Structural Health Monitoring of Infrastructure Using Wireless Sensor System

Dae Woong Ha[1], Jun Su Park[1], Jong Moon Kim[2], Hyo Seon Park[1(✉)]

[1] Department of Architectural Engineering, Yonsei University,
50 Yonsei-ro, Seodaemun-gu, Seoul, Korea
{dwha,junsu,hspark}@yonsei.ac.kr
[2] D S Tek, Inc., 1112, 30, Digital-ro 32-gil, Guro-gu, Seoul, Korea
dstek@dstek.biz

Abstract. In recent years, developments in construction technology have resulted in structures increasing in both size and height, with related safety concerns also increasing. These structures may pose significant risks in scenarios where they suffer significant damage, for example, from external shock or the influence of aging. This paper proposes a wireless sensor structural health monitoring (SHM) system construction and operation method for the verification of structural safety and risk determination in real time. The method first selects the sensor location and type via a simulation of the response of the structure for the construction of the SHM system. The system wirelessly receives the data from the data acquisition system used to collect the data from the sensors attached to the structure. Empirical results obtained by applying the proposed system to the monitoring of the concrete wall of a liquefied natural gas (LNG) tank and measuring the response of the structure confirm the feasibility of our proposed method.

Keywords: Structural health monitoring · Wireless sensor system · Safety of infrastructures · LNG tank

1 Introduction

Concomitant with technological developments in the construction arena, construction of huge high-rise structures is on the increase around the world. Among the high-rise buildings built recently is the Burj Khalifa in Dubai, the tallest building at 828 m. Further, several other buildings around the world have heights in excess of 400 m.

Bridges spanning seas or rivers are also increasing in length and size. One such bridge is the Su-Tong Bridge in China, which has a length of 1088 m. In addition, there are several bridges that are over 800 m in length. Dams, power plants, and gas storage facilities are also constructed as large and complex structures.

When damage occurs in these kinds of infrastructure, the ripple effect is substantial. For example, the damage to the Fukushima nuclear power plant in Japan caused by the earthquake and tsunami in 2011 has led to an ongoing global threat of exposure to radiation.

N. Mitton et al. (Eds.): ADHOCNETS 2014, LNICST 140, pp. 228–234, 2014.
DOI: 10.1007/978-3-319-13329-4_20

Thus, monitoring is essential to ensure that structures and infrastructure are safe. In recent times, structural health monitoring (SHM) systems are being employed to manage structures and ensure that they are safe through real-time measurements.

In the construction of an SHM system, producing the greatest effect at the lowest cost is essential. Consequently, choosing appropriate sensors and the optimal placement position through response analysis of the structure are very important. In addition, a suitable system to obtain accurate data from the sensor is also necessary.

In this paper, we propose a wireless sensor SHM system and discuss empirical measurements of the response of the concrete wall of a liquefied natural gas (LNG) tank. We also discuss the structure of the data acquisition system and the wireless sensor system utilized. In addition, we examine the economy and reality of wireless sensor systems and the SHM system, and outline how they can be usefully applied to other infrastructure.

2 Sensor Specification

In the construction of an SHM system for structure monitoring, the type of sensor employed is important. It is necessary to select a sensor that is able to measure the response of the structure to changes in the ambient environment. Thus, in this section, we discuss several types of sensors that are capable of measuring such responses.

The first type of sensor is the strain gauge sensor, which can measure the strain on the structure. Strain refers to the deformation of a material. Thus, it is possible to measure the deformation of the section on which the sensor is installed using the strain gauge. Further, because strain can be converted to mechanical stress, it is also possible to simultaneously measure the stress on those sections. The strain gauge sensor can be used electrical resistance type, voltage type, and vibrations type according to the method used to obtain the data.

An accelerometer is a sensor that can measure the dynamic response of the structure. This type of sensor can be used to measure the response of a structure to earthquake and wind. Acceleration data are important for understanding the mode shape of the structure due to environmental changes. Piezoelectric, moving coil, and micro-electro-mechanical system (MEMS) sensor types are based on this measurement principle.

A displacement sensor can measure the horizontal and vertical movements of a structure. It is used to measure the displacement of the structure by an external force both during and after construction of the structure. In the case of high-rise structures, in particular, the horizontal displacement can affect usability. Therefore, the data obtained from this type of sensor are very important. There are both contact and non-contact displacement sensors; non-contact displacement sensors are used in the case of structures.

A load cell sensor measures the load on an installation position. It is used primarily to measure the axial force applied to the vertical members of a structure. If the structure is concrete, the deformation generated in response to the axial force acting on the material are used in measuring the amount of deformation.

