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Structural Health Monitoring System of Long-Span Bridges in Korea

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Development and application of structural health monitoring system in Korea have become active since the early 1990's. In earlier applications, health monitoring systems were installed in several existing bridges in order to collect initial field data by full scale load capacity test for design verification and subsequently monitor long-term performance and durability of the bridge as part of an inspection and maintenance program. Recently, modern and integrated monitoring systems have been introduced in most of the newly constructed long-span bridges since the design stage.
This paper outlines the progresses and applications of monitoring systems in Korea for both existing and newly constructed bridges and describes their aims and characteristics

Keywords : *structural health monitoring system, integrated monitoring system, long-span bridges*

1. Introduction

Development and application of Structural Health Monitoring System in Korea have become active since the early 1990's partly because of deteriorating infrastructure systems mostly built in the rapidly industrialized period of 1970's, and partly because of increasing recognition of potential devastating disruption of infrastructure systems due to natural hazards such as typhoons and earthquakes. After the sudden tragic collapse in 1994 of Sungsu Bridge crossing Han River in Seoul, the Korean governmental authorities have issued more stringent requirements on bridge management and operational programs. They include systematic visual inspection, instrumentation, load capacity tests and field measurements for design and construction verification, and long-term performance monitoring and assessment.

Two major existing cable-supported bridges were chosen as subject for implementation of the new governmental requirements to bridge management and operational programs: a cable-stayed bridge, Jindo Bridge built in 1984 and a suspension bridge, Namhae Bridge completed in 1973. The objectives of Health Monitoring Systems, specifically designed and applied to each bridge, were to collect initial field data by full scale load capacity test for design verification and subsequently monitor long-term performance and durability of the bridge as part of an inspection and maintenance program.

Recently, many important long-span bridges have been built in Korea and most of these bridges are equipped with modern and monitoring systems. Unlike those installed in existing bridges, many sensors and acquisition systems for measuring behavior under construction become a part of the long-term health monitoring system. In specific, the monitoring systems installed on highway bridges are integrated into a total bridge management system including inspection, evaluation, estimation and rehabilitation. The system utilizes advanced techniques such as sensing and communication by fiber optic cable, wireless data transmission and internet-based remote acquisition and control.

In order to deploy a successful monitoring system, requirements are: proper instrumentation, reliable signal processing and knowledgeable information processing. The evolution of bridge monitoring sys-tem in Korea may be classified into 3 generations according to its developing stage and functionality.[1)]

System corresponding to the first generation is characterized by a stand-alone field system consisting of sensors, field hardware and online signal transmission to a computer on field. In the second generation, this stand-alone evolved to an overall bridge management integrated system involving two kinds of integrations: operational integration where multiple stand-alone systems operate together and, functional integration where bridge monitoring sys-tem operates with different systems such as bridge management system (BMS) or vehicle monitoring system.[2] The third generation, also called future system, will provide advanced innovative functions like sensor fusion, reliable massive signal transmission, automated surveillance, adaptive signal processing, etc. Many research efforts to-ward the third generation system are actually led to develop and enhance the performance of the current system by introducing new sensing techniques, power generation from bridge vibration, web-based operating system or wireless signal transmission.

This paper outlines the progresses and applications of monitoring systems in Korea for both existing and newly constructed bridges and describes their aims and characteristics.

2. Health monitoring systems for exsisting bridges

Health monitoring systems in Korea at the very beginning were installed in existing bridges in order to collect field data by full scale load capacity tests for design verification and, subsequently, evaluate the health of the structure. Immediately after the collapse of the Sungsu bridge, this first generation of monitoring systems has been applied in existing bridges of which two representative examples, the Namhae and Jindo bridges, are described hereafter.

2.1 The namhae bridge

The Namhae Bridge is the first suspension bridge built in Korea and was open to public in 1973. This is an earth-anchored suspension bridge being composed of 49 hangers, box-type stiffened girder, two towers, and balanced main cable. When this bridge was designed, the load carrying capacity required by code was quite smaller than that by current code requirement. After long period of service along with excessive weight of traveling vehicles, it showed defects such as fatigue cracks at welding and corrosion of steel members. As a result of a safety evaluation of this bridge in 1993,[3] a short term strengthening and rehabilitation were carried out and a long-term maintenance and health monitoring project was established to extend the period of service life and prevent further loss of load carrying capacity.

