Time- and Temperature-Dependent Deflection Monitoring of the I-35W St. Anthony Falls Bridge

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I-35W St. Anthony Falls Bridge

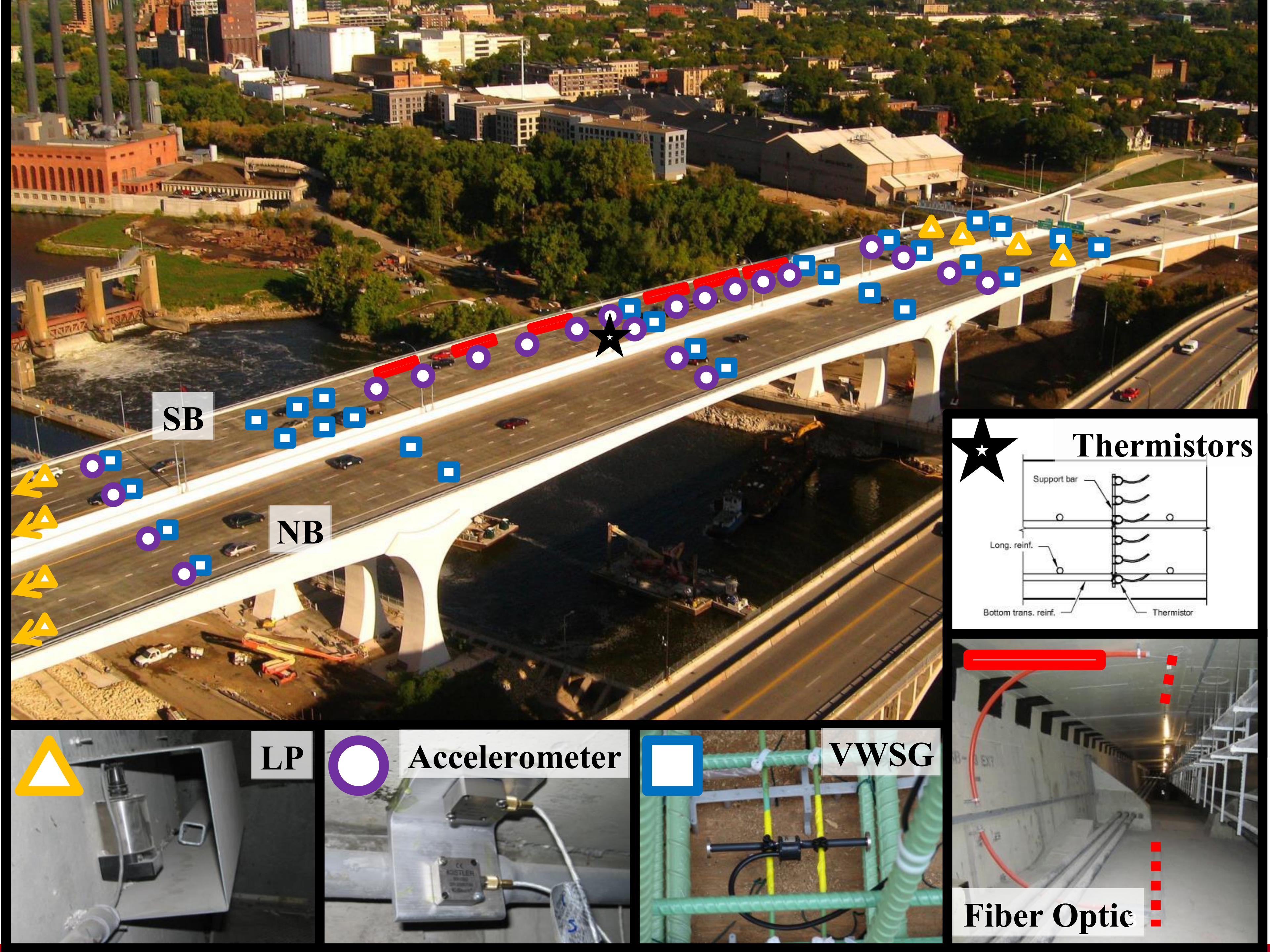
Bridge has been monitored since opening in September 2008

Contains over 500 sensor channels to investigate behavior:

- strain gages
- thermistors
- accelerometers
- linear potentiometers
- fiber optic sensors

Uniquely large data set offers opportunities to:

- Investigate structural characteristics and changes over time
- Observe temperature- and time-dependent behaviors

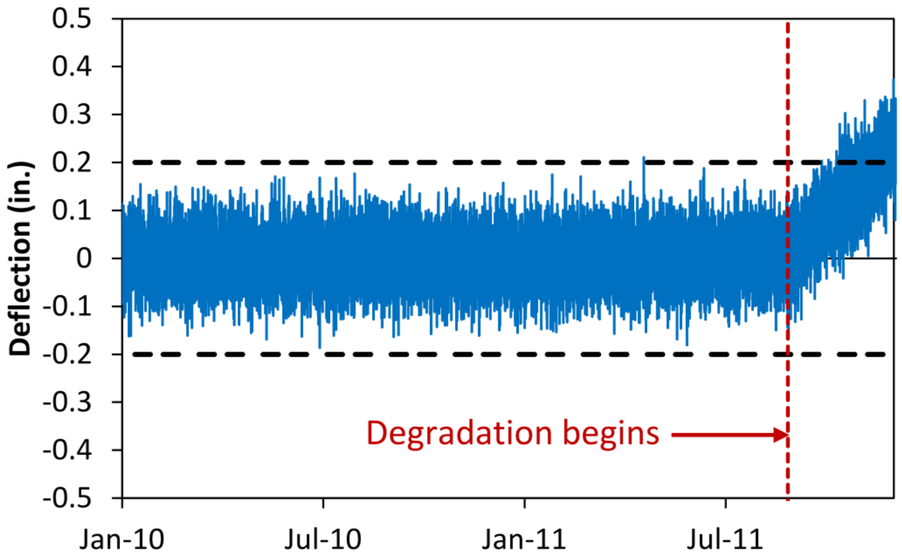


SB
NB
Thermistors
Support bar
Long. reinf.
Bottom trans. reinf.
Thermistor
LP
Accelerometer
VWSG
Fiber Optic

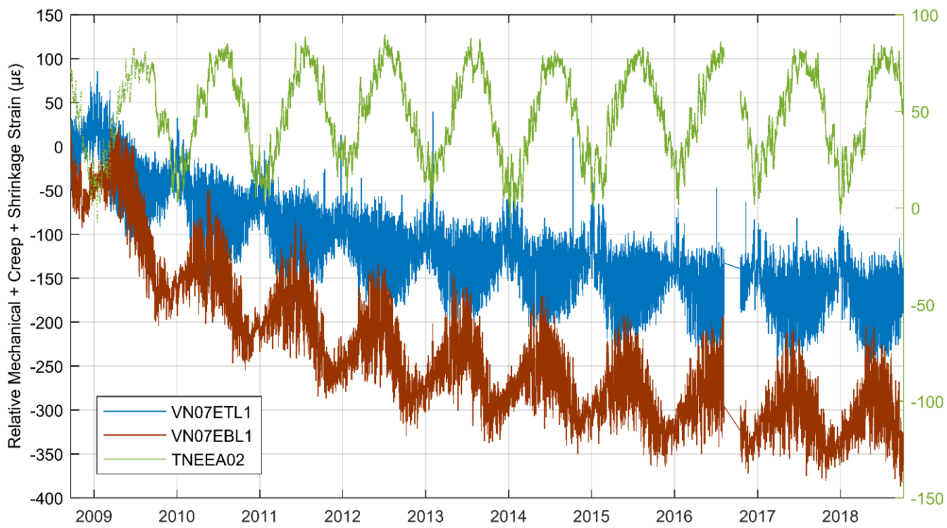
Challenge of Long-Term Monitoring

- Behavior of in-service bridges depend on many complex natural phenomena
- Degradation is not necessarily sudden and can be masked by normal, safe variations in behavior

