Benefits of Structural Health Monitoring of Bridges

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What is Structural Health Monitoring

• Use quantitative information
  – Sensors, measurements, images, etc.

• To make management decisions, to learn about condition, or to establish behavior.

• But, why use SHM.
Traditional Evaluation

1968 - National Bridge Inspection Program initiated

Visual inspection

Conventional Calculations
Basic Testing Concept

- Record **field measurements** on structure subjected to loads to identify actual structural response.
- Field data may be used to “calibrate” an analytical model that closely represents the behavior observed in the field.
- May be used for detecting damage or deterioration, general structural evaluations, and for developing load ratings.
Objective: Short-Term SHM

• Collect data, over a relatively short period of time (several hours to one day), for the purpose of obtaining quantitative information that allows for:
  – Improving qualitative assessments.
  – Improving future designs.
  – Determining “on-the-fly” modifications (e.g., during construction).
Application #1

• Provide structural performance recommendations for evaluation
  – Load distribution
  – Stress level
  – Serviceability (deflection, shear keys)
• Guidelines for evaluation
  – X-section strain compatibility
  – Deflections within AASHTO limits
  – W/ regard to “shear keys” transverse distribution satisfied AASHTO limits

• Decision: Delay replacement
• **Supplementary** laboratory strength tests
Application #2

• Determine if the excessive wind event and associated bridge movement that was reported was “accurate”.

• Install a monitoring system for remote alerting of future events.
• Short-term load test
  – Identify dynamic modal characteristics
    • Strain and acceleration
    • Bridge/wind interaction possible
• Long-term monitoring
  – Girder strain and acceleration, wind speed and direction
    • Data loggers
    • 24x7 data collection

• Alert system
  – Cellular communications
Application #3

- Evaluate effectiveness of strengthening systems
  - Strain profile
  - Stiffness increase
  - Change in load distribution
• Added material (FRP, Steel)
  – Short and long-term evaluations generally reveals that strengthening mechanisms are effective

• Short and long-term increase in stiffness
• Minimal load distribution effect
Application #4

• Primary: Determine if load rating is reasonable
• Secondary: Validate evaluation process for subsequent permit trucks

900,000 lb permit load (~RF 0.5)
• Tested with combinations of one and two loaded tandem axle dump trucks
• Learned about behavior
  – Composite action
  – End restraint
  – **Live load distribution**
    • Improved load distribution characteristics used in hand calculations; changed RF to 0.9
  – Rating w/ validated analytical model
    • RF \( \sim 1.0 \) (permit truck)
• Prediction validity for permit truck
Application #5
• Short term – eliminate panel overstress during construction.
• Long term – monitor redistribution of loads in hangers due to concrete creep.
• Strain (force) correlated with target design values during construction
Application #6 Incremental Launch of the U.S. 20 Iowa River Bridge
Girders Assembled in Launching Pit and Supported by Rollers
Substructure Monitoring

- General pier behavior
- (drilled shaft and driven pile)
  - Column base strain
  - Column base translation and tilt
  - Cap beam tilt
Monitoring Results - Substructure

- Largest day launch cumulative column stress measured was 600 psi
- Residual stress at end of day launch

![Diagram of launch distance (ft) and strain measurement with labels for near and far face, and direction indicators for S and N.]
Superstructure Monitoring

- Girder load distribution
  - Bending
- Cross-frame behavior
- Roller contact stresses
  - Bottom flange
  - Web
  - Flange to web welds
Monitoring Results - Superstructure

- Significant longitudinal flange strain measured $> F_y$

![Graph showing longitudinal strain with CL of Roller at Pier 6]
Monitoring Results - Superstructure

- Significant vertical strain measured

![Diagram showing vertical strain measurements with strain values of -1838 με and -2037 με at specific distances above the bottom of the flange plate.](image-url)
## Monitoring Results - Superstructure

- Cross-frame behavior is complex and sensitive
  - axial forces, biaxial bending, and torsion
- Measured values sometimes exceeded design values

<table>
<thead>
<tr>
<th>Member Type</th>
<th>Design Force</th>
<th>Calculated Force (WB1)</th>
<th>Calculated Force (WB5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Chord</td>
<td>20 kips C</td>
<td>42.6 kips T</td>
<td>86.2 kips T</td>
</tr>
<tr>
<td>Diagonals</td>
<td>38 kips T or C</td>
<td>56.2 kips T</td>
<td>172.1 kips T</td>
</tr>
<tr>
<td>Bottom Chord</td>
<td>20 kips T or C</td>
<td>31.1 kips T</td>
<td>39.7 kips C</td>
</tr>
</tbody>
</table>
Objective: Long-Term SHM

