Smart Structures and Systems, *Vol. 15, No. 3 (2015) 555-576*
DOI: http://dx.doi.org/10.12989/sss.2015.15.3.555

Research and practice of health monitoring for long-span bridges in the mainland of China

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(Received November 27, 2014, Revised January 18, 2015, Accepted January 25, 2015)

Abstract. The large number of long-span bridges constructed in China motivates the applications of structural health monitoring (SHM) technology. Many bridges have been equipped with sophisticated SHM systems in the mainland of China and in Hong Kong of China. Recently, SHM technology has been extended to field test systems. In this view, SHM can serve as a tool to develop the methods of life-cycle performance design, evaluation, maintenance and management of bridges; to develop new structural analysis methods through validation and feedback from SHM results; and to understand the behavior of bridges under natural and man-made disasters, rapidly assess the damage and loss of structures over large regions after disasters, e.g., earthquake, typhoon, flood, etc. It is hoped that combining analytical methods, numerical simulation, small-scale tests and accelerated durability tests with SHM could become the main engine driving the development of bridge engineering. This paper demonstrates the above viewpoint.

Keywords: structural health monitoring; bridge; life-cycle performance evaluation; data

1. Introduction

A number of long-span bridges have been constructed or will be constructed in the mainland of China. The total number of the highway bridges and railway bridges in the mainland of China has ranked number 1 in the world. However, the long-span bridges suffer from the long-term actions of loads and environment, natural disasters, man-made disasters and performance deterioration (fatigue, durability, etc). Therefore, a highly efficient management technology is needed for so many bridges in the mainland of China. SHM technique can aid to understand the performance evolution rules through monitoring, and then provide early alarm and decisions for maintenance.

SHM is considered to originate from smart sensor technology in the early 1990s. A SHM system includes modules for sensing, data acquisition and transmission, data management, data processing, data analysis, modeling, safety evaluation and decision-making. Ou and Li (2010) reviewed the SHM techniques in the mainland of China.

Various smart sensors have been developed over the past three decades. However, optical fiber sensors and wireless sensor networks have the most promising prospects (Ansari 2008, Bao *et al*.

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http://www.techno-press.org/?journal=sss&subpage=8 ISSN: 1738-1584 (Print), 1738-1991 (Online)

1993, Zhou and Ou 2009, Dong *et al*. 2013, Lynch and Loh 2005, Spencer *et al*. 2004, Yu *et al*. 2009). Recent years, the compressive sampling-based data packet loss recovery methods have been proposed as an improvement of the reliability of data transmission of wireless sensors.

Many vibration-based damage detection and model updating approaches have been extensively proposed (Doebling *et al*. 1996, Sohn *et al*. 2003, Li *et al*. 2008, Li *et al*. 2011, Bao *et al*. 2012). However, the accuracy of the vibration-based damage detection and model updating cannot meet the practical requirement due to uncertainties of environment and structures, too few sensors and minor local damage of bridges.

This paper presents an overview of applications of structural health monitoring systems for long-span bridges in the mainland of China. Representative sophisticated SHM systems for long-span bridges are introduced. Based on practical experience, the variables to be monitored, the placement of sensors, the type of sensors, and the sampling rate and scheme of data are described. The methods of data analysis and modeling, and the safety evaluation based on the SHM technique are presented.

2. Applications of SHM systems for long-span bridges in the mainland of China

2.1 Overview of applications of SHM systems for long-span bridges in the mainland of China

A number of SHM systems have been designed and implemented in long-span bridges in the mainland of China. Some of them are listed in Table 1. The table shows that the sophisticated SHM systems are very complex, consisting of hundreds of sensors, complex data acquisition and data transmission systems, database for management and safety evaluation. The systems are operated and remotely controlled online. The data analysis and condition assessment are conducted in both online and offline schemes. The evaluation results are presented in visualization. The data analysis and safety evaluation reports can be automatically generated and sent to the managers.

The variables to be monitored can be categorized into three groups, i.e., loads and environmental actions, local response and global response. The load and environmental measurements record vehicular weight (by weigh-in-motion system and digital camera), the temperature and humidity (by thermal couples, FBG temperature sensors and humidity sensors), the wind (by ultrasonic anemoscope for fluctuating wind and propeller anemometer for static wind), earthquake ground motion (by triaxial accelerometer), the vessel collision(by accelerometer), and rain fall. Local response includes the strain in key elements (by strain gauges, vibrating wire sensors and FBG strain gauges), the cable tension (by accelerometers, load cells, FBG strain sensors and electromagnetic sensors) and damage (by acoustic emission, ultrasonic detection), the corrosion (by electrochemical-based sensors, optical fiber sensors), the reaction force of supports/anchorages (by load cells and displacement transducers), and the scour (by radar, ultrasonic systems, optical fiber sensors, vibrating sensors). The global response includes the acceleration and displacement (by accelerometers, global positioning systems (GPS), displacement transducer, inclination sensors).

2.2 Representative SHM systems for two cable-supported long-span bridges

Two SHM systems are introduced here, one for a suspension bridge and the other for a cable-stayed bridge. Figs. 1 and 2 show the layout of the sensors in these two representative SHM systems for a long-span suspension bridge and a cable-stayed bridge, respectively.

Table 1 Overview of bridges implemented SHM systems in the mainland of China

Name of bridge	Information of bridge (type, span length, total length, tower height, completion year)	Sensors and number	Data used for condition assessment
Xihoumen Bridge*	Suspension bridge,1650m+578m 5.452km, 211.286m 2009	Anemometer (6+2), Temperature & Humidity sensor (7) , Temperature sensor (46+73),Strain gauge (96), Grating-ruler sensor(3), Displacement transducer (4), Cable tension sensor(49), Unaxial accelerometer (22), Triaxial accelerometer (2) , Inclination sensor (16), GPS(15), **Total sensors: 341**	Wind, traffic load, deflection, displacement, vibration, strain, cable force
Jintang Bridge*	Cable-stayed bridge 77 m+218m+620 m+218m+77m 26.54km 204m 2009	Anemometer (2+2), Temperature & Humidity sensor (7) , Temperature sensor (9+166),Strain gauge (144), Grating-ruler sensor(6), Unaxial accelerometer (8+15), Triaxial accelerometer (2) , Inclination sensor (10), Inter connecting pipe (46),Cable tension sensor(72), Load cell(12), , GPS(4), **Total sensors: 505**	Wind, traffic load, deflection, displacement, vibration, strain, cable force
Hong Kong-Shenzhen Western Corridor*	Cable-stayed bridge 180m+90m+75m 5545m 139m 2007	Anemometer (4+1), Rain falling gauge(1), Temperature & Humidity sensor (1) , Temperature sensor (27), Strain gauge (284), Displacement transducer(4), Unaxial accelerometer (30), Triaxial accelerometer (1) , Inclination sensor (6), Inter connecting pipe (15),Cable tension sensor(17), Load cell(6), Weight-in-Motion sensor (2) Digital Camera(2) **Total sensors: 401**	Wind, traffic load, deflection, displacement, vibration, strain, cable force
Qinlinwan Bridge*	Cable-stayed bridge 2×50m+180m+2×50m 1069m 128.485m 2010	Anemometer (1), Temperature & Humidity sensor (3) , Temperature sensor (32),Strain gauge(52), Displacement transducer(4), Unaxial accelerometer (24+29), Triaxial accelerometer (2) , Inclination sensor (8), Inter connecting pipe (24),GPS(2), Vehicle Speedometer(1), Digital Camera(2) **Total sensors: 184**	Wind, traffic load, deflection, displacement, vibration, strain, cable force
Waitan Bridge*	Cable-stayed bridge 225m+90m 1393m 85.243m 2010	Anemometer (2), Temperature & Humidity sensor (3) , Temperature sensor (26),Strain gauge (37),Displacement transducer(4), Unaxial accelerometer (26+14), Triaxial accelerometer (1) , Inclination sensor (6), Inter connecting pipe (20),GPS(1), Vehicle Speedometer(1), Digital Camera(2) **Total sensors: 142**	Wind, traffic load, deflection, displacement, vibration, strain, cable force
Wantou Bridge*	Arch bridge 48m+180m+48m 833m — 2009	Anemometer(1), Temperature & Humidity sensor(2), Temperature sensor(19), Strain gauge(21), Unaxial accelerometer (15), Displacement transducer(4), GPS(1), electromagnetic sensor(10), Digital Camera(2), Vehicle speedometer (1) **Total sensors: 76**	Wind, traffic load, deflection, displacement, vibration, strain, cable force
Mingzhou Bridge*	Arch bridge 100m+450m+100m 1250m	Anemometer(1), Temperature & Humidity sensor(1), Temperature sensor(40), Strain gauge(54), Unaxial accelerometer (15),	Wind, Traffic load, deflection, displacement, Vibration, Strain, cable force

