of advances in SHM techniques since 2005 in mainland China.

INTRODUCTION

Civil infrastructures are often in service for a long period. During service they suffer from environmental corrosion, material aging, fatigue and coupling effects with long-term and extreme loads. The accumulated damage and deterioration in performance reduces safety, reliability and integrity. Therefore, structural health monitoring (SHM) has increasingly attracted the interest of scientists and engineers in the whole world because of the ability to ensure safety and study damage evolution laws of structures.

In mainland China, a great number of civil structures are constructed each year. The durability, safety, reliability and integrity of these structures in the long-term service then become the most critical issue. To solve these 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 decade, Chinese researchers have made great progress and gained fruitful achievements in all aspects of SHM (Ou, 2005). Optic fiber Bragg-grating (FBG) strain and temperature sensors have been developed by Ou et al (Ou, 2005). A kind of novel FBG sensor is fabricated by embedding FBG sensors into fiber reinforced polymer (FRP) bars, as shown in Figure 1. This product is named FRP-OFBG bar. A self-sensing smart cable by either plugging the FRP-OFBG bars into cables or replacing steel bars with the FRP-OFBG bars is further developed, as shown in Figure 2. The accumulated fatigue damage and health status of cables can be diagnosed based on time history of the measured strain by FRP-OFBG bars in cables. Considerable research on performance investigation of FRP-OFBG bars and smart cables has been carried out.

Figure 1 FRP-OFBG bars

Figure 2 Smart cables

Wireless accelerometers are also developed by Ou et al (Ou, 2005). The performance of the wireless sensors has been experimentally verified. A wireless sensor network consisting of 4 wireless accelerometers has been developed. Wireless accelerometers have been mounted on the Shenzhen Diwang Building to measure wind-induced vibrations under typhoon attacks.

Life of most sensors is shorter than that of civil structures. Cement-based composites containing nano-particles and carbon fibers are proposed, which have self-sensing property and can play the role of strain gauge (Ou, 2005) Systematic studies on this sensor and self-diagnostic smart structure have been conducted. Practical applications of these strain gauge in the Chongqing Guangyang Island Bridge and the Zhejiang Chunkai Tunnel are shown in Figure 3 .

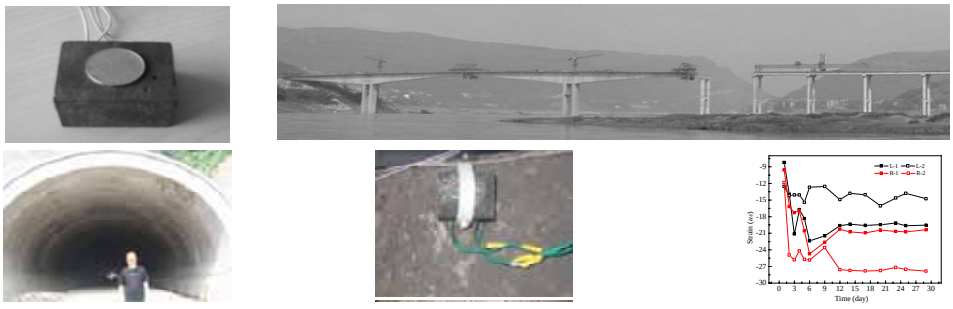


Figure 3 Cement-based strain gauges and implementations in the bridge and tunnel

For implementation of SHM systems into practical civil structures, data acquisition systems, software for signal transmission, Oracle-based database, and software for operation of SHM system via internet have been developed by the authors' group and other companies, such as National Instrument Inc. (NI, USA). The design methods of SHM systems have also been proposed by Li and Ou (2005).

All research achievements and activities on SHM in mainland China made before 2005 have been summarized by Ou (2005). Therefore, this paper only focuses on advances in SHM during the last two years in mainland China.

SMART SENSORS AND INNOVATIVE SENSOR TECHNOLOGY

FRP-Packaged Optical Fiber Sensors based on BOTDA (R) Technique

In the past decade, FBG technology has been comprehensively developed in mainland China (Ou, 2005).

