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Structural health monitoring system for Sutong Cable-stayed Bridge

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Abstract. Structural Health Monitoring System (SHMS) works as an efficient platform for monitoring the health status and performance deterioration of engineering structures during long-term service periods. The objective of its installation is to provide reasonable suggestions for structural maintenance and management, and therefore ensure the structural safety based on the information extracted from the real-time measured data. In this paper, the SHMS implemented on a world-famous kilometer-level cable-stayed bridge, named as Sutong Cable-stayed Bridge (SCB), is introduced in detail. The composition and core functions of the SHMS on SCB are elaborately presented. The system consists of four main subsystems including sensory subsystem, data acquisition and transmission subsystem, data management and control subsystem and structural health evaluation subsystem. All of the four parts are decomposed to separately describe their own constitutions and connected to illustrate the systematic functions. Accordingly, the main techniques and strategies adopted in the SHMS establishment are presented and some extension researches based on structural health monitoring are discussed. The introduction of the SHMS on SCB is expected to provide references for the establishment of SHMSs on long-span bridges with similar features as well as the implementation of potential researches based on structural health monitoring.

Keywords: structural health monitoring system; Sutong Cable-stayed Bridge; subsystem; extension and application of SHMS

1. Introduction

Bridge works as the connection of two separated locations and makes the land transportation network live and energetic. With the rapid development of transportation, numerous bridges have been worldwide constructed or under construction over rivers, seas and canyons (Li *et al*. 2006, Wang *et al*. 2014). Among them, the cable-stayed bridge is distinguished for its beautiful appearance, reasonable mechanical behavior and excellent spanning capability (Gimsing 1983). It is a preferable alternative for cable-stayed bridges to exhibit as both the landscape and spatial

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passage in urban or suburban areas. In engineering applications, the modern practice has advanced the spanning capability of a cable-stayed bridge to a level that the single main span is beyond 1km, such as Russian Island Bridge (1104 m, Russia), Sutong Cable-stayed Bridge (1088 m, China), Stonecutters Bridge (1018 m, China), etc. Due to the outstanding ability, the long-span cable-stayed bridges usually perform as vital components of the main traffic thoroughfares.

As the national key engineering projects, the long-span cable-stayed bridges are usually designed with an expected service life of more than 100 years. In such a long service period, the bridge will inevitably suffer from a great many long-term and short-term environmental actions (e.g., wind loads, thermal variation, environmental corrosion, even earthquakes, tornadoes, etc.), so that many problems including fatigue effects, material aging, component damages, etc. are gradually produced and developed with the time, directly or indirectly causing slow performance deterioration, severe structural damages and even catastrophic collapse to engineering structures (Li *et al*. 2006, Lynch and Koh 2006, Ou and Li 2010). Meanwhile, the structural performance deterioration will be further aggravated by the daily experienced traffic loads. In such a status, the cable-stayed bridge will be structurally deficient, potentially making the bearing capability to cope with both regular and extreme loads gradually decreasing. Hence schedule-driven maintenance is usually carried out to bridge structures. However, the determination criterion for the schedule is still supported by the experience and the structural inspection cannot cover all the components, probably leaving some structural deficiencies undiscovered and further making the public at risk. Therefore, the durability and safety of long-span cable-stayed bridges in their long-term service periods attract intensive attention from operators and civil engineers (Schallhorn and Rahmatalla 2015).

In recent few decades, the structural health monitoring technology provides an efficient approach to monitor the health status and evaluate the working condition of a structure, offering the potentials to ensure the structural sustainability and serviceability during its service life (Aktan *et al*. 2000, Ou and Li 2010, Cho *et al*. 2010, Xu *et al*. 2012). Structural health monitoring is realized by an integrated intelligent system called structural health monitoring system (SHMS). Up to now, many SHMSs have been proposed and successfully applied on full-scale bridges: e.g., the Akashi-Kaikyo Bridge in Japan (Miyata *et al*. 2002), the Tsing Ma Bridge in China (Ni *et al*. 2010), the Jindo Bridge in Korea (Jang *et al*. 2010), etc. The intelligent system consists of various sensors to collect both input actions and output responses, and is equipped with a post-processing module to extract valuable information from the collected data. In such a view, a structure installed with a SHMS can be considered as a full-scale experimental platform, making people to better understand the environmental actions around bridge structures and enhancing the structural response prediction capabilities. On the other hand, the real-time monitoring of the actions and responses makes it feasible to conduct damage detections and condition assessment without manual field examination (Chang *et al*. 2003, Soyoz and Feng 2009), therefore offering the potential to reduce the inspection and repair costs in bridge maintenance, as well as the associated downtime, all while providing increased public safety (Spencer and Cho 2011, Xu *et al*. 2012).

In this paper, the SHMS implemented on a kilometer-level cable-stayed bridge, SCB, is taken as the research object. The detailed structure and functions of the system are systematically introduced. And the constitutions of the SHMS are separately described with four subsystems included. Among them, the main techniques and strategies adopted in the SHMS establishment are illustrated and the encountered problems in both structural health monitoring and system construction are discussed. Afterwards, some extension researches and applications of SHMS during the performance monitoring of SCB is presented, mainly in respect to wind, temperatures, vibration and displacement cases. Among them, the relevant topics enhanced by structural health monitoring are put forward. The introduction and application of SHMS on SCB are wished to provide references for the establishment of SHMSs on similar long-span bridges.

2. Description of SCB

SCB, which first establishes the direct land connection between Nantong and Suzhou, is a long-span cable-stayed bridge (Fig. 1) across the Yangtze River in China. It was the longest cable-stayed bridge in the world and a world-record breaking project when it was open to traffic in 2008. The bridge has a main span of 1088m and double 500 m side spans. Two inverted Y-shaped reinforced concrete bridge towers are constructed supporting the bridge deck with 272 symmetrically distributed cables. The streamline flat steel-box girder is employed as the bridge deck and the wind mouth is adopted to improve the structural aerodynamic stability.

As shown in Fig. 2, SCB is located in the eastern part of the Asian continent and near the entrance of the Yangtze River to the Yellow Sea. In this area, a humid subtropical monsoon climate performs prominently due to the sea-land thermal differences, which leads to obvious seasonal climate. Specifically, the strong north wind from Siberia in the northwest of China in winter together with the typhoon climate from eastern ocean in summer impact the bridge frequently (Wang *et al*. 2013; Wang *et al*. 2015). In such a wind-prone region, the wind actions and wind-induced structural vibrations of SCB need to be carefully monitored during the long-term service life, leaving the potentially inherent problems (e.g., fatigue effects, corrosion, cracks, etc.) desired to be further investigated.

