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A remotely controllable structural health monitoring framework for bridges using 3.5 generation mobile telecommunication technology

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Abstract. A framework for structural health monitoring (SHM) systems is presented utilizing a recent 3.5 generation mobile telecommunication technology, HSDPA (High Speed Downlink Packet Access). It may be effectively applied to monitoring bridges, cut-slopes, and other facilities located in rural areas where the conventional Internet service is not readily available, since HSDPA is currently commercialized in 86 countries to make the Internet access possible in anywhere the mobile phone service is available. The proposed SHM framework is also incorporating remote desktop software to have remote control/operation of the SHM systems. The feasibility of the proposed framework has been demonstrated by field tests on a highway bridge in operation. One can expect that fast advances in the mobile telecommunication technology will further enhance the performance of the SHM network using the proposed framework for bridges and other facilities located in remote areas without the conventional wired Internet service.

Keywords: structural health monitoring; bridges; wireless internet; mobile telecommunication technology; and HSDPA.

1. Introduction

During the past two decades, the structural health monitoring (SHM) systems have been widely studied and implemented on many major bridges over the world, typically Great Belt Bridge in Denmark

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(Andersen and Pedersen 1994), Confederation Bridge in Canada (Cheung, *et al.* 1997), Tsing Ma Bridge in Hong Kong (Lau, *et al*. 1999), Commodore Barry Bridge in the U. S. (Barrish, *et al*. 2000), Akashi Kaikyo Bridge in Japan (Sumitro, *et al*. 2001), and Seohae Bridge in Korea (Kim, *et al*. 2002). It is expected that most of the major bridges will possess proper SHM systems in the near future.

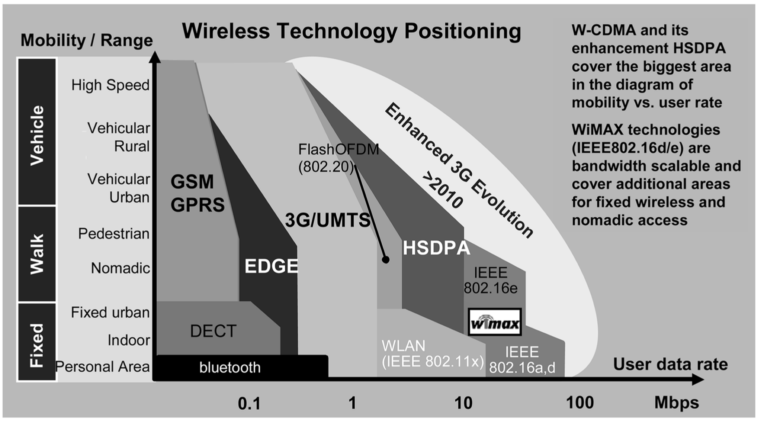
One of the fundamental obstacles in implementing SHM systems for bridges is to construct a communication network that connects bridge sites and the maintenance office. The conventional wired Internet services through telephone lines or cable TV lines are often unavailable in rural areas where bridges are commonly located. In such cases a private network line may be constructed, but the construction and maintenance cost would be significantly high in many cases. Mobile Internet service using CDMA (Code Division Multiple Access) mobile telecommunication network may be an alternative solution. But the speed of data transmission by the conventional CDMA is too slow, so it may be applied only to limited cases with small amount of data for transmission (Lee 2004).

A new 3.5 generation mobile telecommunication technology, HSDPA (High Speed Downlink Packet Access), has made the network implementation problem much easier and more tractable (Kwon 2005). HSDPA commercialized first in Korea is currently available in 86 countries (Global Mobile Suppliers Association, 2008). HSDPA has national-wide service coverage in those countries, so that practically any bridge site may be accessed with a high speed data transmission rate.

In this study, a SHM framework using HSDPA is presented incorporating remote desktop software. The proposed framework has a great advantage that it can be remotely controlled and maintained through Internet accessed by HSDPA at anytime and at any location where the mobile phone service is available.

2. A 3.5G mobile telecommunication technology: HSDPA

Many wireless communication technologies have been developed and available nowadays as shown in Fig. 1. These technologies can be characterized by two major features, mobility (range) and user data rate. In general, high mobility (long range) comes with slow user data rate such as GSM (Global System for Mobile communications), GPRS (General Packet Radio Service), and CDMA, while low mobility (short range) comes with high user data rate such as Wireless LAN (IEEE 802.11x) and WiMAX

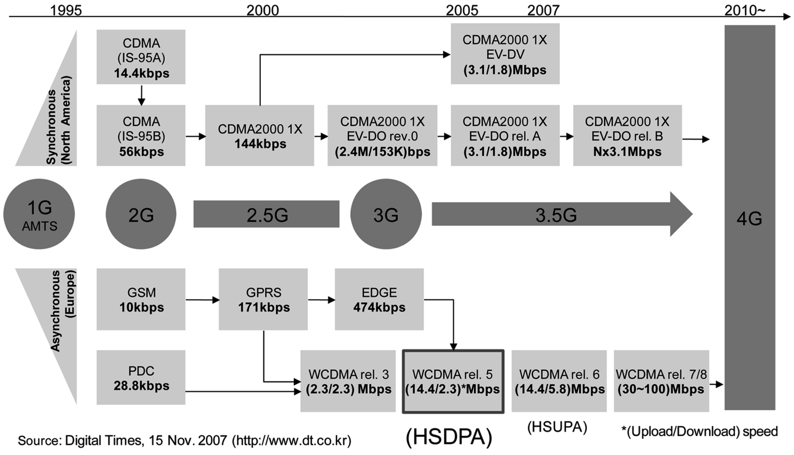


W-CDMA and its enhancement HSDPA cover the biggest area in the diagram of mobility vs. user rate

