Long span bridge health monitoring system in Japan

Sunaryo Sumitro, Yoshimasa Matsui, Masaru Kono, Takuji Okamoto, and Katashi Fujii

Keisoku Research Consultant, Co., Shinagawa-ku, Tokyo 140-0013, Japan
Faculty of Engineering, Hiroshima University, Hiroshima 739-8527, Japan

ABSTRACT
Health monitoring has been one of particular concerns of the engineering community in Japan. Effective monitoring, reliable data analysis, rational data interpretation and correct decision making are challenging problems for engineers who specialized in bridge monitoring field. In this paper, the status of health monitoring of long-span bridges in Japan is briefly reviewed. The monitoring system was developed to be a reliable device to observe the bridge in earthquake and/or typhoon accurately, besides have a self-check function to sense the disorder of the system itself. Current practices in health monitoring of bridges are represented by the example of Akashi Kaikyo Bridge monitoring system. The reliability of the current monitoring system is confirmed by comparing the analyzed simulation results and field-measured results. Furthermore, a newly developed monitoring system is proposed to provide information for structural health maintenance, so called Monitoring Based Maintenance (MBM). This monitoring system is easily accessible, economically feasible and durable through efforts in development of innovative sensors and new generation of automated remote monitoring technology.

Keywords: Long span bridge, monitoring system, earthquake, wind, structural health assessment, maintenance

1. INTRODUCTION
For long span bridges, such as, the world longest suspension bridge, Akashi Kaikyo Bridge, due to the bridge scale, its design adopted some newly developed design codes for aerodynamic, seismic stability and design constants. Some newly developed challenging technologies that have been applied in this super long bridge, such as, wind resistant design, seismic design, run ability of train on suspension bridge, large scale underwater foundation, working platform on the sea and seabed excavation method

The dynamic response against strong wind and earthquake are subjected to unknown factors those are uneasy to predict. Therefore, it is necessary to establish a monitoring system that can collect data on dynamic response of the bridge in order to verify the assumptions and constant used for the design due to strong wind and earthquake. The wind load for long-span bridges has great importance in their structural design. It usually consists of time averaged wind force and some contribution of the dynamic response due to the wind fluctuation, but there still remain uncertainties in expression of wind characteristics to define the accurate and reliable wind load. To overcome this it will be important to compile information of the wind at many bridge site. Here, as the example of monitoring results, the deformation characteristics of the bridge response due to typhoon are elucidated. By comparing the analyzed simulation results through wind tunnel test and field-measured results, the reliability of the current monitoring system is confirmed.

Furthermore, by applying newly developed technology in intelligent material (e.g., TRIP steels) and intelligent systems, together with recent development of information and telecommunication infrastructure technology, a better constructive monitoring system has been managed. Particularly, this new bridge management can include remote monitoring to obtain key information concerning bridge structural health, such as, water flow rates, relative motion, fatigue, and true-stress occurred in structure member that in an accumulated and combined way contribute to the damage profile of the structure. This proposed system is easily accessible, economically feasible and durable to provide information for structural health maintenance. Specifically, the newly developed technology to monitor peak displacements and true-stresses in main cables and anchorages of the bridges is discussed.
2. CURRENT MONITORING SYSTEM

Current long span bridge monitoring system was developed to be a reliable device to observe the bridge in earthquake and/or typhoon accurately, besides have a self-check function to sense the disorder of the system itself.

2.1 Objective

Generally, the objectives of long bridge monitoring are:

(1) Design verification:
   (a) To provide data on structural dynamic response to verify design assumptions used for the strong wind and earthquake.
   (b) To provide data for developing a better further design in a more rational way.
   (c) To develop a reliable health monitoring system that has a self-check function to monitor disorder of the system itself.

(2) Structural maintenance:
   (a) To provide data for analyzing and evaluating on the health behavior of bridge structure.
   (b) To provide data for assessing structural deterioration and performance degradation.

(3) Traffic management:
   (a) To provide data to adjust level of safety traffic control due to earthquake or strong wind.
   (b) To provide data for assessing post-earthquake or post-typhoon structural reliability to manage traffic flow.

The scope of monitoring includes two major types of parameters, i.e., load effects and responses. The load effects refer to those due to wind, earthquake, temperature and live loads (movements, highways or railways). The responses refer to displacements, accelerations, stresses, strains and forces of the members of bridge structure, and displacements and stresses of main cables. Japan as a country in which natural hazards occurs frequently, such as, typhoon and earthquake, monitoring of the peak displacements and real stresses of the main cables and their anchorages are the important subjects to be considered. In the current long span monitoring system the above items have not been taken into account. As the example, primary monitoring items due to design verification of Akashi Kaikyo Bridge is shown in Table 1.