An inclinometer is a sensor that measures the vertical structure and the horizontal tilt. In order to measure the perpendicularity during the construction of high-rise structures, it is installed on the vertical member. It is also installed on the horizontal member in order to measure the horizontal tilt of the structure. It can also be used to measure the horizontal displacement of the ground below, especially uneven settlement of the ground, in order to guarantee safety. This sensor can be electric type, MEMS type, or optic type, according to the measuring element.

An anemometer is a sensor that is placed on the top of the structure. This sensor measures the wind speed and wind direction. The influence of the wind varies according to the shape and position of the structure; therefore, wind speed data are required. It is possible through analysis of the data to also know if the wind results in vertical and horizontal displacement of the structure

3 Proposed Wireless Sensor System

Because the structures we want to monitor are large, the amount of data obtained from the many sensors installed is also significant. In order to transfer such large amounts of data, more cable is required than the number of sensors installed.

However, cable installation is expensive and it is also difficult to work with cabling. Further, if the amount of cable used for data transfer is large, the accuracy of the data may decrease.

Consequently, we propose using a wireless sensor system in order to avoid these problems. A wireless sensor system is economical because there is no need for cables, and it is also suitable for structures that are difficult to access

The wireless sensor system proposed in this paper comprises sensors, sensor nodes and a monitoring server. The sensor nodes comprise slave nodes and master nodes.

The wireless sensor system can be divided into three stages.

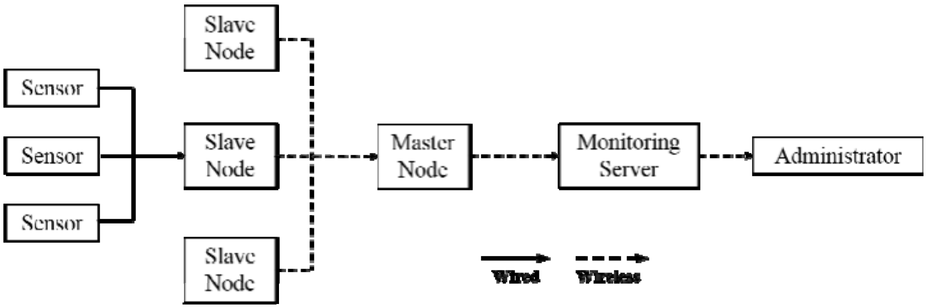

Fig. 1. Wireless sensor system

The first stage consists of slave nodes connected by wires to sensors. These slave nodes have multiple channels; consequently, they can receive data from multiple sensors concurrently.

The second stage comprises short-range wireless communication between the master and slave nodes. The slave nodes transmit sensor data to the master node via radio-frequency (RF) waves.

The third stage comprises wireless communication with the monitoring server and the master nodes. In long distance communication scenarios, code division multiple access (CDMA) is used.

The sensors are connected in parallel by wire to the slave nodes; the length of wire used is minimized. The slave nodes convert the analog data measured by the sensors into digital data. The sensor data collected in this way are sent to the master node over a relatively short distance. Short-range communication, 424 MHz ultra-high frequency (UHF) RF, is used. Texas Instruments CC1020 microprocessors are used in the wireless data conversion devices.

Each master node is installed in a position where it is possible to communicate with multiple slave nodes. Further, each master node is responsible for transmitting the data received from the slave nodes directly to the monitoring server in a remote location via CDMA, the long-range communication method used. CDMA effectively minimizes the effect of several disorders around the structure.

The monitoring server analyzes the data coming from each location and reports to the administrator in real time. The administrator subsequently uses the analyzed data to determine the safety of the structure.

4 Application to the Concrete Wall of an LNG Tank

We applied the wireless SHM sensor system to the monitoring of the concrete wall of an LNG tank. We simulated the responses of the structure through structural analysis of the LNG Tank to construct the SHM system, and thereby determined the best sensing position for the sensor. Figs. 2(a) and (b) show the position of the sensor installed on the structure.

