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# HEALTH MONITORING SYSTEM OF AN IN-SERVICE LONG-SPAN CONCRETE CABLE-STAYED BRIDGE USING SMART SENSORS

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## ABSTRACT

Health monitoring technology has played a successful and powerful role to ensure the safe operation and extend the service life of the bridges. Maintenance costs of the bridges can be greatly reduced to avoid the final closure of traffic caused by frequent overhaul of major losses through early detection of disease. Since in-service concrete cable-stayed bridges have been put into operation for a long time, some degree of diseases occurs. This type of bridge health monitoring system (HMS) is quite different with health monitoring system of new bridges, in which damage must be considered. To ensure the safe use of the bridge in service, it is necessary to develop long-term health monitoring system. Monitoring the long-term and regular change of the mechanical properties of the key parts of the bridges by use of modern means of diagnosis, operational status and endurance capacity can be evaluated to ensure the safe use of the bridge and extend life. Different types of sensors should be installed at the key locations and components where large displacements and stresses are expected to occur. It is concluded that a HMS for long-span bridges should be able to monitor the loading and structural parameters. Monitored results can facilitate the scheduling of bridge inspection and maintenance activities, once the damage is identified.

**Keywords:** *Health Monitoring System, Concrete Cable-Stayed Bridge, Sensor*

## 1. INTRODUCTION

Structural health monitoring (SHM) provides a great tool to predict and assess the structural performance under in-service bridges. The general objectives of SHM may include: (1) assessing structural performance of bridges; (2) predicting the remaining service life of a bridge; and (3) providing a useful decision tool for optimum maintenance scheduling. Structural health monitoring systems have been adopted over the past two decades to evaluate and forecast the structural health condition of long-span bridges.

The ultimate goal of a bridge SHMS is to identify and quantify any local (component-level) and global (system-level) damages in the bridges (Farrar et al. 2003). Damage is normally defined as the intentional or unintentional changes in material and geometric properties of the bridges, including changes in boundary or supporting conditions and structural connectivity, which have adverse effects on the current or future safety and serviceability of the bridge (Kai-Yuen Wong et al. 2007). Actually, all damage evolves from the material, the adverse loading and environmental conditions to local and global damages at various rates. Damage can appear under large transient loads such as historical strong typhoons, strong earthquakes, ship impacting, etc., and may also be accumulated incrementally and gradually over long periods of time due to factors, such as fatigue, scouring and corrosion.

There are many health monitoring systems of bridges around the world, such as China, Denmark, Korea, French and etc. These bridges include Kap Shui Mun Bridge, Tsing Ma Bridge and Ting Kau Bridge in Hong Kong. A SHMS is currently becoming a standard mechatronic system in the design and construction of large-scale and multi-disciplinary bridge projects such as the Shenzhen Western Corridor, Stonecutters Bridge, SuTong Bridge, Shenjiamen Bridge Donghai Crossing and Chongming Crossing (Kai-Yuen Wong et al. 2007).

Health monitoring systems play to ensure the safe operation of the bridges and extend the life of the bridges. At the same time it is very significant to reduce the maintenance costs of the bridges through the early discovery of disease. Health monitoring systems of modern bridges can be summarized into three areas: identification, location and calibration of structural damage, detrimental to the function of the quantitative assessment of the bridges and risk forecast for the use of the damaged bridges.

As the environment of the bridges and the information obtained from SHM, not only are the supplement of theoretical and laboratory investigations, but also can provide the most real-time information of the structural behaviors and in-site environmental parameters. So the bridge health monitoring system will not only monitor and reflect on a particular bridge design, but may become between the research and field laboratories of bridges.

Lijiatuo Yangtze River Bridge is located in Chongqing, China, built in 1997. Its main span is 169m+444m+169m with 24-meter width of the deck. Lijiatuo Bridge is a pre-stressed concrete cable-stayed bridge with twin towers and double cable planes. Lijiatuo Yangtze River Bridge is mainly made up of main girder, cables and towers, shown in Fig.1.

*Figure 1.General view of Lijiatuo Bridge.*

Lijiatuo bridge has been in use for 12 years, in which some degree of diseases are found after inspection and testing. Health monitoring system of an in-service bridge, which must consider the existing damage and disease, is different from a new bridge. Because all of the sensors are installed after the completion of open traffic, monitoring data, which are not absolute value but relative value compared with the design value, have some influence on health assessment of the bridge.

