More than a quarter of the bridges nationwide are structurally deficient.

How Can Structural Health Monitoring Help?

Current Practice - Visual, Periodic Inspection
- Cannot timely detect problems
- Difficult to detect invisible damage

Future Practice - Incorporating Structural Health Monitoring
- 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
- 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

The need for better sensors includes:
- Solar Panel
- Displacement Meter
- Soil Pressure Sensor
- Accelerometer

We Need Tools to Interpret and Use the Data

Bridge Site

Wireless Real-Time Data Acquisition System

Contents

• Recent Advances in Sensors
  - Moiré fringe-based fiber optic accelerometer
  - Wireless sensor network
  - Vision-based remote displacement sensor
  - Distributed fiber optic strain sensor
  - Piezoelectric Impedance Sensor
  - Microwave imaging system
  - Integrated scour monitoring system

• Diagnostics and Prognostics Tools
  - Case Study #1: Post-event damage assessment
  - Case Study #2: Long-term structural health monitoring
  - Case Study #3: Integrated NDE of concrete bridge decks

Moiré Fringe-Based Fiber Optic Accelerometer

• Sensing Principle: Moiré fringe

• Unique Features:
  - 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.

Moiré Fringe

\[ \text{Intensity} = \frac{\text{const.}}{\cos(\pi x/T) \cos(\pi y/T)} \]

Continuous Monitoring of CalIT2 Building

Optical fiber accelerometer

Fiber optic accelerometer

Conventional Accelerometer

Uniquely Suited for Monitoring Large-Scale Civil Infrastructure System in Harsh Environment

Excellent low-frequency performance suited for monitoring long-period structures.
Hwamyung Bridge, a prestressed concrete girder cable bridge
Main Span: 500m, Side Span: 115m x 2, including ramps: 1.039km
To be completed in March, 2013

Wireless Sensor Network

US: M. Shinozuka (UCI)
Korea: J. T. Kim, S. W. Shin (PKNU); C. B. Yun (KAIST)

- Daisy chain connection up to 120 nodes
- Low noise MEMS accelerometers
- Support to connect commercial accelerometers
- Built-in tilt/humidity/temperature sensors

Multi-Wireless Technologies: WiFi/Xstream/XBee/Eco
Support various network topologies
Support real-time monitoring system
Establishment Server and Web-based SHM method

Sensor Deployment

Data Logging at UCI
Web-based Monitoring

Remote Monitoring Framework

Realtime Remote Monitoring - Temporary Connection
FE Model and Modal Extraction

Gimhae Busan
115 m
270 m
115 m
BLC02

200
300
400
500
600

Time (s)

Acceleration (g)

0.279 Hz
0.4134 Hz

Cable Monitoring (BLC02)

1st Vertical Direction
1st Lateral Direction

Remote non-contact measurement by using low-cost video camera

Vision-Based Remote Displacement Sensor

Measurement wt and w/o Target Panel

Robust Against Obstacles and Lighting Change

Robust Image Processing

OC Matching

Lighting Change

Light

0
1
2
3
4
5

Displacements by Vision-Based Sensor and LVDT

Table Test

Great Hanshin-Awaji earthquake

Western Tottori earthquake

- Excellent performance w/o target panel in the dark
  - Time: 11:00 AM, 12/15/2009
  - Time: 5:15 PM, 12/15/2009
Remote Monitoring of Bridge Deformation

Distributed Fiber Optic Strain Sensor

Principle:
– Brillouin scattering

Innovation:
– Stimulated Brillouin scattering - Increasing spatial resolution by 10 times

Applications:
– Crack detection
– Long-distance distributed strain measurement

Detection of Cracks in Fiber Reinforced Concrete

Piezoelectric Impedance Sensor
(C.B. Yun, KAIST, Korea)

Reference-Free Damage Detection Using Dual PZT’s
(H. Sohn, KAIST, Korea)
Detection of Concrete Voids

Experimental vs. Numerical Results

Multi-Frequency Technique

Handheld Real-Time Microwave Imaging Device
Inspection of FRP-Wrapped Concrete

Non-Destructive Detection of Corrosion

Integrated Scour Monitoring System
(KC Chang, NCEER, Taiwan)

Field Scour Monitoring System

Field Bridge Scour Monitoring

The measured data were transmitted through Wi-Fi communication system which is end connected with wired network, then the data was sent to the remote server database in the office.

