국내 교량 건전성 모니터링 시스템의 현황 및 활용

Status and Application of Bridge Health Monitoring in Korea

고 현 무* **추 진 교****

*서울대학교 지구환경시스템공학부 교수 교량설계핵심기술연구단 단장
**교량설계핵심기술연구단 선임연구원, 공학박사

Bridges are incessantly and unavoidably subjected to various manmade as well as natural hazards since their construction. As bridge structures constitute the very vulnerable part of civil transportation system that affect directly the public safety, focus has been done on the active development of bridge health monitoring in Korea since 1990's. Gathering of field data for design verification and monitoring of long-term performance of bridges were performed in the scope of systematic and scientific inspection and management programs. Actually, modern and integrated monitoring systems are introduced in newly-built bridge structures since their design stage. This paper reviews recent development of bridge health monitoring systems in Korea in newly-built bridges with their objectives and major characteristics.

1. INTRODUCTION

1.1 Importance of Bridge Structures in the Road System in Korea

Civil engineering projects constituted the backbone of the development and economic growth of Korea. In the domain of transportation infrastructures, and particularly bridge structures, bridge construction activities have been continuously undertaken in the peninsula. During the 3 decades following the economic boom of 1970's, the bridge stock multiplied by 2 to reach 22,159 bridges and the length multiplied by 5.5 to reach 1,908km in December, 2004, compared to 1974, which reveals the trend to build longer span bridges (Fig. 1). This represents an average of one bridge of 86m constructed every 4.5km of the road network totalizing a developed length of 100,456km[1].

In concern with cable-supported bridges, the current stock is constituted by a total of 10 bridges as summarized in Table 1. It can be seen that the oldest cable-supported bridge is Namhae Bridge built 30 years ago. During this short period, bridge engineering in Korea has achieved outstanding advances that resulted in the construction of many cable-stayed and suspension bridges since 2000. Particularly, Youngjong

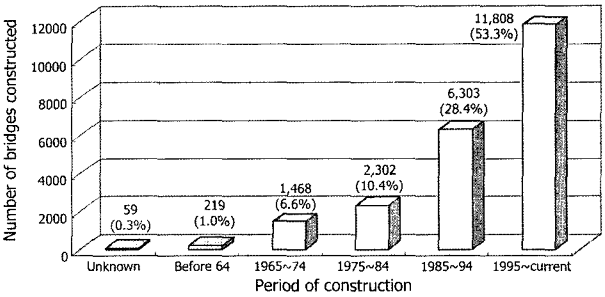


Fig. 1 Number of bridges constructed in Korea by decades (Ministry of Construction and Transportation, 2005)

Table 1 Current stock of cable-supported bridges in Korea (Ministry of Construction and Transportation, 2005)

Designation	Type	Length (main span, m)	Completion
Namhae	Cable-stayed	660.0 (404)	1973
Dolsan	Cable-stayed	450.2 (280)	1984
Jindo	Cable-stayed	484.0 (344)	1984
Olympic	Cable-stayed	1,470 (300)	1990
Haengju	Cable-stayed	1,460 (120)	1995
Seohae	Suspension	7,310 (470)	2000
Youngjong	Suspension	4,420 (300)	2000
Youngheung	Cable-stayed	1,250 (240)	2002
Gwangan	Suspension	8,429 (500)	2002
Samcheonpo	Cable-stayed	436.0 (230)	2003

Bridge, the first three-dimensional self-anchored suspension bridge in the world is representative of the remarkable progresses made in Korea, and interest began to grow about long-span bridges because of their impact on the economy and road network.

Recently, such bridge construction activity has been revitalized by the ambitious plan of the government to link some of the 3,000 islands around the peninsula to the mainland. Ongoing projects intend to link some major islands of the southwestern coast until 2011 to promote economical and social balanced regional development all over the country, and additional investments are also foreseen for the construction of bridges until 2025[2,3)].

