First steps toward integration of Structural Health Monitoring and Nondestructive Evaluation data for decision making

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Acknowledgement: Jeff Weidner The University of Texas at El Paso
Outline

I. Introduction and Objectives
II. Technology Integration Strategy
III. Case study
   I. Observation and Conceptualization
   II. Controlled Experimentation
   III. Processing and Interpretation of Data
   IV. Model Calibration
   V. Utilization of model for Decision Making
IV. Further work
Growing need for data driven decision making to manage highway infrastructures

Lack of standards for integrative applications of NDE and SHM technology tools
Technology Integration Strategy – Structural Identification (St-Id)

**DECISION MAKING**

- Observation and Conceptualization
- Preliminary Modeling
- Controlled Experimentation
- Processing and Interpretation of Data
- Model Calibration and Parameter ID
- Utilization of Model for Simulations

**BUSINESS CASE**

- A-Priori Modeling
- Field Experiments NDE, SHM

**Technology Integration Strategy – Structural Identification (St-Id)**

- Density of concrete
- Modulus of barrier
- Modulus of parapet
- Vertical spring of South Support
- Longitudinal spring of North Support
- Lateral spring of North Support

**Normalized Sensitivity**

- Steps (n)
- Graph showing sensitivity over steps (n) for different parameters.
Case Study – Observation and Conceptualization

Superstructure: FAIR Approaches: FAIR 2008 Inspected by CHERRY WEBER & ASSOCIATES

Cracks arrested by drilling holes and installing bolts

A sample of fatigue crack

Table of Statistics - International Bridge Study Test Structure

<table>
<thead>
<tr>
<th>Year Built</th>
<th>1983-1984</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Spans</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Span #</th>
<th>Span 1</th>
<th>Span 2</th>
<th>Span 3</th>
<th>Span 4</th>
<th>Overall 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>105'</td>
<td>130'</td>
<td>130'</td>
<td>130'</td>
<td>114'</td>
</tr>
<tr>
<td>Width</td>
<td>61.75'</td>
<td>61.75'</td>
<td>61.75'</td>
<td>61.75'</td>
<td>123.5'</td>
</tr>
<tr>
<td>Skew Angle</td>
<td>0°</td>
<td>0°</td>
<td>0°/66°</td>
<td>0°/66°</td>
<td>66°/80°</td>
</tr>
<tr>
<td>Clearance</td>
<td>22+</td>
<td>22+</td>
<td>22+</td>
<td>22+</td>
<td>4</td>
</tr>
<tr>
<td>Lanes</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

## Case Study – Observation and Conceptualization

Performance Concerns identified by researchers and engineers (**missed** by bridge inspectors)

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Serviceability</th>
<th>Safety</th>
<th>Resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Settlement due to Insufficient Drainage</td>
<td>• Fill erosion (settlement of the approach slabs)</td>
<td>• <strong>Fatigue cracks on girder webs</strong></td>
<td>• Bridge serves over 100,000 vehicles per day</td>
</tr>
<tr>
<td>• Bump @ entry</td>
<td>• Excessive vibrations</td>
<td>• <strong>Shear crack on pier cap</strong></td>
<td>• Major link to GWB to NY City and NE</td>
</tr>
<tr>
<td></td>
<td>• Deck cracking</td>
<td>• <strong>Gas Utility pipe</strong></td>
<td>• Major impacts to regional GDP if bridge has to be closed</td>
</tr>
<tr>
<td></td>
<td>• Joint failures</td>
<td>• Water Trunk-line</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Bearing corrosion</td>
<td>• Fractured Bearings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Cracking of Abutments and Piers</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