Laboratory Experiments

- Verification on concepts of the field instrumentations
- Simulation on various scour conditions to verify the monitoring system
- Experimental study on bridge collapse due to scouring and the associated numerical simulations.
Contents

- Recent Advances in Sensors
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  - Case Study #1: Post-event damage assessment
  - Case Study #2: Long-term structural health monitoring
  - Case Study #3: Integrated NDE of concrete bridge decks

Case Study #1 Post-Event Damage Assessment

- Goals:
  - To Detect, Locate, and Quantify Structural Damage
  - To Predict Remaining Capacity of Bridges
  - To Assist Decisions for Post-Event Disaster Mitigation and Speedy Recovering

- Damage Index:
  - Structural Stiffness and Damping identified from Structural Vibration (Ambient, Seismic) Measurement

- Approaches:
  - A Variety of System Identification Techniques for Damage Assessment
  - Link Damage to Remaining Capacity
  - Realistic Experimental Validation

Use of Sensor Data for Decision Support

- Sensor Data from Instrumented Structure
- Post-Event Damage Assessment
- Residual Capacity Estimation
- Long-Term Structural Health Monitoring
- Disaster Mitigation
- Speedy Recovery
- Intelligent Maintenance

Damage Assessment Methods and Experimental Validation

- Seismic shaking table tests of a 3-bent concrete bridge
- Progressive damage caused by increasing ground motion intensity
- Damage assessment by different system identification techniques:
  1. Bayesian Updating
  2. Extended Kalman Filter
  3. Central Difference Filter
  4. Optimization-Based Approaches
     - Quasi-Newton
     - Evolutionary Algorithm
  5. Nonlinear Damping
  6. Neural Networks
Bayesian Updating

\[ X_k = f(X_{k-1}, U_{k-1}, W_{k-1}; \theta) \]  
\[ Z_k = h(X_k, U_k, V_k; \theta) \]

\( X \) is the states, \( Z \) the observations, \( U \) the deterministic input, \( W \) the process noise, and \( V \) the measurement noise.

By Bayesian Theorem, the recursive Bayesian filtering at time step \( k \):

\[
p(X_k|Z_{1:k}) = \frac{p(Z_k|X_k)p(X_k|Z_{1:k-1})}{\int p(Z_k|X_k)p(X_k|Z_{1:k-1})dx_k}
\]

Parameter Estimation

\[ \{X_k, \theta\} \]

Extended State

\[
\begin{align*}
\{X_k, \theta\} &= F\{X_{k-1}, \theta_{k-1}, U_{k-1}, W_{k-1}\} \\
Z_k &= H\{X_k, \theta_{k-1}, U_k, V_k\}
\end{align*}
\]

For SHM purpose, we concern about the changes of \( \theta \) and its distribution

\[ \theta_k = \theta_{k-1} + W_{k-1} \]

\( \phi = I \)

Seismic Shaking Table Test

Identification results based on vibration data are consistent with observed damage sequence based on embedded strain sensors:

Bent 1 yields \( \rightarrow \) Bent 3 yields \( \rightarrow \) Bent 2 yields \( \rightarrow \) Bent 3 buckles
As PGA increases, the bridge column stiffness decreases.

As PGA increases, the bridge column stiffness decreases.

As PGA increases, viscous damping decreases and friction damping increases.

As PGA increases, viscous damping decreases and friction damping increases.
Use of Identified Stiffness for Capacity Estimation

- Pushover curve (based on design data)
- Performance point (by stiffness identification)

DECISION: Open Partially Open Closed

Use of Sensor Data for Decision Support

- Sensor Data from Instrumented Structure
- Post-Event Damage Assessment Residual Capacity Estimation
- Long-Term Structural Health Monitoring
- Disaster Mitigation Speedy Recovery
- Intelligent Maintenance

Case Study #2: Long-Term Structural Health Monitoring

Issues with Field Implementation

- Soil-Structure Interaction Amplitude Dependency
- Modeling of Traffic Excitation Long-Term Monitoring Data
- Vehicle-Structure Interaction Long-Term Monitoring Data
- Bridge Doctor for Decision Support

Earthquake Records, Mw=4.9 Yucaipa Earthquake, June 16, 2005

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Date</th>
<th>Magnitude</th>
<th>Distance (km)</th>
<th>PGA (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yucaipa</td>
<td>Mar 16, 2005</td>
<td>4.9</td>
<td>90</td>
<td>0.017</td>
</tr>
<tr>
<td>S. Clemente</td>
<td>Oct 16, 2005</td>
<td>4.9</td>
<td>135</td>
<td>0.005</td>
</tr>
<tr>
<td>Chino Hills</td>
<td>Mar 17, 2005</td>
<td>4.7</td>
<td>58</td>
<td>0.046</td>
</tr>
<tr>
<td>Inglewood</td>
<td>May 17, 2005</td>
<td>4.7</td>
<td>58</td>
<td>0.046</td>
</tr>
</tbody>
</table>

Identified modal frequencies and damping ratios:

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Pacific Coast</th>
<th>Central California</th>
<th>Los Angeles</th>
<th>San Diego</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.77</td>
<td>4.52</td>
<td>5.25</td>
<td>4.36</td>
</tr>
<tr>
<td>2</td>
<td>2.87</td>
<td>4.30</td>
<td>5.25</td>
<td>4.36</td>
</tr>
<tr>
<td>3</td>
<td>3.59</td>
<td>3.85</td>
<td>5.43</td>
<td>3.46</td>
</tr>
<tr>
<td>4</td>
<td>3.85</td>
<td>3.46</td>
<td>5.75</td>
<td>3.75</td>
</tr>
<tr>
<td>5</td>
<td>4.36</td>
<td>4.36</td>
<td>6.00</td>
<td>4.36</td>
</tr>
</tbody>
</table>

