Applications and researches in bridge health monitoring systems and intelligent infrastructures in Korea

H.M. Koh & J.F. Choo
Seoul National University, Seoul, Korea
Korea Bridge Design & Engineering Research Center, Seoul, Korea

S. Kim
Seoul National University of Technology, Seoul, Korea

H.B. Kil
Korea Highway Corporation

ABSTRACT: Since the last three decades, Korea exerted utmost efforts to expand and strengthen its national infrastructure with focus on the transportation network, and is now undertaking unprecedented bridge construction activities with a total of about 40 long-span bridge projects to link some of its 3,000 islands to the mainland. Since 1990s, issues related to the safety and durability of civil infrastructures resulted in a consensus to adopt approaches for the sustainability of bridges with active development and applications of health monitoring systems for major bridges in the scope of systematic and scientific inspection and management programs. Especially, national R&D programs have been launched recently to promote and prepare for the next generation of civil engineering structures like the Korea Bridge Design & Engineering Research Center (KBRC) and other government-supported research programs. This paper addresses recent development of bridge health monitoring systems in Korea in newly-built bridges with their objectives and characteristics. Innovation of civil engineering using smart structure technology is also reviewed.

1 INTRODUCTION

Development and economic growth were the foremost concerns of the Korean government in the past, where civil engineering projects stood as the backbone of the national land development. In the domain of transportation, and especially bridge construction, remarkable achievements have been realized during the last 3 decades with the bridge stock multiplied by about 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 (Ministry of Construction and Transportation, 2005).

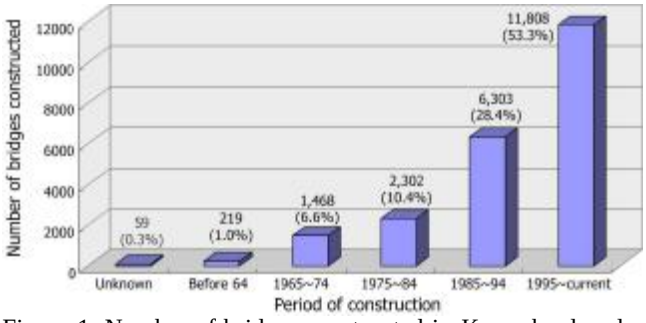

Figure 1. Number of bridges constructed in Korea by decades (MOCT, 2005)

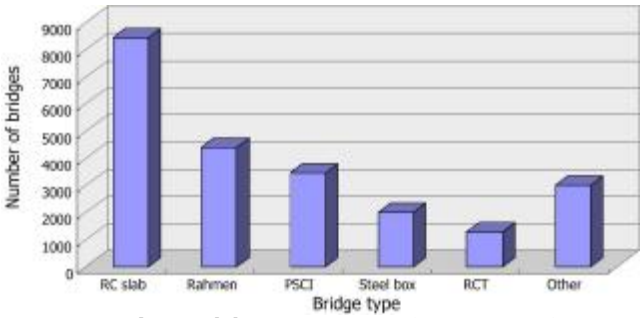

Figure 2. Bridge stock by type in Korea (MOCT, 2005)

An overview of the representative types of the bridge stock is illustrated in Fig. 2. It can be seen that about 57.7% of the bridge stock is composed by RC slab and rahmen bridges. In concern with cable-supported bridges, the current stock is constituted by a total of 10 bridges as summarized in Table 1.

Table 1. Current stock of cable-supported bridges in Korea (MOCT, 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

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 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 with an investment of approximately $4billion until 2011 to promote economical and social balanced regional development all over the country, and additional investments of about $20billion are also foreseen for the construction of bridges until 2025. Fig. 3 depicts the project for the extension of the national road network, and a drawing of Incheon Bridge, the longest cable-stayed bridge in Korea of which construction started in June 2005 to connect Incheon International Airport to the new town of Songdo in the western part of Incheon.

Figure 3. Extension of the national roads in the Korean peninsula and drawing of Incheon Bridge

This unprecedented bridge construction activity will result in the realization of about 40 major bridges with diversified features in the western and southern coasts of which Table 2 lists the long-span bridges currently under construction.

Table 2. Bridges under construction in the western and southern coasts of Korea

Designation	Extension (m)	Type (main span, m)
2nd Jindo	484	Cable-stayed (344)
Geogeum	1,116	Cable-stayed (480)
Wando	500	Cable-stayed (200)
Woonnam	925	Extradosed (155)
Jeokgeum	1,340	Suspension (850)
Dolsan	1,345	Cable-stayed (500)
Goha	3,600	Cable-stayed (500)
Woonam	910	Extradosed (130)
Mooyoung	860	Extradosed (165)
Incheon	12,343	Cable-stayed (800)

This review preludes the future opportunities that will be offered to the international 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 it in the design process.