Following the construction of these new long-span bridges, interest began to grow about their maintenance because of their importance in the economy and road network. In addition, the disastrous collapse of the Sungsu bridge crossing the Han River in Seoul in 1994, only 15 years after its opening to traffic in 1979, emphasized the significance and necessity of maintenance system for bridges not only to avoid human lossbut also economical costs. This accident combined with the fact that a large number of bridges built before 1970 still remains in operation today led the governmental authorities to issue more stringent requirements on bridge management and operational programs, including systematic visual inspection, instrumentation, load capacity tests and field measurements for design and construction verification, and long-term performance monitoring and assessment[4,7,8)].

This review preludes the future opportunities that will be offered to the bridge community since Korea will soon be the country presenting the most diversified bridge construction activities. The bridges to be built all along the coastal areas of the peninsula will constitute precious case studies to exploit the huge database gathered from structural health monitoring (SHM) systems installed in major bridges and applied them the design process.

1.2 Bridge Health Monitoring in Korea

Installation of SHM systems in Korea began since 1995 in order to collect field data by full-scale load capacity tests for design verification of existing bridges and, subsequently, evaluate the health of the structures using stand-alone field system consisting of sensors, field hardware and online transmission to a computer on field. Thereafter, modern technologies were introduced in SHM systems since the design stage to evolve onto an overall bridge management integrated system for the monitoring of long-term performance and durability of newly-built bridges in the scope of systematic inspection and maintenance

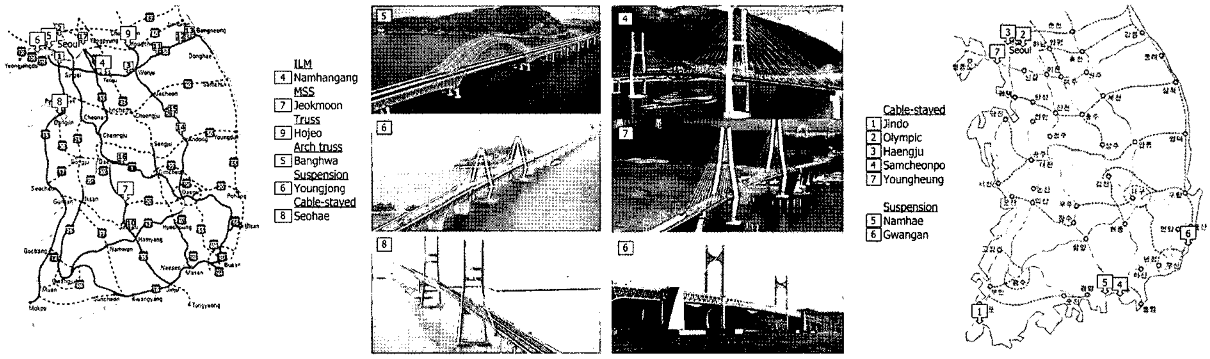


Fig. 2 Major instrumented bridges of the national expressway (left) and national highway (right) networks

programs. More recently, efforts intend to increase and upgrade the monitoring efficiency and performance through sensor-based bridge monitoring systems (SBBMS). Such system will provide advanced innovative functions like sensor fusion using new sensing techniques, reliable massive signal transmission via web-based operating system or wireless signal transmission, automated surveillance, adaptive signal processing, etc. Figure 2 summarizes major and representative bridges equipped with SHM systems in Korea[2),8)].

2. FEATURES OF BRIDGE HEALTH MONITORING

SHM for civil infrastructures targets essentially preventive maintenance (Fig. 3). To that goal, engineers rely on systematic inspection and the sensing system of the instrumented structure. The major objectives can be found in obtaining information to secure safety and serviceability, deciding appropriately and in due time repair and rehabilitation works, extending the service life of the structure with preserving simultaneously its good health, and optimizing the maintenance costs as possible.

Requirements of SHM for bridge structure are thus securing the lifecycle of the structure since issues related to the lifetime and durability aspects of bridge structures are of critical importance. Design of bridge is now targeting a lifetime of at least 100 years. Accordingly, active development and applications of SHM systems for major bridge structures are continuously implemented as a tool to sustain such lifetime perspective in terms of safety, durability and performance.

