Development of an integrated remote monitoring technique and its application to para-stressing bridge system

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ABSTRACT: Bridge monitoring system via information technology is capable of providing more accurate knowledge of bridge performance characteristics than traditional strategies. This paper describes not only an integrated internet monitoring system that consists of a Stand-alone Monitoring System (SMS) and a Web-based Internet Monitoring System (IMS) for bridge maintenance but also its application to para-stressing bridge system as an intelligent structure. IMS, as a web-based system, is capable of addressing the remote monitoring by introducing measuring information derived from SMS into the system through Internet or Intranet connected by either PHS or LAN. Moreover, the key functions of IMS such as data management system, condition assessment and decision-making with the proposed system are also introduced in this paper. Another goal of this study is to establish the framework of a para-stressing bridge system which is an intelligent bridge by integrating the bridge monitoring information into the system to control the bridge performance automatically.

For the purpose of verifying its validity to actual bridge structure, an attempt is made to study the possibility of controlling the actual structural performance by adjusting the cable forces on a 2-span continuous cable-stayed bridge model. The experimental results demonstrate that the implemented monitoring system supplies detailed and accurate information about bridge behavior for further evaluation and diagnosis, and it also opens up prospects for future application of web-based remote system to actual in-service bridges under field conditions.

1 INTRODUCTION

Japan's investments in social infrastructure systems have steadily increased since the high economic growth period that started in the late 1960s. Social infrastructure systems have been reinforced in a short period of time. The public has been provided with stable daily social lives. With the maturing of society, however, shrinking public finance offers only limited funds for infrastructure development. Conventional maintenance practice has difficulty attending to the deterioration of existing infrastructure systems that has been occurring intensively. Future challenges include not only the maintenance of excellent performance of infrastructure with limited funds to hand it over to next generations but also the enhancement of services that infrastructure renders.

Bridges have recently been lacking required performance due to the damage ascribable to the increases of vehicle size and traffic volume, and seeing their performance deteriorated as they have been in service over a long time. Deterioration of bridges in particular has been increasing the need of investigations and inspections, and placing heavy burdens on bridge administrators. To minimize bridge upgrade and maintenance costs while funds are limited, lengthen service lives, reduce life-cycle costs and maintain the level of services provided by bridges, early investigations and remedial actions are required in the course of shift from reactive to proactive response, and appropriate identification and evaluation of bridge conditions and prediction of deterioration are demanded. Few engineers are equipped with bridge investigation, inspection or diagnostic skills. Frequent investigations, inspections or diagnoses are therefore difficult to make. Under such demanding conditions, a conceivable highly accurate and efficient inspection technique is a remote monitoring system for structures via communications networks (Miyamoto et al., 2004).

At present, bridges are designed based on the uniform loading applied to all bridges. Some of the bridges carrying a relatively small volume of traffic are designed to carry the loads of heavy vehicles that are likely to act rarely during their service life, resulting in uneconomical design. If it is made possible to design a bridge so that it can carry the design load equivalent to the loads of vehicles that usually travel and control bridge performance to structurally offset the loads of heavy vehicles that may be hazardous to the bridge, safety and reliability of the bridge may be ensured against such unexpected heavy loads (Kim et al., 2000). Reducing the design load may also lead to the reduction of the volume of materials used. This approach should therefore be taken actively also from a viewpoint of resource saving (Holnicki-Szulc et al.(ed), 1998).

Unexpected heavy loads may be handled by a para-stressing system that exerts required counterforce as required (Montes, 1996). The para-stressing system activates control devices including actuators to offset stresses induced by the strain or deformation of the bridge to restore the bridge to original condition. The para-stressing system is composed of detection and sensing, decision-making and instruction, and control functions. The detection and sensing function involves the sensing of loading and the identification of conditions of structures. The decision-making and instruction function helps determine whether control measures are required or not and send instructions to the control function whenever necessary. The control function is aimed at operating actuators or other devices to apply required forces to the structure.

In this study, an internet monitoring system (IMS) via communications networks was built for a cable stayed bridge model, and then a para-stressing system was developed using the IMS.

