LONG-TERM MONITORING OF SEOHAE CABLE-STAYED BRIDGE USING GNSS AND SHMS

J. C. Park¹ and J. I. Shin² and H. J. Kim³

ABSTRACT

The Seohae cable-stayed bridge, a 990-m long composite cable-stayed bridge, had a structural health monitoring system (SHMS) that was designed in the design and construction stage. The SHMS for the bridge was renovated in 2009. One of the main features of the renovation project was the installation of the global navigation satellite system (GNSS) to improve the disadvantages and limitations of traditional sensors. Based on the GNSS and SHMS monitoring, the long-term displacements and dynamic characteristics of the bridge were evaluated in this paper. Using the least-squares method to fit the temperature-displacement relationship, the measured variation rate of displacement to temperature was obtained and compared with the theoretical value. Dynamic characteristics such as the natural frequencies and mode shapes have been successfully extracted from the GNSS signals.

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The Seohae cable-stayed bridge, a 990-m long composite cable-stayed bridge, had a structural health monitoring system (SHMS) that was designed in the design and construction stage. The SHMS for the bridge was renovated in 2009. One of the main features of the renovation project was the installation of the global navigation satellite system (GNSS) to improve the disadvantages and limitations of traditional sensors. Based on the GNSS and SHMS monitoring, the long-term displacements and dynamic characteristics of the bridge were evaluated in this paper. Using the least-squares method to fit the temperature-displacement relationship, the measured variation rate of displacement to temperature was obtained and compared with the theoretical value. Dynamic characteristics such as the natural frequencies and mode shapes have been successfully extracted from the GNSS signals.

Introduction

Maintenance of bridges is becoming more and more important issue as structures are getting longer and more complicated. The structural health monitoring system (SHMS) of long-span cable-supported bridges has gained acceptance for use as an effective bridge maintenance tool. Lots of cable-supported bridges are monitoring lately with permanent systems, which incorporates a large number of different sensors and equipment. These systems have proved to be valuable tools for long-term maintenance by providing information on the performance and structural condition of cable-supported bridges. However, the systems in early applications showed some problems such as short service life, measurement limitations, massive data, and frequent repairs. To overcome these problems, state-of-the-art technologies like the global navigation satellite system (GNSS) and ICT-based solutions are world-widely developed and applied to the recent SHMSs.

The Seohae cable-stayed bridge, a 990-m long composite cable-stayed bridge, had a SHMS that was designed in the design and construction stage. After more than 9 years of the operation, the system started to show signs of aging and deterioration. The SHMS renovation project was planned and carried out in 2009 [1]. One of the main features of the renovation project was the installation of the GNSS to improve the disadvantages and limitations of traditional sensors. Based on the long-term monitoring data of the GNSS and SHMS, the structural behaviors of the bridge are presented in this paper. Specially, it focuses on the

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long-term displacements and dynamic characteristics of the bridge. Their results are compared to those of traditional sensors such as displacement transducers and accelerometers.

Description of Seohae Bridge

The Seohae Bridge, which opened to traffic in November 2000, is located approximately 65 km south of Seoul in Korea. The total length of the bridge is 7.31 km and it consists of a 990-m long cable-stayed bridge and two different types of pre-stressed concrete (PSC) box girder bridges. The cable-stayed bridge consists of three cable-stayed spans of 200 m + 470 m + 200 m and two 60-m long end spans of simply-supported composite girders (Fig. 1). The deck cross section consists of two longitudinal steel girders spaced 34-m apart, with steel floor beams between these edge girders at 4.1 m on center, and precast concrete panels. The two pylons are H-shaped concrete structures that reach 187 m above sea level. The three cable-stayed spans are supported by a total of 144 cables, ranging in length from 54 to 247 m.

The bridge carries six lanes, three lanes in each direction, with an average daily traffic of approximately 78,000 vehicles. The operation and maintenance of the bridge is performed by Korea Expressway Corporation.

Figure 1. Elevation drawing of Seohae cable-stayed bridge

Structural Health Monitoring System

System Overview

After years of research and development, the SHMS for the bridge was installed in 2000. The system has been successfully operated and helped to understand the structural responses and long-term behaviors of the bridge [2]. After more than 9 years of the operation, the system started to show signs of aging and deterioration. Some of the sensors, data loggers, and accessories have worn out and become malfunctioned. To solve these problems and upgrade the system, the renovation project was planned and carried out in 2009. The main renovation works were to optimize sensor deployments, to improve graphical user interfaces, and to deploy state-of-the-art technologies like the GNSS. Six GNSS receivers were newly installed on the bridge to monitor the static and dynamic behaviors of the stiffening girders and the main pylons (Fig. 2). Four temperature sensors were added to the precast concrete panels as well as the previously installed steel girders, stay cables, and concrete pylons.
Figure 2. Sensor layout of Seohae cable-stayed bridge

The locations of GNSS receivers were determined by a variety of factors, including long-term behaviors, temperature-induced behaviors, natural frequencies and mode shapes, critical sections for design loads, and measurement data continuity between old and new SHMSs. As a result, the GNSS receiver of each 200-m long side span is located 143 m apart from the pylon rather than in the middle of the side span.