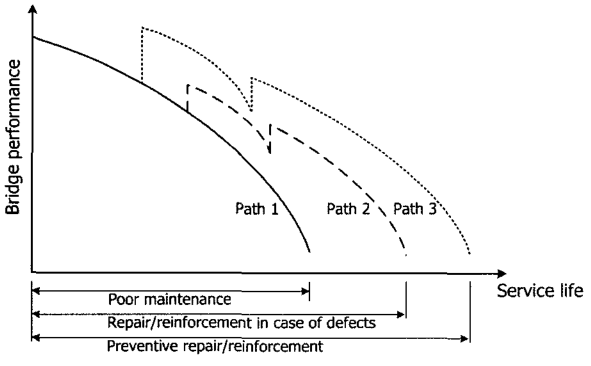


Fig. 3 Concept of preventive maintenance

Automatic measurement of instrumented civil engineering structures is becoming more common for both diagnostic system identification purpose and in-field behavior monitoring during construction. In order to deploy a successful monitoring system, the required considerations are: proper instrumentation, reliable signal processing and knowledgeable information processing. Since instrumentation, which includes sensory device and data acquisition system (DAQs), obtains raw data from the real structure, sensor technology is of critical importance in the development of a monitoring system.

A number of sensor and sensing techniques have been developed in recent years which bear the potential for meeting the eventual need of an automatic monitoring system. These fall into the domain of remote sensing and nondestructive testing. Selection and installation of proper sensors constitute key considerations. Beyond the sensory system itself, some additional facilities need to be located in the field as well as in the control space. These facilities consist of DAQs, temporal data storage device, telecommunication facilities, and other auxiliary devices.

Sensor signal must be processed and interpreted. Immense volume of often noisy signals generated by a multiple-channel sensory should be manipulated concurrently and interpreted intelligently in both hardware and software. The signal processing procedure consists of numerous operations beginning from signal acquisition, generation, to interpretation. In order to assess the current condition of the structure based on signals, called as information processing, it is necessary to devise appropriate computational abstractions and support environments. To develop comprehensive computational environments for these purposes, a model of the information describing the system is required. This model must support a meaningful and computable representation of the components and their complex interrelationships that are characteristic of engineering system, such as physical configurations, sensors, signal processing, and diagnostic knowledge[5)].

3. BRIDGE MONITORING ACTIVITIES IN KOREA

Most of the long-span bridges newly built in Korea is instrumented with modern monitoring systems. Recent systems adopted in new bridges exploit modern technologies from sensing to processing, i.e. many sensors and data acquisition systems that measure the behavior of the bridge during its construction become part of the long-term health monitoring system[2].

3.1 Integrated SHM Systems in New Bridges

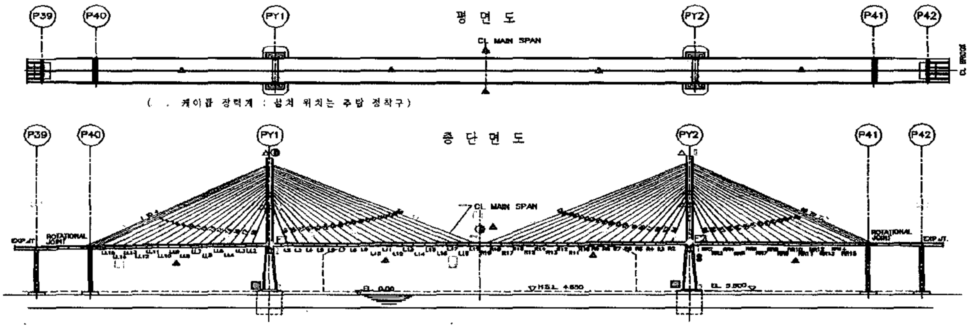
An attempt to integrate health monitoring systems of several bridges together has been achieved to reduce costs and increase significantly the management efficiency. This integrated system includes BMS (Bridge Management System) for systematic decision-making and budgeting of inspection, estimation, rehabilitation and repair. The integrated system for the Seohae, Youngjong and Banghwa bridges may be cited as the best example of the current monitoring system. The data collected at each bridge are processed exclusively at each field station for real-time monitoring and alarming sudden abnormal behavior. Data that are useful for long-term evaluation of bridge condition, as well as periodical inspection data, can be transmitted through high-speed internet line to the management center located far away from the site. Once data are collected at the center, integrated BMS handles them to classify, store and retrieve. This integrated BMS is able to itemize bridge maintenance details and manage status assessment, rating, repair and strengthening history.