Especially, issues related to lifetime and durability aspects of bridge structures being of critical importance, active development and applications of SHM are continuously implemented as a tool to sustain such lifetime perspective in terms of safety, durability and performance. Modern and integrated monitoring systems are actually introduced in newly-built bridges since the design stage. Efforts tending towards the increase and upgrade of the monitoring efficiency and performance are also restlessly undertaken through national research programs, various R&D programs and organizations in order to provide advance innovative functions, as will be seen in the followings.

2 BRIDGE MANAGEMENT SYSTEM IN KOREA

2.1 *Road system in Korea*

The 100,456km of the Korean road system is classified into 5 networks according to the managing authorities: the national expressway network, the national highway network, the metro-city road network, the provincial road network and the city-county road network. Among these networks, the national expressway and highway networks constitute the major road transportation axes in the peninsula representing nearly 50% of the whole Korean bridge stock (Fig. 4).

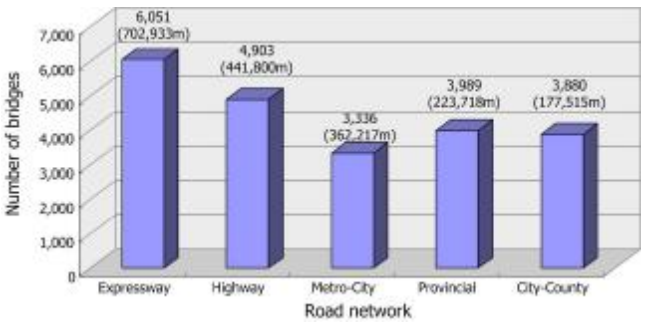

Figure 4. Distribution of bridges by road network in Korea (MOCT, 2005)

The national expressway network is managed by the Korea Highway Corporation (KHC), which is responsible for the construction, operation, maintenance and repair of the expressway network. The network is constituted by 23 expressways developing a length of 2,778km of which 702km are composed by a total of 6,051 bridges.

Regional construction management offices are managing the 14,524km of the national highway

network including 4,903 bridges for a length of 441km. The remaining networks totalize a length of 83,154km comprising 11,205 bridges developing a length of about 763km.

2.2 *The Korean Bridge Management System: KOBMS*

It has been seen that bridge structures occupy a large proportion of the transportation network and that this portion will increase significantly with the bridge construction activities taking place in the coastal areas of the peninsula. Since bridges constitute the very vulnerable part of civil infrastructures affecting directly public transportation and safety, attention has been focused on the development of a total bridge management system (BMS) since early of 1990s (Koh *et al.*, 2004).

Total bridge management system (BMS) attempts to include inspection, evaluation, estimation and rehabilitation of bridges in a systematized organization, which integrates structural health monitoring (SHM) systems installed in bridges (Koh *et al.*, 2003a, b). BMS is an information-oriented system, which aims the global supervision of all the information gathered in every bridge so as to help the supervisor deciding current and future requirements for optimal management and rehabilitation of bridges. Following, to perform scientific and rational management and rehabilitation of bridges, the Korean Ministry of Construction and Transportation (MOCT) together with the Korea Institute of Construction Technology (KICT) developed since 1995 the Korean BMS (KOBMS), which is operating for ordinary road bridges.

The hardware of KOBMS is constituted by regional networks and, high-performance and high-capacity computers to manage efficiently the huge volume of data gathered in bridges. Such network operates interactively by linking the KICT, road facilities of the MOCT, 5 regional offices, 1 R&D office and 18 road management offices since 1996 (Fig. 5).

The software of the KOBMS is composed by a database (DB) recording archives related to bridges, a program computing the investment priorities, a rehabilitation and retrofit techniques DB, a tunnel DB, a program outputting the current state of bridges, a decision-making system performing the essential functions of the BMS (Fig. 5). Especially, the BMS DB stores and compiles about 230 items per bridges including their characteristics, structures, inspection records, load carrying capacity, etc. Investment priorities, as a basic function of the BMS, stand for the process by which one decides the sequence of bridges to be considered for management and rehabilitation in the budget planning. The KOBMS DB arranges 64 basic rehabilitation and retrofit techniques for bridge and defines 120 types of damage that may occur in bridge, so as to select automatically an appropriate rehabilitation and retrofit basic technique for each type of damage. Using the KOBMS DB, a report on the current state of the bridges is published annually and, provides statistics of the basic parameters of the bridges and their current state according to their classification.

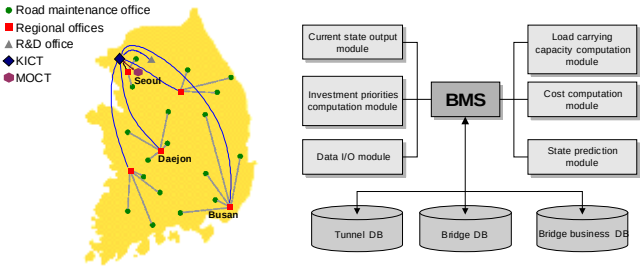

Figure 5. Hardware and software of the KOBMS

The KOBMS made it possible to manage efficiently the huge volume of bridge data in a systematic and effective organization. Moreover, it made it possible to systematize the state evaluation and records management of rehabilitation and retrofit for each bridge as well as for the whole bridge stock. The state of bridges has seen significant improvement while large reduction of the budget invested for their management, being rationally shared, has been obtained.

