Finite Element Model Updating of a PSC Box Girder Bridge Using Ambient Vibration Test

Matthew R Hiatt\textsuperscript{1,}\textsuperscript{a}, Annika C Mathiasson\textsuperscript{2,}\textsuperscript{b}, John Okwori\textsuperscript{3,}\textsuperscript{c} Seung-Seop Jin\textsuperscript{4,}\textsuperscript{d}, Shen Shang\textsuperscript{5,}\textsuperscript{e}, Gun Jin Yun\textsuperscript{5,}\textsuperscript{f}, Juan Caicedo\textsuperscript{6,}\textsuperscript{g}, Richard Christenson\textsuperscript{7,}\textsuperscript{h}, Chung-Bang Yun\textsuperscript{4,}\textsuperscript{i} and Hoon Sohn\textsuperscript{4,}\textsuperscript{j}

\textsuperscript{1}Department of Civil, Environmental and Architectural Engineering, The University of Kansas, Lawrence, KS, USA
\textsuperscript{2}Civil and Environmental Engineering, The University of Maine, 5711 Boardman Hall, Orono, ME, USA
\textsuperscript{3}Department of Computer Science, University of Illinois Springfield, 1 University Plaza, Springfield, IL 62703, USA
\textsuperscript{4}Civil & Environmental Engineering, Korea Advanced Institute of Science and Technology, 373-1, GuSeong-Dong, YuSeong-Gu, DaeJeon, South Korea
\textsuperscript{5}Department of Civil Engineering, The University of Akron, 244 Sumner St. ASEC 210, Akron, OH, USA
\textsuperscript{6}University of South Carolina, Department of Civil and Environmental Eng. 300 Main St., Columbia, SC 29208, USA, USA
\textsuperscript{7}Department of Civil & Environmental Eng., University of Connecticut, Storrs, CT, 06269, USA

\textsuperscript{a}mhiatt@ku.edu, \textsuperscript{b}annika.mathiasson@umit.maine.edu, \textsuperscript{c}jokwo2@uis.edu, \textsuperscript{d}seungsap@kaist.ac.kr, \textsuperscript{e}ss164@zips.uakron.edu, \textsuperscript{f}gy3@uakron.edu, \textsuperscript{g}caicedo@cec.sc.edu, \textsuperscript{h}rchriste@engr.uconn.edu, \textsuperscript{i}ycb@kaist.ac.kr, \textsuperscript{j}hoonsohn@kaist.ac.kr

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Abstract In this paper, in-field ambient vibration testing of a highway bridge in South Korea under traffic loadings has been conducted to update its finite element model for future predictive analysis and diagnosis purpose. The research results presented in this paper are outcomes from an international REU (Research Experience for Undergraduates) program in smart structures funded by US-NSF (National Science Foundation) and hosted abroad by the Korean Advanced Institute of Science and Technology (KAIST). The monitoring, modeling, and model updating of civil infrastructures are vital in maintaining new design and maintenance standards. Using the frequency domain decomposition (FDD), experimental modal properties of the structure were found and, after a finite element model was created and updated based on the modal properties. From the results, it has been concluded that (a) the FDD method successfully identified the modal characteristics of the structure from ambient vibration, (b) that model updating improved the accuracy of the finite element model, (c) Representing the structural supports as springs in the FEM improved the results from the ideally supported model.

Introduction

Civil structures are continuously degraded due to unexpected loading, environmental changes and natural degradation of materials among other factors. Appropriate retrofitting and maintenance requires reasonable damage diagnosis and finite element models well-tuned to current states of built structures. Thus, finite element model updating has received considerable attentions as a means of damage
detection and facilitated advances in model-based retrofitting [1, 2]. Over the past several decades, dynamic modal properties have been widely used for finite element model updating [3-5].

For monitoring of large-scale civil structures, an ambient vibration test (AVT) is deemed to be more feasible than a forced vibration test (FVT). The AVT allows for results to be obtained using the natural excitation of the bridge. FVT for bridges is an unreasonable proposition in many situations due to the structure’s size, and the interference to normal traffic flow. In addition, simpler equipment is required for AVT to identify modal parameters of the in-service structure under normal operating conditions with uncontrollable and unmeasured ambient loads such as traffic and wind loading. During the ambient vibration test, effects of the non-stationary ambient loads can be easily minimized by collecting data for sufficiently long period of time.

