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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.

Keywords: Bridge monitoring; Para-stressing system; Stand-alone monitoring system; Web-based Internet monitoring system; Structural performance

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 (Miyamoto and Isoda 2012). Future challenges include not only the maintenance of excellent performance of infrastructure with limited funds to hand it over to the 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 deteriorate as they have been in service over a long time under aggressive environments. 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 communication networks (Miyamoto and Motoshita 2004).

At present, bridges are designed based on the use of a live load model present in the respective codes, uniformly

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applied to all bridges. Therefore, some bridges carrying a relatively small volume of traffic are designed to carry the loads of heavy vehicles that are unlikely to act during their service life, resulting in uneconomical design. In other cases, non-standard bridges, as long-span bridges (cable-stayed, arches,…), may be subject to very high levels of live load that the bridge most probably will never experience. This is because the live load model in the code is normally calibrated for short- and medium-span bridges, and the direct application to very long spans derives on the over-estimation of the loading. If it was 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 live 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 and Rodellar 1998).

Unexpected heavy loads, such as big earthquake and strong typhoon, 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 the 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 (Yan et al. 2010, 2011). 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 the papers of Magaña et al. (1998) and Casas (2000), the active control of cable-stayed bridges subject to accidental loads due to earthquake is presented. There, only a theoretical approach was made, using a finite element model of a cable-stayed bridge as the prototype where the control algorithms were applied. The research wanted to demonstrate the feasibility and workability of using the control algorithms in the controllability of such a para-stressing system. The results showed that the control algorithms were very effective in reducing the magnitude of the deflections of the deck caused by the vertical component of an earthquake. In the present paper, the control is applied to a physical and not only mathematical model, and the exceptional load is due to the traffic load instead of earthquake. The experience is a new step forward to the implementation in full-scale structures. In this study, an Internet monitoring system (IMS) via communication networks was built for a cable-stayed bridge model and then a para-stressing system was developed using the IMS.

Methods

Outline of integrated remote monitoring system

Monitoring is an important technique for evaluating the soundness and diagnosing bridge performance 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

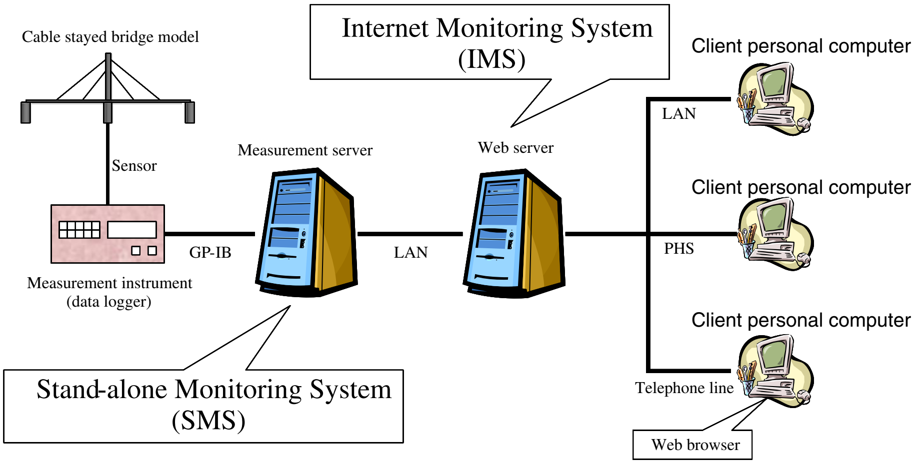
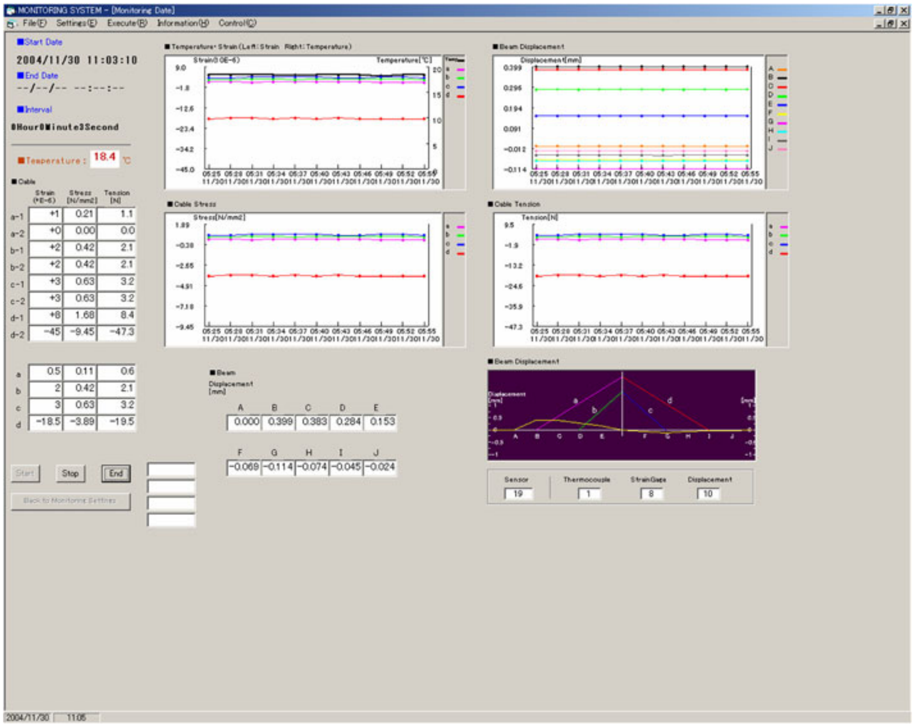


