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Advance Sensor Technologies on Korean Bridges: Field Benchmark Opportunities

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ABSTRACT: The United States and Korea have vast national bridge inventories that require vigilant inspection and repair. With a new generation of sensing technologies and computational tools emerging from interdisciplinary research between civil engineering and other engineering disciplines, bridge management strategies are rapidly improving. Foremost among the new sensors are wireless sensors, EM stress sensors, vision-based displacement sensors and piezoelectric active sensors. For example, wireless sensors eradicate the need for extensive wiring between sensors rendering systems cheaper. EM sensors are powerful tools for measuring stress in bridge cables. Furthermore, active sensors based on piezoelectric materials (e.g. PZT and piezoelectric paint) introduce and record elastic stress waves in local areas of metallic and concrete structures. This paper describes a new US-Korean joint collaboration exploring the installation of these sensors on testbed bridges in Korea. The heterogeneous set of sensors fused into a single comprehensive structural monitoring system effectively capture global and local behavior leading to improvement in structural health assessment.

1 INTRODUCTION

The United States and Korea are both highly developed nations with extensive transportation networks upon which the movement of national and international commerce depends. Because of their societal importance, a paramount concern of the structural engineering community is the long-term durability and operational safety of critical transportation structures such as highway bridges. In the United States, the upkeep and maintenance of bridges is a major challenge due to the size and diversity of national bridge inventories. There exist well over 583,000 highway bridges in the United States that must be inspected every two years (FHWA 2003). Similarly, Korea is also faced with similar challenges as it manages a large inventory of bridges that today exceeds 22,000 bridges. Korea has experienced impressive economic growth over the past decade allowing it to undertake an ambitious transportation infrastructure improvement plan. For example, more than half of the country's 22,000 highway bridges have been constructed within the past 10 years (Koh et al. 2005). Furthermore, the nation has plans to continue adding to its bridge inventory with new long-span cable-stay bridges planned to connect many of the small islands off the Korean coast; already, the government has pledged over $20 billion of investment for construction of these bridges through 2025.

Over the last 50 years, a number of catastrophic bridge failures have occurred in the both the United States and Korea. For example, in the US the Point Pleasant Bridge, Ohio collapsed in 1967 killing 46 motorists. This collapse led to the initiation of the 1971 National Bridge Inspection Program (NBIP) which mandates bi-annual inspection of every highway bridge in the United States (Rolander et al. 2001). Even though bridges are inspected to ensure they meet safety standards, bridge collapses still occur. During the period of 1989-2000, over 134 bridges in the United States partially or totally collapsed (Wardhana and Hadipriono 2003). In addition to collapse, approximately 13% of the national bridge inventory has been classified by the NBIP guidelines as structurally deficient (FHWA 2003). In Korea, bridge failures also occasionally occurred. In 1992, the 1020 m span of the cable-stay New Haengju Bridge partially collapsed resulting in $18 million worth of structural damage (Kunishima 2007). Two years later, the steel truss Seongsu Bridge collapsed into the Han River killing 32 people. Since that time, the Korean government has issued stringent inspection guidelines that include routine visual inspection and the installation of permanent monitoring systems (Yun et al. 2003).

Even though both nations have put in place measures (e.g. mandated inspection) to ensure bridges meet minimum safety standards, bridge failures occur. One reason why current measures fall short is that bridge inspection is primarily conducted by visual inspection (VI). A recent study by the Federal Highway Administration (FHWA) quantified the reliability of VI; this study discovered wide variability in the condition ratings assigned by trained inspectors to a bridge intentionally damaged (Moore et al. 2001). In response to the subjective nature of VI, nondestructive evaluation (NDE) technologies are slowly being adopted to inject greater objectivity in current bridge inspection strategies (Rolander et al. 2001). There is a clear need for the adoption of permanent structural health monitoring (SHM) systems for bridges exposed to excessive live loads (e.g. heavy truck traffic) and extreme events (e.g. seismic). Over the past decade, Korea has been proactive in mandating the integration of SHM systems on newly constructed bridges (Chang 2006). For example, on the reconstructed New Haengju Bridge, a permanent 65-channel monitoring system has been in use since 1996 (Pines and Lovell 1998). While some long-span bridges in the US have been instrumented (e.g. Cape Girardeau Bridge, MO), many of these systems are intended for seismic monitoring (Celebi 2006).