The purpose of this study was to test a real structure using ambient vibration, identify the modal characteristics of the structure. A finite element model (FEM) of the structure was created and updated using downhill-Simplex optimization using the identified modal parameters. The Geumdang Bridge, as seen in Fig. 1, in South Korea was chosen as the test structure. Frequency domain decomposition (FDD) was applied to identify the modal characteristics of the structure. Model updating was performed on this structural model to increase the understanding of the bridge behavior and to keep record of the performance of the structure. Model updating is performed so that the model accurately represents the structure, allowing for damage detection and preventative measures to be taken if the possibility of damage were to be discovered.

This work was completed as part of an international Research Experiences for Undergraduates (REU) in the summer of 2010. The 10 week REU program organized by the University of South Carolina, University of Akron, University of Connecticut and the Korean Advanced Institute of Science and Technology focused in smart structures technologies such as model updating, structural health monitoring and structural control. More information about this REU program can be found at http://sdii.ce.sc.edu/reuss.

In-Field Bridge Structure: Geumdang Bridge in South Korea

The Geunmdang Bridge is located at Geundang-ri, Ganam-myon, Yeoju-gun, Gyunggi-do (Jungbu Naeryuk Expressway) in South Korea. The bridge’s span is 272m (0.169 mile) in length. It has 4 spans of Pre-stressed Concrete (PSC) I-beam girder and 3 spans of PSC Box girder. The highway, constructed from January 1998 through December 2002, was built by the Korea Express Highway Corporation. These bridges were part of a test bed during the process for the development of
methodology of pavement design. The test bed has a total length of 7.7km (4.8 miles). The Geundang Bridge is a part of the test bed. Fig. 2 shows geometrical dimensions of Geundang bridge. At the time of in-field test, the bridge was open to traffic. No structural flaws were found according to visual inspection of the outside and inside of the bridge.

![Figure 2 Geometrical Dimension of GeumDang bridge](image)

**Experimental Ambient Vibration Test**

An ambient vibration test (AVT) of the Geumdang Bridge was performed to determine the modal characteristics of the structure. Thus, in this test, input excitation does not need to be measured. Because only nine sensors were available, four tests were performed with the sensor locations displayed in Fig. 3 in order to identify the mode shapes of the entire bridge. The natural frequencies and mode shapes were identified separately for each test. The mode shapes were combined after modal identification was performed to each data set to obtain the mode shapes of the entire bridge span. The coordinate values at each sensor location are summarized in Table 1.
The sensors were placed at appropriate locations for each test setup. To avoid noisy vibration, the test bed was cleared during data collection. As a pretest, ambient vibration data were sampled for five minutes to verify the test setup and confirm the capability for accurate data collection. On-site confirmation of the natural frequencies and mode shapes were carried out. After sample testing, data were collected for approximately 40 minutes from the ambient excitation of the bridge. A sample of ambient vibration data is plotted in Fig. 4(a) at location “O” during test #2. Fig. 4(b) shows an installed accelerometer (PCB Model 393B12). A laptop computer is connected to a signal conditioner (PCB Model 481A03) through a NI multifunction DAQ card (NI DAQCard-6036E) was used for data acquisition. Nine accelerometers were connected to the signal conditioner through a terminal box (NI BNC-2090).

**Output-Only Modal Identification by Frequency Domain Decomposition Method**

An output-only method, Frequency Domain Decomposition (FDD), was selected as the modal identification method for this test. The FDD method is known to be suitable for AVT which provides...
broadband excitations. The FDD involves identifying the singular values of the power spectral density matrix (PSD). The spectral matrix is decomposed into a set of spectral density functions (singular value decomposition) with each corresponding to a single degree of freedom system [6]. The singular values are selected by the user-friendly technique of peak-picking from the PSD matrix of the measured response, making the FDD method very easy to implement and physically meaningful to the user. The singular values of the PSD function matrix are used to estimate the natural frequencies [7]. Well-separated modes are clearly identified using this technique. Although there is noise in the data, this technique is not sensitive to such errors, and closely spaced modes can still be identified with good accuracy. Harmonic components in the response signals are clearly indicated in this technique [6].