Table 1. Design verification monitoring items

<table>
<thead>
<tr>
<th>Item</th>
<th>Main Focus</th>
<th>Measured Parameter</th>
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<tbody>
<tr>
<td>Earthquake characteristics</td>
<td>Seismic motion and magnitude</td>
<td>Acceleration</td>
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<td></td>
<td>Earthquake frequency characteristics</td>
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<td></td>
<td>Ground characteristics</td>
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<td></td>
<td>Phase difference</td>
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<tr>
<td>Earthquake dynamic response</td>
<td>Acting seismic force</td>
<td>Response acceleration (velocity)</td>
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<tr>
<td></td>
<td>Displacement</td>
<td>Displacement</td>
</tr>
<tr>
<td></td>
<td>Natural frequency</td>
<td>Response acceleration (velocity)</td>
</tr>
<tr>
<td></td>
<td>Superstructure seismic motion</td>
<td>Wind direction and wind speed</td>
</tr>
<tr>
<td>Wind characteristics</td>
<td>Basic wind speed</td>
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<tr>
<td></td>
<td>Design wind speed</td>
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<tr>
<td></td>
<td>Variable wind speed characteristics:</td>
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<tr>
<td></td>
<td>- Intensity of turbulence</td>
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<tr>
<td></td>
<td>- Spatial correlation</td>
<td></td>
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<tr>
<td></td>
<td>- Power spectrum</td>
<td></td>
</tr>
<tr>
<td>Wind dynamic response</td>
<td>Superstructure natural frequency</td>
<td>Response acceleration (velocity)</td>
</tr>
<tr>
<td></td>
<td>Vibration mode configuration</td>
<td>Displacement</td>
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<tr>
<td></td>
<td>Structural damping</td>
<td>Predominant frequency</td>
</tr>
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<td></td>
<td>Gust response</td>
<td>Wind speed and response acceleration</td>
</tr>
<tr>
<td></td>
<td>Action of main tower (TMD)</td>
<td>Response displacement</td>
</tr>
</tbody>
</table>
2.2 Sensor configuration of Akashi Kaikyo Bridge
As one of the examples to represent the current condition long span bridge health monitoring system in Japan, dynamical monitoring of Akashi Kaikyo Bridge is highlighted. Figure 1 shows sensor configuration of Akashi Kaikyo Bridge in which following devices were installed.

2.2.1 Seismometer
Two seismometers were installed in 1A and 4A. To avoid response vibration influence of the 1A foundation to the original seismic motion, the seismometer at this point was installed at a place that has a distance about 100 meters from bridge axis. Another seismometer at 4A was installed at approximately T.P. –20 meters in the granite rock near the 4A concrete block.

2.2.2 Anemometer
In order to determine the wind characteristics of the bridge structure, the distribution of directional wind speed is measured in the longitudinal and transversal directions. To monitor spatial correlation in the horizontal direction, the anemometer is installed in the middle of center span.

2.2.3 Accelerometer
To verify the real dynamic structural behavior due to earthquake of each foundation with design values, a three-component accelerometer was installed in at least one location on each foundation.

2.2.4 Velocity gauge
Velocity gauges were installed to monitor the vibration response due to wind and earthquake of the girders and main tower.

2.5 GPS
GPS units were installed on the tops of the 1A and 2P tower and in the middle of the center span\(^{12}\). The coordinate of 1A was fixed as original point (OPT = Original Point Terminal), and other measure point displacements (MPT = Measure Point Terminal) were calculated in longitudinal, vertical and transversal components.

2.2.6 Girder edge displacement gauge
Displacement gauges were installed on the west and east edges of the 2P center-span side, and on the west side of the 3P side-span.

2.2.7 Tuned mass damper (TMD) displacement gauge
Since the main tower has a height approximate to 300m, it was confirmed through wind tunnel test that vortex oscillation would occur following a wind speed even lower than design wind speed. For stabilization purpose, TMDs were installed inside the tower and its displacement were measured by displacement gauges.

2.2.8 Thermometer
Three cable thermometers were installed in order to compensate with the displacement measured by GPS, and one atmospheric thermometer was installed in the middle of the center span.

2.3 System network
The monitoring system network of Akashi Kaikyo Bridge is shown in Figure 2 and consist of the following parts:

2.3.1 Terminal
Monitoring sensors were divided into blocks based on their location of installation, and adding with data converters and transmitters, terminals were established for each block.
Figure 1. Sensor configuration of Akashi Kaikyo Bridge
2.3.2 Workstation

Collected data at each terminal is transmitted digitally by optic fibers, and those are concentrated by a network workstation located in the 1A information unit room.

2.3.3 Data processor

The data processor located in the 1A information unit room was divided into a data collection portion (mainly for trigger detection and data storage) and a processing portion (to display the monitoring data).

2.3.4 Data control device

Data control device was used for analyzing recorded data, such as, time history data graphing, statistical and analytical processing. The data was formed into a database by a data processor located in control room at Tarumi junction.

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Figure 2. Monitoring system network of Akashi Kaikyo Bridge

3. MONITORING RESULTS

On September 22, 1998, Typhoon No.7 occurred in the central area of the Kii Peninsula (south of Akashi Kaikyo Bridge). Figure 4 shows the time history data for ten minutes before and after the peak wind speed and the maximum recorded transversal displacement. The wind direction and wind speed measured by the anemometer near the middle of the center span are shown in Figures 3(a), (b), respectively, and the transversal displacement of the related girder is shown in Figure 3(c).