• Assess (engineering based) the condition of a bridge continuously without human interaction over long periods of time (days, months, years)
  – “Instantly” detect abnormalities.
  – Assess load carrying capability.
  – Active bridge management system.
The Need

• Bridge owners are looking for autonomous systems that assess structural integrity/safety/etc.
  – Enter structural health monitoring

• Research in this area has been going on for 20+ years...with very, very few successes
  – Previous approaches relied upon dynamics
  – And even fewer attempted field demonstrations
System Attributes Desired by Owners

• Damage detection
  – All types of damage at varying locations
  – Autonomous data collection, reduction, evaluation, and storage
  – Reporting in real-time and in understandable formats

• Load rating (including better capacity estimate) and remaining life estimates
Our Measurement Metric of Choice

- Strain, strain, strain.
- In particular, strain due to the passage of live loads...specifically, five-axle “semi” trucks
  - Heavy weights and large numbers of them on the highway system.
Difficulties with Autonomous SHM

• Unknowns, unknowns, unknowns
  – Vehicle weight and geometry
  – Traffic density and position
  – Dynamic impact and suspension system variability

• Conventional analysis techniques are difficult/impossible to reliably perform
Data, Data, Data
Generic System Architecture

Data

Rating/Capacity Model

Damage Detection

Decision for Bridge Rating

Remaining Life

Long-Term Management

Decision for Bridge Inspection

Truck detection needed
Truck Detection Methodology
Raw Strain Data

Girder Strain Time History

Deck Strain Time History
Fundamental Situations

Desired:

Case #1

Eliminate Concurrent Events: Side by Side

Case #2

Eliminate Concurrent Events: Same lane

Case #3

Case #4

Case #5

Case #6

Case #7
Truck and Lane Detection Basics

Deck bottom sensor line 1

$\text{Deck bottom sensor line 2}$

$L_b + L_t$

North Lane

South Lane

DL23 (DL13)

DL24 (DL14)

DL21 (DL11)

DL22 (DL12)
Axle Detection Using Deck Strain Rate Rates

Benefits of using strain rate
- Eliminate global strain effects
- Clearly shows and exploits the localized strain effects of truck wheel loads
- Accentuates the behaviors of interest

Deck strains

Five Peaks (Axles)
Capabilities

• Can detect: event occurrence, determine passage lane, determine number of axles, estimated (~+/− 0.5’) axle spacing, etc.

• Eliminate instances where multiple trucks are on the bridge at the same time

• Can be applied to bridges of virtually any configuration.
Video - I-80 Bridge: Truck #1
Lane Detection Using Deck Strain Rates

- 5-axle truck #1
- 5-axle truck #2
Lane Detection Using Deck Strain Rates

5-axle truck #1

5-axle truck #2
Girder Strain Data - D2_BF

Strain Range for a 5-axle truck event

Deck Strain Data - DL21
Damage Detection
Pattern Recognition

• Train the system to recognize and develop relationships between sensors that are indicative of typical/normal performance

• Deviations from trained relationships are indicators that something has changed

But what pattern?
Algorithm Fundamentals

• Footprint matching
  – Each traffic event leaves a footprint with distinct strain record shape and magnitude(s)
  – Need a combination of bridge engineering and statistical expertise to create meaningful relationships/patterns
FINALLY! An autonomous temperature compensation algorithm that works.
Capture the pseudo-static behavior
Limitations of First Generation System

• Limits must be established manually
  – Time consuming and subjective
• Notable “spread” in the match relationships
• Sometimes multiple match relationships exist
• Results need some further interpretation
Second Generation System

• Develop and implement an autonomous truck parameter detection sub-system
  – Travel lane, concurrent vehicle presence, number of axles, axle spacing, vehicle weight, and speed
  – Allows decimation of data to reduce spread and potential for multiple relationships