What we would “like” to see…

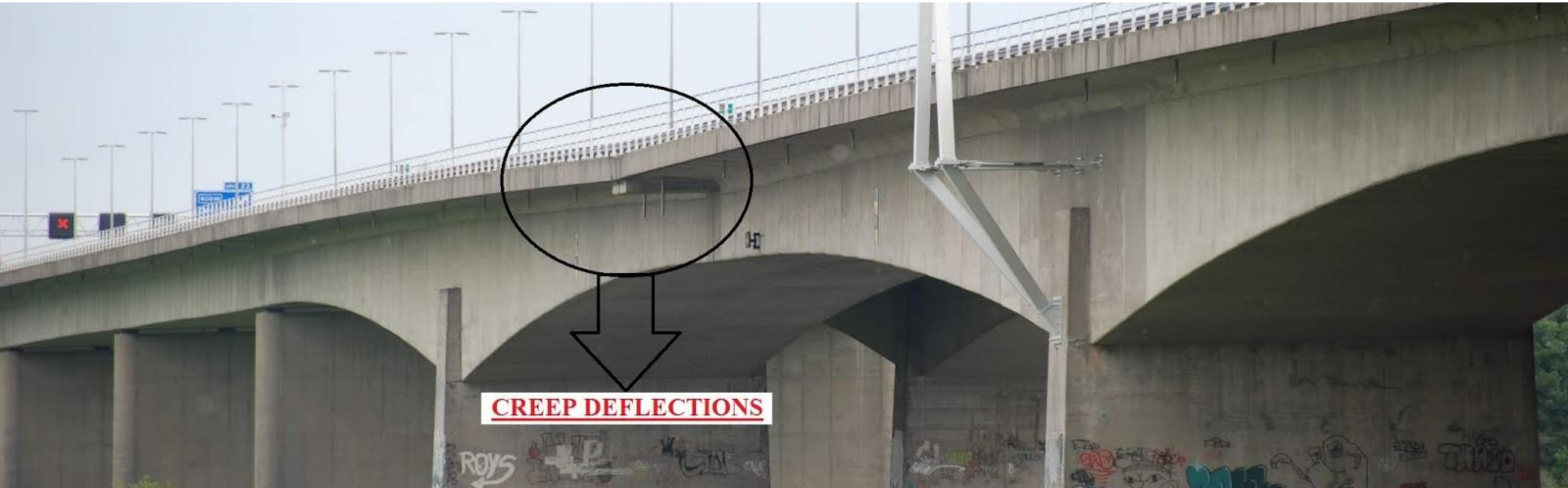


… versus reality



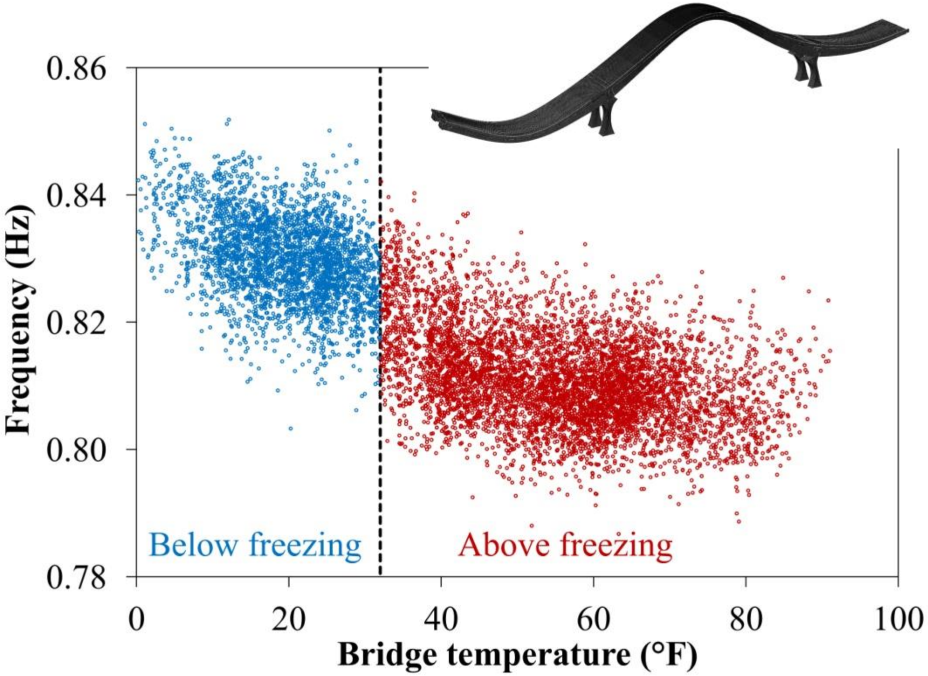
Why temperature and time?

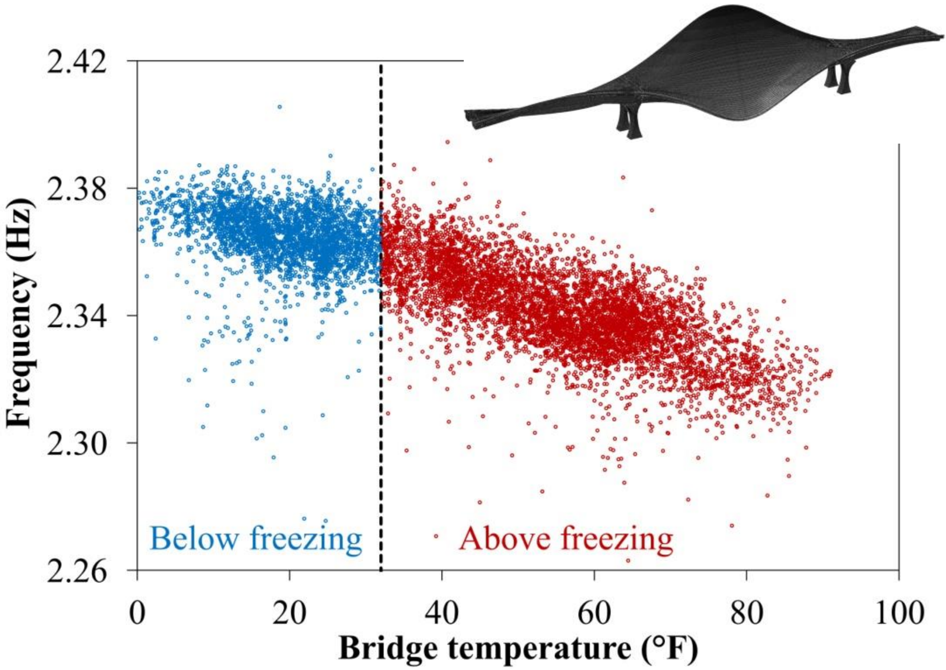
- Understanding normal operational deformation key to extracting anomalous or damage-related readings
- Largest signals from ambient (thermal) loading
- Long-term creep and shrinkage may lead to post tensioning losses or bearing issues
- Many conflicting concrete time-dependent models



