Structural Monitoring and Maintenance, *Vol. 3, No. 1 (2016) 91-114*
DOI: http://dx.doi.org/10.12989/smm.2016.3.1.091

Recent R&D activities on structural health monitoring in Korea

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(Received December 27, 2015, Revised February 22, 2016, Accepted March 2, 2016)

Abstract. In this paper, recent research trends and activities on structural health monitoring (SHM) of civil infrastructure in Korea are reviewed. Recently, there has been increasing need for adopting smart sensing technologies to SHM, so this review focuses on smart sensing, monitoring, and assessment for civil infrastructure. Firstly, the research activities on smart sensor technology is reviewed including optical fiber sensors, piezoelectric sensors, wireless smart sensors, and vision-based sensing system. Then, a brief overview is given to the recent advances in smart monitoring and assessment techniques such as vibration-based global monitoring techniques, local monitoring with piezoelectric materials, decentralized monitoring techniques for wireless sensors, wireless power supply and energy harvest. Finally, recent joint SHM activities on several test beds in Korea are discussed to share the up-to-date information and to promote the smart sensors and monitoring technologies for applications to civil infrastructure. It includes a Korea-US joint research on test bridges of the Korea Expressway Corporation (KEC), a Korea-US-Japan joint research on Jindo cable-stayed bridge, and a comparative study for cable tension measurement techniques on Hwamyung cable-stayed bridge, and a campaign test for displacement measurement techniques on Sorok suspension bridge.

Keywords: smart sensors; structural health monitoring; damage detection; civil infrastructure

1. Introduction

Since as early as 1990s, structural health monitoring (SHM) on civil infrastructure has been a hot issue in Korea. The number of deteriorated infrastructure systems in Korea, built in the industrialized period of the 1970s, has increased rapidly. Such problems with the deteriorated structures are very common all over the world. Hence, there has been big demand to monitor structures in order to ensure the safety and serviceability. So the Korean governmental authorities have issued more stringent requirements on infrastructure, including systematic visual inspection, instrumentation, load capacity tests, and field measurements for design and construction verification, and long-term performance monitoring and assessment (Yun *et al*. 2009).

The modern civil engineering structures such as long span bridges are becoming more complex

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http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

and are expected to be fully functional under severer environmental conditions (Yun and Min 2011). They are often exposed to severe loadings, especially at extreme events such as earthquake and typhoon, which may cause serious concerns on the integrity of the structures, and even collapses that may induce a large number of casualties as well as social and economic problems. To meet the unprecedented demand on SHM of the complex structures, research activities have been promoted on developing smart SHM techniques and implementing them into civil infrastructure. The smart SHM system often offers an opportunity to reduce the cost for the maintenance, repair and retrofit throughout the life cycle of the structure (Spencer *et al*. 2016).

In this paper, recent research trends and activities on SHM of civil infrastructure in Korea are reviewed. The emphasis is given to smart sensing, monitoring, and assessment for civil infrastructure. Firstly, the research activities on smart sensor technology is reviewed including optical fiber sensors, piezoelectric sensors, wireless smart sensors, and vision-based sensing system. Then, a brief overview is given to the recent advances in smart monitoring and assessment techniques such as vibration-based global monitoring techniques, local monitoring with piezoelectric materials, decentralized monitoring techniques for wireless sensors, wireless power supply and energy harvest. Finally, recent joint SHM activities on several test beds in Korea are discussed to share the up-to-date information and to promote the smart sensors and monitoring technologies for applications to civil infrastructure. It includes a Korea-US joint research on test bridges of the Korea Expressway Corporation (KEC), a Korea-US-Japan joint research on Jindo cable-stayed bridge, and a comparative study for cable tension measurement techniques on Hwamyung cable-stayed bridge, and a campaign test for displacement measurement techniques on Sorok suspension bridge.

2. Smart sensor technology

SHM has been rapidly expanding its territory to real-world applications with recent advances in sensor technologies (Yun and Min 2011). Particularly, Korean SHM society has adopted new smart sensors to improve SHM performance and broaden field applications. The smart sensors can provide enhanced information regarding structural conditions and soundness that is impossible or inefficient by the traditional sensor systems. This section introduces four types of smart sensors that have been most popularly studied in Korea, including piezoelectric sensors, wireless smart sensors, optical fiber sensors (OFS), and vision-based sensing systems.

2.1 Piezoelectric sensors

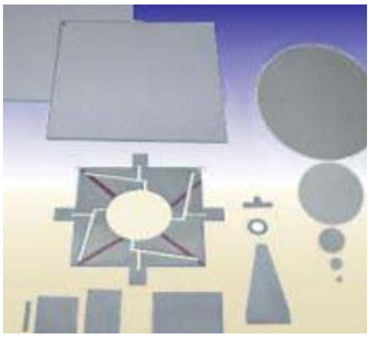
The piezoelectric sensor is relatively a new technology to infrastructure monitoring, while it has shown great potential in local monitoring. Smart piezoelectric materials allow bidirectional electromechanical coupling between the electric field and the mechanical strain. Piezoelectric sensors such as piezoceramic (PZT; lead zirconate titanate) sensors and macro fiber composite (MFC) sensors (Fig. 1) have been widely used in structural dynamics applications (Park *et al.* 2003). Based on this functionality, piezoelectric sensors have been the most extensively used for both impedance-based damage detection (Park *et al*. 2003, Park *et al*. 2006a, Min *et al*. 2010, Park *et al.* 2010) and guided waves-based damage detection methods (Sohn *et al.* 2003, 2009, Kim and Sohn 2006, Park *et al*. 2006b, An *et al.* 2009) since they can be used as both actuators and sensors simultaneously.

With the recent advances of signal processing techniques and the improvement of hardware including MEMS (MicroElectroMechanical Systems) technology and wireless data transmission, piezoelectric sensors become more attractive in on-line SHM as well as non-destructive testing. Some of the related researches and application activities are as follows: (1) Development of a piezoelectric oscillator sensor to detect damages on civil infrastructure (Kim *et al*. 2005, Kim *et al*. 2008), (2) Impedance-based damage detection on civil structures (Park *et al.* 2006a), piezoelectric sensor self-diagnosis using impedances (Park *et al.* 2006, Park *et al.* 2009) and on-line piezoelectric sensors-based SHM using wireless sensor nodes (Park *et al.* 2009, Park *et al*. 2010), (3) Reference-free crack detection using piezoelectric sensors (Kim and Sohn, 2006) and smart dual PZT transducers for damage detection (Sohn *et al.* 2009), (4) High efficient piezoelectric energy harvesting modules (Song *et al.* 2009, Park *et al.* 2013), (5) Embedded piezoelectric sensing technology and various field applications using piezoelectric sensors-based sensing system (An *et al.* 2009, Min *et al*. 2010, Kim *et al.* 2011, Huynh and Kim 2014, Kim *et al.* 2015, Min *et al*. 2016).