## 2. GENERAL FRAMEWORK HEALTH CONDITION SYSTEM

Health monitoring system (HMS) of Lijiatuo bridge is one integrated system combined of structural analysis, communication technology, computer technology, sensor technology and network technology, which can be used in damage identification and condition assessment of bridge maintenance to meet the needs of economic benefits.

In order to make health monitoring system of Lijiatuo Yangtze River bridge become powerful and practical and economical, the below-mentioned principles of design are followed:

1. The guiding ideology of overall design and step-by-step implementation;

2. The concise, practical, reliable, economic and reasonable principle of sensors;

3. Meeting the need of management and operation based on the practical principle, as well as considering the scientific test and design verification

4. The layout of monitoring points or sections according to the structural vulnerability analysis results and the demand of maintenance management;

5. Monitoring the dynamic, static, durability performance of the bridge with the least amount;

6) Monitoring items including the displacement, inclination, deflection, force, temperature, stress, modality and etc.

According to its functional and operational requirements and design principles above-mentioned, the structural health monitoring system for long-span bridges (Lijiatuo bridge) can be divided into four integrated modules. These four integrated modules are: (1) the sensory system, (2) the data acquisition and transmission system, (3) the offline assessment data processing and control system. General framework of the four integrated modules of Lijiatuo bridge is shown in Figure 2.

Current damage detection methods have not yet been well proven for their long-term efficiency in bridge health applications. Damage detection methods and/or instruments in bridge health monitoring are currently regarded as research activities to improve the structural health evaluation techniques. In considering such a background, the operation of a SHMS is therefore divided into two processes, the structural health monitoring process and the structural health evaluation process (KAI-YUEN WONG,2007). The functions of the former process are: (1) to monitor the bridge responses, environmental and applied loads by correlating the measured results directly with the monitoring; (2) to update and calibrate numerical analysis models for future predictive monitoring; and (3) to update the raw data database for subsequent data mining and correlation analysis. The functions of the latter process are: (1) to predict the bridge responses at key locations and points with sensory systems based on the updated and calibrated numerical models; and (2) to predict the potential effects of local damage or instability in bridge components under extreme loads.