Sensor technologies have rapidly advanced in recent years. Advances have come in the form of improved functionality in many SHM system components (*e.g.* sensors, data acquisition systems and automated interrogation algorithms). While individual system components have improved, comparatively less attention has been paid to the integration of sensor technologies into comprehensive SHM systems for bridge structures. The potential cause for this is that research aimed at advancing SHM components can be conducted in the laboratory environment with ease; in contrast, research addressing the challenges associated with system integration necessitates access to actual civil structures serving as the field "laboratory". Access to large-scale civil structures is difficult to obtain in general; this lack of community-wide access to actual civil structures for SHM integration research has been cited by many working group reports as an obstacle to SHM development (Tomizuka et al. 2005).

This paper describes a new international collaboration initiated between the United States and Korea that fundamentally addresses the challenges associated with integrating SHM system components into a comprehensive system for bridges. A variety of new sensor technologies have been selected for integration including wireless sensors, EM stress sensors, vision displacement systems and piezoelectric active sensors. Using these sensors as building blocks, the first phase of the study focuses on the design of a comprehensive SHM system that will be deployed upon a series of highway bridges in Korea. With permanently installed SHM systems in place, the second phase of the study provides open access to both the bridges (e.g. to test new sensors) and the response data continuously collected (e.g. to test interrogation algorithms) as an international testbed for structural health monitoring. Concurrent to the research described herein, the US-Korea collaboration is also focused on using the testbed opportunity to accelerate the development of SHM curricula at the undergraduate and graduate education levels.

2 KOREA TEST ROAD BRIDGES

The Korea Highway Corporation (KHC) has recently constructed a redundant stretch of the Jungbu Inland Expressway near Icheon, South Korea (Fig. 1). The intended purpose of this 7.7 km long highway test-road is to monitor the behavior of highway pavement systems exposed to Korean traffic (trucks and cars). Towards this end, an array of 1897 sensors including strain gages, soil pressure sensors, thermocouples, among many others has been installed during construction. This dense sensor array is wired to a centralized data server housed in the KHC testbed office on the side of the highway segment. The test-road is constructed parallel to the original southbound highway; because it is a redundant section of the road, the KHC can easily close the test-road without interfering with traffic. Along the length of the test-road are three bridges

(Geumdang, Yondai and Samseung Bridges) that carry traffic over irrigated agricultural flood plains. The Smart Infrastructures Technology Center (SISTeC) has previously instrumented the bridges with wired monitoring systems to assess load carrying capacities (Lee et al. 2004). These three bridges are selected as test-bed bridges in this study because the KHC has agreed to offer the authors unfettered access to the bridges with complete control over the bridge loading (e.g. bridges can be closed to ordinary traffic so that calibrated traffic loads can be applied). In addition to these three highway bridges, a more complex long-span bridge is selected as the study's fourth testbed structure.

The Geumdang Bridge (Fig. 2a) is designed using two different structural systems to support traffic loads. First, the northern span is 151 m long and is constructed from 4 pre-cast concrete I-girders and a 27 cm thick concrete deck. The southern span is 122 m long and is constructed from a pre-cast concrete box girder. The box girder cross section is 2.6 m deep while the top surface of the girder (i.e. the road top) is 12.6 m wide. The box girder is a continuous span that is supported along its length by three piers and a concrete bridge abutment. The 122 m long continuous box girder has been previously employed in past system identification tests so its modal properties are well documented (Lee et al. 2004; Lynch et al. 2006).

The Yondai Bridge (Fig. 2b) is a 180 m long curved steel box girder bridge supported by three concrete piers along its length and two concrete abutment structures at both ends. The piers divide the continuous box girder bridge into three sections, each 45 m long. The cross section of the bridge consists of two open steel box girders roughly 2.2 m deep and 2.1 m wide. The top deck of the bridge consists of 32 cm thick reinforced concrete forming a top deck roadway 12.6 m wide.