According to the project, the initial status of the bridge prior to logging the long-term behavior by health-monitoring system was evaluated by geometric survey, static loading test[4] and ambient vibration test.[5] After evaluation of initial status, health monitoring system was installed in the bridge. Fig. 1 shows sensor locations and the specifications of sensors are listed in Table 1.

Table 1. Sensors installed in the Namhae bridge

Sensor		Q'ty	Type
Static	Tilt-meter	10	Electrolytic biaxial (foundation: submersible type)
	Strain gauge	44	Vibrating wire
	Data logger	2	w/ Body, alarming system, modem
Dynamic	Accelerometer	12	Force balanced (uni-axial)
	Seismometer	2	Force balanced (tri-axial)
	Strain gauge	10	Electric resistance
	Joint-meter	4	LVDT
	Anemometer	2	3D-propeller
	DAQ system	2	w/ Body, triggering system, GPS system

2.2 The jindo bridge

Another good example of health monitoring system installed in existing bridge would be the case of the Jindo Bridge which was completed in May 1984. It is a three-span cable-stayed bridge with a main span of 344m long and each side span of 70m long. It has two steel pylons and stay cables are arranged in semi-harp type.

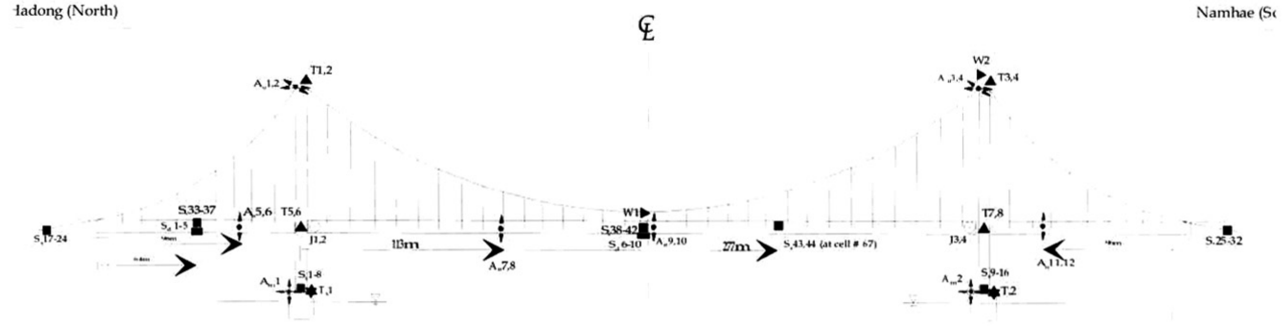

Fig. 1. Location of sensors in the Namhae bridge

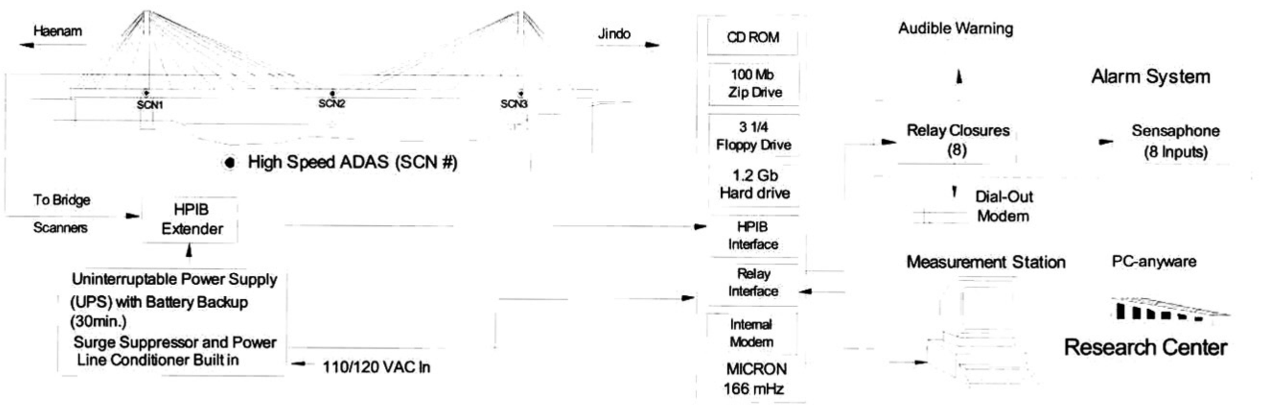

Fig. 2. Conceptual diagram of the health monitoring system installed in the Jindo bridge