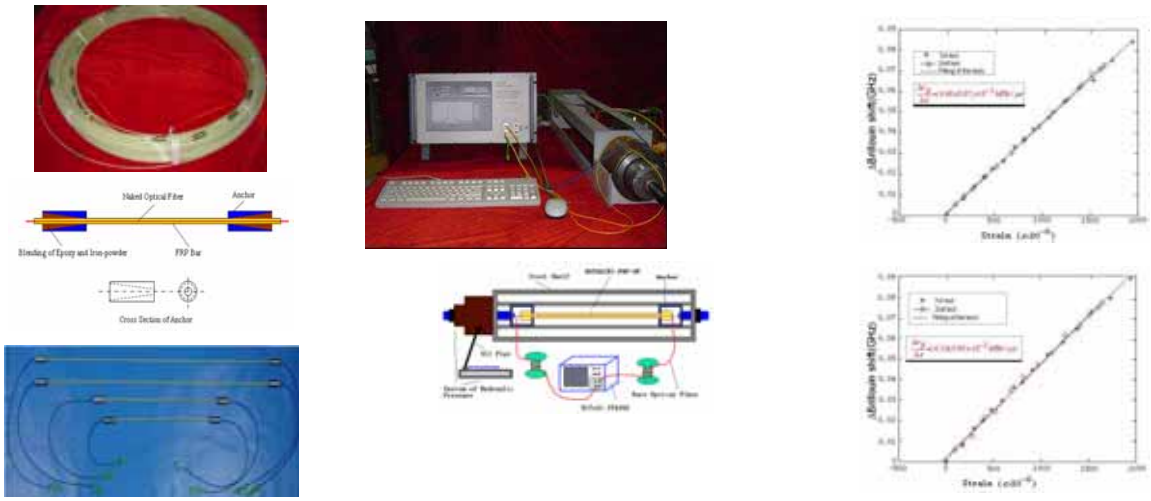


Figure 4 Serial BOTDA(R) GFRP-OF sensors and their strain sensing properties at different spatial and readout resolution

In the past two years, a practical BOTDA or BOTDR solution for long-term SHM of large-scale infrastructures, a series of novel, low-cost, and highly reliable BOTD sensor using FRP-bare optical fiber rebar, as shown in Figure 4, which can be manufactured as long as several kilometers, have been developed in HIT. The sensing properties of GFRP-OFs for strain and temperature at different gauge length are tested under different spatial and readout resolutions using commercial BOTDA. The test results show both high strength and good sensing properties (Figure 4), which can be used in long-term structural health monitoring (SHM) for civil structures.

Wireless strain sensors

Ou et al (Ou, 2005) have comprehensively studied wireless accelerometers and their networks. In recent years, consideration for the chord strain gauge has been extensively used to measure strain of structures, whereas, their cables for signal transmission increase labor and cost, and decrease reliability of SHM systems. A wireless chord strain sensor, as shown in Figure 5, is developed by the authors' group. The performance of the wireless chord strain sensor is verified through static loading tests on a reinforced concrete beam, as shown in Figure 5. It can be seen from Figure 4 that the strain measured by wireless sensors agrees well with those measured by wired chord strain gauge.