The Samseung Bridge (Fig 2c) is constructed using 5 deep steel girders to support a 30 cm concrete deck. The total span of the bridge is 46 m with standard concrete abutments used to support each end of the bridge. Along the length of the bridge, beams and braced stiffener elements are installed between the load carrying steel girders to provide lateral support. The Samseung Bridge has also been previously monitored for traffic-induced mid-span displacements using a camera-based displacement system (Lee and Shinozuka 2006).

The Seohae Bridge is a three-span cable stay bridge with a total span of 7310 m and 31 m wide (Chang 2006). Recently completed in December 2000, the bridge carries 6 lanes of highway traffic of the Seohaean Highway. The total mid-span of the bridge is 470 m. An extensive structural monitoring system is already installed on the bridge to update bridge models.

3 SENSOR TECHNOLOGIES UNDER CONSIDERATION

3.1 *Piezoelectric transducers as active sensors*

Recently, guided waves have been widely used for structural damage detection. Conventional guided wave techniques often identify damage by comparing the "current" data obtained from a potentially damaged condition of a structure with the "past" baseline data collected for a structure in a pristine condition. In contrast, this study will explore the use of a new methodology of damage detection based on Lamb waves that do not require baseline data. In this study, baseline free crack detection in metallic bridge elements will be attempted through the use of surface mounted PZT transducers.

The proposed NDE technique utilizes the polarization characteristics of the PZT wafers attached on both sides of a plate structure as shown in Fig. 3. The arrows in Fig. 3a show the positive poling direction of each PZT element. When the plate is in a pristine condition and four identical PZTs are instrumented as shown in Fig. 3a, it is shown that signal AC becomes identical to signal BD as illustrated in Fig. 3b (Kim and Sohn 2006). Here, signal AC denotes the response signal measured at PZT C when the excitation is applied at PZT A, and signal BD is defined in a similar fashion. However, signal AC becomes no longer identical to signal BD when there is a crack between PZTs A and B (or PZTs C and D) (Fig. 3c and 3d). Crack formation creates Lamb wave mode conversion due to a sudden thickness change in the structure (Cho 2000). While the S_0 and A_0 modes in Fig. 3b are in-phase, the S_0/A_0 and A_0/S_0 modes in signals AB and CD are fully out-of-phase as shown in Fig. 3d (S_0, A_0, S_0/A_0 and A_0/S_0 are defined in Fig. 3). Therefore, the modes converted by the crack can be extracted simply by subtracting

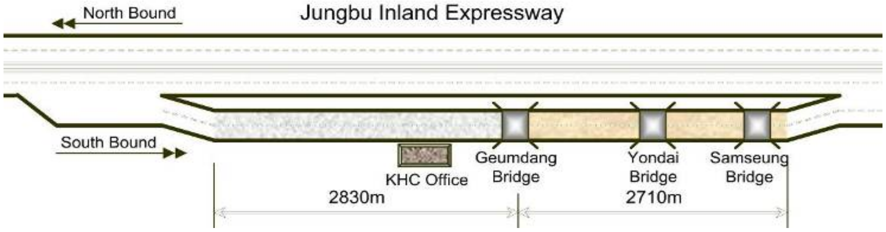


Figure 1. The Korea Highway Corporation's test-road with three bridges constructed along its length.

(a) (b) (c)

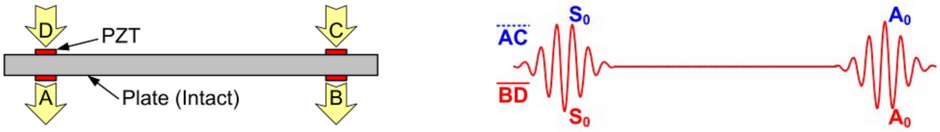
Figure 2. Three test-road bridges: (a) Geumdang Brdige; (b) Yondai Bridge; (c) Samseung Bridge.

signal AC from signal BD. Because this approach relies only on comparison of two signals instantaneously obtained at the current state of the system rather than comparison with previously recorded reference data, this approach reduces false alarms due to changing operational and environmental conditions of the system.