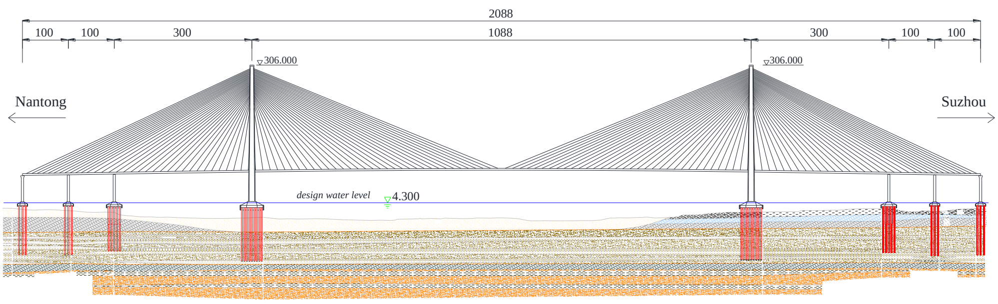


Fig. 1 Layout of the whole structure for SCB (Unit: m)

Fig. 2 Geographical location of SCB

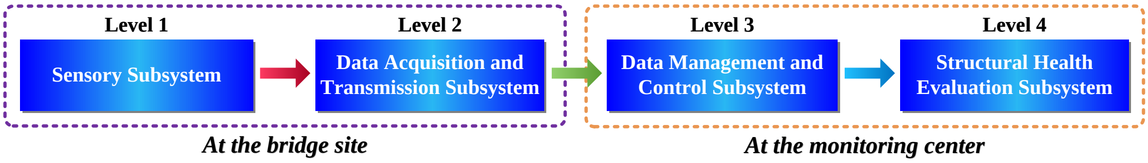


Fig. 3 Structure of the SHMS on SCB

3. Structure and functions of SHMS on SCB

In order to evaluate the health status of SCB, a SHMS has been installed on SCB since its operation in 2008. The structure of the SHMS is divided into four function-independent levels, as shown in Fig. 3, which are namely sensory subsystem, data acquisition and transmission subsystem, data management and control subsystem, and structural health evaluation subsystem. Each level operates with its own hardware and software, increasing the convenience of system repair in the case of failures.

A progressive working mode can be found in the SHMS of SCB (Fig. 3). Each one of the four levels is equipped with a joint to the adjacent part, making the subsystems forced as a linear chain. Hence, any of the four parts is indispensable for the SHMS operation. As the data sources of the SHMS, sensory subsystem (Level 1) is the most fundamental and vital element in the total system. It is composed of various kinds of sensors to collect plentiful information about service loads and corresponding structural responses. As Level 2, data acquisition and transmission subsystem has two main functions: one is to perform as the controller for the data collection in sensory subsystem, the other is to successfully transmit the acquired data to data management and control subsystem. In data management and control subsystem (Level 3), the obtained data will be separately classified, processed, and effectively stored, so that the extracted information will then be timely used for structural health evaluation.

Level 4 is the terminal part of the entire system and operates the functions concerning graphic display, applicability evaluation, durability evaluation, damage detection and prediction, and further structural safety evaluation. Working as the post-processing module of the SHMS, structural health evaluation subsystem absorbs the valuable information from the obtained data and provides the potential to real-timely present the structural health status and alarm for the abnormal conditions (Spencer *et al*. 2004). In such a case, the serviceability and adaptability of the bridge can be well evaluated, and the schedule for the manual inspection and maintenance can be made accordingly.

4. Subsystems included in SHMS of SCB

4.1 Sensory subsystem

Effective collected data is the basis for structural health monitoring, so the sensory subsystem with high performance is the most fundamental and first-step element in a SHMS. The main contents and sensors layout of the SHMS on SCB are mainly determined by the structural static and dynamic characteristics, the importance and durability of structural components, the requirements of the system functions as well as the construction expenditure. The overall sensory subsystem of the SHMS on SCB is shown in Fig. 4. There are 10 types of sensors available in the sensory subsystem, mainly in allusion to the action and response monitoring. All types of the sensors utilized are listed in Table 1. All the sensors can stably work in a temperature environment ranging from -40℃ to 60℃ with high resolution. For example, the anemometer employed can measure the wind velocity up to 60 m/s with a resolution of 0.01 m/s; and the accelerometer has a measurement capacity from -2.5 g to 2.5 g with a resolution less than 2.5 μg (g is the gravitational acceleration). Some typical pictures of sensors implemented on SCB are shown in Fig. 5.

For the action monitoring, the environmental loads concerning wind, temperature, humidity as well as the vehicles are emphatically monitored. Since the dominated wind climates at SCB site, four anemometers are installed on SCB to monitor the wind environment, among which two on the midspan (upstream and downstream) and the other two on the bridge towers (southern tower and northern tower). Temperature is another important factor that influences the static and dynamic behaviors of long-span bridges, so series of temperature meters are distributed on the main girder and the towers of SCB. Considering the structural symmetry, the temperature meters are only installed on the Nantong side with 36 sensors to monitor the thermal condition inside and outside the steel box girder as well as 56 sensors to collect thermal information inside the bridge tower. Seen from a long-term perspective, the air moisture will greatly advance the development of component corrosion, hence 9 humidity sensors are installed to record this influential state variable. For the vehicles monitoring, weight-in-motion systems are settled at the toll station so that the vehicle loading model can be gradually established based on the accumulated measured data.

Table 1 Sensors employed in the SHMS of SCB

No.	Type	Function in the SHMS	Sampling frequency (Hz)
1	Anemometer	Measuring wind speed and direction at the bridge site	1
2	Temperature meter	Measuring temperature on the main girder and in the main tower	10
3	Humidity sensor	Monitoring air moisture inside the main girder and towers	10
4	Global positioning system (GPS)	Monitoring the line shape of the main girder	1
5	Displacement sensor	Monitoring the longitudinal displacement of the main girder	10
6	Accelerometer	Measuring the accelerations on local parts of structures	20
7	Resistance strain gauge	Measuring stress variation and distribution on the main girder and tower	20
8	Vibration wire strain gauge	Validating stress variation and distribution measured by resistance strain gauges	1/12
9	Zero stress-strain meter	Measuring the volume variation rate of concrete	1/12
10	Corrosion system	Monitoring the corrosion state of structures under water or in the air	1/3600