3.1.1 Seohae Bridge

Until the completion of Incheon Bridge(80+260+800+260+80m) in 2009, Seohae Bridge(60+200+470+200+60m) will remain the longest cable-stayed bridge in Korea. Its five spans are constituted by stiffened steel girders with precast slab. More than 10 types of sensors for a total of 180 units are actually installed in the major parts of the cable-stayed (Fig. 4), PSM and FCM bridges[2),7)]

The structural behavior of the cable-stayed bridge has been observed and analyzed during 2 years after its completion. Results showed that the annual variation of the vertical deflection in the stiffening girder satisfies the allowable design limit with a range of 320 to 30mm and that deflection due to live load presents a range of 189.7mm, which represents only 25% of 808.8mm, the design limit(Fig. 5). The stress range in the stiffening girder due to live loads showed good correlation with the volume of traffic monitored during 2 years and, since it represents only 5 to 12% of the design stress, stress margin appears to remain considerable. It could thus be said that actual highway bridge design specifications are producing excessively conservative structures.

The thermal deformation of expansion joints at the extremities of the bridge is also shown to correspond accurately with theoretical predictions (Fig. 5). And, tensioning force in the cables ranged within 95 to 104% of the initial value attesting for the stability of the bridge. Seohae Bridge appears thus to be healthy



Mark	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
▮	Laser disp. sensor	4
⋈	Jointmeter	10
◆	Field control box	4
■	Accelerometer for earthquake	2

Fig. 4 Location of sensors and instrumentation in Seohae Bridge

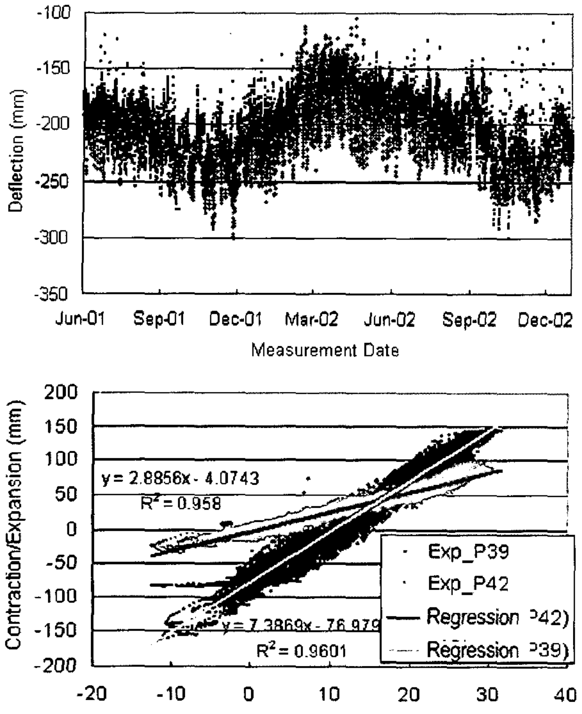


Fig. 5 Annual variation of vertical deflection at the center of the main span and thermal expansion/contraction of expansion joints of Seohae Bridge [5]

in view of its long-term behavior[5)].

