Recent Advances in Structural Health Monitoring

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Vulnerability of Our Civil Infrastructure

Bridge Rebuilt on the Fast Track

A devastating crash caused the collapse of a high-traffic bridge in downtown Birmingham, AL, but it was back in operation only 53 days later.

View of the I-40 bridge engulfed by smoke 1:45 and 1:50 minutes after the crash took place.

Courtesy of LA Times

Courtesy of A Worrall
How can Structural Health Monitoring (SHM) Help?

Current Practice - Visual, Periodic Inspection

• Cannot detect invisible damage
• Cannot timely detect problem

Future Practice - Incorporating SHM

• Use on-structure sensors for continuous monitoring to identify hot spots in real time
• Condition-based inspection focusing on hot spots
Integration of Real-Time Global Monitoring with Targeted Local Inspection

- Use of On-Structure Sensors for Continuous Monitoring for Real-Time Assessment of Global Structural Integrity and Identification of Hot Spots

- Condition-Based NDE Inspection of Targeted Hot Spots
Where Are We Now?
We Need Better Sensors

Solar Penal

Piano wire

Bellow

Soil Pressure Sensor

L.V.D.T Displacement Meter

Strain Gauge

Signal Conditioner TSA-20

DC-5V

To recorder

+ -
Remote Control and Data Acquisition

Bridge Site

UCI Campus

Wireless Real-Time Data Acquisition System
We Need Reliable Methods to Interpret Sensor Data

Server

Client

http://mfeng.eng.uci.edu
Contents

• **Innovative Sensors and NDE Devices**
  - Fiber Optic Accelerometer
  - Wireless MEMS Accelerometer
  - Vision-Based Displacement Sensor
  - Distributed Fiber Optic Strain Sensor
  - Microwave Imaging NDE Device

• **Health Diagnosis Methods and Experiments**
  - Neural Networks and Application in Long-Term Monitoring
  - Traffic Excitation Modeling and Bayesian Updating
  - Extended Kalman Filtering and Shaking Table Tests
  - Nonlinear Damping Analysis and Shaking Table Tests
  - Estimation of Remaining Capacity
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Fiber Optic Accelerometer

- Sensing Principle: moiré fringe

- Unique Feature:

  High resolution and large measurement range, uniquely suited for accurate measurement of both ambient micro-vibration and strong motion.

  Immunity to electromagnetic interference and lightning strikes, safe to use in explosion-prone environments.

  Excellent low-frequency performance, suited for monitoring long-period structures.

Uniquely Suited for Monitoring Large-Scale Civil Infrastructure Systems in Harsh Environment
Shaking Table Test

![Diagram of a building model with Ch1 to Ch5 labeled and Beam, Columns, and Base indicated.]

**Time signal of Sylmar 1.25x**

- Acceleration (g)
  - Time (sec.)

**Power Spectrum Density of Sylmar 1.25x**

- Amplitude
  - Frequency (Hz)

![Graphs showing time and frequency data with Optical Fiber Sensor and Reference Sensor (KINEMETRICS I6083) plots.]

**References**

- FOA Wireless Sensor
- Optical Fiber Sensor
Continuous Monitoring of CalIT2 Building

![Graph showing acceleration vs. time for Fiber Optic Accelerometer and Servo Accelerometer.](image1)

- **Acceleration** $\times 10^{-3} (g)$
- **Time (sec.)**

![Image of Servo Accelerometer and FOA.](image2)

- Servo Accelerometer
- FOA

![Power Spectrum Density of FOA and Servo Accelerometer.](image3)
Wireless MEMS Accelerometer

ULTRA COMPACT
LOW POWER
Real-Time Damage Detection of Water Pipelines

DuraNode

Node B

Node A

Node D

Node C

Valve

Water Input

Diameter of the pipe: 1 in

(a) Node A

0.5g

0.65g

(c) Node C

0.35g

(d) Node D

1.2g
Vision-Based Displacement Sensor

Suitable for measuring long-period structures

Remote and non-contact

Figure 7  Vision-Based Displacement Sensor System
Remote Monitoring of Bridge Response

Vision-based system

Displ. transducer and laser vibrometer

Displ. transducer

Laser vibrometer

Vision-based system

Bridge

Target panel

Reflector

Wire

Ground

Displ. transducer (Contact type)

Laser vibrometer (Non-contact type)

15 ton

30 ton

40 ton
Distributed Fiber Optic Strain Sensor

- **Principle:** Brillouin loss
- **Unique Feature:**
  - High spatial resolution (10cm) and measurement accuracy
- **Applications:**
  - Strain and temperature measurement of large structures up to 40km;
  - Crack detection up to 40 µm
Acoustic Emission Sensor

