MODAL IDENTIFICATION AND FINITE ELEMENT MODEL UPDATING OF A REINFORCED CONCRETE BRIDGE

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This paper summarizes part of the ongoing work conducted in Tunisia within the framework of a research project funded by the Center for Testing and Construction Techniques which is affiliated to the Ministry of Infrastructure. The project deals with the development of a rational methodology for the assessment of older reinforced concrete bridges. This methodology is based on ambient vibration measurement of the bridge, identification of the structure’s modal signature and finite element model updating. The selected case study is the SidiBouAli river bridge which is an eight-span simply supported bridge with a continuous slab. Each span has a length of 25 m and is supported by rubber bearings at the supports. Ambient vibration tests with output-only measurements were conducted on the bridge using a data acquisition system with nine force-balance accelerometers placed at selected locations of the bridge. The Enhanced Frequency Domain Decomposition technique, known to be robust with respect to the complex non-stationary nature of the unmeasured excitation, was applied to extract the dynamic characteristics of the bridge. For model updating, it was assumed that the parameters that can be changed in the model are the concrete modulus of elasticity and the rubber bearing stiffness. The first parameter indicates any possible damage in the bridge and the second parameter reflects the changes in boundary conditions. The application of the proposed methodology led to a relatively faithful linear elastic finite element model of the selected bridge.

INTRODUCTION

Tunisia has more than 3000 bridges with a minimum span length of 3 meters. Several of these bridges are old and designed based on outdated code regulations. A certain number of these bridges has suffered degradation and damage due to traffic and environment. Current bridge inspection techniques are based on visual inspection techniques conducted by experienced engineers. A recent study conducted by FHWA reported that at least 56% of average condition bridge visually based rating in the United States were incorrect due to factors such as inspector’s experience, bridge type and condition. Therefore, there is a need to develop a rational and scientific methodology for bridge inspection and evaluation.

This paper summarizes part of the ongoing work conducted in Tunisia within the framework of a
DESCRIPTION OF THE CASE STUDY

The tested bridge is located on Tunisia’s Highway connecting the cities of Tunis and Sousse at the section where the highway crosses the river of SidiBouAli. This case study, constructed in the early 90’s, is an eight-span simply supported bridge with a continuous slab and a span length of 25 m (Figure 1a). Each span consists of eleven equally spaced longitudinal I-shape girders (Figure 2) which are laterally connected at the supports by cross girders. Each main girder rests on a 40×30×8 cm elastomeric bearing. Because the bridge spans are simply supported and are similar, this study was only limited to only one span shown in Figure 1b.

FINITE ELEMENT MODELING

A three dimensional finite element model of the bridge was elaborated using the SAP2000 computer program based on a detailed geometric model. Two types of elements were used for the finite element modeling of the bridge, namely four and three-noded shell element for the concrete girders and the topping slab and linear spring elements for the elastomeric bearings. The model, shown in Figure 3, uses a total of 6834 shell elements. The x, y and z-coordinates represent, respectively, the longitudinal axis along the bridge, the horizontal transversal axis and the vertical axis (Figure3). The material behavior is assumed to be linear elastic, isotropic and homogeneous. The concrete modulus of elasticity was estimated at 32000 MPa based on concrete samples compression tests. The mass density of concrete was assumed to be 2400 kg/m³. An additional mass of 200 kg/m was added in the model to account for the bridge’s footway and handrail. The stiffnesses of the individual elastomeric bearings were estimated based on an instanteneous modulus of elasticity of 4.8 MPa and an instanteneous shear modulus of 1.6 MPa as follows: Kx = Ky = 2.4 \times 10^9 N/m; Kz = 7.2 \times 10^8 N/m.