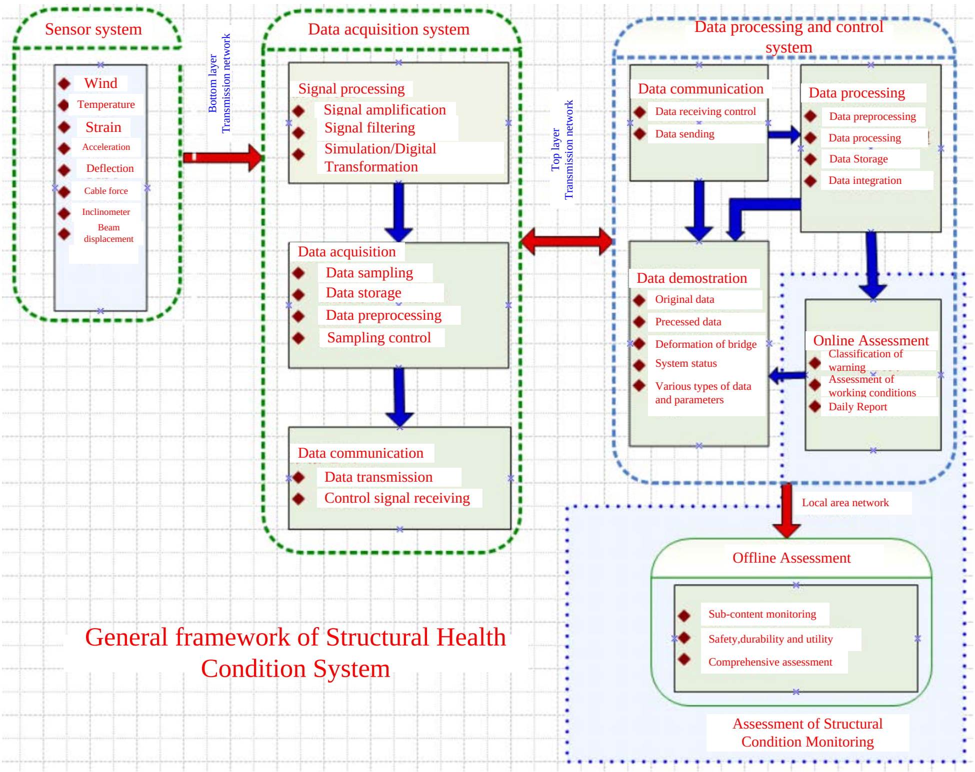

*Figure 2. General framework of HMS.*

## 3. DEFORMATION OF MONITORING

Deformation monitoring of the control sections of bridge can provide a basis for the overall assessment of bearing capacity, operation state and durability. Based on the communicating pipe liquid level measurement principle of the static force level, communicating pipes are installed along the main girder and precise branch tubes are arranged at the key position, in which there is a fixed points located in the transition pier of side span.

Pylons are the main load-bearing structures of cable-supported bridges, whose stiffness are much larger than the flexible cables or deck girders. The pylons' safety are stability due to strong wind and seismic loads, cracks of cross beams of pylons caused by the longitudinal unbalanced loads, and cable sag and the corresponding cable force change lead by concrete creep and shrinkage. Longitudinal layout of deflection monitoring is shown in figure 3. The sensors are expressed by red points or small red rectangles in figure 3, which are similar in other figures.

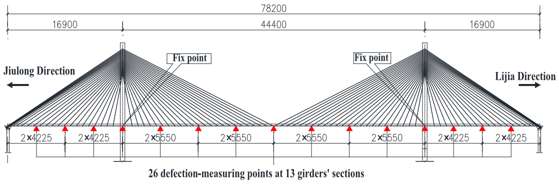

*Figure 3. Longitudinal layout of deflection monitoring*

Lateral displacement of main towers is monitored by tilt meters. Fiber SEN-TILT can be used to real-time monitoring main tower' overall inclination, shown in figure 4~5.

*Figure 4. Static level meter.* *Figure 5. Inclinometers.*

## 4. STRESS MONITORING OF MAIN COMPONENTS

Monitoring of main beam stress in the main girder structure of key parts of the main girder structure internal force monitoring, research on the internal force distribution, local structure and connection in response to various loads, structural damage identification, fatigue life assessment and structural state assessment provides the basis.

Purpose of stress monitoring of main beam is research on internal force redistribution, response of local and connection components under various loads measured at control and key sections of main girder, which provides the basis of structural damage identification, fatigue life assessment and structural state assessment.

Cross sections of stress monitoring for main girder in this bridge are 1/2 cross section and 1/4 cross sections and a pier near top girder section of main span and side spans, which is a total of 7 sections. Each section is arranged on the 5 monitoring points of normal stress. At the same time, 8 strain sensors are arranged in diagraphs near pylons. There are totally 43 strain sensors of girder and diagraphs. Fiber SEN-S1 surface strain sensors are suitable for long term monitoring, which are mounted in Lijiatuo bridge, shown in Figure 6~8.

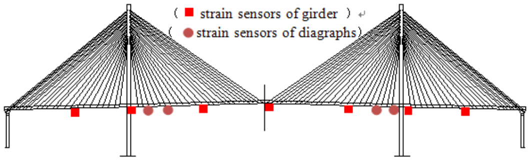

*Figure 6. Longitudinal arrangement of strain sensors of girder and diagraphs.*

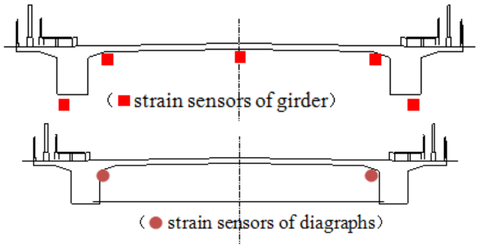

*Figure 7. Transversal arrangement of strain sensors of girder and diagraphs.*

*Figure 8. SEN-S1 fiber surface strain sensor.*

Pylons bear great axial pressures, and generate additional bending moment in the case of possible un-symmetric loads, which is unfavorable for pylons. Therefore it is necessary to monitoring the section stress of main towers. Fiber SEN-S1 surface strain sensors are used to pylons. There are twelve sensors on each pylon. Arrangement of measuring points is shown in figure 9.