Figure 1 Composition of integrated remote monitoring system.



Start Date
2004/11/30 11:03:10
End Date
--/--/-- --:--:--
Interval
0Hour0Minute3Second
Temperature: 18.4 ℃

Cable

	Strain (×E-6)	Stress [N/mm2]	Tension [N]
a-1	+1	0.21	1.1
a-2	+0	0.00	0.0
b-1	+2	0.42	2.1
b-2	+2	0.42	2.1
c-1	+3	0.63	3.2
c-2	+3	0.63	3.2
d-1	+8	1.68	8.4
d-2	−45	−9.45	−47.3

a	0.5	0.11	0.6
b	2	0.42	2.1
c	3	0.63	3.2
d	−18.5	−3.89	−19.5

Beam Displacement [mm]

A	B	C	D	E
0.000	0.399	0.383	0.284	0.153

F	G	H	I	J
−0.069	−0.114	−0.074	−0.045	−0.024

Sensor	Thermocouple	StrainGage	Displacement
19	1	8	10

2004/11/30 11:05

Figure 2 Screen output from SMS.

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, IMS, which enables remote measurement and data collection via communication 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 condition of the bridge in terms of deformation, stress, and other parameters, and to confirm post-control conditions of the bridge.

Outline of stand-alone monitoring system

The 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 periodically 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

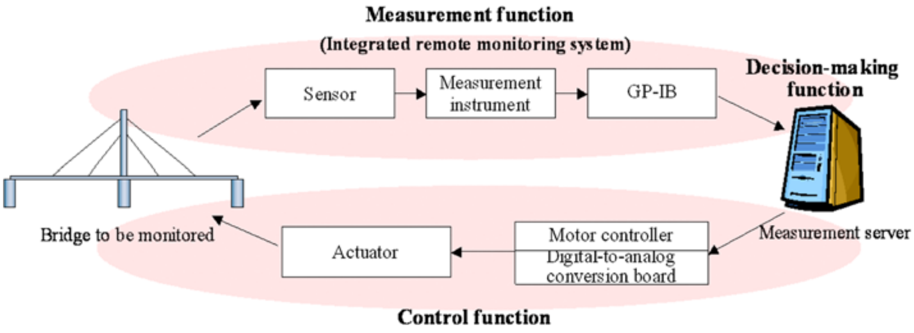


Figure 3 Composition of para-stressing system.

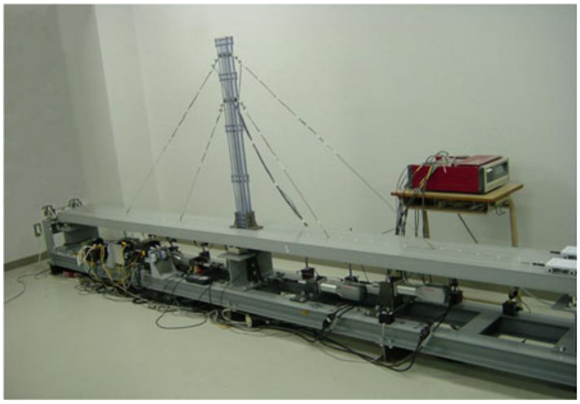


Figure 4 Cable-stayed bridge model.

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 for a two-span cable-stayed bridge model.

Outline of Internet monitoring system

To increase measurement and data collection efficiency of SMS at the bridge site, an IMS using communication networks was built by incorporating a Web server. Using IMS, which is capable of transmitting monitoring data at real time, enables quick identification of bridge performance and response, 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 the 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 security socket layer (SSL) that encrypts data.

