I35W St. Anthony Falls Bridge Structural Monitoring

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“Smart Bridge System”

Design-build project awarded to Flatiron/Manson w/Figg Bridge Engineers featured “smart-bridge” system

features over 500 sensors
- strain gages
- thermistors
- fiber optic sensors
- linear potentiometers
- accelerometers
- corrosion sensors

Sponsored by the Minnesota Department of Transportation
Project Background

University of Minnesota is responsible for data collection and interpretation over initial 3 years.

Objectives:

• Investigate structural characteristics and changes over time
• Evaluate design assumptions (load distribution, deformations, response to environmental effects)
• Evaluate effectiveness of the selected instrumentation
• Develop long-term monitoring system
Outline

- Description of bridge
- Description of instrumentation
- Model development and calibration
- Vision for long-term monitoring

1225' (373 m)

500' (152 m)
Two bridges (NB, SB) each with two boxes.

- Precast Segments (4.1 to 5 m)
- CIP
- 25" (7.6 m)
- 11" (3.4 m)
Description of Instrumentation: VW, thermistors

Instrumented Sections

195 vibrating wire (VW) strain gages
(38 at midspan of Span 2)
243 thermistors

Behaviors of interest:
• Load distribution (curvatures)
• Shear
• Torsion
• Thermal gradient
Description of Instrumentation: Fiber optic sensors

Instrumented Sections

12 Fiber optic sensors
(6 pairs along SB Span 2)

Behaviors of interest:
• Load distribution
  (avg curvatures, 4m gage lengths)
• Deflections
Description of Instrumentation: Linear Potentiometers

Instrumented Sections

12 Linear potentiometers in each box at each expansion joint (4 @ abutment 1, 8 @ pier 3)

Behaviors of interest:
• Overall movement of bridge
Description of Instrumentation: Accelerometers

Instrumented Sections

26 accelerometers  
(bottom of deck in each box)  
10 moveable along the length of SB Span 2

Behaviors of interest:  
• Dynamics of the bridge  
• Local deformations  
• Overall deformation SB Span 2
Description of Instrumentation: Corrosion sensors

Instrumented Sections

4 CorSensys corrosion sensors in deck

Behaviors of interest:
- Depth of corrosion in deck

Sample corrosion data from Smartec
Description of Instrumentation: Resistive strain gages

Instrumented Sections

SB Pier 2 and drilled shafts
VW and resistive strain gages

Behaviors of interest:
• Load distribution during construction* and service

*FHWA Study (Gray Mullins, PI University of South Florida)
Challenges of Structural Monitoring:

- Multiple distinct and independent data sources
- Individual sensor data not meaningful
  - Utilize groups of sensors through section to calculate response
- Volume of data
- What is “normal” behavior?
- How might damage manifest itself in data?

Data Processing  Model Development

- Historical Data
- Finite Element Model
FEM Model Development

Construction of Finite Element Model

- Includes Spans 1 through 3 of Southbound Bridge
- Quadratic Solid Elements for Concrete
- Linear Shell Elements for Steel
FEM Model Development

- Calibrate model using known data
- Consider load effects (truck tests) and environmental effects (temperature/gradient)
- Incorporate information from material tests
  - Creep and Shrinkage
  - Concrete Strength and Modulus
  - Coefficient of Thermal Expansion
Creep and Shrinkage

- Compared to AASHTO LRFD predictions

Creep strains for 2ksi (prestress) loading compared to AASHTO LRFD

Average shrinkage strains compared to AASHTO LRFD

- Creep frames loaded to 2ksi (prestress) and 3ksi (0.45 $f_c$ limit)
  Nominal 28-Day $f_c$ of 6.5 ksi
Material Testing

Coefficient of Thermal Expansion

- Six superstructure concrete beam specimens and two substructure beams in temperature control

<table>
<thead>
<tr>
<th>Mix</th>
<th>Mean CTE (µε/°C)</th>
<th>Std Dev CTE (µε/°C)</th>
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</thead>
<tbody>
<tr>
<td>Superstructure (6500 psi)</td>
<td>10.31</td>
<td>0.65</td>
</tr>
<tr>
<td>Substructure/Pier (4000 psi)</td>
<td>8.73</td>
<td>0.31</td>
</tr>
</tbody>
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FEM Calibration with Truck Test Data

Truck Tests

- 8 trucks for a total load of 400 kips.
- 5 different load configurations at multiple locations across bridge.
FEM Calibration with Truck Test Data

Longitudinal Strain - STI 7SB
Test = 091006-Truck Loads
Location 7 (Midspan of Span 2), Web of SB Bridge

Curvatures (με/IN):
Measured - West Web of Ext. Box: -0.61
FEM - West Web of Ext. Box: -0.61
Measured - East Web of Ext. Box: -0.61
FEM - East Web of Ext. Box: -0.62
Measured - West Web of Int. Box: -0.59
FEM - West Web of Int. Box: -0.61

4-28-10 Annual Transportation Research Conference, St. Paul, MN
FEM Calibration with Truck Test Data

bridge width = 90 ft (27.4 m)
FEM Calibration with Truck Test Data

Curvature along length of Bridge
STI 7SB
Test = 091006-TruckLoads

Station

215+00  216+00  217+00  218+00  219+00  220+00  221+00  222+00  223+00  224+00  225+00  226+00  227+00

Curvature (με/με)

0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
-0.600
-0.700

Abutment 1  Pier 2  Pier 3  Pier 4
Data Analysis

Measured Strain Data for Truck Tests

*Plot represents mechanical strain due to truck loads*
Data Analysis

Measured Strain Data: Opening to Present

*Plot represents mechanical strain plus creep and shrinkage strains

~230 με

~100 με

4-28-10 Annual Transportation Research Conference, St. Paul, MN
Data Analysis

Expansion Joint Data

*Plot represents linear potentiometer lengths in NB Exterior Box; other boxes yield similar results.