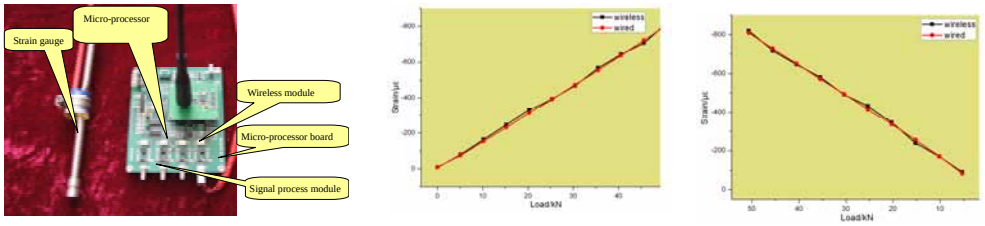


Figure 5 Wireless chord strain gauge and its sensing performance

FBG demodulators

Three types of simple and low-cost wavelength demodulators with high resolution for multi-channel dynamic FBG measurements were developed by Ou and Lu (2007), as shown in Figure 6. The TFBGD-210 is a portable double-channel FBG demodulator with a strain resolution better than 1 pm at a frequency band of 1-100 Hz. The TFBGD-700 is a single-channel FBG demodulator with a strain resolution of 0.5 pm at a frequency of 1 Hz. The TFBGD-9000 is a 16~64-channel FBG demodulator with a strain resolution of 1 pm at a frequency of 300 Hz.

(a) TFBGD-210 FBG (b) TFBGD-700 FBG (c) TFBGD-9000 FBG

Figure 6 FBG demodulators

DAMAGE DETECTION APPROACHES

In recent years, great efforts on structural damage detection methods have been made in mainland China, such as a time-varying character matrix-based damage detection method (He and Ou, 2005), flexibility matrix-based damage detection method (Duan, et al, 2006), wavelet packet spectrum and a wavelet residual force-based damage detection method (Li et al, 2006; Yan, 2006) and an information fusion damage detection method (Li et al, 2006). Only some typical methods are briefly introduced herein.

Flexibility matrix-based damage detection and localization methods

Damage localization approaches based on changes in flexibilities constitute an important technique for damage detection. However, the unavailability of a flexibility matrix with output-only data makes flexibility-based approaches not really applicable in the very important cases of ambient vibrations. Duan et al (2006) proposed the proportional flexibility matrix (PFM)-based method to solve this problem. The proportional flexibility matrix is defined as

$$\mathbf{F}_P = \sum_{i=1}^{N} \varphi_i \varphi_i^T / \gamma_i \overline{\omega}_i^2 \tag{1}$$

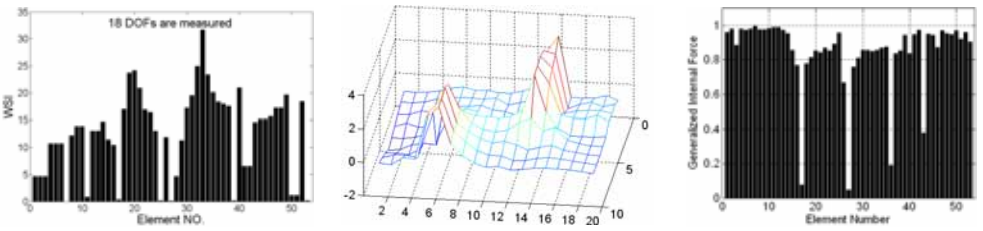
Additionally, to localize multi-damage scenarios, angle – between –string –and –horizon flexibility (ASHF) matrix is further defined as follows

$$\mathbf{F}_\theta = \sum_{i=1}^{N} R_i R_i^T / \overline{\omega}_i^2 \quad R_i = \left[\varphi_{1i}/l_1 \quad (\varphi_{2i}-\varphi_{1i})/l_2 \quad \cdots \quad (\varphi_{ni}-\varphi_{n-1i})/l_n\right]^T \tag{2}$$

Axial strain flexibility (ASF) matrix is defined to identify damage for truss structures as follows

$$\mathrm{ASF} = \sum_{i=1}^{N} \frac{1}{\overline{\omega}_i^2} S_i S_i^T \tag{3}$$

Numerical studied are examined, which are multi-damage localization of a 14-bay planar truss structure (PFM and ASF) and a cantilever beam (ASHF), respectively. The results are shown in Figure 7. It can be seen from Figure 7 that all the three flexibility matrix-based methods can effectively localize the damage.



