Smart Structures and Systems, *Vol. 19, No. 6 (2017) 587-599*
DOI: https://doi.org/10.12989/sss.2017.19.6.587

An Intelligent bridge with an advanced monitoring system and smart control techniques

Ayaho Miyamoto[*1] and Minoru Motoshita[2a]

[1]*Graduate School of Science & Engineering, Yamaguchi University, 2-16-1, Tokiwadai, Ube, 755-8611, Japan*
[2]*Kyowa Sekkei CO., LTD, 2-1-34, Ushitora, Ibaraki, Osaka, 567-0877, Japan*

(Received April 23, 2015, Revised May 12, 2017, Accepted May 15, 2017)

Abstract. This paper introduces an approach to the realization of an ICT-based bridge remote monitoring system that enables real-time monitoring and controlled adjustments for unexpected heavy loads and also for damaging earthquakes or typhoons. In this paper, an integrated bridge remote monitoring system called the "Intelligent Bridge", which consists of a stand-alone monitoring system (SMS) and a web-based Internet monitoring system(IMS), was developed for not only bridge maintenance but also as an application for a para-stressing bridge system. To verify the possibility of controlling the actual structural performance of an "Intelligent Bridge", a model 2-span continuous cable-stayed bridge with adjustable cables was constructed. The experimental results demonstrate that the implemented monitoring system supplies detailed and accurate information about bridge behaviour for further evaluation and diagnosis, and it also opens up prospects for future application of a web-based remote system to actually adjust in-service bridges under field conditions.

Keywords: intelligent bridge; stand-alone monitoring system; internet monitoring system, structural performance; smart monitoring

1. Introduction

Recently, the realization of a bridge as an intelligent structure, called “intelligent bridge”, with functions to sense, make decisions, instruct, and respond according to its condition, has been sought after (Boller *et al*. 2009, JSCE 2000, SSRG 1993, Chang *et al.* 2014). Research in the field of smart structures, together with that of intelligent materials, including intelligent bridges, goes back to the mid-1980s, when it was proposed in the field of space science and spread to industries such as aviation, construction, automotive, and shipbuilding in the 1990s. Since then, the research has primarily focused on intelligent materials. There are only a few studies based on the principles of repulsion or restoration of objects, such as earthquake resistance and vibration control of high rises in the construction field, and on mobile bridges based on the principle of pantograph (Kamada *et al.* 1998, Nakazawa 2009). Bridges have been conventionally designed based on a standard design load specified in codes. Not only bridges in areas with low traffic volume but also many bridges seldom experience the heavy vehicle loads stipulated in the design standards during their service lives. If a bridge can be designed with a lower live load, assuming normal vehicles, and equipped with a system that can sense the danger of a large live load exceeding the design live load strength, then a control device such as an actuator activates to offset the load and restore the safe state of the bridge, the safety and reliability of the bridge can be ensured against heavy vehicles exceeding the design live load strength, though a heavy vehicle that may endanger the bridge is loaded. To make such an intelligent structure a reality, three functions are necessary, 1) a sensor function to measure and monitor abnormal disturbances, vibrations and external forces damaging the condition of the bridge itself; 2) a processor function to make decisions based on measured results and determine the control method and counterforce required for the safety and reliability of the bridge, and 3) an actuator function to put the commands of the processor into action. To construct safe and highly reliable bridges that can stabilize themselves, such a system capable of executing these functions instantly, automatically, constantly is required. Also to maintain and manage the existing social infrastructures, a monitoring system needs to be developed. In this study, a stand-alone monitoring system (SMS), capable of real-time automatic measurement, recording and illustrating the measured results; an Internet monitoring system (IMS), utilizing a network of multiple authorized personnel to operate multiple SMS that view and collect the data; and a remote monitoring system, integrating both SMS and IMS via the Internet to operate both systems without restrictions of time or place, were built. Furthermore, a required counterforce calculation/simulation system based on FEM analysis was developed for controlling the performance of the structures.

A control system (para-stressing system) using the integrated remote monitoring system to control the performance of an intelligent structure, was also developed.

*Corresponding author, Professor
E-mail: miya818@yamaguchi-u.ac.jp
[a] Dr.
E-mail: m.motoshita@kra.biglobe.ne.jp

http://www.techno-press.com/journals/sss&subpage=8
ISSN: 1738-1584 (Print), 1738-1991 (Online)

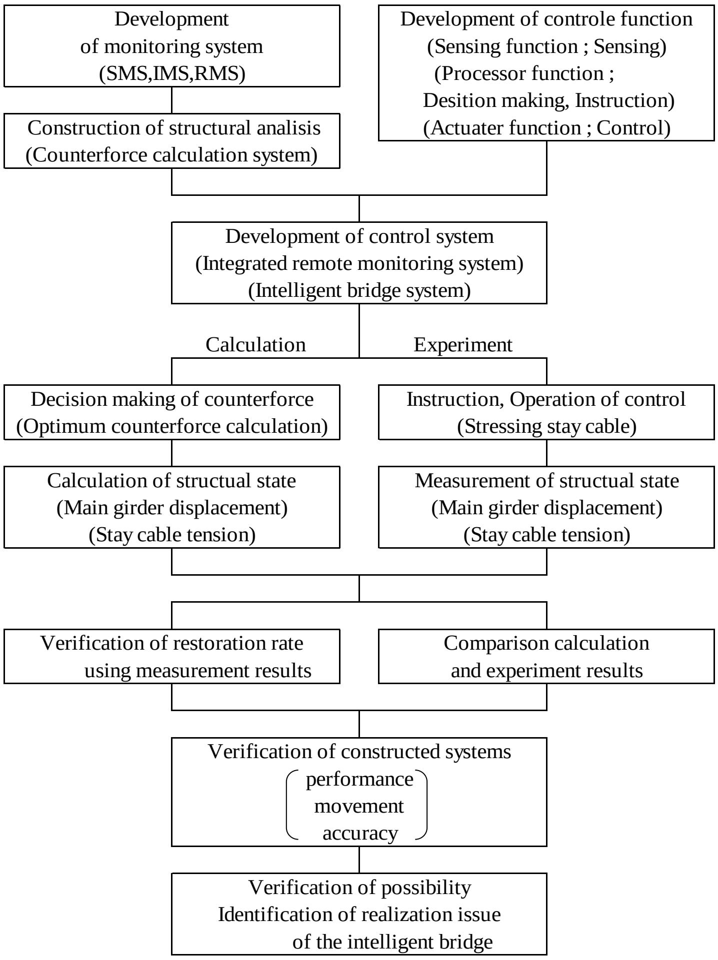

Fig. 1 Flow of the study

This system was applied to the cable-stayed bridge model equipped with the sensor, processor, and actuator functions, as a specific example. A series of control experiments were conducted, 1) measuring to understand the behavior of the model; 2) determining the necessity for controlling and calculating the counterforce; and 3) sending instructions to the control device which makes the required adjustments. These experiments verified the performance of the integrated remote monitoring system, the accuracy of the counterforce calculation system, and the performance of the para-stressing system. All the compiled results verified the possibility of intelligent bridges and identified issues for the realization of the intelligent bridge. The flow of this study is summarized in Fig. 1.