Interactions with Temperature: Modes of Vibration

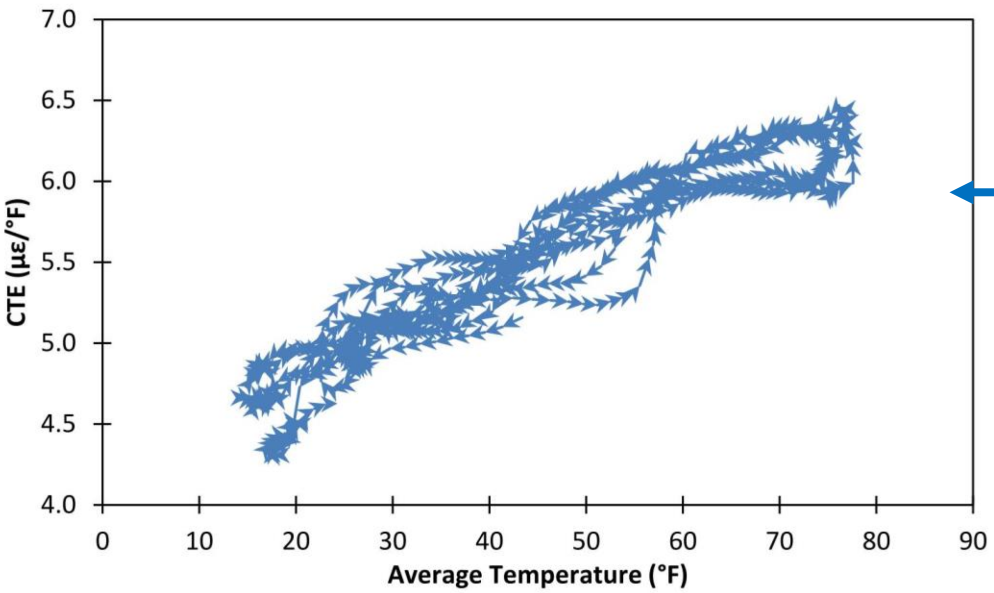
- **Assumption:** Natural frequencies are constant
- **Observation:** Natural frequencies vary with temperature, and not all modes behave in the same way



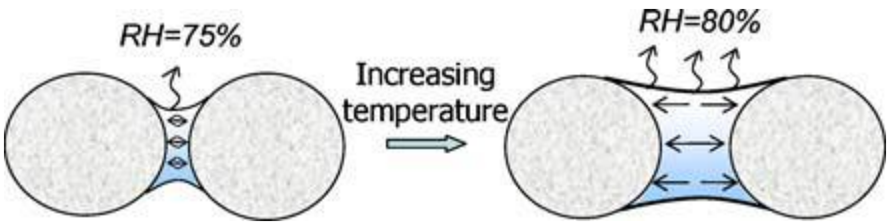


Interactions with Temperature: Thermal Expansion

- **Assumption:** Coefficient of thermal (CTE) expansion of concrete structures is a constant
- **Observation:** Looking at short (month-long) blocks of data shows apparent change in CTE by up to 20%



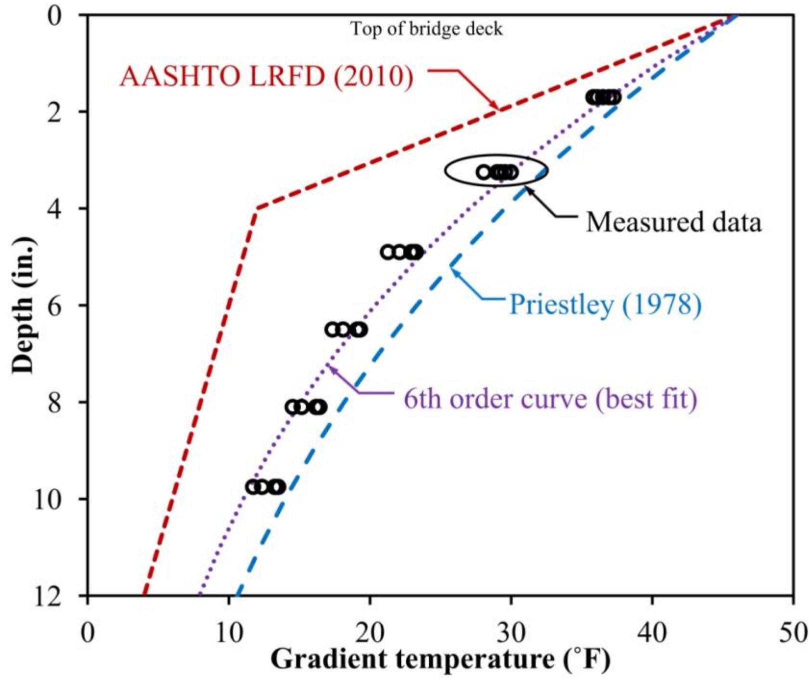
CTE estimated from VWSGs in south span of the southbound bridge

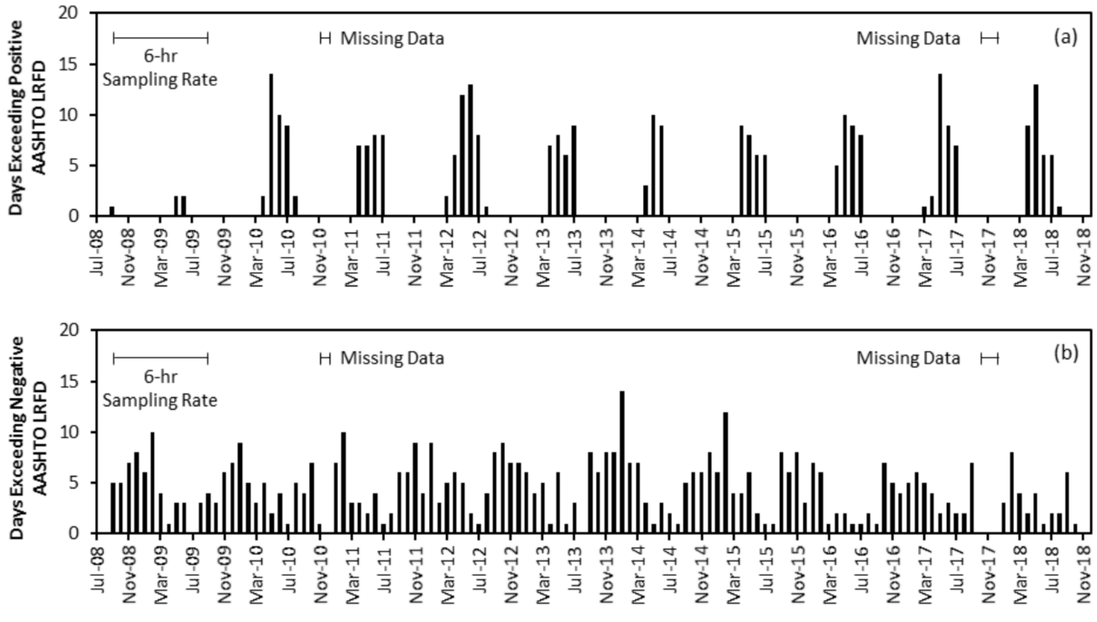


(Grasley and Lange, 2007)

Interactions with Temperature: Thermal Gradients

- **Assumption:** Temperature differences through top deck vary according to AASHTO LRFD design gradients
- **Observation:** Gradients follow fifth or sixth-order polynomial, routinely exceed AASHTO design

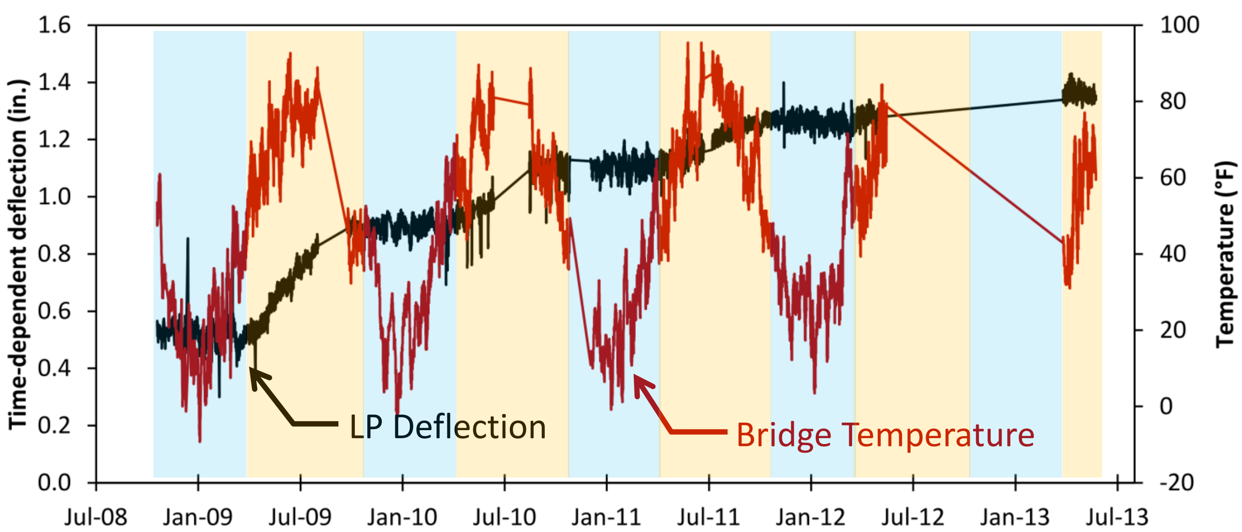




Brown, R.J. et al. (2020). *Ten-Year Review of Monitoring System on I-35W Saint Anthony Falls Bridge*. Report MN 2020-19. Minnesota Department of Transportation, St. Paul.

