Bridge Deck Finite Element Model Updating Using Multi-Response NDT Data

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Abstract

A multi-response parameter estimation method, including an error function normalization procedure, is proposed to allow simultaneous estimation of stiffness and mass parameters for model updating. The initial finite element model (FEM) of the University of Cincinnati Infrastructure Institute (UCII) bridge deck was developed based on preliminary calculations using information gathered from available drawings. The unknown parameters were selected for the grid model based on the results of damage localization, and were successfully updated using structural parameter estimation methods. This paper presents both the updated structural stiffness and mass parameters of the grid model using a few subsets of static and dynamic non-destructive testing (NDT) measurements. The static and modal response from the updated model resulted in a closer match with the NDT data than the responses from the initial FEM of the bridge deck.

Introduction

Structural damage and defects occur in civil engineering structures for a variety of reasons, including impacts of a corrosive environment, aging, fatigue due to cyclic loading, or due to a vehicle collision. Structural parameter estimation is the process of reconciling an a priori finite element model (FEM) of the structure with nondestructive test (NDT) data from the structure. It has enormous potential for use in FEM updating as part of a structural condition assessment program for in-service structures, such as bridges. Damage assessment of structures has received considerable attention from the civil, aerospace and mechanical engineering communities since the 1980’s. Current status and future needs for damage prognosis is presented by Farrar et al. (2003).

After performing damage prognosis, it is necessary to quantify the amount of damage present in the structural members. This can be achieved using structural parameter estimation methods with NDT measurements obtained from the structure. Multi-Response Parameter Estimation creates an environment for the simultaneous use of several different types of excitations (both static and dynamic) and measurements at strategic locations. Each load case or mode of vibration captures a different type of behavior of the structure. Evaluated together, these measurements provide the most robust and useful information for parameter estimation and model updating.
UCII Bridge Deck Laboratory Model

The bridge deck laboratory model (UCII-Grid) was designed at the University of Cincinnati Infrastructure Institute (UCII) to simulate the behavior of a bridge deck. Researchers at UCII built a 12-foot (3.65m) x 6-foot (1.83 m) grid model of a bridge deck. The grid members were 3” (7.62 cm) x 2” (5.08 cm) x 3/16” (.476 cm) structural steel tubing, in both the transverse and longitudinal directions. Figure 1 represents a schematic of UCII-Grid’s final design. The longitudinal and transverse members were connected using 3/16” steel cover plates with 2” x 2” x 3/16” cleat angles and A307 bolts with diameter ¼” for connection. Detail construction drawings for each type of connection are shown in Figure 2.

The model’s connections were designed to support the pre-determined maximum static load of 150 lbs (666 N). Also, the UCII-Grid was designed so the significant modal information for parameter estimation that could be measured within the 0-100 Hz range (Aktan et al., 1997). This is a practical frequency range because most typical steel-stringer bridges have measurable modes within this range. The testing procedure for the UCII-Grid was also designed to excite the structure within the linear elastic range.

Figure 1. Plan View of the UCII-Grid (Aktan et al., 1997)
Figure 2. Connections Details of the UCII-Grid (Aktan, et al., 1997)

Non-Destructive Testing of the UCII-Grid

Both static and modal NDT were performed on the UCII-Grid. For the static NDT, vertical displacements, rotations and strains were recorded. Three identical static NDT were conducted on the UCII-Grid over two days. Based on the data quality analysis performed by Northeastern University (Wadia-Fascetti et al., 1999) only data from the third test was used for parameter estimation. Both static strains and vertical displacements were considered reliable data and were used for parameter estimation.

Experimental modal analysis was used to determine the UCII-Grid’s modal parameters from measured frequency response functions. In modal testing, the response of the structure to a specific excitation, in this case to impact, was measured in the vertical direction at each member intersection. Next, the measured data was processed using frequency or time domain techniques to obtain the natural modal parameters of the structure. Primarily, the stiffness of connections, structural tubing, and the vertical stiffness of the bearing pads were the target of parameter estimation using the vertical deflections of the UCII-Grid.
**Finite Element Model for the UCII-Grid**

The FEM for the UCII-Grid was created in the x-y horizontal plane, with the z-axis was placed in the vertical (gravity) direction. The FEM consisted of 85 nodes, 96 beam elements and four bearing pad stiffnesses (Santini, 2003). Three-dimensional beam elements were used to represent both the beams and the connections zones. For the bearing pads, linear springs with stiffness only in the gravity direction were used.