Outline of para-stressing system

Concept of a para-stressing system

Para-stressing is an intelligent technology based on a new concept of response to external forces acting on structures by controlling structural members including material

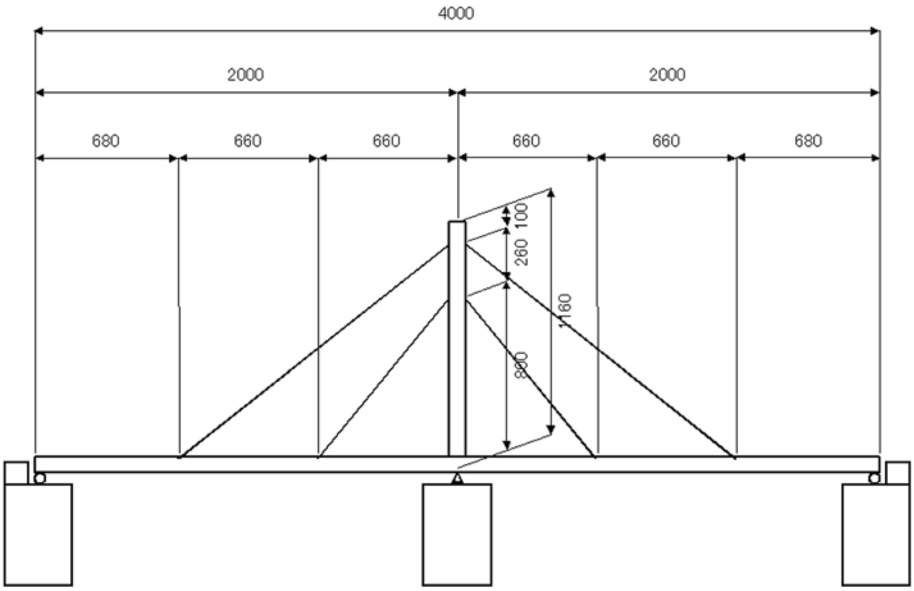


Figure 5 Dimensions of the cable-stayed bridge model (in mm).

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

properties in real time while regarding the entire structure as a self-organized system (Montes 1996). 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 serviceability and safety condition of the bridge 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.

Development of para-stressing system

Described below are the three functions of the para-stressing system shown in Figure 3: sensing, decision-making, and control/actuation 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 the main girder displacement or vibration 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 tension using the actuator on the bridge to offset additional loads of large vehicles.

Results and discussion

Example of application

Description of the structure

To check the effectiveness of the proposed method, a para-stressing system was developed for a cable-stayed bridge model as shown in Figure 4. The dimensions of the bridge model are shown in Figure 5. The two spans have a span length of 2.0 m. The cross-sectional dimensions of the deck which is a box girder with five rooms are 31.0 cm in width and 7.0 cm in height, and for the pylon, the main cross-sectional dimensions are 8.0 cm in width and 5.0 cm in thickness.

Description of the monitoring system

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

Description of the test

The objective function during the tests is to control the maximum deflection in the deck due to the crossing of vehicles. To this end, a para-stressing system is developed, and the following test procedures were also developed.

When a large vehicle reaches the bridge, its weight is measured with a load cell at the starting point of the bridge. When the measured force is uploaded into the system, a program is activated to calculate the counterforce required for controlling the deck deflection. The

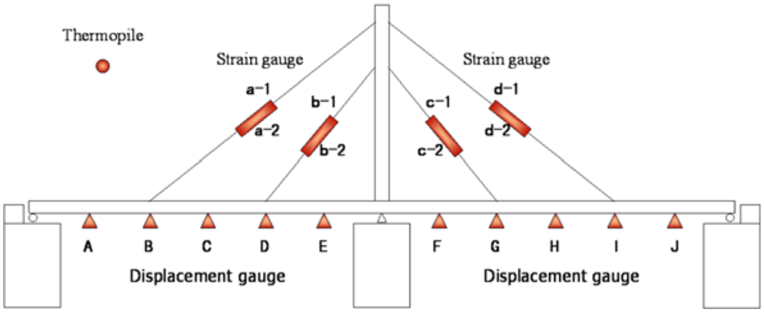


Figure 6 Sensor positions and measurement points.

system calculates the cable tension (optimal counterforce) required to hold the main girder displacement under normal loads (allowable displacement) when the heavy vehicle reaches the first measurement point (A). 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 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 as shown 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 the deck deflection is measured each time the control measure is taken.