2 OUTLINE OF INTEGRATED REMORT MONITORING SYSTEM

Monitoring is an important technique for evaluating the soundness of and diagnosing bridges based on the real-time measurements of strain, displacement, vibration and other parameters. The goal should be not only simply to measure the deformations of bridges but also to obtain useful knowledge for bridge management by efficiently recording, processing and using measurement results. Conventional monitoring relied on manual measurement. Increasing the monitoring efficiency requires the realization of unmanned automated real-time measurement and the development of an environment for providing numerous bridge-associated people with access to necessary data from the place where they need the data. The systems built in this study are the Stand-alone Monitoring System (SMS), which is installed mainly in the field to make real-time measurement and visualize measurement results, Internet Monitoring System (IMS), which enables remote measurement and data collection via communications networks, and another monitoring system, which integrates the two systems. An outline of the integrated remote monitoring system is given in Figure 1. The integrated remote monitoring system is used as a sensing tool for the para-stressing system to identify the present conditions of bridges in terms of deformation, stress and other parameters, and to confirm post-control conditions of bridges.

2.1 *Outline of stand-alone monitoring system (SMS)*

The Stand-alone Monitoring System (SMS) works on a measurement computer installed at the bridge site where field monitoring takes place. SMS measures external forces acting on the bridge and the behavior of the bridge subjected to external forces. SMS constantly measures the stresses and displacements of bridge members and temperature around the bridge using sensors installed in the bridge, visualizes the collected data in graphs and charts, and stores them in a measurement server.

SMS that monitors a cable stayed bridge model is composed of a measurement instrument (data logger) that monitors the behavior of the model, and a measurement server that sends measurement instructions to the measurement instrument and records data (Figure 1). The measurement server is equipped with measurement control and data storage programs, and records monitoring data and displays them in graphs. Figure 2 shows a screen output by SMS.

2.2 *Outline of internet monitoring system*

To increase measurement and data collection

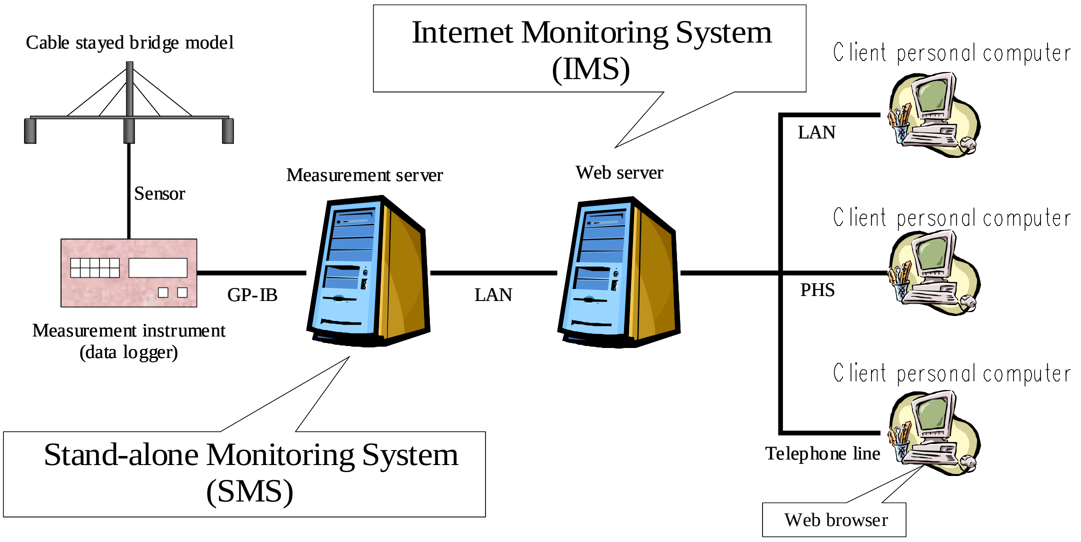

Figure 1. Composition of integrated remote monitoring system

efficiency of SMS at the bridge site, an Internet Monitoring System (IMS) using communications networks was built by incorporating a web server. Using IMS, which is capable of transmitting monitoring data real-time, enables quick identification of bridge use and deformation, and efficient management and use of collected measurement data regardless of time or place. With IMS, early discovery of problems by field monitoring, simultaneous monitoring of multiple bridges, data use for other purposes than bridge management, guarantee of data uniformity and reduction of inspection and other maintenance work also become possible.