3 BRIDGE HEALTH MONITORING SYSTEMS IN KOREA

Installation of SHM systems for bridges in Korea began since 1995, immediately after the collapse of Sungsu Bridge in 1994, 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 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. (Koh *et al.*, 2004). Figs. 6 and 7 and Table 3 summarize major and representative bridges equipped with SHM systems in Korea.

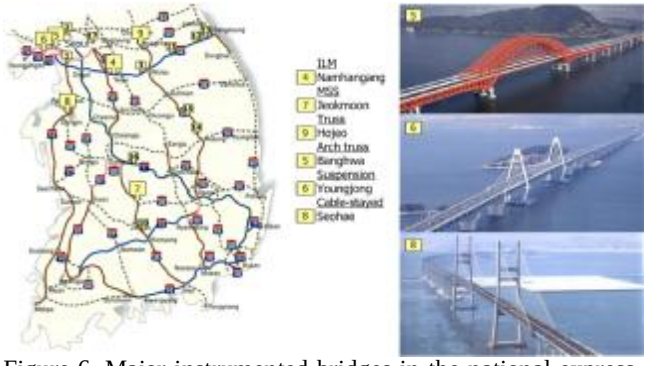

Figure 6. Major instrumented bridges in the national expressway network

Figure 7. Major instrumented bridges in the national highway network

Table 3. List of recent and major instrumented bridges in Korea

Designation	Type	Completion	No. of sensors *	Managing authority
Jeokmoon	MSS	2000.12	112 (102+10)	KHC
Hojeo	Truss	2001.08	76 (69+7)	KHC
Banghwa	Steel arch	2000.11	137 (115+22)	KHC
Youngjong	Suspension	2000.11	380 (209+171)	KHC
Seohae	Cable-stayed	2000.12	183 (44+139)	KHC
Samcheonpo	Cable-stayed	2003.04	66 (15+51)	KHMC**
Gwangan	Suspension	2000.04	51 (21+30)	Busan city

* Total No. of sensors (No. of static sensors+No. of dynamic sensors)
** Korea Highway Management Corporation

3.1 *Application of integrated SHM systems in new bridges*

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 (Koh *et al.*, 2004).

An attempt to integrate health monitoring systems of several bridges together has been achieved to reduce costs and increase significantly the management efficiency (Chang *et al.*, 1996). This integrated system includes BMS as well for inspection, estimation and rehabilitation. 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 in terms of 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 (Fig. 3), Seohae Bridge (60+200+470+200+60m) will remain the longest cable-stayed bridge in Korea, which links Pyoengtaek and Dangjin by crossing the Asan bay (point 8 in Fig. 6). 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. 8), PSM and FCM bridges (Koh *et al.*, 2004).

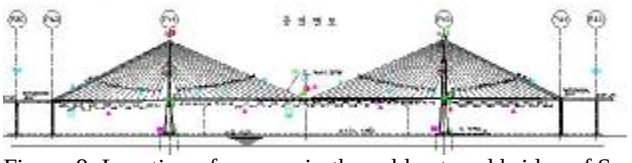
Figure 8. Location of sensors in the cable-stayed bridge of Seohae Bridge

The structural behavior of the cable-stayed bridge has been observed 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 variation range of 189.7mm, which represents only 25% of 808.8mm, the design limit (Fig. 9). 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.

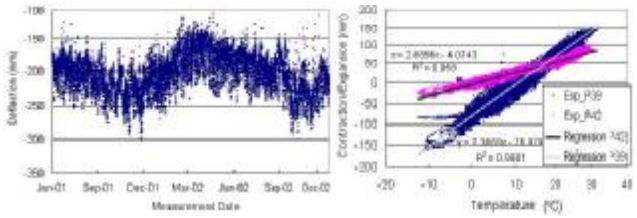
Figure 9. Annual variation of vertical deflection at the center of the main span and thermal expansion/contraction of expansion joints of Seohae Bridge (Park *et al.*, 2003)

The thermal deformation of expansion joints at the extremities of the bridge is also shown to correspond accurately with theoretical predictions (Fig. 9). 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 in view of its long-term behavior (Park *et al.*, 2003).

3.1.2 *Youngjong Bridge*

Youngjong Bridge (125+300+125m), completed in November, 2000, is part of the Incheon International Airport Highway which connects Seoul and Incheon International Airport (point 6 in Fig. 6). Being 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. 10).