Interactions with Temperature: Creep and Shrinkage

- **Assumption:** Creep and shrinkage strains progress smoothly with time
- **Observation:** Temperature affects the rate of creep and shrinkage, which are much slower during winter



Longitudinal deflections are measured by LPs at the expansion joints

Bridge temperature measured at midspan

Methodology 1:
Extraction of Temperature Effects

Step 1: Linear Regression

$$y = \alpha_1 \frac{\int T dA}{T_{ref} A} + \alpha_2 \frac{\int T^2 dA}{T_{ref}^2 A} + \alpha_3 \frac{\int zT dA}{T_{ref} I_x / L_{ref}} + \alpha_4 \theta_{TD} + \alpha_5 + \delta$$

Measured data

Axial elongation
CTE = $\alpha 1 + \alpha_2 T$

Thermal gradients

Modeled time-dependent behavior

Step 2: Subtract Temperature Behavior from Data

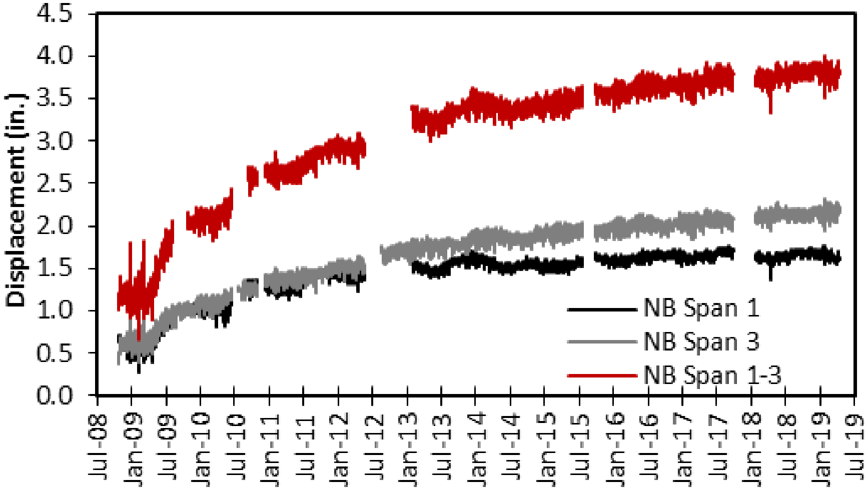
$$TD + \delta = y - \alpha_1 \frac{\int T dA}{T_{ref} A} - \alpha_2 \frac{\int T^2 dA}{T_{ref}^2 A} - \alpha_3 \frac{\int zT dA}{T_{ref} I_x / L_{ref}} - \alpha_5$$

Measured time-dependent behavior

Regression values from Step 1

Hedegaard et al. (2017) "Time-dependent monitoring and modeling of I-35W St. Anthony Falls Bridge I: Analysis of monitoring data." *J. Bridge Engineering,* 22(7): 04017025.

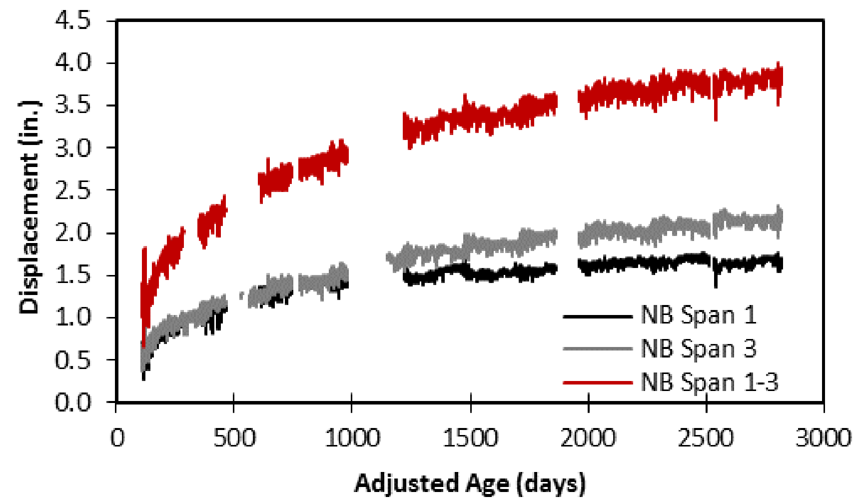
Methodology 2: Adjusted Age for Time-Dependent Rates



$$t_{adj} = \int_{t_{cl}}^{t} e^{\left\{ \frac{Q}{R} \left[\frac{1}{T_o} - \frac{1}{T(t')} \right] \right\}} dt'$$

Temperature history at midspan

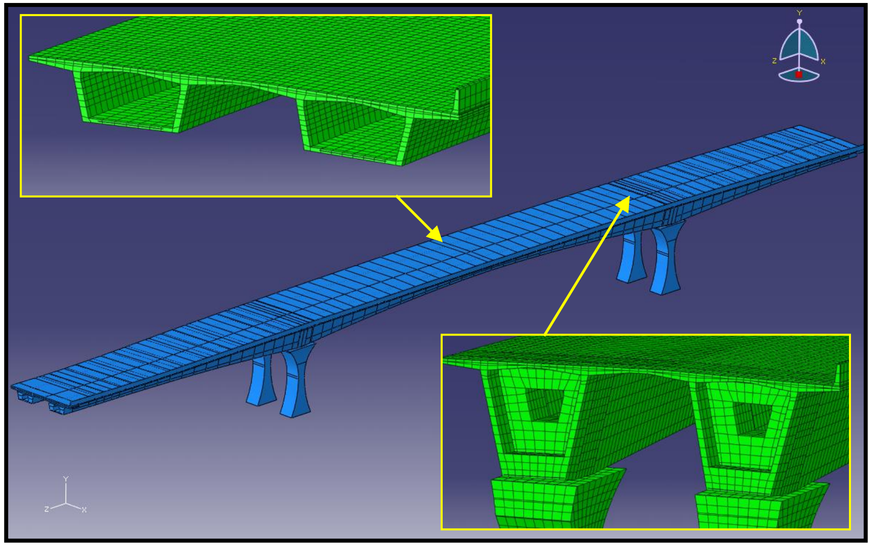
- Arrhenius equation converts to an equivalent time (i.e., adjusted age) at a constant reference temperature T_0



Benefits of Data Processing and Normalization

Anomaly Detection	Deviations easier to detect from expected time-dependent behavior than from total strains and deflections.
Versatility	Effective for temperature- and time-dependent longitudinal strains and deflections.
FEM Comparison	Measured data using adjusted age can be compared to constant temperature FEM results.