WiMAX technologies (IEEE802.16d/e) are bandwidth scalable and cover additional areas for fixed wireless and nomadic access

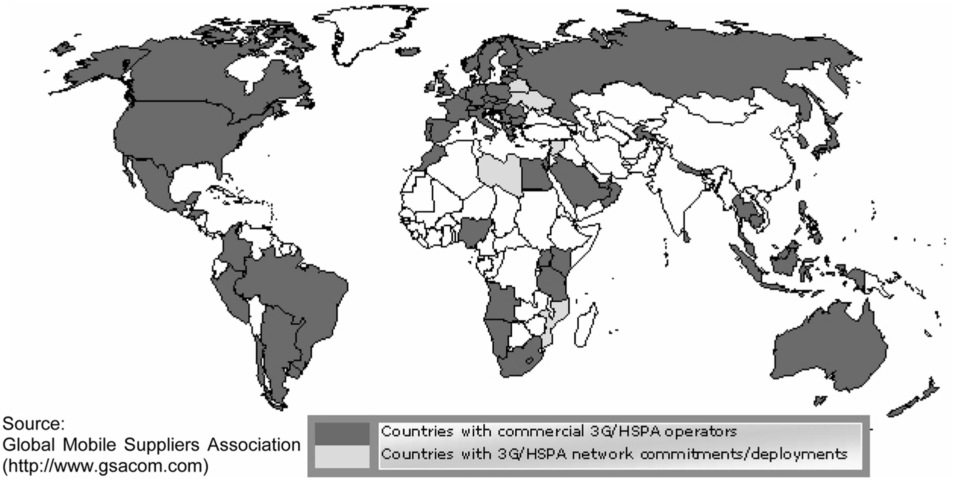
Source: International Telecommunication Union (ITU) website (http://www.itu.int)

Fig. 1 Wireless technologies positioning



Source: Digital Times, 15 Nov. 2007 (http://www.dt.co.kr)

Fig. 2 Evolutions in theoretical maximum data rate of mobile telecommunication technology



Source:
Global Mobile Suppliers Association
(http://www.gsacom.com)

Fig. 3 HSDPA networks

(Worldwide Interoperability for Microwave Access, IEEE 802.16 a/d). In particular, CDMA has a merit in the range of coverage over other technologies, since it has national-wide service area in many countries. So, it is very useful for the network implementation inter-connecting the maintenance office and rural bridge sites where the conventional wired Internet services are not readily available.

The mobile telecommunication technology has been evolved during the last three decades and is commonly categorized into four generations. 1G mobile telecommunication technologies were originally developed to communicate voices which are analog signal. However, 2G technologies, such as GSM, GPRS, and CDMA, employed digital data communication to transmit voice signal, so that Internet access became available using 2G technology. In 3G and 3.5G technologies, such as WCDMA (Wideband CDMA) and WCDMA-HSDPA, the user data rate has been significantly improved through the technological development as shown in Fig. 2. The most advanced technology available in the current market is HSDPA, which was commercialized first in Korea in 2006 and in 86 countries nowadays as shown in Fig. 3.

Upcoming technological evolutions in the mobile telecommunication will be commercially available very soon, and further enhance the performance of the wireless network implementation for the SHM systems in the near future. For example, another 3.5G technology, HSUPA (High Speed Uplink Packet Access) and HSPA+ (High Speed Packet Access Plus) will make the upload data transmission from bridge sites to maintenance offices much faster than the present HSDPA. Furthermore, it is expected that the speed of 4G technology would exceed the speed of the conventional 100 Mbps Ethernet network.

3. A remotely controllable SHM framework

3.1. Architecture

Fig. 4 shows the architecture of the proposed remotely controllable SHM framework. The key element in the architecture is the gateway computer with a HSDPA modem, which can access Internet and interconnect the local area network (LAN) at a bridge site and Internet. When the gateway computer is connected to Internet, the LAN becomes a part of Internet. Thus, all SHM systems and corresponding sub-systems installed at the bridge site can be accessed from the maintenance office through internet. Furthermore, it is desirable to have the on/off control of the Internet connection for efficient data communications. In other words, the Internet connec-tion may be turned on when data transmission is needed, while it may be turned off when data transmission is idle. This function can be controlled by sending SMS (Short Message Service) messages containing connection commands (i.e. on or off) to the HSDPA modem which has a unique mobile phone number as for the conventional mobile phone.

The present architecture has another special feature that the SHM system can be accessed, controlled and maintained by using remote desktop software such as RemoteDesktop® and Virtual Network Computing (VNC) programs. Users with administrator privilege can access computers at the bridge site to check the operation status and modify measurement/signal processing configurations. On the other hand, users with observer privilege can access the measured and processed data through web pages. Details of the remote desktop software are discussed in the subsequent section.