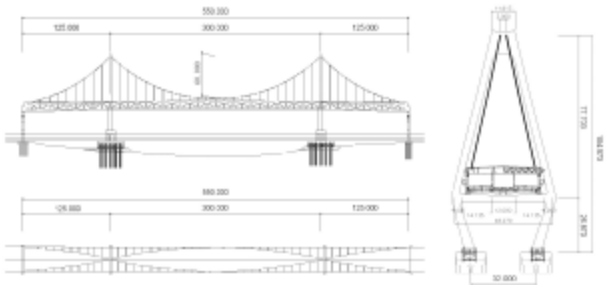

Figure 10. Layout of the suspension bridge of Youngjong Bridge

A total of 393 sensors, including static and dynamic strain gauges, and 23 data loggers are distributed over the bridge. 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 (Kim *et al.*, 2004).

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 (Fig. 11). Comparison of the measured data such as natural frequencies, vibration modes and damping ratios with design values in Table 4 showed good correspondence attesting for the reliability of the bridge (Koh *et al.*, 2002, 2004).

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 (Kim *et al.*, 2004).

Table 4. Dynamic characteristics of Youngjong Bridge identified by forced vibration test

Dynamic characteris-	Natural frequency		Damping ratio	
	Design	Measured	Design	Measured
Flexure	0.422	0.487	0.03	0.06
Antisymmetric flexure	0.716	0.810	0.03	0.03
Torsion	0.781	1.060	0.02	0.023
Antisymmetric torsion	1.195	1.700	0.02	0.05

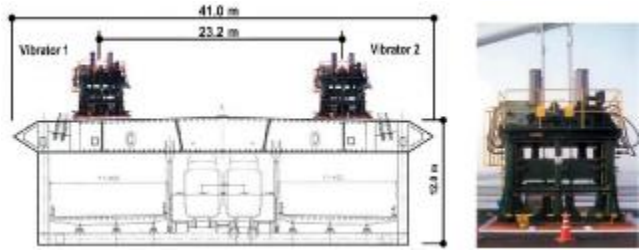

Figure 11. View of the vibrators installed on Youngjong bridge for field loading test

Accelerometers were mounted on 12 hangers to evaluate tension forces. Frequencies computed from responses measured under ambient vibration by these accelerometers during 15 months were used to obtain tension forces. Measurements revealed that the average tension force for the whole set of hangers displayed tendency similar to the fluctuation of the ambient temperature (Fig. 12).

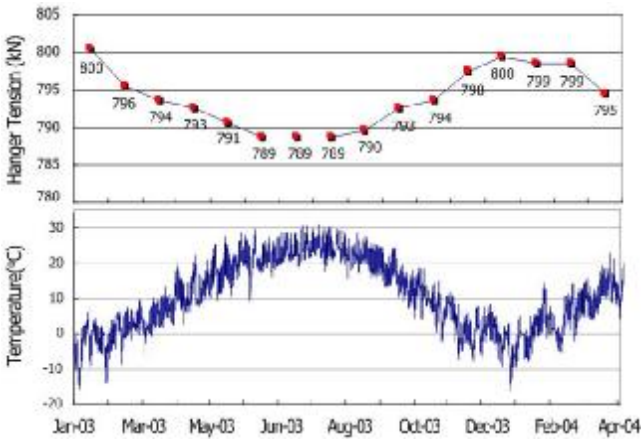

Figure 12. Averaged hanger tension and ambient temperature observed during 15 months

The same seasonal pattern could be observed for the vertical and lateral displacements at mid-span of the stiffening girder measured by means of laser displacement sensor. 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°C in ambient temperature.

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 (Koh *et al.*, 2004; Jang *et al.*, 2003). 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. 13).

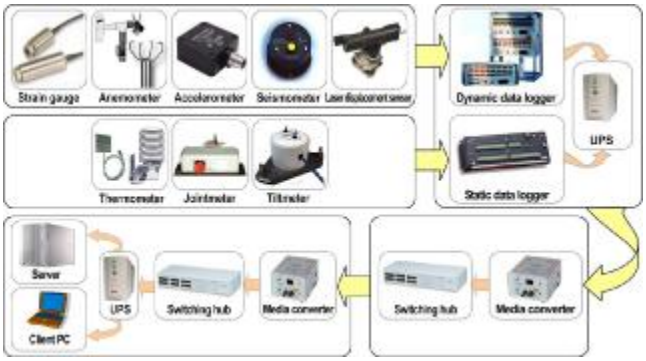

Figure 13. Organization chart of the monitoring system installed in Gwangan Bridge

3.2.1 *Gwangan Bridge*

Gwangan Bridge, located in front of Gwanganri beach in the city of Busan (point 6 in Fig. 7), 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. 13 and 14) has been designed to perform real time monitoring of the structural behavior of the bridge.

