Health monitoring and assessment of long-span bridges

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ABSTRACT: A sizeable number of efforts have been sought to instrument bridges for structural monitoring and assessment. The outcome of these efforts has been difficult to assess, as gauged by advances in the understanding of the definition of structural damage and their role in sensor selection as well as in the design of cost and data-effective monitoring systems. The authors' experience with the design, construction and operation of a monitoring system for the south-bound Kishwaukee Bridge in Illinois has shed light on these concerns. This paper discusses the design and outcome of our monitoring systems. The systems provide bridge engineers with a continuous, low-cost monitoring platform that timely retrieves pertinent information. This paper will also orally address lessons learned from the design and installation of health monitoring systems for several major long span bridges such as Kamikazue Viaduc, Ashidagawa Cable-Stayed Bridge both in Japan and Qianjiang 4th Bridge in China.

1. INSTRUCTION

Bridges play an essential part of a highway network. They are open to traffic, resistant to natural disaster, and undaunted by millions of loading cycles per year. However, bridges are also expensive to maintain and occasionally fail (DeWolf J. T., et al., 1989). Many bridges carry greater average loads than predicted during their design. Thus, the past few years have seen a significant increase in the need to monitor bridge performance. Today, effective bridge management consists of a great need to monitor the real-time conditions of bridges and the deterioration rates of their components, so that efficient and pro-active measures can be taken (Ashkenazi et al., 1997, Cheung et al., 1997, Catbas et al., 2000). By using the latest state-of-the-art technologies, it is possible to use health monitoring systems on highway bridges to determine their behavior and condition, and derive a response to maintenance and inspection needs (DeWolf J. T., et al., 2002).

Bridge health monitoring systems promotes the understanding of bridge behavior under various loads and environmental effects (Bampton et al., 1986, Leitch et al., 1987, Barr et al., 1987, Brownjohn et al., 1994, Lau & Wong, 1997, Macdonald et al., 1997, Miyata et al., 2002). One of the earliest documented bridge monitoring exercises was conducted on the Golden Gate and Bay Bridges in San Francisco. Its purpose was to learn about the dynamic behavior and possible consequences of earthquakes (Carder D. S., 1937). Carder's studies were applied to the probability analysis of damage caused by resonance during seismic excitation. The experimental procedure consisted of measuring ambient vibration data provided by a photographic seismograph that was attached to the bridge. Wind, moving water, traffic, or people working on the bridges caused the recorded vibrations. Wind-induced vibration of the Golden Gate Bridge was studied (Vincent G. S., 1958). Vincent developed a specific monitoring system of accelerometers for the bridge and used measurements to verify that structural modifications to the bridge would prevent objectionable torsional vibrations.

With the development of design theories and construction techniques for long-span bridges, a lot of large bridges were built during the last fifty years. The safety of these giants required long-term bridge monitoring systems to be developed and installed. Typical examples include Commodore Barry Bridge Monitoring System (USA), Jindao Grand Bridge Monitoring System (Korea), Akashi Kaikyo Bridge Monitoring System (Japan), Alamillo Bridge Monitoring System (Spain), Hummer Bridge Monitoring System (UK), and Zhanjiang Bay Bridge Monitoring System (China), etc. In all of these long-

term monitoring systems, the most extensively devised is the Wind and Structural Health Monitoring System (WASHMS) for Tsingma Bridge in Hong Kong, whose sensory system consists of approximately 350 sensors and their relevant interfacing units, including the latest GPS system. However, current long-term bridge monitoring systems lack the specific techniques to provide reliable diagnosis information of bridge conditions. Most of these monitoring systems can only collect data from the sensor network and perform some simple data processing. The work of analysis and assessment has to be done manually by human specialists with the help of different independent analysis tools. For a real-time monitoring system, such as WASHMS, the huge amount of data daily collected with a high sampling rate (e.g., 100Hz) will overwhelm the computers of those bridge engineers and make evaluations difficult and inefficient. This paper provides a reliable supplement to the current research on bridge health monitoring and improves the understanding of bridge behavior during their service life.