20% g
### Case Study – Controlled Experimentation

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational Monitoring</td>
<td>Drexel University</td>
</tr>
<tr>
<td>Austria (VCE)</td>
<td></td>
</tr>
<tr>
<td>University of Sheffield</td>
<td></td>
</tr>
<tr>
<td>Utah State University</td>
<td></td>
</tr>
<tr>
<td>KEC &amp; Sejong University, Korea</td>
<td></td>
</tr>
<tr>
<td>Forced Vibration Testing</td>
<td>Drexel University</td>
</tr>
<tr>
<td></td>
<td>University of Sheffield</td>
</tr>
<tr>
<td>Controlled Load Testing</td>
<td>Drexel University</td>
</tr>
<tr>
<td>Non-destructive Evaluation (NDE)</td>
<td>Rutgers University</td>
</tr>
<tr>
<td>Laser tracking</td>
<td>Western Michigan University</td>
</tr>
<tr>
<td>Long-term Monitoring</td>
<td>Princeton University</td>
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</tbody>
</table>
## Case Study – Processing and Interpretation of Data

### Modal Analysis results comparison: Operational (Ambient) Monitoring VS Forced Vibration test

<table>
<thead>
<tr>
<th>Mode</th>
<th>Ambient Vibration</th>
<th>Forced Excitation</th>
<th>Diff (%)</th>
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<tbody>
<tr>
<td>1</td>
<td>2.89</td>
<td>2.78</td>
<td>1.94</td>
</tr>
<tr>
<td>2</td>
<td>3.79</td>
<td>3.82</td>
<td>0.39</td>
</tr>
<tr>
<td>3</td>
<td>5.23</td>
<td>5.26</td>
<td>0.29</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>6.86</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>9.47</td>
<td>9.18</td>
<td>1.95</td>
</tr>
<tr>
<td>6</td>
<td>11.61</td>
<td>11.68</td>
<td>0.3</td>
</tr>
<tr>
<td>7</td>
<td>12.25</td>
<td>12.25</td>
<td>0</td>
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<tr>
<td>8</td>
<td>14.14</td>
<td>14.8</td>
<td>2.28</td>
</tr>
<tr>
<td>9</td>
<td>15.12</td>
<td>15.51</td>
<td>2.27</td>
</tr>
<tr>
<td>10</td>
<td>20.64</td>
<td>20.22</td>
<td>1.37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Mode Shape</th>
<th>No.</th>
<th>Mode Shape</th>
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<tbody>
<tr>
<td>1</td>
<td><img src="image1.png" alt="Image" /></td>
<td>6</td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>2.78Hz</td>
<td></td>
<td>11.68Hz</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2.png" alt="Image" /></td>
<td>7</td>
<td><img src="image7.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>3.82Hz</td>
<td></td>
<td>12.25Hz</td>
</tr>
<tr>
<td>3</td>
<td><img src="image3.png" alt="Image" /></td>
<td>8</td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>5.26Hz</td>
<td></td>
<td>14.80Hz</td>
</tr>
<tr>
<td>4</td>
<td><img src="image4.png" alt="Image" /></td>
<td>9</td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>6.86Hz</td>
<td></td>
<td>15.51Hz</td>
</tr>
<tr>
<td>5</td>
<td><img src="image5.png" alt="Image" /></td>
<td>10</td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>9.18Hz</td>
<td></td>
<td>20.22Hz</td>
</tr>
</tbody>
</table>
Case Study – Processing and Interpretation of Data

VALIDATION OF EXPERIMENTS BY CORRELATING FLEXIBILITY FROM STATIC and DYNAMIC TESTS

Experiment: Static and Dynamic Comparison

![Image showing static and dynamic test setups and displacement graphs for girder locations 3 and 6.]
Case Study – Processing and Interpretation of Data

Controlled Load testing
Displacements of Girder 1, 3, 6, 8 under controlled load

Long term monitoring
Neutral Axis Analysis (based on one year strain data)
Figure 1 - Results from Half Cell Potential Testing

Half Cell Potential Result

- 90% prob. of corrosion activity
- Corrosion Activity Uncertain
- 90% prob. of no corrosion activity

Lateral Distance (m)

-750 -650 -550 -450 -350 -250 -150 -50 50 150 (mV)

Impact Echo Result

Serious Poor Fair Sound

Lateral Distance (m)

Longitudinal Distance (m)

Electrical Resistivity (ER)