Acoustic emission signal induced by pencil break

Gold deposited surface
Handheld Real-Time Microwave Imaging Device

- Locate, in real time, invisible defects
- Portable & lightweight
- Easy operation requiring no training
Inspection of FRP-Wrapped Concrete
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Structural Health Diagnosis

• **Goal of SHM**
  - Damage Detection
  - Damage Location
  - Damage Quantification
  - Damage Consequences

• **Damage Signature**
  - Structural Stiffness
  - Structural Damping

• **What to Measure?**
  - Structural Vibration (Ambient, Seismic Response, etc.)
Neural Networks

Experimental Modal Analysis

Frequencies & Mode Shapes

Bridge Traffic Vibration Data

Comparison of Natural Frequencies of JEO (Hz)

<table>
<thead>
<tr>
<th>Mode</th>
<th>In-plane node</th>
<th>Out-of-plane node</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.089</td>
<td>2.554</td>
</tr>
<tr>
<td>2</td>
<td>3.716</td>
<td>4.078</td>
</tr>
<tr>
<td>3</td>
<td>4.654</td>
<td>4.686</td>
</tr>
<tr>
<td>4</td>
<td>5.571</td>
<td>5.629</td>
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<tr>
<td>5</td>
<td>9.00</td>
<td>9.597</td>
</tr>
<tr>
<td>6</td>
<td>14.321</td>
<td>17.729</td>
</tr>
</tbody>
</table>

Assessment of structural condition

Change of Stiffness from Baseline

Neural Network

Input layer

Hidden layer

Hidden layer

Output layer
Five-Year Continuous Monitoring

First Modal Frequency (Hz)

- Summer
- Winter

Superstructure Stiffness (%)

- Summer
- Winter

Time (year)
Traffic Excitation Modeling

Improved System Identification

Reconstruct Traffic Excitation

Extract Traffic Information
Vehicle arrival time, speed and type
Extended Kalman Filter for Seismic Damage Assessment

- Use of seismic response and input \( I_1 / I_1^0 \)
- Instantaneous and real-time identification
- Applicable to linear and nonlinear systems
- Baseline free
# Shaking Table Tests of 3-Bent Concrete Bridge

## Ground Motion Description

<table>
<thead>
<tr>
<th>Test</th>
<th>Ground Motion Description</th>
<th>PGA (g)</th>
<th>Damage Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WN-1</td>
<td>White Noise in Transverse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-13</td>
<td>Low Earthquake in Transverse</td>
<td>0.17</td>
<td>Bent-1 yields</td>
</tr>
<tr>
<td>T-14</td>
<td>Moderate Earthquake in Transverse</td>
<td>0.32</td>
<td>Bent-3 yields</td>
</tr>
<tr>
<td>WN-2</td>
<td>White Noise in Transverse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-15</td>
<td>High Earthquake in Transverse</td>
<td>0.63</td>
<td>Bent-2 yields</td>
</tr>
<tr>
<td>WN-3</td>
<td>White Noise in Transverse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-19</td>
<td>Extreme Earthquake in Transverse</td>
<td>1.70</td>
<td>Bent-3 steel buckles</td>
</tr>
<tr>
<td>WN-4</td>
<td>White Noise in Transverse</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Diagram of 3-bent concrete bridge with ground motion tests](diagram.png)
Instantaneous Identification of Stiffness Change Using Seismic Response

![Graphs showing stiffness reduction over time for different tests (T13, T14, T15, T19).]
Identification of Nonlinear Damping Using Ambient Response
Comparison of Damage Assessment Methods

The graph shows a comparison of different damage assessment methods for various locations labeled WN1, T13, T14, WN2, T15, WN3, T19, and WN4. The x-axis represents these locations, and the y-axis represents stiffness reduction methods. Four methods are compared:
- Extended Kalman Filter
- Recursive Bayesian Filter
- Hysteretic Loops Slope

The graph illustrates how each method performs at different locations, with WN2 showing the most significant reduction in stiffness compared to other locations. The y-axis also indicates a non-linear damping effect.
Estimation of Remaining Capacity

<table>
<thead>
<tr>
<th></th>
<th>After T13</th>
<th>After T14</th>
<th>After T15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bayesian Updated</td>
<td>53%</td>
<td>23%</td>
<td>0%</td>
</tr>
<tr>
<td>Simulated</td>
<td>75%</td>
<td>44%</td>
<td>3%</td>
</tr>
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Concluding Remarks

Sensors Network
• Low cost
• Easy to install and maintain
• Field durability and reliability
• Power efficient

Health Diagnosis Methods
• Baseline free
• Real-time or near real-time assessment

Remaining Issues
• Long-term monitoring data
• Damage criteria
• Prognostic as well as diagnostic methods