(a) PFM (b) ASHF (c) ASF

Figure 7 Flexibility matrix-based damage detection results

Damage detection using wavelet packet transform

Wavelet is a powerful tool for time-frequency analysis of signals and has been used to detect damage in many areas. Duan et al (2006) defined the residual wavelet force (RWF) as follows:

$$\mathrm{RWF}(a,b) = \frac{1}{a^2}\mathbf{M}_\mathbf{u}\overline{\mathbf{W}}^{\ddot{\mathbf{X}}}_{\Psi''}(a,b) + \mathbf{K}_\mathbf{u}\overline{\mathbf{W}}^{\ddot{\mathbf{X}}}_{\Psi}(a,b) \tag{4}$$

If the $\mathrm{RWF}(a,b)$ is not zero, then damage occurs.

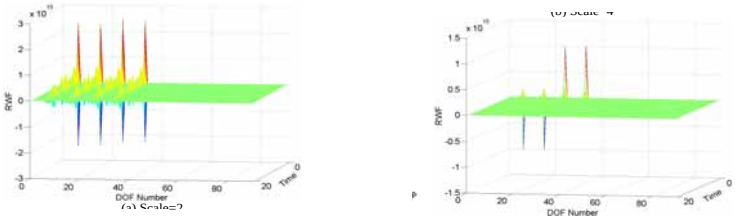


Figure 8 RWF-based damage detection results

A five-story frame is used to examine the method. The results shown in Figure 8 indicate that the method can identify multi-damage scenarios under all wavelet scales.

PRACTICAL STRUCTURAL HEALTH MONITORING SYSTEMS

Almost 100 bridges, offshore platforms, tall buildings, spatial structures, and pavement have been implemented with SHM systems in mainland China at present. Typical examples are introduced here.

An SHM system for the CB32A offshore platform

The offshore platforms located in the Bohai Ocean Gulf, China, suffer from ice pressure in winter. Since the 1980's, ice conditions, ice pressure acted on platforms in Bohai Ocean Gulf have been monitored under the support of China Ocean Oil Company. Based on these facilities, Ou et al (2003) developed an on-line SHM system (operated from 1999) for the platform JZ20-2MUQ, which is one of typical platforms in this area.

Figure 9 The CB32A Platform and its SHM system

In recent years, a new SHM system has been implemented into the steel jacket platform CB32A located in Bohai Ocean Gulf (Ou, 2006), which includes 259 OFBG sensors, 178 PVDF sensors, 56 fatigue life meters, 16 accelerometers, an anemoscope and wave-current meters. A PXI bus technique is employed to collect data synchronously from different sensors. A wireless transmission system is set up for transferring the signal collected on the CB32A to the management agency office. An Oracle-based database is used for management of measured data. The software for damage detection, model updating and safety evaluation is also integrated into the SHM system. The SHM system is operated via internet. The CB32A and the SHM system are shown in Figure 9.

The wind, wave and flow are measured by the SHM system and listed in Table 1. The strain of members is also collected and one case is shown in Figure 10. It can be observed from Figure 10 that the maximum strain is on the order of 25 $\mu\varepsilon$, which is far below the yield strain of steel because the loads listed in Table 1 are quite small.