For practical IMS implementation, however, preventing illegal attacks of Internet invaders such as system destruction, data manipulation and eavesdropping is very important. In IMS, the range of authority of the user to access the system and data is classified into the manipulation of measurement results, data use or data retrieval. Some users are authorized to access the common file server in the web server, but others not. Thus, restrictions are imposed on system use. The system is intended to allow as many bridge-related people as possible to retrieve and use data. Users are classified into administrator, member or guest according to the range of authority (security depth) to restrict access to the system. A multi-level authentication is adopted in which authentication is done at each security depth. Wielding the broadest range of authority of the administrator requires authentication at three security depths. This system adopts server authentication, client authentication and password authentication based on SSL (security socket layer) that encrypts data.

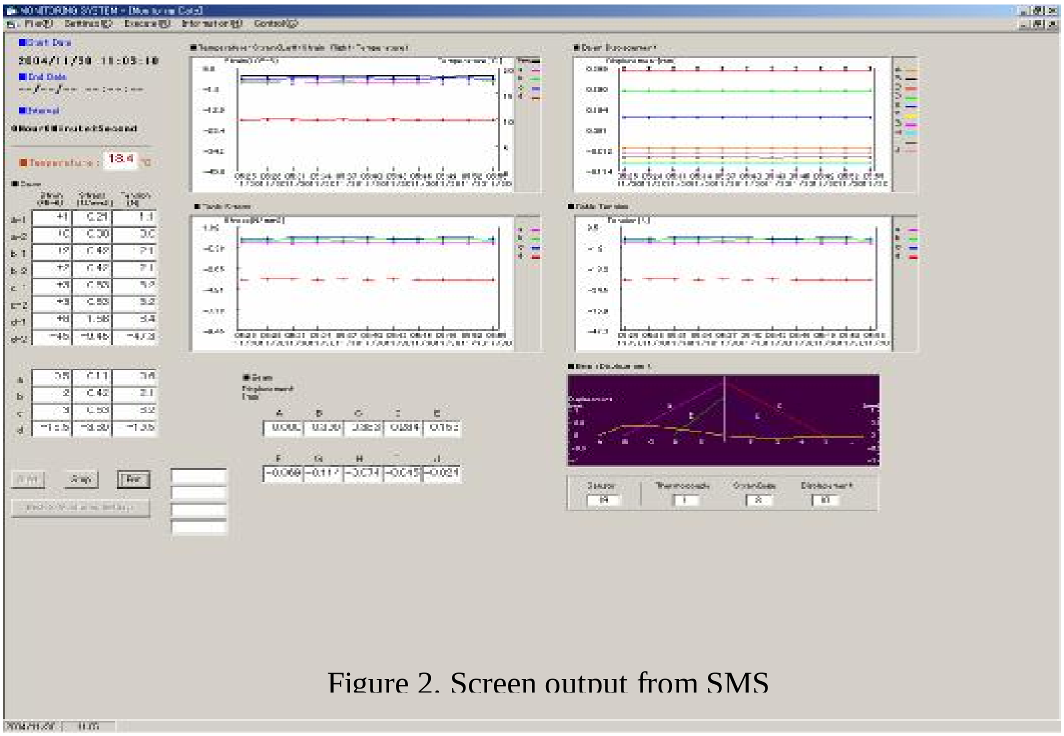

Figure 2. Screen output from SMS

3 OUTLINE OF PARA-STRESSING SYSTEM

3.1 *Para-stressing system*

Para-stressing is an intelligent technology based on a new concept of resistance to external forces acting on structures by controlling structural members including material properties real-time while regarding the entire structure as a self-organized system. Shown in Figure 3 is a self-organized structure that senses, determines and controls external forces by itself. The system senses the conditions of the bridge based on the measurements obtained by the integrated remote monitoring system, determines the present conditions using the measurement server, and sends control instructions to the actuator whenever necessary. A system was constructed for automatically carrying out a series of these jobs.

3.2 *Development of para-stressing system*

Described below are three functions of the para-stressing system shown in Figure 3: sensing, decision-making and control functions.

Sensing function

The sensing function is intended to accurately identify the conditions of the bridge. The integrated remote monitoring system is used to perform this function. With the para-stressing system, displacements of main girders are controlled by varying the cable tension of the cable stayed bridge model. The sensing function is therefore responsible for accurately grasping cable tension before and after the control measure is taken.

