Strain-Based Structural Health Monitoring -An Owner's Perspective-

by:

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South Carolina DOT

Bridge Management:
-Challenges and Solution -

- *Safety is Job 1*
- *Aging bridges a concern.*
- *Long term funding a concern.*
- *Developing and evaluating options.*
- *Can we get more useful life - HOW?*
- *Are there methods we can use that are commercial with reliable suppliers?*
- *Will we get a return on investment?*
- *Let's at least try SHM – little to lose.*

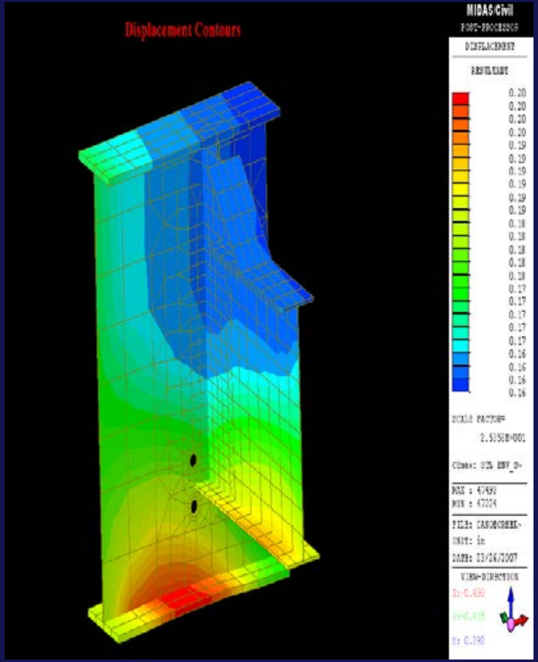
SHM Adoption Timeline

- *Our objective was to see if SHM could provide the essential information to allow safe life extension.*
- *We believed strain-based data was the key to understanding bridge condition and behavior.*
- *Our first two bridges were the Pee Dee and Santee:*
  - *Pee Dee replacement underway; keep old bridge open.*
  - *Santee replacement delayed; needed safety envelope.*
  - *SHM systems installed on both bridges in 2009.*
- *Our third bridge was the Ravenel in Charleston:*
  - *Large cable-stayed bridge; opened in 2005.*
  - *Two systems installed; mid-span and stay 56.*
  - *Strain and temperature data to characterize response.*

What We Learned So Far

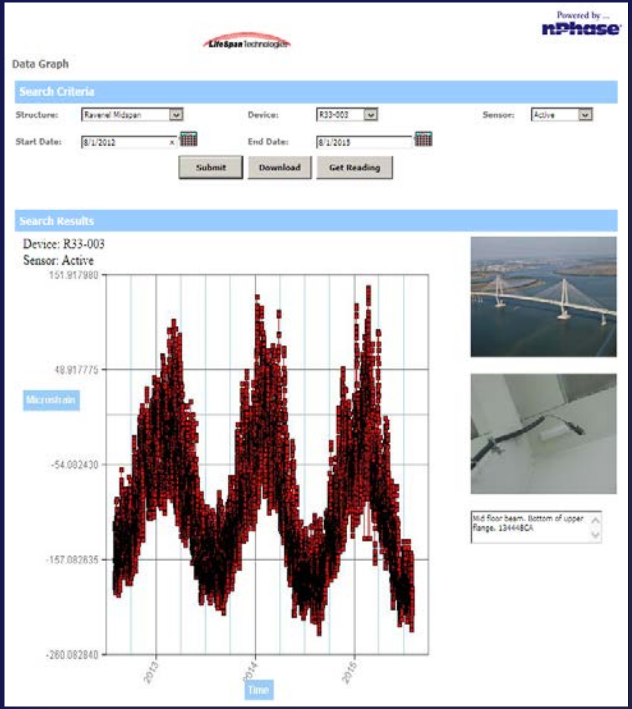
- Monitoring provided sufficient data to catch overloaded trucks on the Pee Dee Bridge.
- We saved $700K by monitoring the Pee Dee vs. re-habbing the steel to support 40T loads.
- We kept the Santee open for 5+ years, safely deferring a $50 million dollar replacement.
- The Ravenel Bridge is very “stiff”, as expected, and has minimal strain values due to live load.
- Temperature changes drive a significant amount of observed strain:
  - Live load strain values remain well within expectations.
  - High strain values can point to frozen bearings.

Strain-Based SHM Basics



- *Provides precise and timely capture of key structural response data.*
- *Strain, especially peak, is key to understanding and managing structural risk.*
- *Temperature effects easy to separate from total strain.*
- *Data/graphs via Internet.*
- *System reliability crucial.*
- *Out-of-tolerance alerts.*

Strain-Based SHM Benefits



- *Analysis is straightforward.*
- *Enhanced user safety.*
- *Safe deferrals of projects; reduced funding demand.*
- *Better project prioritization.*
- *Option development, e.g. rehab versus replacement.*
- *Easy, low-cost prevention or removal of unnecessary load restrictions.*
- *Return on investment is typically substantial.*
- *More informed risk management.*

Pee Dee River Bridge

- *Last 18 to 24 months of service.*
- *Needed to stay open for legal loads - approximately 46 mile bypass.*
- *Truck ADT = 488*
- *Option #1: Fix steel for $825,000.*
- *Option #2: Monitor for $125,000.*
- *Saved $700,000 based on normal decision making protocols.*
- *System easily removed for re-use.*

North Santee River Bridge

- *Both SB bridges over the Santee Rivers slated for replacement, based on NBIS findings, however the North Santee bridge was in more critical condition.*
- *Funding was available to replace ($50M) but political environment was not conducive at the time.*
- *Only option: monitor -vs- possibly restrict loads until replacement feasible.*
- *Have safely deferred replacement actions for 5+ years with an expected 3 to 5 additional years.*
- *At 5%, saving $2.5M per year in avoided "interest"; up to $25M in value generated before replacement.*

Other SC Bridges

- *Used strain-based data to evaluate load demand and structural response on 20 rural, short span bridges.*
- *About 50% of bridges evaluated did not require load restrictions.*
- *A steel truss swing bridge had it’s safe load restriction increased based on strain-based structural response, thus benefitting 3 sea islands - sole access route.*

Expanded SHM Program

- *Eleven new SHM systems on order for a variety of bridges and applications:*
  - *Strain-based global condition assessment*
  - *Inclinometers for bearing operation*
  - *Inclinometers for tower response to load*
  - *Crack propagation on steel and concrete*
- *Expanded monitoring on Ravenel Bridge.*
- *Increased load testing of other bridges for structural performance and posting .*
- *SCDOT Is "all in" for SHM, especially strain-based monitoring:*
  - *Limits data capture and analytical costs*
  - *Strain and temperature data support global condition assessments*