3.2. Remote control by remote desktop software

Remote desktop software is a system for remote access and administration which allows GUI applications to be run remotely on a server, while being displayed locally. There are several remote

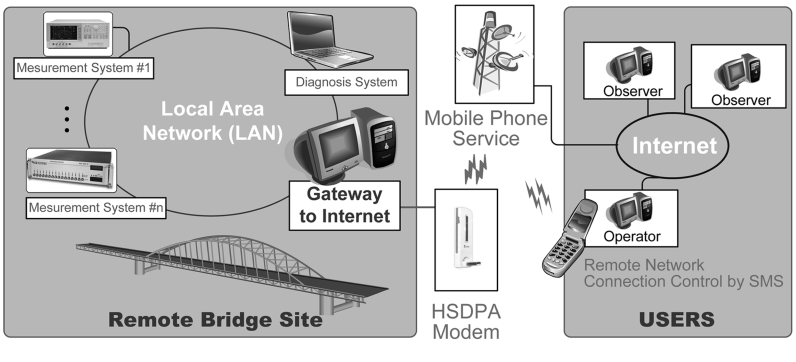


Fig. 4 Architecture of remotely controllable SHM framework

Table 1 Remote desktop environment under varying network speed

Speed of Network	Remote desktop environment
33 kbps	Sufficient for accessing desktops with very simple imagery, with reduced colorresolution and frame-rate
128 kbps	Sufficient for accessing desktops with simple imagery, with reduced color resolution
1 Mbps	Sufficient for accessing desktops with simple imagery in full color, or complex imagery with reduced color or frame-rate
100 Mbps	Most tasks will be indistinguishable performed remotely from if they were performed locally

desktop programs available in Windows, Linux, and other operating systems. Remote Desktop® in Windows XP® and Virtual Network Computing (VNC) programs are commonly used between Windows machines and between cross platforms, respectively. By using a remote desktop program, a user can access the host servers located at a bridge site to monitor and modify the SHM procedures.

Remote desktop software usually compresses the transferred image or reduces the number of the displayed colors to reduce the amount of data for transmission and to speed up the operation of the data transmission. Remote desktop environment under different network speeds is shown in Table 1. However, as the mobile technology evolves further, remote operations with full color may be possible.

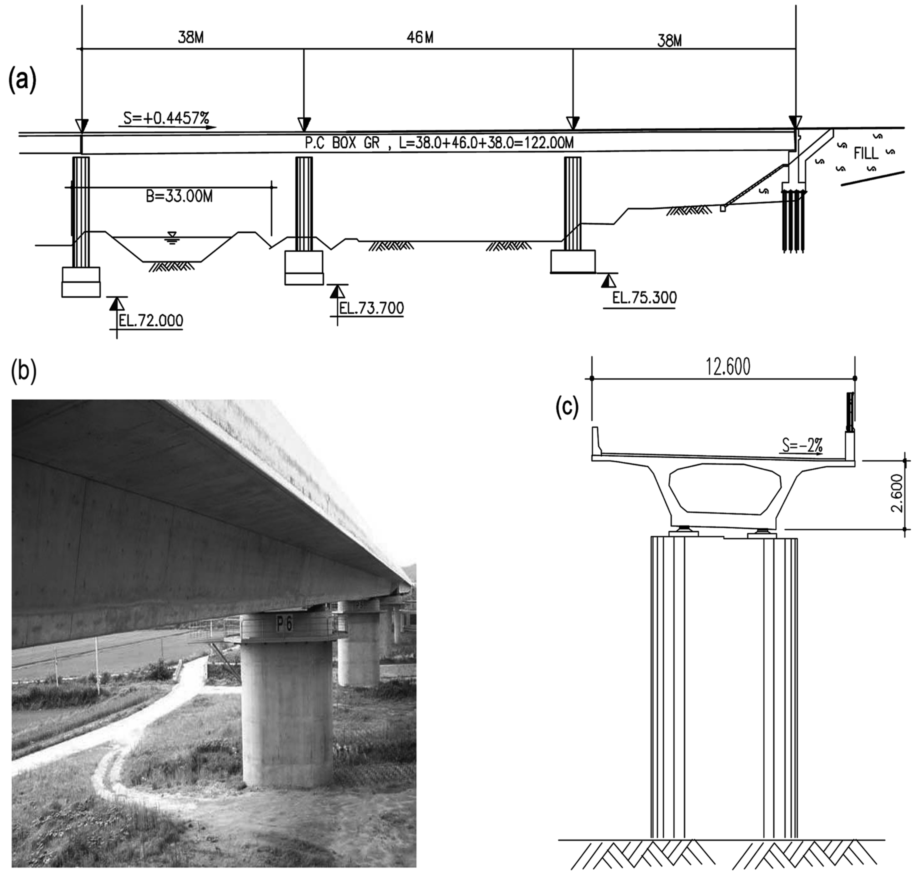


Fig. 5 Geumdang bridge: (a) Elevation view, (b) Perspective view, and (c) Typical cross-section geometry

Fig. 6 SHM system architecture implemented in Geumdang Bridge


(a) Measurement Server (b) Assessment Server

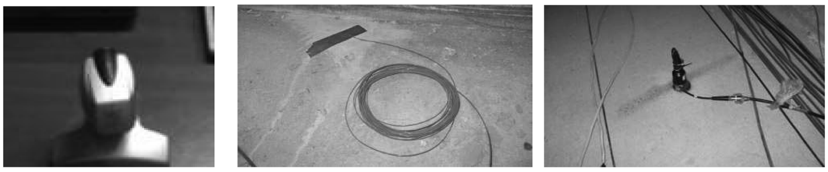
Fig. 7 Measurement and assessment servers

4. Field application

4.1. SHM system implemented on Geumdang Bridge

The feasibility of the proposed SHM framework was investigated on a highway bridge, Geumdang Bridge in Korea shown in Fig. 5, which is a 3-span continuous pre-stressed concrete box-girder bridge of 122(m) long. The box section is supported by three piers in addition to a bridge abutment. The placement of the bridge piers provides the box girder section with a mid span of 46 (m) and two side spans of 38 (m).