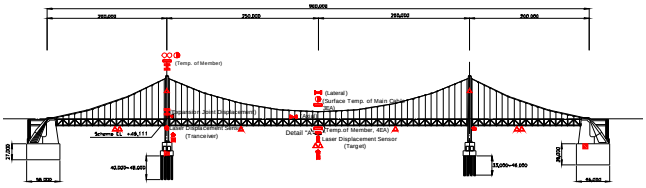

Figure 14. Location of sensors in Gwangan Bridge

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. 15) helped to make decision of blocking and reopening of the bridge to traffic so as to ensure public safety during the typhoon.

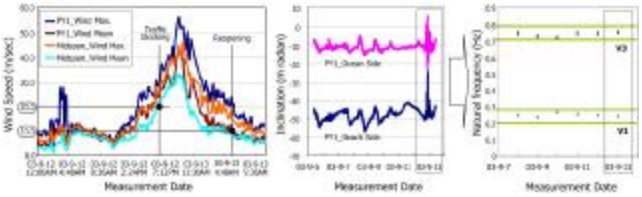

Figure 15. Wind speeds measured in the pylon and mid-span, and inclination of the pylon with corresponding natural frequencies of Gwangan Bridge during Maemi typhoon

3.2.2 *Samcheonpo Bridge*

Samcheonpo Bridge is a three-span cable-stayed bridge with composite girder, located in the Hallyeo maritime national park and connecting Sacheon city to Changsung Island (point 4 in Fig. 7). The health monitoring hardware system for the management of Samcheonpo Bridge (Fig. 16) is similar to Gwangan Bridge.

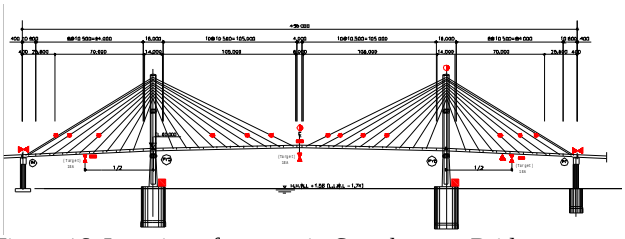

Figure 16. Location of sensors in Samcheonpo Bridge

A forced vibration test was performed on the cable-stayed bridge for system identification purpose just after its completion and before opening. The objective was to determine the initial values of the dynamic properties of the bridge for comparison with design values and calibration of the analytic model.

The excitation force was induced by the sudden braking of a fully loaded truck of 29.7ton and acceleration responses were measured at 14 points. According to the number of measuring points and loading characteristics, vibration modes up to the 7th mode could be distinguished. Experimental results were shown to correspond accurately with design values and calibration of the analytic model made it possible to reduce RMS error of the predicted responses to 2.61% (Yoon *et al.*, 2003).

4 INTELLIGENT INFRASTRUCTURES THROUGH NATIONAL R&D PROGRAMS

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 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 in Korea 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.

In order to sustain the ongoing construction activities of infrastructure systems and the promising technological achievements realized to date, the Korean R&D community agreed with the necessity to develop and construct a new generation of high performance facilities by means of enhanced materials, advanced structural systems and technologies as well as improved specifications or standards in a lifetime perspective. These researches are led by a large variety of R&D programs of which national research programs like KBRC, the Korea Panel on Structural Control and Monitoring, and other related organizations and authorities.

4.1 *Korea Bridge Design & Engineering Research Center (KBRC)*

KBRC (www.kbrc.re.kr) was established at Seoul National University through a national research program launched in 2003 by the MOCT according to the long-term TRM for the advancement of bridge technology. The Center especially addresses the advancement of bridge technology and will be the core of new research and technology transfer program in the area of bridge technology.

KBRC in partnership with industry, academia and research institutes aims to develop and implement more durable and safer bridge structures. The products of the program will be intelligent bridges of the next generation that last longer in a lifetime perspective and have lower maintenance demands or maintenance free bridges in harmony with innovative and advanced technologies, and ecological requirements. Another outcome of the program will be the establishment of reliability-based code and standards in accordance with the international codes. The ambition of the KBRC is to bring Korea into the top-ranking of the bridge-builder nations in the near future through such advanced analysis and design technologies.

4.1.1 *Objectives of KBRC*

The rapid evolution of computational structural analysis together with the rise of IT technology and material engineering-related technologies make it possible to perform more complex computation for bridge structures. In addition, high performance and high strength materials also begin to take larger place in the construction of bridges. The combination of such various technologies allowed the construction of longer span bridges since the late of the last century with records of lengths approaching 2,000 meters. And, one can predict that this tendency will continue continuously in the years to come to create a new generation of bridges that will break records of length, performance and longevity.

The next generation of bridge will present extended lifetime with resilient and long-term performance, provide optimized structural efficiency and cost-effectiveness all along its life-cycle, and combine high-performance materials with innovative construction and design methods. Therefore, performance objectives and priorities to be met are: reliability-based design together with aesthetic design considering ecological constraints; shortened construction time; extended lifetime with reduced life-cycle cost (LCC), at the most, maintenance free management; immunity against natural or accidental hazards; functional adaptability; and nature-friendly materials recyclable after decommissioning (Fig. 17).