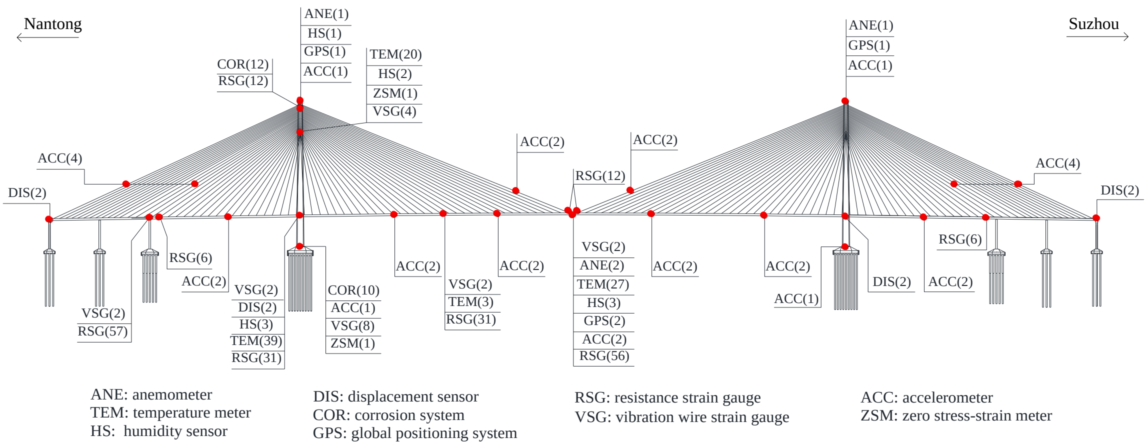
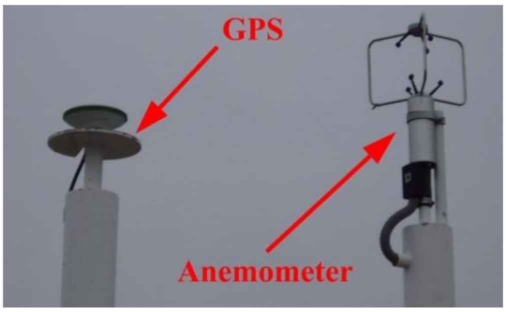
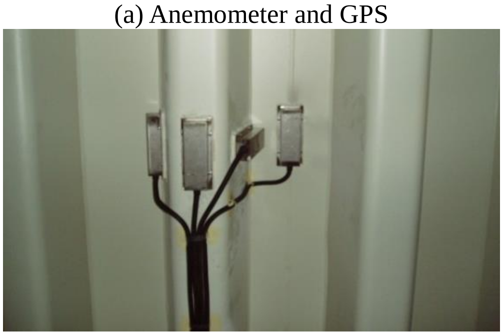


Fig. 4 Sensors layout in the SHMS of SCB

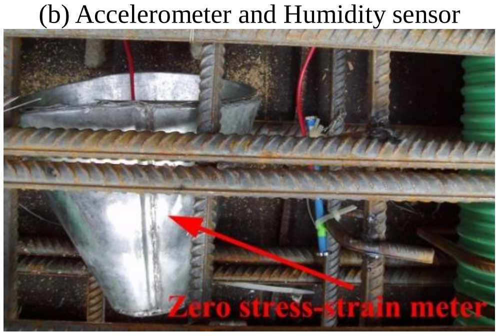


(a) Anemometer and GPS

(b) Accelerometer and Humidity sensor



(c) Resistance strain gauge



(d) Zero stress-strain meter

Fig. 5 Typical pictures of sensors installed on SCB

In respect to the response monitoring, the intensive concentration are mainly on many state parameters of the main components such as displacement, acceleration, stress distribution, corrosion status, etc. Considering the force transferring path between components in a cable-stayed bridge, the line shape of the main girder is an important parameter that greatly influences the structural mechanical behavior. On this occasion, two GPSs are installed in the middle of the main girder and the other two separately on the northern and southern towers, so that the absolute and comparative line shape of the main deck can be observed in real time. For another part, excessive longitudinal displacement of the main girder is bad for the mechanical behavior of the whole bridge system as well as the replace interval of expansion joints (Ni *et al*. 2007). As a result, four pairs of displacement sensors are symmetrically distributed on SCB, installed between the end pier/tower and the main girder in each side to monitor the comparative displacement, as shown in Fig. 4.

With regard to dynamic external actions, the bridge will inevitably suffer from local or whole structural vibrations. For the upper structure, 7 pairs of bi-directional accelerometers are distributed on the main girder, where 5 pairs evenly distributed on the main span and one pair in the middle of each largest side span. The bi-directional accelerometer is installed to measure the lateral and vertical acceleration responses of the main girder. On top of each bridge tower, one bi-directional accelerometer is settled to monitor the longitudinal and lateral vibrations. The longest cable of SCB has achieved to 577 m and its vibration is much more prominent than that of other cables. Therefore, each longest cable is equipped with a bi-directional accelerometer to record in-plane and out-plane vibrations. Also, a middle-sized cable in each plane is selected for monitoring in order to check the force variations of the stay cable during the long-term services. In addition, a tri-axial accelerometer is installed in each interface of the bearing platform and the bottom of the bridge tower so that the 3D ground motions under severe disasters (e.g., earthquakes) can be accurately recorded.

Reflecting the structural performance in a more refined level, stress is a key local parameter that connects to the material strength and directly shows the structural safety status. Hence, a great many resistance strain gauges are distributed on several typical sections of the main girder with some vibration wire strain gauges to conduct cross-checking. On the inner wall of the southern tower, also a number of resistance strain gauges accompanied by several zero stress-strain meters buried in concrete are available on three typical sections. In such a case, the stress distribution and variation in the steel box girder and the tower can be obtained to give signals for structural evaluation and alarming, as well to further enhance the comprehension of the structural mechanical behaviors under environmental actions (e.g., temperature, wind).

From a long-term point of view, the durability of such a huge engineering structure is especially important to the sustainable service and therefore attracts intensive attentions from the government and civil engineers. Corrosion is a permanent issue that is of special concern in engineering structures. The development of corrosion will inevitably cause performance deterioration and even collapses to structures. For the cable-stayed bridge, the non-replaceable bridge tower is the last defense against structural collapse, so its durability should be specially monitored during the long-term services. On this circumstance, a group of corrosion monitoring systems is installed in the northern tower of SCB, including 10 on the bearing platform and 12 in the upper concrete pylon, to monitor the corrosion status of the parts under water or in the air.

4.2 Data acquisition and transmission subsystem

Data acquisition and transmission subsystem can be divided into two parts: data acquisition system and data transmission system. The data acquisition system consists of both hardware and software platforms. In this application, LabVIEW, a software product by National Instruments (NI), USA, is employed to write the program for signal collections. The serial digital collection technique with VISA drive is used to collect all of the data. The analog voltage signals outputting from different sensors are converted into digital signals by NI ExpressCard-8421/2 from NI Company. The serial max baud rate can achieve 460.8 kbits per second on the Windows operating platform.