	— 2011	Triaxial accelerometer (2) , Displacement transducer(4), GPS(3), electromagnetic sensor(22), Digital Camera(2), Vehicle speedometer (1) **Total sensors: 145**	
Caofeidian 1# Bridge*	Cable-stayed bridge 138m+138m 2.35km 120m 2010	Anemometer (2), Temperature & Humidity sensor (2) ,FBG temperature sensor (34),FBG strain gauge (34), Weight-in-Motion(1), Unaxial accelerometer (38), Triaxial accelerometer (1) , Bi-Inclination sensor (4), Inter connecting pipe (14),Digital Camera(2) **Total sensors: 132**	Wind, Traffic load, deflection, displacement, Vibration, Strain, cable force
TonglinYangtze River Bridge*	Cable-stayed bridge 80+90+190+432+190+90+80m 2592m 153.65m 1995	Anemometer (1), Temperature & Humidity sensor (1) ,FBG temperature sensor (32),FBG strain gauge (32), FBG displacement transducer(4),Vehicle speedometer (1), Inter connecting pipe (22),GPS(10) **Total sensors: 103**	Wind, Traffic load, deflection, displacement, Vibration, Strain, cable force
Hangzhou Bay Bridge*	Cable-stayed bridge 70+160+448+160+70m (South Channel Bridge) 100+160+318m (North Channel Bridge) 36km 178.8m(North Channel Bridge) 194.3m(South Channel Bridge) 2008	North Bridge: Anemometer (2+2), Temperature & Humidity sensor (6), Weight-in-Motion sensor (2), FBG temperature sensor (24),FBG strain gauge (58), Unaxial accelerometer (28+49), Triaxial accelerometer (2) Displacement transducer (10),Inter connecting pipe (36), GPS (4), Digital Camera (2) **Total sensors: 225** South Bridge: Anemometer (2+1), Temperature & Humidity sensor (5), FBG temperature sensor (20),FBG strain gauge (46), Unaxial accelerometer (22+25), Triaxial accelerometer (2) Displacement transducer (9), Inter connecting pipe (18),GPS (4) **Total sensors:154**	Wind, Traffic load, deflection, displacement, Vibration, Strain, cable force
Nanjing Fourth Yangtze River bridge*	Suspension bridge 410.2 + 1418 + 363.4m 28.996km 230.9m 2012	Anemometer (4+2), Temperature & Humidity sensor (14), Weight-in-Motion sensor (2), Temperature sensor (6+15),Strain gauge (36), Unaxial accelerometer (39), Bi-accelerometer (16),Triaxial accelerometer (4) Displacement transducer (12),Inclination sensor (17), GPS (19), GPS basestation (2) **Total sensors: 188**	Wind, Traffic load, deflection, displacement, Vibration, Strain, cable force
Jiaxing-Shaoxing Bridge*	Cable-stayed bridge 70+200+5×428+200+70m 10.137km 169.964~173.174 m 2013	Anemometer (4+1), Rain falling gauge (1), Temperature & Humidity sensor (11),Scour sensor (7), Corrosion sensor (12), Weight-in-Motion sensor (1), Temperature sensor (45),Strain gauge (182), Unaxial accelerometer (156+38), Triaxial accelerometer (2) Displacement transducer (54),Inter connecting pipe (48), Inclination sensor (18), GPS (5), GPS basestation (1),Digital Camera (48) **Total sensors: 634**	Wind, Traffic load, deflection, displacement, Vibration, Strain, cable force
Taizhou Yangtze River Highway Bridge	Suspension bridge Main span 1080 m, 2940 m 191.5 m 2012	Anemometer (1),Temperature and Humidity sensor (1), Static GPS (11), Uniaxial accelerometer (39), Triaxial accelerometer (12), Strain gauge (168),Temperature sensor (42)	Environment information: wind speed; atmospheric temperature; humidity; internal temperature of the bridge. Displacement of the bridge; displacement of bridge support; acceleration; strain and stress

Donghai Bridge	cable-stayed bridge 420 m 32.5 km 195 m 2006.	Temperature sensor 70, Strain monitoring point64, Static GPS 9, Anemometer 3, Accelerometer56, Fatigue meter 48, Extensometer 8, Water Pressure Sensor 76, Cable tension sensor 16, Corrosion sensor 36	Environment information: wind speed; atmospheric temperature; humidity; internal temperature of the bridge. Structural response: overall displacement of the bridge; displacement of bridge support; acceleration; strain and stress
Su-Tong Yangtze River Bridge	Cable-stayed bridge 1088 m 2088 m 300.4 m 2008	Displacement meter: 12, Hygrometer: 9, Accelerometer: 38, Magnetic dynamometer: 16, Inclination sensor: 6, Strain gauge: 333, Fiber optic sensor: 16, Anemometer: 11, GPS base station: 12; Corrosion sensor: 12; Non Stress Meter: 2.	Environment information: wind speed; atmospheric temperature; humidity; internal temperature of the bridge. Structural response: overall displacement of the bridge; displacement of bridge support; acceleration; strain and stress.
Jiangyin Yangtze River Highway Bridge	Suspension bridge 1385m 2008m 193m 1999	Fiber optic strain sensor: 1680, Accelerometer: 35, Fiber optic temperature sensor: 36, GPS base station: 9, Hygrometer: 2, Temperature sensor: 2, Triaxial ultrasonic anemometer: 2, Displacement meter: 4, Barometer: 2, electromagnetic sensor: 14.	Displacement and vibration of main girder and bridge tower; tension force of suspension cable; temperature field; humidity; wind speed.
Nanjing Second Yangtze River Bridge	Cable-stayed bridge 628m 2938m 195.41m 2001	Total station 22 prisms on the main girder, 16 displacement measurement points for each tower), vibrating wire strain gauge, electromagnetic sensor, anemometer, temperature sensor, hygrometer	Alignment and strain of main girder; tension force of stay cables; displacement of bridge tower; temperature field of main girder; vibration of main girder and bridge tower; traffic load; wind speed.
Nanjing Third Yangtze River Bridge	Cable-stayed bridge 648m 1288m 215m 2006	Accelerometer: 43, Strain gauge: 488+244, Temperature and humidity sensor: 6, Anemometer: 2, cable tension sensor: 168, displacement sensor: 72, Deflection sensor: 42, Bearing force sensor: 12	Alignment and strain of main girder; tension force of stay cables; displacement of bridge tower; temperature field of main girder; vibration of main girder and bridge tower; traffic load; wind speed and humidity; Bearing force.
Zhenjiang-Yangzhou Yangtze River Highway Bridge (Cable-stayed bridge)	Cable-stayed bridge 406m 756.8m 146.9m 2005	Accelerometer: 80, Strain sensor: 60, Anemometer: 1, Temperature sensor: 24, GPS base station: 8	Alignment and strain of main girder; tension force of stay cables; vibration of tower, steel box girder, main cable and stay cables; temperature field of main girder
Zhenjiang-Yangzhou Yangtze River Highway Bridge (suspension bridge)	Suspension bridge 1490m 2430m 209.9m 2005.	Accelerometer: 93, Strain sensor: 72, Anemometer: 1, Temperature sensor: 40, GPS base station: 8.	Alignment and strain of main girder; tension force of stay cables; vibration of tower, steel box girder, main cable and stay cables; temperature field of main girder
Chonghai Yangtze River Bridge	Six-span continuous beam steel bridge102m+4×185m+102m 2011	Anemometer: 2, Temperature and humidity sensor: 8, Structural temperature sensor: 72, Expansion joint displacement sensor: 8, Deflection sensor: 9, Strain sensor: 72, Vibrometer: 26, Collision sensor: 21, External tendon force sensor: 16.	Load：Wind speed; atmospheric temperature; humidity; structure temperature; pavement temperature; traffic load; Structural response: acceleration(vibration of main structure, earthquake, collision), structure deflection; strain and stress; displacement of support and

