Overview of integrated health monitoring system installed on cable-stayed bridge and preliminary analysis of results

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Research Paper

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The Junshan Yangtze River Bridge, built in Wuhan, China in 2001, is a steel box girder cable-stayed bridge with a main span of 460m. Due to decades of service, the bridge suffered gradual degradation and some damage. Structural health monitoring has attracted worldwide attention due to its capacity of monitoring structural damage, assisting maintenance and management, and ensuring safe operation of bridges. To monitor the performance status of bridges and generate a timely safety alarm, an integrated health monitoring system has been designed and implemented on bridges. This paper provides a thorough account of the monitoring system used at the Junshan Yangtze River Bridge. It mainly focuses on the selection of monitoring variables and arrangement of sensor points, the data collection and transmission system, the data storage and management strategy, and the user interface system. All kinds of monitoring data collected under daily operation, such as vehicle load, deflection, displacement, and cable tension, are analysed. Monitoring data for an extreme condition, which involves two heavy trucks of 178 tons moving across the bridge, are also analysed. The results indicate that the monitoring system works well and that some local welded joints may experience fatigue damage.

Key words:
health monitoring, cable-stayed bridge, damage detection, bridge maintenance

Prethodno priopćenje

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Pregled integriranog sustava za praćenje stanja ovješenog mosta i preliminarna analiza rezultata

Most Junshan preko rijeke Jangce, izgrađen u kineskom gradu Wuhanu 2001. godine, po svojoj je konstrukciji čelični sandučasti ovješeni most, a dužina glavnog raspona mu iznosi 460 m. Desetljeća korištenja dovela su do postupnog propadanja mosta, a zabilježena su i određena oštećenja. Danas se diljem svijeta velika pažnja posvećuje monitoringu stanja konstrukcija jer omogućuje praćenje oštećenja na konstrukciji, pomaže u održavanju i upravljanju, te omogućuje sigurno korištenje mosta. Kako bi se omogućilo praćenje stanja mosta, te pravodobno upozorilo na probleme vezane za sigurnost, na ovom je mostu ugrađen integrirani sustav praćenja stanja ove građevine. U radu se detaljno opisuje sustav praćenja koji se primjenjuje na Mostu Junshan preko rijeke Jangce. Postupak uglavnom uključuje odabir varijabli praćenja i raspoređivanje senzora na određenim točkama, primjenu sustava za prikupljanje i prijenos podataka, strategiju pohranjivanja podataka i upravljanja podacima, te sustav korisničkog sučelja. Analiziraju se sve vrste podataka prikupljene tijekom svakodnevnog korištenja, kao što su npr. opterećenje vozila, progib, pomak i napetost kabela. Također se analiziraju i podaci dobiveni praćenjem u ekstremnim uvjetima, prolaz preko mosta dva kamiona od 178 tona. Rezultati pokazuju da sustav praćenja dobro funkcionira te da se na nekim zavarenim spojevima mogu očekivati oštećenja uslijed zamora.

Ključne riječi:
praćenje stanja, ovješeni most, otkrivanje oštećenja, održavanje mosta

1. Introduction

With the development of new materials and rapid advances in the design and construction technology, many long-span and complex bridges have been constructed worldwide. Although the safety of a structure is increased by reasonable design and high-quality construction, adverse factors, including but not limited to the environmental corrosion, material ageing, and fatigue damage, negatively affect the bridge, and may even lead to catastrophic collapse. In the past several decades, many bridge catastrophes have been reported all over the world. Traditional bridge inspection techniques have disadvantages such as excessive duration, poor timeliness, and traffic interruptions, which is why an effective monitoring system, allowing smart system identification and damage detection, is needed. In recent years, a great deal of research has focused on the structural health monitoring (SHM) technique [1-4]. To ensure structural safety during its service life, the SHM system (SHMS) has been designed and implemented on many important bridges in the United States [5-7], Europe [8-12], Canada [13, 14], Korea [15-17], and Japan [18-20]. In China, the SHMS has been implemented on a large number of long-span bridges [21-24]. Nowadays, it has become a trend to monitor operational conditions, detect damage, assess performance, and define maintenance, using data measured by SHMS [25-28]. Therefore, the issue of how to design SHMS and analyse the monitoring data has become a critical concern in the research of structural health monitoring.

This paper presents the design and implementation of an integrated SHMS on the Junshan Yangtze River Bridge in China. Various measured data collected by SHMS are analysed in detail to evaluate the operational status and thus to provide maintenance suggestions to the bridge administration authority. The monitoring of structural response under extreme conditions is also analysed and discussed in the paper. Appropriate conclusions are presented in the final part of the paper.

2. Design and implementation of SHMS

2.1. General design of SHMS for Junshan bridge

The Junshan Yangtze Bridge, located in Wuhan City of Hubei province in China, is a semi-floating five-span continuous cable-stayed bridge, as shown in Figure 1. The bridge is a part of the highway over the Yangtze River, which connects Jinkou town and Junshan town, using the upstream side for travelling from Junshan to Jinkou. The span arrangement is 48 m+ 204 m+460 m+204 m+48 m. The main beam is a steel box girder structure 3.024 m deep and 38.3 m wide. The net width of the deck, which accommodates six lanes, is 33.5 m. The height of tower from the pile cap to the top is 163.5 m. A total of 72 pairs of cables are installed between the girder and towers. The bridge was completed and opened to traffic on December 15, 2001. Some photos of construction and components of this bridge are shown in Figure 2. With the economic development, the traffic over this bridge is very busy, and most of the traffic is composed of heavy vehicles. Due to over-loaded vehicles, environmental corrosion, material ageing, and fatigue, some damage has been established during periodic inspection, such as cracks in the steel box girder and the tower wall, and failure of some parts of the cable stay dampers. Although this damage has been repaired, new damage is likely to occur in the future. For timely identification of the operational status and provision of proper maintenance suggestions, an integrated SHM consisting of more than 300 sensors has been designed and implemented to monitor the Junshan Bridge.

Figure 1. Layout of Wuhan Junshan Yangtze Bridge

Figure 2. Details of Wuhan Junshan Yangtze Bridge: a) Hoisting of steel box girder; b) The welded detail in steel box girder; c) Deck; d) Cable

The general monitoring procedure is conducted as follows. Firstly, the monitoring parameter and layout of measured points are determined based on structural analysis using finite element analysis, existing damage survey data, and maintenance requirements. Then various types of sensors and instruments are chosen and installed on the bridge. Secondly, all kinds of sensor signals, such as analogue signals, digital signals and optical signals, are collected by the site data acquisition system and then transmitted to the central database via the optical fibre transmission network. Thirdly, a database system and storage tactics are developed for the storage and management of measured data. Finally, the user interface system is developed, to make it convenient for the manager to monitor the operational status, obtain safety alarm information, and make response.

