Health Monitoring System for Donghai Bridge in Shanghai

LIMIN SUN，DANHUI DAN，and ZHI SUN

ABSTRACT:

Donghai Bridge is a linkage connecting the Luchao Port in Shanghai and the Yangshan Island Deep Water Port. The bridge crosses the East China Sea and lies on soft clay, so the durability against ocean environment and the un-uniform settlement of foundations are especially concerned. This paper introduces the design, implementation and trial operation of the structural health monitoring system of bridge. Some key issues were investigated during the design. Vulnerability of the bridge under wind, earthquake, and traffic and ship collision was analyzed for determining types, locations and number of sensors. The concrete and steel corrosion against ocean environment were monitored since the construction stage. Complied with common levelling methods, the GPS technique was adopted for measuring the settlement of foundations. Two evaluation approaches, an on-line one and an off-line one, were adopted in the SHM system. There are 478 sensors installed to the whole bridges, to monitor wind speed, seismic ground motion, ship collision, temperature, settlement, structural deformation, structural stress, structural vibration, fatigue and so on. 8 bridge sections are under monitoring, including 2 cable stayed bridges and 6 continuous girder bridges. The system has been completed in June, 2006 and are under trial operation now.

DONGHAI BRIDGE

Donghai Bridges [1] is a linkage connecting the Luchao Port in Shanghai and the Yangshan Island deep water Port in Zhejiang Province (Fig.1). The linkage is about 32 km long and consists of 2 cable-stayed bridges and a large number of spans of continuous and simply supported bridges. It crosses the East China Sea and lies on soft clay so the durability against ocean environment and the un-uniform settlement of foundations are concerned. The construction of the bridge is completed and the bridge has opened to traffics in Oct., 2005. A structural health monitoring system was designed and installed to the bridge. This paper introduces the design, implementation and trial operation of the structural health monitoring system for bridge.

Limin SUN, Prof., Dept. Of Bridge Eng., Tongji Univ., Shanghai, China
lmsun@mail.tongji.edu.cn

Fig. 1 *Donghai Bridge in Shanghai, China*

STRUCTURAL HEALTH MONITORING SYSTEM FOR DONGHAI BRIDGE (SHMSDH)

Outline

Donghai Bridge is the first large scale cross-sea bridge in China. The natural environment of the bridge site is complicated. The hypsography is complex and the temperature and humidity are high in summer. The area is also affected frequently by strong wind and thunder storm. In addition, the bridge structures are subjected to a corrosion ocean environment.

Structural health monitoring system for Donghai Bridge (SHMSDH) [2] was designed to be able to automatically collect the data of displacement, force, stress and so on of the structure through the sensors embedded in or installed on the surface of the structure. Besides SHMSDH, an artificial inspection process was also suggested to provide additional data for structural assessment.

Design principles

The design concept of SHMSDH is that the system should be succinct, practical, reliable, and economical. The main objective of the system is to support the maintenance and management of the bridge. Structure engineers played a leading role as the designers of the system, assisting by equipment engineers, network engineers and software engineers.

The monitored bridge spans include the representative continuous beam spans, the important structures such as the main navigation channel cable-stayed bridge and Kezhushan cable-stayed bridge, as well as the structure components which are unreachable or difficult to be inspected by human after the construction. The monitored items are closely related to structural safety, durability and serviceability. The assessment of bridge is based on a combination of automatic monitoring system and artificial inspection process. The number of sensors was minimized with satisfying the requirement of data collection. The hardware and software of the system are replaceable and updatable.

Monitored spans and items

The monitored bridge spans are shown in Fig. 2. The bridge sectors monitored are the main navigation channel cable-stayed bridge with a main span of 420m, Kezhushan cable-stayed bridge with a main span of 332m, 3 sub-navigation channel continuous frame bridges with spans from 120-160m, and 3 sectors of 50m, 60m and 70m span continuous girders which are representative spans of Donghai Bridge. Other 13 sectors will be monitored regularly for deflection of bridge girders, un-uniform settlement of foundations and scouring of seabed near pile foundations. An open air station was built at Dawugui Island for corrosion monitoring and experiments of structural component under water or expositing to air.