			expansion joints; external tendon force.
Shanghai Yangpu Bridge	Cable-stayed bridge 602m 1172m 208m 1993	Strain sensor: 40, Piezoelectric sensor: 5	Acceleration; traffic load; tension force; strain; deformation; overall displacement, etc.
The Xiabaishi Bridge	Prestressed concrete continuous rigid frame bridge 145m+2×260m+145 m 810m 2003	Accelerometer: 153(49 measurement points plus 2 reference points for vertical, longitudinal and horizontal directions each).	Vibration of the bridge
Qingzhoucable-stayed bridge	Cable-stayed bridge 605m 1185m 175m 2002	Accelerometer: 348(180 for bridge deck and 168 for each stay cable), Level gauge, Total station, Deflection sensor.	Vibration of bridge deck and stay cables; deflection of bridge deck; displacement of tower, tension force of stay cables.
Wulongjiang Bridg	Prestressed concrete T-frame bridge 58m+3×144m+58m 548m 1971 (retrofitted in 2007, SHM system was implemented in 2007).	Anemometer, Temperature and humidity sensor, GPS base station, Vibrating wire strain gauge, Fiber optic strain sensor, Accelerometer.	Temperature field of bridge structure, humidity, wind direction, bridge displacement and acceleration, strain of concrete.

Fig. 1 shows that eight anemoscopes are installed on the deck and towers to measure the inflow of wind. Temperature and humidity sensors are installed on the bridges. It is noted that there is no sensor for vehicular weight in Fig. 1. In fact, weigh-in-motion systems have been embedded into each lane at one cross section of girders, which are included in traffic management system, rather than in structural health monitoring system. The accelerometers are installed on the free field near the bridge piers to measure seismic input and to investigate the travelling wave effects. Strain gauges are installed on the girders to investigate strain and fatigue damage. Since fatigue damage has been extensively observed in the “U” reinforced rib on the top of steel box-girders, strain gauges are attached to the upper plates of the box-girders. Load cells are installed at the anchorages of the main cables to measure the cable tension. Load cells and accelerometers are attached on the cables/hangers to measure the tension force and the vibration of the cables/hangers. For suspension bridges, the longest hangers near the tower are likeliest to be excited into oscillations and equipped with accelerometers. For the global response, the acceleration of cables, girders and towers are measured by accelerometers. The displacement of the main cables, towers and girders is measured by both GPS and inclinometers. The relative displacement between the tower and the girder is measured by displacement transducers.

At the six-tower cable-stayed Jiashao Bridge, similar with the suspension bridge above, anemoscopes are installed on girders and top of towers to record wind; humidity and temperature are measured by humidity and temperature sensors; weigh-in-motion systems have been embedded in one end of bridge to measure vehicular weight, speed and volume; and rainfall sensor is also used for monitoring rainfall intensity. The turbulence in the river is dramatic, scour is severe and should be closely monitored by SHM. Scour sensors and corrosion sensors are installed on the pier. Pressure transmitter is densely installed on the girder to measure the displacement. The displacement of the towers is measured by inclinometers and GPS, and the vibration of girders and towers is recorded by accelerometers. Accelerometers also measure the cable tension force and oscillation. Strain sensors have been attached on girders and piers. Displacement transducers have been installed at the connections of girders and piers and joint mentioned below. Considering such long bridge, stressed induced by temperature variations must be released. To that end, a joint is installed in the middle of the structure. The joint has very complex configuration and it requires particular attention during the design of the SHM system. Many sensors have been installed on this joint, as shown in Fig. 2 (in the middle of entire bridge span).

2.3 Lessons from the practice of SHM technique

The lessons from the practice of sophisticated SHM systems are summarized as follows:

The maximum vehicular loads, seasonal wind and typhoons, and temperature have been obtained and compared with those in design codes and with the design parameters. The SHM systems have observed overweight vehicles.

The measured strain and cable tension forces are much smaller than the design values under normal operating conditions. As a consequence, fatigue damage of the steel box girders and cables is also small. Normally, fatigue life of bridge structures is much longer than that specified in design codes.

The displacement of the main cables in suspension bridge is very small at normal operating conditions.

Bridge acceleration is induced mainly by wind and heavy trucks. For suspension bridges, the girder and the hangers close to the towers are readily excited to dramatic oscillations, as shown in Fig. 3. For cable-stayed bridges, stay cables, particular the longer ones, may oscillate under wind. Vortex-induced-vibration has been observed at the girder of the suspension bridge, as shown in Fig. 4.