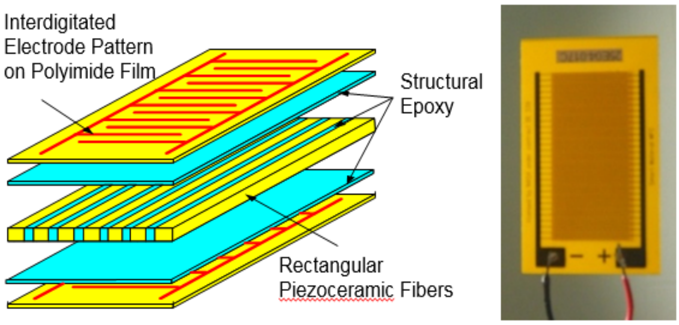
2.2 Wireless smart sensors

The wireless smart sensor has been introduced to SHM as a promising alternative to the traditional wired sensor systems, which are quite inefficient with high cost and maintenance difficulties (Farrar 2001). Wireless smart sensors have been regarded as an alternative tool for economical and accurate realization of SHM system since the maintenance cost of the SHM system is an important consideration as the system gets older. Wireless smart sensors have been developed considering the following essential features: sensing capability, on-board computation, wireless communication, self-powered, plug-in functionalities, and low cost. The cost effectiveness of the wireless smart sensor enables dense arrays of sensors to be implemented on a large civil structure.

The wireless smart sensor technology for infrastructure monitoring has significantly advanced in the recent decades, producing a wide variety of sensor platforms. A Mote may be the most famous commercialized prototype, which is initially developed at the University of California-Berkeley and subsequently commercialized by Crossbow (Zhao and Guibas 2004). Whereas the sensor hardware design and laboratory-scale validation were the most important and common focus in the beginning stage, research efforts have been moved to full-scale testing in the recent years.



(a) PZT sensors



(b) MFC sensors

Fig. 1 Various piezoelectric sensors

A notable full-scale implementation of the wireless smart sensors for civil infrastructure monitoring is the wireless smart sensor network deployed in the Jindo Bridge, a 480 m cable-stayed bridge located in South Korea (Nagayama et al. 2010; Rice et al. 2010; Jang et al. 2010, Cho *et al.* 2010, Yun *et al.* 2014; Sim *et al.* 2014). The research was conducted as an international collaboration between KAIST in South Korea, the University of Illinois at Urbana-Champaign in USA, and the University of Tokyo in Japan. The purpose of the collaborative project was to validate their hardware and software system using the Imote2 smart sensor platform in terms of scalability to a large wireless network, robustness for long-term monitoring in the harsh environment, decentralized data processing algorithms, multi-hop communication, effectiveness of power management with energy harvesting, and performance of high-definition acceleration and strain sensing. An important example of these features was to realize the decentralized data processing for long-term monitoring of cable tensions of the Jindo Bridge (Sim *et al.* 2014). Acceleration of each cable was measured and processed to calculate the tension force of the cable, which was in turn collected to the central base station. Because only a cable tension value from each node is wirelessly transferred rather than receiving whole time history data, the wireless communication for data transfer could be drastically reduced, resulting in the minimized power drain and the increased communication stability.

Most wireless smart sensors are intrinsically ideal for multi-metric sensing that utilizes multiple different types of measurements to produce better assessment results and has been considered to have great potential to improve the performance of SHM algorithms. A leading group of the multi-metric sensing using the wireless smart sensor is Pukyong National University in South Korea that mainly has focused on combining impedance-based monitoring with the conventional vibration-based assessment (Kim *et al*. 2009, Park *et al*. 2010, Kim *et al.* 2011, Hong *et al*. 2012). The hybrid system combining the impedance and the vibration information enabled sensitive damage monitoring of PSC girder bridges. The multi-metric sensing strategy as well as the vibration-based analysis were utilized in the smart wireless sensing system deployed in the Hwamyung Bridge (Fig. 2), a cable-stayed bridge located in Busan, South Korea (Ho *et al.* 2012, Nguyen *et al*. 2013, Kim *et al*. 2013, Kim *et al*. 2014).

The wireless smart sensor can be also used for local damage monitoring. Liu *et al*. (2014) developed a wireless system for fatigue crack detection of steel structures. This system detects fatigue cracks based on nonlinear ultrasonic wave modulation (Sohn *et al.* 2014, Lim *et al*. 2014). The wireless crack detection system is later enhanced with wireless power transmission, which can resolve the power supply problem, one of the most challenging issue in wireless smart sensor research (Kim *et al.* 2016).

2.3 Optical fiber sensors

The OFS has been widely adopted for monitoring of civil infrastructure due to its advantages such as durability, immunity to electromagnetic interference, lightweight, high sensitivity, wide bandwidth, and easiness in implementing multiplexed sensors. The most widely measured quantities using OFSs include strain, temperature, and pressure. The fiber Bragg grating (FBG) sensor (Fig. 3) represents the most widely used technology among OFSs (Johnson *et al*. 1999, Ryu *et al.* 2002, Shu *et al.* 2002, Kim *et al*. 2003a, b, 2005, 2010, Park *et al*. 2007, Huynh and Kim 2016). Durability of OFSs has drawn much interest from the structural engineers, especially for long-term SHM.

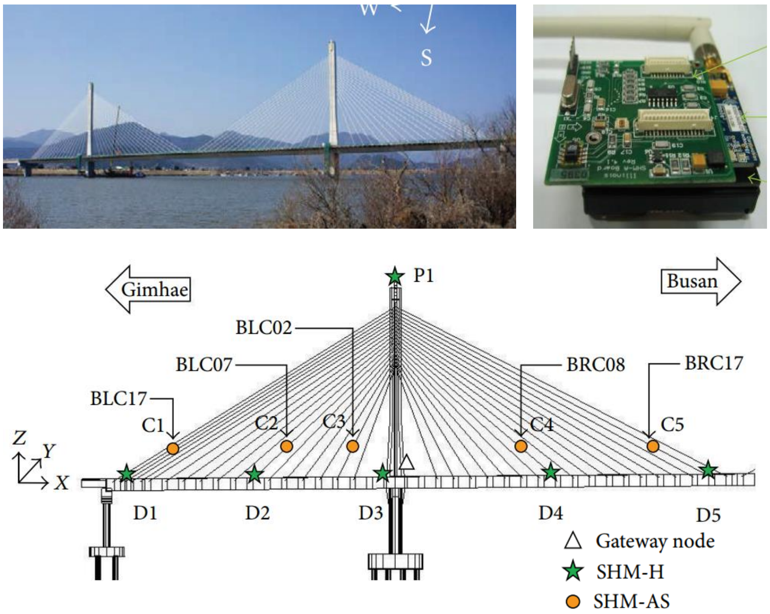


Fig. 2 Wireless Sensor deployment in the Hwamyung Bridge (Ho *et al*. 2012)

Recently, cost-effective systems including low-cost FBG interrogators and Brillouin optical time domain analysis (BOTDA; Kwon *et al.* 2001, 2003, 2009, Zhou *et al.* 2008) sensors have been developed for the application into large civil infrastructure. Some of the related development and application activities on OFSs are as follows: 1) Development of multiple fiber Bragg grating (FBG) sensor systems using wavelength-swept fiber laser and code division (Ryu *et al.* 2002), 2) FBG sensors for vibration-based monitoring and weigh-in-Motion measurement, and structural integrity test for nuclear containment structures (Kim *et al.* 2010, Kim *et al*. 2003a, Kim *et al.* 2005), 3) Retrofit of concrete structures using carbon fiber sheets with FBG sensors (Kim *et al.* 2003b), 4) Fiber optic accelerometer systems for large-size structures (Feng *et al*. 2006), 5) Damage localization techniques using strain mode shapes (Park *et al*. 2007a), and 6) Improvement of capability of BOTDA sensors and their application to Oil leakage monitoring for off-shore pipelines (Kwon *et al.* 2001, 2003, 2009).