An Owner's Considerations

- *Benefits for the Owner are key:*
  - *Deferred capital expenditures-less funding demand*
  - *Risk and safety management*
  - *Maintenance management*
  - *Avoid/remove unnecessary load restrictions*
  - *Compliance with MAP-21 Asset Management, e.g. "data-driven, risk-adjusted"*
  - *Limit political prioritization of projects*
- *Benefits for the User also important:*
  - *Enhanced safety*
  - *Minimize detours and user cost*
- *Benefits for both should be considered!!!*

Closing Thoughts

- *SHM strain-based technology is fully commercial and very effective!!!*
- *Work with experienced SHM firms – recent evaluation of ~10 firms was eye-opening.*
- *Don’t shortchange monitoring periods.*
- *Use appropriate analytics for data generated.*
- *Plan for and ensure a return on investment.*
- *Don’t wait for others to provide SHM “guidelines”; you can be creating value for your agency – NOW!!!*

Questions?

Structural Health Monitoring for Life Extension of a Rail Rapid Transit Overpass

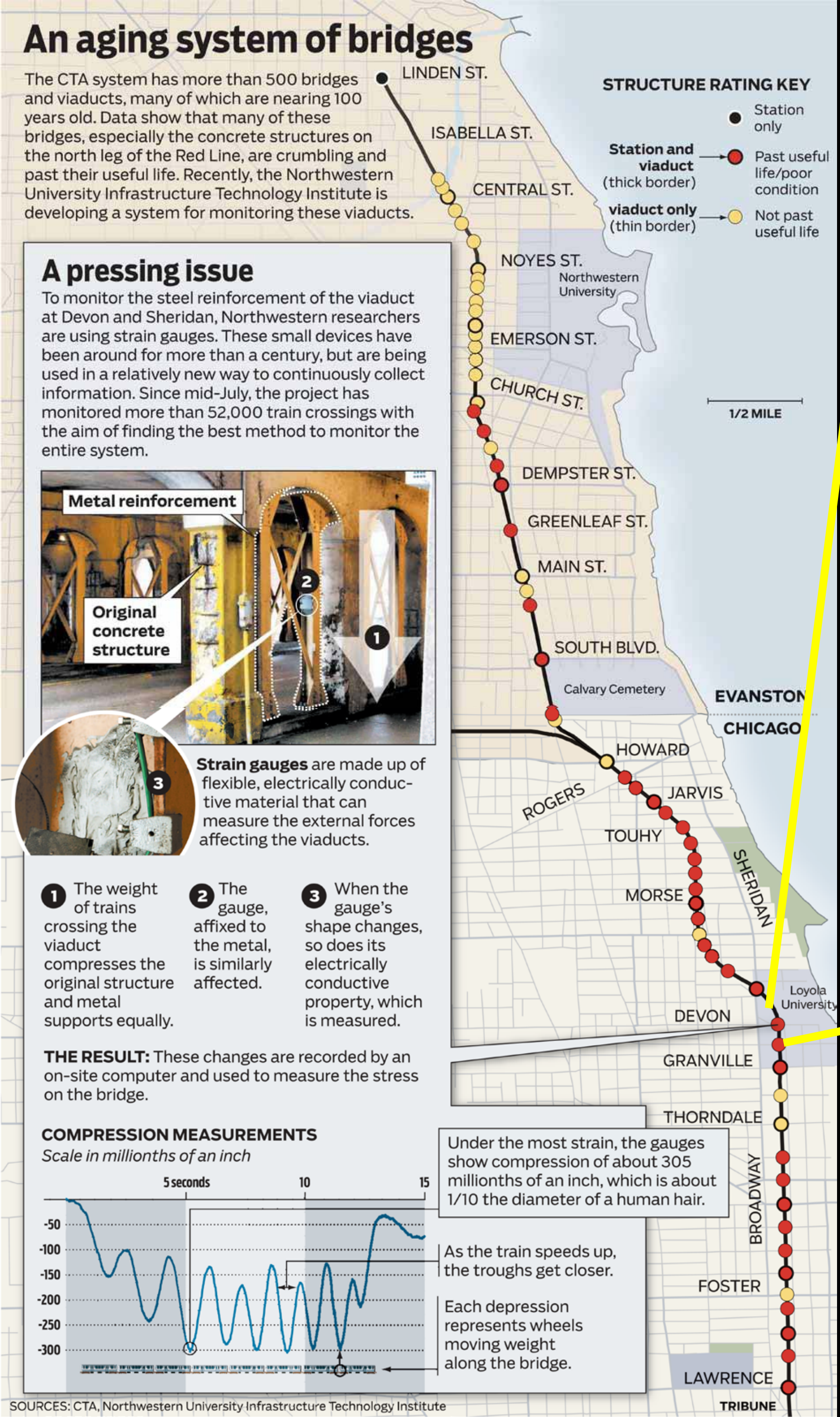
David E. Kosnik, Ph.D., P.E.