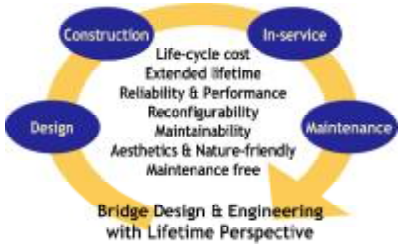

Figure 17. Features of the next generation of bridge technology with a lifetime perspective

In order to prepare for the next generation of bridge technology, the Center has set five strategic objectives, which are (1) establishment of advanced three-dimensional analysis methods and design technology, (2) development of reliability-based bridge design codes and specifications, (3) development of sustainable bridge design technology based on a lifetime perspective, (4) innovation of bridge design technology integrating leading technologies such as IT and (5) promotion of international exchange and collaboration program.

4.1.2 *Major research topics of KBRC*

As an essential part of our daily environment, modern bridge structures must be smart and flexible enough to cope with tests to its durability, reliability, adaptability and functionality as well as being aesthetically pleasing. As a bridge project is undertaken, planning and designing requirements on lifetime longevity require a perspective involving multidisciplinary technologies and techniques. The needs for a universal set of design specifications and engineering technologies are thus critical in establishing a unified transportation system.

An important place is devoted to response-control technology to enhance the immunity of long-span cable-supported bridges against natural or accidental hazards (Fig. 18). This theme attaches special importance on developing control measures and devices adapted to low and moderate seismicity like it is the case in Korea. This research has already seen successful implementation through the revision of the seismic design specifications of the current Highway Bridge Design Specifications.

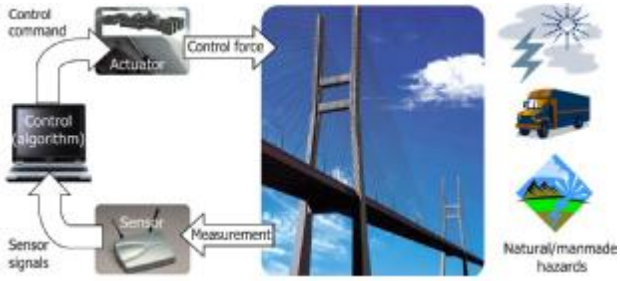

Figure 18. Sensor-based response-control for the immunity of infrastructures against natural or manmade hazards

Material failure also constitutes a major concern of the Center since bridge by their location and functions are facing large varieties of damaging environments like the corrosion of concrete due to salt attack. For example, a large number of bridges constructed in marine environment exhibits severe problems of corrosion in the splash zone. This is the case of Sunshine Skyway Bridge in Florida, of which post-tensioning cables of the piers have reached an extreme degree of deterioration affecting its safety. In order to prepare for such drawback, a special theme has thus been implemented in collaboration with industry to develop a new type of corrosion sensors embedded in concrete.

SHM occupies also an important place in order to provide design database in a lifetime perspective. As has been seen through the applications of SHM in Korea, the analysis of the database provides useful information about the validity of applied empirical and theoretical models as well as predicted values used during the design process. Therefore, this topic intends to reflect the analysis results of measurement database in the design and specifications of bridge structures focusing on the extension of the lifetime with reduced LCC and maintenance. Attention is also paid on establishing guidelines for the constitution of SHM system in compliance with the actual design.

Fig. 19 summarizes schematically the approach adopted by the Center to achieve intelligent infrastructures with a lifetime perspective.

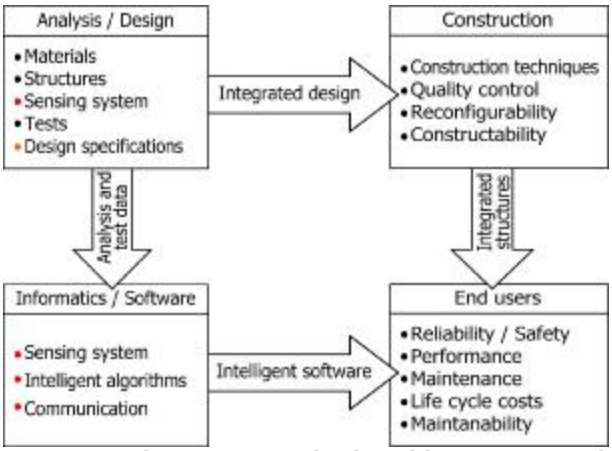

Figure 19. Schematic approach adopted by KBRC toward intelligent and smart structures with a lifetime perspective

4.2 *Other related national R&D programs*

4.2.1 *Smart Infra-Structure Technology Center (SISTeC)*

SISTeC was established at the Korea Advanced Institute of Science and Technology in 2002 as an engineering research center sponsored by the Korea Science and Engineering Foundation (KOSEF).