3.2 *Piezoelectric paint sensors*

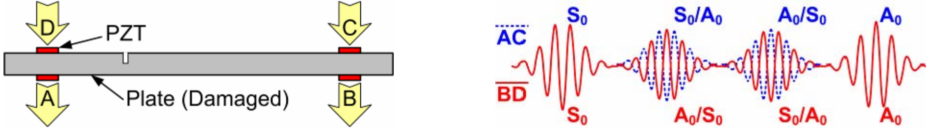
Recently, piezoelectric paint that uniformly cures at ambient temperatures has been studied by Zhang (2005). Piezoelectric paint typically comprises of tiny piezoelectric particles mixed within a polymer matrix and therefore belongs to the piezoelectric composite family. Similar to the previously described PZT elements, the piezoelectric paint develops a voltage when it is subjected to an elastic stress wave. This research will deploy piezoelectric paint specimens upon metallic and concrete bridges for acoustic emission (AE) sensing. AE consists of a propagating wave generated by a sudden release of energy within a material, such as energy from a crack. Preliminary experimental results indicate piezoelectric paint provides a promising low-cost transducer for on-line monitoring of the occurrence and propagation of fatigue cracks in steel structures based upon AE signatures. Piezoelectric paint is ideal for AE sensing because of its relatively flat frequency response curve over the ultrasonic bandwidth from 30 to 800 kHz.

When applied to the surfaces of host structures, an AE sensor made of ambient-cured piezoelectric paint (Figure 4) and a preamplifier has several advantages over conventional AE sensors including: (1) piezoelectric paint is very flexible and conforms to curved surfaces (e.g. welds)



(a) An intact plate with 4 PZT transducers with identical polarization directions

(b) Comparison of signals AC and BD without a crack: the S_0 & A_0 modes are identical



(c) A damaged plate with 4 PZT transducers with identical polarization directions

(d) Comparison of signals AC and BD with a crack: the S_0/A_0 & A_0/S_0 modes are out-of-phase

Figure 3. Extraction of Lamb wave modes generated by cracks using poling directions of PZT transducers. (A_0 and S_0 denote symmetric and anti-symmetric modes; A_0/S_0 denotes A_0 to S_0 mode conversion.)

for close-range acoustic wave monitoring; (2) through judicious selection of the polymeric matrix, the composite properties of the piezoelectric paint can be tailored to meet the specific requirements of the application; (3) good frequency response over a broad range of acoustic frequencies thus making AE signal interpretation relatively easy; (4) ease to make into different patterns with adjustable tickness; and (5) low-cost with each sensor costing about $10 compared to $300 for conventional AE sensors. In particular, the low cost attribute of paint-on piezoelectric sensors encourage the adoption of large numbers of such sensors on structures.

3.3 *Magnetoelastic (EM) sensors*

Stress measurements taken from steel reinforcement, prestressing strands, and cables for suspension bridges can be important parameters for assessing the health of concrete and suspension bridges. While highly important, measuring stress in such structural elements can be extremely challenging using traditional strain gages. In contrast, magnetoelastic (EM) sensors are being developed for measuring actual stresses in steel strands and cables (Wang et al. 1998; Chen 1999). EM stress sensors function by utilizing the dependency of the magnetic properties of structural steels with their state of stress (Mix 1987). These properties are measured by subjecting the steel to a pulsed or periodic magnetic field, which can be accomplished without any contact. Changes in flux through circuits surrounding the steel allow those magnetic properties to be sensed and deduced through Faraday's law. EM sensors are suitable for measuring quasi-static loads under any environmental condition.