2. Background and purpose of the study

2.1 Background of the study

The intelligent bridge, in a narrow definition, often refers to a bridge equipped with the sensor function (detection or sensing function), processor function (decision-making and instruction functions), and actuator function (control function), which can maintain the safety and designed performance of the bridge through the structure itself, performing all of these functions in response to unexpected environmental changes and disturbances (JSCE 2000, Yanev 2007, Nader *et al.* 2012). If an intelligent bridge becomes a reality, these functions enable the construction of a safe and highly reliable bridge. Furthermore, using the intelligent sensor and processor functions of the intelligent bridge, the bridge administrator can constantly monitor as well as diagnose the bridge condition from a remote location, making possible this rational and efficient bridge monitoring. The intelligent technology of the bridge is extremely effective not only for realizing the intelligent bridge but also for building the bridge maintenance and management system. Much of Japan's deteriorating social infrastructure system was put in place during a period of high economic growth; its repair, reinforcement, and upgrading demands will either occur at the same time or dramatically increase in the not-so-distant future. Maintenance and management or lengthening the service life of the social infrastructure system has become an urgent issue. The time has come to drastically steer the strategy from a conventional, passive, symptomatic style of maintenance and management to a strategic, preventive style, to consider a production management system encompassing the production process and the maintenance and management of the social infrastructure system as a whole.

Fig. 2 shows the bridge construction process and performance verification by monitoring. (1) through (5) indicate the current construction processes of a bridge, where (1) the owner formulates the performance requirements of the bridge, (2) the structural information obtained from (1) is compiled and the design is drafted, and (3) its behavior is predicted through calculation. After (4) confirming the required performance based on the prediction result, (5) the bridge is constructed and put into service. Although the process up to construction is a one-way process, adding monitoring processes (6) to (10) allow behavior measurement (measurement performance), and various performances during not only design but also construction can be verified in both directions, making possible the modification of the calculation model during design, reverification of the required performance, and application to the long-term performance verification.

Adding a monitoring process to the actual construction process, maintenance, and management of new and existing bridges creates various forms of construction process and maintenance and management.

For a new bridge, a rational intelligent bridge will be planned, considering the design load and unexpected heavy load settings, the control method and counterforce settings, and the bridge performance. In maintenance and management of an existing bridge, monitoring will allow the evaluation and confirmation of the bridge performance to determine the required performance, including repair and reinforcement, and continued monitoring will make possible the estimation of performance deterioration and residual life. If the performance upgrade of an existing bridge is required, installation of more control devices will be planned, considering the control and the bridge performance as in the case of a new bridge.

The intelligent bridge, compared to a bridge designed under standard conditions, offers possibilities to reduce: the initial construction cost and materials by reducing the design load; the number of inspections necessary during its service life; and the maintenance and repair costs through rational structural self-diagnosis; and the future potential life cycle costs. The recent dramatic improvement in computers and structural control technology, the substantial reduction in costs of sensors and computers, and the development of data communication technology independent of wired or wireless connections, such as the Internet and mobile phones, have created a favorable environment for making intelligent bridges with vastly superior functions a reality.

Individual technology elements of bridge monitoring have been sufficiently and impressively developed. These include measuring technology represented by various sensors, communication technology represented by computers and the Internet, and technology to understand the degree and cause of damage and to forecast its progression. The capacity for building a system integrating these technologies or a framework for bridge construction integrating the various systems, however, is not sufficiently developed.

2.2 Purpose of the study

The standard for an intelligent bridge is for it to be equipped with sensing, processing, and actuating functions. At the same time, the building of a system to establish the control method and to establish a rational counterforce, a control system equipped with an efficient control method, and a system to transmit all information required for control, is necessary (Boller *et al*. 2009, Casas 2000, Yamamoto 1999).

In this study, a simulation for making an intelligent cable-stayed bridge model and control tests of this model were conducted with the para-stressing system: 1) to verify the performance, movement, and accuracy of the constructed systems (such as integrated remote monitoring system); 2) to verify the possibility of building an intelligent cable-stayed bridge; and 3) to identify issues during the realization of intelligent bridges. In here, normal vehicle traffic is defined as the design live load, and heavy vehicles that rarely travel on the bridge as the large live load. The simulation using the system built in this study was to control the displacement of main girder members by adjusting the tension of the stay cables and to ensure the safety of the bridge in the event of a large live load.

This study conducted calculations and experiments as shown in Fig. 3. In the calculations, the optimal counterforce, calculated by the counterforce calculation system on the bridge model, was applied to understand the behavior of the bridge after the application of the counterforce. In the model experiment, after a large live load was loaded on the intelligent cable-stayed bridge model and the displacement of the main girder members and tension of the stay cables were measured, the actuator was used to apply the optimal counterforce on the stay cables to control the displacement of the main girder members, then the stay cable tension and main girder displacement were measured after the control. Furthermore, the rate of restoration of main girder displacement was calculated by comparing the calculated and experimental results to verify the intelligence of the cable-stayed bridge, and the calculation method and its accuracy were verified.

3. System development

3.1 Purpose of the system development

The monitoring system in this study is an important technology to measure the stress on the bridge, displacement, and vibration in real time, and to evaluate the measured results and diagnose the bridge performance. The purpose of the system goes beyond merely understanding the changes in the bridge, but lies with effectively using the obtained information to manage, record, and process the measured results. Monitoring conventionally relies on manual measurements, but realization of unmanned and automatic real-time monitoring is necessary to improve the efficiency of monitoring.