Table 1 lists initial assumed properties for the UCII-Grid. The material properties for all beam elements were $E = 29\times10^6$ (200GPa) and $\rho = 7.324\times10^{-4}$ lbs-s$^2$/in$^3$ (652.8 kg/m$^3$). All members were constructed using Grade 50-ksi steel. The $I_{yy}$ of the connections was found to have no major influence on the analysis as the major bending is about the local xx-axis (vertical direction) (Javdekar, 2004).

<table>
<thead>
<tr>
<th>Member Type</th>
<th>$A_h$ in$^2$ (m$^2$)</th>
<th>$A_m$ in$^2$ (m$^2$)</th>
<th>$I_{xx}$ in$^4$ (m$^4$)</th>
<th>$I_{yy}$ in$^4$ (m$^4$)</th>
<th>$J$ in$^4$ (m$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubes (TS 3 x 2 x 3/16)</td>
<td>1.64 (0.0011)</td>
<td>1.64 (0.0011)</td>
<td>1.86 (7.74e-7)</td>
<td>0.977 (4.07e-7)</td>
<td>2.16</td>
</tr>
<tr>
<td>Exterior connections</td>
<td>1.64 (0.0011)</td>
<td>3.7 (0.0024)</td>
<td>1.86 (7.74e-7)</td>
<td>7.73 (3.20e-6)</td>
<td>2.20</td>
</tr>
<tr>
<td>Interior connections</td>
<td>1.64 (0.0011)</td>
<td>3.7 (0.0024)</td>
<td>1.86 (7.74e-7)</td>
<td>11.70 (4.80e-6)</td>
<td>2.20</td>
</tr>
</tbody>
</table>

The section properties for the tubes were taken directly from the AISC Manual of Steel Construction (1996) for a TSS 3 x 2 x 3/16”. The section properties for the connections were calculated considering that both the tubing and the connections plate are part of the section. No adjustments were made to $A_m$ (cross sectional area used for mass calculation) to account for the additional weight of the bolts and the clip angles or the loss of weight due to drilled holes. This mass is accounted for in the adjusted “$A_m$” of the section. Initial Stiffness of each bearing pad in the vertical direction is assumed as 2.5 kips/in, consistent with the results of the load tests on bearing pads that were conducted at UCII.

**Model Updating through Parameter Estimation**

Structural model updating was performed using PARIS, a program developed at Tufts University. PARameter Identification Program, PARIS® (Sanayei, 1997) is a Matlab®-based software package for parameter estimation and finite element model updating using NDT data. This program can use static measurements (displacements, rotations, and strains) and can use natural resonance frequencies and associated mode shapes for parameter estimation. PARIS can simultaneously use different types of loadings and sets of sparse measurements for parameter estimation. It can form several error functions and different types of objective functions to be used with various solution techniques. PARIS is used for all parameter estimations of the UCII-Grid in this paper.
UCII Grid Model Updating

For the results presented in this paper, parameter estimation was conducted in two stages. First, the four bearing pads and the two grouped moment of inertias of the interior and exterior connections \( (I_{\text{inner}}, I_{\text{outer}}) \) were estimated. Next, the results of the previous parameter estimation were used progressively as initial values to estimate the two grouped masses of the interior and exterior connections \( (Am_{\text{inner}}, Am_{\text{outer}}) \). This iterative process was repeated until a close match between the analytical and NDT responses is achieved. The static vertical displacements were obtained at 16 measurement locations while loading each of the 21 joints one at a time. This resulted in 21 load cases and 16 displacement measurements. The Load cases E-3, G-3 and I-3, were selected during data quality checks (Wadia-Fascetti et al., 1999). The static measurements selected were vertical measurements at Nodes G-3, I-3, K-1, K-3 and K-5 in addition to the vertical measurements at the four bearing pads at A-1, A-5, M-1 and M-5. These eleven measurements were selected based on a new measurement selection technique developed using Fisher information matrix based on the sensitivity matrix (Sanayei and Javdekar, 2002). These measurements were used for simultaneous estimation of four bearing pad stiffness \( (K) \), and two grouped connection moment of inertias \( (I) \). A by-product of using different measured responses is the different units associated with those measurements. Error function normalization (EFN) is used to alleviate the numerical differences without impacting the integrity of the algorithm (Santini, 2003).