2.2. Arrangements of measuring points

Environmental conditions, loads and structural response parameters were monitored in order to meet structural safety, serviceability, durability, and maintenance requirements. The arrangement of sensors was determined according to the results of the finite element analysis (FEA), and damage and risk analysis gathered from similar bridges, such as the Shandong Binzhou Yellow River Highway Bridge [29].

Wind is an important source of excitation that can cause large deformations and vibrations of the structure. According to design documents, the designed maximum wind speed is 27.6 m/s at the bridge site, which is the speed to which cable-stayed bridges like the Junshan Bridge are sensitive. Considering the large measurement range (wind speed: 0~70 m/s, wind direction: 0~360 degree), good linearity (0.1 %), high reliability and economy, two mechanical anemometers were installed on top of the towers. Proper wind load characteristics can be obtained based on wind speed and direction measurements.

Humidity not only causes the eroding and ageing of the material but also influences the measuring data of the automatic sensor testing system, which is why 4 hygrometers were placed on the top of pylons, on the deck at mid-span, and in the interior of the steel box girder, respectively. Digital hygrometers LTM9901M made by a Chinese manufacturer were chosen. They have the measuring range from 0 % to 100 % Relative Humidity(RH), accuracy of ±3 % RH, and resolution of 0.1 % RH.

To monitor temperature fields of the structure, a total of 132 thermometers were installed at different sections of pylons, on the superstructure, and on some cable-stays. The thermistor type and thermocouple type thermometers have a relatively low accuracy, anti-interference, and durability, and they are unsuitable for distributed monitoring. The installation of fibre Bragg grating (FBG) thermometer is complex, and its long-time maintenance and replacement are difficult. Consequently, digital thermometers LTM8877, made by a Chinese manufacturer, were chosen in this system because of their high accuracy, stability of performance, convenience of distributed monitoring, and easy

maintenance. They have a broad range of -55 °C to 125 °C, accuracy of 0.5 °C, and resolution of 0.0625 °C. Figure 3 shows the field photo of anemometer and hygrometer installed on the bridge.
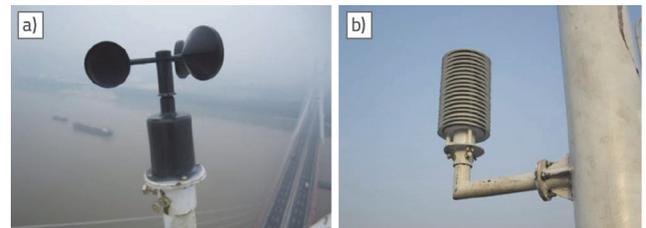

Figure 3. Anemometer and hygrometer installed on the bridge: a) Anemometer; b) Hygrometer

To identify the traffic load across the bridge, a six lanes weigh-in-motion (WIM) system was installed on the deck of the bridge. The installation of the bending plate weighing system based on the strain sensor requires a big slotting on pavement and it is very difficult to maintain and replace the sensors. The vehicle detection and recognition system based on microwave and radar techniques cannot identify the weight of the vehicle. Therefore, a WIM system based on the piezoelectric film sensor was adopted in this SHM system. The adopted WIM system has a good accuracy and durability, it is easy to maintain and replace the sensors, and it inflicts little damage to pavement. Figure 4 shows a field photo of the WIM sensor and demodulator installed on the bridge.

Figure 4. The WIM system installed on the bridge: a) WIM; b) Demodulator

Although some sudden loads, such as earthquake and ship collision, can be expected to occur very rarely, their energy is quite huge and can lead to damage of the structure. A triaxial servo accelerometer GT41 made by a Chinese manufacture was selected for installation at the bottom of the pylon. The measured data can be used to assess the health status of the bridge after a catastrophic event. The accelerometer has a broad frequency range of DC to 120 Hz and large scale range of ±19.6 m/s^2, and it has a high sensitivity of 2.5 V/g, where g is the acceleration of gravity.

Structural space deformation is the reflection of the mechanical characteristics, and is an important index affecting normal operation of a bridge. Four load cases were calculated using finite element analysis as follows:

1. The first case is grade-I vehicle load defined by Chinese design code.

2. The second case is that one with pylons developing settlement of 5 cm.
3. The third case is to decrease temperature of the structure from 20 °C to -9 °C for the steel beam, and from 20 °C to -3 °C for concrete pylons.
4. The last case is to raise temperature of the structure from 20 °C to 46 °C for the steel beam, and from 20 °C to 34 °C for concrete pylons.

The envelope results of the four load cases are listed in the Table 1.

Table 1. Bridge deformation calculated by FEA

Item	Maximal [m]	Minimal [m]
Vertical deflection of the girder at mid-span	0.465 (up)	-0.876 (down)
Longitudinal displacement at the top of the tower	0.282 (offset to side span)	0.391 (offset to mid-span)
Longitudinal displacement of bearing	0.361 (leave away from mid-span)	0.388 (close to mid-span)

Laser transducers and total stations are unsuitable for the long-term monitoring of a long-span bridges. The connected pipe liquid level sensor based on the pressure transmitter has high accuracy, long measuring distance, good long-term stability and durability, and thus it was chosen to monitor vertical deformation of the beam. A total of 16 deflection sensors were installed along the main girder, with two sensors installed upstream and downstream in the main span to monitor torsional deflection of the beam.

The aforesaid displacement sensors can only be used for relative displacement. To monitor the absolute displacement of the bridge, three global positioning system(GPS) sensors were installed on top of the pylons and the mid-span of the beam to monitor the space deformation of the bridge, while one GPS sensor was placed at the central room as reference station.

The inclination of pylons also reflects mechanical characteristics of a bridge. Four servo tiltmeters LCF-100 are installed on the top of two pylons to monitor inclination in the longitudinal and transverse directions of the towers, respectively. This sensor type has good long-term stability, broad range (±1 °C~±90 °C), high resolution (1μ rad), large operating temperature (-18 °C~70 °C), and excellent control of temperature draft.

Bearings should withstand deformations of the beam under all kinds of loadings such as the traffic load, temperature, shrinkage and creep of concrete, so that the operation condition of the bearings needs to be monitored. The long-term stability of displacement sensor of pull on the rope is not good, and it is susceptible to environmental temperature. The measuring range of the Linear Variable Differential Transformer (LVDT) displacement sensor is not large and its installation is complex. Thus, the magnetostrictive displacement sensor was chosen due to its large range (50~7600 mm), high accuracy, good long-term stability, and convenience of installation. The measuring range and resolution of the sensors were chosen according to the calculated results obtained by FEA. Figure 5 shows the installation photos of the deflection gauge, magnetostrictive displacement sensor and GPS.

Stress is one of the most important variables of structural status. The critical cross-sections that are selected for monitoring are those suffering large stresses under operational loads. They could be determined through finite element analysis on the structure at the operation stage. The result shows that critical cross-sections subject to large stresses are at the assistant pier, mid-span of the side span, the quarter span, and mid-span of the main span. The maximum and minimum stresses at the top of beam are 48.6 MPa and -39.0 MPa, and 35.7 MPa and -47.8 MPa at the bottom. It shows that critical cross-sections suffering large stresses are at the assistant pier, mid-span of the side span, the quarter span, and mid-span of the main span. In addition, the bottom of the tower is also a critical section, so that a total of 130 strain gauges were installed in these critical sections.