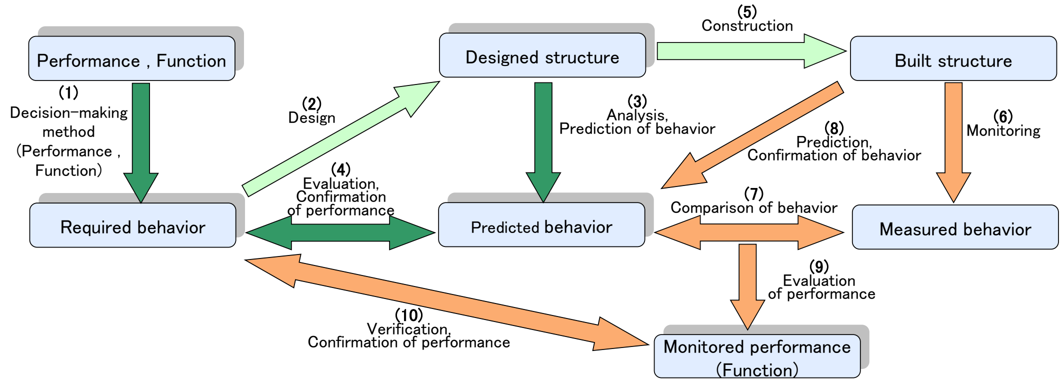

Fig. 2 Construction process and performance verification for bridge

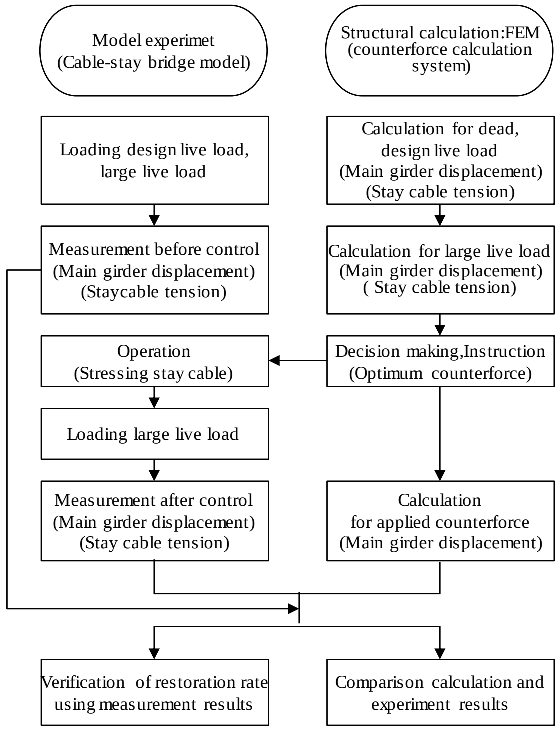

Fig. 3 Flow of the bridge model experiment

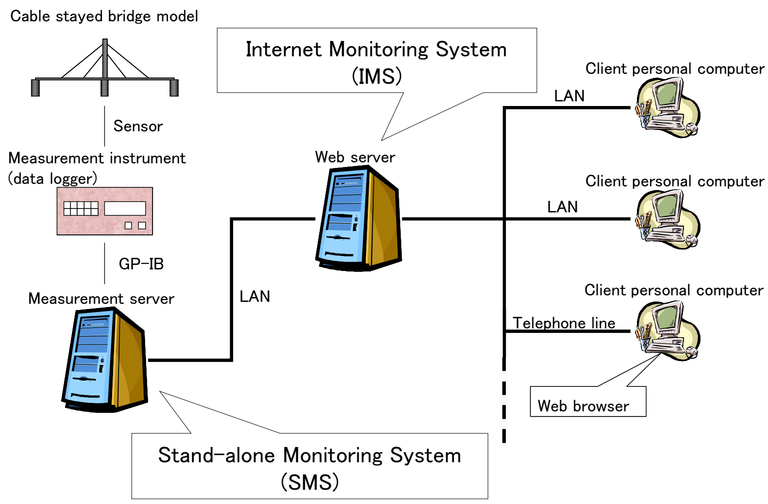

Fig. 4 Composition of the integrated remote monitoring system

At the same time, building an environment in which many authorized personnel can view or obtain required data as necessary is required. In the present study three systems: SMS, primarily installed in the field, which measures and displays real-time results in charts; IMS, which allows multiple authorized personnel at remote locations to measure, collect, and view data; and a remote monitoring system that integrates both of these systems, were built (see Fig. 4).

3.2 Integrated remote monitoring system

The integrated remote monitoring system consists of two systems, namely SMS and IMS. SMS can control the measuring instruments and read the measured data from the sensors installed on the bridge, but they are only operated on the computer in the field, available to limited users. To effectively use the measured data for bridge management it is necessary to access or collect data promptly. A system is required that allows many authorized personnel in the maintenance office at remote locations to check the measured data and system movement status and to remotely instruct the measurements to be taken (Casas 2000, Holnicki-Szulc and Rodellar 1998, Kim *et al*. 2000, Yang *et al*. 2011). Fig. 4 shows the structure of the monitoring system consisting of SMS and IMS. The realization of intelligent structures requires the building of a system capable of self-organization of the structure, self-sensing of the external forces, self-decision-making, and self-controlling of instructions. Building on this integrated remote monitoring system, and adding a system that automatically operates the sensing, decision-making and instruction, and control functions, a para-stressing system was developed, as shown in Fig. 5.

3.2.1 Overview of the SMS

SMS is a monitoring system that operates on the computer installed to the bridge site; measures the behavior of the bridge, such as the stress on and displacement of the bridge members by using the sensors attached to the bridge; displays the collected data in chart format; records to the measurement server; and transfers the data to the Web server; and thus provides a basis for making the remote monitoring of a bridge possible (Magana *et al*. 1998, Kanefuji 2000, Nakatsu *et al.* 2011).

The measurement server in SMS consists of the measurement control and data recording program, and functions to record the monitoring data and display them in chart format.

3.2.2 Overview of the IMS

To improve the measuring and data recording efficiency of the SMS installed on the bridge site, IMS, Internet monitoring system, needs to be built. As long as there is an environment with Internet connectivity, it is possible to quickly recognize the bridge condition, to expedite management, to use collected data, and to send instructions without restrictions of time and location by using an IMS which is capable of sending and receiving the data in real time. The IMS allows the early discovery of issues in field monitoring, the simultaneous monitoring of multiple bridges, the use of data for purposes other than bridge management, and the reduction in investigation and bridge maintenance. In practical terms it is crucial for the IMS, to have absolute protection against Internet hackers. Without such protection the system is vulnerable to destruction, data falsification, or interception by unauthorized personnel or impersonators. The access scope of the users of IMS needs to be categorized or its usage needs to be restricted to allow some users access to the common file server of the web server, while other users are not permitted. While the system should be built with the intention to allow as many authorized personnel as possible to search and use the data, its access should be restricted by categorizing them to system administrators, authorized users, and special authorized users and requiring multi-level authentication according to these respective safety levels. This study adopted and set up the server, client, and password authentications based on encrypted SSL for a wide range of connections equivalent to administrator authentication.

