DEVELOPMENT OF LIMIT STATE BASED STRUCTURAL HEALTH MONITORING THRESHOLDS FOR EFFICIENT BRIDGE MANAGEMENT

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What is it?

First common challenge seen with SHM
- Lack of a common definition

A process aimed at providing accurate and in-time information concerning structural health condition and performance (Princeton)

The process of implementing a damage detection and characterization strategy for engineering structures (LANL)

The practice of identifying and tracking quantitative performance metrics through measured data and analytical models (IIS)
What you can measure is not what you need; what you need, you cannot measure.

Observable Responses (Measurable)

Unobservable Attributes ("Health", "Condition", "Damage", "Capacity")

SHM

Bridge Management Metrics

How can we provide actionable information from SHM and integrate into Bridge Management frameworks?
Benefit to Owner Steward

Overly Optimistic

Overly Pessimistic

Experience Generated

Perception

“Bubble” fueled by excitement and over-selling (snake oil)

“Backlash” fueled by lack of tangible benefits

Conception of Paradigm (technology transfer)

Reality

Present Day
June 1-3, 2016:

FHWA held a workshop to “develop, discuss, and debate future research directions of NDE and SHM.”

Key outcomes:

- Foster on-going Government-Industry-Academe Collaboration
- No representation in AASHTO SCOBS
- SHM Guidance needed
- NDE Research Roadmap

What is the Most Important Research Topic for NDE and SHM? (Run-off)

- Monitoring corrosion rate and section loss
- Estimation of remaining service life
- Establishing the cost-benefit of NDE/SHM
- NDE/SHM reliability
- Measurement of total stress
- Data fusion, analysis, and visualization
Meanwhile…

- Continue to engage with peers and colleagues on best practices and share experiences
- Our opinion on best practices to SHM
  - Constant engagement with the end-user
  - Design, not procurement.
  - Definition of clear *performance requirements* at the RFP stage
    - Allows for creative design by bidders on providing the translation of measurements to actionable information
Performance Requirement Framework

1. End-User Engagement
2. Risk Assessment
3. Input-Output Analysis
4. Instrumentation Design
5. Definition of Performance Criteria
Risk Assessment

We can reduce the cost of uncertainty premium by using technology.
Input-Output Analysis

- **Inputs**: Parameters independent of the bridge structure which tend to act upon the bridge
  - Wind, vessel impact, overloads, temperature gradients, etc.
- **Outputs**: Response of the bridge as a function of material or structural properties
  - Displacement, strain, surface temperature, rotation, etc.
Armed with required input and output measurands, the SHM system can be designed:

- Type / size / location of sensors
- Data acquisition strategies
- Protection strategies / ruggedization (as necessary)
- Level of supporting analysis needed (if necessary) - Hand analysis, FE models and hazard simulation

How does this relate to bridge management?
Performance Criteria

- Metrics used to establish acceptable levels of hazards or vulnerabilities
- Serve as the foundation for alerting and integration into ITS / TMC / AM systems
- Directly informed
  - Tend to be institutional or code-based and related to Inputs
    - Maximum legal loads
    - Maximum allowable wind speeds
- Indirectly informed
  - Tend to relate to structural safety (ie, Outputs)
    - Usually require structural engineering analysis
    - Remaining capacity
    - Allowable movements
End-User Engagement

1. End-User Engagement

2. Risk Assessment

3. Input-Output Analysis

4. Instrumentation Design

5. Definition of Performance Criteria
CASE STUDY: MULTI-GIRDER STEEL BRIDGE

ENGINEERING-BASED PERFORMANCE METRICS TO SUPPORT BRIDGE MANAGEMENT
A 46 year old bridge will be subject to nearby site construction with significant loading (1,000T + ).

