STRUCTURAL HEALTH MONITORING IN TRANSPORTATION INFRASTRUCTURE APPLICATIONS – NEW PERSPECTIVES

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Outline of This Presentation

• Introduction and Objectives
• Current SHM Systems
• New SHM for Structural Behavior
  – Structural behavior monitoring and attributes
  – Three illustrative examples
    o Crack detection and quantification with one coaxial cable
    o Corrosion monitoring and quantification with one optical fiber with multiplexed sensors
    o Scour monitoring and quantification with wireless smart rocks

• Concluding Remarks
Introduction

- Transportation Infrastructure Characteristics
  - Large scale, large inventory, and complex
  - Subjected to multiple hazards (uncertain)
  - Operated in harsh environment
  - Multiple deterioration and failure modes
  - Incoherent design and operation conditions

ASCE reported little change in the condition of the nation’s bridges (~600,000) and water systems since 2005, and the cost for improvement has reached to $2.2 trillion in 2009.

Scour is the No.1 cause of over 1500 bridge collapses.
Introduction

• Typical Structural Behavior
  – Due to environmental effects/service loads

Corrosion is the No.1 cause of bridge maintenance (approximately $10B expenditure per year).
Introduction

• Typical Structural Behavior
  – Under service loads

1/22/03 Paseo Suspension Bridge Collapse, Kansas City, MO - Fatigue and Fracture

1999/2005 Blanchette Bridge Stringer Crack - Fatigue and Fracture
Introduction

• Typical Structural Behavior
  – Under extreme loads

  5/12/08 M7.9 China Earthquake
  2/27/10 M8.8 Chile Earthquake
  8/29/05 Hurricane Katrina
  9/22/10 Flood
Objectives

• Develop SHM systems
  – that can aid in bridge maintenance and ensure the safety of bridges.
  – that are low cost and low maintenance over time.
  – that directly give mission-critical data for design and retrofit of bridges.
Current SHM Systems

- Up to date, most SHM applications in civil infrastructure are based on vibration data.
- SHM System on Bill Emerson Cable-Stayed Bridge
  - 84 accelerometers with wireless transmission
  - One data recorder inside each tower
  - A central computer at MO free field site connected to internet for real-time monitoring
Vibration-based diagnosis and prognosis has been integrated into the maintenance and management of rotating machineries

- Capital-intensive assets for utilities and industry
- Failure leading to damage to the asset and surrounding substation parts, and power outages
- Coherent design and operation conditions, making maintenance easier

- Fatigue and fracture due to vibration loads (certain and repeatable)
- Well-defined failure mechanism
  - fatigue and fracture
Current SHM Systems

• Issues in Civil Infrastructure Applications
  – Incoherent design and operation conditions, making bridge maintenance a challenge with vibration-based technologies
    • Overwhelming collected data
    • Mathematically daunting “interpretation”
    • High cost-benefit ratio (significant maintenance)
    • Challenge in damage or deterioration detection with significant uncertainties in interpretation
  – Technology-driven development
New SHM for Structural Behavior

- Structural Behavior Monitoring (SBM)
- Problem-Driven Approach
- SBM Attributes (not all inclusive)
  - Damage/deterioration transfer from a structure to sensors
    - Reliable data collected from known, well controlled sensors
  - Direct monitoring and assessment of structural behaviors under operation conditions
    - Buckling, crack, corrosion, fatigue, fracture, scour & yielding
  - Coupled local and distributed measurements
    - Local vs. global multi-resolution measurements
  - Integrated monitoring and mitigation strategies
New SHM for Structural Behavior

• Needs for Real-Time Monitoring
  Time Scale versus Real Time Monitoring (RTM) of Major Behaviors

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Time Scale</th>
<th>Need for RTM</th>
<th>Data Usefulness</th>
<th>Monitoring</th>
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<tbody>
<tr>
<td>Buckling</td>
<td>Seconds</td>
<td>High</td>
<td>Low</td>
<td>Periodic</td>
</tr>
<tr>
<td>Crack</td>
<td>Seconds</td>
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<tr>
<td>Yielding</td>
<td>Minutes</td>
<td>High</td>
<td>High</td>
<td>Continuous</td>
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<tr>
<td>Scour</td>
<td>Hours</td>
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<tr>
<td>Fatigue</td>
<td>Years</td>
<td>Low</td>
<td>High</td>
<td>Periodic</td>
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<tr>
<td>Corrosion</td>
<td>Years</td>
<td>Low</td>
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</tbody>
</table>