OPTIMUM SENSOR LOCATION

The developed finite element model is transferred to the program FEMTools which is then used to simulate tests based on predefined locations and directions of the accelerometers. FEMTools, essentially, reduces the finite element model into a test model. The modal assurance criterion (MAC) is then used as a correlation analysis tool between the
numerical and the simulated experimental mode shapes. After several attempts, it was decided to have five measurement points along each of the eleven beams (Figure 4) where the z and the y-components of the acceleration are measured at each point. Additional points were measured at the supports including the x, y and z-components of the acceleration. This sensor configuration led to the MAC plot shown in Figure 5. This figure clearly indicates that there is an almost one to one correspondence between between the numerical and the simulated experimental mode shapes with a MAC value of 100% for the first ten vibration modes, meaning an almost perfect correlation.

Figure 3. Finite element model of one bridge span

Figure 4. Sensor location shown in dark dots across the bridge span (3-D and bottom views)

Figure 5. MAC Plot of Finite Element Mode Shapes (FEMS) versus Simulated Experimental Mode Shapes (SEMS)
AMBIENT VIBRATION TESTS

A proper evaluation of the bridge requires an accurate estimation of its modal signature (frequencies, mode shapes and damping ratios) based on measurement of the vibratory response. For large structures, ambient vibration tests with output-only measurements are preferred over forced vibration tests where both the excitation and the response are measured. The reason is that the measured response in an ambient vibration test is representative of the actual operating conditions of the structure which vibrates under its natural excitation loads such as traffic, wind, and microtremors.

Ambient vibration tests were conducted on the bridge using a sixteen-channel data acquisition system called Vibration Survey System Model VSS-3000 with nine force-balance accelerometers, model FBA-ES-U. A picture of the data acquisition setup is shown in Figure 6. The sensors, which are capable of measuring accelerations of up to ±0.25g with a resolution of 0.1µg, convert the physical excitation into electrical signals. Each accelerometer is connected to the data acquisition system using a 100m long cable. Cables are used to transmit the electronic signals from sensors to the signal conditioner. The signal conditioner unit is used to improve the quality of the signals by removing undesired frequency contents (filtering) and amplifying the signals. Vibration experiments were conducted during 10 minutes at a sampling frequency of 100 Hz. Signals converted to digital form are stored on the hard disk of the data acquisition computer.

Figure 6. Data acquisition system and an accelerometer fixed to the bridge

Figure 7. Average of normalized singular values of spectral density matrices of all data sets using EFDD algorithm

MODAL SIGNATURE IDENTIFICATION

The complex non-stationary nature of the unmeasured excitation requires the use of robust output-only modal identification techniques such as the Enhanced Frequency Domain Decomposition method and the Stochastic Subspace Identification methods. These methods were recently applied successfully to buildings and bridges. These techniques are available in the program Artemis Extractor. In the present study, the Enhanced Frequency Domain Decomposition (EFDD) technique was applied to accurately extract the modal signature of the bridge. Table 1 shows the measurement-based estimates of the natural frequencies of the first five modes using the EFDD method. Table 1 also shows the natural frequencies computed by the program SAP2000 and the relative error between these frequencies and the identified test frequencies. The error varies between 10% and 29% for the first four vibration modes which clearly indicates the need to update or correct the finite element model. The measurement-based estimates of the damping ratios identified by the EFDD technique, shown in Table 1, reveal a relative variability and range approximately in the interval between 4% and 9%. The values of the damping ratios for the first three modes appear to be reasonable while the fourth and fifth mode damping ratios appear to be highly estimated by the EFDD technique.

Table 1. Measurement-based estimates of the natural frequencies and damping ratios using the EFDD technique and computed frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>Estimated from Measurements using EFDD Technique</th>
<th>Computed by SAP2000</th>
<th>Relative error in frequency (%) between test and model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimated from Measurements using EFDD Technique</td>
<td>Computed by SAP2000</td>
<td>Relative error in frequency (%) between test and model</td>
</tr>
<tr>
<td></td>
<td>Frequency (Hz)</td>
<td>Damping Ratio (%)</td>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>1</td>
<td>4.30</td>
<td>4.60</td>
<td>4.78</td>
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<tr>
<td>2</td>
<td>4.94</td>
<td>4.39</td>
<td>5.85</td>
</tr>
<tr>
<td>3</td>
<td>6.18</td>
<td>5.99</td>
<td>7.97</td>
</tr>
<tr>
<td>4</td>
<td>9.10</td>
<td>9.43</td>
<td>10.05</td>
</tr>
<tr>
<td>5</td>
<td>13.07</td>
<td>8.54</td>
<td>12.83</td>
</tr>
</tbody>
</table>
FINITE ELEMENT MODEL UPDATING