- Characteristics:
  - 1,767’ total length
  - Two-span continuous steel multi-girder approach
  - Continuous steel truss
  - Four lanes
  - Varied substructures
    - Pile-supported abutments
    - Pile-supported piers
    - Piers on bedrock
- Note: Confidential project
Goals:

- Determine feasibility of SHM
- Establish performance requirements of interest
  - Monitor for permanent rigid body translations of the two piers in all three directions
  - Monitor for permanent rigid body rotations of the two piers in all three dimensions
  - Ensure that any measured rigid body movements do not impact the load rating of the steel multi-girder span with respect to Strength and Serviceability limit states.
  - Ensure that any measured rigid body movements do not generate cracking in the reinforced concrete piers.
  - Ensure that any measured rigid body movements do not bottom out any of the movement systems.
Risk Assessment

- One fundamental risk that motivated this project..

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPMT</td>
<td>• Overstressing of superstructure components</td>
</tr>
<tr>
<td></td>
<td>• Cracking of piers</td>
</tr>
<tr>
<td></td>
<td>• Bottoming out movement systems</td>
</tr>
<tr>
<td></td>
<td>• Differential settlement</td>
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</tbody>
</table>

## Input – Output Analysis

<table>
<thead>
<tr>
<th>Performance Metric Input</th>
<th>Output</th>
<th>Sensing Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid body translations</td>
<td>• Thermal</td>
<td>• VW Displacement</td>
</tr>
<tr>
<td></td>
<td>• Heavy load</td>
<td>• Laser Distance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Weather</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Local Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• VW Strain</td>
</tr>
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<td></td>
<td>• Expansion / contraction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Translation</td>
<td></td>
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<tr>
<td></td>
<td>• Axial force</td>
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<tr>
<td></td>
<td>• Support movement</td>
<td></td>
</tr>
<tr>
<td>Rigid body rotations</td>
<td>• Thermal</td>
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<tr>
<td></td>
<td>• Heavy load</td>
<td>• Weather</td>
</tr>
<tr>
<td></td>
<td>• Live load</td>
<td>• Local temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Expansion / contraction</td>
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<tr>
<td></td>
<td>• Rotation</td>
<td></td>
</tr>
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</table>

* VW = Vibrating Wire type sensors
Definition of Performance Criteria – Superstructure Capacity

- 3D FE refined load rating computation
  - Agency and AASHTO defined rating vehicles
  - Required to simulate the occurrence of live load together with movements defined under the performance requirements
  - Added benefit to owner was improved live load ratings (>1) due to refined analysis
  - Automation used to cut down analysis time
- Allowable superstructure ratings given support movements were computed.
  - In line with NCHRP 12-103
Definition of Performance Criteria – Serviceability

- When would onset of cracking occur in reinforced concrete piers due to p-delta effects from settlement?
- Again used FE model to simulate nonlinear (geometric) analysis that evaluated multiple movement levels until cracking stress levels were exceeded.

**Pier 1 - Rotation about Y Axis**

![Graph showing Stress (psi) vs Rotation (degrees)]

- Stress (psi) axis ranges from 0 to 1100.
- Rotation (degrees) axis ranges from -4 to 4.
- Red line represents Modulus of Rupture.
- Blue line represents Maximum Stress.