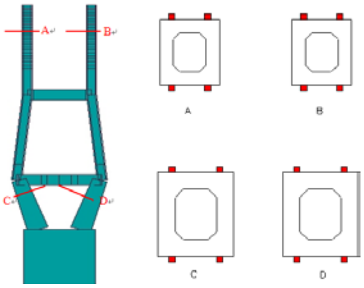

*Figure 9. Measuring points of pylons.*

## 5. TEMPERATURE MONITORING

Distribution monitoring of temperature field can provide the original basis of bridge design. Bridge working condition changes, such as deformation and stress change can be compared in different temperatures. It is essential for the quantitative analysis of the bridge design theory, the validation and refinement.

Fiber temperature sensors are used in Lijiatuo bridge, shown in figure 10. Multi-point temperature measurement system is constituted in series. Temperature sensors are in parallel with the network node connected to the network bus for communication with the computers, to achieve the automatic remote monitoring of temperature.

*Figure 10. Surface Fiber temperature sensors.*

## 6. DYNAMIC CHARACTERISTICS MONITORING

Cable fatigue and safety can be studied through the continuous monitoring of cable vibration characteristics. Vibration characteristics of the main beam are mainly related with stiffness, mass distribution, damping, as well as the ambient temperature, cable force, traffic conditions, tower vibration, wind conditions, etc.

Vibration can be measured by acceleration sensors. Because the natural vibration characteristics of towers, girder and cables are different, the technical choice of sensors is considered by the performance of the sensors (frequency range, sensitivity, sample characteristics, etc.).SEN-AL fiber accelerometers, shown in fig.11~12,are selected after comparison and selection.

*Figure 11. SEN-AL fiber accelerometers.*

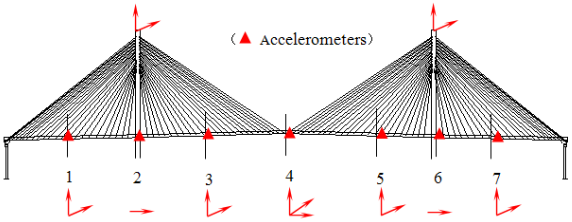

*Figure 12.Arrangement of accelerometers .*

## 7. CABLES FORCE MEASURE

Cables are very important components in cable-stayed bridges. The basic functions of Natural frequency and the tension force are:

$$T = 4m'l^2\left(\frac{f_n}{n}\right)^2 \qquad (1)$$

Cable force is be related with the temperature, wind conditions, traffic conditions and the main beam vibration, vibration measurement tower , etc.

Monitoring of cable forces, not only provide a basis of the overall assessment of the safety and durability of the bridge to provide a basis, but also can detect the integrity and corrosion of cable anchoring system and the protection system. during the operation, accurate knowledge of cable forces is beneficial to monitor and adjust the cable tension force.

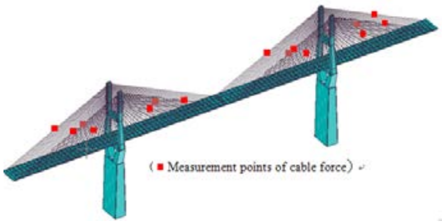

*Figure 13. Measurement points of cable force.*

## 8. WIND PARAMETERS MEASUREMENT

Wind speed has a great impact on cable-stayed bridges. Wind is the main load of bridges, which can affect the normal operation of the bridge. Lijiatuo bridge is an in-service cable-stayed bridges, which is increasingly sensitive to speed and direction of wind. Therefore, real-time wind monitoring and performance evaluation are necessary.

Wind speed and direction monitoring is a long-time work. HFY-1A wind anemometer should be adopted due to the considerations of long-term monitoring and signal transmission.

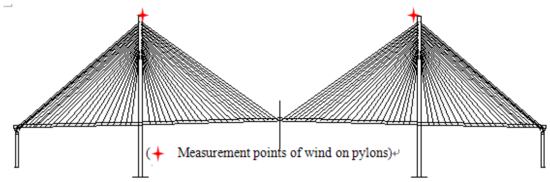

*Figure 14. Measurement points of wind on pylons.*

## 9. SUMMARY OF EACH SENSORS

Sensors is summarized in the table 1. Overall arrangement of sensor in Lijiatuo bridge is shown in figure15.