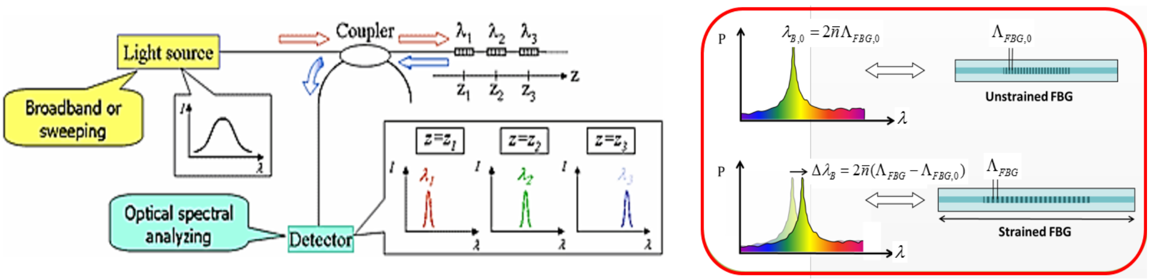


Fig. 3 Schematic of FBG sensor system

2.4 Vision-based sensing system

The measurement of displacement responses from a full-scale civil engineering structure is often challenging. Imaging a suspension bridge constructed over a river: installing traditional displacement transducers such as LVDT is intractable. Recently, innovative advances have been achieved for displacement sensing including global positioning system (GPS, Knecht and Manetti 2001), laser Doppler vibrometers (Nassif *et al*. 2005) and vision-based systems (Wahbeh *et al*. 2003). Due to the cost effectiveness and convenient sensor instrumentation, the vision-based method has attracted significant research efforts for possible alternative to the conventional displacement sensing approaches.

Lee and Shinozuka (2006b) developed a real-time displacement measurement system using digital image processing technique. The camera-based displacement measurement system has been applied to estimate load carrying capacity of a steel girder bridge and has been extended to measure the displacement of a high-rise building structure using a novel partitioning approach (i.e., successive estimation of relative displacements and rotational angles throughout a large flexible structure) (Lee *et al*. 2007b, Park *et al*. 2010). Kim *et al.* (2009) developed a novel technique to measure multi-point dynamic displacement of structures using digital image correlation technique and sub-pixel enhancement algorithms. Field tests have been made on a steel girder bridge and the test results showed good agreements with the conventional transducer.

Another vision-based approach was developed by Myung *et al*. (2010) to incorporate a multiple paired structured light (SL) system (Fig. 4). An improved version of this system named Visually Servoed Paired Structured Light System (ViSP) was experimentally verified in full-scale structures of a frame building and a railway bridge (Jeon *et al*. 2013). A motion capture system to monitor 3-D movements of a structure was developed by Park *et al.* (2015). A free vibration test using a three-story building model was utilized to capture dynamic displacement with a deformed shape. Also, Park *et al.* (2015) developed a vision-based algorithm to monitor bolted connection for detecting loosening of bolts. A sequential images captured were acquired and processed via Hough transform to indicate the change in bolt-nut angles. Laboratory tests has been made successfully on a wind-turbine tower structural which had bolted connections with a set of loosening scenarios.

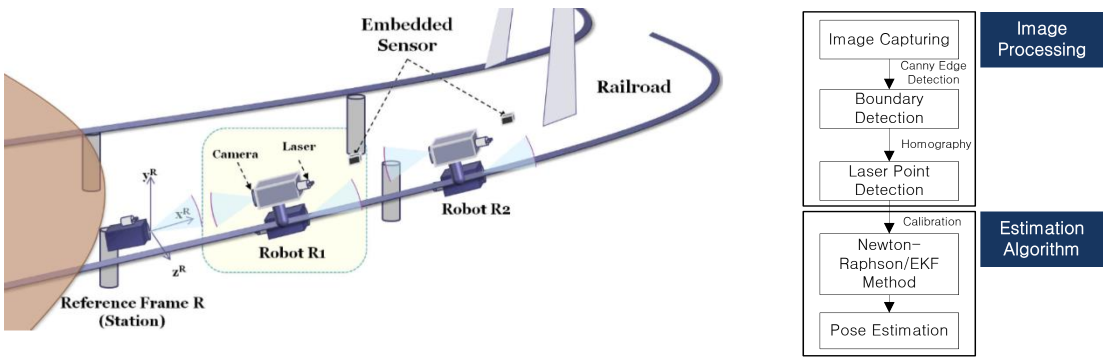


Fig. 4 Schematic diagram of vision-based displacement measurement system (Myung *et al*. 2011)

3. Smart monitoring and assessment techniques

The monitoring and assessment of structural integrity is the ultimate motivation for the practice of SHM tasks on infrastructural systems (Yun and Min 2011). Many researchers have developed novel sensing technologies and monitoring techniques for the practical SHM applications. For example, the SHM system for long-span bridges mainly includes a number of sensors, a huge amount of signal transmitting wires, data acquisition instruments, and one or more centralized data storage servers. The stored data in the centralized servers are handled for off-line signal and information analysis for damage monitoring and safety evaluation. However, the costs associated with installation and maintenance of SHM systems can be very high. The high costs associated with wired SHM systems can be greatly reduced through the adoption of wireless sensors. One of great advantages for using wireless sensors is that autonomous operations for the SHM can be implemented by embedding advanced system technologies. Therefore, the new paradigm by adopting smart sensor nodes may offer an autonomous and cost-efficient SHM.

For the realization of the smart SHM system, the development of smart monitoring and assessment techniques as much as the development of smart sensors are important topics (Lynch *et al*. 2003, Nagayama 2007, Wang *et al*. 2007, Zimmerman *et al*. 2008, Lu *et al*. 2008). In this section, recent research and development on those techniques are reviewed on a few selected topics including global and local SHM techniques, decentralized SHM techniques for wireless sensors, and wireless power supply and energy harvest.

3.1 Vibration-based global monitoring technique

The SHM is usually carried out with global and/or local manners, which can be categorized by their interests on monitoring scopes. For global health monitoring, vibration-based techniques have been developed to assess the structural integrity of the entire system by using vibration responses. Vibration responses such as acceleration signals are measured and modal properties are extracted thereafter (Kim *et al.* 1995, 2003, 2007, Yun *et al.* 1997, 2000, Feng *et al.* 1998, Jang *et al.* 2002, Kwon *et al.* 2003, Yi *et al*. 2004, Kang *et al.* 2005, Park *et al*. 2007, Shin and Oh 2007, Choo *et al*. 2009). Then, the results are compared with the baseline data, which may assess the overall safety of the structure.