The items to be monitored are: a) environment of bridge site including temperature, wind speed, wave height and current washing around foundations; b) static and dynamic response of bridge including deformations of towers of cable-stayed bridges, deflections of continuous girders, un-uniform settlements of foundations, displacements of dampers installed between girders and towers of cable-stayed bridges, strains of girders, vibration of girders and towers, tensions of stay cables, and temperatures of structures; c) durability of structure including fatigue of steel structures and chloride corrosion of concrete.

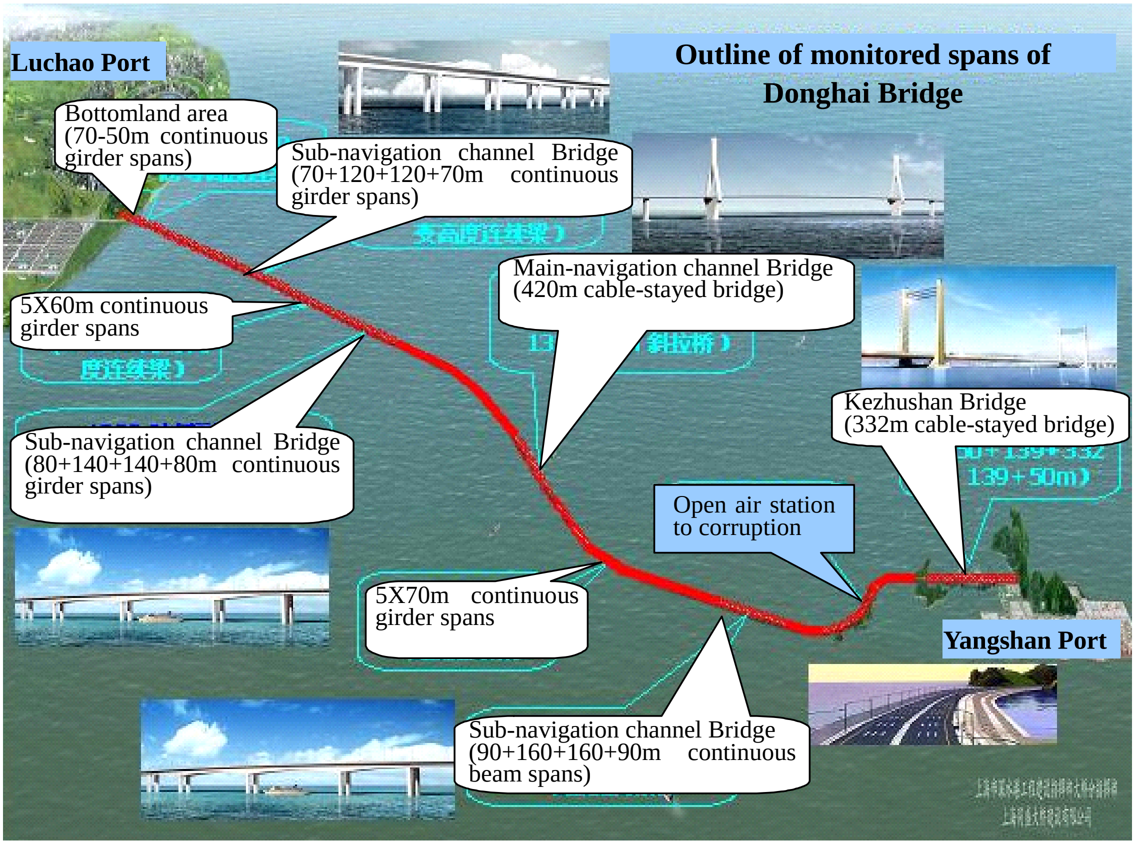

Fig. 2 *Monitored spans of Donghai Bridge*

Primary sensing technologies

(1) GPS for monitoring deformations

3 measurement points were installed at the main navigation channel bridge. 2 of them are at the tops of two towers and the third one is at the mid-span of the girder. 5 measurement points are at Kezhushan Bridge, in which 2 are at the tops of each tower

and 1 is at the mid-span of the girder. Two reference points are set at the Luchao port and the Xiaoyangshan port.