The primary goal of the center is to develop smart structure technologies relevant to the assurance of operational and structural safety and the improvement of lifecycle cost effectiveness for large civil infrastructures. The purpose of the establishment of SISTeC is the development of smart sensors, materials, monitoring, assessment, retrofit and control technologies for efficient analysis, design, construction and maintenance of large infrastructures. The researches led by SISTeC can be classified into 4 areas: smart materials and sensors; analysis and design of smart structures; smart monitoring, control and maintenance; and smart geo-technologies (Yun *et al.*, 2005).

4.2.2 *Infra-Structure Assessment Research Center (ISARC)*

Steel and concrete materials constitute the major construction materials for civil infrastructure construction. Mass construction is now looking for maintenance and management of pre-built large civil infrastructures. Non-destructive testing (NDT) methods, advanced techniques of sensor technology for health monitoring and smart construction materials are core interests of recent studies in worldwide.

Among those recent studies, the development of assessment techniques for existing structures and their supplements are the key elements to resolve

maintenance and management issues. Therefore, ISARC (www.assess.or.kr) has been launched as national research program in 2003 by the MOCT in order to meet public interests and demands for safety and transparent evaluations for structures.

Its objectives are the establishment of performance-based evaluation system as well as evaluation criteria, the development of NDT techniques and the systematic prediction for lifecycle.

4.2.3 *The Korea Panel on Structural Control and Monitoring*

The Korea Panel on Structural Control and Monitoring was established in December 1998 to further the activities and collaborate with international organizations. The Panel consists of more than 100 members of active researchers and practitioners in universities, research institutes, industries and governmental organizations. All the members are active researchers in the field of structural engineering, earthquake engineering and wind engineering. The objective of the Panel is to advance the science and practice of structural control and monitoring in Korea by holding regular workshops and seminars, exchanging information among members, and extending technical cooperation among academia, research and industry sectors.

5 TEST-ROAD OF THE KOREA HIGHWAY CORPORATION

Pavements in Korea are currently designed according to road pavement design specifications developed by USA and Japan, which produce pavement design that cannot reflect the unique domestic characteristics. To remedy the absence of appropriate pavement design, the KHC undertook, since 1997, researches on test-road for long-term development of pavement design specifications and improvement of pavement-related technologies, which resulted in the completion of a test-road in December, 2002 and its opening to traffic in March, 2004 (Jang *et al.*, 2004).

The KHC test-road, the first operational test-road in Korea as well as in Asia, will make it possible to design optimal pavement thickness and to select efficient pavement and maintenance materials by means of long-term monitoring data. The final objective is to extend the lifetime of pavement constructed in Korea and optimize the budget invested for its construction and maintenance.

5.1 *Layout of the test-road*

The test-road (Fig. 21) is constituted by two lanes of 7.7 km beginning at a distance of about 1 km from Yeoju IC in the southern direction far away and running in parallel to Jungbu Inland Expressway.

The 7.7 km of the test-road are divided into two groups according to the type of pavement: asphalt and concrete. The concrete pavement group itself is composed by two types of pavement presenting a total of 25 sections, Jointed Plain Concrete Pavement (JPCP) and Continuously Reinforced Concrete Pavement (CRCP) according to concrete slab thickness, sub-base thickness, sub-base material type and steel reinforcement. The asphalt pavement is constituted by 15 asphalt concrete pavement sections with three design variables that are the base course thickness, the base course material, and the sub-base thickness.

Three test bridges are also included in the test-road: a steel plate girder bridge with precast deck, a steel box girder bridge and a prestressed concrete girder bridge, in order to examine long-term performance of the bridge under traffic load.

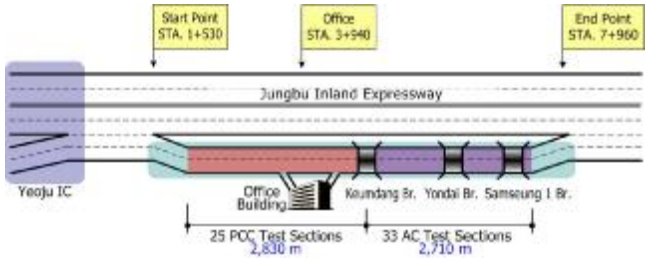

Figure 21. Overall view and composition of the test-road

5.2 *Measurement sensors and monitoring system of the test-road*

In order to monitor load-associated pavement responses and environment-associated long-term pavement performance, a total of 1,261 sensors of 11 types were installed in the concrete test pavement sections (Fig. 22), and 636 sensors of 6 types in the asphalt pavement sections (Fig. 23). These sensors are strain gauges, soil pressure gauges, thermocouples, crack measurement gauges and water content gauges. In addition, Weigh-In-Motion (WIM) and Automatic Weather Station (AWS) are available and they provide the traffic and environmental data.