Mostly vibration-based SHM is performed by two major tasks: data processing for feature extraction and information processing of the extracted feature. Then the damage identification has been traditionally carried out by recognizing patterns of the information in the modal properties regarding the element level damage indices. Here three well-known approaches are introduced including the modal sensitivity method, the modal flexibility method, and the soft-computing method.

Kim and Stubbs proposed an improved damage indication method to predict locations and severities of damage in structures using the changes in the modal strain energy (Kim and Stubbs 2002). The accuracy of the damage prediction was numerically assessed for a two-span continuous beam using a few vibration modes. Kim *et al.* presented a methodology to estimate the location and size of damage in a structure for which a few natural frequencies or a few mode shapes are available. A frequency-based damage detection method and a modeshape-based damage detection method were developed, and experimental evaluations were performed on prestressed concrete girders under temperature variations (Kim *et al*. 2003, Kim *et al.* 2007). Recently, Nguyen *et al.* (2015) implemented those methods for damage detection in wind-turbine tower structures in Jeju, South Korea.

Koo *et al.* (2008) proposed a new method in which anomaly in the uniform load surface calculated by modal flexibility was treated as a damage feature. It is based on the explicit relationship between the damage and the damage-induced deflection and constructs a simple mapping from the damage-induced deflection to the actual damage location. Tomaszewska (2010) considered the effect of statistical errors in order to distinguish between true and false damage detection results, based on structural flexibility and modal curvature approaches. The changes in the modal flexibility can be utilized for damage estimation of the structure instead of the stiffness changes (Madhwesh and Ahmet 1992, Pandey and Biswas 1994, Toksoy and Aktan 1994, Zhang and Aktan 1995, Zhao and DeWolf (1999).

There has been the advance in the soft computing techniques such as neural network (NN) and outlier analysis techniques for on-line global monitoring with its excellent pattern recognition capability (Yun and Bahng 2000, Lee and Yun 2007a). Lee *et al*. (2002, 2005) presented a NN-based damage estimation of a bridge structure as in Fig. 5, which is based on the changes in the modal properties extracted from the ambient vibration data under traffic loadings. The mode shape differences between before and after damage, were used as damage features to relieve the effect of the inevitable modeling errors. A field validation was performed on a span of the old Hannam Grand Bridge over Han River in Seoul, Korea to confirm the applicability of the NN-based approach.

Vibration-based monitoring and damage detection techniques have been applied to the evaluation of the load carrying capacity of bridge on the basis of traffic-induced ambient vibration data (Kim *et al*. 2001, Lee *et al.* 2002, Lee *et al.* 2005, Yi *et al.* 2007). Environmental effects including temperature, vehicle-bridge interaction effects, and supporting conditions were considered for more reliable evaluation of load carrying capacity. The approach consists of (1) ambient vibration tests on a bridge; (2) identification of modal properties extracted from the ambient acceleration data; (3) enhancement of the initial FE model of the bridge structure based on the identified results; and (4) estimation of the load carrying capacity using the updated FE model. The proposed approach has been validated on various types of bridges by cooperative researches between academia and the bridge authorities in Korea (Yun *et al*. 2009).

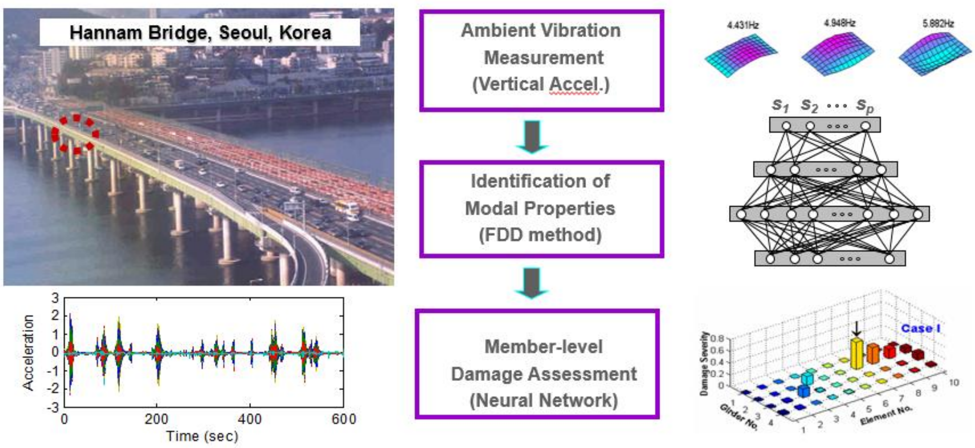


Fig. 5 Vibration-based damage detection on Hannam Grand Bridge

3.2 Local monitoring with piezoelectric sensors

Based on the previous works, vibration-based global approaches may not be able to distinguish multiple damage types. Also, the number of sensors in the sensor array is generally limited to cover the entire structure and the modal information is often not sensitive enough to detect damage occurred locally. To overcome this problem, local monitoring on selected critical areas should be combined with global monitoring. This section introduces the research activities on smart local monitoring techniques using piezoelectrical materials.

Local SHM with piezoelectric materials can be broadly classified into two different types of active sensing-based techniques: electromechanical impedance-based methods and guided waves-based methods. Electromechanical impedance-based techniques have been developed as a tool for real-time local structural damage assessment on critical members of large structures such as bridges, pipe lines, buildings, and power plants (Giurgiutiu and Rogers 1997, Tseng *et al.* 2000, Zagrai and Giurgiutiu 2001, Park *et al.* 2003, Park *et al.* 2006a, Min *et al.* 2015). Since damages cause a change in the structure's local mass, stiffness, or damping properties and consequently its mechanical impedance, the structure's mechanical integrity can be assessed by monitoring the electrical impedance of the piezoelectric sensor. For quantitative assessment of damage, statistical damage indices such as root mean square deviation (RMSD), cross-correlation deviation (CCD), mean absolute percentage deviation (MAPD), and covariance change are calculated (Park *et al.* 2003).

Tensile force measurement in prestressing systems is one of major issues in the civil engineering field because a conventional lift-off test is time-consuming, expensive, laborious, and difficult to apply to bonded tendon system. Thus many researchers have proposed various types of methods to tackle this sticking point. Among them, piezoelectric sensors-based approaches are receiving attention due to their high potential and convenience in setting up. Nguyen and Kim (2012) and Huynh *et al*. (2015a, b) inserted a simple shaped interface washer between a structure and an anchorage block, and then a change in the washer's mechanical properties was investigated. A piezoelectric patch was attached on the center of washer, and the loss of tensile force was detected by monitoring the stress change or the change in impedance of the washer. Experimental results on a large-scale prestressed concrete girder showed that this approach can be effectively applied when insufficient space exists to attach the piezoelectric patch to the structure or when structural impedance signatures are very weak to analyze. Min *et al*. (2016) proposed a simple method to estimate the remaining tensile force of tendons and simultaneously detecting damages of the anchorage block by incorporating multiple piezoelectric patches. Based on two types of relationship curves between the tensile force and the statistical index and between statistical indices of two different patches, both tensile force and health condition could be monitored effectively. This methodology was applied to a real-scale 19 strands anchorage system and the results showed quite accurate estimation of the remaining tensile forces and damage status (Fig. 6).