The finite element model updating consists of obtaining a reasonable correlation between experimental and numerical modal properties. It was assumed that the updating parameters are the concrete modulus of elasticity and the rubber bearing stiffness. The modulus of elasticity indicates any possible damage or stiffness reduction in the bridge which means physically that this parameter can only be reduced. On the other hand, the rubber bearing stiffness, which was assumed to increase as a function of age, reflects the changes in boundary conditions. The updating consists of performing a sensitivity analysis of the model stiffness matrix with respect to changes in these parameters. This translates to taking the derivative of the stiffness matrix with respect to these parameters. The updating was performed based on two indicators that were applied simultaneously using the vertical displacement (z-direction): (a) comparison between computed and measured frequencies; and (b) comparison between computed and measured mode shapes. The comparison between the frequencies is estimated using the relative error between the computed and measured frequencies, while the comparison between the computed and measured mode shapes is evaluated using a correlation analysis tool known as Modal Assurance Criterion (MAC). The model updating is an iterative procedure performed using the program FEMTools.

Table 2 shows the test and model frequencies after updating obtained using 40 iterations. The relative error, which was before updating between 10% and 29% for the first four vibration modes (Table 1), became less than 2% as shown in Table 2. The first five vibration modes after updating are shown, respectively, in Figures 8 to 12. Figure 13 shows the MAC Plot between the updated Finite Element Mode Shapes (FEMS) and the Experimental Mode Shapes (EMS). This figure indicates that there is an almost one to one correspondence between the numerical and the experimental mode shapes for the first five vibration modes. Furthermore, the diagonal MAC value ranged between 73% and 87% for the first three vibration modes. Table 3 gives the percentage number of elements in terms of changes in parameters selected for model updating. This table indicates that 42% of the concrete elements remain intact while 30% of the elements undergo a stiffness reduction between 80% and 100% of their initial value and an additional 15% undergo a stiffness decrease between 60% and 80%. Table 3 shows that more than 50% of the rubber bearing elements remains intact while the remaining elements undergo an increase in stiffness. It is worthy to mention that the most important bearing stiffness is the z-component.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Test Frequency (Hz)</th>
<th>Model Frequency after updating (Hz)</th>
<th>Relative error between test and model frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.30</td>
<td>4.22</td>
<td>-1.9</td>
</tr>
<tr>
<td>2</td>
<td>4.84</td>
<td>4.85</td>
<td>0.2</td>
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<tr>
<td>4</td>
<td>9.10</td>
<td>8.97</td>
<td>-1.4</td>
</tr>
<tr>
<td>5</td>
<td>13.07</td>
<td>11.60</td>
<td>-11.2</td>
</tr>
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CONCLUSIONS

A rational methodology for the assessment of older reinforced concrete Tunisian bridges was applied on the SidiBouAli river bridge as an alternative to a visual inspection methodology. This methodology is based on ambient vibration measurement of the bridge, identification of the structure’s modal signature and finite element model updating. The modal properties for the first five vibration modes were successfully identified using the Enhanced Frequency Domain Decomposition technique. The error in the model frequencies before updating ranged between 10% and 29% for the first four vibration modes which clearly indicates the need to update the finite element model. These errors became less than 2% after updating. Furthermore, a good correlation between the experimental and finite element mode shapes was obtained at least for the first three vibration modes. The parameters selected for updating are the concrete modulus of elasticity and the rubber bearing stiffness. The concrete modulus of elasticity indicates any possible damage in the bridge, while the rubber bearing stiffness reflects the changes in boundary conditions. Finally it can be concluded that the application of the proposed methodology on this particular bridge led to a relatively faithful linear elastic finite element model.

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REFERENCES