FEM Time-Dependent Modeling



Hedegaard et al. 2017

- 3D FEM including full erection procedure for Southbound Bridge spans 1-3
- Includes aging, creep, shrinkage, and relaxation for 150 adjusted age years

- Creep and Shrinkage Models Applied:
  - ACI 209R-92
  - AASHTO LRFD (2010)
  - CEB-FIP Model Code 1978
  - CEB-FIP Model Code 1990

  Asymptotic Creep

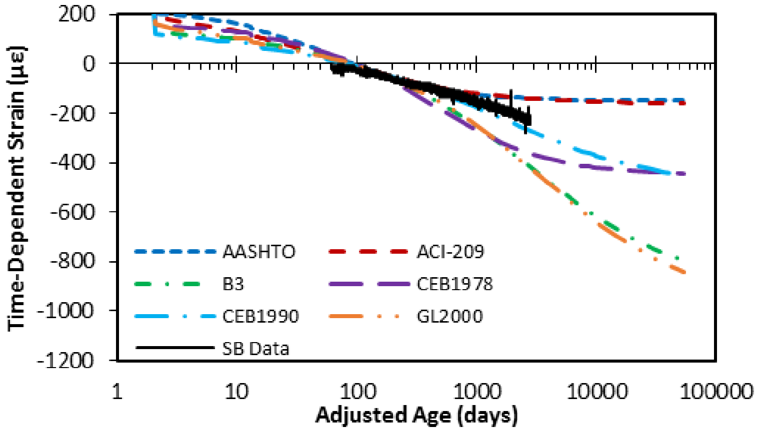
  - B3
  - GL 2000

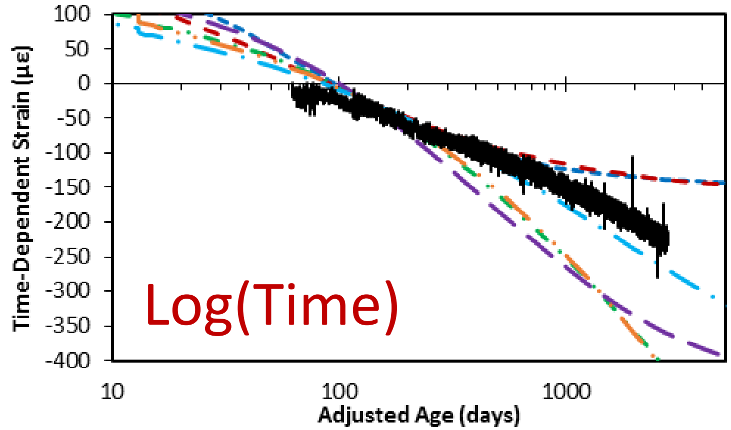
  Logarithmic Creep

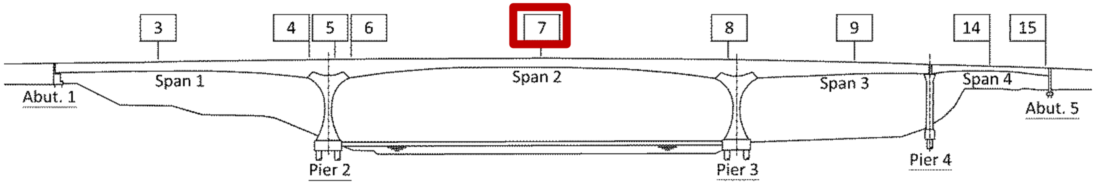
Hedegaard et al. (2017) "Time-dependent monitoring and modeling of I-35W St. Anthony Falls Bridge II: Finite Element Modeling." *J. Bridge Engineering,* 22(7): 04017026.

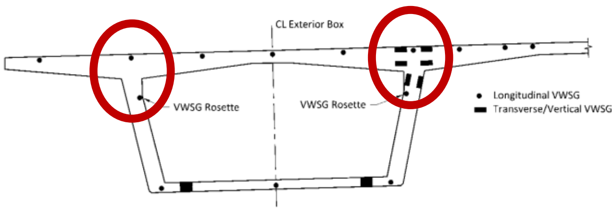
Comparison with FEM Predictions

- Linear regression to extract TD behavior performed on data from September 1, 2008 through October 16, 2018
- Compared with FEM predictions at a constant temperature
  - FEM set equal to measured strains at 6 AM CST on March 22, 2009 (124 adjusted age days)