3.3 Decentralized monitoring for wireless sensors

Wireless sensor systems can overcome the limitation of the conventional sensor systems which collect and process the measured data in the centralized way. The limitation of the centralized processing is about data inundation and low fault-tolerance caused by long cables. By forming a wireless smart sensor network (WSSN), the wireless sensor system enable the decentralized processing fully utilizing the computing capability of smart sensors. The basis of the decentralized processing comes from grouping local networks into clusters. Based on the sensor's performances (e.g., fault tolerance, radio accessibility, computing capability, and power supplier), a hierarchical network of wireless smart sensors is formed, as shown in Fig. 7.

For the autonomous decentralized SHM systems, Gao and Spencer (2008) suggested an autonomous decentralized SHM system embedded with vibration-based damage detection algorithms; Nagayama *et al.* (2007) has implemented iMote2 sensor platform incorporating with TinyOS (Levis *et al*. 2005), middleware services, and a flexibility-based damage detection algorithm; Zimmerman *et al*. (2009) has proposed a decentralized modal analysis scheme using chain-like topology of the wireless sensor network with frequency-domain output-only modal analysis techniques; Sim *et al.* (2010) has developed decentralized data aggregation to determine the global modal properties with high fidelity. These proposed decentralized systems have been successfully implemented and validated for modal identifications of lab-scale and on-site structures such as a truss model and Jindo Bridge in Korea (Fig. 8).

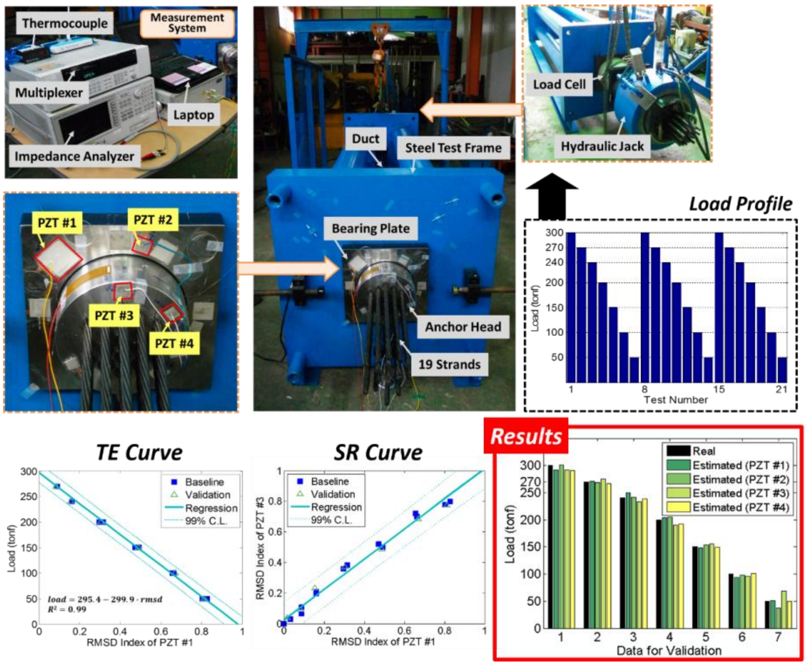


Fig. 6 Tensile force estimation and nearby damage detection with multiple piezoelectric sensors on 19-strand anchorage system (Min *et al*. 2016)

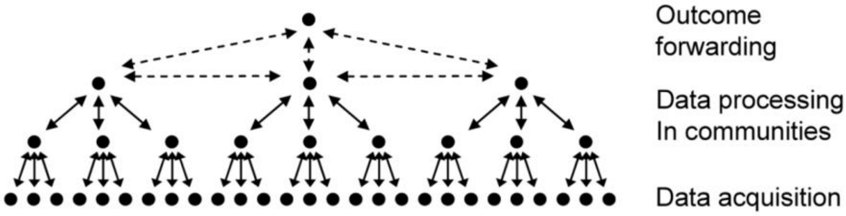


Fig. 7 Decentralized processing scheme (Nagayama *et al*. 2010)

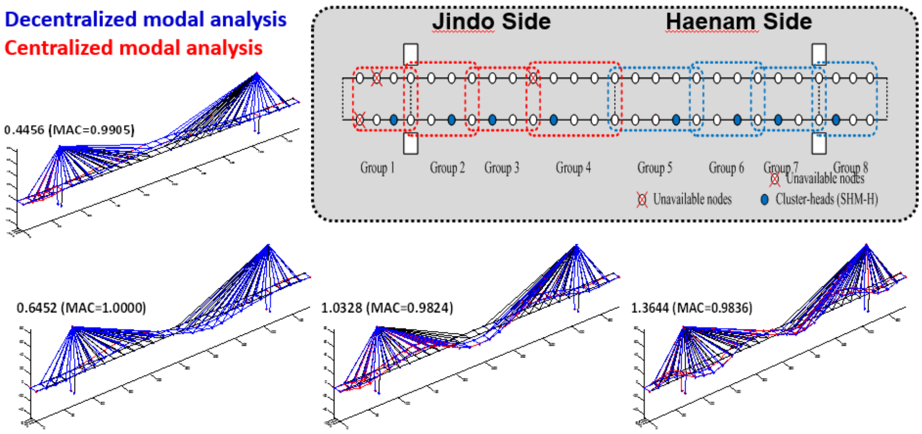


Fig. 8 Decentralized identification of modal properties in Jindo bridge

3.4 Wireless power supply

As compared to conventional passive sensors (e.g., accelerometers and strain gauges), wireless active sensing devices (e.g., PZT transducers) often require relatively high electrical power (Yeatman 2009). Despite research attempts on energy harvesting, the amount of harvested energy often falls below the levels need for active SHM sensing systems (Park *et al*. 2008). A potential approach for the wireless power supply is to employ radio frequency (RF) microwave transmission technologies (Brown 1996) to wirelessly transmit the power to an active sensor node. RF microwaves are transmitted across the atmosphere or space to a receiver which receives and directly convert the microwaves into DC power. By charging the capacitor in the sensor node, Mascarenas *et al*. (2007) used wireless RF transmission to deliver electrical energy to power a piezoelectric impedance sensor node. Although the experimental validation showed good performance of the wireless power supply for the wireless impedance node, the microwave transmission can be attenuated when it travels through the atmosphere to the receiver.