2. KISHWAUKEE BRIDGE MONITORING

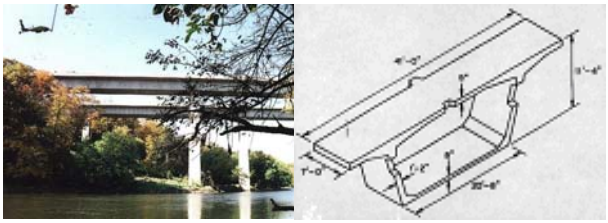


Fig. 1 Kishwaukee river bridge

As shown in Figure 1, Kishwaukee River Bridge (Rockford, IL) is a post-tensioned precast segmental box–girder superstructure opened to traffic in 1980. The bridge has five spans with lengths of 170 ft + 3 x 250 ft+170 ft (51.8 m+3 x 76.2 m + 51.8 m). As the first-generation of segmental structures, the Kishwaukee Bridge engineers chose the design of a single shear-key joint usually located close to the centroid of the cross-section. These joints are quite vulnerable especially during polymerization of the glue. A very serious problem arose after completion of the bridge. It was found that epoxy did not harden properly in the most of the joints. The epoxy was not able to carry any shear stresses and instead was acting as a lubricant that caused a reduction of the friction coefficient. Therefore, a substantial part of the shear force was concentrated at the shear keys (Wang M. L., et al., 2001). The inclined cracks went through the joint because the horizontal length of the compression struts was limited to the length of one segment. After bridge engineers found the cracking problem, many steel pins were used on the webs to stop the propagation of shear cracks, a method that has been proven successful. However, nobody knows whether the shear cracks will propagate for the future. Therefore, a long-term monitoring system is indispensable and should be installed for structural surveillance of the Kishwaukee Bridge to provide continuous health records for the bridge management department (Lloyd, G., et al., 2004a).

Since a major problem of the Kishwaukee Bridge is the existence of shear cracks on its webs, a specifically designed structural health monitoring system was installed on the Kishwaukee Southbound Bridge (Lloyd, G., et al., 2004b). This system monitors and records the strain, crack opening displacement, and acceleration of the bridge, as well as the temperature outside and inside the bridge girder. Thus, the operation and management for this bridge is transformed into a more objective and quantitative process. This process provides for optimal integration of experimental, analytical, and informational system components (Lloyd, G., et al., 2004c). In addition, the outcome of the process provides valuable information for current evaluation of structural integrity, durability, and reliability (Lloyd, G., et al., 2003a). Using this information, composed of the sensory system, data acquisition system, and health assessment system, the bridge owner and maintenance authorities can make rational decisions in assigning the budgets for both maintenance and repair.

2.1 *Static load test*

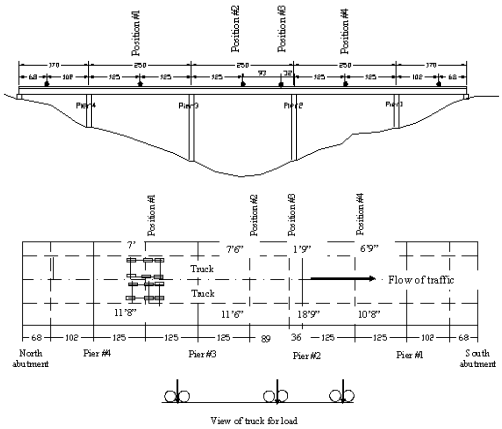


Fig. 2 Static diagnosis load test

In order to determine the actual health status of Kishwaukee Southbound Bridge and set up the baseline for the following long-term health monitoring, we did two static load tests in 2000. The bridge was tested for service loading conditions. The

weight of the trucks was comparable to the weight of the design truck defined in AASHTO LRFD Bridge Design Specifications. The design weight of the truck (72 kips) was amplified by a dynamic factor of δ = 1.3. Four different positions of the trucks were proposed on the bridge, as shown in Figure 2.

Visual inspection of the shear cracks determined the most damaged webs in the bridge (Lloyd, G., et al., 2003b). Web SB2-N4-E was chosen for in-situ measurement of deformation due to shear forces. Three linear variable displacement transducers (LVDT) were installed at the interior surface of the web, close to the neutral axis, as shown in Figure 3. Measured displacements were used for estimation of the web's shear stiffness. The load stage using trucks located in position #2 (second load) was selected for assessment, because neither transverse bending moments nor vertical axial stresses accompanied the imposed load in the web of segment SB2-N4. Shear forces generated by trucks located in position #3 (second load) were used for calculation of the steel stress increment in reinforcement.