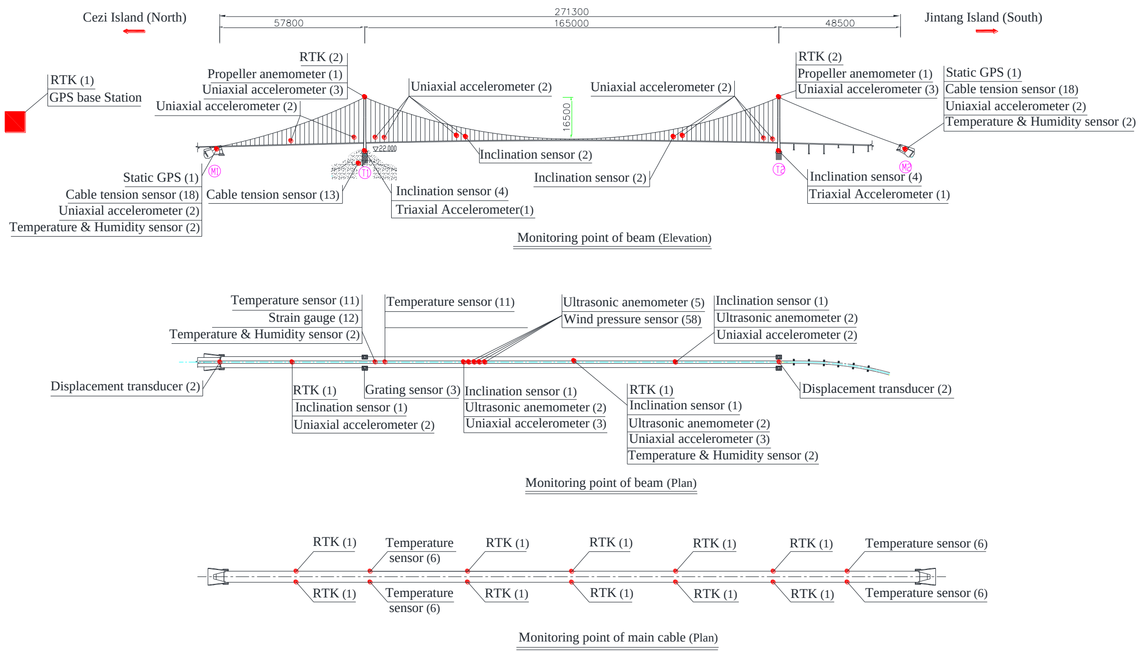


Fig. 1 Layout of sensors in a suspension bridge in China

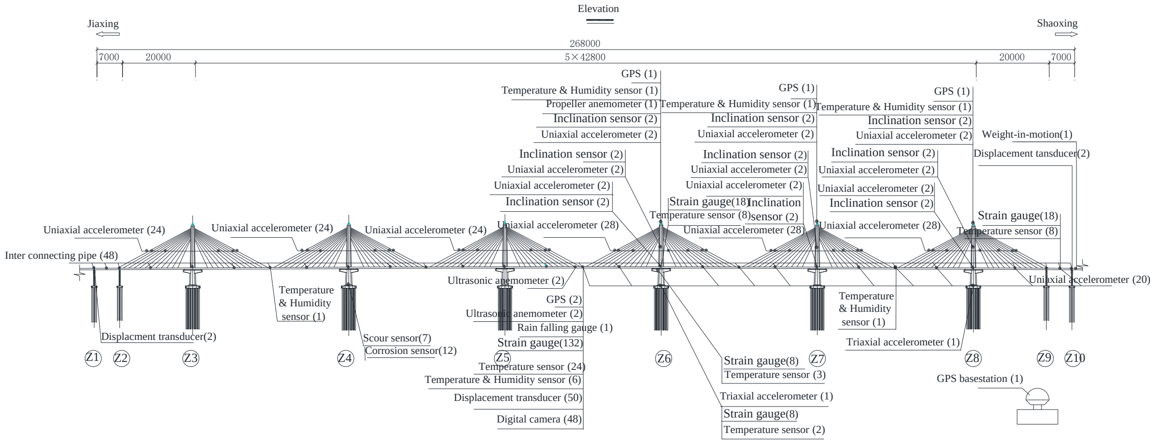


Fig. 2 Layout of sensors for a six-tower cable-stayed bridge in China

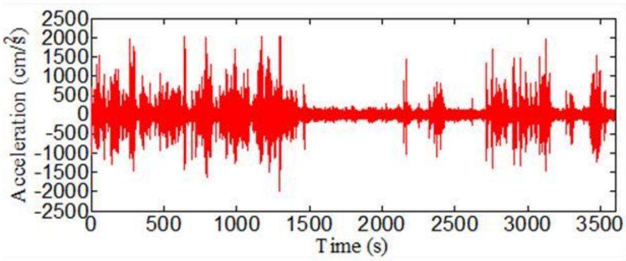


Fig. 3 Wind-induced-vibration of hanger

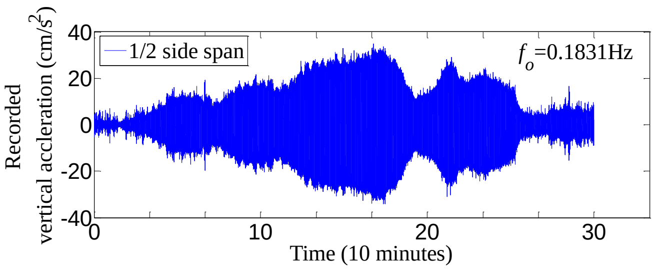


Fig. 4 Vortex-induced-vibration of girder

The natural frequencies, damping ratios and mode shapes are obtained based on the monitored acceleration by using the stochastic subspace identification method (SSI). The natural frequencies may vary with temperature. Damping ratios are more scatter than the frequencies and vary with the wind-induced vibrations due to aerodynamic effects. This has also been observed by Jo *et al*. (2009) and Koh *et al*. (2009) in the suspension bridges in Hong Kong and Korea, respectively.

The sensor life-spans are much shorter than the life-span of bridges. The maintenance of the

SHM system can extend the life-span of the whole SHM system. Furthermore, the long-term performance and stability of sensors cannot be completely ensured. Durable, replaceable and maintainable sensors are needed

Some variables are still very hard to monitor, such as wind load, fatigue damage, cracks inside concrete, corrosion inside concrete structures, cables and anchorages. The wave-propagation methods may be a potential solution for minor local damage detection.

The data sampling scheme and data store schemes require special attention in order to avoid accrual of mega-data. Compressive sensing technology may be used in SHM in the future (Bao *et al*. 2011). Cloud technology provides an efficient and convenient tool for SHM data management.

The data quality provided by SHM systems is not entirely satisfactory. Some data are contaminated by strong noise, even incorrect, e.g. ultrasonic anemoscope cannot work properly under rain conditions. Methods for automatic data processing, and data quality confirmation, and correction must be developed.

Deterioration in structural performance is hard to obtain by the monitored data at this stage. More efficient sensors for local minor damage monitoring should be developed in the future.

Methods for data driven-based diagnosis at macro-scale view and model-based diagnosis at fine scale will become a hot topic in this field. The relationship between the output and input is not unique. One individual output may be a multiple-coupled effects of loads and environmental factors. This is not clear in field SHM, which is quite different from laboratory tests. It is particularly hard to investigate the behavior of bridges under an individual loads and environmental factors. Decomposition methods obtaining unique projections between single individual output and single individual input should be particularly investigated. Big data may be a tool to solve this issue.

3. Data analysis, modeling and safety evaluation based on SHM technology

3.1 Analysis and modeling of loads

Vehicular, wind and temperature are the main loads for long-span bridges. Here, we focus on vehicular load, which causes the ultimate state-based failure of the structure and fatigue cumulative damage. The weigh-in-motion device is widely employed to measure the vehicular loads. Using the monitored data, the extreme value and fatigue spectrum of the vehicular load can be established.

Zhang (2013) systematically investigates the vehicle load based on SHM system. The extreme value model of vehicle includes inter-arrival times between vehicles and weight probabilistic model. The analysis of the monitored vehicle load datasets indicates that the inter-arrival times of vehicles at normal conditions can be simulated by a Gamma process; while at dense conditions, the analysis of the monitored vehicle load datasets shows that the inter-arrival time follows a Weibull distribution. Considering the tail distribution is much important to the extreme value model, a truncated distribution of vehicle weights that incorporates empirical and generalized Pareto distribution(semi-parametric distribution) is proposed (Zhang 2013, Gu *et al*. 2014) and the approach for determining the threshold of the above semi-parametric distribution is presented. The extreme value distribution estimation of vehicle loads at the Nanjing 3rd Yangtze River Bridge is calculated by using the proposed semi-parametric model and the monitored vehicle loads. The results are shown in Fig. 5.