CTLGroup
Naperville, Illinois

Strain-based SHM for an Informed Extension of Bridge Lifetime

TRB Webinar – October 7, 2015

CTA Devon-Sheridan Overpass



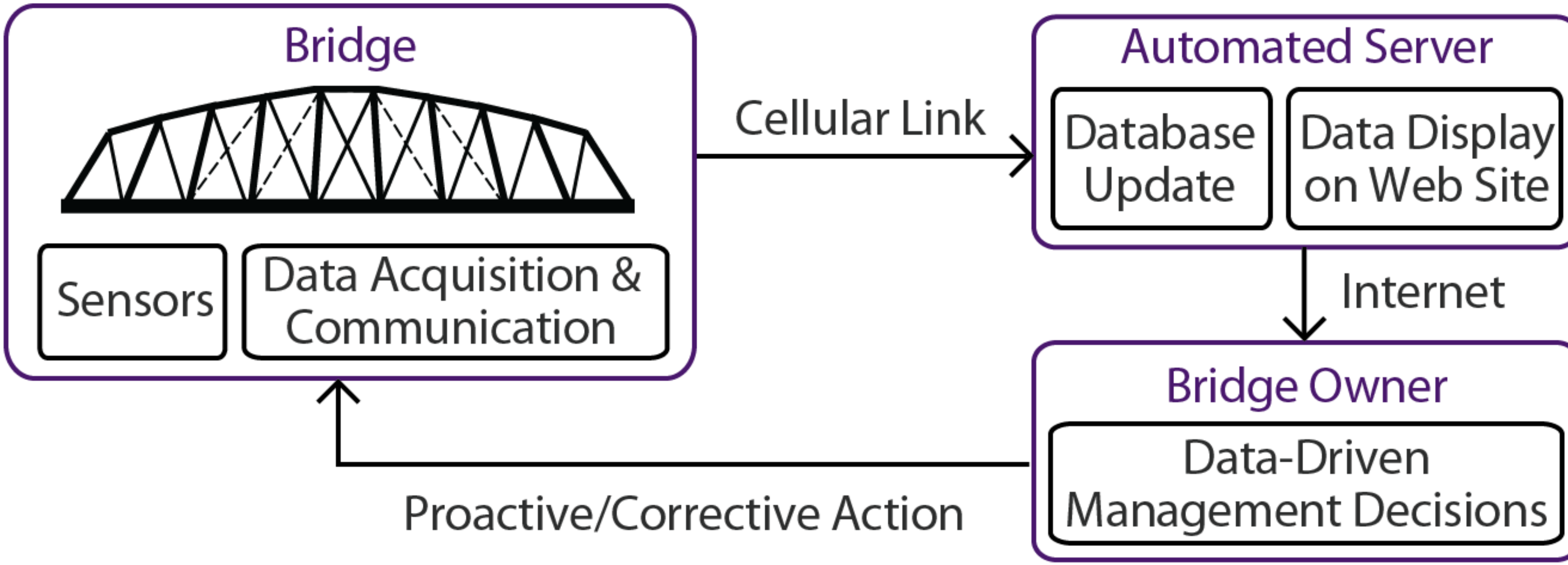
Chicago Tribune

November 28, 2010

CTA Devon-Sheridan Overpass

- Built early 1900s
- Two tracks of local Red Line service: 360 trains/weekday, 24 hours
- Two tracks Purple Line express service: 90 trains/weekday, rush hours only

Structural Health Monitoring process as deployed on CTA Viaduct



SHM is process of intelligently collecting data from sensors on critical components, transmitting data back to the office or lab, generating meaningful reports, making decisions, and taking action based upon live data.

Motivation for Structural Health Monitoring

General

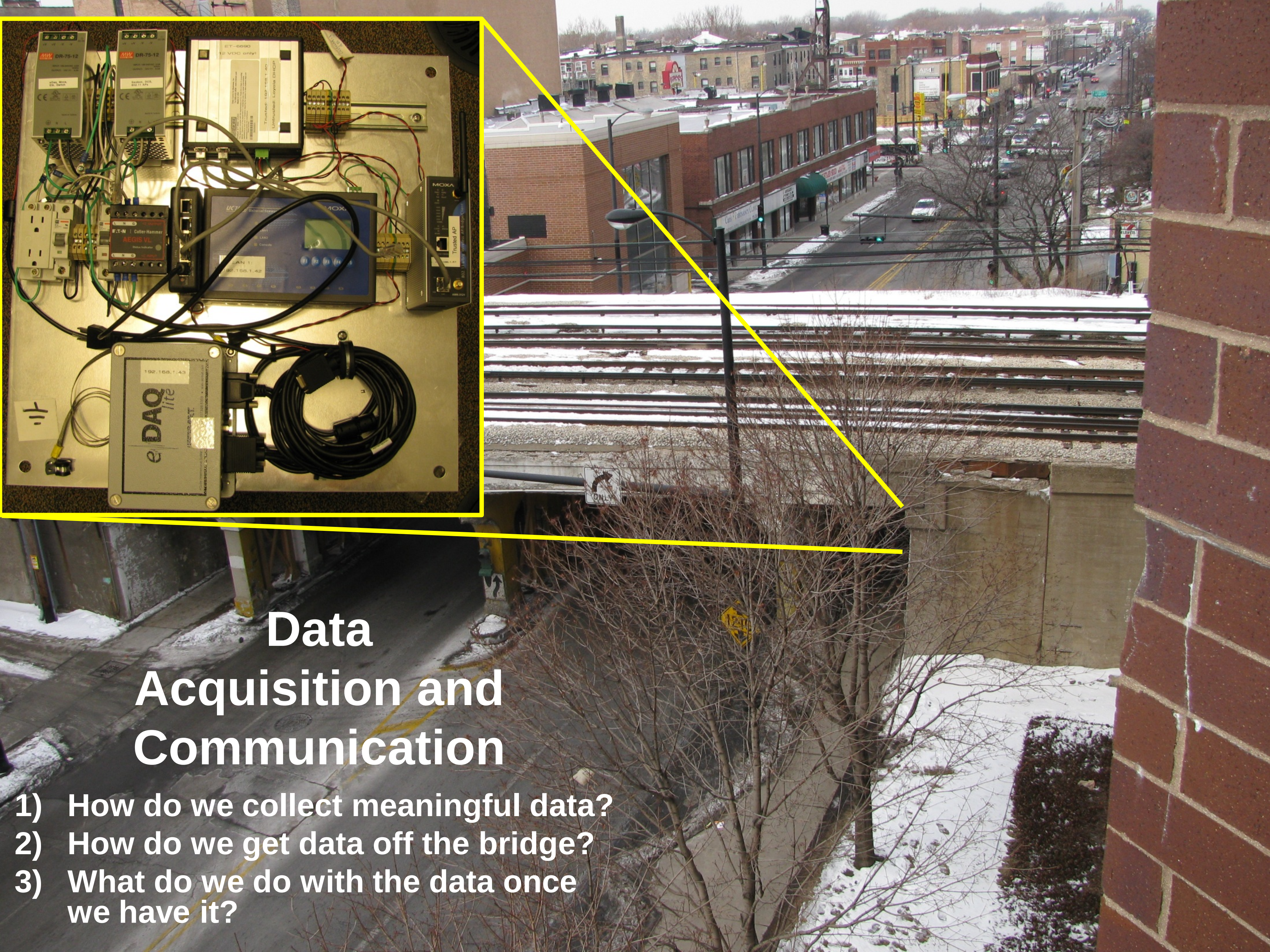
- Supplement the National Bridge Inspection Program with performance data between inspections
- Provide performance data for bridge components that are obscured or difficult to reach
- Measure quantities that are invisible to the eye – e.g., strain

CTA Devon-Sheridan Bridge

- Provide data for column and retrofit performance for management and prioritization of repairs for this and similar bridges
- Support long-term planning – will major bridge work be required before capital improvements in 2020s?