Earthquake Records, Mw=4.9 Yucaipa Earthquake, June 16, 2005

43 accelerometers

Scaled Power Spectral Density

Recorded ground motion at Caltech building site:

<table>
<thead>
<tr>
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<th>PGA (g)</th>
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<td>4.7</td>
<td>58</td>
<td>0.046</td>
</tr>
</tbody>
</table>
The variations of modal parameters with the peak ground accelerations:

- Frequency (Hz) vs. PGA (cm/sec²)
- Damping ratio (%) vs. PGA (cm/sec²)

Identification of Stiffness by Neural Networks:

- Input layer
- Hidden layer
- Output layer

Experimental Modal Analysis:

Bridge Traffic Vibration Data

Assessment of structural Health

Change of Stiffness from Baseline

Bridge Traffic Vibration Data

Idenfication of Stiffness by Neural Networks

Traffic Excitation Modeling by Integration of Vibration and Traffic Monitoring

Bayesian Updating

Traffic Video

Image processing - Vehicle type, annual time & speed

Traffic Excitation Modeling

Stiffness Degradation

Temperature Effects

Five-Year Continuous Monitoring of Jamboree Bridge

Superstructure Stiffness (%)

Stiffness Degradation

Temperature Effects

Vibration Tests at West St. Bridge

Eight-Year Continuous Monitoring of West St. On-Ramp

Vehicle-bridge interaction causes notable variation of natural frequencies

Traffic Excitation Modeling

Stiffness Degradation

Temperature Effects

Vibration Tests at West St. Bridge

8-Year Continuous Monitoring of West St. Bridge
Natural Frequencies from AVT

\[ f_1 = 1.904 \text{Hz} \]
\[ f_2 = 2.344 \text{Hz} \]
\[ f_3 = 2.637 \text{Hz} \]

**FDD using truck induced vibration**

- **X:** 2.315
  - **Y:** 4.084e-006
- **X:** 2.655
  - **Y:** 1.245e-005
- **X:** 3.285
  - **Y:** 5.211e-006

**FDD using AVT data**

- **X:** 1.904
  - **Y:** 1.366e-007
- **X:** 2.344
  - **Y:** 2.011e-007
- **X:** 2.637
  - **Y:** 5.895e-008

**Truck Modal Shapes**

- Truck Modal Shapes corresponding to bridge natural frequencies:
  - **f:** 1.904Hz
  - **f:** 2.344Hz
  - **f:** 2.637Hz

- Truck Modal Shapes corresponding to chassis natural frequencies:
  - **f:** 2.930Hz
  - **f:** 6.055Hz

**Bridge Doctor Software**

- **Sensor Data from Instrumented Bridges**
  - **Post-Event**
    - **Rapid Damage Screening**
    - **Detailed Damage Assessment**
    - **Condition Assessment**
    - **Remaining Capacity Estimation**
  - **Long-Term**
    - **Intelligent Maintenance**
    - **Post-Event Disaster Mitigation & Speedy Recovery**

**Case Study #3: Integrated NDE of Concrete Bridge Decks**
(N. Gucunski, Rutgers University)

- Electrochemical methods for corrosion assessment
- Impact echo for delamination detection
- Ground Penetrating Radar (GPR) inspection
- Ultrasonic Surface Wave (USW) testing of concrete modulus
Electrochemical Methods for Corrosion Detection

**Half-Cell Potential**
- Principle of Half-Cell Potential Measurement
  - Half-cell probe (reference electrode)
  - Voltmeter
  - Current flow
  - Iso-potential lines
  - Potential: -414 mV

**Electrical Resistivity**
- Principle of Electrical Resistivity Measurement
  - Current flow
  - Iso-potential lines
  - Voltage $U$
  - Resistivity $\rho = \frac{2\pi d U}{I}$

**Half-Cell Potential Measurement and Map**
- Half-cell potential (mV)
- Distance from west abutment (feet)

**Electrical Resistivity Measurement and Map**
- Electrical resistivity (kohm*cm)
- Distance from west abutment (feet)

**Delamination Detection by Impact Echo**
Impact Echo Validation with Cores

Distance from west abutment, ft

GPR – Ground Coupled System

Air-Coupled (Horn) Antenna GPR System

GPR – Raw Scan and Condition Map

Deteriorated Zone

GPR Scan – 2.6 GHz, Municipal Drive Bridge, Warren County, NJ

Ultrasonic Surface Waves (USW) Method

Depth considered less than layer thickness
USW Testing Using PSPA

Concrete Modulus from USW
(Bridge R1, Iowa)

Distance from west abutment (ft)
Young's Modulus (ksi)

1500 5500 5500 7500

• Periodic Visual Inspection
• Continuous Monitoring + Condition-Based Inspection

Sustainable Transportation Infrastructure
Paradigm shift