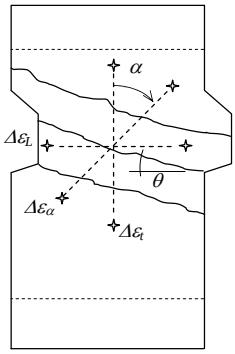


Fig. 3 LVDT Sensors on the web

The average shear strain and shear stiffness of the cracked web are:

$$\Delta\gamma_{Lt} = \frac{2\left[\Delta\varepsilon_\alpha - \Delta\varepsilon_L \sin^2(\alpha) - \Delta\varepsilon_t \cos^2(\alpha)\right]}{2\cos(\alpha)\sin(\alpha)} \quad (1)$$

$$(GA)_{ir} = \frac{\Delta V}{\Delta\gamma_{Lt}} \quad (2)$$

To determine the global flexural stiffness of the bridge, strain gauges were installed at the webs of segments located next to the closures. Measured concrete strains were used for calculation of curvature in Eq. 3 and evaluation of the modulus by Eq. 4:

$$\Delta\chi_{meas} = \left(\Delta\varepsilon_{upper} - \Delta\varepsilon_{lower}\right)/d_{gs} \quad (3)$$

$$E_c = \Delta M / \left(\Delta\chi_{meas} I_i\right) \quad (4)$$

The assessed value of modulus was still in the range from 35,000 MPa to 40,000 MPa. This value is very similar to the design value, while the tangent shear modulus has been reduced about 50-55% by shear cracks. Therefore the change of bridge shear stiffness has little influence on its flexural stiffness. Dynamic tests and FEM simulation also corroborate the negligible effect of shear stiffness on flexural stiffness.

2.2 *Half-scale model test*

In order to determine the shear carrying capacity of Kishwaukee Bridge, a half-scale I-beam model was cast in the Lab. The following parameters are measured in this experiment: Deflection of the end of cantilever; Flange strains; Web strains; Reinforcement strains; Prestressing force; Elongation of the strands.

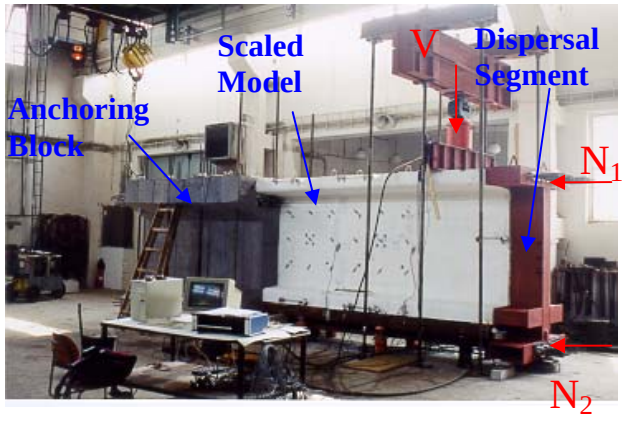


Fig. 4 Arrangement of half-scale experiment

Figure 4 presents the arrangement of the half-scale experiment. The three half-scale I-beam segments were put between the anchoring block and the dispersal segment. The friction between the joints of three segments was reduced to a certain degree to simulate the unhardened epoxy problem on the southbound Kishwaukee Bridge. The prestressing reinforcement was delivered by the low relaxation strands with a high yielding point of 1800 MPa. The upper prestressing force N_1 was applied with eight 3-strand tendons in the top flange while four 4-strand tendons were used to apply the lower prestressing force N_2 under the bottom flange. The shear force V was applied with a hydraulic jack.

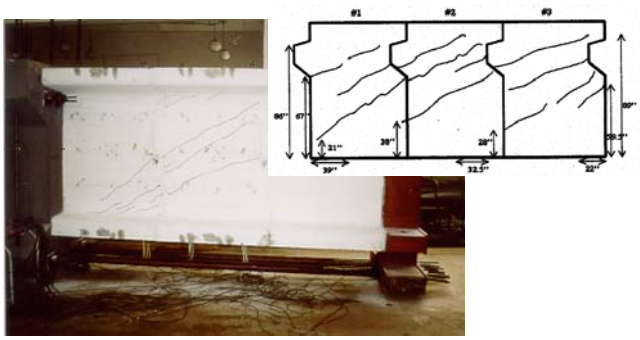


Fig. 5 Propagation of shear cracks on the I-beam webs

The propagation of shear cracks on the I-beam webs is shown in Figure 5. According to the visual inspection records, the type and inclination of these shear cracks are very similar to the actual cracks on the southbound Kishwaukee Bridge. It indicates the destructive experiment successfully simulated the actual damage condition of Kishwaukee Bridge.