Table 2. Sensors installed in the Jindo bridge

Sensor	Q'ty	Location	Sensor	Q'ty	Location
Tiltmeter	6	Pylon	Joint-meter	2	P39, P42
Accelerometer	12	Steel girder	Cable tension	24	Stay cable
Strain gauge	8	Pylon	Anemometer	2	PY1 top, mid span
	36	PC slab	Thermocouple	14	Girder, pylon, air, cable
	5	Steel girder	Seismometer	2	PY1, PY2 base
Laser disp.	1	PY1, mid span	BWIM	6	Asphalt pavement

A safety evaluation project for this bridge was carried out in 1993 and it was found that camber at mid-span had become lower than the original design profile and one stay cable had lost tensioning force by small amount and some natural deterioration had been occurred.[6] And also, it is turned out that the bridge deck is weak for torsional flutter by aero-dynamic study. Since 1996, the health monitoring system along with the total Bridge Management System has been adopted in this bridge.[7] The conceptual diagram of monitoring system is shown in Fig. 2. It is mainly composed of three parts: automated data acquisition system, automated data processing system and data management system. Among these systems, data acquisition and processing system are located in the station near by the bridge and management system is located in an office that is far from the site. Total of 66 sensors are installed in the bridge and three static and three dynamic loggers are placed in the bridge. Sensor locations and their specifications are shown in Table 2.

3. Health monitoring systems for new bridges

Unlike earlier applications of health monitoring system, where conventional sensors, loggers and transmission methods were used and individual system served each bridge independently, recent systems that are usually adopted in newly built bridges employ many modern technologies from sensing to processing. Also, an attempt to integrate health monitoring systems of several bridges together has been made in order to reduce the total cost and to increase efficiency of management work. This integrated system includes Bridge Management System (BMS) as well for inspection, evaluation, estimation and rehabilitation. Among many health monitoring systems in newly built bridges, an integrated system for Youngjong Bridge,[8] Banghwa Bridge[8] and Seohae Bridge[9] may be the best example for the current trend of monitoring and bridge management system. An integrated BMS and monitoring system will be discussed after brief description of sensors and data acquisition system for each bridge.

3.1 The seohae bridge

As the longest cable-stayed bridge in Korea, the Seohae bridge has been constructed in 2000 to link Pyongtaek and Dangjin by crossing the Asan bay. The bridge has a total length of 990 m with five spans (60 m + 200 m + 470 m + 200 m + 60 m) of stiffened steel girders with precast slab. The main cable-stayed span (470 m) and the