3.1.2 Youngjong Bridge

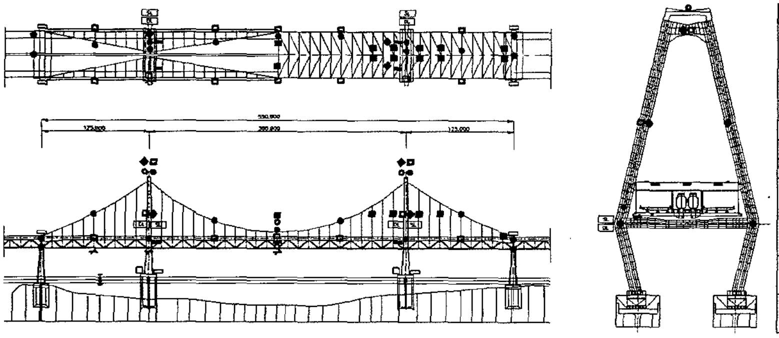
Since Youngjong Bridge(125+300+125m), completed in November, 2000, is the first bridge foreign visitors meet when arriving in Korea, particular attention has been paid on its design with unique features such as three-dimensionally profiled suspension cables, self-anchoring, and double decks for both automobile and train traffic (Fig. 6).

A total of 393 sensors, including static and dynamic strain gauges, and 23 data loggers are distributed over the bridge (Fig. 6). The hardware system was designed to collect data remotely, and the software system was developed to process data and display results in a custom-designed format. The monitoring system has been completed in 2001 and a huge volume of signals has been collected up to date. These signals were carefully analyzed for verifying the system performance and implementing further use for bridge health assessment[5)].

The SHM system has been exploited at first to identify the dynamic properties of the bridge before opening by means of field loading test using two vibrators, which generated flexural and torsional vibrations of the bridge. Comparison of the measured data such as natural frequencies, vibration modes and damping ratios with design values showed good correspondence attesting for the reliability of the bridge[2)].

During the system stabilization period, signals showed regular pattern of fluctuation along with the daily and seasonal temperature changes. Some typical signal patterns are described hereafter[5)].

Accelerometers were mounted on 12 hangers to evaluate tension forces. Frequencies computed from acceleration responses measured under ambient vibration during 15 months were used to evaluate hanger tension forces. Measurements revealed that the average tension force for the whole set of hangers displayed similar varying trend to the fluctuation of the ambient temperature (Fig. 7). The same seasonal pattern according to the variation of temperature could be observed for the vertical and lateral displacements



Mark	Category	Measurand	Sensor	Q'ty	Location
●	Load	Temperature	Thermometer	21	Cable, deck
				12	Tower
○		Wind speed/direction	Anemometer	5	Tower, cable, deck
□		Earthquake	Accelerometer	3	Tower foundation
×	Response	Geometry	Laser disp. sensor	5	Girder
⬠			Potentiometer	4	Expansion joint
◆			Tiltmeter	10	Tower
■□		*Hanger tension*	*Accelerometer*	12	Hanger
=		Strain	Static strain gage	32	Anchor bolt
				42	Deck cross section
				40	Anchor plate
				8	Link shoe
▬			Dyn. Strain gage	76	Deck cross section
				99	Etc.
□		Acceleration	Accelerometer	4	Tower
■				10	Deck