3.3 Para-stressing system

3.3.1 Concept of the para-stressing system (Montes 1996, Miyamoto and Motoshita 2004)

Para-stressing is a type of intelligent technology based on a new concept that responses to the external forces acting on a structure can be made by the whole structure to preserve its members as a self-contained self-organized and self-controlled system. Fig. 5 shows the organized structure of the para-stressing system, in which the structure itself, an intelligent bridge, senses the external forces, makes decisions, and sets controls. Using the integrated remote monitoring system, a para-stressing system was built that: senses and measures changes and stress of the bridge; makes decisions about the live load strength, service, and safety level set by the measurement server; calculates the counterforce when control is required and sends the control instructions to the control device; gives instructions to the control function to restore the performance; and executes this series of operations automatically.

3.3.2 Development of the para-stressing system

The para-stressing system, a concept for the intelligent bridge, is a system consisting of sensing, decision-making, and control functions, as shown in Fig. 5, all of which are carried out through the integrated remote monitoring system.

The sensing function accurately understands the condition of the bridge, and in this study utilizing the para-stressing system that controls the displacement of the main girder by adjusting the tension of the stay cables of the cable-stayed bridge model, it plays an important role in the accurate measurement and understanding of the tension of the stay cables before and after the control operation in this experiment.

The decision-making function calculates the tension of the stay cable necessary to restore the displacement of the main girder to that of the design live load when a large live load is applied, as well as instructs and makes decisions to

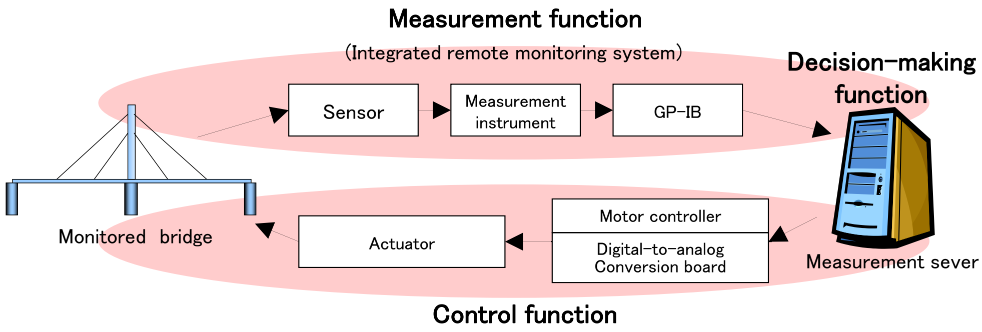

Fig. 5 Composition of the para-stressing system

repeat the instruction to the control device until the stay cable tension and the optimal counterforce match, by comparing the measured tension of the stay cable and the calculation value of the optimal counterforce during controlling.

The control function adjusts the stay cable tension by stressing and loosening the stay cables using the actuator installed on the bridge to offset the excess live load.

4. Control system

4.1 Purpose and overview of the control system

When a large live load, larger than the design live load, passes through the bridge in question, the main girder members are substantially displaced and stress exceeding the design stress is applied.

To allow a large live load to travel safely on the bridge, a given counterforce by required counterforce calculation system needs to be applied upon the bridge to control the displacement and excessive stress. The control system to secure the safety of the bridge is necessary for an intelligent bridge and is an important part of the control function of the bridge.

This experiment adopted a mechanism to adjust the stay cable tension of the cable-stayed bridge model by applying a counterforce using the technique to wind the stay cable from the pylon and to restore excessive displacement of the main girder, due to the large live load, to that of the design live load.

4.2 System construction

4.2.1 Counterforce calculation method

In this study, the optimal counterforce to restore the main girder displacement upon application of a large live load to that of the design live load was defined as the minimum counterforce required for restoration, and it was calculated by FEM analysis of a cable-stayed bridge model.

In the experiment conducted in this study, a technique was adopted to restore the main girder displacement of the cable-stayed bridge model by tensioning the stay cables using an actuator. Therefore, the stay cable tension acting as the counterforce needed to be determined. When the temperature of only the stay cable-among all of the members of the cable-stayed bridge model is decreased, the tension of the stay cable increases, and the main girder displacement decreases. In this study, this phenomenon was taken advantage of to calculate the counterforce by FEM analysis. Specifically, the temperature of the stay cable was repeatedly lowered to increase the stay cable tension until the main girder displacement was restored to a predetermined amount in the FEM analysis. At this point, the tension of the stay cable was deemed to be the necessary counterforce.

4.2.2 Overview of the counterforce calculation system

This study constructed a counterforce calculation system to obtain a more appropriate counterforce in FEM analysis.

This is an important system to calculate the necessary counterforce to control the displacement of the main girder due to the large live load, in addition to understanding the normal conditions to calculate the stay cable tension and the displacement of each member. In addition to calculating the counterforce, it considers the validity of the calculation system and simultaneously outputs the displacement of each member of the bridge and stay cable tension, and diagrams the displacement as the calculation results under four conditions; namely, dead load applied state, design live load applied state, large live load applied state, and state when the counterforce is acting. The counterforce calculation system process is shown in Fig. 6. Fig. 7 shows the state of the main girder displacement displayed on the system screen during counterforce computation.

4.3 System verification

A commercial universal FEM analysis program, “DIANA RELEASE 7.2” (DIANA 2000), was used to compare and verify its calculation results with those by this system, to verify the validity of the calculation results by the counterforce calculation system built in this study.

The calculation results of main girder displacement and stay cable tension under dead load and live load were compared. In the validation calculation, the uniformly distributed dead load of 160.0 N/m and concentrated live load of 50.0 N were used, and the live load was applied at the intersecting point of the main girder and the outer stay cable (joint (5); see Figs. 7 and 8), where the maximum displacement of the main girder member would occur.