Decision-making function

The decision-making function calculates the tension that should be applied to cables to reduce main girder displacement due to large vehicle loads to the level under normal loads (optimal counterforce for controlling displacement). The cable tension measured by the sensing function is compared with the calculated counterforce. Control instructions are continually sent to the control function until the cable tension becomes identical to the optimal counterforce.

Control function

The control function varies cable tension by stressing or relaxing the

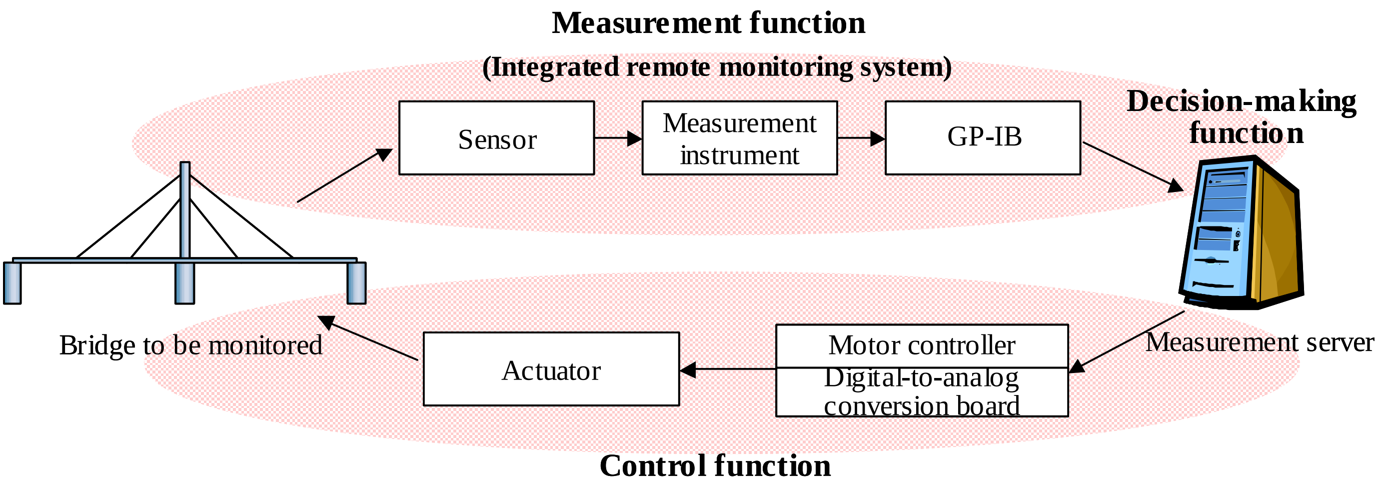

Figure 3. Composition of para-stressing system

tension using the actuator on the bridge to offset additional loads of large vehicles.

3.3 *Bridge model to be monitored*

The para-stressing system was developed for a cable stayed bridge model and the effectiveness of the system was verified.

3.3.1 *Outline and dimensions of cable stayed bridge model*

The para-stressing system was developed for the cable stayed bridge model shown in Figure 4. The dimensions of the bridge are shown in Figure 5.

3.3.2 *Measurement points and sensor positions*

The measurement items used for the para-stressing system are listed in Table 1. The positions of sensors and main girder displacement measurement points are shown in Figure 6.