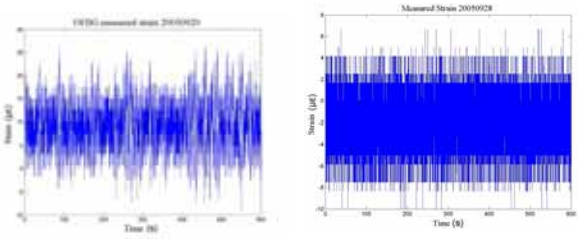


Figure 10 Measured strain by OFBG

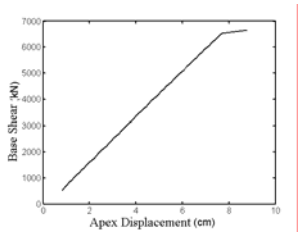


Figure 11 Warning thresholds of the CB32A

For steel jacket platforms, base shear can be regarded as an index to evaluate structural safety. The pushover static nonlinear analysis method is employed to obtain base shear force capability, as shown in Figure 11. It is worth noting that the base shear force capability indeed decreases due to corrosion, fatigue and other faults in long-term service. The method of calculation of time-variant base shear force capability with consideration of above factors is proposed. Generally, a structure is designed to meet the requirements of limited state and serviceability. Correspondingly, two warning levels are proposed, one is the yield base shear force and another is ultimate capability. Based on the measured acceleration, the FEM is updated using the sensitivity analysis method. The base shear force of the CB32A is calculated using measured loads and updated FEM and listed in Table 2, which indicates that the shear force is much smaller than the warning thresholds and the CB32A is more reliable at present.

Table 1 Measured loads on the CB32A Platform by the SHM system

Time	Wind speed m/s	Wind direction D	Current speed m/s	Current direction D	Wave height m	Wave direction D
06-1-27:03:24	5.13	293.72	0.199	134	0.23	0.2
06-1-27:03:54	5.30	301.73	0.185	134.1	0.23	0.2
06-1-27:04:24	3.85	318.02	0.221	125.4	0.23	0.2
06-1-27:04:56	3.90	309.47	0.247	146.2	0.23	0.2

Table 2 Safety evaluation of the CB32A based on the SHM system (Unit: kN)

Time	Shear force	Yield warning threshold	Ultimate warning threshold	Safety evaluation
06-1-27:03:24	12.10	9390.4	12520.6	Safe
06-1-27:03:54	12.44	9283.2	12377.6	Safe
06-1-27:04:24	8.62	10208.7	13611.6	Safe
06-1-27:04:56	9.35	11068.4	14757.9	Safe

An SHM system of theHarbin Songhua River cable-stayed bridge

The Harbin Songhua River Cable-stayed Bridge is a bridge with a main span of 365 m. An SHM system has implemented into this bridge before it opened to traffic on August 26, 2004, which consists of FBG strain and temperature sensors, wireless accelerometer networks and 3 GPS, data acquisition system, database and structural performance, as shown in Figure 12. The system continuously collects data for 7 days twice each year, not operates in real time.

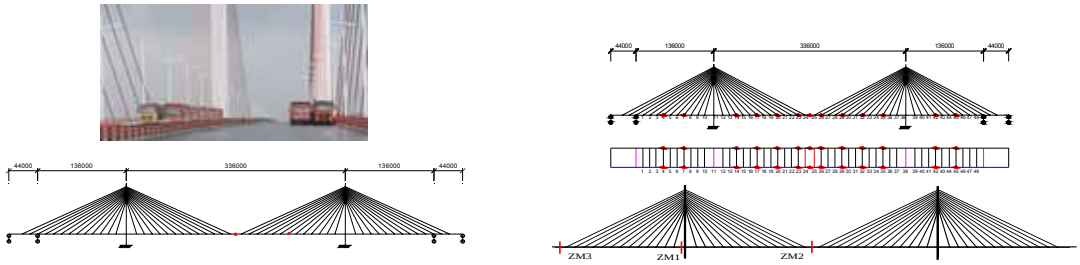


Figure 12 The Harbin Songhua River Cable-stayed Bridge and its SHM system (Accelerometers, GPS and FBG strain sensors)

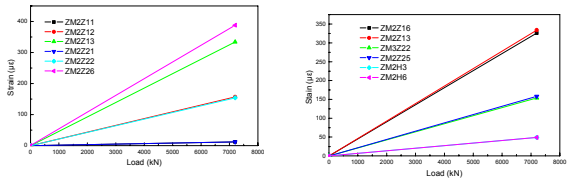


Figure 13 Measured strain on cross section ZM2

On August, 2004, the static and dynamic tests were carried out before the bridge opened to traffic. The strain of the girder is measured and shown in Figure 13. It can be seen that the strain linearly increases with loads and is much smaller than the yield strain of steel.