SHM is intended to supplement, not replace, visual inspection

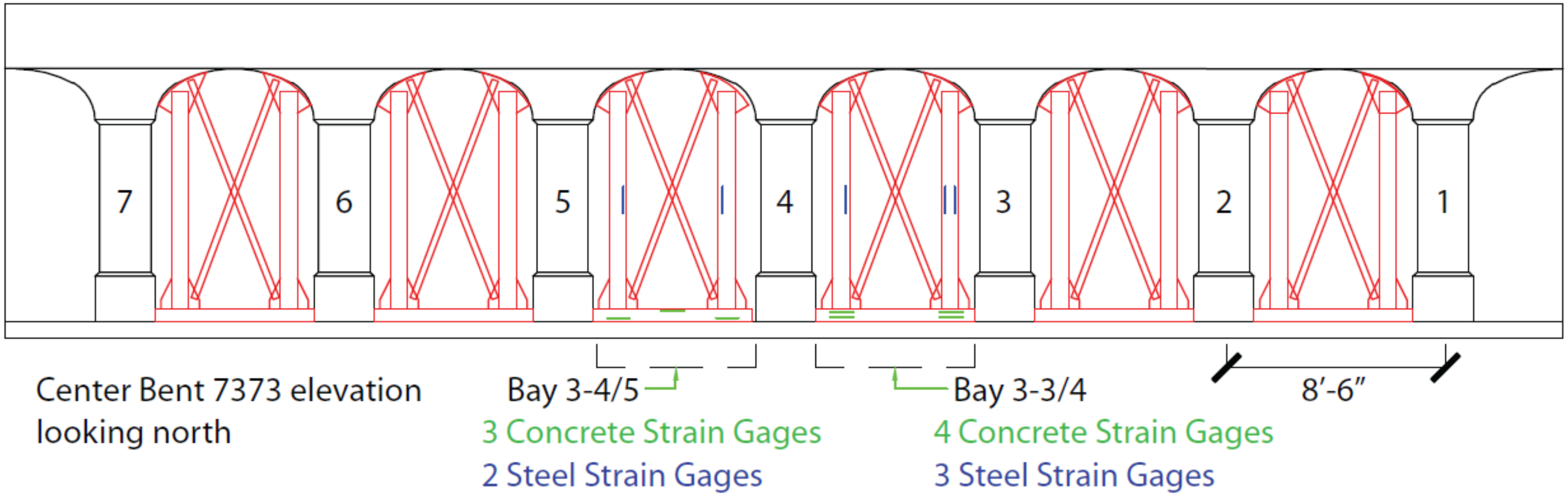
SHM is particularly useful on aging, complex, non-redundant/fracture critical, or other special bridges



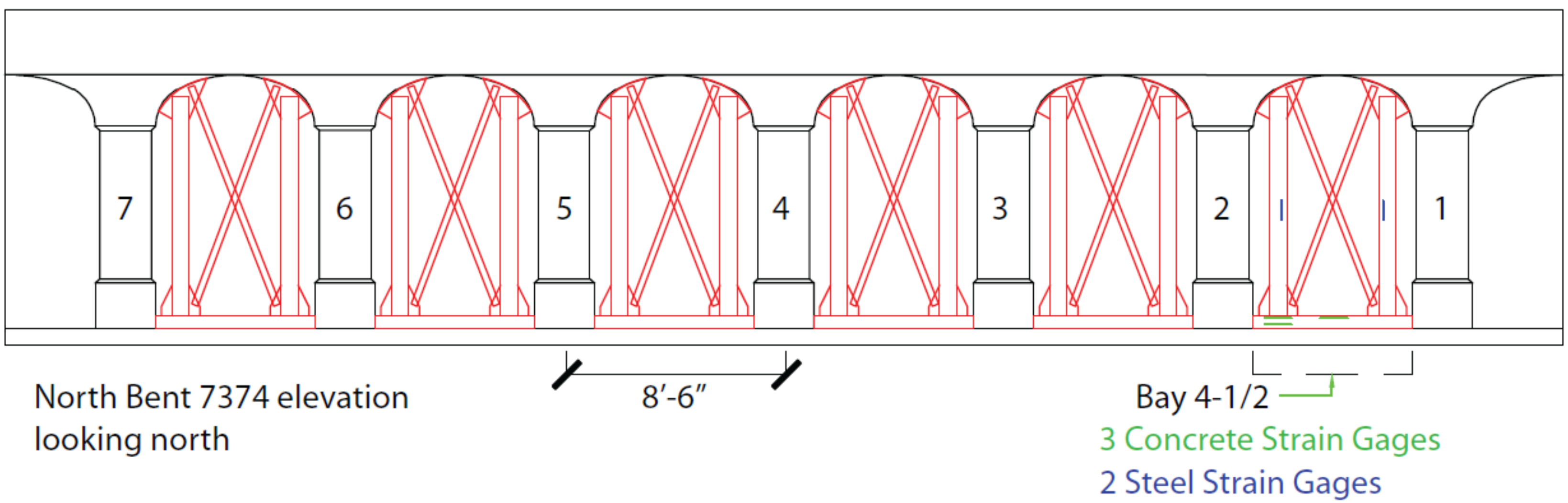
Data Acquisition and Communication

1) How do we collect meaningful data?
2) How do we get data off the bridge?
3) What do we do with the data once we have it?

Challenge 1: Collecting Meaningful Performance Data



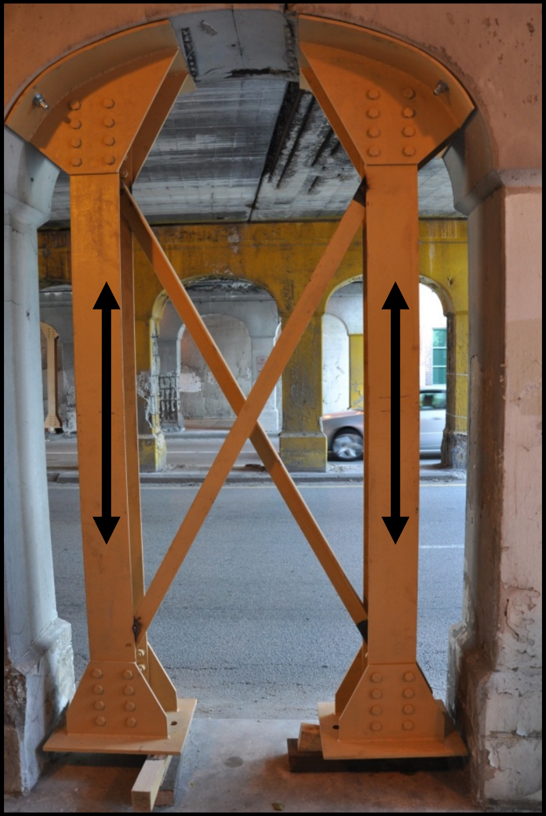
Center Bent 7373 elevation looking north