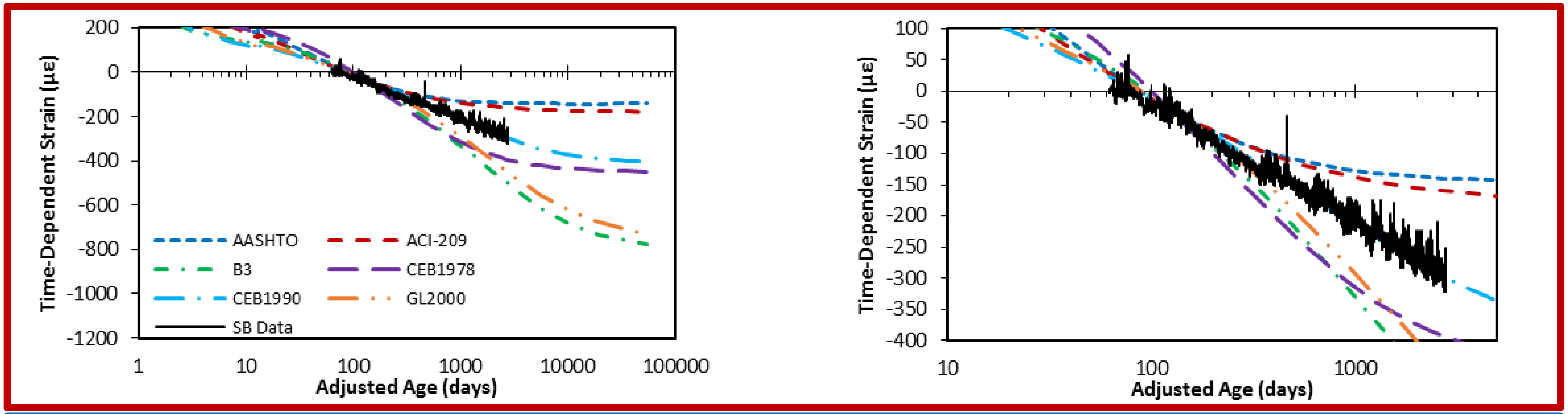


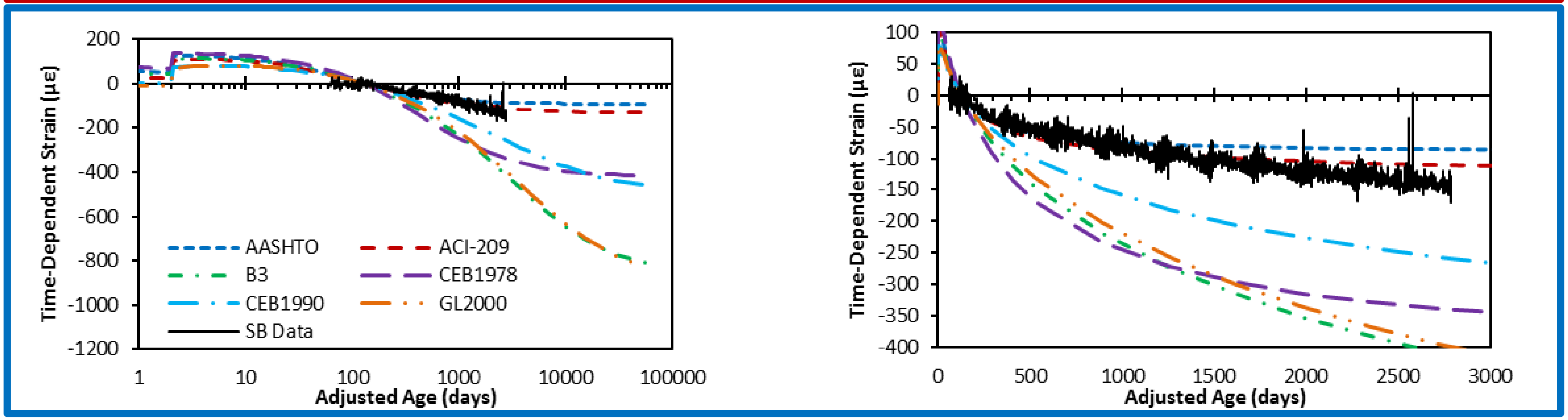


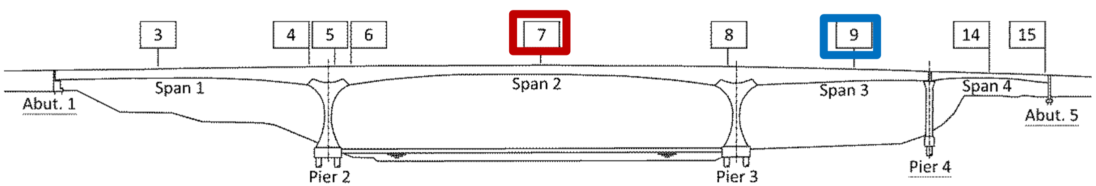


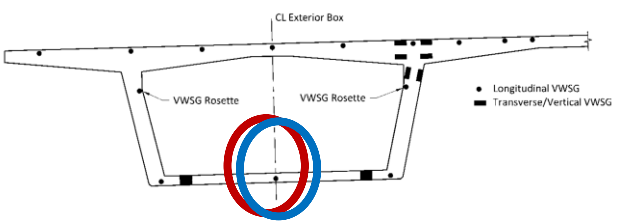


Comparison with FEM Predictions



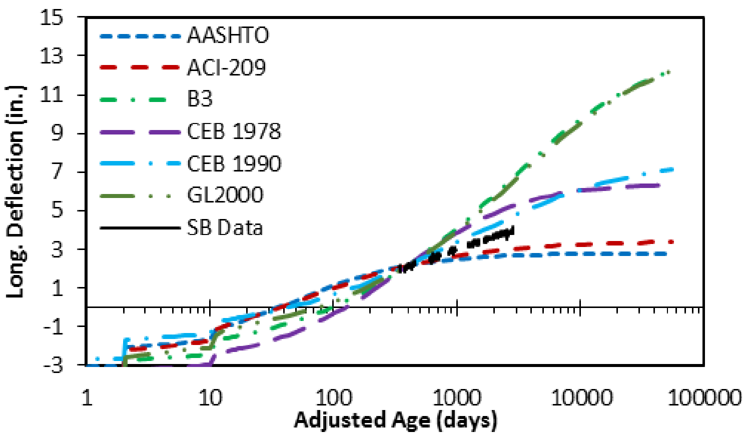


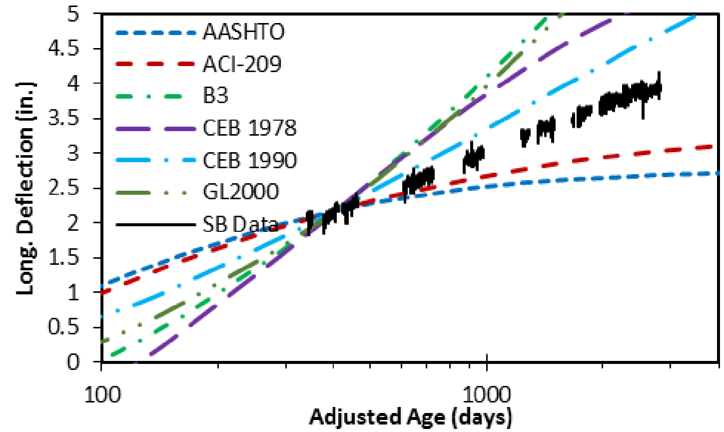




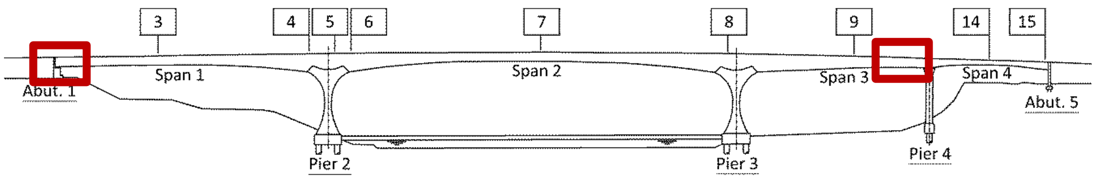
Comparison with FEM Predictions

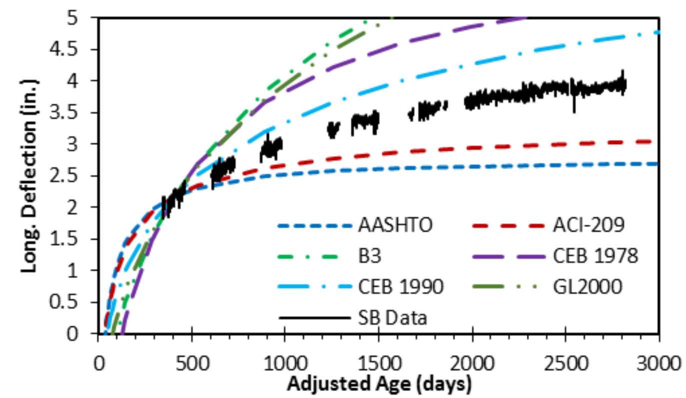
- Linear regression performed on data from September 28, 2009 through April 18, 2019