The SHM system architecture utilizing the proposed framework was depicted in Fig. 6. A HSDPA


(a) Camera (b) Thermo-coupler (c) Accelerometer

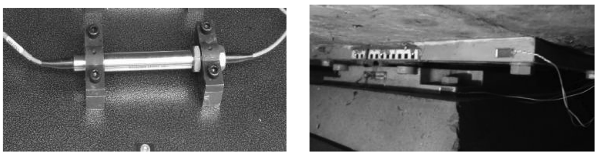

(d) Optical fiber sensor (e) Piezoelectric sensor

Fig. 8 Sensor types used for shm system

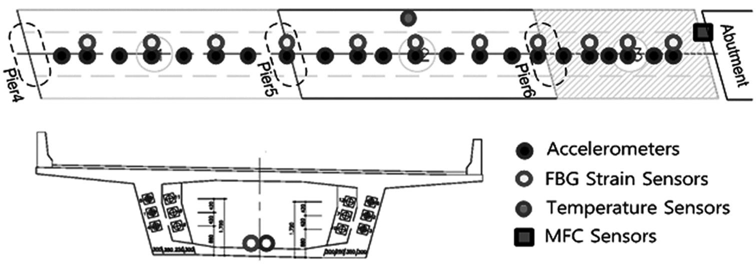


Fig. 9 Layout for sensor placement

modem (CHU-628S, SKTelecom) was used to access Internet, and its connection was controlled by SMS messages using a mobile phone. As shown in Fig. 7, two kinds of servers were used for reliable operations: 1) measurement server which takes care of measuring and archiving the structural responses, and 2) assessment server which takes charge in signal processing, structural health assessments, and displaying analysis results. The assessment server was also used as a gateway computer for data transmission.

Totally, 45 sensors were installed including 3 web-cameras for traffic and equipment monitoring, 3 thermo-couplers for temperature monitoring, 25 accelerometers for vibration monitoring, 11 FBG (fiber-brag grating) type optical fiber sensors for dynamic strain monitoring on the girder, and 3 MFC (macro-fiber composite) type piezoelectric sensors for impedance monitoring on a bridge bearing as shown in Figs. 8 and 9 show a layout for sensor placements on Geumdang Bridge. Continuous real-time monitoring was conducted during a period of three weeks. During the demonstration tests acceleration and dynamic strain measurements were continuously recorded for 20 minutes with 50 (Hz) sampling frequency at every 2 hours. The static measurements were repeated every 15 minutes. All the measured data were transmitted to the assessment server. Then, output-only modal analysis for the acceleration and dynamic strain measurements (Brinker, *et al.* 2001, Peeters and Roeck 2001) was carried out for global SHM scheme, while cross correlation-based analysis for the impedance measurements (Koo, *et al.* 2007) was performed for local SHM scheme. Details on the structural response measurements and their signal-processing results are described in Section 4.3.

The SHM system has functionality to report the structural integrity to the control office in real-time. Damage alarming shall be sent in real-time to the control office thought Internet or to the administrators by SMS, when abnormality is observed in structural behavior. Aforementioned automated procedures for periodic measurement, archiving, signal-processing and health assessment procedures were programmed mainly by MATLAB® and partially by LABVIEW®.

Average data rate attained by the present HSDPA modem was found to be 2.08 Mbps for downlink and 112 kbps for uplink. The data rate for the current measurements was found to be about 122 kbps (54 Mbyte/hour), so real-time data transmission of the measured raw signals to the maintenance office was not possible. Thus, it is more appropriate to send only small amount of data after signal processing and data mining are carried out in the assessment server at the bridge site. However, the above uplink data rate of the HSDPA is almost sufficient for accessing remote desktop with simple images and reduced color resolution as described in Table 1.

4.2. Remote control by remote desktop software

As discussed in the previous section, the uplink data rate attained by HSDPA modem was sufficient for

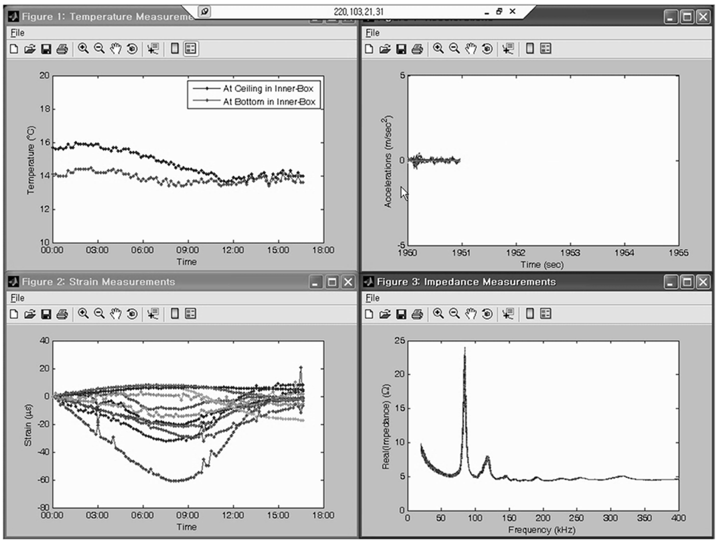


Fig. 10 Screenshot of measurement server connected by remote desktop® in Windows XP®