For such a cable-stayed bridge, the total span length has exceeded 2000m and there are various types of sensors distributed on the main components, leading to the difficulty and complexity in the layout of transmission wires. Additionally, the collected signal is easily disturbed by the electromagnetism and further distorted during long-distance transmission. Hence in order to transfer accurate data to the monitoring center, the transmission wires must be divided into several parts to shorten the transmission distance and each part needs to be equipped with a data acquisition station.

As shown in Fig. 6, there are seven data acquisition stations on the main girder and two substations on the bearing platform in the SHMS of SCB. Each data acquisition station is responsible for the data collection of the corresponding sensors. And all of the acquired data will be transmitted to data management and control subsystem via the optical fiber ring network (data transmission system). The optical fiber ring network connects all the concerned parts together by the fiber switches, so the collected data can be fast transmitted with strong anti-interference capacity through Internet. In respect to the distribution of the data acquisition stations, five of them are uniformly distributed in the main span and the other two (MS1 and MS7) in the middle of each side span (Fig. 7), respectively. The two substations SS2-1 and SS6-1, which are affiliated to MS2 and MS6 respectively, are installed on the bearing platform to take charge of the sensors nearby. MS2 and MS6 are just on top of the cross-beam of the bridge tower, so the sensors in the upper part of the towers are directly linked to these two stations. All the sensors are connected to the corresponding data acquisition stations using optical fibers and the longest transmission distance is successfully limited within 300m. Therefore, the long-distance transmission can be avoided and the collected data will be effectively transmitted with little interference.

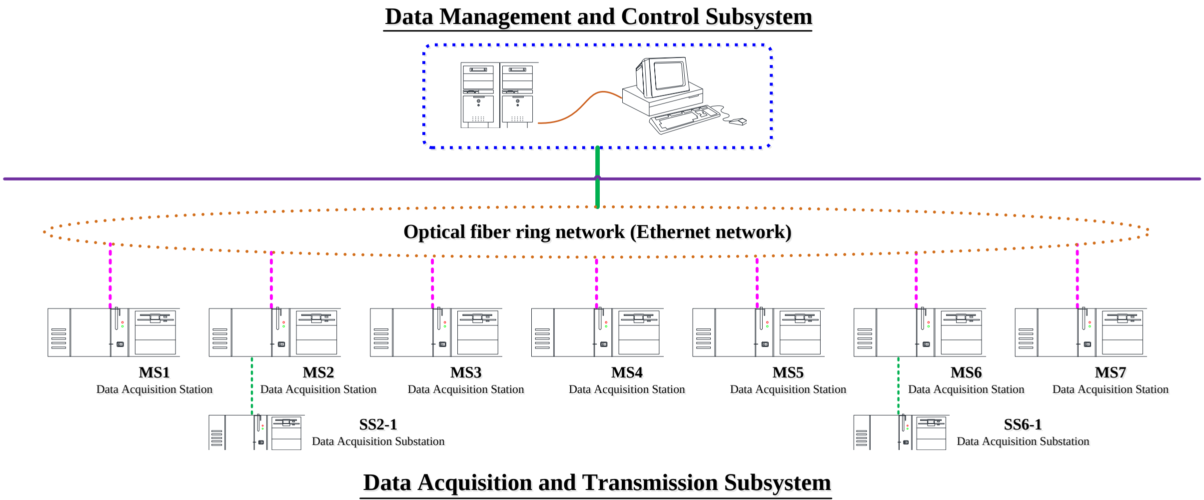


Fig. 6 Components of the Data Acquisition and Transmission Subsystem

4.3 Data management and control subsystem

Data management and control subsystem is the central system of a SHMS and operates the functions about module control, data storage, data processing, information mining, etc. The whole structure and system constitution of the data management and control subsystem can be seen in Fig. 8. Data management and control subsystem performs as the governor of the data acquisition and transmission subsystem. It realizes the remote control of the data acquisition stations through the optical fiber ring network, hence making it possible for the administrator to check the working condition of each data acquisition station via the visit to data management and control subsystem.

Due to the enormous data amount accompanied by various data types during long-term monitoring, data storage is one of the most important function in the data management and control subsystem. In order to improve the device utilization and reduce the risk of data loss, a distributed storage scheme is adopted for the massive data preservation in the SHMS of SCB. In each data acquisition station, the local hard disk is taken as the data storage media to temporally preserve the obtained data for about 15 days. Meanwhile, the collected original data will be timely transmitted to the storage center in data management and control subsystem. Once the data loss turns up in the rechecking process, the preserved data in data acquisition station will be resubmitted to overwrite the vacancies. Though the quantity of the collected data is quite large due to various sensor types, big amounts of sensors, and high sampling frequency, the data is carefully accumulated in the monitoring center for the potential to conduct extensional researches, as discussed in the fifth part.