At present, there are three types of strain sensors: those with the resistive strain gauge, with the vibration wire strain gauge, and with the fibre Bragg grating (FBG) strain gauge. The resistive type has poor durability and low capacity of anti-electromagnetic interference, and its sensitivity is somewhat low. Strain gauges with vibration wire are unsuitable for the distributed and dynamic monitoring. The FBG strain gauge has good durability, sensitivity and high capacity of anti-electromagnetic interference, and it is suitable for the distributed and dynamic monitoring, which is why it was adopted in this SHMS. A FBG strain gauge made by a Chinese manufacturer was selected. It has a measuring range of ±1500 με, an accuracy of ±2~3 με and a resolution of 1 με.

Stay-cables are the major force-bearing components, and the variation of cable tension has a considerable impact on structural performance. Furthermore, the rain and wind load can also cause vibration of stay-cables. In the system, 36 uniaxial servo accelerometers were installed on parts of cable-stays to monitor dynamic response and to identify the cable forces based on spectrum method.

The Junshan Bridge has the fundamental modal frequency of 0.31 Hz as predicted by finite element

Figure 5. Installation photos of deflection gauge, magnetostrictive displacement sensor and GPS: a) Deflection gauge; b) GPS; c) magnetostrictive displacement sensor

Figure 6. FBG strain gauge and accelerometers measuring cable tension and vibration: a) FBG strain gauge; b) accelerometer; c) accelerometer

Table 2. Monitored variables and sensors

Type	Variable	Sensor	Total
Environment	wind	anemometer	2
	humidity	hygrometer	4
	temperature	thermometer	132
	vehicle loading	WIM	6
Load	earthquake, ship impact	triaxial accelerometer	1
Response	stress	FBG strain gauge	130
	inclination	tiltmeter	4
	deflection	deflection gauge	16
	space deformation	GPS	4
	bearing displacement	magnetostrictive displacement sensor	2
	vibration	accelerometer	12
	cable tension	accelerometer	36

identified by analysing the measured response, and then the identified result can be used for updating the finite element model of a structure. In consequence, a more accurate structural model can be treated as a baseline model for statistical analysis and performance evaluation of bridges. In addition, when bridges encounter some extreme events, such as earthquake, ship collision, traffic accident, or harsh weather, the monitoring response can be used to analyse the operational status and assess safety of a structure. A total of 12 uniaxial servo accelerometers were installed on the tower and girder to monitor the dynamic response.

Figure 6 shows the FBG strain gauge, accelerometer measuring cable tension, and accelerometer monitoring vibration of the bridge. The monitored variables and the types of sensors are summarized in Table 2, and the general arrangement of the measuring points is shown in Figure 7.

2.3. Data collection and transmission

analysis. The experience with similar bridges shows that the vibration amplitude under normal ambient excitation is in the order of cm/s². Therefore, a uniaxial servo accelerometer GT02, made by a Chinese manufacturer, was selected for installation on the bridge. It has a broad frequency range of DC to 120 Hz and good performance at low frequency, and it has large scale range of ±19.6 m/s², sensitivity of 255 mV/m/s², and a large limitation of anti-impact of more than 2450 m/s².

The structural vibration response reflects dynamic characteristics of bridge. Structural frequencies and modal shapes can be

The monitored data were collected by the site acquisition station and transmitted to the central room by the optical fibre network. The total length of the bridge is 964 m, and diverse data are monitored by sensors including voltage, current, light signal, etc. Considering the communication range and the layout of diverse sensors, five data acquisition units (DAUs) were deployed at different cross-sections of box girders to collect signals from the surrounding sensors, taking into consideration the allowable maximum distance between the sensors and DAUs to eliminate transmission loss/noise and to protect the DAUs from interference. The data are then transmitted to the site
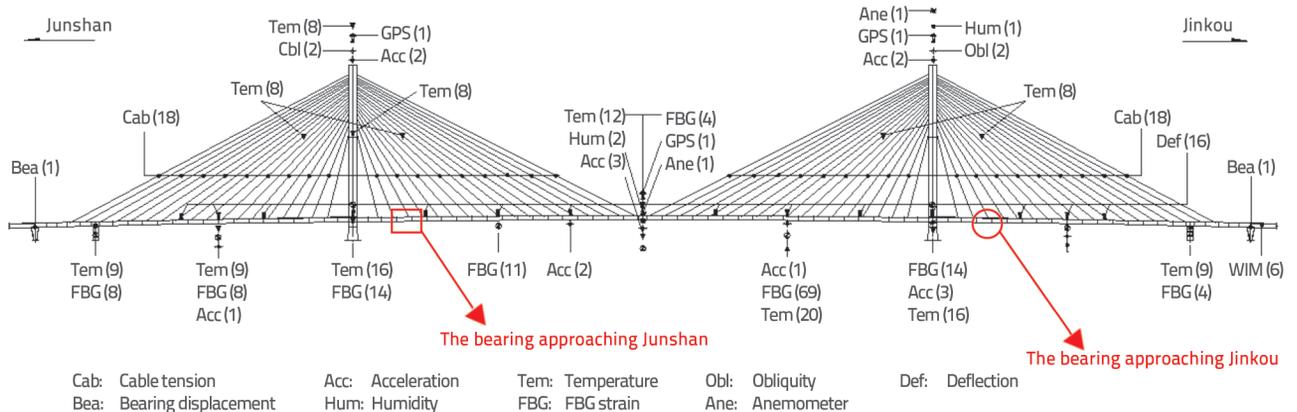

Figure 7. General arrangement of all measuring points at Junshan Bridge

acquisition stations. To ensure the durability and stability and to decrease the communication distance, two site acquisition stations were placed in the lower beam of the pylons, where structural vibrations and variations of temperature and humidity are small. Ensuring the reliable transmission of the diversity signal, the whole network topology of the Junshan Bridge is composed of four groups of transmission networks:

- The first is the trunk optical fibre transmission network which takes charge of data transmission among the two site acquisition stations and the central room. The measured data including wind, humidity, temperature, inclination, deflection, bearing displacement, are firstly aggregated to the nearest DAUs, and then the data are transmitted to the site acquisition station with RS-485 bus. The acceleration signal is transmitted to a special conditioner placed in the acquisition station using an RVVP cable. To ensure the redundancy and reliability of the transmission data among site acquisition stations and the central room, the servers on site and in the central room are connected using multiple fibres, and a fibre distributed-data interface (FDDI) dual-loop fibre Ethernet is designed and implemented to transmit mutually data among them.
- The second is the FBG strain monitoring network. The data measured by strain sensors is the light signal, which needs to be demodulated by special fibre demodulation instrument. Because the operational environment in central room is better than that on the site, the fibre demodulation instrument is placed in the central room, and the monitored strain data is not transmitted to the site acquisition station but to the instrument using fibre, and then the demodulated result is stored and uploaded to the database server.
- The transmission network for vehicle load is the third network. The WIM system is installed on the deck of the approach bridge. Confined to the communication range of data measured by the WIM system, their demodulation

computer is placed in the box girder near the system. The demodulated result is directly transmitted to the central room using fibre.