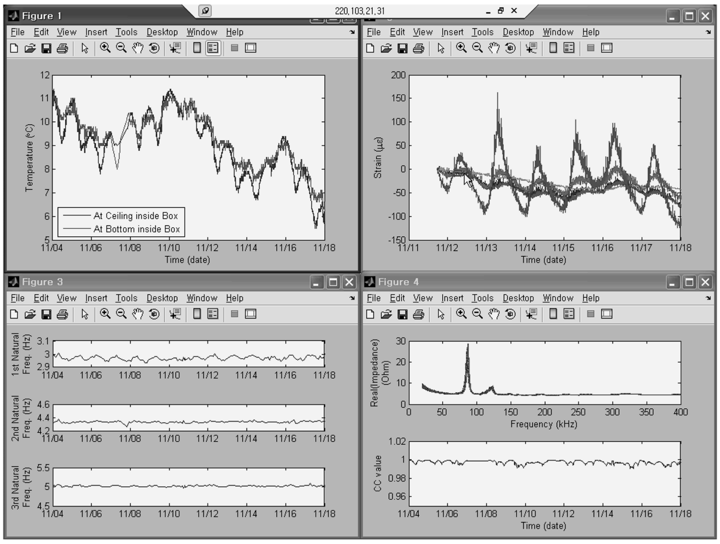


Fig. 11 Screenshot of assessment server connected by remote Desktop® in Windows XP®

accessing remote desktops by Remote Desktop Software with reduced color resolution. Both measurement and assessment servers at Geumdang Bridge site were connected and maintained successfully by Remote Desktop® in Windows XP®. Fig. 10 shows an example screenshot of the measurement server connected by Remote Desktop® application in Windows XP®. Real-time measurements of temperature, accelerations, dynamic strains, and impedances are displayed. Fig. 11 shows a screenshot of the assessment server, where the upper part displays the accumulated measurements of temperature and static strain, respectively, while the lower part presents the signal processing results for the modal analysis for the acceleration/dynamic strain measurements and the cross correlation analysis for the impedance signatures, respectively. Through the tests on Geumdang Bridge, it has been found that the present remote

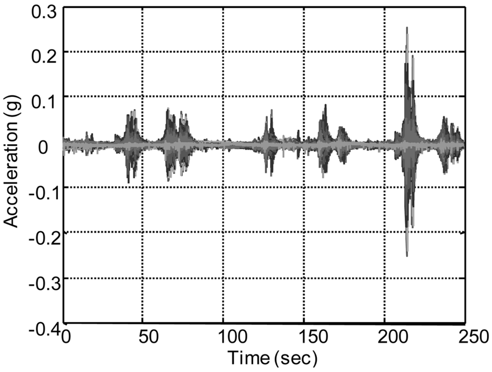


Fig. 12 Ambient acceleration measurements

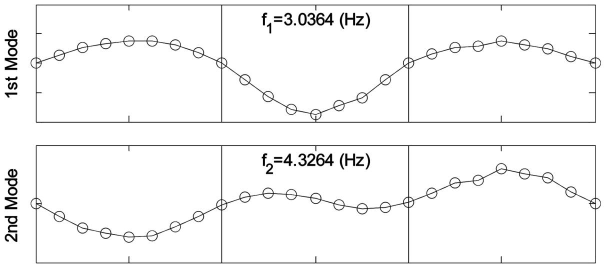


Fig. 13 Natural frequencies and mode shapes from the acceleration measurements

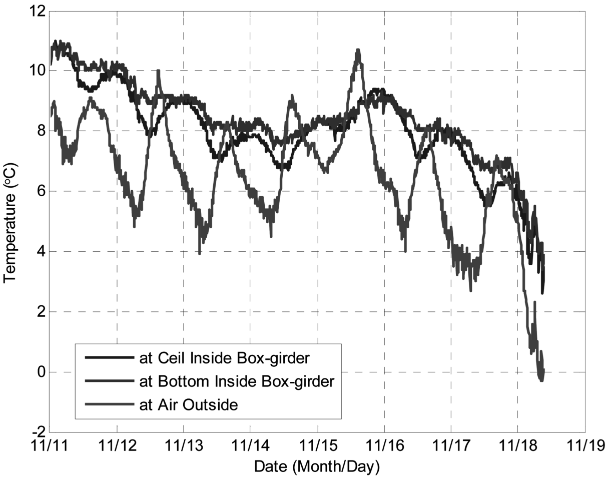


Fig. 14 Temperature measurements

desktop application is very practical and tractable enough to access, control and maintain the SHM systems under ambient field conditions at rural bridge sites.