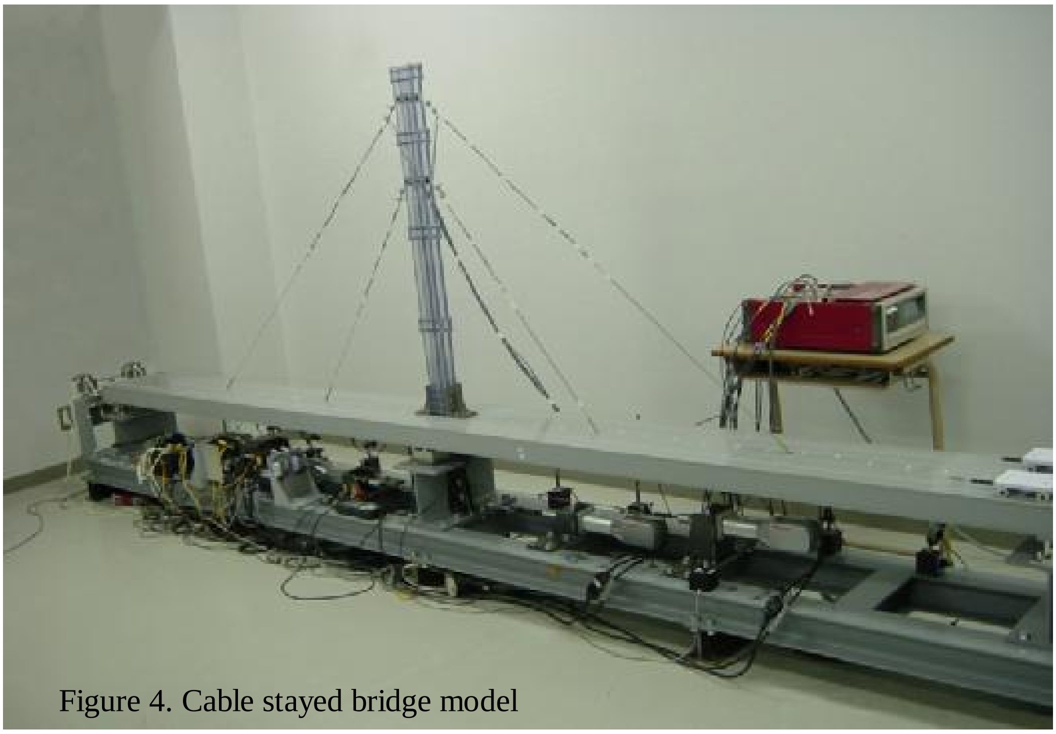

Figure 4. Cable stayed bridge model

3.4 *Control of displacement by para-stressing system*

When a large vehicle reaches the bridge, its load is measured with a load cell at the starting point of the bridge. When the measured load is input into the system, a program is activated to calculate the counterforce required for controlling displacement. The cable tension (optimal counterforce) required to hold the main girder displacement when a large vehicle reaches the first measurement point (A) below the main girder displacement under normal loads (allowable displacement) is calculated. Once the optimal counterforce is determined, instructions are sent to the actuator to start operation, and stressing of stay cables starts and the monitoring system starts monitoring at the same time to measure cable tension. The decision-making function compares the measured cable tension with the optimal counterforce, and repeatedly stresses and relaxes cable tension until an agreement is reached. When the adjustment of tension is finished, the load is moved to measurement point A where a displacement gauge is in place in Figure 6. When the large vehicle reaches measurement point A, the above process is repeated for the next measurement point B. Operation is repeated from the time a large vehicle reaches the starting point of the bridge model until the vehicle reaches the end, and main girder displacement is measured each time the control measure is taken.