Table 2 presents the results of simultaneous updating of the four bearing pad stiffness values and two-moments of inertia using error function normalization based on the initial values of the error function. Columns (1) to (3) in this table indicate the error function used and loads and measured DOF (MDOF), respectively. In this case, the Static Stiffness error function (SS) was used for parameter estimation (Sanayei et al., 1997). Columns (4) through (9) indicate the unknown parameters namely two grouped moment of inertias and four bearing pad vertical stiffness. It was observed that the outer connections were estimated to have higher stiffness than the inner connections. The inner connections were observed to have more or less the same values as initially assumed. The pad stiffness values were estimated to be higher for almost all bearing pads. However, pads M-1 and M-5 seem to be less stiff than the other pads. The variability in the pad stiffness may be attributed to the variable displacements under the loads used for parameter estimation. These results were confirmed using Genetic Algorithm (GA) optimization technique.

Table 2. Stiffness-Based Parameter Estimates Using Static NDT Data

<table>
<thead>
<tr>
<th>Error Func.</th>
<th>Loads</th>
<th>MDOF</th>
<th>( I_{xx} ) inner</th>
<th>( I_{xx} ) outer</th>
<th>( K_{A1} )</th>
<th>( K_{A5} )</th>
<th>( K_{M1} )</th>
<th>( K_{M5} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
<td>(9)</td>
</tr>
<tr>
<td>SS</td>
<td>E3,G3,I3</td>
<td>A-1, A-5,G-3, I-3, K-1, K-3, K-5 M-1, M-5</td>
<td>2.54</td>
<td>1.61</td>
<td>7.20</td>
<td>8.66</td>
<td>2.88</td>
<td>5.63</td>
</tr>
</tbody>
</table>

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The parameter values from Table 2 were used as the initial values for the mass-based parameter estimation. Table 3 presents the results of two grouped masses of the connections using the first 5 modes and all the 21 available vertical modal displacements. Columns (1)-(3) of this table represent the error function used, the modes and measured DOF used for parameter estimation. In this case, Modal Stiffness error function (MS) was used for parameter estimation (Gornshteyn, 1992). The columns (4) and (5) represent the unknown mass areas of the outer and inner connections respectively. It was observed that the mass area estimates obtained were smaller than initially assumed but larger than that of the tubes themselves.

**Table 3. Mass-Based Parameter Estimates Using Modal NDT Data**

<table>
<thead>
<tr>
<th>Error func.</th>
<th>Modes</th>
<th>MDOF</th>
<th>(A_m)-Outer (in(^2))</th>
<th>(A_m)-Inner (in(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS</td>
<td>1,2,3,4,5</td>
<td>All 21 Vertical Displacements</td>
<td>2.21</td>
<td>2.62</td>
</tr>
</tbody>
</table>

The parameter estimates obtained were used to update the model of the UCII-Grid. Figure 3 shows the plot of NDT static displacements, responses of the initial and the updated model along the lines 1, 3 and 5 of the UCII-Grid for two representative load cases E3 and G3. It can be observed that the updated model represents a much better match with the NDT data especially along the Lines 5 and 3 of the UCII-Grid. The displacements at the bearing pads of the updated model match closely with the NDT data, except near the pad M-1 and M-5. The discrepancy at pads M-1 and M-5 may be attributed to the original variability in the NDT data itself particularly in load case I-3. Connections in the middle are slightly stiffer than the updated model indicates. The results were observed to be satisfactory overall.