4.3. Monitored structural behaviors

An acceleration measurement under traffic loads is shown in Fig. 12, and the estimated natural

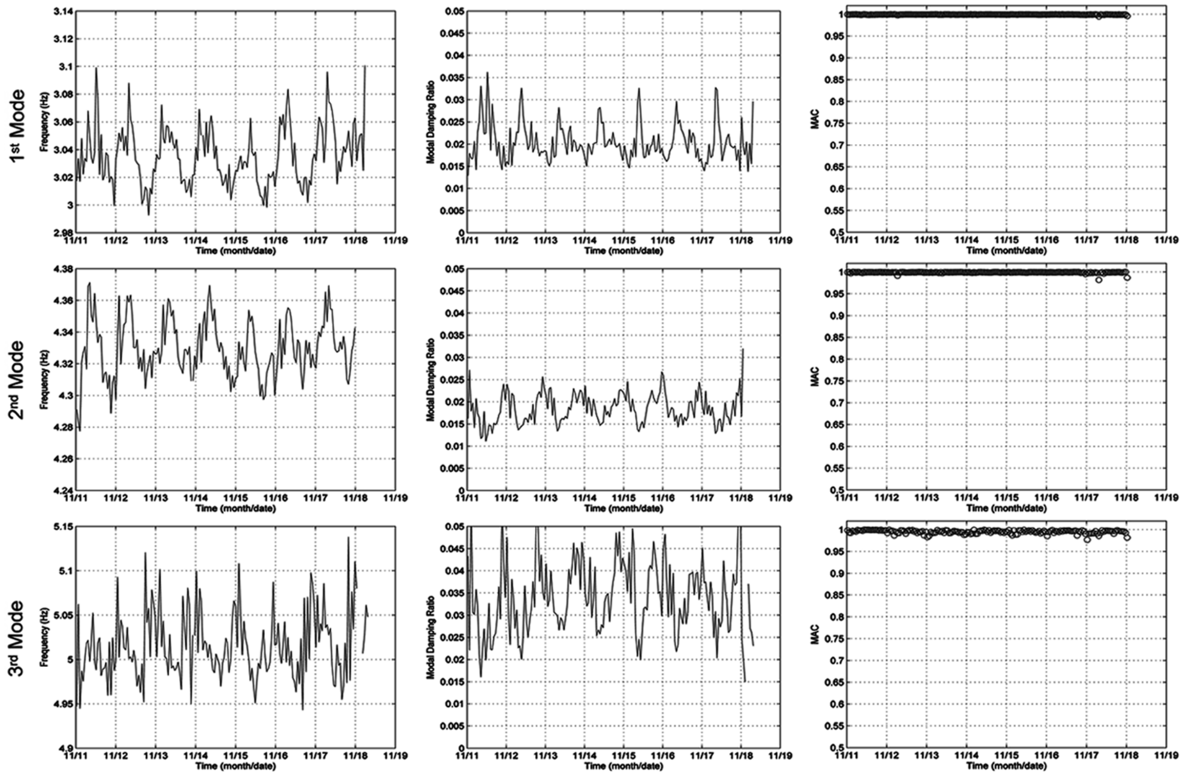


Fig. 15 Estimated natural frequencies, damping ratios, and macs for the first three modes

Table 2 Ambient deviations in estimated modal parameters from accelerations

Modes	Natural frequency		Damping ratio		MAC	
	Average (Hz)	Ambient deviation (%)	Average (%)	Ambient deviation (%)	Average	Ambient deviation (%)
1st	3.035	2.13	2.04	77	0.9994	0.46
2nd	4.330	1.22	1.84	47	0.9989	1.7
3rd	5.015	2.45	3.42	63	0.9949	1.8

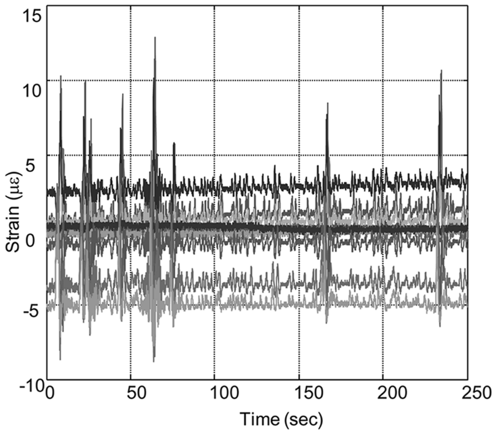


Fig. 16 Dynamic strain measurements from FBG sensors

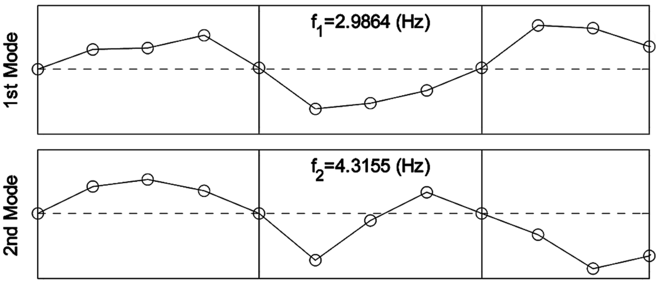


Fig. 17 Natural frequencies and strain mode shapes from dynamic strain measurements