Obtaining the singular value decomposition (SVD) of the spectral matrix, the spectral matrix is decomposed into a set of auto spectral density functions, each corresponding to a single degree of freedom system. The SVD is a generalized eigenvalue and eigenvector decomposition method for a non-rectangular matrix.

Finite Element Modeling and Determination of Updating Parameters

Finite Element Model. A Finite Element Model (FEM) was constructed in an in-house finite element package using 54 Bernoulli-Euler beam elements, implementing 55 nodes and 110 degrees of freedom (DOFs) of which 55 were translational and 55 rotational. The FEM was modeled with 4 spring supports with a stiffness value of 100 GPa initially assumed. The moment of inertia and Area of the cross sections were computed with the program Gsection. Eigen analysis was performed to obtain the natural frequencies and mode shapes with MATLAB. The resulting natural frequencies were 3.065, 4.550, 5.792, and 11.914 Hz. The DOFs used for updating were taken from the full model by selecting the mode shapes relating to translational DOFs and then choosing the DOFs corresponding to the sensor locations. Such process of selecting sensor DOFs from the full numerical model eliminates possible errors that may be caused by using standard dynamic reduction methods such as SEREP and IRS. Needless to say, the limited number of sensors definitely could also generate errors in updating parameters. However, since the updating parameter (Young’s modulus) selected in this paper is sole representative of the entire structure, the error in the updating parameter is expected not to be too significant.

Determination of Updating Parameters. Parameters influencing the dynamic response of the structure are selected to be updated to improve the model and, for this study, the structure’s stiffness and the support conditions were determined as the updated parameters. The parameters chosen for model updating were the Young’s modulus of the material (E) and the vertical spring stiffness (K) at the four supports. The vertical spring stiffness at the supports was updated so that the support conditions of the model would more closely coincide with the support conditions of the real structure. After visual inspection performed before the tests, the sectional integrity of the bridge was considered as healthy. However, the material properties of the PSC bridge girder could not be evaluated on the site. Thus, possible reduction of flexural stiffness of the bridge girder has been considered in terms of material stiffness.

Optimization Technique for Model Updating

The objective function chosen for minimization is shown in Eq. 1 below

\[
\beta = \sum_{i=1}^{n} \left(1 - \frac{f_i}{f_i^c}\right)^2 + \sum_{i=1}^{n} (1 - MAC_i)^2
\] (1)
where $\beta$ is the scalar value of the objective function, $f$ is the natural frequency, the superscript $c$ denotes computed value from the FEM, the superscript $e$ indicates experimental value and MAC is the Modal Assurance Criterion which is shown below in Eq. 2.

$$MAC = \frac{\| \varphi_i^T \varphi_i \|^2}{\| \varphi_i^T \varphi_i \| \| \varphi_i^T \varphi_i \|}$$

where $\varphi_i$ represents the $i$-th mode shape. The selected method for the minimization of the objective function was the downhill-simplex or Nelder-Mead method. The downhill-Simplex method or Nelder-Mead method is a nonlinear optimization method for multidimensional unconstrained problems [8].

The goal of the simplex method is to find the global minimum of an objective function by expanding, shrinking, reflecting, or contracting a polytope based on the dimension of the space in which the simplex method is working. The dimension of the polytope is $N+1$ where $N$ is the dimension in which the optimization is taking place. Drawbacks of the simplex method include the possible convergence at a local minimum of the objective function or convergence to an unreasonable parameter result. To correct for the convergence at a local minimum of the objective function, several values for the initial guess of a parameter must be selected. Emphasis must be placed on physical understanding of the expected values of the parameters as the magnitude of the initial guess for a given parameter may determine the success of the optimization. An initial guess far from the true value may cause a divergence.

The first mode shape and natural frequency was given a higher weight when evaluating the objective function due its dominant behavior in the structure’s dynamics. Only the first two mode shapes and natural frequencies were considered in the objective function evaluation due to large discrepancies between the experiment and FEM in the third and fourth mode shapes. These discrepancies caused unreasonable parameter values to be obtained during the optimization.