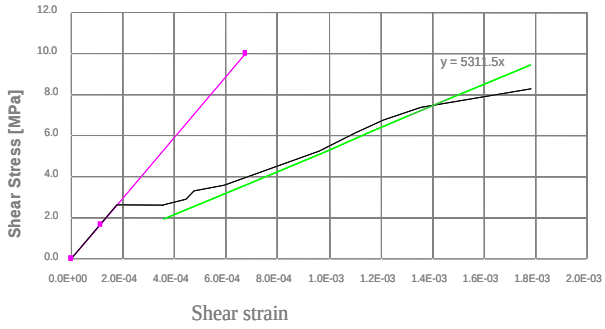


Fig. 6 Shear stress and shear strain

The relationship of shear stress and shear strain is shown in Figure 6. After the linear elastic phase, the concrete cracked and the steel reinforcement carried much of the shear force itself, which is evident from the graph. About the yielding point of shear reinforcement, the reduced tangent shear modulus was roughly 5300 MPa. According to the analysis of the static load test, the current tangent shear modulus is approximately 6740 MPa at the worst location (SB2-N4) of the southbound Kishwaukee Bridge. This means the shear steels are still in the safe region of stress-strain curve. However, more strict regulations should be encouraged such that no overweight truck passes over the bridge, which might induce failure.

3. BRIDGE MONITORING SYSTEM

Smart Health Monitoring System (SHMS) was developed by the Bridge Research Center at the University of Illinois for IDOT (Wang X., et al., 2004). This section describes the following aspects of the monitoring system: objectives and features, sensor types and their locations, system modulus and functions. The architecture diagram of SHMS can be seen in Figure 7.

As shown in the diagram, the system consists mainly of three parts:

1) Sensor Station;
2) DB servers (including two servers);
3) Application server.

3.1 *Objectives and features of SHMS*

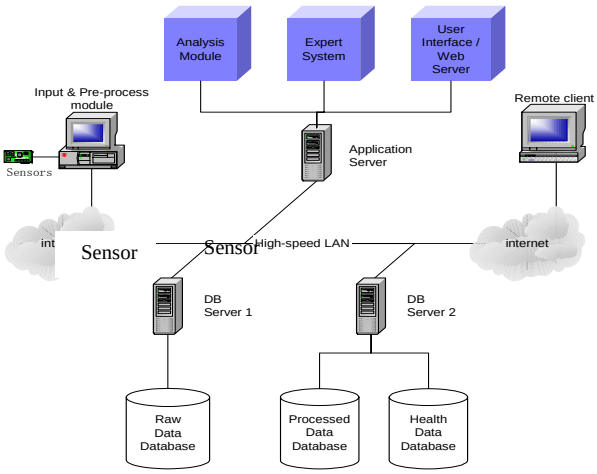


Fig. 7 Architecture of SHMS

The goals of the SHMS can be described as follows (Wang X., et al., 2002):

1) To enable users to monitor bridges in real-time from anywhere via the internet;
2) To detect and locate damage or degradation in structural components and send out warnings to bridge authorities in time;
3) To automatically generate health evaluation reports based on statistical analysis results.

The four major features of the SHMS are:

1) Distributed data pre-processing strategy and modular structure;
2) High capability and efficiency of data archiving and processing;
3) Integrated rule-based expert system and multi-level warning strategy;
4) Ethernet-based data transmission and web-based server application.