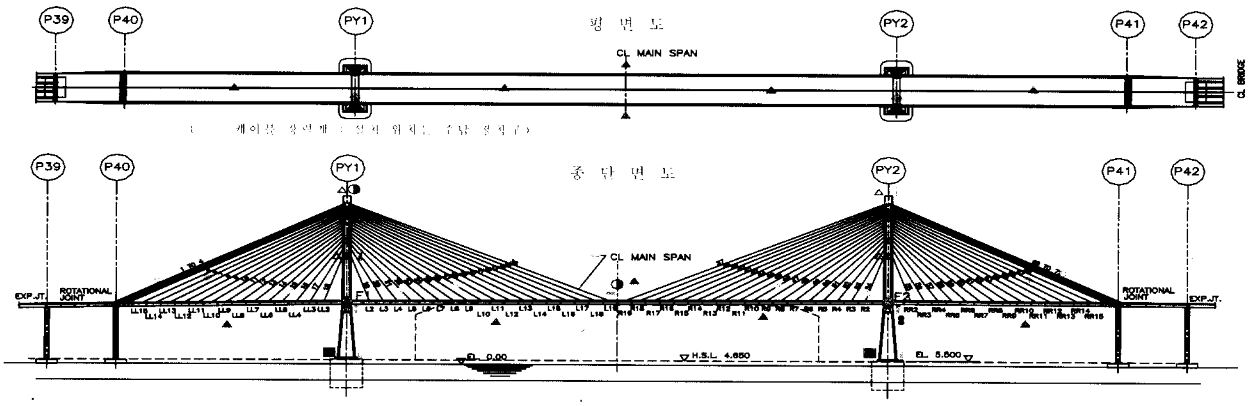

Fig. 3. Location of sensors in the Seohae bridge

Table 3. Sensors installed in the Seohae bridge

Sign	Sensor	Q'ty
◑	Anemometer	2
●	Cable tension force (accel.)	12 @ 2
▲	Accelerometer (deck)	6
△	Accelerometer (tower)	4
|	Tiltmeter	6
—	Thermometer	14
⊡	Static strain gage	12
▣	Dynamic strain gage	82
8	Laser disp. sensor	4
▶◀	Jointmeter	10
◆	Field control box	4
■	Accelerometer for earthquake	2

Table 4. Sensors installed in the Yeongjong bridge

Sign	Sensor	Q'ty
●	Thermometer	33
==	Static strain gauge	122
—	Dyn. strain gauge	175
◆	2D tiltmeter	10
■	1D accelerometer	12
▣	2D accelerometer	14
□	3D accelerometer	3
⊙	Anemometer	4
×	Laser disp. sensor	3
⬟	Potentiometer	4
SL	Static data logger	2
DL	Dyn. data logger	2

two side spans are connected at the tower locations.

More than 10 types of sensors for a total of 180 units are actually installed in the principal parts of the cable-stayed bridge, PSM and FCM bridges of the Seohae bridge (Table 3, Fig. 3). The signals collected by these sensors are transmitted in real time to the main server via optical or wireless data logger. The cable-stayed bridge itself has a total of 111 sensors, which collect data every 10 minutes in case of static measurement and, compute representative values (maximum, minimum, average) from the 100 data recorded every second in case of dynamic measurement.

3.2 The yeongjong bridge

The Yeongjong bridge is a self-anchored suspension bridge (125 m + 300 m + 125 m) with a double-deck warren truss girder carrying both rail-way and roadway. A total of 380 sensors, listed in Table 4, were planned to be installed at locations shown in Fig. 4.

Table 5. Sensors installed in the Bangwha bridge

Sign	Sensor	Q'ty
●	Thermometer	12
=	Static strain gage	82
—	Dynamic Strain Gage	4
⊕	2-D Accelerometer	8
⊟	1-D Tiltmeter	10
⊞	2-D Tiltmeter	7
➡	Longitudinal Disp. Transducer	4
○	Anemometer	2

3.3 The banghwa bridge

The Banghwa bridge, opened to the public in 2000, is an important bridge crossing the Han River and leading to the Incheon International Airport Expressway. Even though it spans 2,559 m to cross the river, the main bridge is a balanced arch-truss of 540 m. The monitoring system