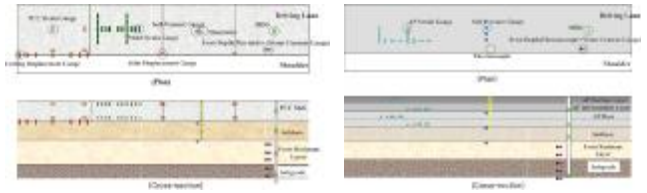
Figure 22. Location of the sensors installed in the concrete pavement (left) and asphalt pavement (right) sections of the test-road

Both automatic and manual monitoring systems have been considered for field data acquisition system installed in the KHC test-road in order to improve its efficiency and continuity.

Two types of automatic systems have been implemented. The first system exploits thermometer

and water content gauges to measure the evolution of temperature and water content in the pavement layers according to weather changes (Fig. 23). The second system is composed of WIM system and automatic weather observation station.

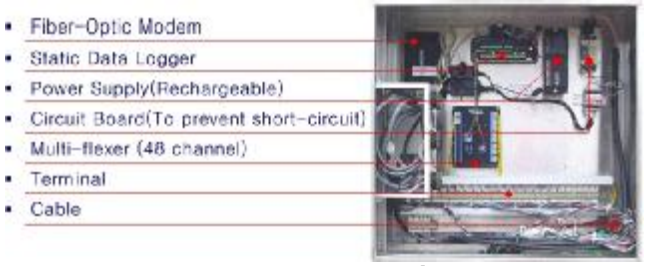

Figure 23. Automatic monitoring circuit box

The manual monitoring system consists of a data gathering vehicle, loading control system to apply particular loading, 58 manual monitoring circuit boxes connecting the gauges to the data gathering device, static data logger, and driving information monitoring system to measure the driving (dynamic) information of testing vehicles.

Several tests have been performed on the test road using the manual measuring system. For example, static loading and dynamic moving load tests using vehicle load have been conducted to analyze the behavior of the pavement regard to temperature, strain and soil pressure.

6 CONCLUSIONS

Recent development and applications of SHM for newly built bridges in Korea have been addressed. Observations obtained through integrated SHM system as well as 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 is detected.

Current researches focus on developing systematic decision algorithm for repair and strengthening, and improving SHM hardware performance so as to lengthen service life of bridges and ensure serviceability and safety.

Researches on intelligent infrastructures in Korea are actively performed through national research programs in numerous directions related to damage and damping assessment using SI scheme, monitoring system for pre/post-earthquake structural assessment, innovative technology for the response control and integrated optimal design of structures, and development of remote control system via internet for the monitoring and control of structures.

Some of up-to-date research topics of national research organizations have been reviewed as well as the test-road of KHC. It can be ascertain that, in a near future, research results will see applications on field in view of the unprecedented construction activities that are taking place in Korea.

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REFERENCES

Chang, S.P. and Kim, S. 1996, Online structural monitoring of a cable-stayed bridge, *Smart structures and materials: Smart systems for bridges, structures and highways, SPIE, 2719: 150–158.*

Jang, J.H., Jeong, J.H., Kwon, S.M. and Park, H.G. 2004. Long-term monitoring operation of the test-road in Korea Highway Corporation (KHC). *North American Euro Pacific workshop for sensing issues in civil structural health monitoring, Oahu, Hawaii, USA, 10-13 November 2004*.

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.*

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.*

Koh, H.M., Chang, S.P., Kim, S.K., Kim, C.Y. and Kim, W.J. 2002. Development and application of health monitoring system for bridges in Korea, *Proc. of 1st int. conf. on bridge maintenance, safety and management, Barcelona, 14-17 July 2002.*

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. *Proc. of int. workshop on structural health monitoring of bridges- Colloquium on bridge vibration, Kitami Institute of Technology, Japan, 1-2 September 2003.*

Koh, H.M., Choo, J.F., Kim, S. and Kim, C.Y. 2003b. Recent application and development of structural health monitoring systems and intelligent structures in Korea. *Proc. of 1st int. conf. on structural health monitoring and intelligent infrastructure, Tokyo, Japan, 12-15 November 2003.*

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.*

Korean Ministry of Construction and Transportation (MOCT). 2005. Bridge status protocol.

Park, C.M. and Park, J.C. 2003. Evaluation of structural behavior using full scale measurements on the Seohae cable-stayed bridge. *Proc. of annual conf. of the Korean Society of Civil Engineers (KSCE), Korea, 2003*: 571-576.

Yoon, J.G., Lee, J. and Kim J.I. 2003. FVT signal processing for structural identification of cable-stayed bridge. *Proc. of 2003 fall workshop of the Korean Society for Noise and Vibration Engineering (KNSVE).*

Yun, C.B. and Spencer B.F. 2005. Smart structure technologies for maintenance of infrastructure. *Proc. of 4th int.*

conf. on safety of infrastructure (ISSI), Gyeongju, Korea, 22 July, 2005.