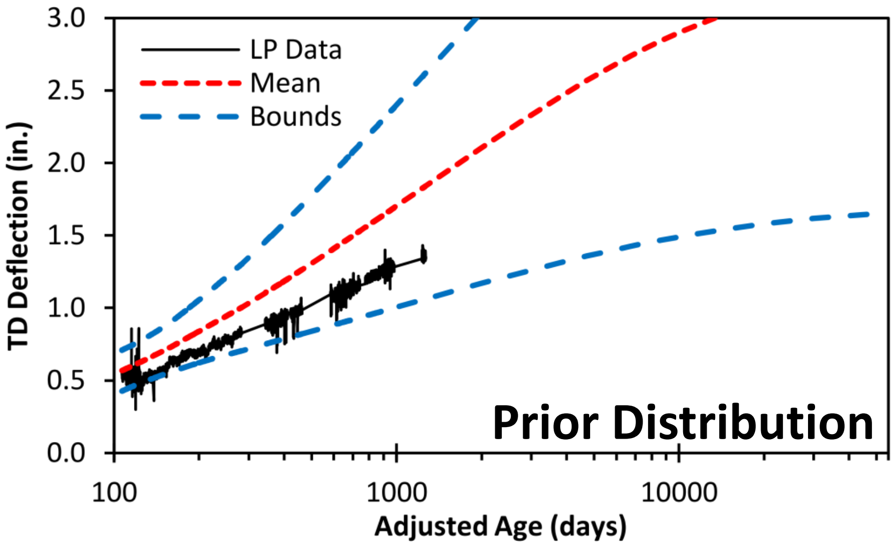
← Total shortening of Spans 1-3 →

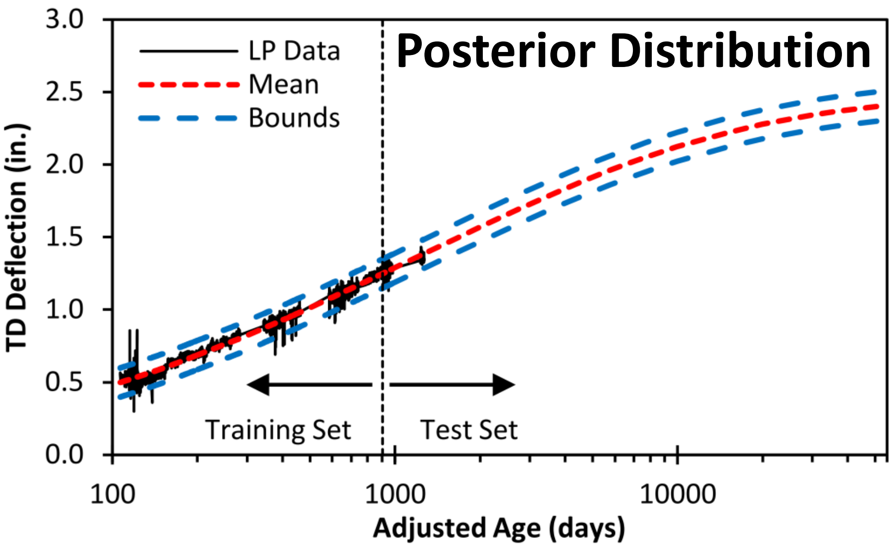




Short-Term Anomaly Detection

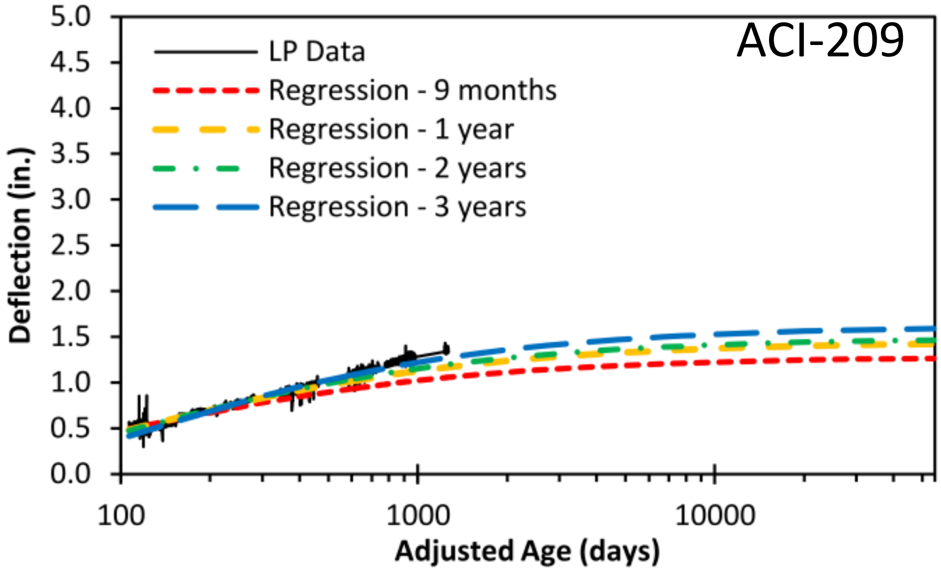
- Use Bayesian regression to predict the time-dependent behavior over a specific test set
- Prior distribution mean from FEM results and uncertainty of creep and shrinkage models (~30% coefficient of variation)



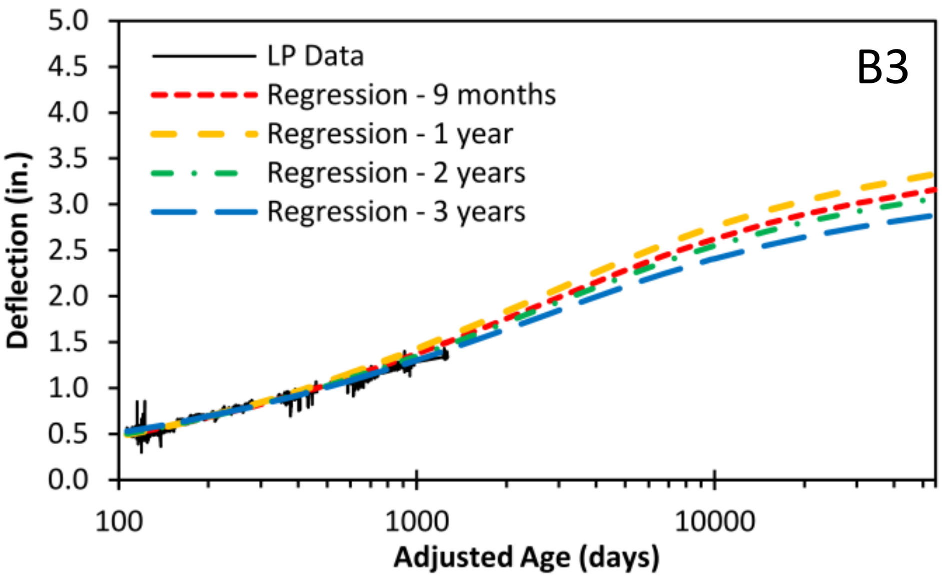


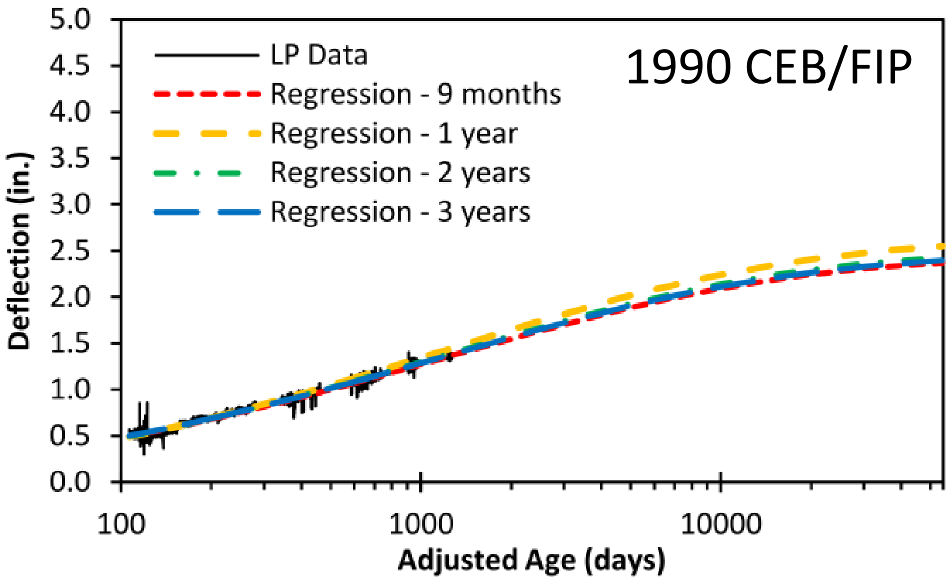
95%-credible bounds for Southbound south span LP using 1990 CEB Model Code

Short-Term Anomaly Detection

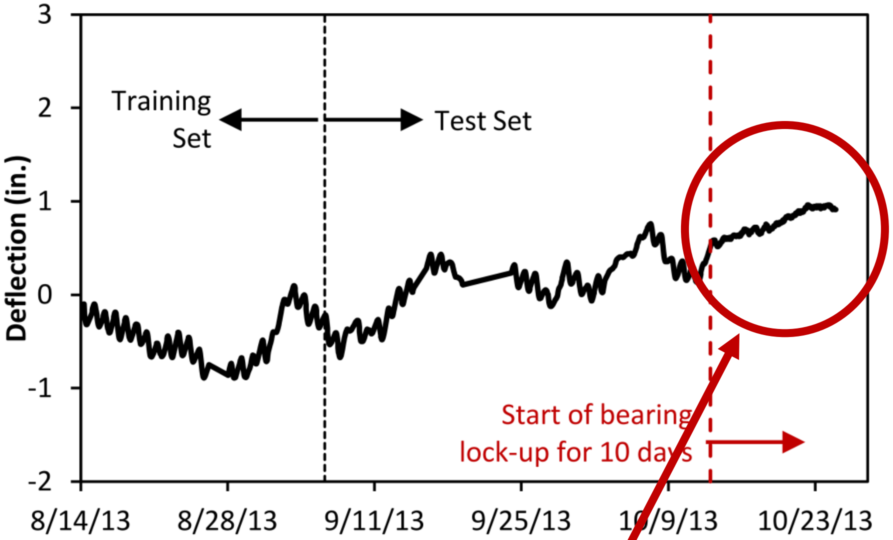


- Bayesian regression was performed assuming that the shape of the time-dependent curve was deterministic
- End-of-service predictions different for each time-dependent model