**Results and Discussions**

From the initial value of 3.00x10^{10} Pa (standard value for concrete), Young’s modulus was updated to 2.55x10^{10} Pa as shown in Fig. 5. The initial value for vertical spring support stiffness was assumed to be 3x10^{12} Pa for model updating. It can be assumed that the support stiffness is higher than that of the general material. The updated values for $K_1$, $K_2$, $K_3$, and $K_4$ were found to be 3.11x10^{12}, 3.13x10^{12}, 3.26x10^{12}, and 2.99x10^{12} N/m, respectively. Those updated parameters are summarized in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Value</th>
<th>Updated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (Pa)</td>
<td>3.00 x 10^{10}</td>
<td>2.55 x 10^{10}</td>
</tr>
<tr>
<td>$K_1$ (P4) (N/m)</td>
<td>3.00 x 10^{12}</td>
<td>3.11 x 10^{12}</td>
</tr>
<tr>
<td>$K_2$ (P5) (N/m)</td>
<td>3.00 x 10^{12}</td>
<td>3.13 x 10^{12}</td>
</tr>
<tr>
<td>$K_3$ (P6) (N/m)</td>
<td>3.00 x 10^{12}</td>
<td>3.26 x 10^{12}</td>
</tr>
<tr>
<td>$K_4$ (A) (N/m)</td>
<td>3.00 x 10^{12}</td>
<td>2.99 x 10^{12}</td>
</tr>
</tbody>
</table>

The natural frequencies of the test structure were found to be 2.875, 4.065, 4.632, and 11.207 Hz after selecting the natural frequencies with the frequency domain decomposition method (FDD), as previously discussed. The initial FEM yielded natural frequencies of 3.065, 4.550, 5.792 and 11.914 Hz. The FEM was then updated and new natural frequencies of 2.827, 4.195, 5.341, and 10.987 Hz were obtained. The natural frequency results are summarized in Table 3. The MAC values from the
updated FEM were 0.9896, 0.9919, 0.9578, and 0.8755 for modes 1-4, respectively. The experimental mode shapes and the mode shapes from the updated FEM are found in Fig. 6.

Table 3: Results Summary of Modal Properties from Model Updating

<table>
<thead>
<tr>
<th>Natural Frequencies (Hz)</th>
<th>Natural Frequency Error</th>
<th>MAC Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EXP</td>
<td>Initial FEM</td>
</tr>
<tr>
<td>1 2.875</td>
<td>3.065</td>
<td>2.827</td>
</tr>
<tr>
<td>2 4.065</td>
<td>4.550</td>
<td>4.195</td>
</tr>
<tr>
<td>3 4.632</td>
<td>5.792</td>
<td>5.341</td>
</tr>
<tr>
<td>4 11.207</td>
<td>11.914</td>
<td>10.987</td>
</tr>
</tbody>
</table>

According to the results, the natural frequencies seem to be more sensitive to the selected parameters than MAC values do. As shown in Table 3, changes of the MAC values were negligible. Thus, the averaged material stiffness (E) over the entire span was reasonably assessed in the presented model updating as the natural frequency errors were significantly reduced after updating.
Summary

This study presents the modal identification and model updating of the Geunmdang Bridge. Four true peaks were selected from the decomposition using the Frequency Domain Decomposition (FDD) method. The natural frequencies and mode shapes were calculated and shown to be accurate and well estimated. The result clearly states that the technique is able to estimate close modes with high accuracy and the technique is not sensitive to noise in the sensors. Representing the structural supports as springs in the FEM improved the results of the model updating procedure from the ideally supported model. Model updating of the Geumdang Bridge FEM improved the accuracy of the modal characteristics when compared to the real structure. The large decrease in natural frequency error and the high MAC values show that the updated FEM is a more accurate model than the initial. A large discrepancy in mode shape is evident in the third mode shape for the mid-span. Further testing needs to be completed to determine the discrepancy in the third span is due to some measurement error or if something else is influencing the mode shape at this location. Future work includes testing the capabilities of different modal characteristic identification methods such as Stochastic Subspace Identification (SSI) and testing the robustness of a different model updating method like the genetic algorithm.

Acknowledgement

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