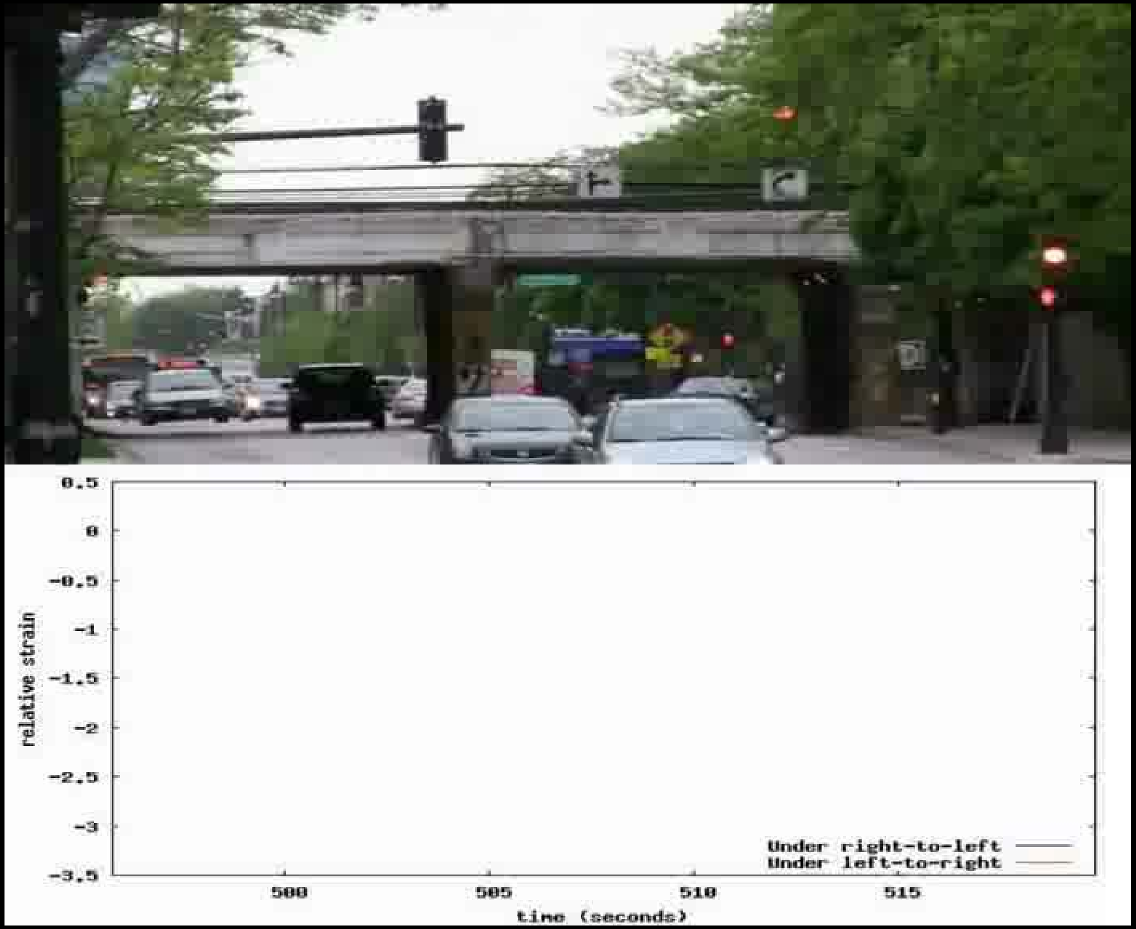


North Bent 7374 elevation looking north

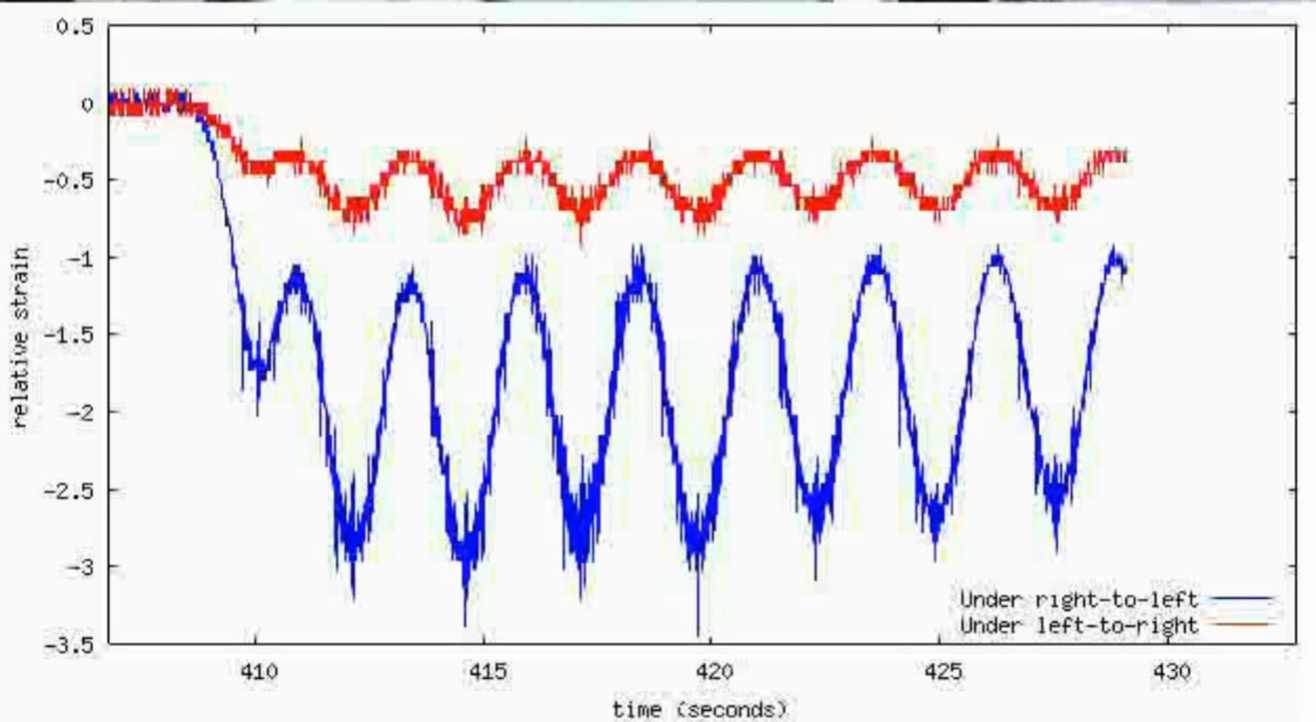

Q-3-34-W-3

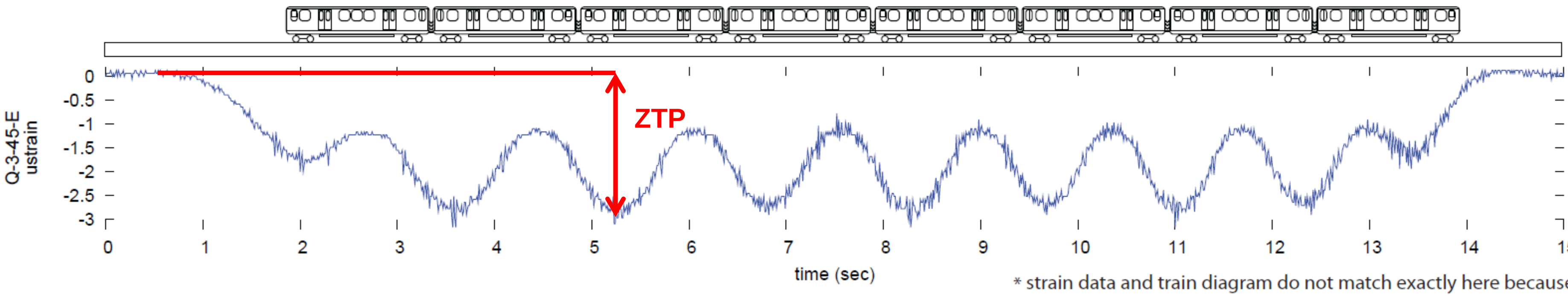
Steel Strain Animation





Steel Column Strain Sensor Traces

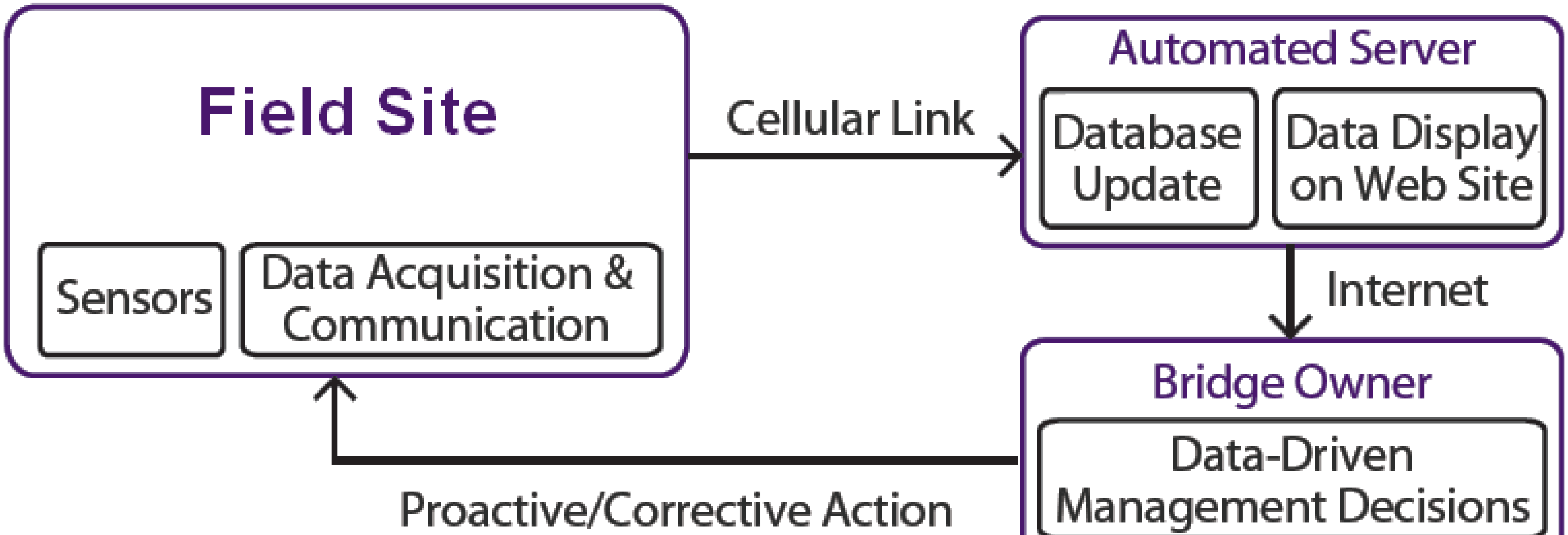