(2) Fatigue sensor

Fatigue sensors were installed at the two cable-stayed bridges, i.e., The Main Navigation Channel Bridge and the Kezhushan Bridge, for monitoring the fatigue of steel girders especially at a position with high stress such as cable anchorage boxes. For real-time monitoring, the total time history and the overshot number of stress exceeding a threshold value can be obtained. For off-line assessment, the fatigue sensors can provide data for fatigue evaluation, fatigue lifetime prediction and fatigue analysis of high stress structural components.

(3) Levelling for un-uniform settlements of piers

Artificial levelling will be carried out regularly for monitoring the un-uniform settlements of bridge piers. The levelling measurement can provide results with high accuracy and these will be used for cross-checking the data from the GPS and the communicating vessels.

(4) Communicating vessel for girder deflections and un-uniform settlements

A system consists of communicating vessels was adopted for monitoring girder deflections and un-uniform settlements of continuous girder bridges. For bridge girders with large altitude variation, the system is combined by several sub-systems of communicating vessels. The liquid surface level in a vessel can be recorded automatically to obtain the altitude at measurement points. The reference altitudes can be obtained from the Lucho port by levelling, and it will be counterchecked every 3 or 6 months.

(5) Corrosion monitoring

The monitored items include the infiltration depth of the chlorine ion into concrete, the density distribution of chlorine ion, the rust state of steel bars, the influence of crack to rust of steel bar and the effectiveness of experiment of cathode protection for steel pipe piles. The structural components at atmosphere, at a position of wave splash and at a position of sea level variation are monitored. Two monitoring means were adopted: a) an corrosion exposition station was established at the bridge site, which has a similar ocean environment to the bridge. The state of corrosion is mainly monitored through test samples which are exposed to the environment in the station. The electrochemistry measurements and strength tests will be regularly carried out to obtain data and relationships between corrosion condition and environmental factors. b) As an assisting means, sensors were embedded into the structure to automatically collect the data related to structure corrosion.

Modules of SHMSDH

The structural health monitoring system for Donghai Bridge (SHMSDH) consists of five modules, i.e., sensor system; data acquisition and transmission system, data processing and control system, structural health evaluation system, as well as portable inspection and maintenance system.

EVALUATION SYSTEM OF SHMSDH

Flow of evaluation

The condition of structural health is evaluated according to the data from the monitoring system and other inspections. The evaluating process includes two parts, namely on-line evaluation and off-line evaluation. The function of the former is to alarm the management authority of the bridge when the structure has any safety problems, as well as to produce a regular monthly report to the management authority of the bridge, especially aiming at structural safety. The function of the later is to produce an emergent evaluation report after the occurence of accidental events, as well as to give a regular annual total report about the safety, durability and serviceability based on the integrated and detail analyses by experts.

On-line evaluation

The on-line evaluation system is an automatic system which can analyze the data collected by the sensors and then can make a preliminarily judgement on the structural safety by comparing the measurement with some pre-set control values. The system, combining other information from traffic and navigation monitoring system and regular artificial inspections, is able to automatically make a decision of whether it is need to alarm the management authority and to immediately conduct an off-line evaluation.

Off-line evaluation

The off-line evaluation system will process some advanced analysis, such as structural static analysis, modal analysis, correlation analysis between the bridge behaviors and environmental factors and so on. The system needs massive structural analysis and judgments by experts before an integrated evaluation of structural condition.

KEY ISSUES FOR SHMSDH

Some important issues were investigated before the design of the structural health monitoring system for Donghai Bridge [4].

Conceptual design of a health monitoring system

The design concept of the structural health monitoring system for Donghai Bridge was thought over. It was emphasized that the main purpose of the system is to enhance the maintenance and management of the bridge. The principle of design was determined to be succinct, practical, reliable and economical. The feasibility studies of the sensing technologies were strictly required.

Vulnerability analysis of the bridge structure

Vulnerability analysis of a bridge structure is the basis to determine the items need to be monitored. The vulnerability of the typical spans of Donghai Bridge subjected to strong wind, earthquake, ship collision and heavy traffic were analyzed. The results of vulnerability analysis instructed the design of sensor type and distribution. The static and dynamic structural analyses were also carried out for the design of a SHMSDH and some baseline models were established.