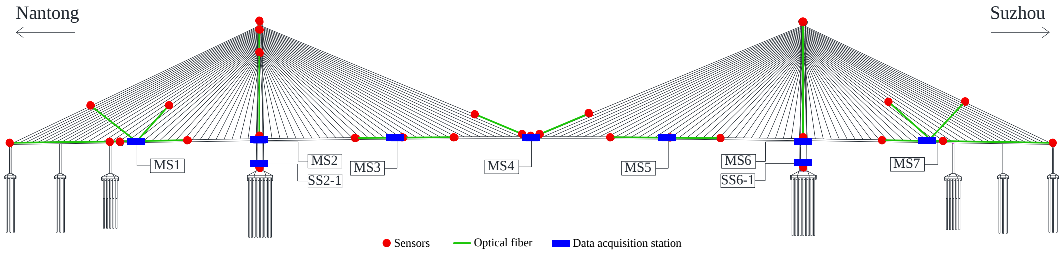


Fig. 7 Layout of the data acquisition station on SCB

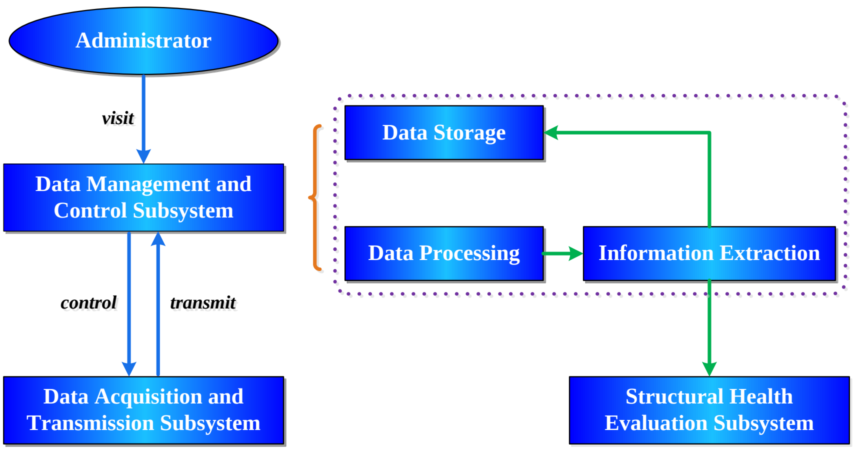


Fig. 8 System constitution of the data management and control subsystem

Data processing is a key step that turns vast amounts of data into applicable information for structural health evaluation. In this module, a series of modern mathematical algorithm and computer procedures has been integrated to serve for the information extraction from the massive original data. For example, in SHMS of SCB, the measured modal parameters are derived from the accelerations of the main components; the thermal field of the steel box girder is established from long-term monitoring of the temperature distribution; the wind spectrum model for the bridge site is obtained from the analysis of the measured strong wind data. Therefore, a valuable database can be formed with the accumulation of the extracted information. It should be noted that the timely extracted information are stored in monitoring center so as to be taken as the benchmark for the normal working condition, and then provide the data basis for the structural health evaluation and decision making.

4.4 Structural health evaluation subsystem

In SHMS, structural health evaluation subsystem is the terminal part and performs as the soul or core. With the extracted information from data management and control subsystem, this subsystem is accomplished by several functional severs or working stations and provides an integrated software for result presentation and graphic display (Fig. 9). During the design stage, two main difficulties concerning structural health evaluation are encountered. One is how to remove the noise from the original signals and extract valuable information for condition assessment; the other is how to reasonably analyze the extracted information and provides suggestions to structural alarming and regular maintenance. The first difficulty has been to some extent alleviated with some advanced mathematical techniques (e.g., wavelet transform and empirical mode decomposition) in data management and control subsystem (Galiana-Merino *et al*. 2003, Kopsinis and McLaughlin 2009), while the latter is solved by a five-level analytic hierarchy process as shown in Fig. 10.

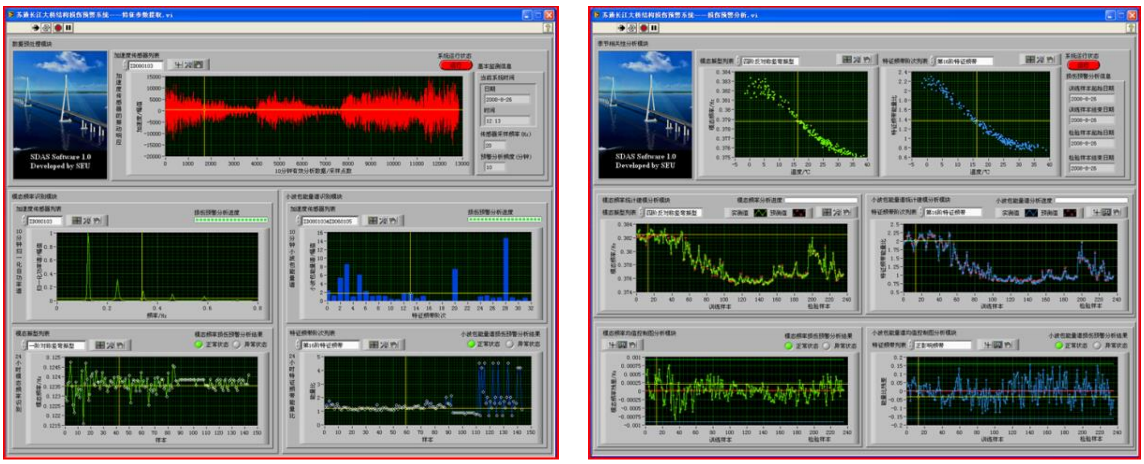


Fig. 9 Software interface of the structural health evaluation subsystem of SCB

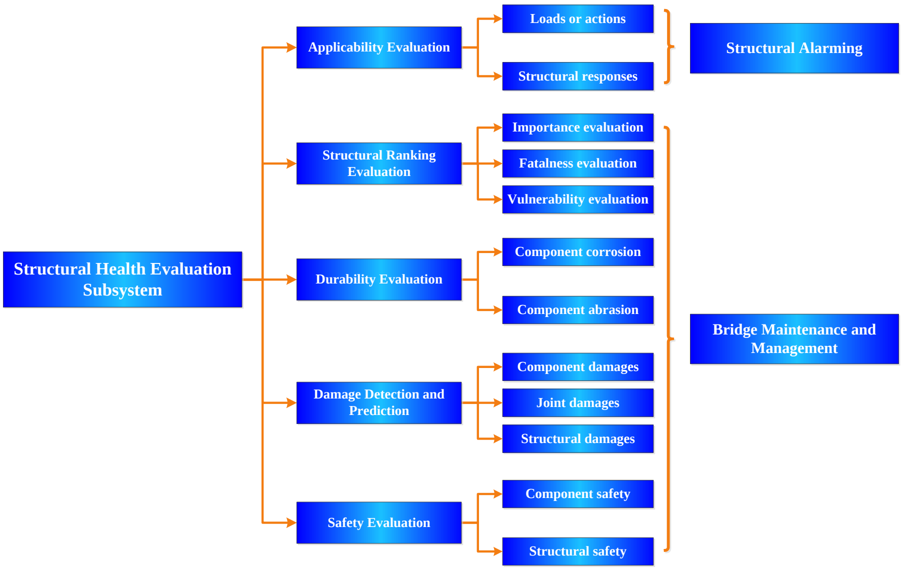


Fig. 10 Hierarchies for structural health evaluation subsystem in SHMS of SCB

In the five-level analytic hierarchy process, structural health evaluation subsystem is divided into five modules, namely application evaluation module, structural ranking evaluation module, durability evaluation module, damage detection and prediction module as well as safety evaluation module. The first part mainly focuses on the measured actions and responses, on the one hand to monitor if the acquired value has exceeded the permitted limits and on the other hand to conduct response prediction for structural alarming. If the measured or predicted responses are overranging, some reasonable suggestions or measures can be taken to prevent the occurrence of disasters. For example, if the dynamic responses of SCB are so large that it has influenced the safety of passing vehicles during typhoons, the structural evaluation subsystem will give an alarm to get the bridge closed to traffic.