Fig. 6 Location of sensors and instrumentation in Youngjong Bridge

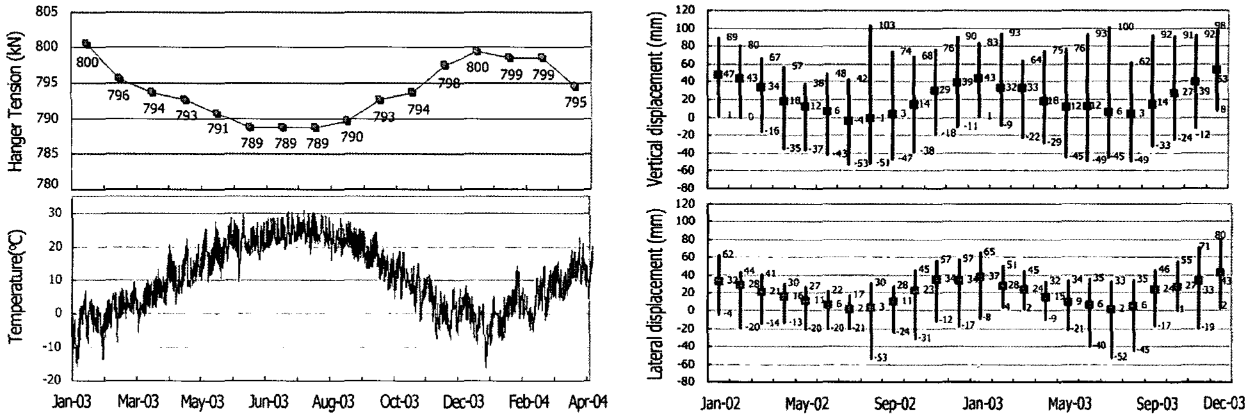


Fig. 7 Averaged hanger tension and ambient temperature observed during 15 months (left) and vertical and lateral displacements at mid-span observed during 2 years (right)

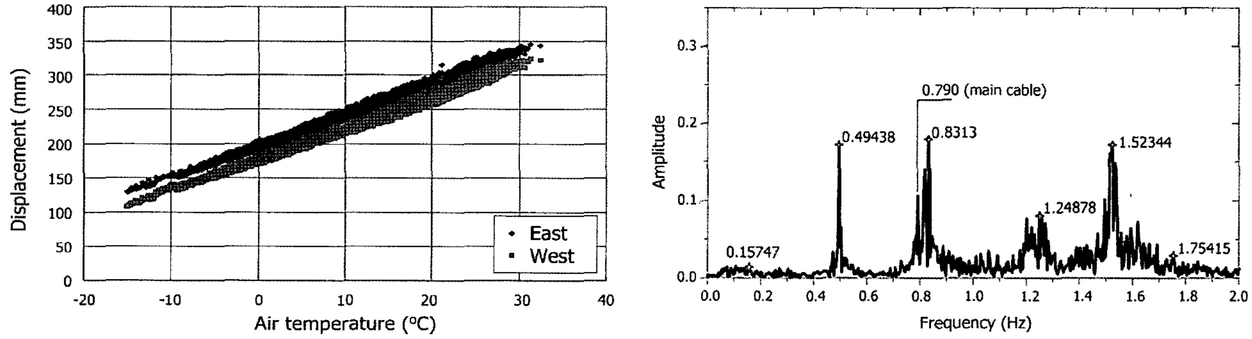


Fig. 8 Joint displacement vs. ambient temperature measured in Youngjong Bridge (left) and FFT spectrum ambient acceleration signals measured in Youngjong Bridge (right)

at mid-span of the stiffening girder measured by means of laser displacement sensor (Fig. 7). Joint displacements at both ends were seen to present quasi-linear relationship with temperature, with a displacement averaging 46mm for a thermal variation of 10℃ in ambient temperature (Fig. 8). Acceleration data measured under ambient vibration were exploited to analyze the dynamic properties of the bridge (Fig. 8), and the frequencies of the first and second modes were measured to be 0.494 and 0.831Hz, which correspond fairly to the results of field vibration tests (0.487 and 0.810Hz).

Long-term responses of Youngjong Bridge were thus verified to be governed by daily and seasonal variations of the temperature, which revealed that the bridge behaves as- expected. Such conclusion led researchers to assess the actual state of the bridge through the analysis of structural responses with respect to temperature. Kim et al.(2004) applied the ARX model, a statistical time series analysis method, to analyze the bridge data. Evaluation of the health of the structure could be done through threshold values expressed by a mean, standard deviation, and appropriate confidence level.

3.2 Application of Sensor Based Bridge Monitoring System

Recently, Sensor-Based Bridge Monitoring System (SBBMS) has been effectively applied on newly built bridges to increase monitoring efficiency and performance by exploiting new sensor technologies$^{2),6)}$. The purposes of SBBMS are providing information (1) to assess the behavior of the bridge, (2) to ensure serviceability and safety during its service life and (3) to help design, construction and maintenance. Application of SBBMS can be found in Gwangan and Samcheonpo bridges.