System Operation

The real-time continuous monitoring data from the bridge is sent over an optical fiber network to the maintenance office and stored in the server. It is also possible to log into the system via the internet and watch the real-time and stored data. The system continuously provides an overview of the structural health of the entire bridge. The normal logging procedure is to sample traditional sensors at 100 Hz and GNSS receivers at 20 Hz. At the end of each 10 minute sampling, statistics such as maximum, mean, minimum, standard deviation, kurtosis, skewness, median, etc. are calculated for each sensor and stored in the database. The system has been used individually or in combination with the other systems such as the Road Weather Information System, the Freeway Traffic Management System, the Bridge Management System, the Variable Message Signs, and CCTVs.

Long-term Monitoring Results

Long-term Displacements

As well as six GNSS receivers, the applicable sensors to measure the displacements of the bridge are one laser-based displacement transducer, two joint displacement transducers, and six tiltmeters as shown in Fig. 2. Sensor type, location and notation selected for the long-term analysis are listed in Table 1. Each GNSS receiver measures the transmitting time of GNSS
signals emitted from four or more GNSS satellites and these measurements are used to obtain its position (i.e., spatial coordinates) and reception time. Generally, the displacement meaning a position’s change is defined by the North-East-Up coordinates. Therefore, coordinate transformations were performed to obtain longitudinal, transverse and vertical displacement components of the bridge.

Table 1. Definition of sensor type, location and notation

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Location</th>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS receiver</td>
<td>North side span</td>
<td>NSWE-*</td>
<td>L: longitudinal</td>
</tr>
<tr>
<td></td>
<td>Top of pylon PY1</td>
<td>NPWE-*</td>
<td>T: transverse</td>
</tr>
<tr>
<td></td>
<td>Main span (east girder)</td>
<td>MSEA-*</td>
<td>Z: vertical</td>
</tr>
<tr>
<td></td>
<td>Main span (west girder)</td>
<td>MSWE-*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Top of pylon PY2</td>
<td>SPWE-*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>South side span</td>
<td>SSWE-*</td>
<td></td>
</tr>
<tr>
<td>Joint displacement</td>
<td>Top of pier P39</td>
<td>EXP_P39</td>
<td></td>
</tr>
<tr>
<td>transducer</td>
<td>Top of pier P42</td>
<td>EXP_P42</td>
<td></td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>Steel girder at L17</td>
<td>T-L17x-xF</td>
<td>6 ea</td>
</tr>
<tr>
<td></td>
<td>Concrete panel at L17</td>
<td>T-L17x-xS</td>
<td>4 ea</td>
</tr>
</tbody>
</table>

To evaluate long-term temperature-induced behaviors, the measured data of traditional sensors and GNSS receivers from 2010 to 2012 were used in the analysis. Figs. 3 and 4 show typically the temperatures and thermal movements measured by traditional sensors, respectively. Figs. 5 and 6 show the longitudinal displacements measured by GNSS receivers at each side span. It can be seen that the thermal movements and longitudinal displacements tend to have seasonal changes according to temperature variations.

The bridge displacement due to the thermal effects is related to the temperature of the members such as girder, deck, pylon, and stay cable. The thermal movement of members can be represented by the effective temperature, a theoretical temperature calculated by weighting and adding temperatures measured at various locations within the cross-section. The weighting is the ratio of the sub-area of the cross-section for a particular sensor to the total area of cross-section [3]. It is reasonable to estimate the effective temperature considering the direction of thermal movements. For example, the temperatures measured at the floor beam between two edge girders (section L17) almost do not contribute to the longitudinal thermal movements of the bridge. Considering this fact, the effective temperatures were calculated. Figs. 7, 8, 9 and 10 show the relationships between the effective temperatures ($T_e$) of the section L17 and thermal movements measured at some locations of the superstructure. Linear relationship can be observed for the longitudinal displacement responses in all locations.