3.2 *Sensor types and locations*

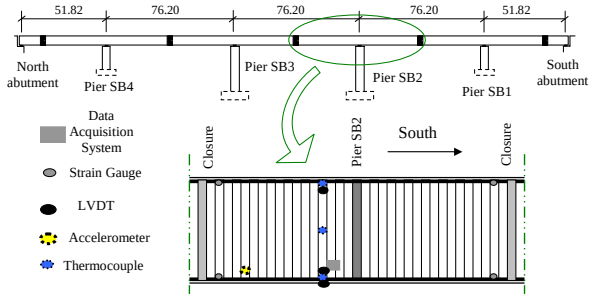


Fig. 8 Sensor location of SHMS in the box-girder bridge

One objective of developing the SHMS is to monitor long-term structural changes of pre-stressed concrete box-girder bridges with minimum types and numbers of specific sensors[5]. As shown in Figure 8, a sensor station is configured to read four types of sensors: thermocouples (types J and K), LVDT sensors, strain gages (all sampled at 1 Hz); and

capacitive accelerometers (sampled at 100 Hz). This suite of sensors was selected based upon previous assessments carried out with two static load tests conducted during 2000 (Wang et. al, 2001). After pre-processing and analyzing the collected data, the system can display to users real-time raw data, statistical data, mechanical analysis, health reports and maintenance suggestions. It also can send multi-level warnings in real-time. System parameters such as warning thresholds are set for the strain and displacement measurements. Moreover, SHMS allows users to gain access to data, manipulate data and configure the system via the Internet based on various user privileges.

3.3 *Sensor substation*

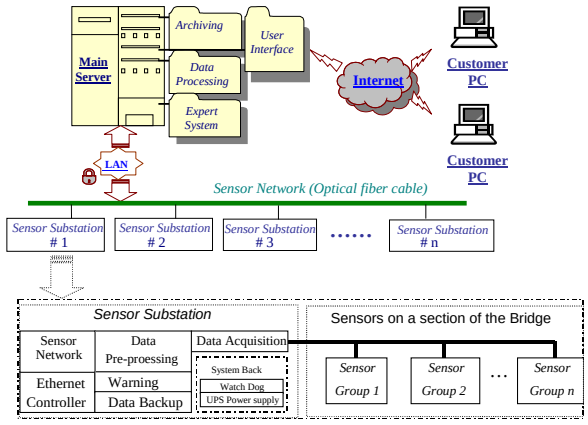


Fig. 9 Scheme of sensor substation system

Sensor station is an industrial computer system located on a bridge as shown in Figure 9. It can take the following responsibilities:

- Data acquisition:

It collects real time data from sensors.

- Pre-Processing:
  - Data validation
  - Digital filtering
  - Data reduction
  - Data classification
- Data transmission:

  Raw data and pre-processed data will be transferred and saved into the DB servers over the internet.
- Early warning:

  Based on the pre-processed data over some preset thresholds, a sensor substation can send an early warning to the system administrator.

The central unit of a sensor substation is a rack-mount industrial computer (top rack) that hosts a data acquisition board with an independent microprocessor. Signal conditioning modules and anti-aliasing filters are contained in a separate enclosure (lower rack). These components are mounted in a ruggedized and vibration-isolated chassis for easy transport and rapid setup, as shown in Figure 10. The chassis contains an internal A/C device for cold/hot weather operation. The sensor network consists of an Ethernet network card and two modems. An ISDN modem is used for the real-time data transmission. And another 56K Dial-up modem is reserved as a backup for communication in urgent cases. Although the system is supplied with a keyboard and mouse, power-up is automatic, and restart can be remotely controlled via the internet. Therefore, apart from the installation and maintenance, setup and operation is quick and convenient.

Fig. 10 Sensor station in rack-mount chassis

The data acquisition system is designed around a Microstar Laboratories DAP4000 14bit programmable data-acquisition board installed in a Linux-based (SuSe 8.0) AT-industrial chassis. In addition to satisfying the precision and aggregate bandwidth required, its on-board processor greatly minimizes the programming required for basic structure monitoring analyses. The analog inputs to the board are brought to an expansion chassis with an interface backplane. Analog interface cards were selected to allow channel-by-channel sensor conditioning for different types of sensors. Equipment adhering to these specifications was selected in order to maintain the long-term viability of the system and to simplify any required maintenance. In a sensor substation, the raw data from various kinds of sensors are pre-processed for data reduction and data classification. After the continuous running for two years, it proves that the data-preprocessing module can minimize the network traffic for data transmission and efficiently relieve the burden of the application server and DB servers.