• Analogy with Human Health Monitoring

<table>
<thead>
<tr>
<th>Phase of Life</th>
<th>Human Body</th>
<th>Engineering Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birth</td>
<td>Birth Monitoring</td>
<td>Construction Monitoring</td>
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<tr>
<td>Normal Life</td>
<td>Regular Check-up</td>
<td>SHM</td>
</tr>
<tr>
<td>Abnormal Life</td>
<td>Clinical Monitoring</td>
<td>SBM</td>
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</table>
New SHM for Structural Behavior

• SBM Application in Transportation Network
  – Select representative bridges for monitoring and assessment
  – Analyze a bridge to identify potential failure modes
  – Instrument the bridge with special sensors and collect data directly related to the potential failure modes
  – Apply adaptive data analysis to extract features that are causative to the failure modes (optional)
  – Predict the remaining life of the bridge structure and apply that information for infrastructure management
Three Illustrative Examples

• Crack Detection and Quantification with One Coaxial Cable

• Corrosion Monitoring and Quantification with One Optical Fiber Coated with Nano Particles for Multiplexed Sensors

• Scour Monitoring and Quantification with Wireless Smart Rocks
Illustrative Example 1

- Coaxial Cable Sensor for Crack Monitoring

![Coaxial Cable Sensor (Chen et al. 2004)]

- Current flow path
- Partial separation of spirals
- Crack Transfer Mechanism

Steel spiral separation

![Steel spiral separation]
Coaxial Cable Crack Sensors

- Electric Time Domain Reflectometry

Digital sampling oscilloscope with a SD-24 TDR sampling head

Incident voltage step → Coaxial cable → Reflected voltage step

Distance between points of monitoring and discontinuity

Measurement of Topology-based Cable Sensors

3D Plot from Dynamic Measurements
Coaxial Cable Crack Sensors

- Direct Measurement – Local and Distributed
Coaxial Cable Crack Sensors

- Dual Measurements due to Memory Feature

Reflection coefficients obtained from shake table testing of a 1/5-scale RC column.
Illustrative Example 2

- Optical Sensors for Corrosion Monitoring
  - Nano Iron Particles Coated Gratings and Mechanism
Optical Corrosion Sensors

- Corrosion Test Results

With no coating (in salt solution) \( \lambda = 1566.05 \text{nm} \)

With no coating (in air) \( \lambda = 1571.5 \text{nm} \)

Coated LPFG in 3.5\% salt solution \( \lambda = 1566.05 \text{nm} \)

Coated LPFG in air \( \lambda = 1570.45 \text{nm} \)

Immersion time (hours)

Wavelength (nm)

\[ \lambda = -0.54 \times \exp(-t/210.9) + 1564.878 \]

\[ R^2 = 0.99 \]
Illustrative Example 3

• Smart Rocks for Scour Monitoring and Mitigation

A pragmatic but highly innovative, cost-effective, real-time bridge scour management system has been recently proposed with passive/active smart rocks for integrated monitoring and mitigation of foundation scour.
Smart Rocks for Scour Monitoring

- Passive Smart Rocks with a Magnetometer

![Image of a bridge with flowing water and steel rebar]

**Location Response Function**

**Location Response Function**

**Strength-Distance Curves**

- Magnet 6cm*6cm*6cm
- Steel plate (0.75cm*15cm*75cm)
- Steel rebar (#8, length: 15cm)

**Graph Details:**
- Distance between Object and Magnetometer (m)
- Magnetic Field (nT)
- Instrument accuracy: 0.1 nT
Smart Rocks for Scour Monitoring

- Active Smart Rocks with Embedded Electronics

Prototype Electronics

Measured Voltage in Water/Air
Concluding Remarks

• The shift from SHM to SBM will create a new paradigm for monitoring and preserving the structural integrity of civil infrastructures.
• This advance will generate new research interests that satisfy both the academic quest for scientific and technological explorations and the pragmatic needs for retrofit design and maintenance solutions in deteriorated bridges.
• This advance will change engineers’ perception from unfavorable SHM to receptive SBM.
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