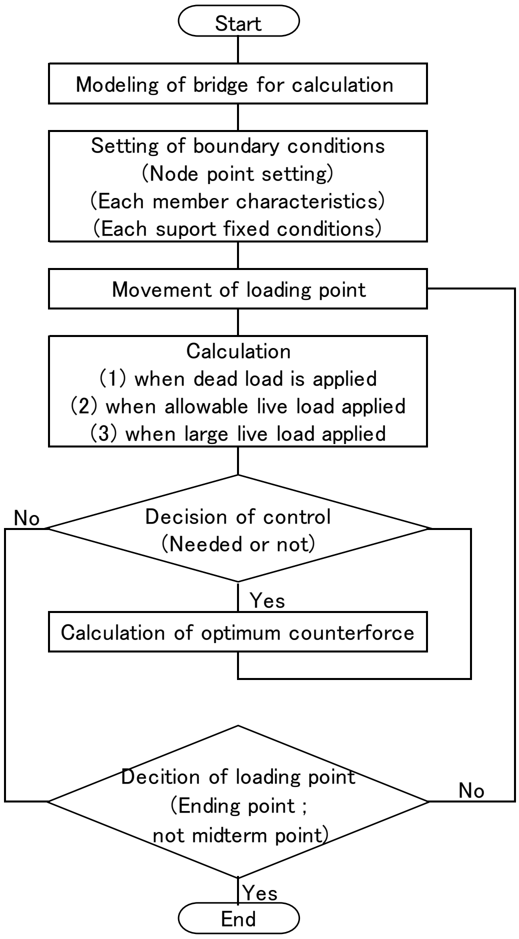

Fig. 6 Flow of the counterforce calculation system

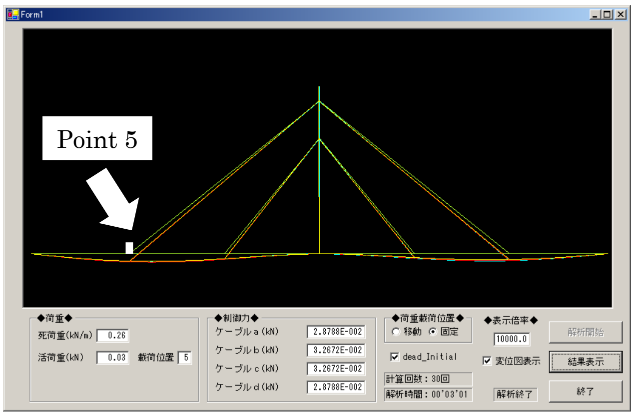

Fig. 7 Screen output of the counterforce calculation system

Table 1 shows the comparison FEM and DIANA RELEASE 7.2. According to the calculation results of this system and DIANA RELEASE 7.2, there were slight differences in the results for both dead load and live load. The maximum displacement differential in the vertical direction of the main girder, 0.006 [mm], as opposed to 0.788 [mm] under the live load of 50.0 N, is likely to have little effect as the calculation results in the counterforce calculation. The same is true for the stay cable tension, where the 0.100 [N] maximum differential of the stay cable, as opposed to the 38.210 [N] maximum tension of the stay cable under the live load of 50.0 N, is expected to have little effect on executing calculations in this control system. Considering these facts, the FEM analysis results according to this system are deemed sufficiently reliable.

Table 1 Comparison FEM and DIANA of calculation results

Point	Dead Load (160 N/m)				Live Load (50 N)			
	Displacement (mm)			Ratio	Displacement (mm)			Ratio
	FEM	DIANA	Differ	F/D	FEM	DIANA	Differ	F/D
3	0.334	0.336	0.002	0.994	0.473	0.475	0.002	0.996
5	0.526	0.528	0.002	0.996	0.753	0.755	0.002	0.997
7	0.522	0.526	0.005	0.992	0.75	0.756	0.006	0.992
9	0.354	0.355	0.001	0.997	0.523	0.524	0.001	0.998
11	0.126	0.126	0.000	1.000	0.208	0.209	0.001	0.995
13	0.000	0.000	0.000	....	0.000	0.000	0.000	....
15	0.126	0.126	0.000	1.000	0.068	0.069	0.000	0.986
17	0.354	0.355	0.001	0.997	0.266	0.267	0.001	0.996
19	0.522	0.524	0.002	0.996	0.428	0.430	0.002	0.995
21	0.526	0.528	0.002	0.996	0.448	0.450	0.002	0.996
23	0.178	0.178	0.000	1.000	0.290	0.292	0.002	0.993
Cable	Cable Tension (N)			Ratio	Cable Tension (N)			Ratio
	FEM	DIANA	Differ	F/D	FEM	DIANA	Differ	F/D
a	21.02	21.12	0.100	0.995	22.37	22.46	0.100	0.996
b	32.43	32.53	0.100	0.997	38.11	38.21	0.100	0.997
c	32.43	32.53	0.100	0.997	34.13	34.22	0.090	0.997
d	21.02	21.12	0.100	0.995	25.67	25.77	0.100	0.996

5. Monitoring control tests using cable stayed bridge model

5.1 Overview of the cable-stayed bridge model

A model testing the monitoring control by the para-stressing system on the bridge model (bridge length of 4.0 m) shown in Photo 1 was conducted in this study. The main girder consists of a box section with five rooms, which is 310 mm wide and 70 mm high, and the pylon of a box section, which is 80 mm wide in the direction of centerline of the bridge and 50 mm in the perpendicular direction. Fig. 8 shows a sketch of the structure of the bridge model, monitoring sensor, tension control mechanism of the stay cables, and actuator location, and Table 2 shows the sensor measurement items and number of measuring points.

5.2 Verification of the restoration rate

5.2.1 Description of the experiment

The displacement of the main girder because of the live load was restored by the control operation in the experiment by using the para-stressing system developed in this study. The primary objective function of the experiment is to validate the effect of the restoration. The model experiment was carried out as per the procedure shown in Fig. 3. When a heavy vehicle reaches the bridge, the load cell placed at the starting point of the bridge measures its load strength. When the measured load is applied on the cable-stayed bridge, the program that calculates the counterforce necessary to control the main girder displacement is activated. When a large live load reaches the first displacement measuring point (A) in Fig. 8, the counterforce calculation system calculates the optimum counterforce (stay cable tension) to hold the main girder displacement under the design live load. Once the optimal counterforce is determined, instructions are sent to the actuator to start operation, stressing/releasing of stay cables starts and, at the same time, the monitoring system begins to measure cable tension. The measured stay cable tension and the optimal counterforce are compared, and the operation to make the stay cable stress and relax is repeated until an agreement is reached. Once the stay cable tension is adjusted, the large live load moves to the measuring point (A) where the instrument to measure the main girder displacement is placed, as shown in Fig. 6. When the large live load reaches the measuring point (A), the above process is repeated for the next measuring point (B) in Fig. 8. Operation is repeated from the time a large vehicle reaches the starting point of the bridge model until the vehicle reaches the end, and the deck deflection is measured each time the control measure is taken.

The allowable live loads represent the live loads that normally travels on the bridge which are lower than the present design standards. The large live loads are the live loads that rarely travels on the bridge and that may be a hazard to the bridge. In the test, the main girder displacement was measured under large vehicle loads while no control measures were taken and when displacement was reduced to the level under allowable loads.