*Table 1. Summary of each sensors.*

| Num. | Classification | Type | Total |
|---|---|---|---|
| 1 | Strain sensors | SEN-S1 | 67 |
| 2 | Temperature sensors | SEN-T1 | 67 |
| 3 | Accelerometers | SEN-AL | 26 |
| 4 | Cable tension meters | JMM-268-C | 16 |
| 5 | Inclinometers | SEN-TILT | 8 |
| 6 | Displacement sensors | SEN-D2 | 4 |
| 7 | Static water levels | SEN-HOR | 11 |
| 8 | Anemometers | HFY-1A | 1 |

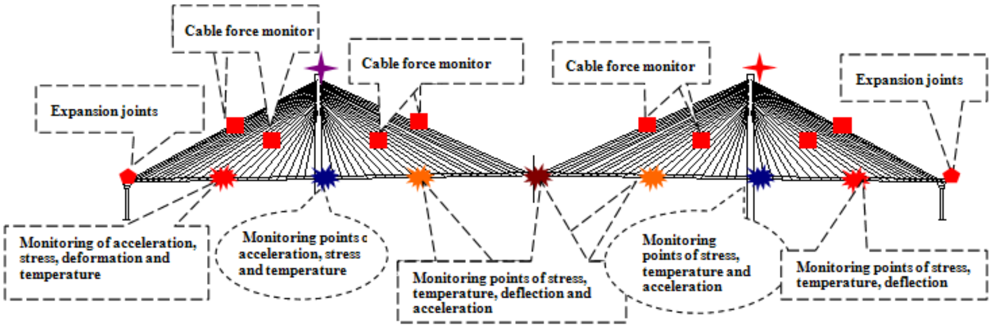

*Figure 15. Overall arrangement of LHMS in Lijiatuo bridge.*

## 10. DATA ACQUISITION SYSTEM

Data acquisition subsystem of HMS in Lijiatuo bridge is integrated by optical fiber sensing network, cable force automation test system and comprehensive information network.Data are collected by combining comprehensive methods of real-time monitoring, regular inspection and detection.

Data are collected and transmitted by combining comprehensive methods of real-time monitoring, regular inspection and detection. Real-time monitoring is automatic data collection mode of sensors. Regular inspection is manual input-data mode. Real-time monitoring of the acquisition mode is shown in fig.16.

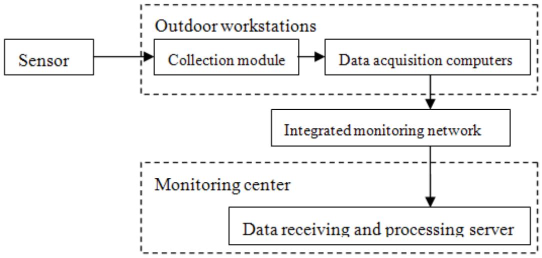

*Figure16. Real-time monitoring mode.*

Acquisition sub-system of fiber sensor is PI03 optical fiber sensing network analyzer, shown in fig.17.

*Figure17. PI03 optical fiber sensing analyzer.*

Cable force acquisition subsystem are consisted of the JMM-268-C digital accelerometer, bus type multipoint collection controller, monitoring station and monitoring software. The sensors are connected by RS-485 bus type in series. Measurement data collected at multiple points control module is transmitted to the monitoring station, and saved to the database, shown in fig.18.

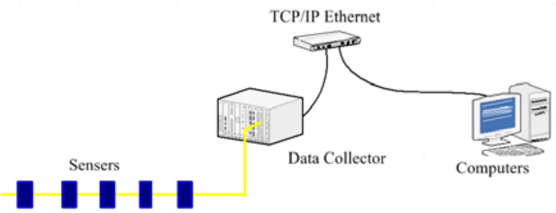

*Figure18. Cable force acquisition subsystem*

Main girders, cables and pylons are monitored at the same time. Because optical fiber sensors have different wavelength of reflected light, stress, temperature, acceleration, deflection, displacement sensors of each monitoring section bunched together, occupying one or more channels of the optical fiber sensing network analyzer. At the same time cable force information is obtained by cable automated acquisition system. Two kinds of information on optical fiber network are transmitted to the monitoring center, whose data are analyzed and processed. The transmission network topological graph of HMS in Lijiatuo bridge is shown in figure19.