The operational principle of the sensor is straightforward; two coils are wound on the steel stranded member including a primary and secondary sensing coil (Figure 5). Magnetization forces (H) are introduced into the primary coil by a current, I, which in turn produces an output voltage (V_{out}) across the secondary coil due to mutual inductance. The output voltage changes with the permeability (μ_r) of the steel core. The output voltage can then be calibrated to measure the applied stress (σ):

$$\mu_r(\sigma,T,H) = 1 + \frac{A_0}{A_f}\left(\frac{V_{out}(\sigma,T,H)}{V_0} - 1\right) \tag{1}$$

Here, V_{out} indicates the integrated secondary voltage with a strand or reinforcement bar in the solenoid, with V_0 is the integrated voltage without the strand or reinforcement bar in the solenoid. A_0 and A_f represent cross-sectional areas of the sensing coil and the steel element (*e.g.* cable or rebar), respectively. The permeability must be measured under technical magnetic saturation in order to diminish the effect of eddy currents and to achieve a uniform magnetization within the material. The temperature (T) and stress (σ) dependency with respect to relative permeability (μ_r) are calibrated extensively for many cable sizes and different kinds of steel strands fabricated in different countries. In general, stress is linearly related to values of permeability minus initial permeability at zero stress.

3.4 *Displacement sensing using high-resolution cameras*

Their exists a lack of sensors suitable for measuring displacements in bridges; as a result it is not a popular response quantity to be measured even though it is one of the most important descriptors of bridge behavior. Recently, some promising advances have been made for displacement sensing including GPS, laser Doppler vibrometers and vision-systems. A real-time displacement measurement system using digital image processing techniques currently under development will be deployed for accurately measuring displacements in the testbed bridges (Lee and Shiozuka 2006). The systems consists of target ranging objects, a telescopic lens, a digital camcorder, and a laptop computer where advance target recognition software is used to track and spatially range the targets mounted to the surface of the bridge. Given the high data rate of the camera (30 fps), displacements can be acquired at 30 Hz.

3.5 *Wireless sensor networks*

While large sensing networks have been installed successfully in structures around the world, the commercial viability and widespread adoption of SHM systems has been stymied by the

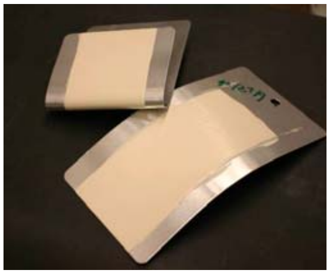


Figure 4. Piezoelectric paint applied upon aluminum plates.

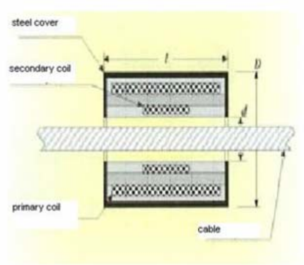


Figure 5. EM sensor for cable stress measurement

Figure 6. Low-cost wireless sensor for SHM

high cost of installing and maintaining the extensive lengths of wiring needed in a structural monitoring system. As a result of these high costs, wireless sensing technologies have emerged as a cost-effective replacement for traditionally tethered sensing systems. In the last decade, numerous wireless sensing platforms have been developed for both academic and commercial use (Lynch and Loh 2006). A fusion of sensing and communication functionality takes place within a wireless sensor, with analog-to-digital converters (ADCs) included for data acquisition, low-power microprocessors for embedded data analysis, and wireless radios for data transmission. Given the microprocessor integrated within each wireless sensor node, the computational resources of the monitoring system are now thrust forward to the individual sensors where measurement data can be locally interrogated; this is a more significant paradigm shift than the eradication of wires by using wireless communications. To date, a number of academic wireless sensor prototypes have been proposed explicitly for structural monitoring. Alternatively, some researchers have adopted commercial wireless sensor platforms (*e.g.* Crossbow). A low-cost wireless sensor proposed by Wang et al. (2007), as presented in Figure 6, will be used to collect bridge response data (using strain gages and accelerometers), process measurement data, and communicate data to bridge engineers.

Other self-contained wireless sensors incorporating actuation functionality will also be deployed in this study. Actuation allows a wireless sensor node to actuate PZT transducers for damage detection (Lynch 2005; Inman & Grisso 2006). In this study, a wireless sensor node capable of actuating PZT transducers for impedance-based damage detection will be deployed. Similar to Mascarenas et al. 2006, the wireless node features a low-cost impedance measurement circuit ideally suited for the application. For wireless monitoring systems, power saving is essential for the preservation of battery energy. To provide better performance for damage detection and to reduce power consumption associated with wireless data transmission, it is proposed to embed a principal component analysis (PCA) data compression algorithm into the on-board chip of the active sensor node.