3.4 *DB servers*

DB servers host the three databases and three configuration databases:

- Data databases (as shown in Figure 11):
    - Raw Data Database:

All the pre-processed data will be transferred from sensor substations to the raw data database;

- Processed Data Database:

Statistical Analysis Module will process all the pre-processed data then save them into the processed data database;

- Health Data Database:

An integrated rule-based expert system will evaluate the health status of the bridge based on the processed data then generate a health report.

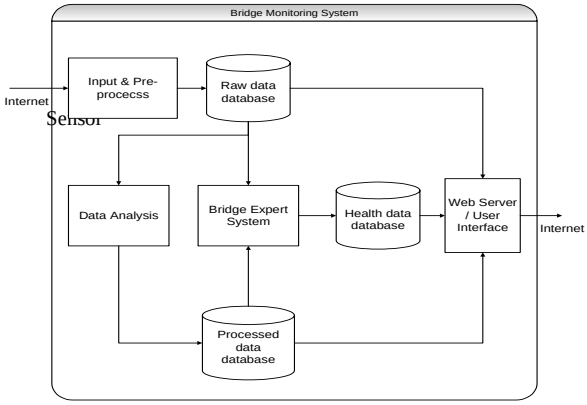


Fig. 11 Flow chart of db module

- Configuration databases:
    - Preset Database:

Stores static and dynamic characteristics of a bridge for health assessment, such as bridge geometrical and material parameters, original natural frequencies, designed lifetime, etc. They are determined after the bridge construction is finished and cannot be modified.

- Adjustable Database:

Stores processing parameters of SHMS, such as sampling rates, multi-level thresholds for warning/alert, etc. Privileged users via the web browser can access and adjust them.

- System Database:

Stores all the information of system management, such as authorized users list and their privileges, system configurations, etc. System administrator via the web browser can manage them.

Due to the high volume of sensor data, data will accumulate quickly in the DB and the performance and maintainability of a table will be impacted because of too much data. So after a certain time interval (e.g. 1 day), old raw data will be archived to another archive table and be cleaned from the current tables. An automatically running program on the database server accomplishes this job. This way, the raw data DB can be kept in a controllable size and work in an efficient manner and the user can access the archive data from the web. When there are too much data in the archive table (e.g., after 2 years), users can export the data to other media such as CD-R, DVD or Tape to archive the historical data. If users want to query these data, another dedicated DB or DB server can be established to handle these requests.

3.5 *Application server*

The application server is the central server that does most of the job. It communicates with the bridge station, accesses database servers, performs analysis and gets requests from users and responds to the users. Three modules run on this server:

- Analysis Module:
    - Temperature Effect Analysis;
    - Traffic Effect Analysis;
    - Dynamic Analysis;
    - Bootstrap Statistics Analysis.
- Expert System Module (detailed description shown in Section 3):
    - Ruler-based Bridge Health Diagnosis System;
    - Multi-leveled Warning System;
    - Automated Heath Report System;
    - Expert Suggestions System for Decision-making.
- Web Server / User Interface Module:

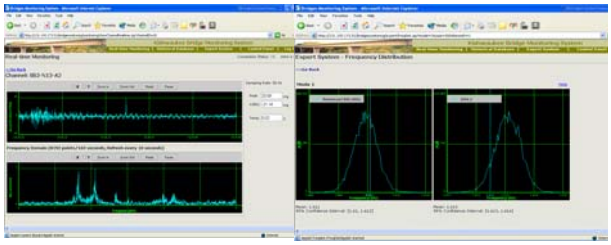
This module is designed to be the user interface between the system and the users. Generally, there are two parts of this module, one accesses the data stored in the system, including raw, processed and health data. The other part of the module manages the whole system, such as configuring bridges, sensors and users. This module offers the following functions to users:

- Data displaying (historical and real-time)
- Statistics data review
- Health reports view
- Notification of warnings and alerts
- Maintenance suggestions
- Data downloading
- System configuration
- Data analysis configuration
- User and privilege management

4. GLOBAL AND LOCAL HEALTH EVALUATION

Kishwaukee bridge monitoring system has been collecting and processing data and generating evaluation and health reports for three years. The system can analyze the frequency distribution, crack opening displacement, shear strain in the web, and traffic information for the Kishwaukee Bridge. Automated warning/alarm system is in effect to warn against any local structural damage on the bridge, system problems, sensor dysfunction, and data errors.