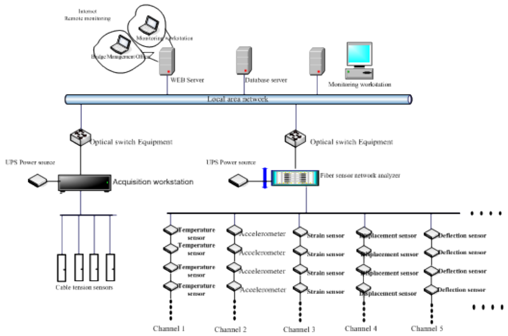

*Figure19. Transmission network topological graph .*

## 11. CONCLUSIONS

This paper has described a smart sensor modular architecture that has been used in the structural health monitoring system for in-service long span cable-supported bridges, such as Lijiatuo bridge. Health monitoring system for long-span bridges can be divided into four integrated modules. These four integrated modules are: (1) the sensory system, (2) the data acquisition and transmission system, (3) the offline assessment data processing and control system.

Each module is well-designed and encapsulated in order to ensure the reliability of measured data by smart sensors. Different types of sensors should be deployed at the key locations and components where large displacements and stresses are expected to occur so that the measured data can be validated by correlation among themselves.

Finally, it is concluded that a SHMS for long-span bridges should be able to monitor the loading and structural parameters so that the bridge performance under current and future loadings conditions can be evaluated. Such evaluated results should be able to facilitate the scheduling of bridge inspection and maintenance activities, and be able to determine not only the cause of damage, but also the extent of remedial work, once the damage is identified.

## ACKNOWLEDGEMENT

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## REFRENCES:

[1] Ando, S., Nara, T., Ono, N. and Kurihara, T. (2007). “Real-time orientation-sensitive magnetooptic imager for leakage flux inspection.” *IEEE Transactions on Magnetics*, 43(3):1044-1051.

[2] Brownjohn, J.M.W., and Xia P.Q. (2000). “Dynamic assessment of curved cable-stayed bridge by model updating.” *ASCE, J. Structural Engineering*, 126 (2): 252-260.

[3] Cho, S., Jo, H., Jang, S. A., Park, J., Jung, H.-J., Yun, C.B., Spencer, B.F. Jr., Seo, J.(2010). “Structural Health Monitoring of a Cable-Stayed Bridge Using Smart Sensor Technology: Data Analysis.” *Smart Structures and Systems*, 2010

[4] Farrar, C. R. and Worden, K. (2007). “An introduction to structural health monitoring.” Phil. Trans. R. Soc. A365, 303–315.

[5] Gentile, C. and Gallino, N. (2008). “Condition assessment and dynamic system identification of a historic suspension footbridge.” *Structural Control and Health Monitoring*, 15:369-388.

[6] Giacosa, L. M., De Stegano, A., Civera, P. and Ansari, F. (2008). “Long-term structural health monitoring of the 2006 Torino’s Olympic pedestrian cabled-stayed bridge.” *Proc. World Forum on Smart Materials and Smart Structures Technology*. In CD-ROM.

[7] Kim S., Pakzad, S., Culler, D., Demmel, D., Fenves, G., Glaser, S., and Turon, M. (2007). “ Health Monitoring of Civil Infrastructures using Wireless Sensor Networks”. *Proc. 6th Int. Conf .on Information Processing in Sensor Networks*, pp. 254-263.

[8] Lee, J. W., Kim, J. D., Yun, C. B., Yi, J. H. and Shim, J. M. (2002). “Health-monitoring method for bridge under ordinary traffic loadings.” J. Sound and Vibration, 257 (2): 247-264.

[9] Peil, U. (2005). “Assessment of bridges via monitoring.” *Structure and Infrastructure Engineering: Maintenance, Management, Life-cycle Design and Performance*, 1(2): 101- 117.

[10] KAI-YUEN WONG.Design of a structural health monitoring system for long-span bridges[J]. *Structure and Infrastructure Engineering*, 3(2), June 2007, 169-185