4-28-10 Annual Transportation Research Conference, St. Paul, MN
**Data Analysis**

**Thermal Gradients**

- Expected to have a large impact on bridge behavior
- Essential for understanding stresses
- Provides model input to investigate thermal

Measured Thermal Gradients at midspan of Span 2 on 4/9/2009

300 mm

3.5 m
Data Analysis

Modal Frequencies

- FFT can be performed on the dynamic data to obtain modal frequencies.

Modal frequencies at midspan of Span 2 on 5/9/2009

- Modal frequencies dependent on environmental conditions such as temperature and thermal gradient.
Data Analysis

Modal Frequencies in FEM

Primary Mode: 0.82153 Hz
Secondary Mode: 1.5274 Hz
Tertiary Mode: 2.1315 Hz
Torsional Mode: 2.2156 Hz
FEM Model Development

Additional FEM Work

- Calibrate model to known thermal loading
- Run time-dependent analysis given creep and shrinkage models
- Run “damage scenarios”
  - Strand Corrosion/Breakage
  - Possible cracking?
- Determine whether damage will be measurable by instrumentation
Vision for long-term monitoring system

Tasks required for long-term monitoring

- Establish response metrics “baseline” behavior metrics
  - Using measurements from first three years
  - Using calibrated FEM to “fill in” other cases
- Quantify potential damage (Using calibrated FEM)
- Automate calculations and analyses
- Notify users of anomalies
Response metrics include:

- Local displacements using accelerometer data
- Global displacements integrating curvature from strain data
- Dynamic mode shapes and damping ratios
- Expansion joint movement
- CorSenSys corrosion data
Vision for long-term automated monitoring

Automated Monitoring:

- Historical bridge data
- FEM extreme load cases
- FEM damage scenarios

Systems functioning??

- Measured Response
  1. Stress/Strain
  2. Movement/Deflections
  3. Curvature
  4. Modal Frequencies

- Expected Response
  1. Modeled Behavior
  2. Corrosion Threshold
  3. Error Estimates

Model

Comparison

Data ➔ Processor ➔ Model ➔ Comparison ➔ Output

- OK
- Investigate further
- Take action

- FEM damage scenarios
Vision for long-term automated monitoring

Automated Model (runs in background)

- Automatically checks bridge status
- Creates “Expected Response” using…
  - Historical bridge data (e.g., measured deck deflections)
  - Corrosion thresholds
  - FEM results in form of “look-up table” with error estimates
    - Consider thermal gradient effects
    - Extreme loading conditions (consider for error estimates)
    - Likely damage scenarios (consider for error estimates)
Vision for manual monitoring

Manual Monitoring:

- **Data** → Processor → Model Input
  - 1. Static Tests
    - 1.1. Load Position
    - 1.2. Load Magnitude
  - 2. Dynamic Tests
    - 2.1. Load Arrangement
    - 2.2. Vehicle Velocity
  - Model (FEM and Historical Data)

- **Measured Response**
  - 1. Stress
  - 2. Movement/Deflections
  - 3. Curvature
  - 4. Modal Frequencies

- **Expected Response**
  - 1. Modeled Behavior
  - 2. Error Estimates

- **Comparison** → **Output**
Vision for manual monitoring

Manual Model (periodic, optional)

- Used to check bridge status during scheduled testing
- Load magnitudes and positions known
- Run detailed FEM models to provide comparison
Vision for long-term monitoring

Automated model

- Load unknown
- Pre-run analyses

Manual model

- Load known
- Detailed analyses

Platform provided to be flexible and scalable to multiple bridges (using nCode)

Supplement manual bridge inspections
Summary

- Data from over 500 sensors combined to establish metrics for monitoring
- Examination of bridge response shows large influence of thermal effects
- Historical data and calibrated FEM used to establish expected metrics and error limits
- Automated/manual monitoring system planned to be flexible and scalable
- System intended to supplement manual bridge inspections
Questions?
FUTURE? ?

• Research sensor development, networking, communication…
• Wireless sensors…
• On-board processing…
• Remote interrogation…
Sources

- American Concrete Institute, *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary*, June 2008
- Minnesota Department of Transportation, *As-built Construction Plan for Bridge Nos. 27409 and 27410*, November 2008
Data Analysis

Thermal Gradient Magnitudes

*Magnitude defined by highest top flange thermistor (TSETB001) minus thermistor near bottom flange (TSEWC001)
Objectives of Structural Monitoring:

- Data processing and analysis automation
- Notification of anomalies
  - Are metrics out of range?
  - Are all systems operational?
- Supplement manual bridge inspections
- Flexible and scalable to multiple bridges
Vision for Long-Term Automated Monitoring System

Automated Monitoring Plan:

- Past bridge data
- FEM extreme load cases
- FEM damage scenarios