After establishing the baseline of bridge health, a long-term monitoring system can be used to provide the continuous health information of a bridge. For concrete bridges, cracks, especially the shear cracks act as the main role of local damages. And the global health information of a bridge can be represented with the bridge stiffness. Both global and local conditions of bridges need be evaluated in order to determine their in-service behavior and justify rehabilitation and repair plans. The global health information can be provided by dynamic measurement, while the local damage can be captured by static type of sensors such as strain gages, linear variable displacement transducer (LVDT), etc. It is not enough to evaluate the health condition of a bridge on the basis of the global health information or local damage information only.



(a) Real-time Acceleration & Modal Frequencies (b) Bootstrap Distribution of Modal Frequencies

Fig. 12 Pre-processing and post-processing of acceleration and frequencies

Raw acceleration data are collected and preprocessed to obtain the natural frequencies in a sensor substation. The acceleration and frequency data are then transferred into the database server via the Internet in real time, as shown in Figure 12(a). After that, the application server will analyze the data to get the hourly bootstrap mean and its confidence intervals, as shown in Figure 12(b).

Based on the five dynamic tests from 1999-2000, the global dynamic characteristics of the bridge are obtained from the acceleration data with the related temperature values. Those structural parameters are setup as the baseline of global health assessment. Temperature has a significant influence on the natural frequencies of a structure. Hence, it is important to derive the relationship between temperature and natural frequencies, i.e., how much the frequency will change due to the variation of 1 ^{o}C To a certain degree, this relationship can represent the change of the bridge bending stiffness due to temperature variations.

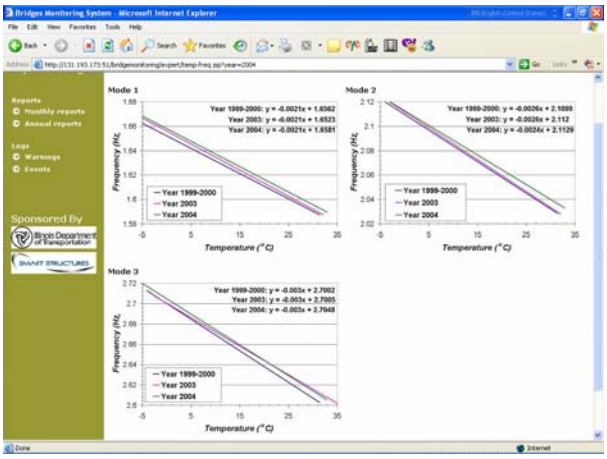


Fig. 13 Relationship between frequencies & temperature

Figure 13 provides temperature-related regression curves and parameters of the first three modes from year 1999 to year 2004. As shown in the figure, the changes of the first two modes due to the variation of 1 ^{o}C during 2004 are almost the same as the baseline (1999-2000). However, the analysis about mode 3 during year 2004 shows a little increase in the frequency change due to the unit temperature variation.

TABLE 1 Bootstrap mean values of mode frequencies

Year	*Mode1 (Hz)*	*Mode2 (Hz)*	*Mode3 (Hz)*	*Mode4 (Hz)*
2004	1.617	2.064	2.644	2.979
2003	1.612	2.057	2.645	2.953
1999~ 2000	1.611	2.058	2.638	2.948

The first four resonant frequencies in the vertical direction are listed in Table 1. All the bootstrap mean values are compared at 20 ^{o}C after temperature compensation. As shown in the table, the first two resonant frequencies didn't change a lot during these two years, while the mode 3 and mode 4 of year 2003 shows a little larger decrease from the baseline (1999-2000). The above analysis indicates there is no obvious change in the structure stiffness during these two years. However, according to the theory of dynamic analysis, the changes of higher modes usually reflect the development of local damages. In

order to verify the result of global health assessment and inspect the state of local damage, it is necessary to carry out the specific local health evaluation.

The raw data of crack opening displacement are preprocessed in sensor substation and transferred into the database server via the internet, as shown in Figure 14(a). Then based on the hourly record of crack opening displacements, the application server will analyze those data to obtain their bootstrap distribution and confidence intervals. The result is shown in Figure 14(b).