The Modal Assurance Criterion (MAC) values given in Table 4 were calculated using the first five natural frequencies and associated modes of the updated model based on Ewins (1986). The MAC values of 1 represent a perfect match and 0 represents no match. It was observed that the MAC values of most of the modes had improved over the initial model. Some degree of coupling is seen in modes 4 and 5 and in modes 6 and 7. However, these coupling were reduced compared to the initial model.

Similarly, the updated FEM frequencies have a considerably better match with the NDT data than with the initial model as seen in the visual representation of frequencies in Figure 4. In this figure, Case “K&I_updated” uses the parameter estimates of Table 2 and Case “Am_Updated” uses Tables 2 and 3.

In the structural parameter estimation, it should be noted that only the first five modes were used. However, the results of all of the modes were improved after updating the mass parameters. Although certain modeling and experimental errors may have influenced this estimate, it is a feasible estimate of the true parameters of the grid.
Conclusions

Parameter estimation is perhaps the most crucial stage in model updating of structures. Its results can also be used as a platform for damage assessment, which quantifies the amount and the location of major disparities between the computed response and NDT data. Multi-Responses Parameter Estimation provides a robust approach for stiffness-based and mass-based parameter estimation and finite element model updating. As a direct outcome of this research, the UCII-Grid parameters were successfully updated and significant improvement was observed in the static displacements, modal frequencies, and mode shapes of the updated finite element of the bridge deck laboratory model. The successful parameter estimation has been possible due to several improvements used in this paper such as error function normalization, use of multi-response NDT data, stiffness and mass parameter estimation, and use of selected subsets of measurements.

Acknowledgements

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References


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Figure 3. Comparison of Vertical Static Displacements
Load Cases E-3 and G-3 at Grid Lines 1, 3 and 5
Figure 4. Comparison of 9 Modal Frequencies (Hz) at Each Stage of Updating

Table 4. MAC Values of Updated Finite Element Model vs. NDT data

<table>
<thead>
<tr>
<th>Modes</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9971</td>
<td>0.0002</td>
<td>0.0006</td>
<td>0.0001</td>
<td>0.0003</td>
<td>0.0008</td>
<td>0.0108</td>
<td>0.0776</td>
<td>0.0002</td>
</tr>
<tr>
<td>2</td>
<td>0.0018</td>
<td>0.9888</td>
<td>0.0072</td>
<td>0.0012</td>
<td>0.0007</td>
<td>0</td>
<td>0.0002</td>
<td>0.0001</td>
<td>0.0005</td>
</tr>
<tr>
<td>3</td>
<td>0.0023</td>
<td>0.0019</td>
<td>0.9617</td>
<td>0.0041</td>
<td>0.0039</td>
<td>0</td>
<td>0.0029</td>
<td>0.0002</td>
<td>0.0683</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.0015</td>
<td>0.0001</td>
<td>0.8361</td>
<td>0.2094</td>
<td>0.0002</td>
<td>0.001</td>
<td>0.0003</td>
<td>0.0022</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.0029</td>
<td>0</td>
<td>0.0542</td>
<td>0.8575</td>
<td>0.0013</td>
<td>0.0097</td>
<td>0.0084</td>
<td>0.0002</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.0011</td>
<td>0.015</td>
<td>0.0031</td>
<td>0.0009</td>
<td>0.873</td>
<td>0.0186</td>
<td>0.0023</td>
<td>0.0863</td>
</tr>
<tr>
<td>7</td>
<td>0.0511</td>
<td>0.0007</td>
<td>0.0025</td>
<td>0.018</td>
<td>0.0004</td>
<td>0.0047</td>
<td>0.1176</td>
<td>0.7993</td>
<td>0.0004</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0.0141</td>
<td>0.0036</td>
<td>0.0109</td>
<td>0.0226</td>
<td>0.0016</td>
<td>0.7703</td>
<td>0.2335</td>
<td>0.0088</td>
</tr>
<tr>
<td>9</td>
<td>0.0004</td>
<td>0.0008</td>
<td>0.073</td>
<td>0</td>
<td>0</td>
<td>0.0268</td>
<td>0.0012</td>
<td>0.0041</td>
<td>0.9269</td>
</tr>
</tbody>
</table>