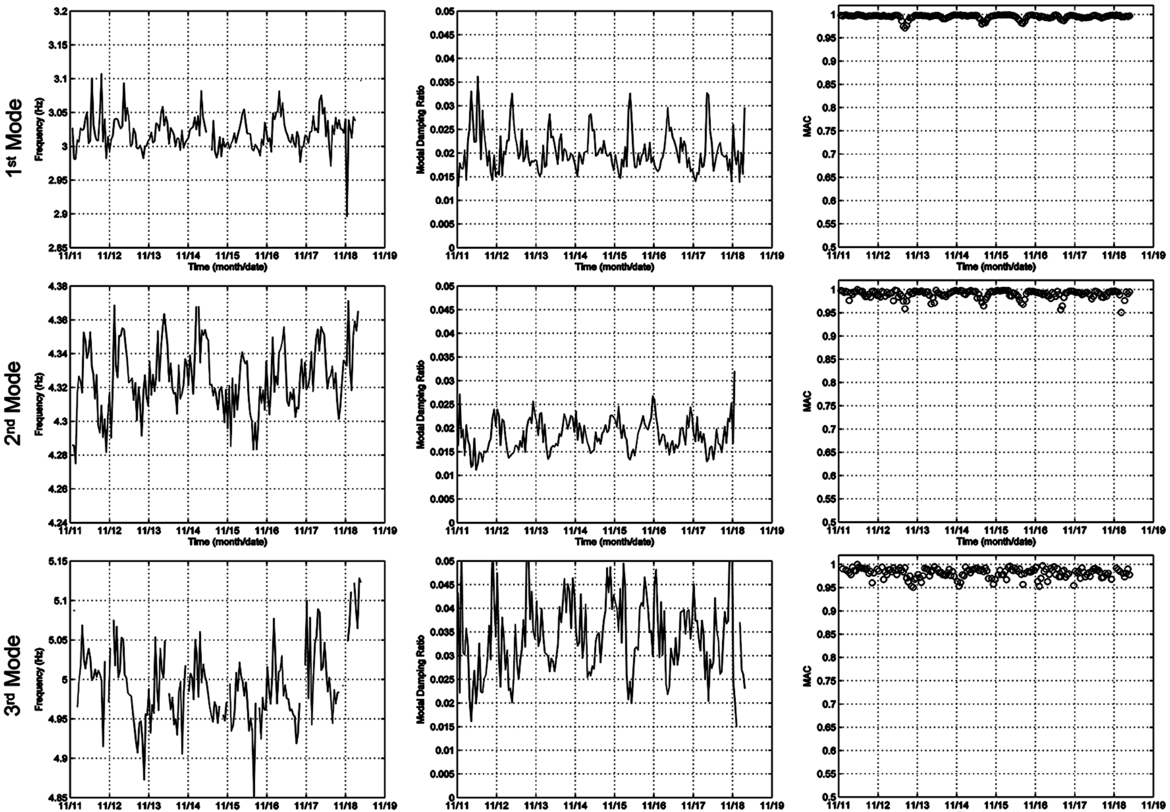


Fig. 18 Estimated natural frequencies, damping ratios, and macs for the first three strain modes

frequencies and mode shapes are shown in Fig. 13. As the ambient environment (i.e. temperature) changes as shown in Fig. 14, the estimated modal parameters fluctuated as in Fig. 15. During the measurement period of 8 days, about 2.1%, 1.2%, and 2.5% deviations were observed in the 1st, 2nd and 3rd natural frequencies with respect to the averaged values, as summarized in Table 2.

Dynamic strain measurements from FBG sensors are shown in Fig. 16. The estimated natural frequencies and strain mode shapes are shown in Fig. 17. It has been found that estimated modal parameters fluctuated as shown in Fig. 18. During the measurement period of 8 days, it was observed that the 1st, 2nd and 3rd natural frequencies had about 1.8%, 1.3% and 2.1% deviation with respect to the

Table 3 Ambient deviations in estimated modal parameters from dynamic strains

Modes	Natural frequencies		Damping ratios		MAC	
	Average (Hz)	Ambient deviation (%)	Average (%)	Ambient deviation (%)	Average	Ambient deviation (%)
1st	3.042	1.88	2.08	195	0.9994	3.37
2nd	4.327	1.3	2.07	58	0.9989	2.4
3rd	5.032	2.1	3.38	80	0.9949	3.1

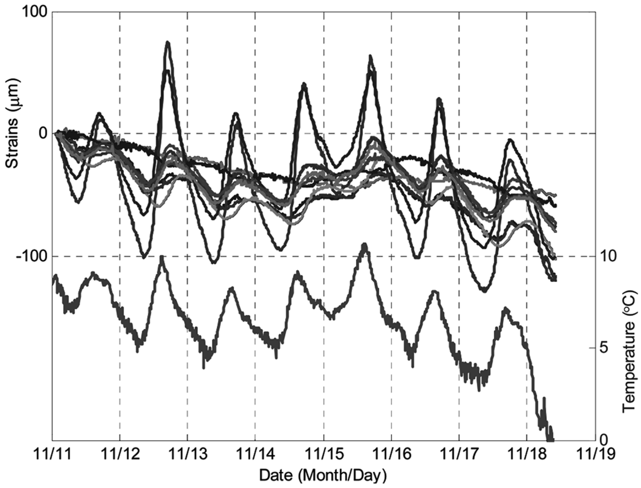


Fig. 19 Estimated static strain and temperature at the ceiling inside of box-girder