**Graph Legend**
- **Red** - Modulus of Rupture
- **Blue** - Maximum Stress
Given the height of the piers, it was most likely to bottom out movement mechanism before reaching other limit states.
<table>
<thead>
<tr>
<th>Movement</th>
<th>Allowable</th>
<th>Governing Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pier 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Ry (°)</td>
<td>0.15</td>
<td>Pier Serviceability - Differential Rotation</td>
</tr>
<tr>
<td>- Ry (°)</td>
<td>0.06</td>
<td>Kinematic - Abutment 1 Expansion Joint</td>
</tr>
<tr>
<td>+ Dx (in)</td>
<td>2.2</td>
<td>Pier Serviceability - Differential Longitudinal Movement</td>
</tr>
<tr>
<td>- Dx (in)</td>
<td>0.91</td>
<td>Kinematic - Abutment 1 Expansion Joint</td>
</tr>
<tr>
<td>+ Dy (in)</td>
<td>0.35</td>
<td>Pier Serviceability - Differential Transverse Movement</td>
</tr>
<tr>
<td>- Dy (in)</td>
<td>0.55</td>
<td>Pier Serviceability - Differential Transverse Movement</td>
</tr>
<tr>
<td>+ Dz (in)</td>
<td>0.2</td>
<td>Pier Serviceability - Differential Settlement</td>
</tr>
<tr>
<td>- Dz (in)</td>
<td>0.3</td>
<td>Pier Serviceability - Differential Settlement</td>
</tr>
<tr>
<td>Pier 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Ry (°)</td>
<td>0.3</td>
<td>Kinematic - Span 3 Rocker Bearing</td>
</tr>
<tr>
<td>- Ry (°)</td>
<td>0.09</td>
<td>Kinematic - Span 3 Rocker Bearing</td>
</tr>
<tr>
<td>+ Dx (in)</td>
<td>4.34</td>
<td>Kinematic - Span 3 Rocker Bearing</td>
</tr>
<tr>
<td>- Dx (in)</td>
<td>1.32</td>
<td>Kinematic - Span 3 Rocker Bearing</td>
</tr>
<tr>
<td>+ Dy (in)</td>
<td>0.75</td>
<td>Pier Serviceability - Transverse Movement</td>
</tr>
<tr>
<td>- Dy (in)</td>
<td>0.55</td>
<td>Pier Serviceability - Transverse Movement</td>
</tr>
<tr>
<td>+ Dz (in)</td>
<td>6.2</td>
<td>Superstructure Rating - Negative Bending Interior Girder</td>
</tr>
<tr>
<td>- Dz (in)</td>
<td>6.2</td>
<td>Superstructure Rating - Negative Bending Interior Girder</td>
</tr>
</tbody>
</table>
Implementation

- Geotechnical consultant computed expected movements
  - Well within SHM thresholds
- Real-time display created for on-site situational awareness
- System performance tested with a CAT-777D vehicle loaded to 200T:
  - 20 Hz sampling
- Long-term sampling ongoing to document condition of bridge and better define baseline responses during heavy moves:
  - 15 minute sampling
This specific case study is hoped to demonstrate how SHM systems can be used to translate raw measurements into actionable information that can be integrated into management structures

- Simple as visual alert
- Complex as integration with TMC or other controls

End-user buy-in and understanding of how thresholds were established and computed are essential

Sensors should only be used if they can (directly or indirectly) inform a specific performance metric

- “I have a solution – what’s your problem?” versus “Where do your concerns lie?”
SHM / Asset Management Session

Please contact ndubbs@iisengineering.com if interested

CALL FOR ABSTRACTS - STRUCTURES CONGRESS 2018

The SEI National Technical Program Committee has opened the call for abstract and session proposals. Several new types of sessions will be available:

- Innovative Executive Sessions (IES) with opportunities for interaction
- Comprehensive Sessions that can extend beyond the traditional 90 minute time-frame
- Panel Sessions including multi-discipline project teams, debates or other formats.
- Case Studies on timely topics
- Other creative sessions that encourage audience participation and even breakout groups

All session proposals and abstract submissions are due June 5, 2017. Learn more on the Congress website.
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A Pennoni Company

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What frameworks to testing of bridges even exist?

\[ MAC = \frac{\left| \varphi_{\text{ana}}(i)^T \cdot \varphi_{\text{exp}}(i) \right|^2}{\varphi_{\text{ana}}(i)^T \cdot \varphi_{\text{exp}}(i) \cdot \varphi_{\text{exp}}(i)^T \cdot \varphi_{\text{ana}}(i)} \]
SHM Design Approach – Crawl, walk, then run…

1. **Should SHM be Considered?**
   - Heuristic-Based Decision

   - **Yes**
     - **Risk Level?**
       - Identify hazards, vulnerability, exposure and uncertainty through document review, field inspection (possibly with measurements), etc.

     - **High Risk**

     - **Can the Risk be Reduced through Further Analysis?**
       - Hand calculations, finite element modeling, etc.

     - **Yes**
       - **Is the Uncertainty and Vulnerability Still High?**

         - **Yes**
           - **Consider St-Id 3-6**
             - Dependent on hazard (e.g. overload truck hazard may utilize live load testing)

         - **No**

     - **No**

2. **No SHM System**

3. **Low Risk**

   - **Benefit / Cost of SHM System?**

     - **High**
       - **SHM System Design**

     - **Low**

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     - **Low**