Using the least-squares method to fit the temperature-displacement relationship, the following linear function can be obtained.

$$D = S_m \cdot T + C$$

where $D$ is the displacement (mm), $S_m$ is the slope that actually means the measured variation rate of displacement to temperature (mm/°C), $T$ is the temperature (°C), and $C$ is the constant. The thermal movement in design can be determined as:
Figure 3. Temperatures at section L17

Figure 4. Thermal movements at pier P39

Figure 5. Longitudinal displacements at NSWE location

Figure 6. Longitudinal displacements at SSWE location

Figure 7. Relationships between $T_e$ and EXP-P39

Figure 8. Relationships between $T_e$ and EXP-P42
\[ \Delta T = \alpha \cdot \Delta T \cdot L \]  

(2)

where \( \Delta T \) is the thermal movement (mm), \( \alpha \) is the coefficient of thermal expansion (mm/mm/°C), \( \Delta T \) is the temperature variation (°C), and \( L \) is the expansion length (mm). Eq. 2 can be expressed as:

\[ \frac{\Delta T}{\Delta T} = \alpha \cdot L \]  

(3)

Applying \( \Delta T = 1 \) °C in Eq. 3, define \( S_T \) as:

\[ S_T = \frac{\Delta T}{1} = \alpha \cdot L \]  

(4)

where \( S_T \) is the theoretical variation rate of displacement to temperature (mm/°C). Comparing \( S_T \) with \( S_m \), the structural soundness of a bridge for the thermal movement can be evaluated. Table 2 summarizes the comparison results of the Seohae cable-stayed bridge. It is observed that the measured \( S_m \) at each location is almost the same order as the theoretical \( S_T \). It is concluded that the bridge’s thermal behaviors are healthy.

Table 2. Comparisons of the variation rate of displacement to temperature

<table>
<thead>
<tr>
<th>Notation</th>
<th>EXP_P39</th>
<th>NSWE</th>
<th>NPWE</th>
<th>MSWE</th>
<th>SPWE ( ^2 )</th>
<th>SSWE</th>
<th>EXP_P42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion length (m)</td>
<td>730</td>
<td>613</td>
<td>470</td>
<td>235</td>
<td>0</td>
<td>143</td>
<td>260</td>
</tr>
<tr>
<td>Variation rate of displacement to temperature (mm/°C)</td>
<td>( S_T )</td>
<td>7.30</td>
<td>6.13</td>
<td>4.70</td>
<td>2.35</td>
<td>0</td>
<td>1.43</td>
</tr>
<tr>
<td></td>
<td>( S_m )</td>
<td>7.497</td>
<td>6.230</td>
<td>4.410</td>
<td>2.123</td>
<td>0.277</td>
<td>1.953</td>
</tr>
</tbody>
</table>

Note 1: When \( \alpha = 0.000010 \) (for concrete) \( \sim 0.000012 \) (for steel)

Note 2: Origin point for longitudinal thermal movement

Fig. 11 shows the relationships between expansion lengths (L) and measured \( S_m \) at each location of the bridge. Strong linear relationship can be observed. A slope is obtained by
using the least-squares method to fit the $L$ and $S_m$ relationship. This slope means the measured coefficient of thermal expansion ($\text{mm/mm/}^\circ\text{C}$) physically. In case of the Seohae cable-stayed bridge, the measured coefficient of thermal expansion is $0.0106\times10^{-3}$ (unit calibration) $= 0.0000106$, which is reasonably within the coefficients of concrete and steel.

![Graph showing the relationship between L and S_m](image)

Figure 11. Relationships between $L$ and $S_m$

**Dynamic Characteristics**

Typically, the GNSS has been used for measuring the static or dynamic displacements of cable-supported bridges [4]. Accelerometers are mostly used for measuring vibration and extracting the dynamic characteristics of general or cable-supported bridges. As shown in previous Fig. 2, 21 accelerometers to measure ambient vibration responses are installed at the girders and pylons. The uni-axial accelerometers with $\pm1g$ full-scale are the force-balance type that can measure low frequency band ranging from 0.01 to 50 Hz. Ambient vibrations of the bridge are measured continuously.

Several studies have been performed to expand the utilization of the GNSS to the measurement area of traditional sensors [5]. Xu et al. showed that the natural frequencies of a suspension bridge could be obtained from the GNSS-based monitoring [6]. Based on the real-time kinematic GNSS monitoring data of the Seohae cable-stayed bridge, the extraction of mode shapes as well as natural frequencies was tried in this paper.

The three-dimensional finite element model of the bridge as shown in Fig. 12 was established to evaluate the structural response and acquire dynamic characteristics. Two simply-supported end spans were not modeled in modal analysis.