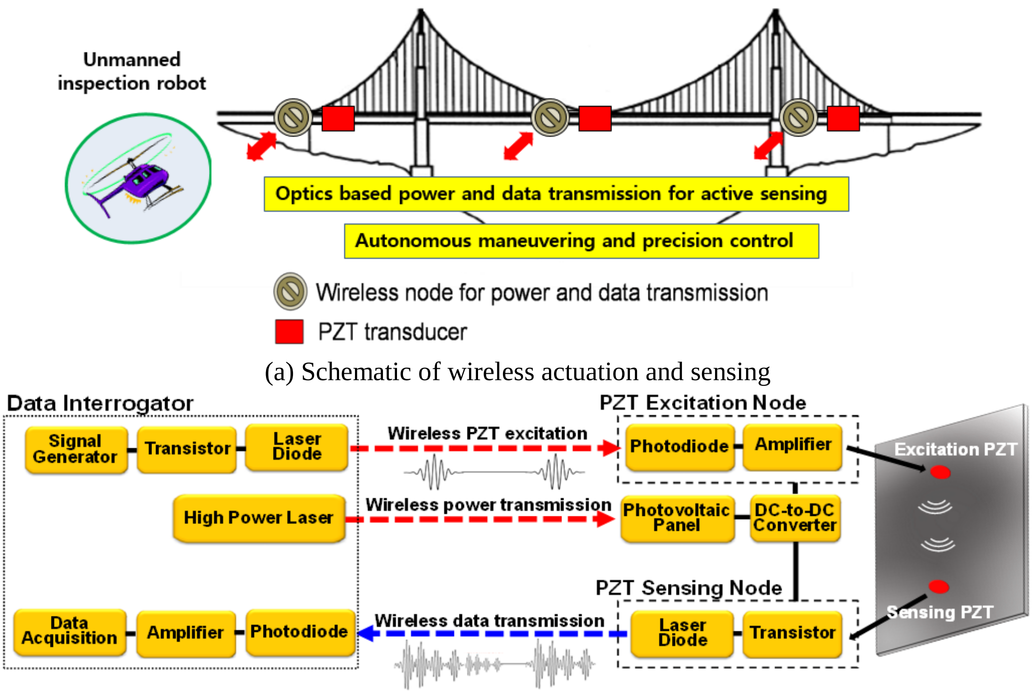
By adopting the advantage of optoelectronics, Park *et al*. (2010) suggested an optical system for wireless power and data transmission (Fig. 9). A waveform generated by modulation of a laser is wirelessly transmitted to a photodiode connected to a PZT sensor on the structures. Then, the photodiode converts the light into an electrical signal and excite the PZT sensor. Finally, the reflected response signal received at the same PZT is re-converted into a laser and wirelessly transmitted back to another photodiode located in the data acquisition unit for data processing. Due to the highly directional and collimated radiation with a low divergence angle, the laser-based energy transmission can be used for a long distance without attenuation and focus onto a small region.

3.5 Energy harvest

Once the battery has consumed all of its power, replacement of the battery located remotely can become a high-cost and tedious, or even impossible work. Due to the advances in wireless technology and low-power electronics, the energy harvesting has been recently paid more attention. Many researchers in the SHM and sensing network community have proposed alternative power sources such as sunlight, thermal gradient, human motion, and vibration.

Among many potential alternative sources, the solar power is regarded as the strongest candidate for real SHM applications to civil infrastructure (Mathuna *et al*. 2008, Jang *et al*. 2010, Ho *et al.* 2012). For long-span bridges, wind energy can be considered as another promising energy source since these structures are usually located in windy areas. To power wireless smart sensors deployed on a cable-stayed bridge, Park *et al*. (2010) suggested to use small wind-powered generators. The experimental results showed the maximum output power of 27.3 mW at 3.0 m/s of wind speed (Fig. 10).

Instead of energy harvesting, several researchers attempted to minimize the battery usage under the same operating configuration of wireless smart sensors. In general, the wireless transmission of measured data consumes more power than local computation of data. To reduce the power consumption of wireless transmission, therefore, the data processing and compression by local interrogation of measured data has been widely investigated. Lynch *et al.* (2003) has embedded many SHM algorithms (e.g., Fast Fourier Transform, Auto-Regressive, Random Decrement, and Frequency Domain Decomposition) into the computational core of wireless smart sensors to reduce the wide bandwidth of time-history vibration data. For autonomous SHM of large civil structures, Rice *et al.* (2010) has developed a flexible framework to minimize the power consumption in a large-scale wireless sensor network. The strategy of the flexible framework is based on defining threshold values which are used to wake the sensors up from the sleep-mode.

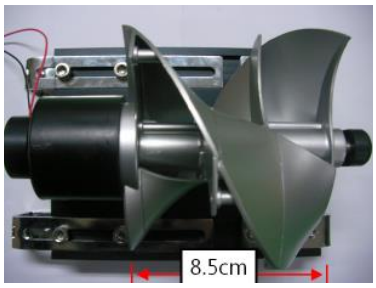


(a) Schematic of wireless actuation and sensing

(b) An overall schematic

Fig. 9 Optics-based wireless guided wave generation and non-contact sensing (Park *et al*. 2010)

(a) Solar panel on sensor node
(Jang *et al*. 2010)



(b) Blade of small wind turbine
(Park *et al*. 2010)

Fig. 10 Energy Harvesters

4. Recent joint SHM activities on test beds

4.1 KEC Bridge monitoring test beds

For a Korea-US joint research to explore emerging smart sensors and sensing tools on bridges, three bridges on a test road of the Korea Expressway Corporation (KEC), which is located in Jungbu Inland Expressway near Icheon, South Korea (Fig. 11), were selected as test beds under the agreement of the KEC. A series of collaborative field tests have been performed using piezoelectric sensors (KAIST, Sungkyunkwan Univ., Univ. of Maryland), wired and wireless accelerometers (KAIST, KEC, Michigan Univ., and Univ. of California-Irvine), wireless active sensors (KAIST), and vision-based monitoring system (Sejong Univ.). Various sensing systems have been deployed on the testbed bridges where the internet access was provided for participants so that instruments and measurement systems can be accessed remotely using Remote Desktop software. Each participating group validated the feasibility of their own sensors and data/information processing algorithms (Lee *et al*. 2006a, b, 2007b, Lynch *et al*. 2006b, Yun *et al*. 2009, An *et al*. 2009).

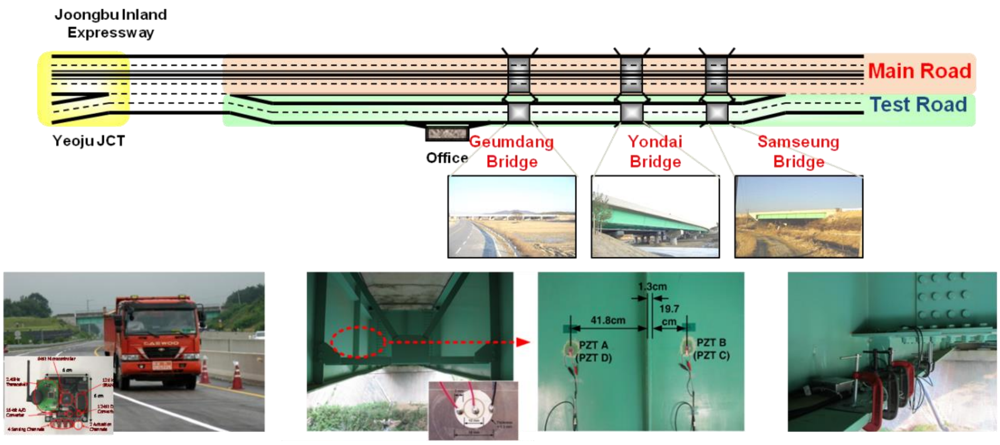
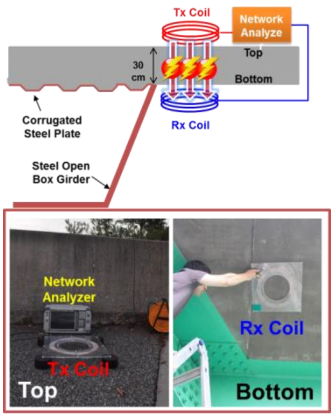
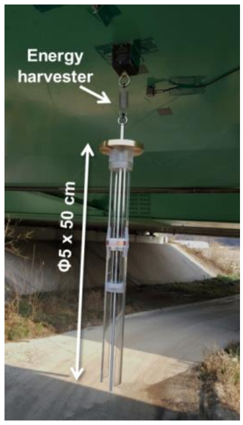