In May, 2005, the in-situ test has carried out. The strain of the girder was continuously collected for two weeks and some results are shown in Figure 14. It can be seen from Figure 14 that the strain measured by ZM2-Z2-3 and ZM2-Z2-6 (attached to the girder at mid-span) is almost the same, which is reasonable because these two sensors are located in the same position. Additionally, the peak value of time-history of stress shown in the right hand chart of Figure 14 is generated by crossing vehicles and the baseline variation is induced by temperature change with day and night alternation.

To further analyze distribution of stress, the time-history of stress shown in last figure of Figure 14 is categorized into 65 segments and each segment lasts for one hour. The peak value of each segment is picked up and then statistic analysis is conducted, the results is shown in Figure 15. It can be seen from Figure 15 that the maximum stress is about 46 MPa; 59% of stress amplitude is in 30-40 MPa and 15% of stress amplitude is in 40-50 MPa, which means that heavy vehicles frequently cross this Bridge. The fatigue accumulated damage should be further investigated.

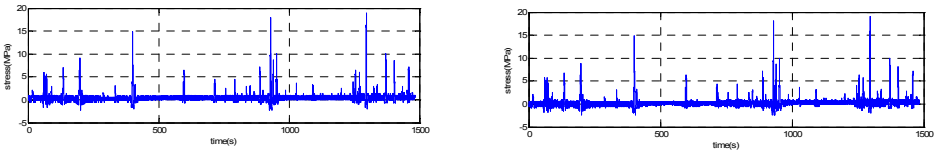


Figure 14 Time history of girder strain measured by ZM2-Z2-3 and ZM2-Z2-6 OFBG strain sensors at mid-span

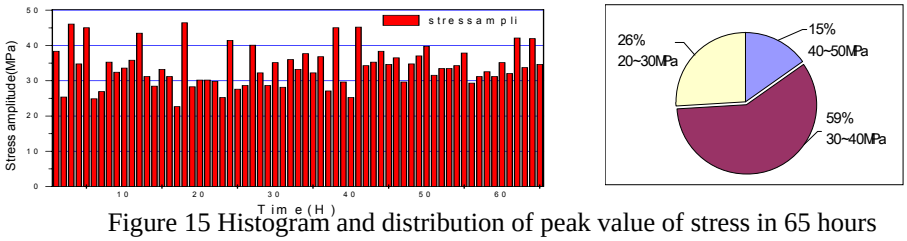


Figure 15 Histogram and distribution of peak value of stress in 65 hours

The stress of two cross-sections of girder at two opposite sides of the tower foot are also measured and the histogram of the peak stress is shown in Figure 16, in which the maximum stresses are about 19 MPa and 29 MPa, respectively. They are smaller than that at the mid-span.

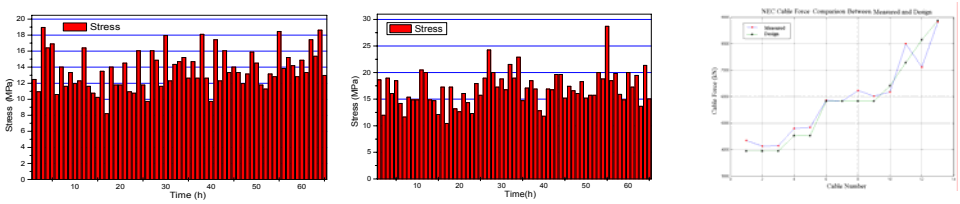


Figure 16 Histogram of measured stress amplitude for 65 Hours of sensor ZM1-Z2-6 and ZM3-Z2-6

Figure 17 Measured tension forces of cables

The cable tension force obtained based on vibration of cables in 2005 and 2004 are shown in Figure 17. It can be seen that the cable forces vary little. The natural frequencies are obtained based on vibration of the bridge and listed in Table 3, which were measured in August, 2004 and May, 2005. It can be seen from Table 3 that the frequencies only change little, which may be attributed to environmental factors. Therefore, the performance of the bridge does not degrade in one-year service.