* strain data and train diagram do not match exactly here because this southbound train was speeding up as it left the Loyola station

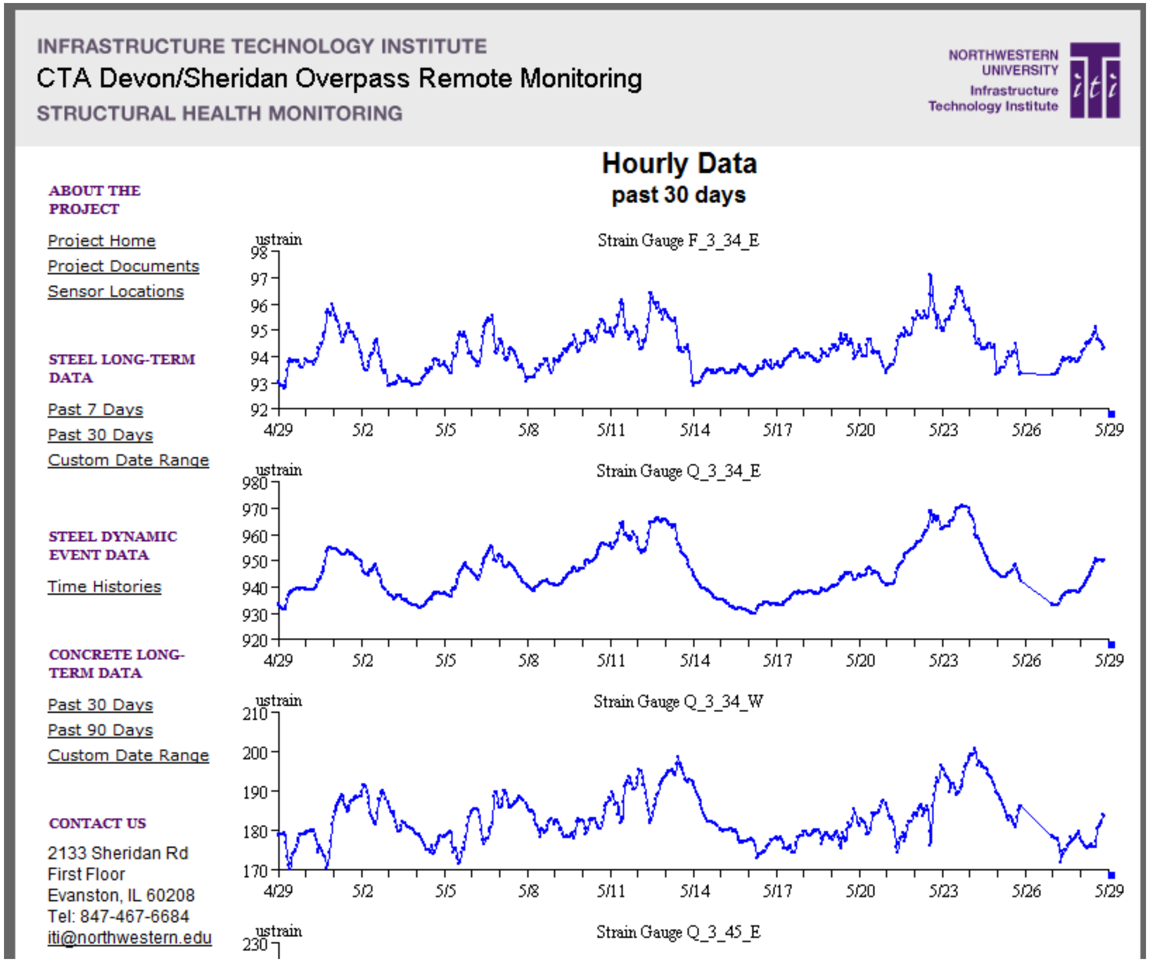
Challenges 2 and 3: Getting the Data Off The Bridge and Doing Something Useful With It