- The last one is the GPS fibre network. The monitoring data is transmitted to the GPS receivers by RS232 cable. Because the transmission distance of RS232 cable is very short, the electronic signal is transformed to the light signal, and then it is transmitted to the demodulating computer in the central room by the fibre network.

The user can explore and manage all the measured data and analyse the results in central room or visit the system remotely through internet.
The entire data collection and transmission network of the Junshan Bridge is shown in Figure 8.

2.4. Data storage and management

The functions of data storage and management are implemented through the database system. To meet the requirement of the storage and management of the diverse and massive data, the monitoring database was built using the Microsoft SQL server. Because the volume of the long-term monitoring data is very extensive, different storage strategies are applied for the static and dynamic data, respectively. The static data, such as temperature and deflection, which change slowly and their sampling frequency is low, are collected and stored entirely in the database server. The dynamic data with high sample frequency, such as stress and acceleration, are acquired continuously in the site acquisition station. Only a part of the data and statistical analysis results are uploaded to the database in the central room; Older data are periodically deleted, and only the latest two weeks monitoring data are stored in the field acquisition station. When the bridge encounters an extreme event, such as an earthquake, accident, ship collision, or harsh weather, the threshold triggering collecting strategy is activated, and then all data during the accident will be acquired and stored for further structural analysis and safety evaluation.

2.5. User interface system

An interface system is developed to inspect and analyse monitoring results. There are two modes of the user interface system. The first one is the client/server (C/S) mode that can quickly process all kinds of complex requirements, but it requires installation of many different client software on computers of the user. It is inconvenient for the development and maintenance of the software system. The other one is the browser/server (B/S) mode that
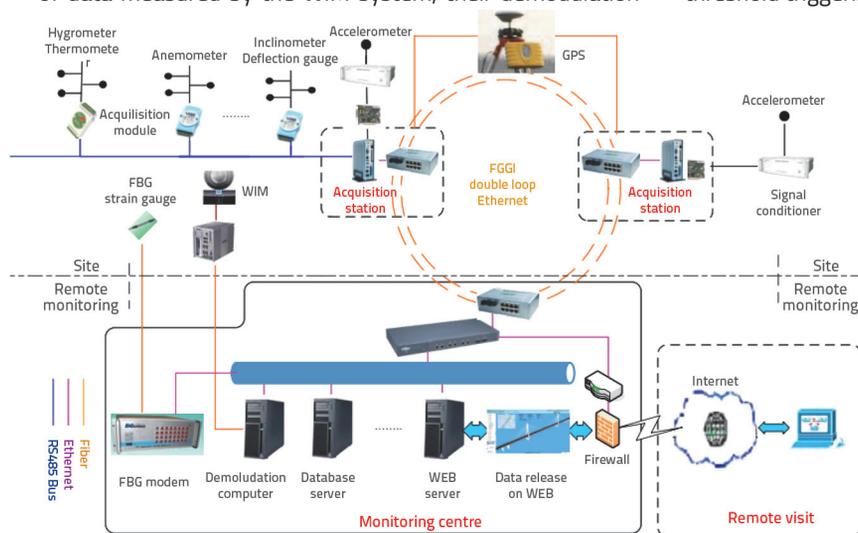

Figure 8. General collection and transmission network of Junshan bridge

is not suitable for complex and quick signal processing by the client, without requirement of client software in user's computers. All the functions are provided by the server, and a user can visit and control the system according to the authorisation given through the general browser software.

To meet the remote visiting and real-time monitoring requirements, the combination of C/S and B/S modes was adopted in designing the interface system of the Junshan Bridge. The C/S mode is applied to communicate among the field acquisition station, the storage and management system, and the database server. The data acquisition software, the database software and all kinds of analysis software were developed and installed in the corresponding server. As a consequence, it can achieve quickly on-line data collecting and high data processing. On the other hand, the interface among the web browser, database server, and user are designed as B/S mode. All functions are provided by the web server, and the user can conveniently visit the system through the web browser. No client software needs to be installed in the user's computers, and so the maintenance and update of system function can very easily be made by revising the software installed on the server.

The mode of the user interface system at the Junshan bridge is shown in Figure 9, and the web interfaces of SHMS of the bridge are shown in Figure 10.
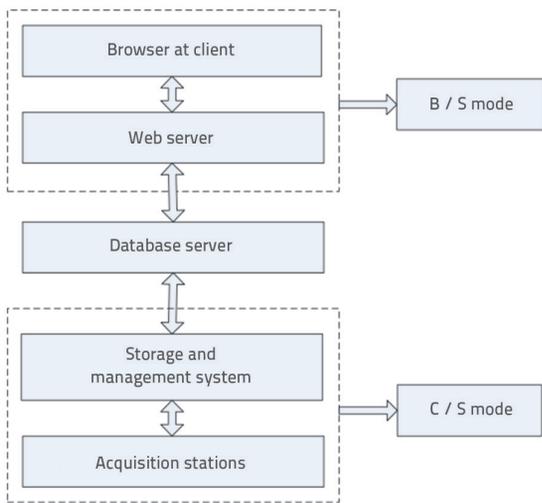
Figure 9. Mode of user interface system at Junshan Bridge
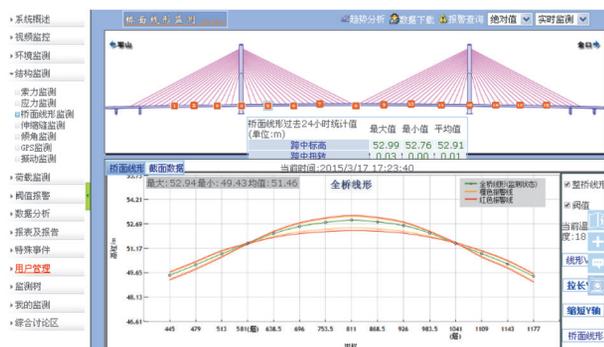
Figure 10. Web interfaces of SHMS at Junshan Bridge