4 TESTBED STRATEGIES

The testbed bridges offered to the US-Korea collaborative research team represent an unprecedented opportunity for advancement of sensors and structural health monitoring systems. To maximize the benefits derived from the testbed bridges, future efforts are staged in three phases.

4.1 *Phase I - Deployment of proposed sensors on testbed bridges*

During the first phase of the study, the proposed sensors will be deployed upon the testbed bridges. For example, the PZT and piezoelectric paint sensors will be applied to the steel surfaces of the Yondai and Samseung Bridges to monitor each bridge for fatigue cracking in select hot-spot locations. Displacement measurements will also be taken of all three bridges with displacement markers mounted to bridge mid-span locations. Strain gages and accelerometers interfaced to wireless sensors will be deployed in high density upon all three bridges. Efforts will also be made to utilize the wireless sensors for measuring the output voltages of the piezoelectric sensors. To validate performance, EM sensors will be attached to the cables of the Seohae Bridge to measure stress. In addition, accelerometers interfaced to wireless sensors will also be attached to the steel cables to estimate stress based on measured vibration characteristics. For all of the testbed bridges, data from the sensors will be collected using existing data acquisition systems already installed on the bridges. The advantage of using the existing data acquisition systems is that it already has a cellular link to a data server located at the Korea Advanced Institute for Science and Technology (KAIST) which can be accessed anywhere by the internet.

4.2 *Phase II - Open access to the international smart structures community*

Currently, there is a lack of permanent SHM systems where researchers can examine the long-term durability of sensors and SHM technologies. To address this need, the testbed bridges will be opened to the international structural health monitoring community during the second phase of the study. As new sensors are proposed, researchers will have an opportunity to visit the testbed bridges to test their devices. The existing monitoring system can then be used as a baseline system to which future sensor performances can be compared.

Another major obstacle to the advancement of SHM is the lack of access to actual structural data that researchers can use to develop damage detection algorithms. With dense arrays of sensors installed on four test-bed bridges in Korea, a tremendous amount of structural response data will be generated. The research team has plans to post all data sets generated from the testbed bridges on-line for the broader international community. Hence, researchers can freely download data and validate system identification and damage detection algorithms.

4.3 *Phase III - Integration of the testbed and smart structures education*

It can be expected that smart structures will radically transform the civil engineering discipline as we know it today. To keep pace with these changes and to better prepare civil engineering graduates for new technology adoption, changes in current course curricula are needed. In collaboration with Professors B.F. Spencer, Y. Fujino and Prof. Guo-Qiang Li, the authors are in the process of developing an international summer camp program on “Smart Structures Technology.” Through a three week program of coursework, lectures, labs, and site visits, civil engineering graduate students will learn about smart structures technology in an international setting. In total, ten graduate students selected from the US, Korea, Japan, and China will participate in this program. Participants from each country will be funded by NSF, KOSEF, JST, NNSFC, and SISTeC, respectively. The five year program will have a rotating host as follows: Korea in 2008, the US in 2009, Japan in 2010, China in 2011, and Korea in 2012.

Testbed bridges can also be a powerful platform for improving existing curricula by offering educators with real examples of how emerging sensor technologies work and the benefits derived. Furthermore, bridge response data can be used as data sets when teaching system identification and damage detection methods. The US-Korea collaboration will package smart structure course modules for educators and post data on-line for educational use.

5 CONCLUSIONS

This paper describes the early efforts of a US-Korea collaboration in research and education recently formed to accelerate the advancement of sensors and SHM. The cornerstone element of the collaboration is a set of four testbed bridges located in Korea. First, new sensors under development in the US and Korea will be installed to evaluate sensor performance while generating rich data sets on bridge behavior. The bridges will also be opened to the international research community as field benchmarks for testing. The goal of the collaboration is to achieve a broader adoption of SHM in practice.

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