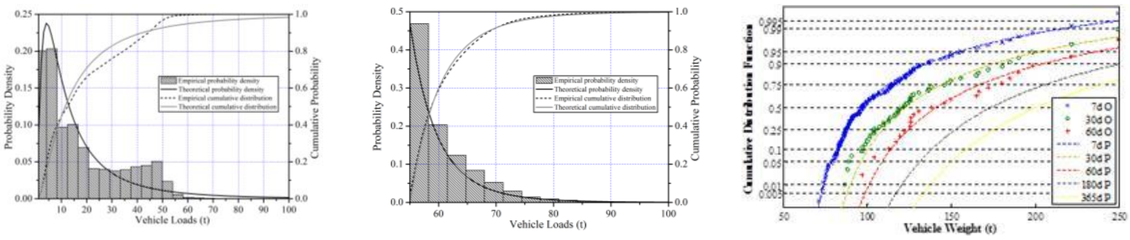


Fig. 5 Extreme value model of vehicles

Lan *et al*. (2011) establishes a fatigue spectrum model for the vehicle load based on the Miner model of the fatigue effect. The volume of the traffic over the life-span of a bridge is predicted by a Logistic model. This model can be updated with the monitored data.

The vehicular loads are distributed over a bridge. The identification and modeling of vehicular loads taking account of vehicle spatial distribution, especially for the heavy trucks, proposed by Bao *et al*. (2013) by use the compressive sampling method. Chen *et al*. (2014) use the combination of weigh-in-motion systems and cameras (computer vision technique) to identify temporal-spatial distribution of heavy trucks.

3.2 Vortex-induced vibration of long-span bridges

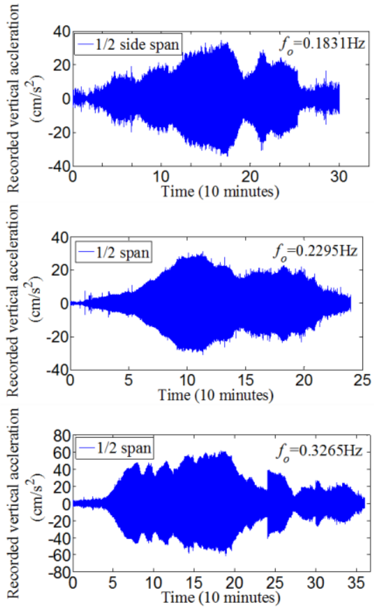
Long-span suspension bridges are wind-sensitive structures. Vortex-induced vibration of bridges with twin-box girders have been observed in several bridges. Fig. 6 shows representative records of vortex-induced vibrations of a suspension bridge. The wind conditions which induce this kind of vibration have been identified and analyzed as shown in Fig. 6. It can be seen that the vortex-induced vibration of the girder occurs at wind speed within 4-14 m/s with a direction of perpendicular to the bridge and with slight turbulence. Wind along the bridge span may be non-uniform, which can decrease the vortex-induced vibration amplitude (Li *et al.* 2011, Li *et al*. 2014, Laima *et al*. 2013)

3.3 Vibration monitoring, tension force identification and fatigue damage assessment of cables/hangers

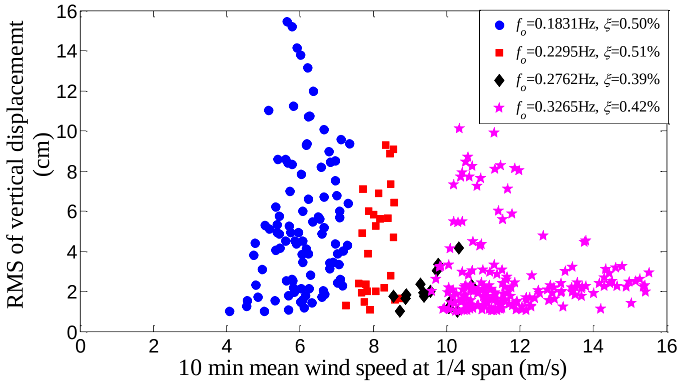
Cables and hangers are among the most important elements for long-span bridges. These elements suffer from wind-induced vibrations, parametric excited vibration, corrosion and fatigue or their coupled effects and may even break during accidents, or may cause driver discomfort. The vibration monitoring and tension force identification of cables and hangers are very critical to ensure structural and public safety.

(1) Vibration of cables and hangers

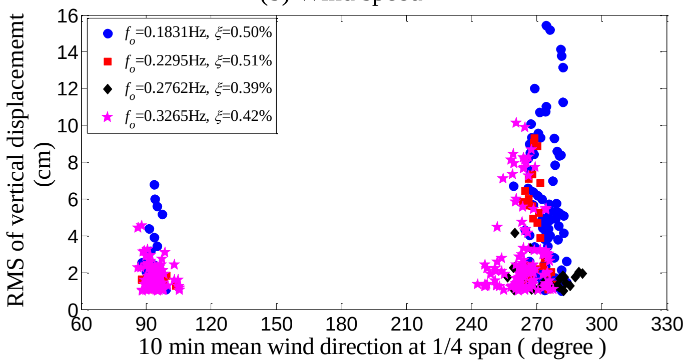
The vibration of cables and hangers has been monitored. One representative vibration of the hanger in a suspension bridge is shown in Fig. 7. It can be seen that the two monitored accelerations are quite different. The former is with larger amplitude and many high frequency components, while the latter is with small amplitude and low frequency components, implying collisions between neighbor hangers in the former case.



(a) Vortex-induced vibration of girder with various modes under different wind conditions



(b) Wind speed



(c) Wind direction

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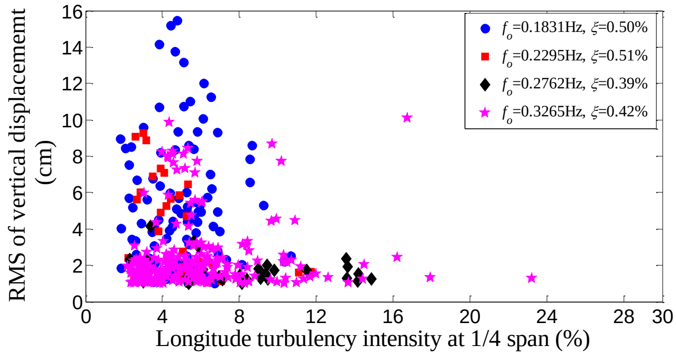
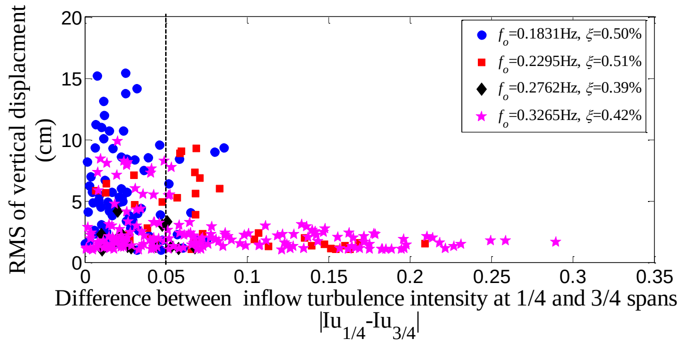