3. Analysis of measured data

3.1. Temperature and humidity

The environmental humidity is one of important influence factors causing corrosion in steel structures. Four hygrometers are installed on the top of the tower, the deck at mid-span, and the interior of steel box girder. The data obtained on Mar 5 2015 from the sensor in the steel box girder is analysed. The sampling period lasted one minute. Figure 11 shows the curves of humidity and temperature with respect to time in one day.
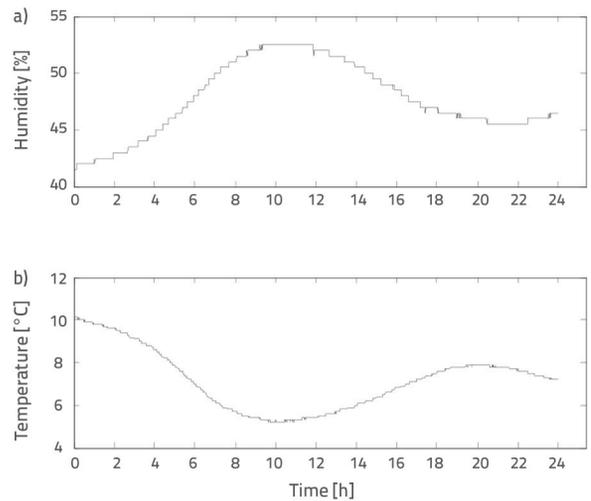

Figure 11. The curves of humidity and temperature (a) humidity and (b) temperature

As shown in Figure 11, the humidity in girder varies between 41.5 % and 52.5 % in one day, while the temperature changes between 5.2 °C and 10.1 °C. The max variation of humidity is 9 %, whereas that of temperature is 4.9 °C. The humidity declines with an increase of temperature, and vice versa. By monitoring humidity, the SHMS can remind the bridge manager to take rational maintenance measures, such as to open the dehumidifier to alleviate the corrosion risk at the steel box girder, when humidity is very high.

3.2. Vehicle load

The WIM system with six lanes is installed on the deck to monitor vehicle load. The lanes are numbered as 1,2,...,6. Vehicles from Jinkou side to Junshan side cross the bridge on the downstream while vehicles from Junshan side to Jinkou side travel on the upstream. The layout of six lanes is shown in Figure 12. The WIM system will identify the axle load, vehicle speed, type of vehicle, and the number of vehicles at every lane. The data obtained from the WIM system can be used to build the vehicle bridge model for structural assessment. Here the data gathered on 7 March 2015 are used for statistical analysis. All lanes are numbered as 1 to

6 from upstream to downstream. Figure 13 shows vehicle distribution result per lane and time. The mean weight and speed of vehicles in all lanes are shown in Figure 14.
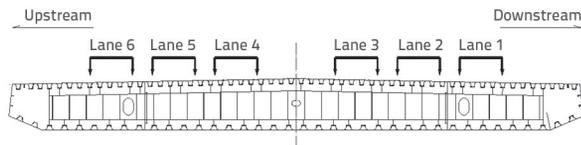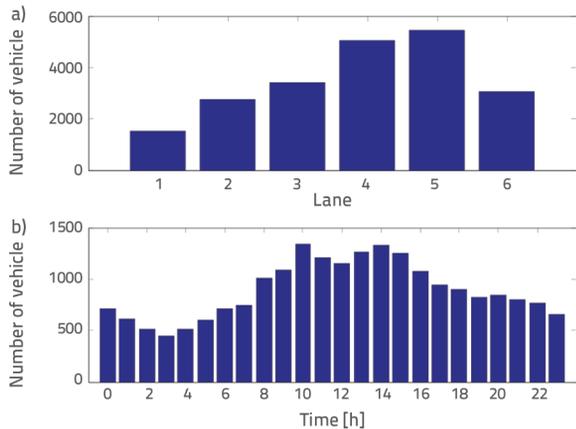

Figure 12. Layout of six lanes

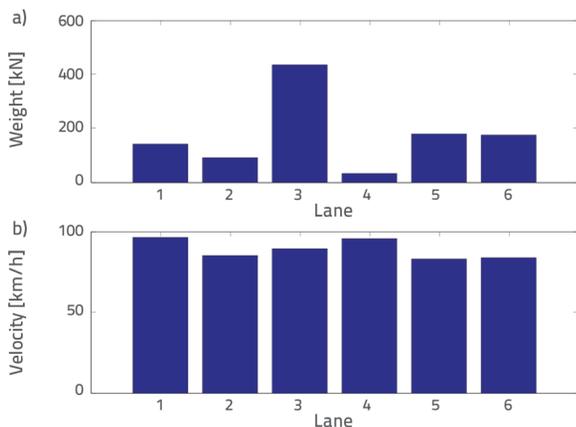**Figure 13. a) vehicle distribution per each lane; b) vehicle distribution in 24 hours**

Figure 14. a) mean weight distribution in every lane; b) average speed distribution in every lane

As can be seen in Figure 13, a total of 21279 vehicles cross the bridge in one day, with most vehicles, as many as 5440, pass through lane 5 and the lowest number of vehicles use lane 1. Figure 14 shows that the mean weight of the vehicles is the greatest in lane 3. The daily traffic on the bridge is busy, especially from 8am to 4pm. Because the bridge is located on a highway, the average speed of vehicles in every lane varies between 80 km/h and 100 km/h, the highest speed reaching 95.9 km/h in lane 1.

It is very important to monitor the heavy load across the bridge as it may cause structural fatigue damage. Figure 15 shows the distribution of the vehicles beyond 300 kN in every lane, and the distribution of overloaded vehicles in lane 5 at every hour.
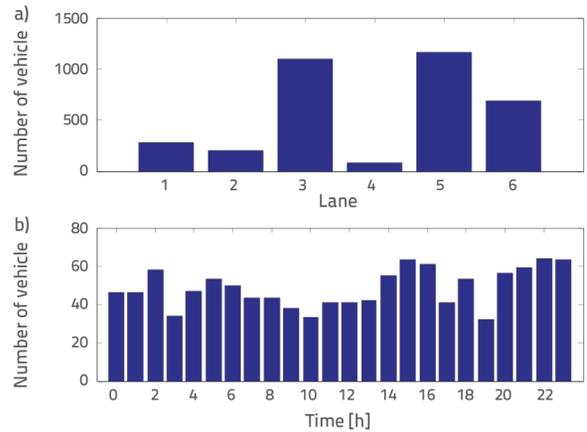

Figure 15. a) overloaded vehicles beyond 300kN in every lane; b) overloaded vehicles in lane 5 at every hour

Figure 15(a) shows that the number of overloaded vehicles in lane 5 and lane 3 exceeds the corresponding number in other lanes, with the maximum of 1162 in lane 5. Therefore, more attention should be paid to the maintenance of the steel box beam near lanes 5 and 3. Figure 15(b) indicates that the number of overloaded vehicles crossing lane 5 is dispersed and that there is no clear rush hour.