The types of loads used in the test are listed in Table 2. The allowable loads represent the weight 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, 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. 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 exceptional live load was 40 N and the allowable live load was 10 N. First, the main girder displacement was monitored while an exceptional 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 (δ_1). Afterwards, the main girder displacement was measured when the main girder displacement under the load of 40 N was intended to be reduced to that under an allowable live load of 10 N. The measured result was used as data in the case where control measures were taken (δ_2). The difference was calculated between displacements in the cases with and without control measures and compared to the deflection obtained when the normal load of 10 N is applied (δ_3). In this way, the efficiency of the para-stressing system can be defined. The efficiency of the system is measured in terms of the so-called *rate of restoration R*, defined as follows:

$$R(\%) = \frac{\delta_1 - \delta_2}{\delta_1 - \delta_3} \times 100$$

Table 2 Types of loads

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

Table 3 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

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

Test results

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

Rates of restoration at respective measurement points when the load was controlled at points A to E are listed in Figure 8.

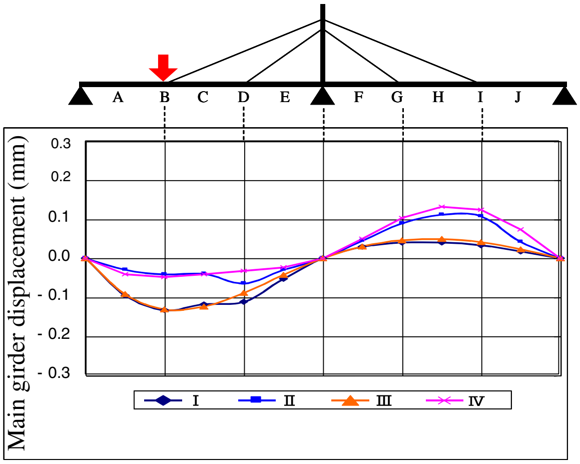
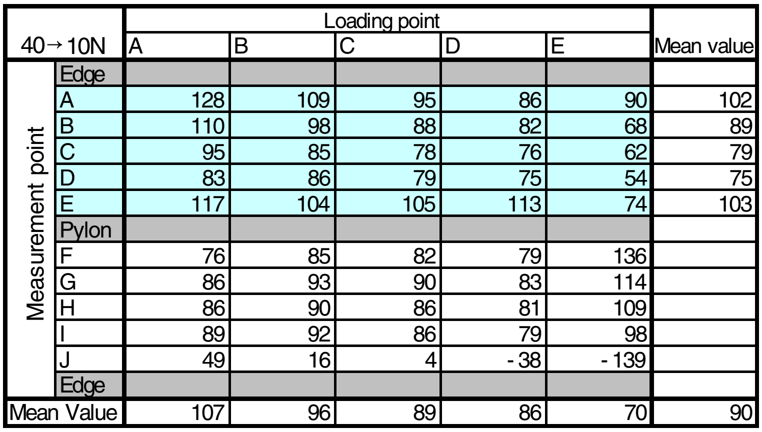


Figure 7 Comparison of results in case (i) at loading point B. I, main girder displacement under exceptional vehicle load without any control measures (test result (δ_1)); II, main girder displacement under exceptional vehicle load when cable tension was controlled with the objective of reducing the deflection to that corresponding to the normal vehicle (test result (δ_2)); III, main girder displacement under exceptional vehicle load without any control measures (FEM result); IV, main girder displacement under exceptional vehicle load when cable tension was controlled (FEM result).



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

Figure 8 **List of measurements in test case (i) (rate of restoration in %).**

Discussion

Figure 7 shows a good approximation between experimental and FEM results. This suggests the validity of the adopted FEM model for the development of the para-stressing system. According to Figure 8, 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 is much higher than that of the pylon.

Figure 8 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.

Conclusions

This paper introduces an IT-based bridge remote monitoring system which enables real-time monitoring and control for unexpected heavy loads such as big earthquake and strong typhoon. The integrated remote monitoring system is also composed of not only the Internet but also other types of information technology such as the latest information processing and soft computing technologies.

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

1. The monitoring system built in this study is effective not only for investigating or inspecting structures but also for building a para-stressing system to control the bridge performance under exceptional loads.
2. The para-stressing system developed in this study achieved a rate of restoration of 80% related to the vertical deflection of main girders. Although this is a quite effective value, further investigation on the structural properties of the bridge to increase the rate of restoration is needed.
3. Both the monitoring and para-stressing systems are dependent on communication networks. The following requirements should therefore be satisfied.
    (a) As a security measure, SSL 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 a level further.
    (b) 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.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

AM and MM established an idea of the integrated remote monitoring system for existing bridges and also of the theoretical background. They also carried out many kinds of experimental works as para-stressing system. JRC contributed numerous discussions and advice. All authors read and approved the final manuscript.

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