By applying wind-tunnel test results and the wind resistant design guidelines for Akashi Kaikyo Bridge, a transversal displacement of 5.41m and a vibration amplitude of 2.56m were calculated. The field-measured values showed a transversal displacement of 5.17m and a vibration amplitude of 0.78m. It is confirmed that the field-measured values for transversal displacement have good agreement with the calculated results, but the vibration amplitude was about one-third of the calculated value.
4. NEW PROPOSED HEALTH MONITORING SYSTEM

Bridge structures normally behave elastically which are designed to deform and reverse to their original configuration. When a bridge structure is loaded beyond its normal limits, it behaves plastically and becomes permanently deformed and weakened. Often this damage is invisible, but as strains in the bridge structure increase and the bridge structure edges closer to structural failure \(^9\). Changes in girder strains, joint rotations and crack growth are indicators for evaluating structural integrity. By monitoring such changes closely, it is possible to provide quantitative clarity to assess bridge’s structural health.

New innovative methodologies are proposed to monitor peak displacement and real stress in main cable and anchorage of the bridges. It is considered that an intelligent monitoring system should be supported by sensors which fulfill ‘AtoE’ characteristics as follows: (A)ccuracy: sensor should have a reliable accuracy; (B)enefit: commercial price of the sensor should be reasonable; (C)ompact: sensor’s shape should be small enough; (D)urability: serviceability of the sensor should be durable and long-lived; and (E)xpress: sensor should be easy to operate and time consumed for measurement should be close to real time measurement. Here, two types of sensors are introduced, i.e., Peak Displacement sensor (PD sensor) and Elasto-Magnetic stress sensor (EM sensor).

4.1 Peak displacement sensor

Peak displacement sensor with a digital data acquisition network has been developed \(^5\). The goal is to establish a structural health monitoring system that could be adapted to a variety of measurement applications and that would fulfill ‘AtoE’ characteristics \(^7\). One channel of the dual-output gauge measures relative displacement with high precision and the other channel measures peak displacement and passively retains that value for later interrogation. Therefore, with one of these gauges, the structure after a critical event (such as earthquake or typhoon) can be interrogated, and the maximum distance of structure deformation during the event can be determined. These sensors require no electrical power except to read out the stored peak-displacement values. Figure 4 shows the application of peak sensor on monitoring the peak displacement of bridge pedestal damper.
4.2 Elasto-Magnetic stress sensor

Stress sensor that can reliably monitor true-stress in tendons and cables has been developed \(^6\) (Figure 5). The elasto-magnetic sensor is a novel new approach to monitor cable forces in bridge cables and anchorages \(^13\). Based on the fact that the permeability of ferromagnetic materials is a function of magnetic history and applied field (stress and temperature), permeability function is characterized at technical saturation experimentally. Besides fulfilling ‘AtoE’ characteristics, the sensor boasts a theoretically unlimited service lifetime and can be applied to any structure built with circular steel reinforcements or cables and does not influence structural integrity in any way.

4.3 Real time monitoring system

Multiple sensors are comprised by a complete real time monitoring system with a digital network to acquire, process and store the measured data. In a periodical intervals, the network returns the data to a central control room by cellular phone, satellite, or conventional telephone circuit. From there, the data is distributed confidentially via intranet or internet, therefore, one whose secret password can immediately assess the structure’s condition from anywhere in the world without actually visiting structure’s site as shown in Figure 6. Such real-time, quantitative information greatly improves structural safety inspections and provides valuable information for directing timely maintenance relief to those areas of the structure most in need of repair, so structural lives of bridge structure can be extended.

Peak displacement and real stress monitoring technologies are the most advanced, efficient and effective means to ascertain structural health. The engineered solutions which are based on these technologies, offer the following benefits: (i) the systems do not require continuous power supply which can be expensive in remote locations; (ii) the systems measure the most important variables, peak strain and true stress; (iii) the systems allow data to be transmitted confidentially over the internet to any location around the world on a real-time basis.

![Figure 4. Application of PD sensor on monitoring peak displacement of bridge pedestal damper](image1)

![Figure 5. Application of EM sensor on monitoring true-stress in bridge cables](image2)

![Figure 6. Proposed health monitoring system network (modified from SMS system network)](image3)
5. CONCLUDING REMARKS

The current status of health monitoring system of long-span bridges in Japan is briefly reviewed and a newly developed innovative monitoring system is introduced. As the concluding remarks it is summarized as follows:

1) The reliability of the current long span bridge monitoring is confirmed by comparing the analyzed simulation results through wind tunnel test and field-measured results.

2) New innovative technologies to monitor peak displacement and true-stress are proposed. Furthermore, a real time monitoring system with a digital network to acquire, process, store and transmit the measured data is discussed.

3) The proposed real time monitoring system provides valuable information for directing timely maintenance relief to those areas of the structure most in need of repair, so the following items can be achieved:
   a) Planned repair or replacement of the structure before catastrophic collapse;
   b) Improved allocation of scarce maintenance funding for the highest risk structure member;
   c) Determination of structural health after catastrophic events, such as, earthquake and/or typhoon.

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