3.3. Displacement of bearing

To monitor the bearing displacement, 2 Magnetostrictive displacement sensors are installed at the expansion joint on both sides of Jinkou and Junshan, respectively. The displacement data on 7 March 2015 were collected with the sampling frequency of 1 Hz, and the displacement for bearing is defined as positive when it points away from mid-span of the main span. Figure 16 shows the displacement curve of the bearing at Jinkou side marked in Figure 7 by a circle, and Figure 17 shows the regression analysis result between the temperature of the main girder and the displacement of this bearing.
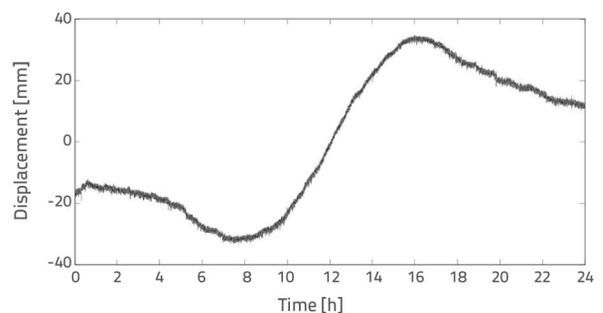

Figure 16. Curve of bearing displacement at Jinkou side

The blue dashed line is 95 % confidence interval of the regression result. The similar analysis results of bearing approaching Junshan side, marked in Figure 7 by a block, are shown in figures 18 and 19, respectively.
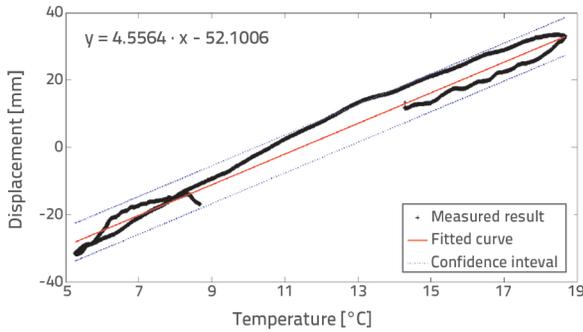

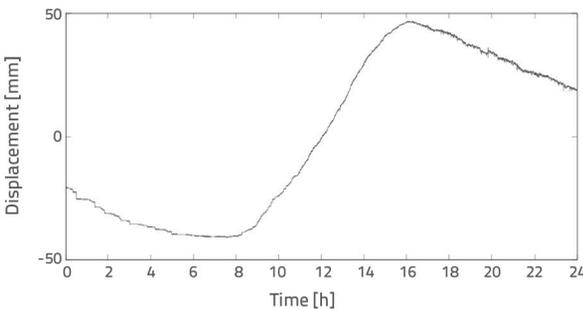**Figure 17. Regression curve between displacement of bearing and temperature of beam**

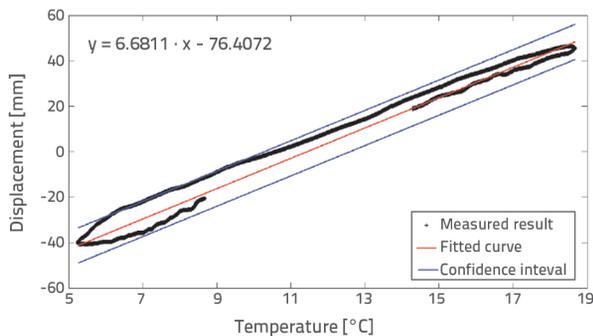**Figure 18. Curve of bearing displacement at Junshan side**

Figure 19. Regression curve between displacement of bearing and temperature of beam

The regression result indicates that there is a good linear relation between the beam temperature and displacement of bearings at both sides. The corresponding correlation coefficients at Jinkou side and Junshan side are 0.9918 and 0.9928, respectively. Based on the regression equation shown in figures 17 and 19, it can be concluded that when the temperature rises by 1 °C, the displacement of two bearings in both sides will increase by about 4.6 mm and 6.7 mm, respectively, and the sum of the displacement of two bearings is 11.3 mm, which is in good agreement with the

result (12.2 mm) calculated by the finite element analysis (FEA). The monitoring result indicates that the bearings operate well.

3.4. Cable tension

A total of 36 accelerometers are installed on the 36 cable-stays, which are consecutively numbered as 1, 2, 3,…36 from the side of Jinkou to Junshan, and the sample frequency is 20 Hz. The power spectrum method is used to identify the cable tension at every hour. Because the cable tension changes with load and environmental factors, the data measured at 2:00 a.m. are analysed. At that time, the structural temperature field is uniform. For comparing the cable tension, the result of periodical test conducted in January 2006 is taken as the benchmark value. Figure 20 shows the cable tension identified on March 5 2015 and the deviation between the monitoring and benchmark results. As shown in Figure 20, the deviation of cable tension is less than 3 %, which indicates that the operational status of the cable-stays is normal.
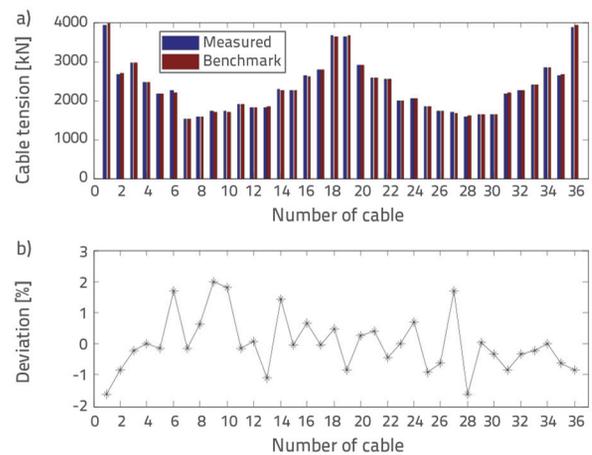

Figure 20. a) Cable tension at 2:00 am; b) Deviation between measured cable tension and benchmark results

3.5. Fatigue evaluation

Based on the measured stress data, a hot spot stress method is applied to evaluate fatigue of the steel box girder at the Junshan bridge. Considering the stress characteristics of the steel box girder, two dangerous regions are mainly evaluated: the welded joint between deck and U-rib, and the welded joint between the diaphragm and lower edge of the U-rib. Six measured points were selected for both joints, and were numbered consecutively from the left to the right, like 2-1, 2-2,…, 2-6. Figure 21 shows the layout of the measured points.
Firstly, a FEM model of the steel box girder segment is developed to analyse the stress concentration factor (SCF). The local model is shown in Figure 22, and the calculated SCFs of two types of welded joints are 1.55 and 1.49, respectively.