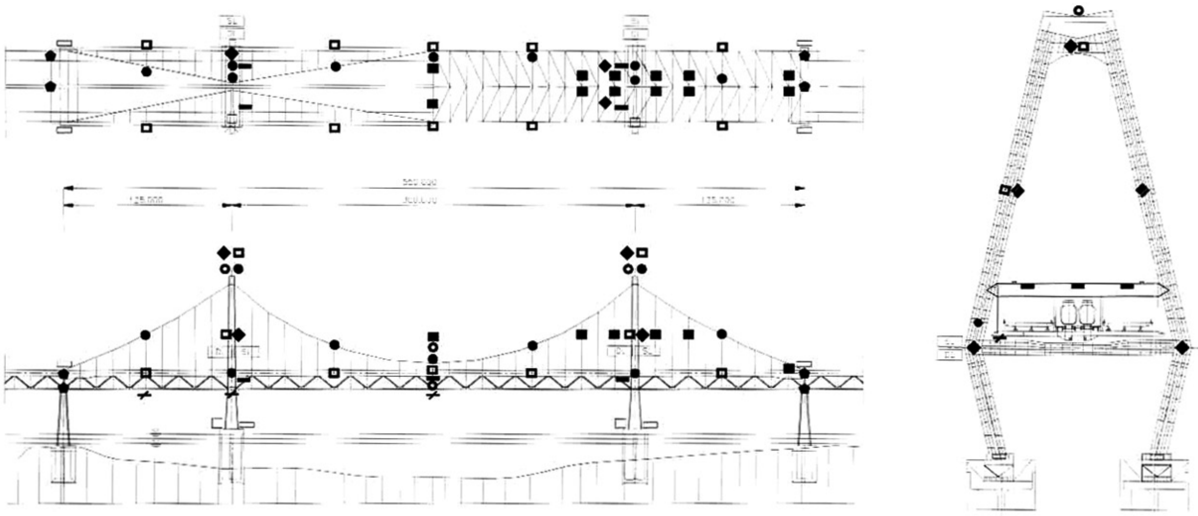

Fig. 4. Location of sensors in the Yeongjong bridge

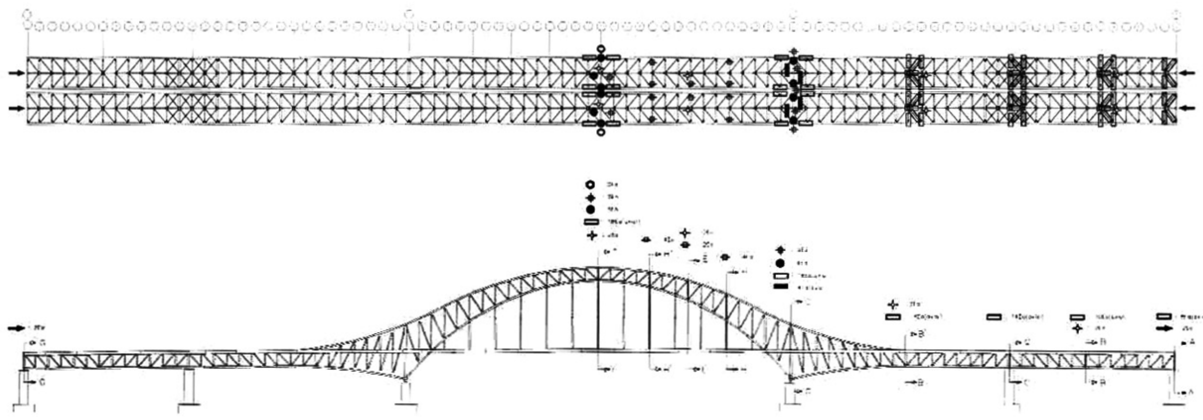

Fig. 5. Location of sensors in the Banghwa bridge

of the bridge includes the sensors listed in Table 5 and installed at the locations shown in Fig. 5. This system is managed together with the system of the Yeongjong bridge by the same authority.

3.4 The gwangan bridge

The Gwangan bridge, the central part of Gwangan principal road, is located in front of Gwangan town beach and is the longest suspension bridge in Korea with its 900m overall length. It is an earth-anchored suspension bridge with a double-deck warren truss girder carrying roadways. The pylon is a steel tower where the main cable is sustained with its stiffening girder at 105 m height.

The health monitoring hardware system for the maintenance of the Gwangan bridge has been designed to perform real time monitoring of the bridge structural behavior. Composed by dynamic monitoring instruments like laser displacement sensor, anemometer, accelerometer, and by static sensors such as tiltmeter, thermometer, and joint meter, the monitoring system processes signals, analyzes data and stores the data acquired from the sensors in the Monitoring Center. Fig. 6 illustrates the location of the measurement instrumental devices and their specifications are listed in Table 6.

3.5 The samcheonpo bridge

The Samcheonpo bridge, located in the Hallyeo maritime national park and opened to the public in April 2003, has been constructed to connect Sacheon city and Changsun island. It is a 436 m long three-span (103 m + 230 m + 103 m) cable-stayed bridge with composite girder.