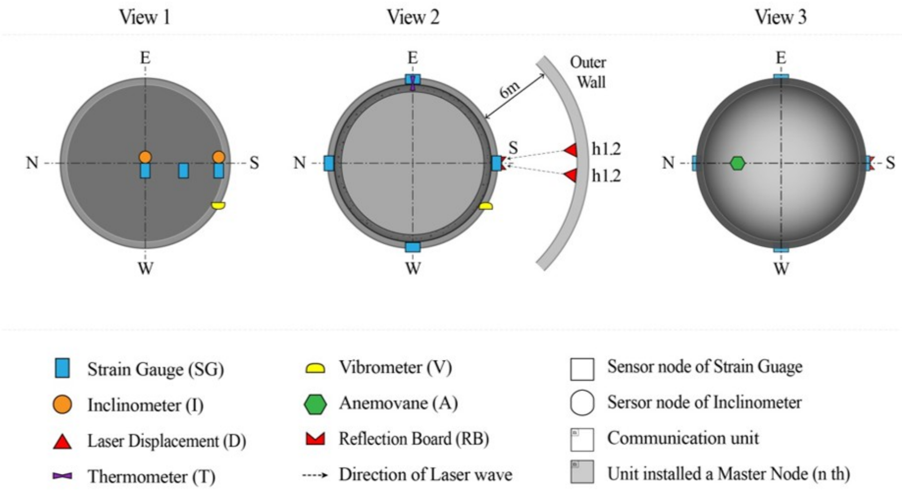

Fig. 2. (a) The installed sensor position (plane)

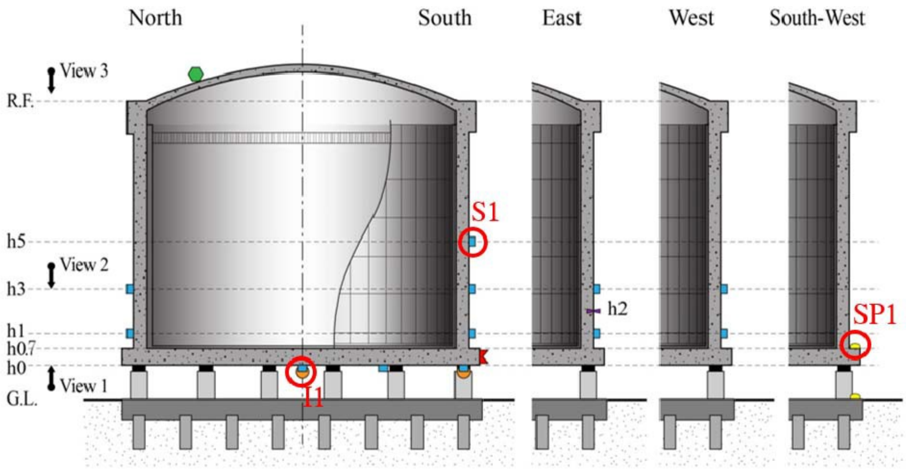

Fig. 2. **(b)** The installed sensor position (elevation)

Examples of the resulting data from each sensor measured over a period of time are displayed in Fig. 3.

The strain and temperature data were measured once every 5 h, about five times per day. The speed data were measured approximately six times per hour via a dynamic sensor. Further, the inclination was measured once every 5 h, about five times per day.