Table 3. Result of fatigue evaluation

Measurement point	Damage degree [%]	Expected service life [year]	Measurement point	Damage degree [%]	Expected service life [year]
1-1	0	>>100	2-1	52.6	190
1-2	0	>>100	2-2	29.3	342
1-3	0	>>100	2-3	595.9	17
1-4	0	>>100	2-4	3.8	2625
1-5	14.2	705	2-5	510.1	20
1-6	31.9	314	2-6	348.2	29
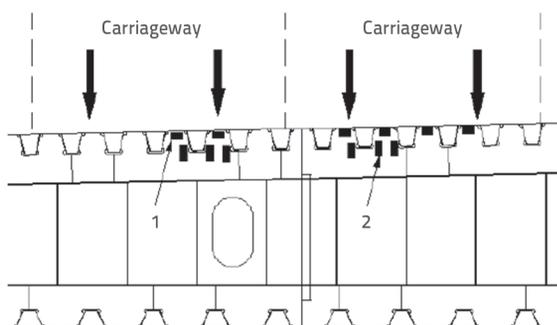
Figure 21. Layout of measuring points
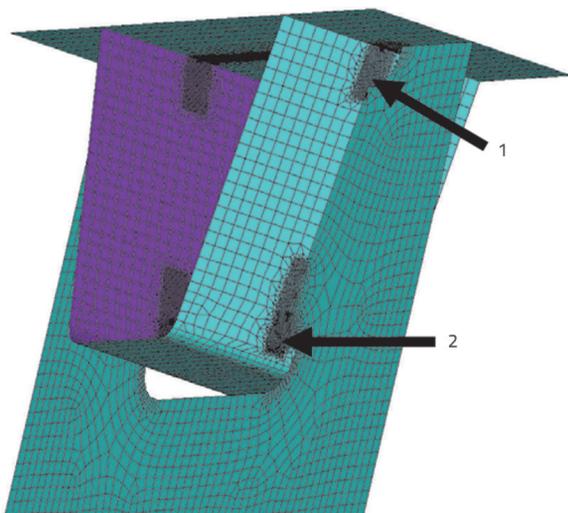
Figure 22. Local finite element model

Afterwards, the stress data collected from 3 to 18 November, 2011 were analysed, and the hot spot stress data were statistically analysed, and the standard daily stress spectrum was acquired by the rain-flow counting method.

Finally, the fatigue performance was evaluated based on the linear cumulative damage criterion and fatigue strength curves. The evaluation results are listed in Table 3.

It is seen from the result that the damage degree of the first kind of welded joint is far less than 100 % at the end of the design service life. For the second kind of welded joint, the damage degree of most of the measured points is larger than 100 %, except for points 2-1 and 2-4. In consequence, fatigue damage may occur in the welded joints between the diaphragm and lower edge of the U-rib. The main reason is that the flexure deformation is constrained by the diaphragm, which will cause a very large secondary bending stress. At the same time, the vertical flexure deformation of the diaphragm will cause large bending stress and shear stress in the plane. Some fatigue cracks were identified in this region of the bridge, so that it may be concluded that the region is a weak part of steel box girder and that it needs major monitoring and strengthening maintenance.

4. Bridge monitoring during extreme conditions

Two heavy trucks weighing 178 tons moved across the bridge from Jinkou side to Junshan side on 2 November 2011. The trucks were semi-trailers with multiple axles. One had 15 axles and the other had 16 axles. For the safety of the bridge, the traffic was temporarily closed from 08:32:00 to 09:14:24, and the trucks crossed the bridge at the speed of 10km/h. The first truck arrived at the expansion joint at Jinkou side at 08:43:39 and left the expansion joint at Junshan side at 08:49:32, and the time of the arrival and leaving of the second truck was 09:03:53 and 09:10:01, respectively. The weather was fine with the temperature of 18.7 °C and the breeze of 2.6 m/s. The first truck readying to cross the bridge is shown in Figure 23.

Figure 23. Photo of truck ready to cross the bridge

The structural response was monitored by SHMS while trucks were crossing the bridge. The numerical analysis was performed by FEA to validate the monitoring result. Because the bridge was temporarily closed, the results of the live load effect were extracted. Figure 24 shows the deflection at the middle of the Jinkou side span, while FEA result is also plotted by the red dashed line for comparison. Figure 25 shows the result of the downstream measuring point at the middle of the main span.
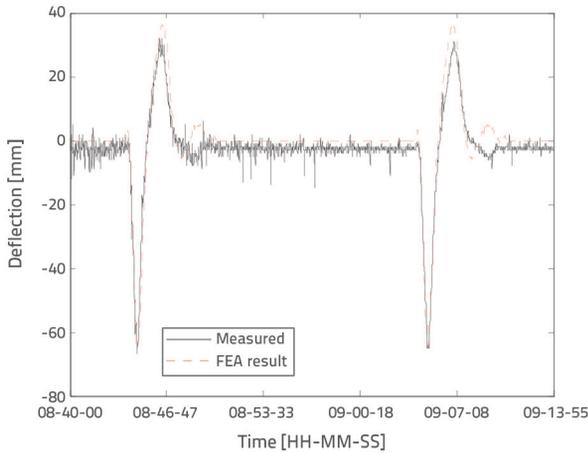

Figure 24. Deflection curve at the middle of the Jinkou side span
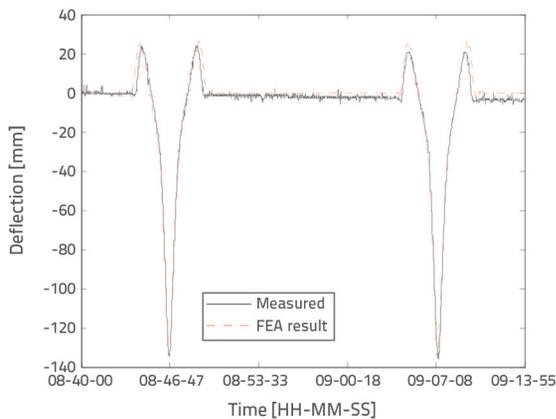

Figure 25. Deflection curve at the middle of the main span (downstream)

As shown in figures 24 and 25, the structural response was precisely monitored by SHMS when two trucks were crossing the bridge, and the measured result agrees with that of the FEA result. The maximum deflection of the beam at the side and main spans was 67 mm and 136 mm, respectively. The residual deformation after trucks passed the bridge was very small, which indicates that the deformation is elastic and that the force characteristics of the structure did not change.

The installed GPS monitored the longitudinal and transverse displacement at the top of the towers, and the tiltmeter monitored the longitudinal and transverse inclination at the top of the towers. Here, the longitudinal displacement and inclination of the tower at the Junshan side is collected and analysed, and the displacement and inclination from Jinkou to Junshan is defined as positive. The monitored result is shown in Figure 26.
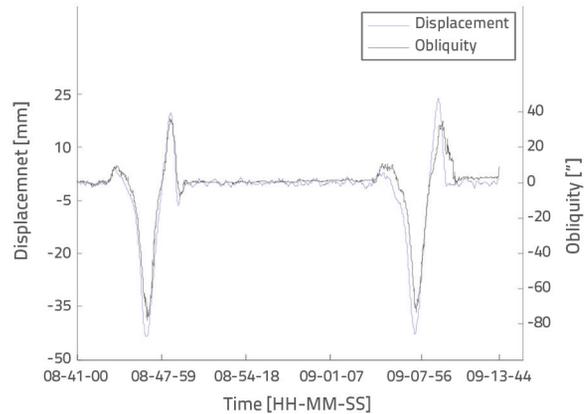

Figure 26. Monitoring longitudinal displacement and inclination of Junshan tower

The result indicates that the variation of longitudinal displacement is in accordance with that of the inclination, which corroborates good cross-calibration from different types of sensors. The maximum displacement and inclination is 43.8 mm and 78.0'', respectively, and the minimum is 23.9 mm and 36.5'', respectively.