(d) Wind turbulence



(e) Discrepancy in longitudinal turbulence intensity

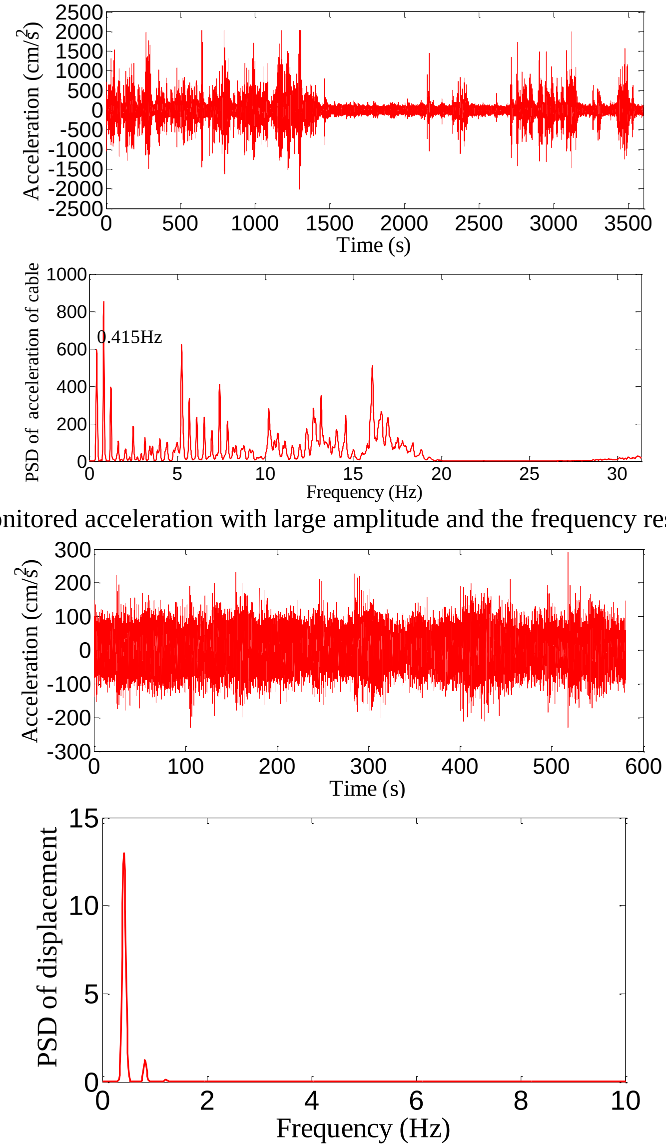
Fig. 6 Time histories of representative recorded wind-induced vibrations and corresponding wind conditions

Dramatic vibrations of cables are also observed in a cable-stayed bridge, as shown in Fig. 8. It can be seen from Fig. 8 that the acceleration is very large, while the displacement is very small, implying that the cable vibration contains high frequency components and modes. This demonstrates the cable vibration is the vortex-induced with high multiple modes (Chen *et al.* 2013).

2) Identification of cable tension force

Self-sensing smart cables have been developed (Li *et al*. 2009, Ou and Li, 2010), with embedded glass fiber reinforced polymer (GFRP) bars. They contain FBG sensors and are anchored at the two ends of the cable together with the steel wires. However, the sensors in the smart cable are hard to replace.

Vibration-based cable tension identification is the most widely applied method because the equipment is easily replaced and with a low cost. This method obtains the cable tension force by using the relationship between cable tension force and natural frequency of the cable. However, this method can only identify the average cable tension over a time period, while the time-varying cable tension force in real time is needed for fatigue damage assessment. Li et al (2014) proposed a time-variant cable tension force identification method by using the extended Kalman filter (EKF) and the observed acceleration of the cable. The time variant cable tension force is regarded as a state variable of the cable dynamic system, and can be identified by using the EKF. The identified accuracy and robustness of the proposed method is validated through numerical study and a small-scale test. The results are shown in Fig. 9. Furthermore, Yang *et al*. (2015) proposed a data-driven identification algorithm for time varying cable tension force using blind source separation.



(a) Monitored acceleration with large amplitude and the frequency response

(b)Monitored acceleration with small amplitude and frequency response

Fig. 7 Monitored acceleration of a hanger with different vibration patterns

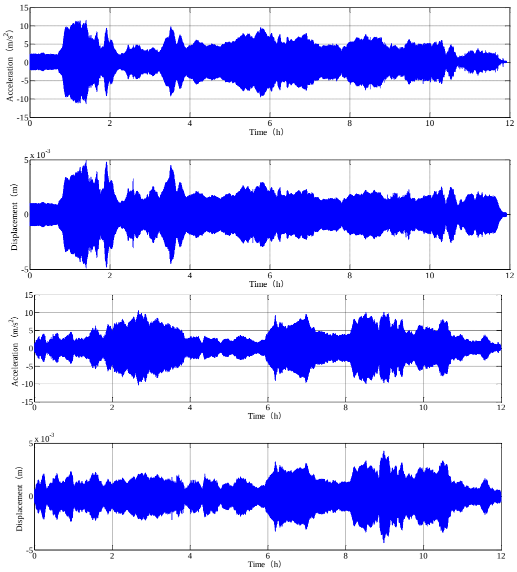
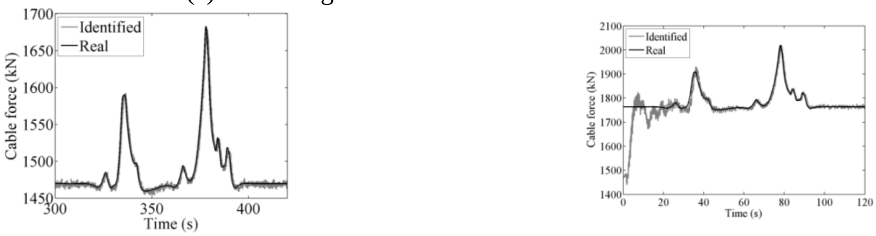
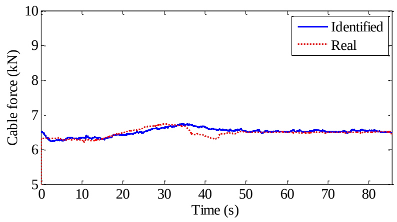


Fig. 8 Vortex-induced vibration of a stay-cable in a cable-stayed bridge

(a) under single vehicle with and without noise



(b) under multiple-vehicles with noise and initial errors



(c) test result

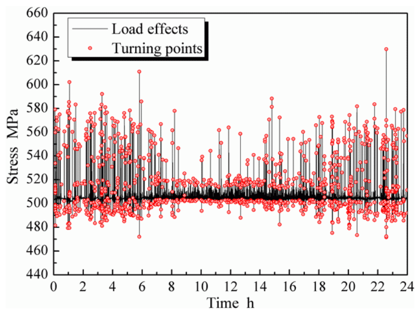
Fig. 9 Time-variant cable tension identification method using EKF

(3) Fatigue damage assessment

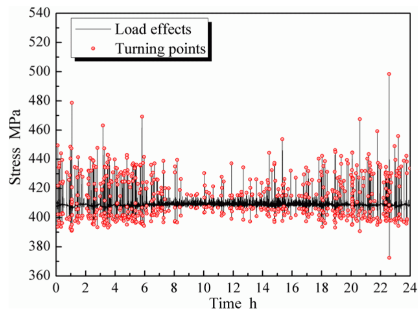
Once the stress time history of the cable is obtained by the monitoring or identification results, the fatigue damage of the stay cable can be calculated by the rain flow method and the Miner fatigue model. Each wire can be modeled as a series of elements, while the whole parallel wire cable can be simulated as a parallel model. Li *et al.* (2012) analyze the fatigue life of cables and discussed the failure criteria of the cable by using the approach proposed by Faber *et al*. (2003). Li *et al*. (2009) assess the fatigue damage for stay cables in a cable-stayed bridge in Tianjin, China, based on the monitored stress of self-sensing smart cables. The results are shown in Fig. 10. It can be seen from Figs. 10(a) and 10(b) that the vehicular effect on the short cables is larger than that on the long cables; moreover, the cable force is almost independent of the temperature. It can be concluded from Fig. 10(c) that the fatigue damage is very slight, which is inconsistent with the observations on actual bridges.