All of the rest four parts work for the bridge maintenance and management. As indicated in Fig. 10, the components of SCB will be ranked by their importance, fatalness and vulnerability according to the finite element (FE) analysis (e.g., for earthquakes, flutter, buffeting) at the early stage. The ranking results are taken as the basis for the layout of sensors as well as the concentration during daily inspection and maintenance. The durability evaluation mainly aims to evaluate the corrosion status of rebar in concrete and the abrasion of bearings, while the obtained results can be used to update the component rankings and provide durability information for safety assessment and structural maintenance. In damage detection and prediction module, the component, joint and structural damages will be estimated and positioned using a hybrid method based on both field measurements and FE analysis (Wang *et al*. 2014). If an obvious damage pattern is reported, a field inspection will be conducted to have an appropriate examination. It is important to note that the FE model of SCB should be timely updated with the field measured information so that accurate predictions of the structural performance can be made to provide references and suggestions for decision making about the maintenance schedule. In the application of SCB, the difference between measured modal frequencies and calculated ones by updated FE model is within 5% (Wang *et al*. 2014). In the safety evaluation part, the evaluation is mainly conducted at two different scales, component and structure. For each scale, the structural safety assessment is decomposed into several parts with explicit requested indexes. For example, the evaluation for component is focused on stress distribution, damage and corrosion status, while the displacement changes of the span, the vibration status of the main girder, the variation of modal parameters, etc. are employed for evaluating the whole structure. If all the parameters are under permission, the whole structure is determined to be safe enough for the subsequent service, or some maintenance needs to be carefully conducted accordingly.

5. Extension and application of SHMS for field measurement

The SHMS performs as an efficient platform for the monitoring of environmental actions and structural responses during short-term or long-term service periods, offering the potential to carry out health evaluation for civil structures and accordingly give suggestions for structural regular maintenance. However, the daily accumulated data can not only serve for the structural condition assessment, but also provide the opportunity to conduct some extended researches based on the field-measured data (Li *et al*. 2015). So some extensions and applications on account of the SHMS will be discussed in the following parts. The hot research topics concerning wind environment monitoring, temperature monitoring, vibration monitoring and displacement monitoring are herein selected to be taken as examples, making an introduction to the potentially existing values of SHMS in civil engineering.

5.1 Wind environment monitoring

The field measured wind data is of great value in bridge wind engineering since it is obtained at the bridge site and reflects the original characteristics of natural wind. As the wind data accumulated, a reliable database including many vital wind parameters can be established. The database can be used for verifying the existing analytical theory and provide references for the revision of specification in wind engineering. Here, two typical examples are presented to illustrate the application of the recorded wind data.

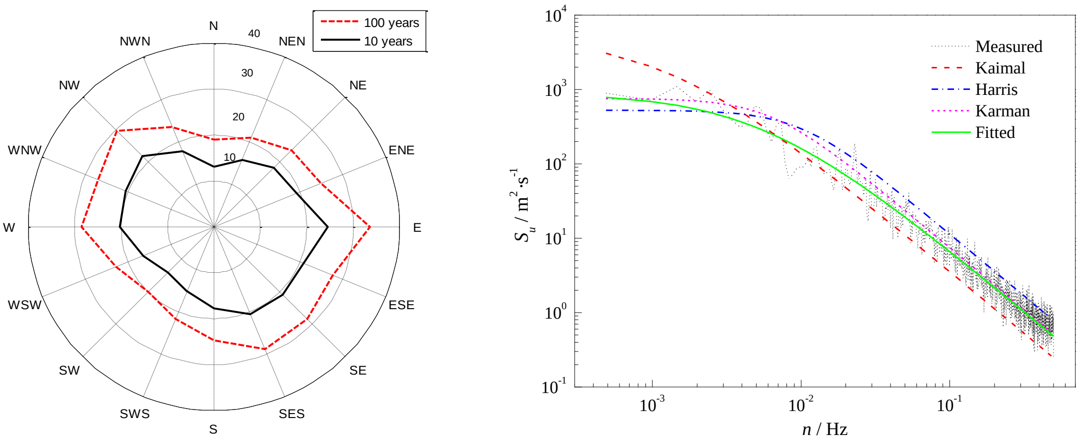
(1) Prediction of the extreme wind speed at the bridge site is an interesting and important topic in wind engineering. The accurate prediction greatly relies on a statistical model derived from long-term monitored wind data. Conventionally, the original wind records are collected from selected weather stations. However, the real wind field of the bridge site is not only related to the climate, but also heavily depends on the surrounding terrains. Hence, there are several issues in such a data collection, such as the reasonable conversion of the wind records from the weather station location to the bridge site, the elevation changes of the measurement point, frequency changes of the different wind recording instruments, etc. In such a status, the development of SHMS in civil engineering provides another promising approach to obtain the original wind data and simultaneously get the aforementioned problems circumvented. As shown in Fig. 11(a), a prediction of extreme wind speed considering the effect of wind direction can be made based on the four-year accumulated data (Wang *et al*. 2015).

(2) Wind velocity power spectrum (WVPS) plays as a dominant role in the accurate prediction of structural wind-induced responses. In current wind-resistant specification for highway bridges of China (Ministry of Communications of PRC 2004), two empirical models respectively proposed

by Simiu and Panofsky are taken as the horizontal and vertical spectra for both numerical analysis and wind tunnel test. However, the WVPS heavily depends on the surrounding terrains, which results in the inconsistency between the commonly used empirical models and the site measured spectrum (Fig. 11(b)). Therefore, a wind spectrum model adapted to the native topography can be established according to the accumulated strong wind data by SHMS, and further provide references for the revision of related codes.