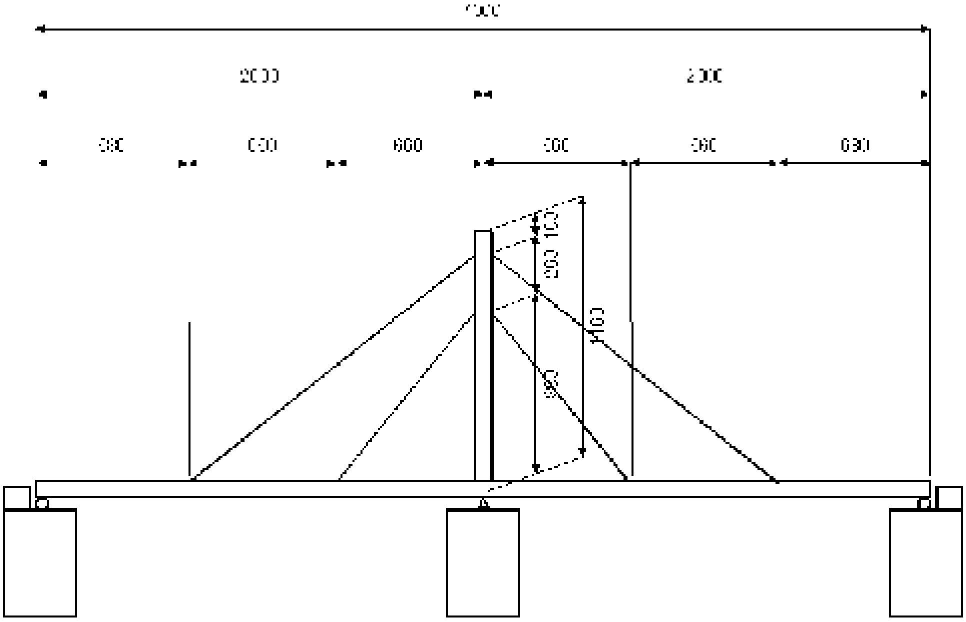

Figure 5. Dimensions of the cable stayed bridge model (mm)

Table 1. 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

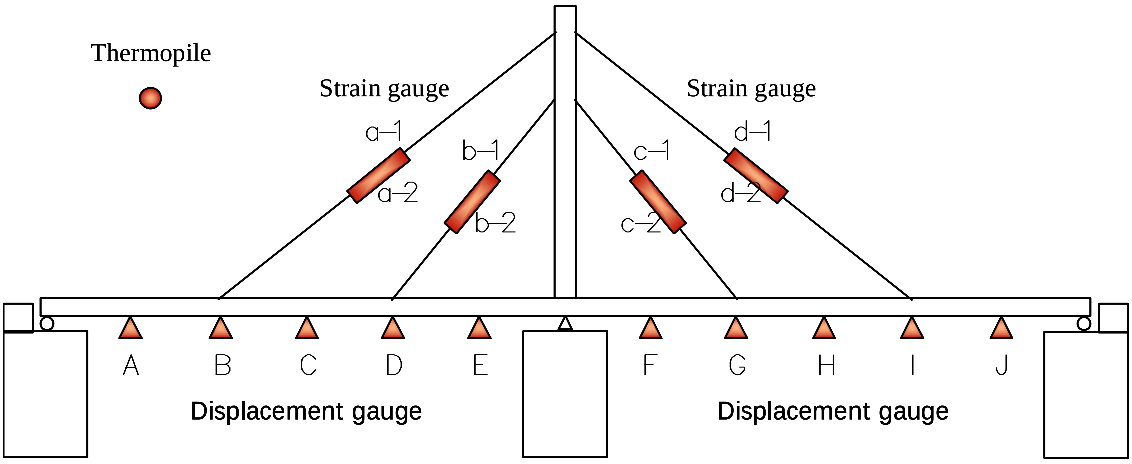

Figure 6. Sensor positions and measurement points

4 CONTROL OF MAIN GIRDER DEFLECTION UNDER LOADING

4.1 *Test method*

The types of loads used in the test are listed in Table 2. The allowable loads represent the loads of vehicles that normally travel on the bridge, which are lower than the present design standards. The large vehicle loads are loads applied by vehicles that rarely travel on the bridge and are likely to be hazardous to the bridge. In the test, 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 from displacement owing to control measures. Tests were conducted in four cases with varying combinations of large vehicle and allowable loads as shown in Table 3.

In test case (i) in Table 3, the large live load was 40 N and the allowable live load was 10 N. Main girder displacement was monitored while a large live load of 40 N was applied. The obtained data were used as the data in the case without any control measures. Then, main girder displacement was measured when the main girder displacement under a large live load of 40 N was reduced to that under an allowable live load of 10 N, and the measurement result was used as data in the case where control measures were taken. The variance was calculated between displacements in the cases with and without control measures to identify the quantity of restoration when main girder displacement under a large vehicle load of 40 N was reduced to that under an allowable load of 10 N. The variance was then compared with the quantity of restoration obtained by FEM analysis to verify the effectiveness of the para-stressing system.

In cases (ii) through (iv) in Table 3, similar tests were conducted with varying combinations of large and allowable live loads.

4.2 *Test results*

The results of test case (i) in Table 3 are discussed here. Figure 7 compares the test result when a large vehicle load was applied at loading point B with FEM analysis result.

Shown below is the legend for Figure 7.