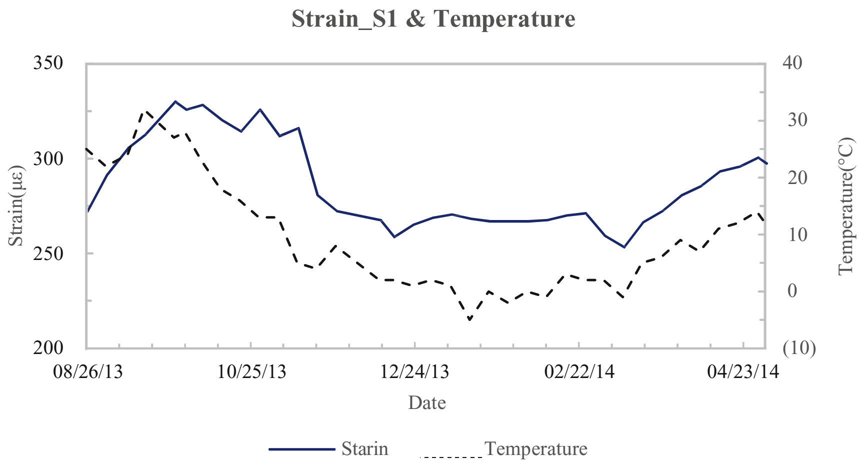

Fig. 3. Strain and Temperature data

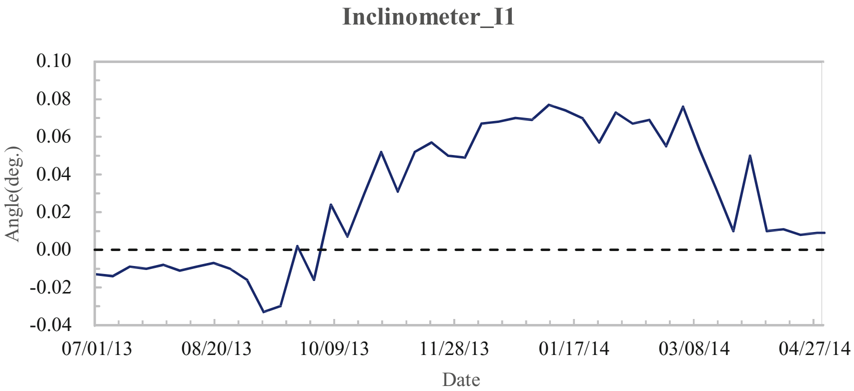

Fig. 4. Inclination data

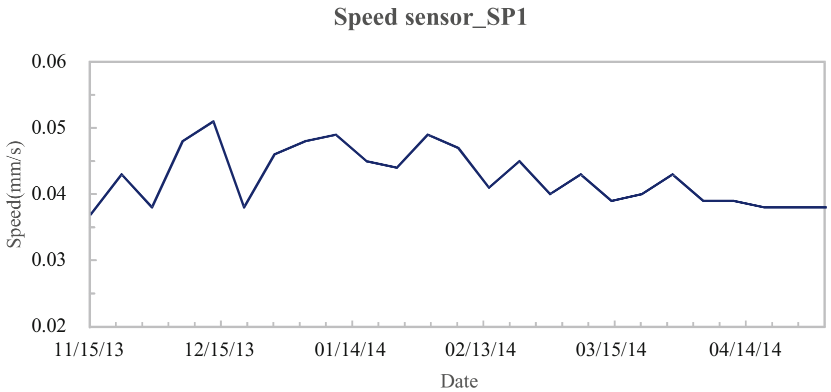

Fig. 5. Speed data

Fig. 3 shows that the strain is directly proportional to the temperature changes. Considering that it is a concrete structure, the strain value between 250 με and 350 με is a relatively small value. Thus, the strain occurring at the installation can be accorded to temperature changes.

We used a speed sensor instead of an accelerometer. A speed sensor can also be a part of an accelerometer. The results of the data analysis indicate that the speed range, 0.03 mm/s to 0.05 mm/s, is safe. The value obtained by the inclinometer placed on the floor of the structure does not exceed 0.077°, the maximum value, which indicates safety.

There were no major problems affecting the measurement because no significant meteorological activity occurred during the measurement period.

5 Conclusion

In recent years, developments in construction techniques have resulted in an increase in the construction of large high-rise structures. When damage occurs in such structures, especially social infrastructures such as bridges, dams, and power plants, the effect of the damage is felt over a very wide area. By monitoring the safety of such structures using an SHM system, when emergencies occur, damage can be minimized.

Consequently, in this paper, we proposed a wireless sensor SHM system and applied it to an actual structure (the concrete wall of an LNG Tank), an examined its efficacy. It was possible to collect and analyze the data obtained from the sensors installed, and to predict the response of the structure to determine whether it was behaving stably within certain standards. Our proposed system made it possible to observe at a glance the changes occurring in the structure overall, and to perform efficient monitoring. Further, our proposed system makes it possible to ensure safety by immediately responding to any risk factor observed consequent to viewing the data in real time using the wireless sensor system, and to extend the life of the structure.

Using the proposed monitoring system, we were able to analyze the LNG Tank during its operation via the data collected from the sensors in the concrete wall of the LNG Tank. Future monitoring systems will need to be able to monitor structures continuously from construction to completion.

Acknowledgments. This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korea government (MSIP) (no. 2011-0018360).

References

1. Lynch, J.P., Loh, K.J.: A Summary Review of Wireless Sensors and Sensor Networks for Structural Health Monitoring
2. Chang, P.C., Flatau, A., Liu, S.C.: Review Paper : Health Monitoring of Civil Infrastructure, SAGE journals (2003)
3. Joseph, P., Robert, S., Alan, M., David, C., John, A.: Analysis of Wireless Sensor Networks for Habitat Monitoring, Wireless Sensor Networks, pp 399–423 (2004)
4. Farrar, C.R., Worden, K.: An introduction to structural health monitoring. Phil. Trans. R. Soc. A **365**, 303–315 (2007)
5. Jerome Peter Lynch: An overview of wireless structural health monitoring for civil structures, Phil. Trns. R. Soc. A **365**(345), 372 (2007)