5.2 Temperature monitoring

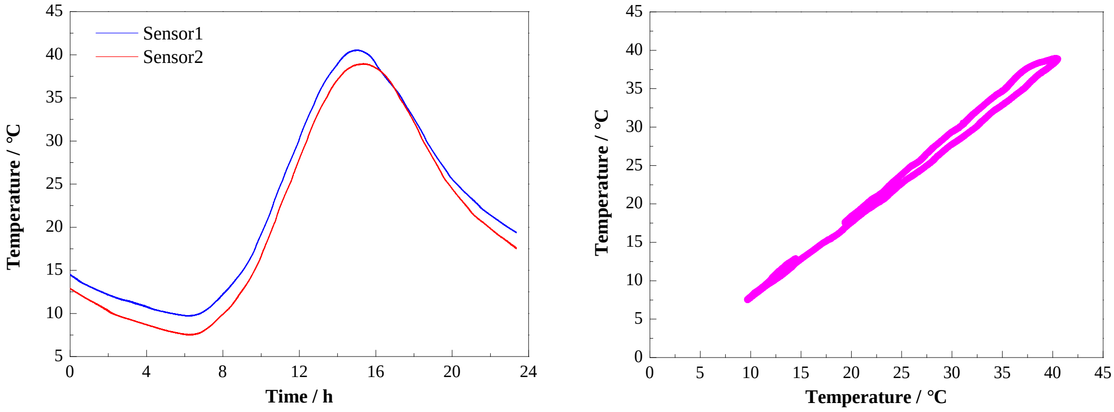
In the SHMS of SCB, a series of temperature sensors are distributed on some typical sections to monitor the thermal distribution along the span and the section. The temperature field of the steel box girder can be presented through measurements, e.g., as shown in Fig. 12(a). The temperature data are measured at the middle section of the main girder, and the sensors distribution is shown in Fig. 13. As the temperature accumulated over the years, the statistical probability model considering the spatial effects, can be established based on the mathematical analysis (e.g., correlation analysis as Fig. 12(b), transverse correlation means the correlation along the section). Here, the spatial effects refer to the temperature differentiation along the span or section due to the combined influence of solar radiation, daily air temperature variation, wind speed and direction, etc. Based on the statistical probability model, the thermal field of the steel box girder is easy to be simulated with Monte Carlo method. Meanwhile, the efficiency of the modeled time-histories can be validated by the measured benchmark temperature. For determinate structures, the temperature has little influence on the changes of internal forces and displacements. However, as a long-span cable-stayed bridge, SCB is a complicated indeterminate structure and the thermal effects must be considered during the full-life cycle. That means the monitoring and prediction of thermal fields makes great sense in engineering applications (Yarnold and Moon 2015).



(a) Prediction of extreme wind velocity (Unit: m/s)

(b) Establishment of wind spectrum model (S_u=WVPS; n=natural frequency)

Fig. 11 Application of the monitored data in wind engineering



(a) Temperature time history (b) Transverse correlation of temperature

Fig. 12 Monitoring of the temperature on the steel box girder

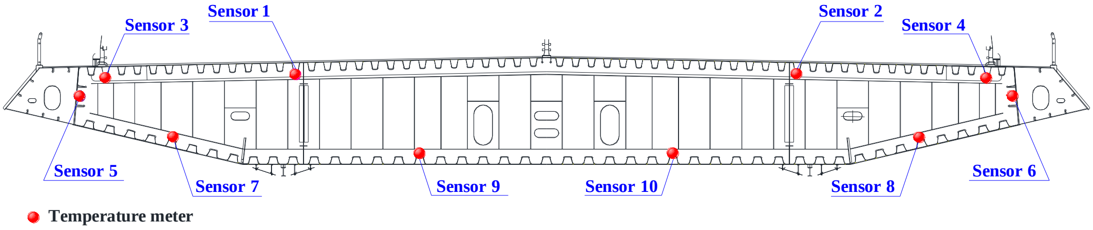


Fig. 13 Distribution of temperature meters on the middle section of the main span

5.3 Vibration monitoring

Acceleration is a typical parameter that stands for component vibration status. It is obtained from the accelerometers as the most direct and accurate measured structural state variable. In SCB, the acceleration of the main components can be monitored by the SHMS during both extreme events and normal conditions. For example, Fig. 14 provides a set of acceleration data of the main girder during a typhoon period. Among them, the torsional acceleration has been multiplied by half width of the main girder in order to unify the unit. In current researches, the acceleration is mainly utilized in two aspects: one is modal identification and model updating (e.g., modal identification as described in Fig. 15(a)); the other is the verification of existing analytical theory or reduced-scale model experiments (e.g., verification of the correlation between acceleration and wind velocity, as shown in Fig. 15(b)). The first one extracts the effective identifying information of a structure from SHMS and provides a reliable connection between FE model and realistic engineering structure (Li *et al*. 2012). The latter offers a favorable approach that is available to enhance the understanding of environmental actions and the capability of response predictions. For example, wind-tunnel test and numerical simulation are two main approaches to study structural buffeting performance and conduct structural response predictions. However, the experimental or calculated results may not be accurate enough due to reduced-scale model effects or many assumptions (Wang *et al*. 2014). Therefore, the measured results (e.g., the relationship between acceleration and wind speed as shown in Fig. 15(b)) on a full-scale bridge structure can be utilized to verify the existing experiments and simulations, and further make improvements to current analytical theories or methods, which will finally result in the better understanding of the wind-induced structural vibration mechanism.