I: Main girder displacement under large vehicle load without any control measures (test result)

II: Main girder displacement under large vehicle load when cable tension was controlled (test result)

III: Main girder displacement under large vehicle load without any control measures (FEM result)

IV: Main girder displacement under large vehicle load when cable tension was controlled (FEM result)

Table 2. Types of loads

Allowable live load	Large live load
Below allowable design load	Exceeding allowable design load
10N , 30 N	40 N , 50 N

Table 3. Test cases

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

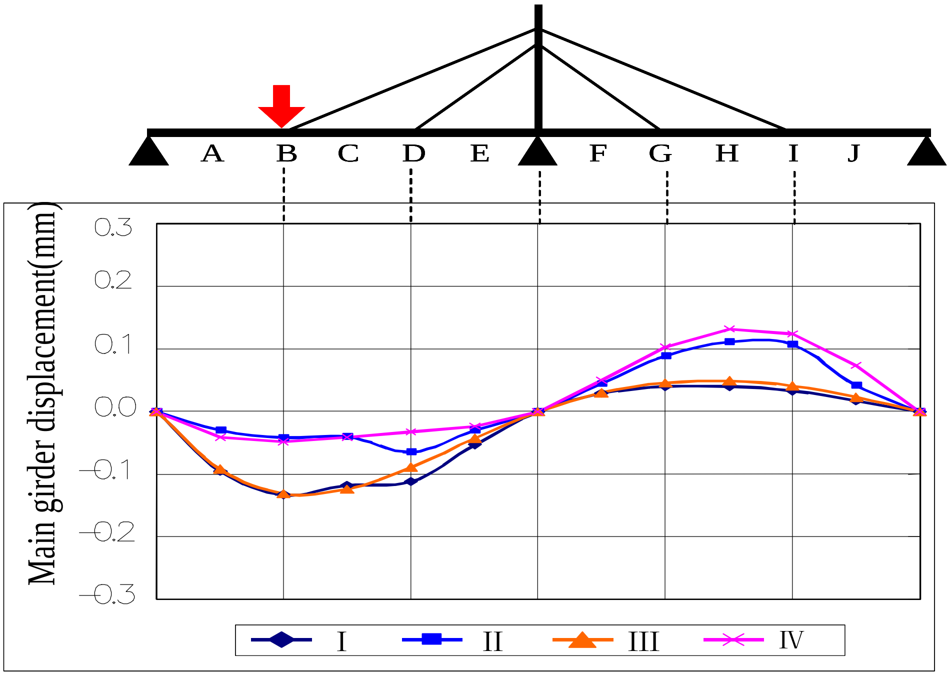

Figure 7. Comparison of results in Case (i) at loading point B

Table 4. List of measurements in test case (i) (rate of restoration in %)

40→10N		Loading point					Mean value
		A	B	C	D	E	
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

$$\mathit{Rate\ of\ restoration(\%)} = \frac{\underline{\mathit{Restoration\ in\ test\ with\ control\ measures}}}{\mathit{Restoration\ in\ FEM\ analysis}} \times 100$$

Rates of restoration at respective measurement points when the load was controlled at points A through E are listed in Table 4. The rate of restoration after control measures were taken are calculated by,

4.3 *Discussions*

Figure 7 shows an approximation between test and analysis results. This suggests the validity of adoption of FEM analysis for the development of the para-stressing system. According to Table 4, the rate of restoration is nearly 80% despite variation according to the measurement point. Thus, the para-stressing system was effective for restoring the bridge after displacement.

As is obvious from Figure 7, large negative displacement occurred in the unloaded span. 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 may have been 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. What remains to be done is to calculate the optimal counterforce for controlling displacement corresponding to the structural properties to increase the rate of restoration.

5 CONCLUSIONS

The major results of this study and the tasks for the future are described below.

1) The monitoring system built in this study is effective not only for investigating or

inspecting structures but also for building para-stressing systems.

2) The para-stressing system developed in this study achieved a rate of restoration of 80% after the displacement of main girders. Increasing the rate of restoration further based on the structural properties of bridges is required.

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

(1) As a security measure, SSL (security socket layer) that encrypts data has been used, and a multi-level authentication has been adopted according to security depths. Efforts are required to enhance the security level further.

(2) Simultaneously monitoring multiple bridges by a single bridge management system or using para-stressing systems requires efficient data processing, guarantee of data reliability and homogeneousness, and early detection of and recovery from system malfunctions.

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