As shown in Figure 7, quite a few FBG strain gauges are installed at individual sections along the steel box girder to monitor the structural stress response. In each section, four measuring points are arranged on two steel webs at the downstream and upstream, and two measuring points are installed at the top and bottom of each steel web, as shown in Figure 27.

The monitoring results for the upper measuring points on the downstream webs in the section at the middle of the Jinkou side span is shown in Figure 28. For comparison, the result calculated by FEA is plotted in the same figure using the red dashed line. Figure 29 shows the results of the lower measuring points, while the results of the top and bottom measuring points in the section at the middle of the main span are shown in figures 30 and 31, respectively.
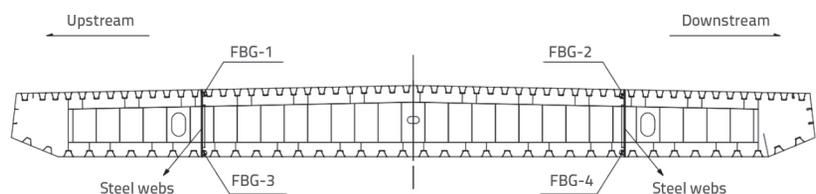

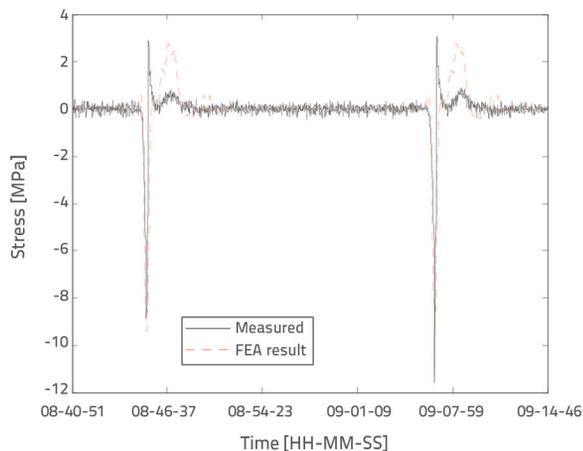Figure 27. Layout of stress measuring points on steel webs

Figure 28. Stress curve of upper measuring point at middle of Jinkou side span (downstream webs)
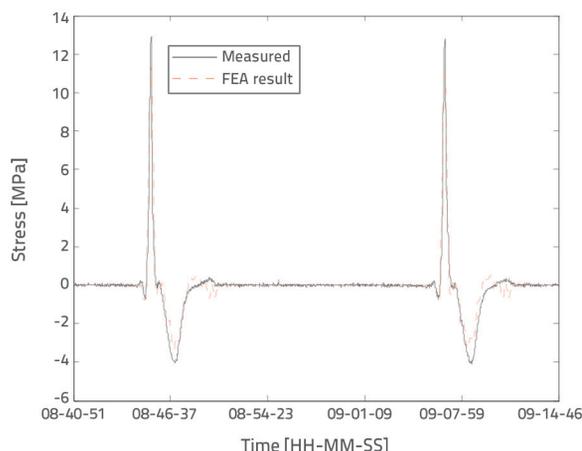

Figure 29. Stress curve of lower measuring point at middle of Jinkou side span (downstream webs)
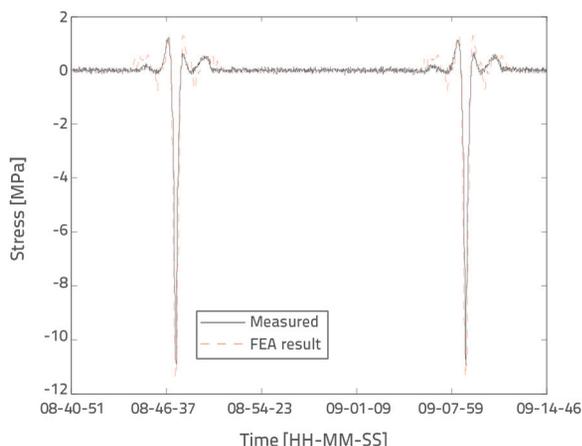

Figure 30. Stress curve of upper measuring point at middle of main span (downstream webs)
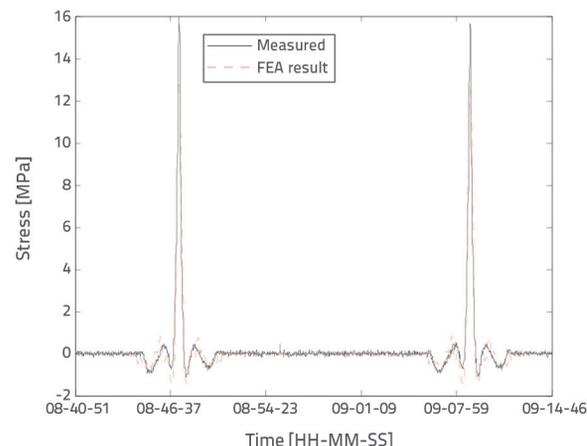

Figure 31. Stress curve of lower measuring point at middle of main span (downstream webs)

In Figure 28, some discrepancy can be noted between the measured stress and the FEA result, maybe because the sensor was not precisely installed on the girder, i.e. at the designed angle and position, so that, in a certain range, the measured time series may not agree well with theoretical values.

Figures 29 to 31 show that measured results are consistent with FEA results. Under the load of trucks, the top of the steel webs is mainly under compression, and the bottom of the webs is under tension. The maximum and minimum stress in the side span is 12.9 MPa and -11.6 MPa, and the result in the main span is 16.0 MPa and -10.9 MPa. Therefore, it can be concluded that stresses at steel webs in the main span are larger than those in the side span.

In addition, the structural deformation and residual stress values were very small after the heavy trucks crossed the bridge, which indicates that the whole structure is in elastic state and that mechanical characteristics have not changed.

5. Conclusion

The design and implementation of the SHMS for the Junshan bridge are introduced in this paper. Various measured data under both daily operation and extreme conditions are analysed in detail. The monitoring results by GPS and tiltmeter at the same location are in agreement, which indicates that different types of sensors make good cross-calibration. In addition, the measured results are consistent with simulation results implying that the SHMS works well and can timely and accurately monitor all kinds of data. The analysis results under the extreme load indicate that the entire structure is in elastic state and that mechanical characteristics have not changed after the heavy trucks crossed the bridge. The results of fatigue evaluation show that some local welded joints may experience damage and that major monitoring and strengthening maintenance is needed in these regions. Furthermore, the system with the full-scale structure and massive real-world monitoring data

provides a good basis for further research in structural damage detection, performance evaluation, design theory validation, and field experimental analysis.

Acknowledgment

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