Our Framework for Data Exchange and Infrastructure Management

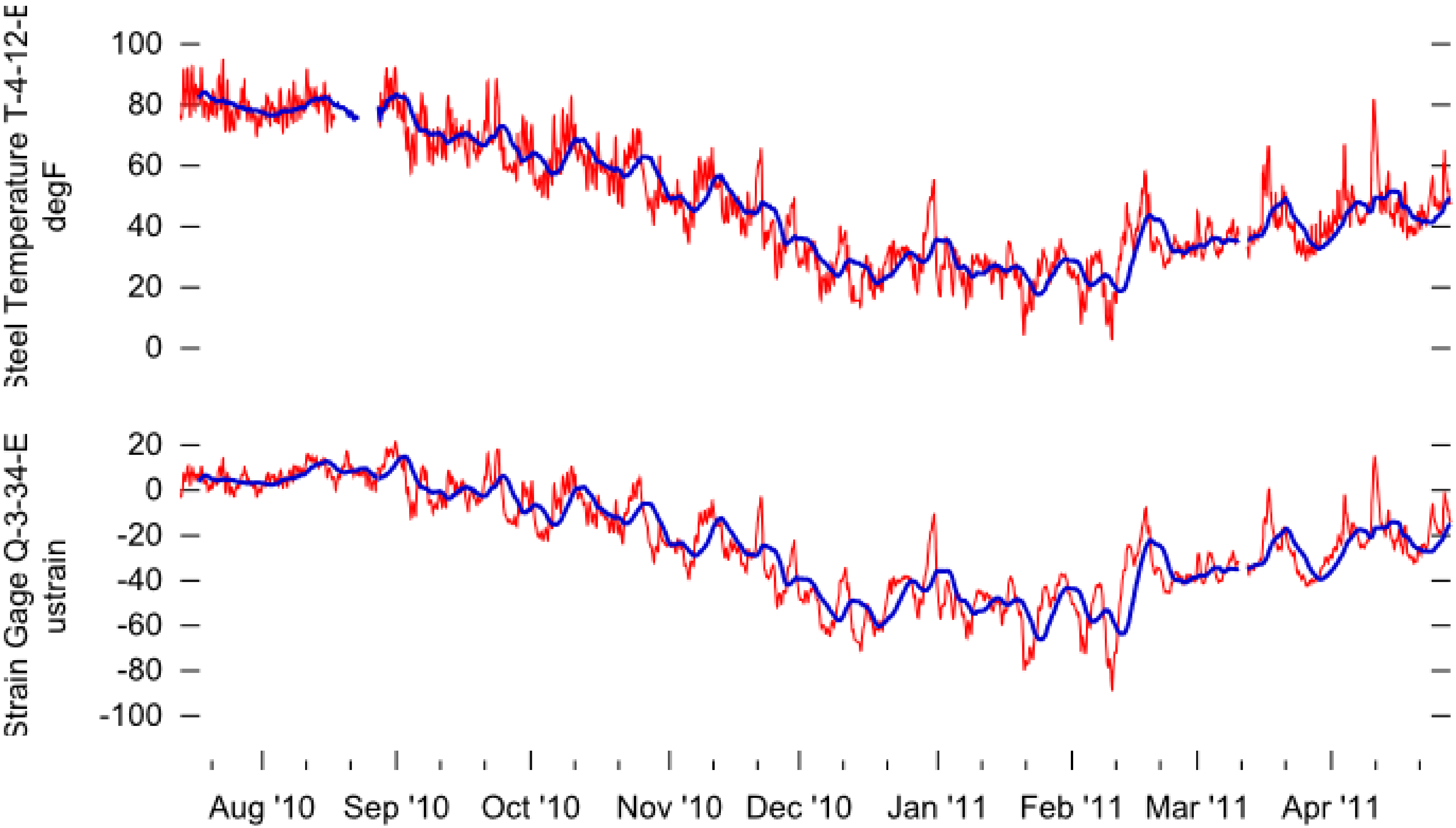


Archive & Distribute Data Via a Web Site

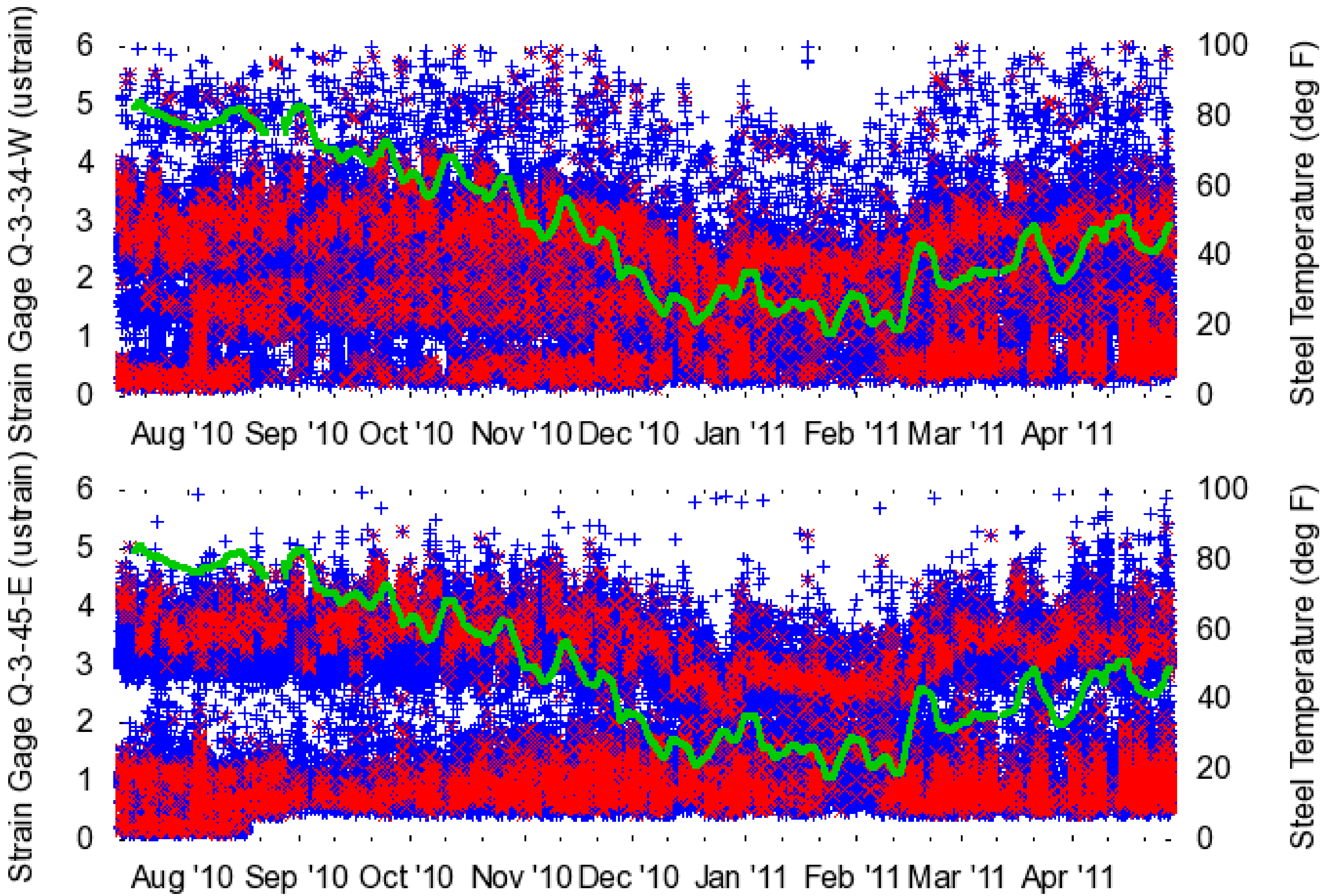
- Every day, new data are entered into the Web-accessible relational database