(4) Corrosion effects on fatigue damage of steel wires and stay cables

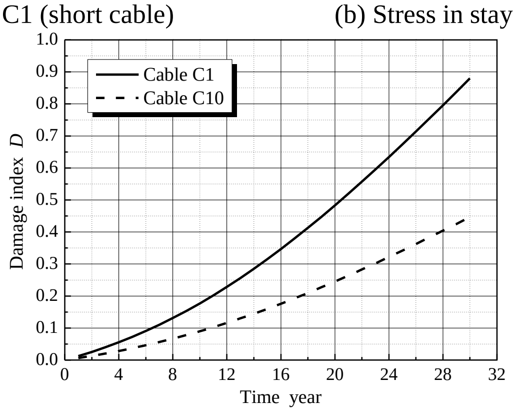
Li *et al*. (2012) investigate the fatigue life of corroded steel wires and stay cables that have been in use for 18 years in a coastal city and replaced during the repair of the bridge. The test results indicate that pitting corrosion dramatically shortens the fatigue life of the steel wires in stay cable and makes the fatigue life more random, as shown in Fig. 11. Pitting corrosion supplies the initial defects in the cable, which accelerate the fatigue damage process.



(a) Stress in stay cable C1 (short cable)



(b) Stress in stay cable C10 (long cable)



(c) Fatigue damage of C1 and C10

Fig. 10 Fatigue damage assessment for stay cables

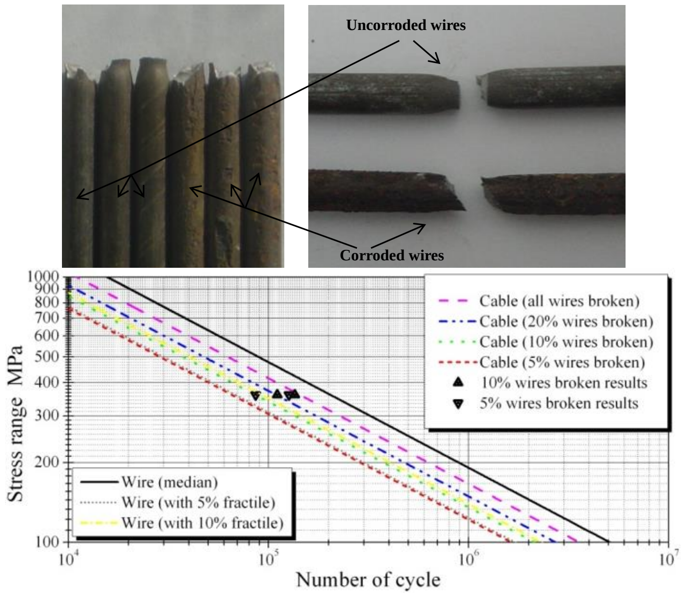


Fig. 11 Fatigue failure of individual steel wires and fatigue life of cables with corrosion

4. Brieft introduction to the design code of SHM systems for large highway bridges authorized by the Ministry of Transportation of China

The Ministry of Transportation of China has authorized a Design Code of SHM Systems for Large Highway Bridges to be issued in June, 2015. The design code includes the sensors, as well as the data acquisition, data analysis, alarms, and safety evaluation. The design code contains 8 chapters, listed in Table 2 as follows

Table 2 Content list of the design code of SHM systems for large highway bridges

Chapter 1	General requirement
Chapter 2	Terminology and symbols
Chapter 3	General Technical Specifications for SHM System
Chapter 4	Monitored Variables and Sensor Locations Selection
Chapter 5	Sensors
Chapter 6	Data Acquisition, Transmission and Management
Chapter 7	Data Analysis, Structural Safety Evaluation and Alarm
Chapter 8	Integrated SHM Systems and Software Packages

4.1 Mandatory regulations in bridges implemented with SHM systems

Bridges must be equipped with SHM systems if they have at least one of the following features: RC beam bridges with a span ≥ 150 m; arches with a span ≥ 200 m; cable-stayed with a span ≥ 300 m; suspension with a span ≥ 500 m; and other complex and important bridges.

4.2 Variables to be monitored and sensor locations

The monitored variables are categorized into three groups, i.e., loading and environmental variables, global response (vibration acceleration and deformation) and local response of a structure.

Loading and environmental variables include vehicle weight, wind velocity, earthquake ground motion and harsh environmental conditions (temperature, humidity, chloride, etc.).

Global responses of bridges include acceleration and displacement of structures.

Local responses of structures include strain, crack, fatigue, scour, corrosion, broken of structural members, displacement and reactions at bearings, supports and joints.

The locations of sensors for load and environmental monitoring should be determined by practical experience.

For global structural response, accelerometer locations can be determined by optimization methods; and displacement transducers locations can be determined by structural analysis.

The locations of sensors for local structural responses are determined based on structural and vulnerability analysis, e.g., the points of elements or cross section of highest stresses and importance, whose failure would cause structural failure.

4.3 Regulations of sensors

Because the sensor life-span is much shorter than that of the bridge, the sensors must be durable, maintainable and replaceable. The sensors in SHM systems for large bridges are divided into two types, inside the structure and on the surface of the structure. The durability of embedded sensors should not be shorter than 20 years. The life-span of sensors attached to the surface of a structure should be longer than 3-5 years and they should be maintainable and replaceable.

4.4 Regulation of data acquisition

Data should be collected in the following categories: data collected only above a pre-set threshold; data collected at a fixed time, e.g., every 4 or 6 hours; and event-driven data collection, e.g., the event of a vessel collision with a bridge pier. Data explosion and data management confusion should be avoided.

4.5 Alarm, data analysis and structural safety evaluation

An alarm can be given based directly on the data. Data analysis should be conducted and a report should be automatically generated and sent to the manager.

The structural safety evaluation is divided into three levels as follows:

Level 1 is performed based on the monitored data analysis and the comparison between monitored values and designed ones.

Level 2 can be performed following an extreme event or an accident, e.g., earthquake, typhoon, overload, vessel collision, etc. For instance, the amplitude, duration, dominant frequency, response spectrum of acceleration of ground motion, the structural response amplitude and residual deformation, the natural frequency and damping ratio are analyzed. If the amplitude of the earthquake ground motion is larger than the design value, or the structural response excesses the design value or material strength, or residual deformation is observed, the frequency decreases or damping ratio increases to compare with the healthy status, the structural safety should be conducted as specified in level 3.