The health monitoring hardware system for the main

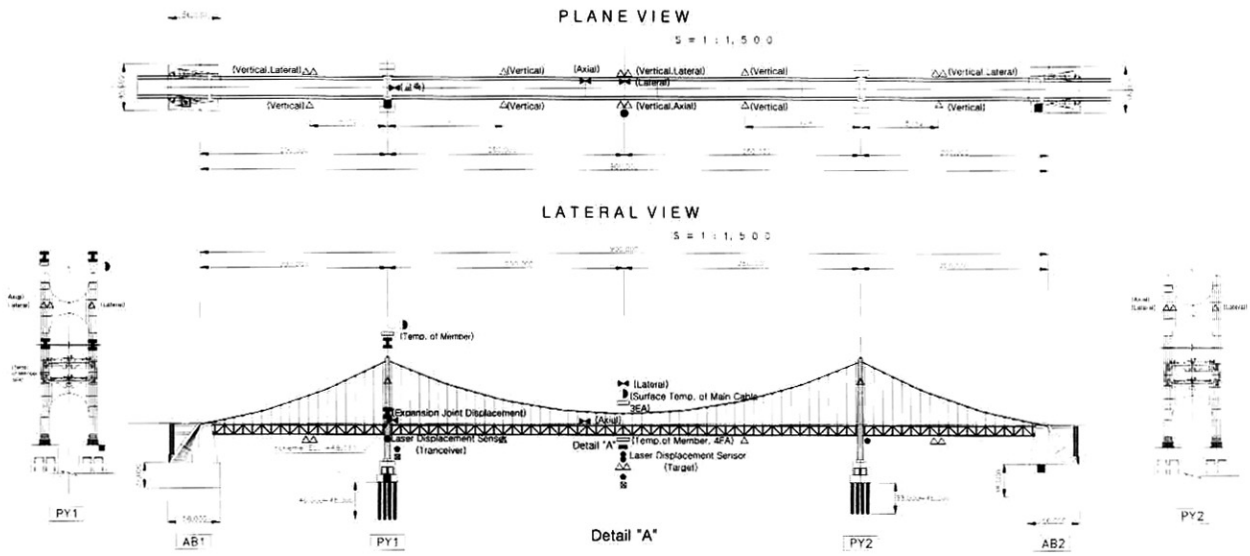

Fig. 6. Location of sensors in the Gwangan bridge

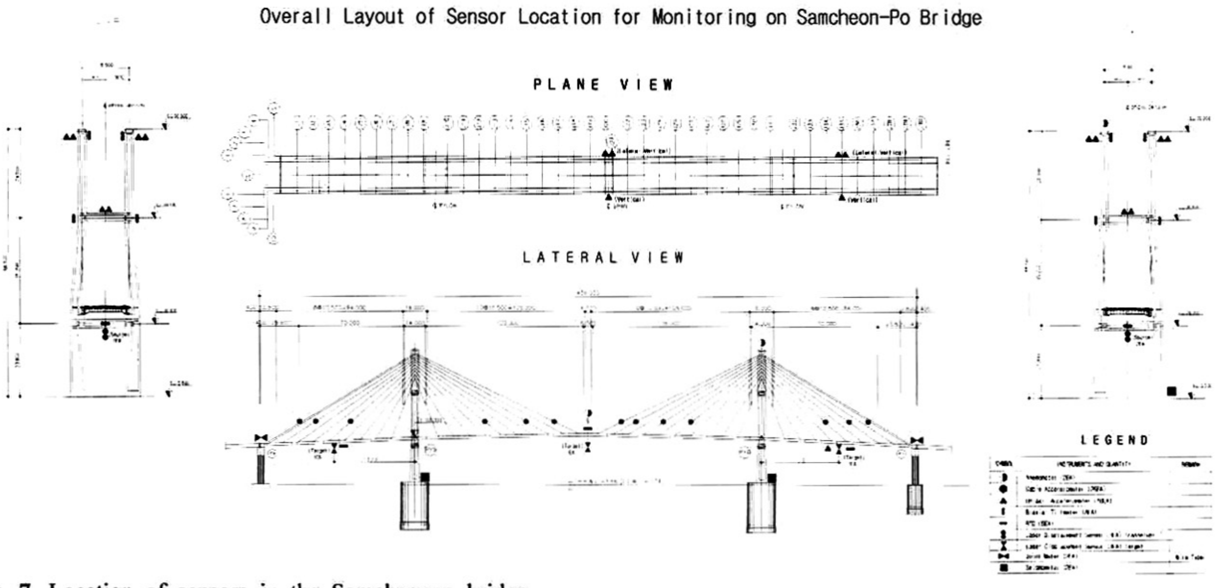

Fig. 7. Location of sensors in the Samcheonpo bridge

Table 6. Sensors installed in the Gwangan bridge

Sign	Sensor	Q'ty
◐	Anemometer	3
□	Thermometer	14
■	Seismometer	2
●	Laser disp. sensor	1
I	Tiltmeter	4
▶◀	Jointmeter	3
−	Strain gauge	4
△	Accelerometer	20

Table 7. Sensors installed in the Samcheonpo bridge

Sign	Sensor	Q'ty
◑	Anemometer	2
−	Thermometer	5
■	Seismometer	2
⧗	Laser disp. sensor	3
|	Tiltmeter	8
▶◀	Jointmeter	2
●	Cable tension (accelerometer)	26
▲	Accelerometer	18

tenance of the Samcheonpo bridge is similar to the one of the Gwangan bridge. Fig. 7 depicts the location of the measurement instrumental devices and their specifications are listed in Table 7.