The objective of the test was to confirm the restoration of the displacement, thanks to control measures. Table 3 presents the strength of the large live load and design live load and their combination in cases (i) to (iv). Experimental case (i), as shown in the table, where a large live load and design live load were 40 N and 10 N, respectively, is explained and examined in the next paragraph.

In test case (i) in Table 3, the large live load was 40 N and the allowable live load was 10 N. First, the main girder displacement was monitored while a large live load of 40 N was crossing the bridge. The obtained deflection in each measuring point (A to J) was used as the data in the case without control measures ($\delta m1$). Afterwards, the main girder displacement under 40 N load controlled to that under 10 N was measured at each measuring point. The measured result was used as the main girder displacement after control ($\delta m2$). The effectiveness of the para-stressing system was tested by comparing the difference in the measured main girder displacement before and after control (actual restoration amount) and the difference between the measured main girder displacement under 10 N design live load (*δm3*) and that before control (*δm1*) (expected amount of restoration), by considering the rate of restoration *Rr*(%) defined as follows

$$Rr = \frac{\delta m1 - \delta m2}{\delta m1 - \delta m3} \times 100\% \qquad (1)$$

where,

δm1: Measured displacement of the main girder without the displacement control when large live load is applied,

δm2: Measured displacement of the main girder after the displacement control when large live load is applied,

δm3: Measured displacement of the main girder when normal live load is applied.

5.2.2 Experiment results

The results of test case (i) in Table 3 are discussed here. Fig. 9 compares the experiment result when the large live load was applied at loading point (5; measurement point (B)) with finite element method (FEM) analysis result.

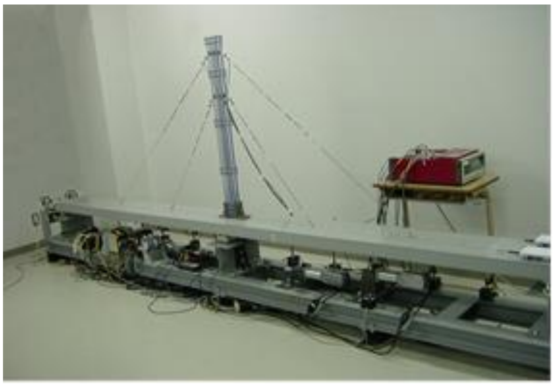

Photo 1 Cable-stayed bridge model

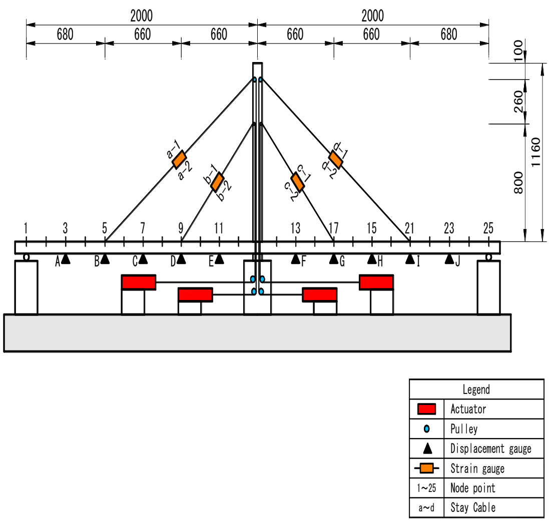

Fig. 8 Composition of the cable-stayed bridge model (in mm)

Table 2 Measurement items

Sensor	Measurement item	Number of measurement points
Thermopile	Temperature	1
Strain gauge	Cable tension and stress	8
Displacement gauge	Main girder displacement	10

Table 3 Test case and load strength (Experiment for the restoration rate)

Test cases	Large live load (N)	Allowable live load (N)
Case (i)	40	10
Case (ii)	40	30
Case (iii)	50	10
Case (iv)	50	30

The lines graphed in Fig. 9 show the main girder displacement below:

I: Main girder displacement under exceptional vehicle load without any control measures (test result (*δ1*)),

II: Main girder displacement under exceptional vehicle load when cable tension was controlled with the objective of reducing the deflection to that corresponding to the normal vehicle (test result (*δ2*)),

III: Main girder displacement under exceptional vehicle load without any control measures (FEM results),

IV: Main girder displacement under exceptional vehicle load when cable tension was controlled (FEM results).

5.2.3 Consideration of the experiment

The agreement between experimental result (I) and analysis result (III) and between experimental result (II) and analysis result (IV), as shown in Fig. 9, validates the appropriateness of the FEM analysis adopted in the development of the para-stressing system. The rates of restoration listed in the blue cells (the edge A to E) in Table 4 are nearly 80% despite variation according to the measurement points. Thus the para-stressing system adopted in this study is effective for restoring the bridge displacement.

Fig. 9 shows that a large negative displacement occurred on the unloaded side. This phenomenon is attributable to the balance of stiffness between the main girders and pylon of the cable-stayed bridge model. The stiffness of the main girder is much higher than that of the pylon. Table 4 shows that the rate of restoration was higher near the end of the bridge than near the pylon. This is attributable to the structural properties of the cable stayed bridge model dependent on the stiffness balance among the main girders, pylon, and cables.

5.2.4 Summary of the experiment

In this study, an IT-based para-stressing system for a bridge which enables real-time monitoring and control for unexpected heavy loads as well as damaging earthquakes or strong typhoon was developed. The para-stressing system is also composed of not only the Internet but also other types of information technologies such as the latest information processing and soft computer technologies.

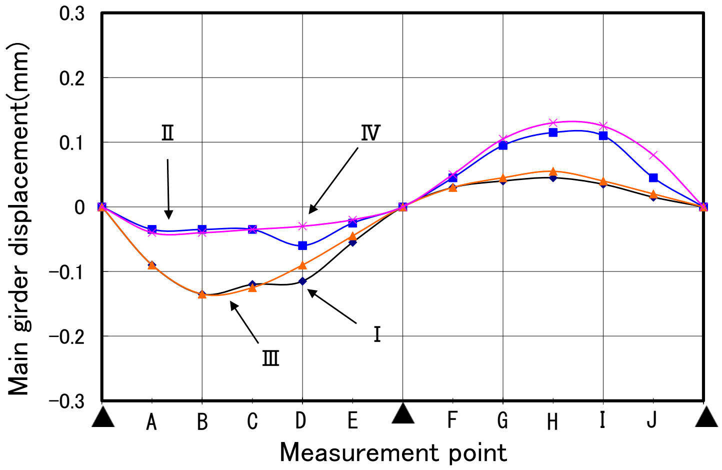

Fig. 9 Comparison of the results in Case (i) at loading point 5

The major results of this study and the tasks for the future are summarized below:

a) The integrated remote monitoring system built in this study is effective not only for investigating and inspecting structures, but also for building a para-stressing system to control and restore the bridge performance to its normal state when abnormal loads are applied.

b) The para-stressing system developed in this study achieved a rate of restoration of 80% for the main girder displacement. Although this is a quite effective value, to increase the rate of restoration, it is necessary to investigate the structural properties of the bridge.

c) Both the monitoring and para-stressing systems are dependent on communication networks. The following requirements should therefore be satisfied:

(i) Although SSL that encrypts data has been used, and a multi-level authentication has been adopted according to security depths as a security measure. Further efforts are required to improve the security a level.