The hardware system performs measurement and data acquisition of the bridge behavior by remote sensing using sensors and data loggers, and the software system achieves data processing, storage, analysis and display in customized form (Fig. 9).

Gwangan Bridge (Fig. 10) is the longest suspension bridge in Korea. It is an earth-anchored suspension bridge with a double-deck warren truss girder carrying roadways. The pylons are steel towers where the main cables are sustained with the stiffening girder at 105m height.

The monitoring hardware system (Figs. 9 and 10) has been designed to perform real time monitoring of the structural behavior of the bridge. The SHM system was used to produce alarm/warning when typhoon Maemi struck Busan in September, 2003. Measurement of the wind speed at the pylon and mid-span of the bridge (Fig. 11) helped to make decision of blocking and reopening of the bridge to traffic so as to ensure public safety during the typhoon.

4. CONCLUSIONS

Recent applications of SHM systems for newly built bridges in Korea have been addressed. Observations obtained through integrated SHM system and SBBMS were seen to be exploited effectively and diversely, i.e., such as system identification of bridge characteristics for design verification or calibration of analytic model, assessment of long-term behavior and, giving alarm when abnormal behavior or conditions are detected.

Health monitoring systems are essential for the long-term management of civil infrastructures in terms of behavioral study of the structure under real environment and reduction of uncertain assumptions in design process. However, need is for supplemental technologies like system identification and damage