![Three-dimensional finite element model](image)

Figure 12. Three-dimensional finite element model
To extract the dynamic characteristics, one hour GNSS data at the sampling rate of 20 Hz were used in the analysis. Acceleration data measured at the same period and long-term monitoring results were also used for comparing. First, three directional displacement signals for each GNSS receiver were obtained. Fig. 13 shows a total of 18 displacement signals for the order of SSWE, SPWE, MSEA, MSWE, NPWE, and NSWE. Using the normalization process and a third order Butterworth filter for the displacement signals, the pass band's signals from 0.15 Hz to 0.99 Hz have been isolated. Then, the acceleration data by double differentiation for these signals were obtained and analyzed in the frequency domain. Five dominant natural frequencies ranging from 0.2 Hz to 0.7 Hz have been extracted by the fast Fourier transform (Fig. 14) and compared to the results of long-term monitoring and accelerometers (Table 3). Table 3 shows that the natural frequencies from GNSS receivers and accelerometers agree quite well. These are also consistent with the finite element analysis results as the differences are less than 4%. It means that the real-time kinematic GNSS can be used for extracting the natural frequencies.

![Figure 13. Displacement time series](image1.png)

![Figure 14. FFT results for GNSS signals](image2.png)

**Table 3. Comparisons of natural frequencies and modal assurance criterions**

<table>
<thead>
<tr>
<th>Mode no.</th>
<th>FE analysis</th>
<th>Long-term monitoring</th>
<th>GNSS receivers</th>
<th>Accelerometer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency</td>
<td>Frequency</td>
<td>Frequency</td>
<td>Frequency</td>
</tr>
<tr>
<td></td>
<td>(Hz)</td>
<td>Difference (%)</td>
<td>(Hz)</td>
<td>MAC</td>
</tr>
<tr>
<td>$1^{st}$ ($f_1$)</td>
<td>0.2654</td>
<td>0.2595</td>
<td>0.2637</td>
<td>0.2625</td>
</tr>
<tr>
<td>$3^{rd}$ ($f_2$)</td>
<td>0.3292</td>
<td>0.3250</td>
<td>0.3271</td>
<td>0.3235</td>
</tr>
<tr>
<td>$7^{th}$ ($f_3$)</td>
<td>0.4413</td>
<td>Not stored</td>
<td>-</td>
<td>0.4517</td>
</tr>
<tr>
<td>$9^{th}$ ($f_4$)</td>
<td>0.5371</td>
<td>0.5260</td>
<td>0.5273</td>
<td>0.5310</td>
</tr>
<tr>
<td>$11^{th}$ ($f_5$)</td>
<td>0.5968</td>
<td>0.5750</td>
<td>0.5811</td>
<td>0.5800</td>
</tr>
<tr>
<td>$13^{th}$ ($f_6$)</td>
<td>0.6319</td>
<td>0.6259</td>
<td>0.6299</td>
<td>0.6225</td>
</tr>
</tbody>
</table>

Note 1: Mean values measured by accelerometers at every 15:30 during 2001~2009
The experimental mode shapes of the bridge were extracted using the time domain decomposition (TDD) technique [7]. The TDD technique, which extracts the mode shapes in the time domain, is the most effective in extracting the high resolution mode shapes on particularly long-span bridges. The bending mode shapes extracted from GNSS signals are shown in Fig. 15 against those obtained from the modal analysis of the finite element model. The GNSS results are marked as circles and the finite element results as continuous lines. Note that the circle between each pylon (and pier) and superstructure in Fig. 15 is displayed to help readers understand. Clear correspondence of the mode shapes was found for the five bending modes.

The modal assurance criterion (MAC), which varies from zero for no correlation to one for perfect correlation, was used for evaluating the correlation of the analytical and experimental mode shapes [8]. Previous Table 3 shows the MACs. The MAC values are close to one both GNSS receivers and accelerometers. It means that the real-time kinematic GNSS can be used for extracting the mode shapes.

(a) 1st ($f_1$) mode
(b) 3rd ($f_2$) mode
(c) 9th ($f_4$) mode
(d) 11th ($f_5$) mode
(e) 13th ($f_6$) mode

Figure 15. Extracted bending mode shapes

Conclusions

The structural health monitoring system for the Seohae cable-stayed bridge was renovated in 2009. The installation of the GNSS was included in the renovation project. Based on the GNSS and SHMS monitoring, the long-term displacements and dynamic characteristics of the bridge were evaluated.

Using the least-squares method to fit the temperature-displacement relationship, the measured variation rate of displacement to temperature was obtained and compared with the theoretical value. The measured value at each location is almost the same order as the theoretical value. It means that the bridge’s thermal behaviors are healthy. The coefficient of
thermal expansion by the measured temperature-displacement relationship is identified as 1.06E-5, which is reasonably within the coefficients of concrete and steel.

The five natural frequencies were extracted from the GNSS signals of the bridge. Using the TDD technique that extracts modal parameters in the time domain, the corresponding mode shapes of the bridge have been successfully extracted as well. It is concluded that the real-time kinematic GNSS can be used for extracting the dynamic characteristics of cable-supported bridges.

Acknowledgments

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