(ii) In the application of the para-stressing system, the simultaneous monitoring of multiple bridges by a single bridge managing system, efficient data processing, ensuring the data reliability and integrity, and early detection and recovery from system malfunctions are required.

5.3 Comparison calculation and measurement

5.3.1 Overview of the experiment

The para-stressing system, developed by integrating the integrated remote monitoring system, and the counterforce calculation system in this study were applied to the cable-stayed bridge model to verify the functions of each system and the monitoring control system, and to confirm that the experiment created an intelligent cable-stayed bridge.

In this experiment, the counterforce calculation system calculated the optimal counterforce necessary to restore the displacement of the main girder to the design live load when it is loaded with a large live load; this was controlled by the actuator. The main girder displacement before, after, and during each stage of stay cable tension was measured and the validity of the counterforce calculation system and the possibility of its application to the para-stressing system were verified by comparisons with the calculated values and the measured values.

A large live load (40 N or 50 N) was loaded on the main girder displacement measurement point (B or D; loading point 5 or 9), and the tension of all four stay cables and the main girder displacement were measured. Next, the optimal counterforce required to control the stay cables by the counterforce calculation system was obtained and implemented by the actuator in the same manner as in the model experiment in the previous section, and the stay cable tension and main girder displacement after the control were measured. Table 5 shows the types of live load, load combination, and loading point in each case of the experiment. The respective measured results and FEM calculation results before and after the control were compared with the ratio of restoration (*Rma*) below to verify the validity of the counterforce calculation system and the control operation.

$$Rma = \frac{\delta m1 - \delta m2}{\delta a1 - \delta a2} \qquad (2)$$

where,

$\delta m1$: Measured displacement of the main girder when large live load is applied,

$\delta m2$: Measured displacement of the main girder after the displacement control when large live load is applied,

$\delta a1$: Calculated displacement of the main girder when large live load is applied,

$\delta a2$: Calculated displacement of the main girder after the displacement control when large live load is applied.

5.3.2 Results of experiment and consideration

The ratios (*Rma*) of the calculated and experimental values of the main girder displacement differential before and after the control are shown in Fig. 10.

Brackets and parentheses in Fig. 10 indicate the loading points of the large live load; brackets indicates that the loading point was point (5) and parentheses indicate that the loading point was point (9)(see Fig. 8).

Table 4 List of the measurements in test case (i) (Rate of restoration; %)

40→10N		Loading point A	B	C	D	E	Mean value
Measurement point	Edge						
	A	128	109	95	86	90	102
	B	110	98	88	82	68	89
	C	95	85	78	76	62	79
	D	83	86	79	75	54	75
	E	117	104	105	113	74	103
	pylon						
	F	76	85	82	79	136	
	G	86	93	90	83	114	
	H	86	90	86	81	109	
	I	89	92	86	79	98	
	J	49	16	4	-38	-139	
	Edge						
Mean Value		107	96	89	86	70	90

Table 5 Test case and load strength (Experiment for the comparison calculation and measurement)

Allowable live load (N)	Large live load (N)	Test cases: Loading point: 5	Test cases: Loading point: 9
10.0	40.0	Case-A	Case-G
	50.0	Case-B	Case-H
20.0	40.0	Case-C	Case-I
	50.0	Case-D	Case-J
30.0	40.0	Case-E	Case-K
	50.0	Case-F	Case-L

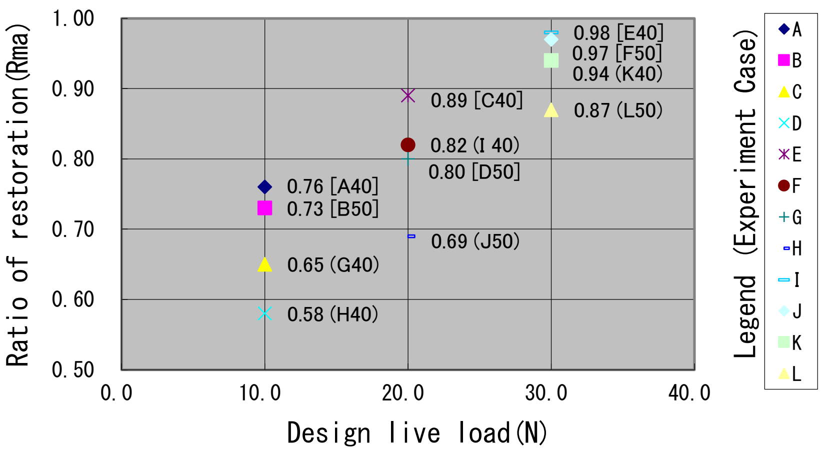

Fig. 10 Comparison calculation and measurement (*Rma*) results

a) When the large live loads were equal, the greater the design live load strength, the closer the measured values to the calculated values.

b) When the loading point and the design loads were equal, the smaller the large live load strength, the more similar the measured values to the calculated displacement.

c) Of loading points (5) and (9), the measured and calculated displacements were similar at loading point (5). This result indicates that the smaller the large live load strength, the more similar the measured and calculated displacements.

d) When the large live load strength was varied, the smaller the large live load strength, the more similar the measured values to the calculated displacement.

5.3.3 Summary of the experiment

This experiment focused on controlling the displacement of the main girder. Main results and future topics of studies are summarized below:

a) In the cable-stayed bridge model, the experimental and calculated values showed differences according to the differences in loading point, design live load, and large live load, but controlling the main girder displacement by adjusting the tension of the stay cables was verified to be valid.

b) Regardless of the loading point, it was found that the smaller the strength variance of the design and the large live load, the more similar the displacement values to those of the calculated value. The accuracy of displacement of the main girder members of the cable-stayed bridge model was confirmed to improve by reducing the strength differential of the design and the large live load.

c) Regardless of the combination of the large and design live load, the closer the loading point to the pylon, the greater the differential between the experimental and calculated values.

(i) It is assumed that the pylon tilted more than predicted in the calculation value when the stay cable tension was adjusted, due to the much lower stiffness of the pylon than that of the main girder.