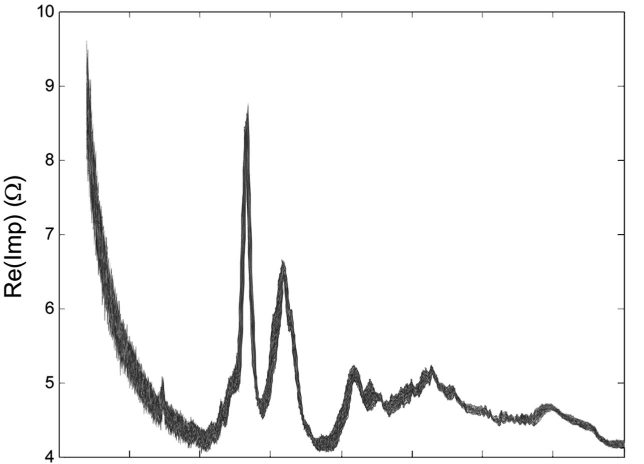
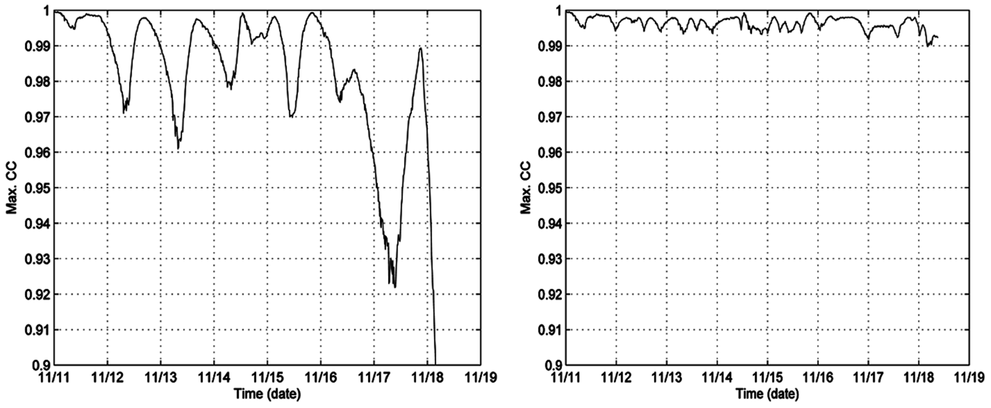


Fig. 20 Impedance measurements for varying temperature

average values, as summarized in Table 3. It is very interesting to observe that the estimated natural frequencies based on the acceleration data are almost identical to those based on the dynamic strain. Static strain measurements were estimated based on the dynamic strain measurements by applying a low-



(a) Maximum CC before EFS (b) Maximum CC after EFS

Fig. 21 Maximum cross-correlation coefficients (cc) before/after effective frequency shifts

pass filter in order to eliminate the vibration components as shown in Fig. 19. It has been found that the estimated static strains were highly correlated with the temperature inside the box-girder. This might be caused by the thermal strain of the structure and the temperature effect on the FBG strain sensors. Further investigations on the structural behavior are highly desirable considering temperature-compensation on the strain measurements. Fig. 20 shows impedance measurements during 8 days and it was found that there exist significant deviations in the impedance measurements. The effective frequency shift (EFS) method (Koo, *et al.* 2007) was employed to compensate the temperature effects. Figs. 21(a) and 21(b) show the maximum cross-correlation coefficient (CC) values of the impedance signatures before and after the EFS. The high values of CC (i.e. greater than 0.99) after EFS indicate that the EFS reasonably compensated the temperature effect.

4.4. Limitations and further improvements

The current SHM framework may have two limitations. One is the limitation on the data- transmitting rate achieved by HSDPA, which is still relatively slow compared to the conventional Ethernet with 100 Mbps. In general, the data-transmitting rate of HSDPA may be adequate to transfer static measurements, but not dynamic measurements. For an example, the average uplink speed of HSDPA at Geumdang Bridge was 112 kbps so that raw signal of dynamic measurements with data rate 122 kbps cannot be transferred to the control office in real-time as discussed in Section 4.1. Therefore, the color resolution of remote-desktop software had to be reduced for smooth operations. However, as discussed in Section 2, the data transfer rate is expected to be gradually increased due to technological evolution for mobile telecommunication such as HSUPA, HSPA+ and 4G technologies.

The other is the limitation on robust operation under unpredicted events such as power supply failure, server down and communication system down. When the gateway computer is not operational or inaccessible under these events, the remote SHM system will become useless. Thus, additional hardware systems may be needed to guarantee the gateway computer alive and to provide the functionality of the remote diagnosis and trouble shooting of the SHM systems.

5. Conclusions

This paper presents a novel framework of SHM systems utilizing HSDPA mobile telecommunication technology and remote desktop software. The proposed SHM framework shows great benefits such as remote control and operation of the SHM system and a low cost network implementation. The feasibility of the proposed framework has been demonstrated by a field application on a highway bridge at which the conventional Internet service is not available. By using a remote desktop program, a user could successfully access both measurement and assessment servers located at the bridge site, to monitor and modify the SHM procedures. It has been confirmed that the SHM system placed at a bridge site can be easily accessed via Internet from any place in real time by utilizing the HSDPA technology and remote desktop software.

Acknowledgement

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Nomenclature

AMTS : Advanced Mobile Telephone System
bps : Bits Per Second
CDMA : Code Division Multiple Access
GPRS : General Packet Radio Service
GSM : Global System for Mobile communication
HSDPA : High Speed Downlink Packet Access
HSPA+ : High Speed Packet Access Plus
HSUPA : High Speed Uplink Packet Access
SHM : Structural Health Monitoring
SMS : Short Message Service
VNC : Virtual Network Computing
WiMAX : Worldwide Interoperability for Microwave Access
WCDMA : Wideband CDMA

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