Fig. 11 Korea-US joint research on KEC test road bridges (Yun *et al*. 2009)



(a) Wireless power transmission system



(b) Vibration energy harvester

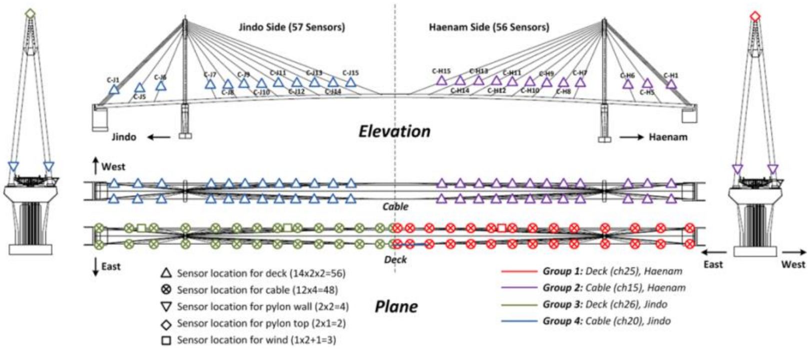
Fig. 12 Research on power system of wireless sensors

The test road has been continuously used as an effective test-bed due to its redundancy in passing the traffic. Especially, the KAIST team has been actively studied a wireless power transmission (WPT) system and a vibration energy harvesting system as shown in Fig. 12. On Yondai Bridge with a composite box girder, WPT over the concrete slab and steel open box has been severely tested to investigate the feasibility of passive sensors powered by a running car on the bridge without a battery (Kim *et al*. 2015, Jung *et al*. 2015). For wireless sensors that require higher power, a vibration energy harvester was developed and tested on Yondai Bridge to charge the battery using the structural vibration excited by passing traffic on the bridge (Yang *et al.* 2015). Both systems are highly demanded to widen the applicability of wireless sensors that have weakness in supplying the sustainable power.

4.2 WSN-based SHM practice on Jindo Bridge

An international test bed for state-of-the-art wireless smart sensor technology has been developed on a cable-stayed bridge in Korea (The 2nd Jindo Bridge) through a trilateral collaborative research among Korea (KAIST, Seoul Nat'l Univ., Sejong Univ.), the US (Univ. of Illinois at Urbana-Champaign), and Japan (Univ. of Tokyo). The wireless vibration-based SHM was introduced mainly in conjunction with the collaborative research in this section. For specific and detailed information, the following literatures can be referred: Rice *et al*. (2010), Jang *et al*. (2010), Cho *et al.* (2010), and Nagayama *et al.* (2010).

The key component of the wireless smart sensors used in this research is iMote2 (MEMSIC, 2010), and it is stacked with a sensor board and a battery board as shown in Fig. 13. Two types of sensor boards, SHM-A and SHM-W sensor board have been developed by University of Illinois at Urbana-Champaign. SHM-A multi-scale sensor board is developed to measure 3-axis acceleration as well as temperature, humidity, and illuminance, whereas SHM-W sensor board is to measure wind speed and direction interfaced with an ultrasonic anemometer. The flexible framework for large-scale wireless smart sensor network proposed by Rice *et al.* (2010) are implemented in this research to minimize the power consumption of wireless smart sensors and automate the operation of SHM system.

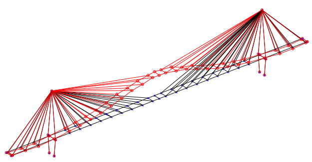


(a) Sensor Locations

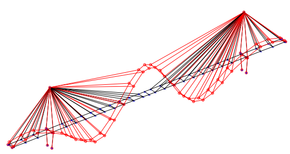
(b) Sensor node

Fig. 13 Sensor nodes deployed on the second Jindo Bridge (Spencer *et al*. 2016)

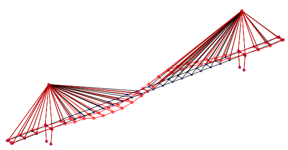
Total of 70 wireless smart sensor nodes were deployed on the bridge in the first year of the deployment (Jang *et al*. 2010), and they are extended to 113 nodes from the second year (Spencer *et al*. 2016). The nodes mainly measure 3-axis acceleration, except three wind-sentry nodes interfaced with anemometers. Fig. 13 shows the locations of 113 nodes. The whole network is composed of four sub-networks controlled by two base stations. Each base station takes charge of each half of the network (e.g., Haenam and Jindo sub-networks), and each sub-network is divided into two based on the locations of nodes (e.g., deck and cables). The cable nodes are programmed to monitor cable tension in the automated manner (Sim *et al*. 2014), and some of them were used to test the multi-hop communication (Spencer *et al.* 2016). The deck nodes employ decentralized data aggregation to efficiently utilize limited bandwidth by condensing sensor data (Sim *et al*. 2010). All sensor nodes were powered by solar panels with rechargeable batteries for sustainable energy harvesting.



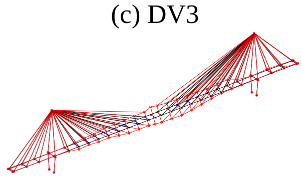
(a) DV1



(c) DV3



(b) DV2



(d) DT1

Fig. 14 Example mode shapes and MAC values correlating to FE model analysis (Spencer *et al*. 2016)

Table 1 Natural frequencies using wireless, wired monitoring system, and FE analysis (Spencer *et al.* 2016)

Modes	WSSN (Hz)		Wired system (Hz)	FE analysis (Hz)
	Haenam sub-network	Jindo sub-network		
DV1	0.4462	0.4462	0.4395	0.4422
DV2	0.6454	0.6471	0.6592	0.6471
DV3	1.0331	1.0326	1.0498	1.0010
DV4	1.3559	1.3421	1.3672	1.2472
DV5	1.5549	1.5490	1.5869	1.3490
DV6	1.6528	1.6346	1.6602	1.4596
DT1	1.7977	1.8022	-	1.7888
DV7	1.8710	1.8704	1.8555	1.5858
DV8	2.2594	2.2609	2.3193	2.1154
DV9	2.8121	2.8133	2.8076	2.5612

For output-only modal analysis, the stochastic subspace identification (SSI) method (Overschee *et al*. 1993) was employed to identify the modal properties using the acceleration data from the wireless smart sensor network. The modal analyses were independently carried out on the data from two sub-networks and combined subsequently. In Table 1, the natural frequencies obtained from the wireless system show excellent agreements with those obtained from the wired monitoring carried in 2007. They are also very close to those from FE analysis up the third vertical modes, while those for the higher modes are generally larger than FE results. The global mode shapes were constructed as shown in Fig. 14, and they showed good agreements with the FE analysis results with modal assurance criterion (MAC) values over 0.9.