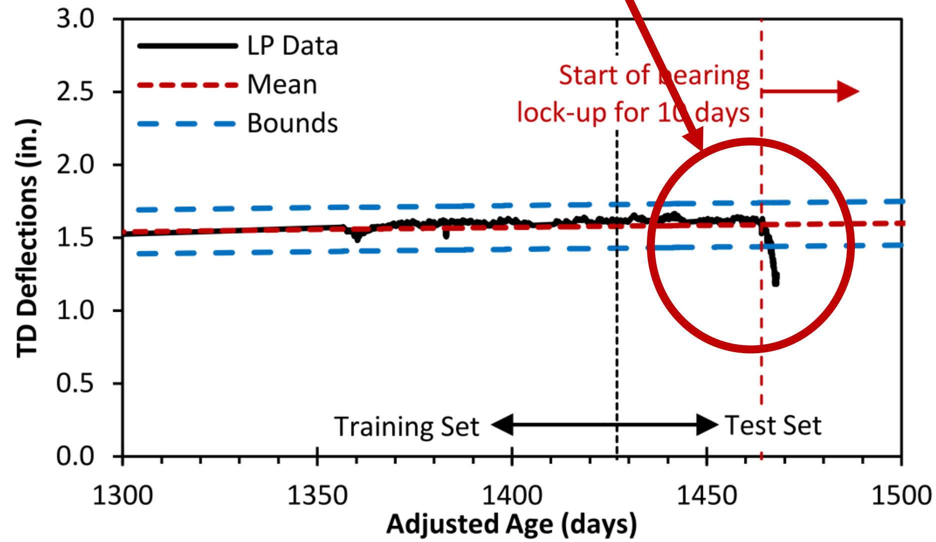


Short-Term Anomaly Detection



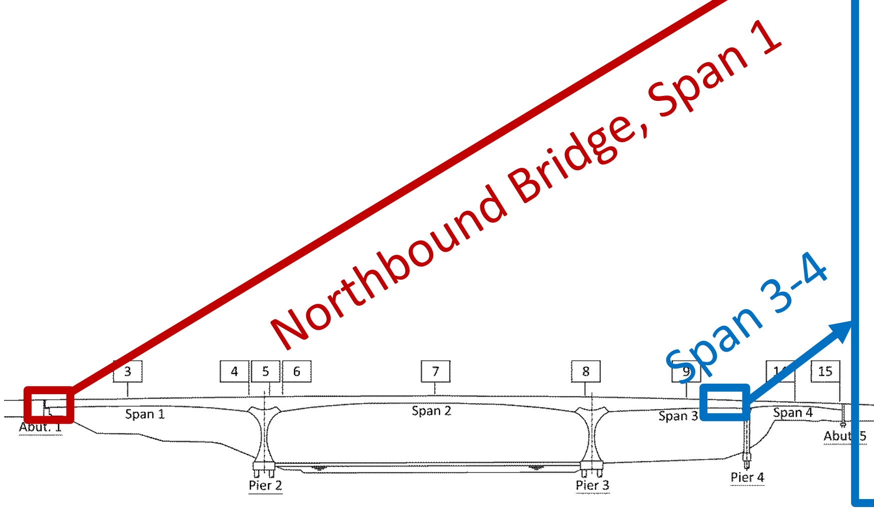
Anomalous behavior clearly seen after Bayesian regression

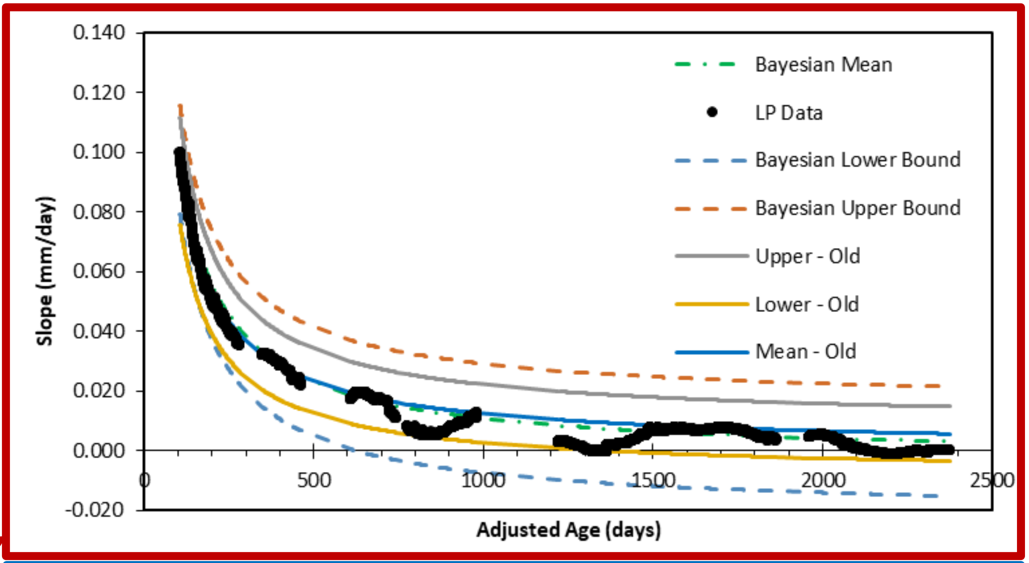
Bearing "lockup" simulated by changing thermal response

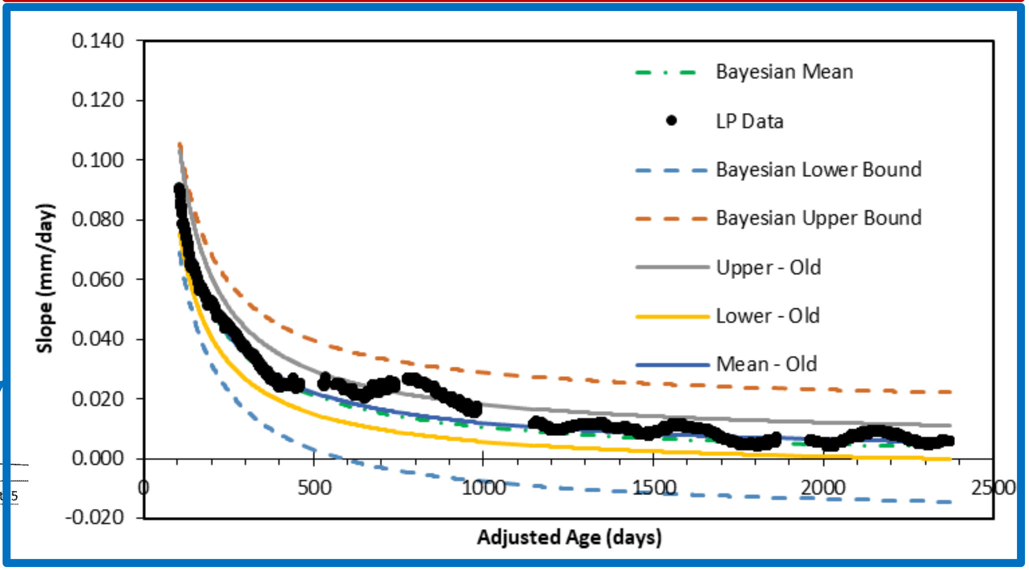


Long-Term Anomaly Detection

- Computed time-dependent displacement rates (for example mm/day) at expansion joints
- Bayesian regression used on displacement rates, showing 99% credible bounds







Summary and Conclusions

Temperature Effects	Temperature is much more than axial thermal expansion – has many complex interactions with bridge behavior.
Feature Extraction	Extracting time-dependent deformation from raw data helps observe trends and anomalies.
Bayesian Regression	Bayesian regression can be effective tool to account for uncertainty in monitoring data and modeling predictions.

Questions?

DEPARTMENT OF TRANSPORTATION