High Moderate Low Decreasing corrosion rate indication

Electrical Resistivity (ER) test by Rutgers University

Ultrasonic Surface Wave Result

Lateral Distance (m)

-38 -28 -18 -16 -14 -12 -10 -8 -6 -4 -2

Attenuation at top rebar level (dB)

-38 -28 -18 -16 -14 -12 -10 -8 -6 -4 -2

Ground Penetrating Radar (GPR)

NDE test by Rutgers University

NDE Test
## Case Study – Model Calibration

**Experimental tests**

**FE modeling**

**Modal Parameter ID**

**Parameter Selection and define Bounds**

**Model Calibration**

**Scenario analyses**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Experimental frequencies base on all vibration test (Hz)</th>
<th>Calibrated by Drop Hammer test (Strand7)</th>
<th>Calibrated by Dynamic Impact test (Strand7)</th>
<th>Calibrated by Static Truck Proof-Load test (Strand7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.81</td>
<td>3.05 (8.48%)</td>
<td>2.85 (1.37%)</td>
<td>2.6 (-7.52%)</td>
</tr>
<tr>
<td>2</td>
<td>3.72</td>
<td>3.94 (6%)</td>
<td>3.71 (-0.19%)</td>
<td>3.8 (2.23%)</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>4.21 (-)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5.22</td>
<td><strong>5.92 (13.32%)</strong></td>
<td>5.54 (6.05%)</td>
<td>5.21 (-0.27%)</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td></td>
<td>8.69 (-)</td>
</tr>
<tr>
<td>6</td>
<td>9.30</td>
<td>9.7 (4.27%)</td>
<td>8.99 (-3.36%)</td>
<td>9.78 (5.13%)</td>
</tr>
<tr>
<td>7</td>
<td>11.60</td>
<td>10.65 (-8.22%)</td>
<td>10.61 (-8.56%)</td>
<td>11.58 (-0.2%)</td>
</tr>
<tr>
<td>8</td>
<td>12.28</td>
<td>12.81 (4.32%)</td>
<td>13.13 (6.92%)</td>
<td>13.06 (6.35%)</td>
</tr>
<tr>
<td>9</td>
<td>14.89</td>
<td>14.76 (-0.87%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>15.43</td>
<td>15.44 (0.09%)</td>
<td>14.75 (-4.38%)</td>
<td></td>
</tr>
</tbody>
</table>
Case Study – Utilization of model for Decision Making

- Fatigue cracks occurred primarily due to distortion of the wind braces (which were directly welded to the girder webs and appeared to be redundant for lateral loading), so removal of wind bracing elements should be considered;
- Deteriorated or damaged bearings should be replaced with multi-directional elastomeric bearings since FE model simulations indicated ideal bearing movements were not uniaxial along the longitudinal direction of the span;
- The pier-cap with shear cracking should be post-tensioned by coring through the concrete cap in conjunction with epoxy injection;
- Mitigation of excessive vibrations should be considered to improve durability and performance.
Further Work

VIRTUAL LABORATORY for LEVERAGING BRIDGE TECHNOLOGY

BRIDGE ASSET MANAGEMENT DECISION SCENARIOS REQUIRING QUANTITATIVE OBJECTIVE DATA
Based on bridge maintenance, repair, retrofit and decommissioning examples provided by bridge owners

Case Studies of Technology Leveraging to Address Bridge Performance Concerns

CLASSIFICATION and BASIC PRINCIPLES OF NONDESTRUCTIVE EVALUATION (NDE) AND STRUCTURAL HEALTH MONITORING (SHM) APPROACHES:

- MATERIAL-LEVEL ASSESSMENT
- STRUCTURAL ASSESSMENT
- GEOTECHNICAL ASSESSMENT
- MONITORING
- INTEGRATION, INTERPRETATION and DECISION-MAKING

SIMULATIONS AND SENSOR LAB
Case Study – Utilization of model for Decision Making

3D presentation in Cl3ver website

A case study of Highway Bridge Inspection and Testing  Drexel University