4.3 Comparative study on cable tension measurement techniques

Cables are the primary load carrying members of long-span bridges such as cable-stayed bridges and suspension bridges. Cables may be damaged by corrosion or fatigue, and the damaged cable resists less force than the usual one. Thus, the integrity of cables is assessed by measuring the cable tension force. To compare the “pros and cons” of available cable tension measurement methods in the field, a test-bed for comparative study on cable tension measurement techniques has been developed on a cable-stayed bridge (Hwamyung Bridge) under construction in Korea (shown in Fig. 15). Among 72 cables hanging the bridge, two cables (BLC02 and BLC04) were selected as test cables. The comparative study was carried out by international collaboration between the US (Northeastern Univ.) and Korea (KAIST, Pukyong National University (PKNU) and Hyundai Engineering and Construction (HEC)). More specific and detailed information on the test-bed can be found in Cho *et al*. (2013) and Yim *et al*. (2014).

Three famous methods to measure cable tension were tested on the bridge: Lift-off test, an electro-magnetic (EM) sensor method, and vibration method. For two test cables, the lift-off test, the EM sensor method (Wang *et al*. 2006), and the vibration method (Shimada 1994) are carried out by HEC, Northeastern University, and KAIST-PKNU team. The lift-off test, which directly measures the tension of the cable using a load cell with pulling the cable, is carried out on the second tensioning stage after key segment installation to control the bridge shape, and the other tests followed the lift-off tests. The test setup of comparative study on a cable is shown in Figure 16. From this comparative study in field, the measurement accuracy, facility, and cost of three famous cable tension measurement methods are investigated to help the engineers and practitioners who have interests in the maintenance of cable-stayed bridges or cable-stayed structures (Cho *et al.* 2013).

4.4 Campaign test for displacement measurement techniques on suspension bridge

Due to the relative characteristic that requires a fixed reference point, displacement is considered hard to be measured on bridges using conventional contact-type transducers, such as LVDTs (linear variable differential transformers) or ring gauges. Thus, many alternative measurement devices or techniques have been developed for the bridge displacement. Researchers in Super Long Span Bridge Research Group of Korea developed a test-bed on a suspension bridge in Korea (Sorok Bridge shown in Fig. 17(a)) to test their alternative methods together. To the end, various sensors were installed on the bridge as Fig. 17(b): fiber Bragg grating (FBG) strain gauges (by Pusan National Univ. and Inha Univ.), accelerometers (by Seoul National University), a vision-based system (by Sejong Univ.), and a differential global positioning system (DGPS, by Hyundai Engineering and Construction).

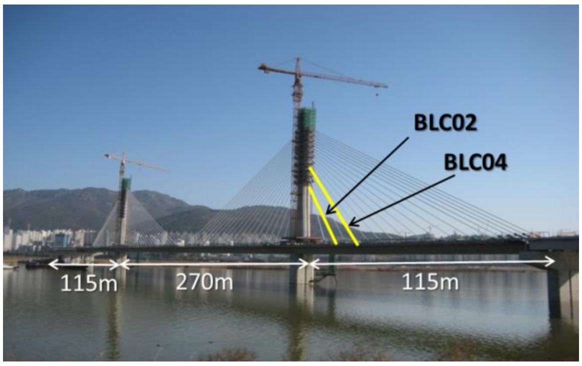


Fig. 15 Hwamyung Bridge and test cables

Fig. 16 Test setup for comparative study

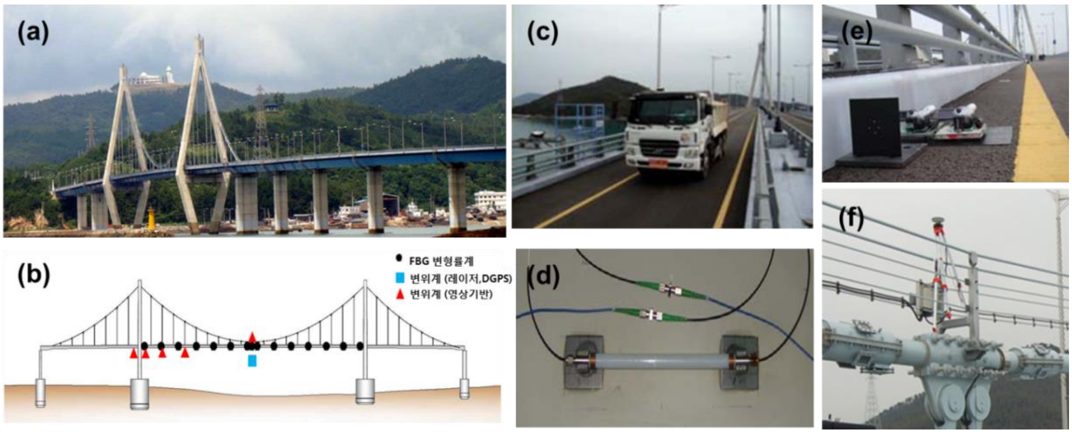


Fig. 17 Benchmark test on Sorok Bridge

A loading test is carried out to excite the bridge as shown in Fig. 17(c). The FBG strain gauges (Fig. 17(d)) are used to test indirect displacement measurement techniques by converting strain into displacement using modal mapping (Shin *et al.* 2009) and modal decomposition (Chang *et al.* 2009). An accelerometer can be converted into displacement using a finite impulse response (FIR) filter (Lee and Hong 2009). The vision-based system (Fig. 17(e)) measures displacement by recording video of a target attached on the bridges in noncontact manner (Lee *et al.* 2009). The DGPS (Fig. 17(f)) measures accurate displacement by referring to another global positioning system receiver installed at known coordinates (Kim and Seo 2009). The laser displacement meter that was permanently installed on the center of the mid-span is also used to provide a comparative displacement for the test.

5. Conclusions

In this paper, recent research trends and activities on SHM of civil infrastructure in Korea were reviewed. This review focused on smart sensing, monitoring, and assessment for civil infrastructure. Firstly, the research activities on smart sensor technology was reviewed including optical fiber sensors, piezoelectric sensors, wireless smart sensors, and vision-based sensing system. Then, a brief overview was given to the recent advances in smart monitoring and assessment techniques such as vibration-based global monitoring techniques, local monitoring with piezoelectric materials, decentralized monitoring techniques for wireless sensors, wireless power supply and energy harvest. Finally, recent joint SHM activities on several test beds in Korea were discussed to share the up-to-date information and to promote the smart sensors and monitoring technologies for applications to civil infrastructure, which included a Korea-US joint research on test bridges of the Korea Expressway Corporation (KEC), a Korea-US-Japan joint research on Jindo cable-stayed bridge, and comparative study for cable tension measurement techniques on Hwamyung cable-stayed bridge, and a campaign test for displacement measurement techniques on Sorok suspension bridge.

Acknowledgements

This work was supported by a Research Grant of Pukyong National University (2015 year).

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