Monitoring technology and evaluation method for concrete durability

The monitoring of concrete durability for the Donghai bridge is one of the most important items. The monitoring technology for corrosion of concrete and steel bar in reinforced concrete structures was investigated. The durability evaluation method of the concrete girders and piers in Donghai Bridge were also studied in account of the ocean environment conditions. The evaluation method based on density distribution diffuse rate of chlorine ion and permeability of concrete was proposed. The index for durability evaluations was established according to Chinese, European and American standards.

GPS for deformation monitoring of the cross-sea bridge

Donghai Bridge is a long cross-sea bridge. GPS is the most appropriate technologies for bridge deformation monitoring. This study focused on the application of the GPS technology in sensing the spatial position and the dynamic deformation of bridge. The main research tasks include: a) optimum locating of the GPS measurement points and base stations; b) accuracy; c) dynamic component measurement of deformation; and d) long-term deformation measurements such as foundation settlements.

Fatigue gauge

A fatigue gauge was developed for monitoring the fatigue of the girders of the two cable-stayed bridges. The researches for implementation of the fatigue gauge include: a) calibration of fatigue gauge; b) development of strain multiplier for fatigue sensor and software for data processing; c) fatigue strength and durability of bond for sticking strain multiplier to bridge structure; and d) evaluation method of fatigue damage and remaining life.

Technology of data transmission

Existing data communication technologies include 485, Lon works and Ethernet TCP/IP. Aiming to the characteristic of SHMSDH, a reliable and flexible network structure for data control, collection and transmission was proposed. And the corresponding specification and standards were also established. The proposed communication network takes in some advanced network technologies and it is compatible for multi-medium transmission such as conventional wire, optical cable, wireless and so on. The system also supports remote monitoring and control.

Evaluation method on structural condition after accidents

An essential function of SHMSDH is on-line diagnosis and evaluation of the bridge after accidents. Static and dynamic characteristic parameters were studied and picked-up, and the threshold values for these parameters were determined for judging whether the structure is in its normal or abnormal condition.

Evaluation method on structural serviceability

The serviceability evaluation for Donghai Bridge mainly considers the wind influence to the operation of bridge. The influence on the aerodynamic performance of the bridge caused by various vehicles composition was studied. The vibration level of bridge subjected to various wind speed and direction was analyzed. The limitation for opening to traffic was investigated. According to the research results, an instruction for manual serviceability evaluation and maintenance for Donghai Bridge was established.

MAIN FEATURES OF SHMSDH

The software for SHMSDH was developed and the system can be accessed via internet by authorized users (Fig. 3). The maintenance engineers can monitor the operation state of the bridge. The researches can access the data base to download the historical data and get real time data for analysis. The administrator can set the system parameters, change the data sampling rule, and maintain the sensors and other hardware online.

Fig. 3 *Main features of SHMSDH*

REMARKS

The research topics related to structural health monitoring are the hottest research area in civil engineering in China, since management and maintenance of infrastructures will gradually turn into the main societal demands after a construction rush of the country [3]. In the authors' opinion, more efforts should be put into the following issues in the future:

1) Design concept of SHMS implementation for a bridge should be considered circumspectly. Generally, the cost of a SHMS will take about 0.5-2.0% of the total of construction of a bridge. The installation of SHMS should do support the maintenance and management of the bridge.

2) Vulnerability analysis of a whole bridge system is necessary for the design of a SHMS. The structural components those easily damaged in the sense of causing safety, durability or serviceability problems of structures should be found out.

3) Deformation measurement technology for large span bridges is lacking. The precision of GPS is not satisfied and it is still expensive.

4) Cable corrosion inspection and protection is a very important issue for cable-stay bridges and PC bridges.

5) Fatigue monitoring technology should be developed for monitoring the fatigue problems of steel bridge girders subjected to heavy traffic loads.
6) Wireless sensor and data transmission are arrestive technologies. SHMS can be consumedly improved with the development of these technologies.
7) Durability of sensor and data transmission system is concerned seriously by bridge management authorities. Design lifetime for large span bridge is longer than 50 years even to 100 years. So a SHMS with comparative durability is required. Hardware with longer lifetime should be developed and the replacement of sensors and other hardware should be considered in the system design.
8) System integration is important for implementation. The compatibility and optimization of system should be investigated.
9) Establishing of alarming value for structural safety, evaluation and assessment of structures based on SHMS should be further addressed.

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