Table 4 Natural frequencies of the bridge measured in 2004 and 2005 (Unit: Hz)

		1st	2nd	3rd	4th	5th	6th
Vertical modes	2004	0.361	0.449	0.826	1.168	1.181	1.342
	2005	0.356	0.444	0.820	1.122	1.171	1.342
Torsion modes	2004	0.593	0.777	1.015			
	2005	0.593	0.777	1.015			

An SHM systems for the Yonghe Bridge

The Yonghe Bridge was constructed and opened to traffic in 1987. The bridge is damaged significantly, so it was strengthened last year. An SHM system is implemented into this bridge during the maintenance, including FBG strain and temperature sensors embedded into RC girder, smart cables, EM sensors mounted on cables, accelerometers, GPS, anemoscopes and displacement transducers, as shown in Figure 18. The modal parameters of the bridge are obtained by analysis of measured acceleration under ambient vibration, the two mode shapes are shown in Figure 19.

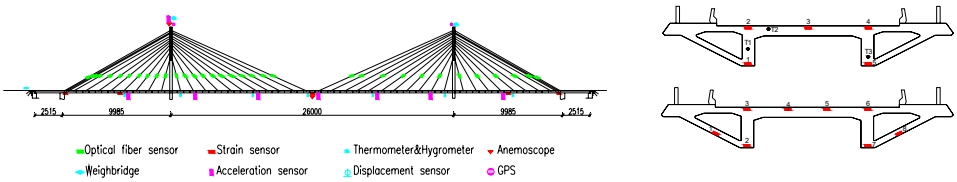


Figure 18 The SHM system of the Yonghe Bridge

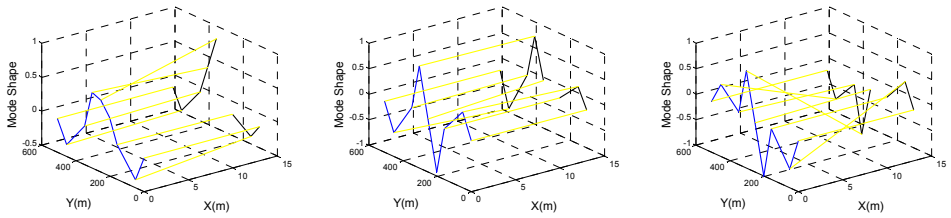
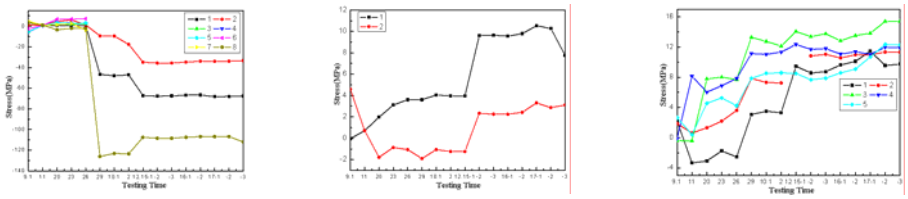


Figure 19 Measured two mode shapes



Longitudinal prestress bars Transverse prestress bars Concrete stress of section 3

Figure 20 Measured stresses of longitudinal and transverse prestress bars and concrete

Cable strain and force are measured by FBG sensors and accelerometers, respectively. The stress of concrete and pre-stress reinforced bars of the girder is measured and shown in Figure 20. It is observed that the measurement of concrete stress is much larger than the design value, which is caused by concrete creep. The concrete creep can be calculated by the formula given by the Prestressed Concrete Institute

$$C(t,\tau) = f(\tau)(t-\tau)^{0.5}/10 + (t-\tau)^{0.6} \tag{5}$$

The calculated creep degree is 23 με/ MPa. The real concrete stress is then obtained by removing concrete creep and shown in Figure 20 (Sep.1 2006-Dec.17 2006)

An SHM systems for the Shenzhen Bridge

The Shenzhen Bridge is a single-tower cable-stayed bridge connecting Shenzhen and Hongkong. An SHM system is implemented into this bridge by the China Highway Bridge Design Institute, as shown in Figure 21.