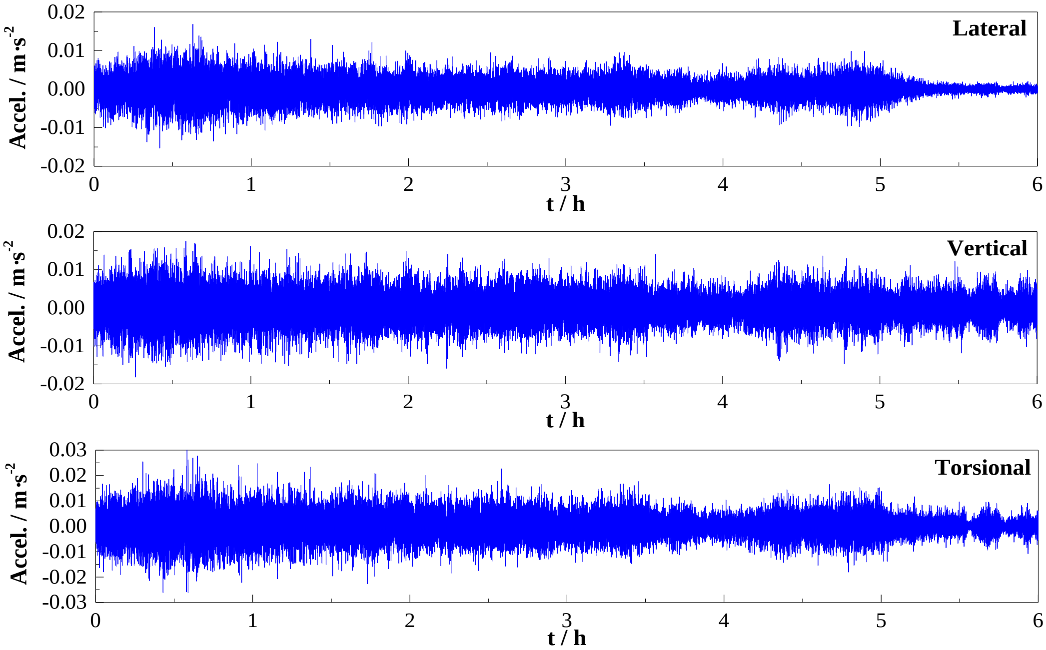
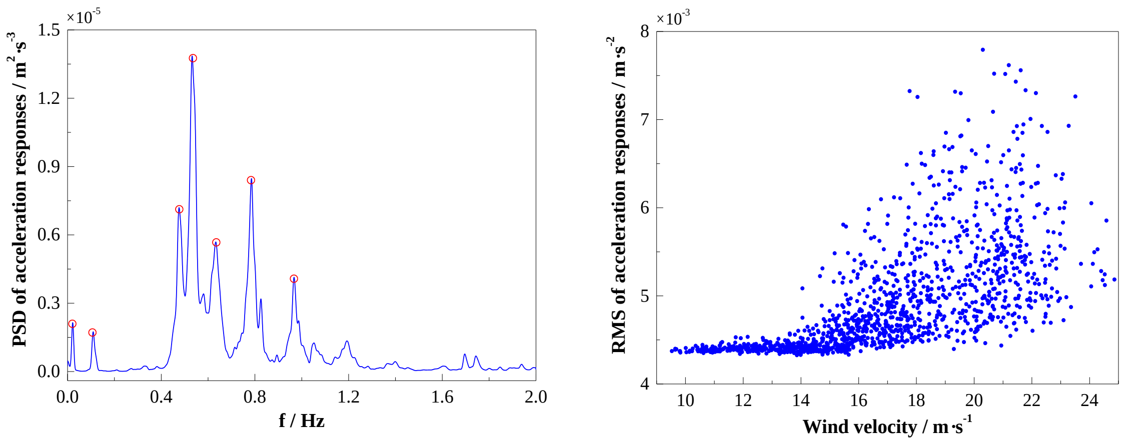
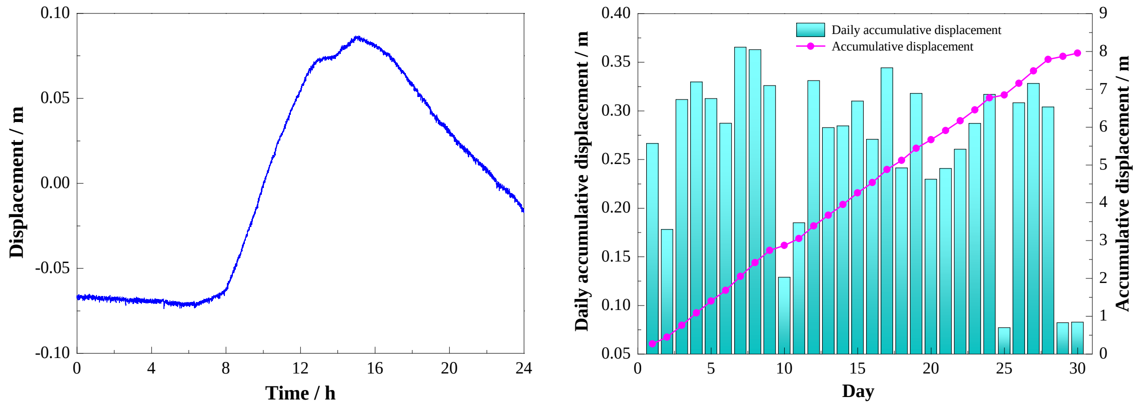


Fig. 14 Example of measured accelerations on the main girder



(a) Modal identification (b) Acceleration versus wind velocity

Fig. 15 Application of the recorded acceleration responses



(a) Displacement time-history (b) Accumulative displacement

Fig. 16 Monitoring of the displacement for the expansion joint

5.4 Displacement monitoring

There are two types of displacements monitored in the SHMS of SCB. One is realized by the GPSs at the midspan and on top of the towers, and the main function of the GPSs is to monitor the static displacement of the main girder and make sure the line shape of the main girder is stable. The other is achieved by the displacement sensor with an aim to measure the longitudinal dynamic displacements of the main span. The expansion joint and vertical bearing are two significant components in SCB. However, their performance is to a great extent influenced by the longitudinal displacement due to the caused abrasion effects. So continuous monitoring of the actual longitudinal movements and comparison with the existing codes can provide verification to the design standard (Ni *et al*. 2007). Here, the monitoring of the longitudinal displacement is taken as an example. As an important consideration in bridge design, the longitudinal movements of the main span caused by temperature variations is shown in Fig. 16(a). That is also the daily displacement variation of the expansion joint at Nantong side. Since the service life of an expansion joint or a vertical bearing greatly relies on the total experienced displacement (also called accumulative longitudinal displacement of the main span, as shown in Fig. 16(b)), an accurate prediction of the accumulative displacement based on long-term recorded data can offer reliable information for decision making on performance evaluation of expansion joint.

It should be noted that the current or potential extension researches based on SHMS are not limited to the examples mentioned above. More researches concerning wind environment monitoring, temperature monitoring, vibration monitoring, displacement monitoring and even earthquake monitoring can be conducted to cope with encountered practical problems. And the intensions of all the extension researches are the same, which is to solve practical problems with the aid of the accumulated recorded data.

6. Conclusions

The recent development of SHMS makes it possible to conduct real-time health monitoring and safety evaluation for engineering structures, and therefore can provide timely suggestions for schedule making according to the current structural status. In this paper, a state-of-the-art SHMS on a world-famous cable-stayed bridge, namely SCB, is introduced in detail. The SHMS of SCB mainly contain four subsystems including sensory subsystem, data acquisition and transmission subsystem, data management and control subsystem, and structural health evaluation subsystem. The four parts are independent from each other but connected to accommodate with the functions just like a linear chain.

In total, 10 types of sensors are available in the sensory subsystem to collect the structural action or state information such as displacement, acceleration, temperature, etc. Data acquisition and transmission subsystem is responsible for the control of the sensory subsystem as well as the data transmission to data management and control subsystem. Following the data processing stage in data management and control subsystem, the extracted information will be supplemented to structural health evaluation subsystem. Using the measured and extracted information, a five-level analytic hierarchy process is adopted for the decision making on both structural alarming and regular maintenance.

The condition of SCB has been monitored for more than 7 years, during which some extension researches have been successfully conducted. The successful conduction of existing researches proves that the data collected by the SHMS of SCB is reliable. The measured data of the SHMS can not only be used for monitoring of structural health, but also can provide valuable data for a great many extension researches and applications, which are probably related to wind environment, temperature, vibration, displacement, corrosion, etc. All the extension researches are meaningful to solve encountered practical problems, likewise enhancing the understanding of environmental actions and response prediction capabilities of long-span cable-stayed bridges.

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