• Systematic approach for
  – Establishing normal limits
  – Direct interpretation that shows damage occurrence and location
Data Selection
For the undamaged structure, the strain of one sensor can be used to predict the strain of another sensor (counter to most structural analyses)

\[ S_{\text{pred},ij} = a_{0,ij} + a_{1,ij} \times S_j \]

\[ R_{ij} = S_i - S_{\text{pred},ij} = S_i - (a_{0,ij} + a_{1,ij} \times S_j) \]

\[ CRS_i = \sum_{j=1}^{40} R_{ij,\text{std}} - \sum_{i=1}^{40} R_{ij,\text{std}} \quad (i = 1 \text{ to } 40) \]

\[ R_{ij,\text{std}} = \frac{R_{ij} - \mu_{ij}}{\sigma_{ij}} \]

\[ \begin{cases} UCL_i = \mu_i + 3\sigma_i \\ LCL_i = \mu_i - 3\sigma_i \end{cases} \]
Damage Detection and Localization

• Post-training (i.e., monitoring stage)
  – Calculate residual matrix using the training stage prediction models
  – Calculate CRS
  – Plot data on the control chart
  – Out of limit points indicate structural damage
Second Generation Validation

- US30 bridge over the South Skunk River
  - Two-girder, fracture critical bridge
  - Multiple fatigue sensitive locations
Typical Results

• Training data collected
  – 3,653 heavy, right-lane, five-axle trucks
Fatigue Crack Induced
Findings

• Damage of multiple types and multiple levels can be autonomously detected
• A correlation exists between damage level and damage indicator data (remaining life...)
• Unfortunately, algorithm has a higher than expected false-positive rate
Third Generation Improvements

- More robust prediction model – orthogonal regression
Third Generation Improvements

• Damage detection model enhancement

Full Model:
\[ Y = k_1(\alpha_1 + \alpha_3x) + k_2(\alpha_2 + \alpha_4x) \]

where:
\[
k_1 = \begin{cases} 
1 & \text{for training data} \\
0 & \text{for post training data} 
\end{cases}
\]

and:
\[
k_2 = \begin{cases} 
0 & \text{for training data} \\
1 & \text{for post training data} 
\end{cases}
\]

Reduced Model:
\[ Y = \gamma_1 + \gamma_3x \]

Model similarity test:
\[
F = \frac{[\text{RSS}(\text{reduced}) - \text{RSS}(\text{full})]/[\text{df}_{\text{RSS}(\text{reduced})} - \text{df}_{\text{RSS}(\text{full})}]}{\text{RSS}(\text{full})/\text{df}_{\text{RSS}(\text{full})}}
\]
Sensor 19 (microstrain)

Sensor 15 (microstrain)

Training Data
Post-Training Data
Linear (Full Model)
Linear (Reduced Model)

No damage

Damage!
Third Generation

• False-positive rate appeared to drop
• All damage still detected
• Additional need: autonomous analysis of F-test results (currently being developed)
  – Perhaps a return to control chart concepts!
Fourth Generation

• Statistical strain range damage detection based upon quadruple redundant approach
• Four methods
  – Strain range
    • Single truck
    • Group size of ten
  – Cross-prediction method
  – $F_{SHM}$
• Fully autonomous data collection, reduction, and analysis software.
Strain Range Method Added

Single truck

Group of ten
Load Rating
Automated Load Rating Determination

• Use bridge response from unknown/partially known trucks.
• Use WIM data to statistically estimate the unknown truck features.
• Benefits: does not require bridge closure to perform load tests, load ratings can be estimated frequently (daily), allows for tracking changes with time.
Note: Automation of a proven approach

Hardwired strain gages

Wireless truck position indicator

Structural modeling

Model analysis and optimization with field collected data

Engineering based data interpretation

Accurate Assessment
Analytical Model Calibration

Select a Set of Strain Data with Maximum Strain of 90~100

Sample a Truck from WIM Database with Weight of 70~80 kips, Axle Spacing #3: X ± 2 ft, and Transverse Position of Lane Center ± 2 ft

Structural Health Monitoring System

Analytical Model Calibration

600 Runs

Load Rating using Calibrated Model

Next ‘Big’ Truck

Load Rating Distribution
Other On-going Enhancements

• Capacity estimate from service level measurements.

• Remaining life estimation algorithm.
SHM Capabilities

Robust, self-sustaining system.
Data collection, visualization, and analysis
Cyber-security threat protection

Advanced Capabilities.
Load rating and displacement monitoring
Damage detection
Remaining life

Integrated control components.
De-icing spray system activation
Vibration control system
Benefits of Using SHM

• No subjectivity in the data and/or information.
• Can make decisions with greater confidence.
• Data/information can be collected/used as frequently as desired (must be cautious to not get overwhelmed by data volume).
Thank You!

Questions?