4. Example of monitoring data analysis

The actual behavior of the Seohae cable-stayed bridge has been analyzed by means of measured data gathered during 2 years after its completion. On the basis of these 2 years data, the following observations have been obtained.

The variation of vertical displacement in the stiffening girder ranged from -320 to 30 mm, which satisfies the allowable design limit and, its daily variation due to thermal and live loads averages 119.3 mm with a maximum of 216 mm, which represents only 25 % of the design limits. As illustrated in Fig. 8 depicting the monthly variation of stress range in the stiffening girder, the range of the stress in the stiffening girder due to live loads showed good correlation with the actual traffic volume monitored during these 2 years and, as it represents only 5 to 12 % of the design stress, it appeared that the stress margin of the member is still considerable.

According to such observation, it can be affirmed that designing long-span cable-stayed bridges based on the ordinary highway bridge design specifications may result in excessively conservative structures. Measurement data obtained through systematic health monitoring may thus constitute a very precious material that may be utilized in the future to draw out design specifications adapted to long-span bridges. Resulting from the analysis of data, the deformations of the bridge deck and tower due to thermal variations are also shown to correspond accurately with theoretical estimations. An essential parameter in the management of cable-stayed bridges is the cable tensioning. Data showed that the tensioning force ranged within 95 to 104 % of the initial value, attesting for the stability of the bridge.

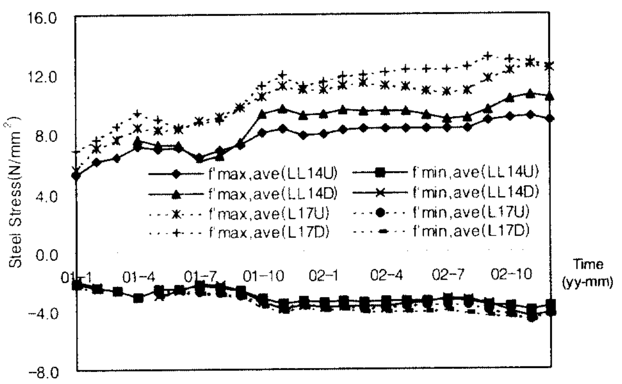

Fig. 8. Monthly variation of stress range in the lower stiffening girder flange of the Seohae bridge

A synthesis of all these results makes it possible to conclude that the actual behavior of the Seohae bridge is healthy. However, much more data are required to analyze correctly the behavior of the bridge subjected to long-term actions such as creep and thermal effect and to manage more efficient maintenance. To reach such goal, the monitoring system operates continuously so as to provide reliable data-base.

5. Conclusions

Progress and applications of bridge health monitoring system in Korea has been briefly addressed by following its developing stages. Representative health monitoring systems in Korea that have been adopted in bridges at different ages, beginning with existing bridges built in the 1970's to new-born bridges and illustrating the development of health monitoring have been described.

Health monitoring has seen large developments in a very short period of time to obtain more reliable information on the actual state of the structures. A challenging task for which domestic and international research efforts persevere to bring advanced innovative functions like sensor fusion, reliable massive signal transmission, automated surveillance, adaptive signal processing, etc. Many research efforts toward the third generation system are actually led to develop and enhance the performance of the current system by introducing new sensing techniques, power generation from bridge vibration, web-based operating system or wireless signal transmission.

Although health monitoring system itself plays an important role to study real behavior of structures in real environment and to reduce uncertainties in further design process, it has been being combined with other technologies such as System Identification (SI) and Damage Detection theory, Bridge Management System (BMS) and Artificial Intelligence (AI) to give overall estimation of bridge condition and to make proper maintenance decision and, finally, to lengthen the service life of structures. Current re-searches are focusing on implementing decision algorithm for repair and strengthening method, priority and budgeting as well as to improve hardware performance of health monitoring system.

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