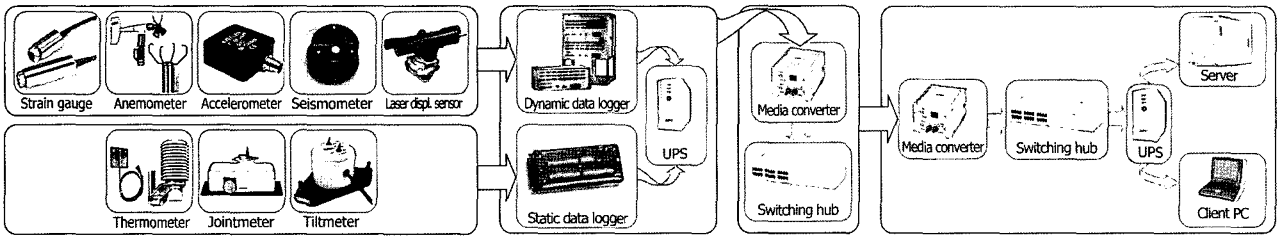


Fig. 9 Organization chart of the monitoring system installed in Gwangan Bridge

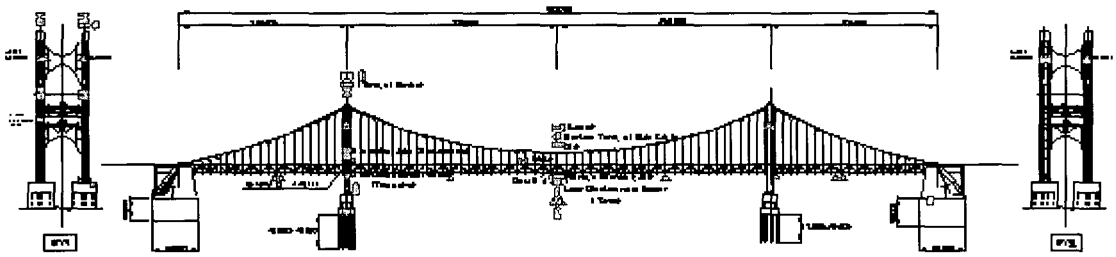


Fig. 10 Location of sensors in Gwangan Bridge

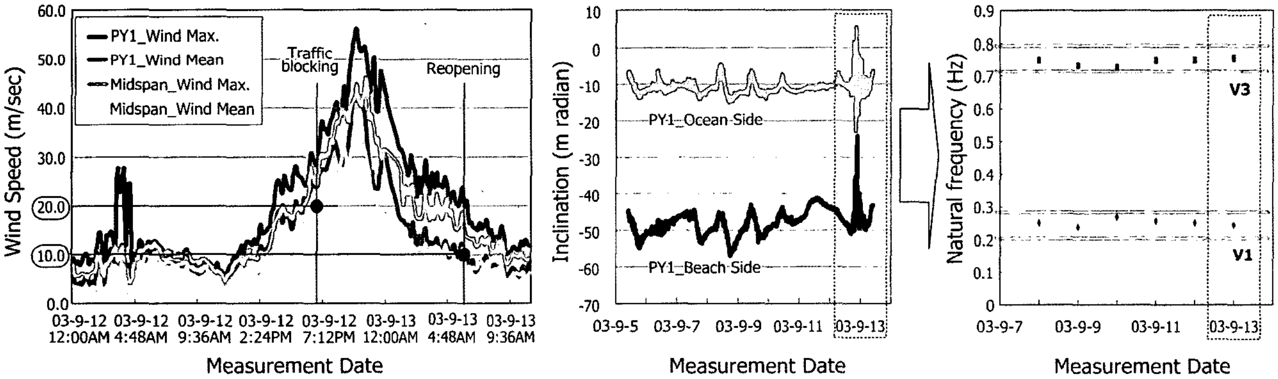


Fig. 11 Wind speeds measured in the pylon and mid-span, and inclination of the pylon with corresponding natural frequencies of Gwangan Bridge during Maemi typhoon

detection techniques, response-control tools and algorithms, construction methods and material-related technologies to generate SHM systems that enable bridge engineers to derive overall evaluation of the bridge state and adequate decision-making. The combination of such technologies with health monitoring will finally create structures exhibiting reliable and extended lifecycle. Therefore, current researches are continuously tending toward the improvement of the hardware of SHM systems like SBBMS, and the implementation and integration of innovative technologies like system identification and damage detection techniques involving artificial intelligence as well as lifecycle cost concepts.

REFERENCES

1. 박기태 (2005). 전국 교량 현황 분석. 대한토목학회지, 2005.05, 제53권 제5호, pp. 129~134
2. Koh, H.M., Kim, S. and Choo, J.F. (2004). Recent development of bridge health monitoring system in Korea. North American Euro Pacific workshop for sensing issues in civil structural health monitoring, Oahu, Hawaii, USA, 10~13 November 2004.
3. Koh, H.M., Choo, J.F., Kim, S. and Kim, C.Y. (2003). Recent application and development of structural health monitoring systems and intelligent structures in Korea. Keynote lecture, 1st international conference on structural health monitoring and intelligent infrastructure, Tokyo, Japan, 12~15 November 2003.
4. Koh, H.M., Choo, J.F., Kim, C.Y. and Park, C.M. 2003a. Progress of research and applications in structural health monitoring of bridges in Korea. Keynote lecture. International workshop on structural health monitoring of bridges-Colloquium on bridge vibration, Kitami Institute of Technology, Japan, 1~2 September 2003.

5 Kim, S., Kim, C.Y. and Lee, J. (2004). Monitoring results of a self-anchored suspension bridge. North American Euro Pacific workshop for sensing issues in civil structural health monitoring, Oahu, Hawaii, USA, 10~13 November 2004.

6. Jang, J.H., Kim, S. and Kim, W.J. 2003. Sensor based bridge monitoring system. Proc. of int. workshop on structural health monitoring of bridges- Colloquium on bridge vibration, Kitami Institute of Technology, Japan, 1~2 September 2003.
7. Koh, H.M., Choo, J.F., Kim, S. and Kil, H.B. (2005). Applications and researches in bridge health monitoring systems and intelligent infrastructures in Korea. Keynote/State-of-the-art lecture. 2nd international conference on structural health monitoring and intelligent infrastructure, Shenzhen, China, 16~18 November 2005.
8. Koh, H.M. and Choo, J.F. (2005). Advanced bridge research and monitoring activities in Korea, Invited lecture, Summer academy SAMCO, Zell am See, Austria, 5~9 September 2005.