(ii) Because the loading point near the pylon is a joint where the increase in displacement caused by the live load is unlikely to occur, compared to a loading point distant from the pylon, this is not expected to be a serious problem.

6. Conclusions

The vibration control of bridges is thoroughly studied, and many engineers recognize the importance of smart monitoring, but studies on building intelligent bridges have been poorly developed. Some of the reasons for this slow development are the large scale, time, and spatial difficulty in forecasting the characteristics of disturbances such as winds and earthquakes; and the necessity for compelling reasons regarding the safety and reliability of bridges and their life cycle costs because many of them are public assets.

This study constructed systems for an intelligent bridge using a cable-stayed bridge model and conducted a monitoring control experiment of the cable-stayed bridge model using this system. In the experiment, conducted on the cable-stayed bridge model, a series of operations were performed, from detecting the load applied to the bridge model, understanding the condition of the bridge and judging its safety, and calculating the counterforce in a dangerous condition to instructing and controlling the control device to restore the safe condition, and mobilizing all sensing, processor, and actuator functions from the para-stressing system utilizing the integrated remote monitoring system and counterforce calculation system built in this study. The stay cable tension and main girder displacement of the cable-stayed bridge model in each phase of the operation were measured, and the measured results were calculated and compared with the calculation and examined to verify the technique to make a bridge intelligent, the performance and accuracy of various systems developed for controlling, and the possibility of realizing this intelligent bridge.

The main conclusions obtained in this study can be summarized as follows:

1) The techniques adopted for making an intelligent structure and the systems built in this study were verified to be appropriate and valid. The integrated remote monitoring system, in particular, is useful for building the para-stressing system and monitoring the state of structure, and the sensing and decision-making function components of the para-stressing system can be practically applied to monitoring of the structure.

2) The para-stressing system produced promising results in the rate of restoration, as per the countering obtained by the measured values of the model experiment for making a cable-stayed bridge intelligent, and the comparison of experimental and calculation values confirmed a high degree of accurate control. To improve the rate of restoration and accuracy, it is important to understand and utilize the structural properties of the structure members, such as their relative stiffness.

3) There are still issues with network security measures, data processing efficiency, and measures in the event of system failure for the practical application of the para-stressing system.

The series of operations in this experiment were all executed automatically, except the control operation. The implementation of tension by drawing the stay cables was partially manually carried out. Development of pulse generator board, motor controller program, and other components to automatically control the actuator installed on the cable-stayed bridge model from a PC are expected to be required in the future. Development of actuators capable of instantaneously generating enormous counterforce will also be an issue for application to actual bridges.

References

Boller, C., Chang, F. and Fujino, Y. (Ed.) (2009), *Encyclopedia of Structural Health Monitoring*, A John Wiley and Sons Ltd. Publication, London, UK, **1-6**.

Casas, J.R. (2000), “Structural control of bridges: Recent experiences in cable-stayed bridges”, Structural Control for Civil and Infrastructure Engineering, *Proceedings of the 3rd International Workshop on Structural Control*, Paris, World Scientific, New Jersey.

Chang, K.C., Kim, C.W. and Kawatani, M. (2014), “Feasibility investigation for a bridge damage identification method through moving vehicle laboratory experiment”, *Struct. Infrastruct. Eng.*, **10**(3), 328-345.

DIANA(Finite Element Analysis) User’s Manual (Dynamic Analysis, etc)” (2000), TNO Building and Construction Research, Release **7**.

Holnicki-Szulc, J. and Rodellar, J. (1998), “Requirements and potential applications in mechanical and civil engineering”, *Smart Structures*, NATO Science Series, Kluwer, Boston, **65**.

JSCE Committee of Structural Engineering (Ed.) (2000), *Structural Engineering Series 10*, Bridge Vibration Monitoring Guidelines, The Japan Society of Civil Engineers (JSCE), Tokyo, **10**.

Kamada, T., Fujita, T., Murai, N., Aizawa, S., Tohyama, K., Hatayama, T. and Arikabe, T. (1998), “Active vibration control of buildings with smart structures using piezoelectric actuators”, *Earthq. Eng. Symposium Proceedings*, **10**(3), 2941-2946.

Kanefuji, H. (2000), *An Introduction of Visual Basic-6 to*

Automatic Measuring System, Gijyutsu-Hyohron Co., Ltd.
Kim, S., Yoon, C. and Kim, B. (2000), "Structural monitoring system based on sensitivity analysis and a neural network", *Comput. - Aided Civil Infrastruct. Eng.*, **15**(4), 309-318.
Magaña, M.E., Rodellar, J., Casas, J.R. and Mas, J. (1998), "Active control of cable-stayed bridges", *Smart Structures*, NATO Science Series, Kluwer, Boston.
Montes, S. (1996), "A Global concept for 21st century bridge: Para-stressing", *Proceedings of the FIP Symposium on Post-tensioned Concrete Structures*, London, UK.
Miyamoto, A. and Motoshita, M. (2004), "An Integrated Internet Monitoring System for Bridge Maintenance", *Proceedings of the 2nd International Workshop on Structural Health Monitoring of Innovative Civil Engineering Structures*, ISIS Canada Research Network, Manitoba, Canada.
Nakatsu, K., Furuta, H., Nomura, Y., Takahashi, K., Ishibashi, K. and Miyoshi, N. (2011), "Practical Application of Long-term Bridge Management System using Genetic Algorithm", *Japan Society for Fuzzy Theory and Inteligent Infomatics*, **23**(4), 469-479.
Nakazawa, M., Ario, I., Tanikura, I. and Ono, S. 2009), "Development of mobile bridge based on the multi-folding microstructures Cncept", *Proceedings of the 64th Annual Conference of the Japan Society of Civil Engineers*, JSCE.
Nader, M. Okashaa, D.M. and Frangopol, D. (2012), "Integration of structural health monitoring in a system performance based life-cycle bridge management framework", *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, **8**(11), 999-1016.
Smart Structure Research Group (SSRG) (Ed.) (1993), *SMART STRUCTURES*, p.14.
Yamamoto, S. (1999), *Health Monitoring*, Kyoritsu Publishing Company Co., Ltd, Tokyo, Japan.
Yang, Y., Kumaraswamy, M., Pam, H. and Mahesh, G. (2011), "Integrated qualitative and quantitative methodology to assess validity and credibility of models for bridge maintenance management system development", *J. Management Eng.*, **27**(3), 149-158.
Yanev, B. (2007), *Bridge Management*, John Wiley & Sons, Inc., New Jersey.

CC