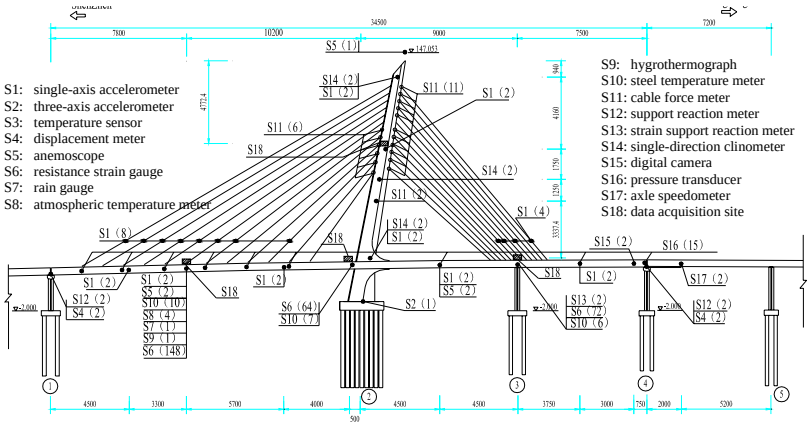


Figure 21 The SHM system of the Shenzhen Bridge

DATA MINING TECHNOLOGIES

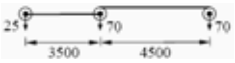
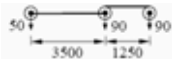
Life-cycle model of vehicles

Vehicles are one of most frequent loads on a bridge. A vehicle load can be measured by weigh-in-motion, which can be integrated into a structural health monitoring system. Once a vehicle load is measured, both the extreme value distribution of heavy vehicle and the vehicle fatigue load spectrum can be predicted. The authors have obtained the extreme value distribution in service-life based on the SHM system of the Dongying Yellow River Bridge

$$F_T(x) = \exp(-\exp(-(x-b)/a)) \tag{6}$$

Authors also utilize Logistic Model to predict the long term variation of annual average daily traffic (AADT) and further obtain the vehicle fatigue loads spectrum, as shown in Table 4.

Table 4 Vehicle fatigue load spectrum of highway bridges

Type of vehicle	Total axles	Sketch (axle weight: kN axle space: mm)	Total weight/ kN	Frequency (%)
M1	2		115	21.17
M2	3		165	1.21
M3	3		230	5.36
M4	4		305	12.66
M5	5		445	4.03
M6	6		595	4.50

Variant of modal parameters under varying ambient

Numerous investigations have indicated that modal parameters of a structure are significantly impacted by varying environmental and operational conditions. Authors proposed a method using principal component analysis (PCA) combined with artificial neural networks (ANNs) to delete the impact of temperature on frequencies. The method has been used to deal with modal frequencies of the Yonghe Bridge, the Shandong Binzhou Yellow River Bridge and the National Swimming Centre. The frequency of the National Swimming Centre (removing temperature impact) is shown in Figure 22.

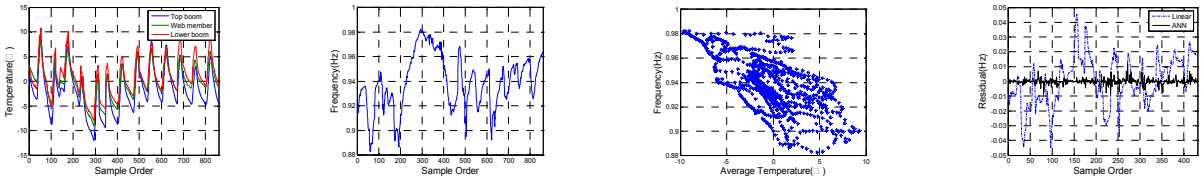


Figure 22 Frequency vs temperature of the National Swimming Centre

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