(a) Real-time Crack Opening Displacement

(b) Bootstrap Distribution & Confidence Interval

Fig. 14 Pre-processing and post-processing of crack opening displacement

In order to find out whether the shear cracks propagated during year 2003, it is necessary to analyze the relationship between temperature and crack opening displacements, i.e., to find how much the crack opening displacement will change due to a variation of 1 ^{o}C. To a certain degree, this relationship represents the change of shear stiffness of the webs due to the temperature variation.

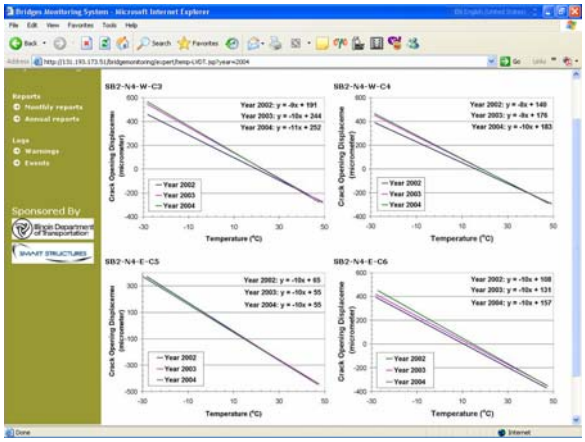


Fig. 15 Relationship between crack opening displacement and temperature

Based on the data of these two years, the analysis result of crack opening displacements is given in Figure 15 according to their locations. During the last three years, the crack opening displacements due to temperature show some difference between the west web and the east web. As shown in the graph, on the west web, the crack opening displacement increased at the rate of about 1 micrometer per year. But on the east web of SB2-N4, the corresponding parameters are almost the same as before. The difference between the west web and the east web is possibly due to the heavier traffic on the west side of the bridge. This result conforms to the visual inspection of Illinois Department of Transportation. According to the analysis on crack opening displacement, we can evaluate the average shear strain of the cracking webs.

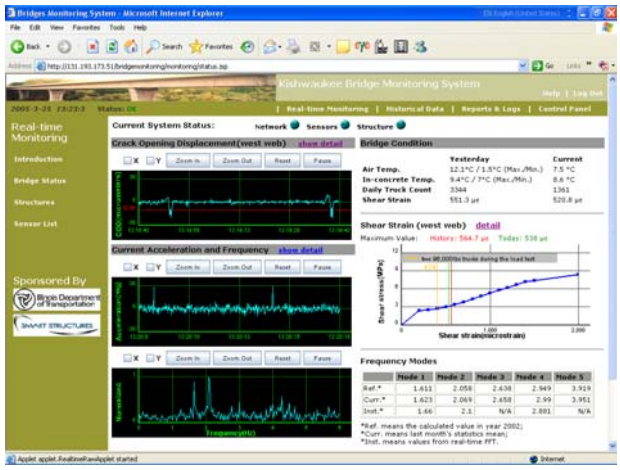


Fig. 16 Main Interface of DIBMS

Based on the global and local measurements, the rule-based expert system gives the shear carrying capacity of the bridge with ductile mode of failure. Figure 16 presents the shear stress - shear strain curve of the cracked web at Segment SB2-N4. As shown in the graph, the monthly maximum shear strain is over the baseline of the static load test in 2000. However, its monthly mean value is still far below the yielding point. It indicates that the most damaged segment (SB2-N4) is still working in the nonlinear-elastic zone.

5. CONCLUSION

A real-time bridge monitoring system includes a real-time data acquisition system and a real-time data transmission system. The system provides the current health status of the bridge in real-time, which makes it possible to predict the upcoming dangerous structural changes and send out warnings on time. This system can also help to build the most detailed and complete database for the health analysis. The key is to use the minimum number of sensors to collect, process, and analyze real-time dynamic and static data from the most critical positions of the bridge.

A large-scale real-time monitoring system can generate huge amounts of data every day. The excessive information will overwhelm and decrease the productivity of bridge engineers if there is no integrated program of data preprocessing and health

diagnosis in the monitoring system. All the real-time raw data shall be pre-processed in the bridge to increase the speed of data transmission, save the capacity of database, and improve the efficiency of health assessment.

Automatic measurements should not be considered to be the be-all and end-all of bridge health monitoring. Its place is firmly entrenched in assisting engineers to conveniently carry out the damage detection, analysis, and evaluation of bridges.

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