Level 3 includes model-based ultimate state and fatigue evaluation. The structural model should be updated based on the monitoring of global response and local response, e.g., the element can be updated based on crack monitoring; the resistance of a bridge is then obtained based on the updated model; the monitored loads and environmental actions or the design loads and environmental actions are applied on the updated model and increase step by step up to collapse of the bridges. The maximum loads and environmental actions are in terms of ultimate loads and environmental actions. The ratio of the ultimate loads and environmental actions with respect to the monitored loads and environmental actions are the safety level. The evaluation criteria have been suggested in the design code based on level 3 results.

4.6 Integrated SHM systems and software packages

The SHM systems should integrate all software packages and hardware. The software includes a platform for the entire system operation, data acquisition software, data transmission protocol, database, data processing and analysis, automatic safety evaluation, and result visualization.

5. Future trends and challenges

SHM technology has been researched and developed extensively for three decades. The goals, the benefits and the gap between the goals and current technologies of SHM technology should be recognized.

The WiFi-based wireless sensor technology and mobile wireless sensor technology (Bao *et al*. 2012, Bao *et al*. 2013) may be a future trend.

The most challenge are obtaining exact models of damaged structures (the damage may be caused by a disaster or long-term performance deterioration), exact loads and environmental actions, and safety evaluation and service lifetime prediction. The possible solution for exact structural models may be combining the monitoring and inspection information, by structural analysis and damage detection, modeling of damaged bridges and model updating techniques. Based on the exact structural model, the performance deterioration of structural even element resistance can be obtained. The exact loads and environmental actions may be obtained by more monitoring devices and identification algorithms. Based on the updated damaged structure model and the exact loads and environmental actions, the safety evaluation and lifetime prediction can be well performed, which is the main goal of structural health monitoring.

SHM is an *in-situ* field test technology covering various research topics in multiple disciplines, as shown in Fig. 12. It can serve for structural engineering, wind engineering, earthquake engineering, and so on, as shown in Fig. 13. In-situ field tests become the 4^{th} important structural research tool, along with analytical methods, numerical simulations, and small scale model tests, as shown in Fig. 14. SHM acts as an engine promoting the development of engineering as a discipline.

Big data technology not only provides a powerful tool for research of structural health monitoring, but also may provide an opportunity to find new phenomena and develop new research areas based on structural health monitoring. Cloud technology will help us to more efficiently and conveniently manage and utilize data.

The further development of SHM technology may be a precursor towards to a smart society, including the sensing of every variable everywhere, powerful signal processing capability, automatic signal transmission, convenient mobile receivers everywhere, and remote control. This trend will raise many challenges.

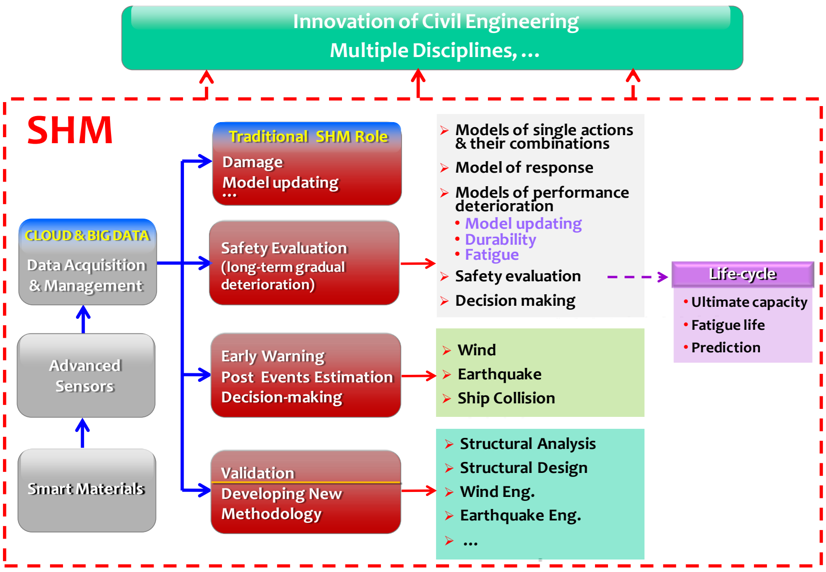


Fig. 12 Research issues for SHM technology

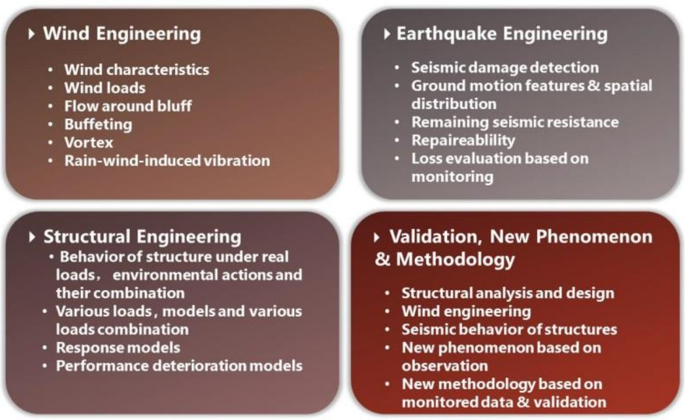
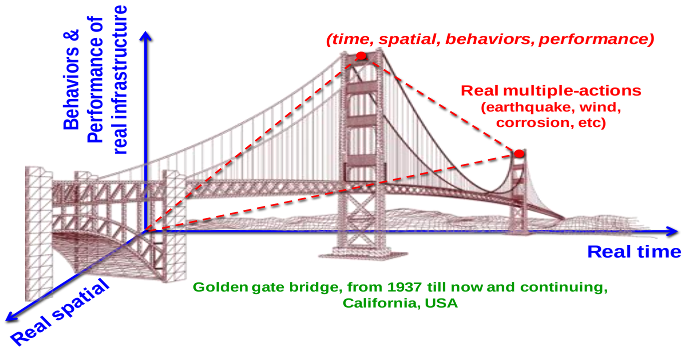
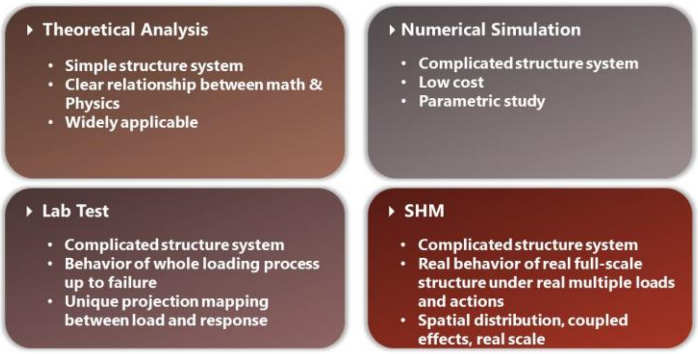


Fig. 13 The future trends of SHM technique in structural engineering



(a) The positive role of SHM technique in structural engineering



(b) Four scientific research tools

Fig. 14 Positive roles of four research tools as the main engine driving development of engineering disciplinary

Acknowledgments

The authors gratefully acknowledge the financial support provided by the Natural Science Foundation of China (Project No:51161120359, 9121530), the Ministry of Science and Technology (Project No. 2011BAK02B01 and 2011BAK02B02), the National Basic Research Program of China (Project No. 2013CB036305) and the Sino-US collaboration project (No. S2015GR1198).

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