- Comprehensive, searchable database eliminates problem of multiple data files
- Displays for long-term and dynamic data
- Reporting capability



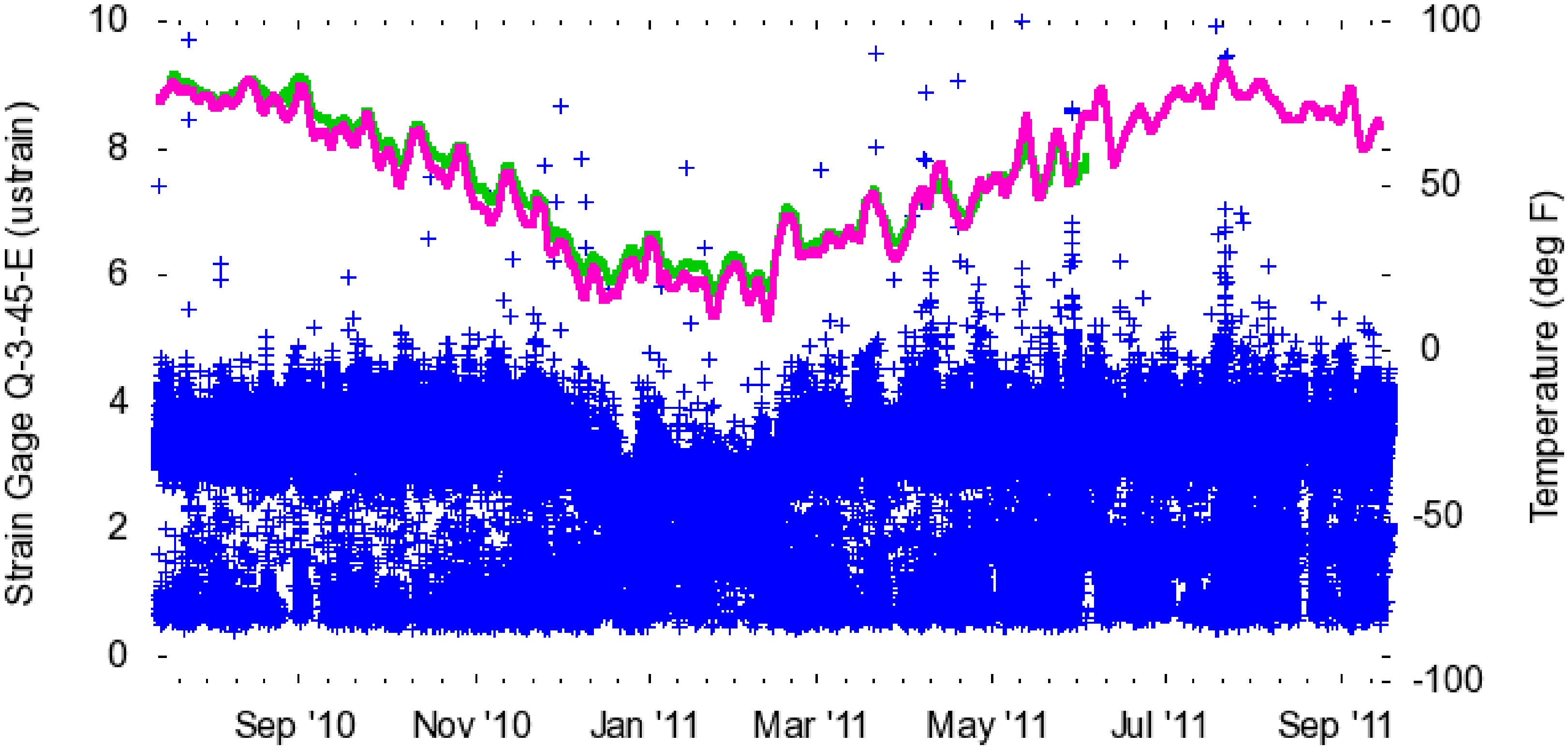
Long-Term Steel Strain vs. Temperature

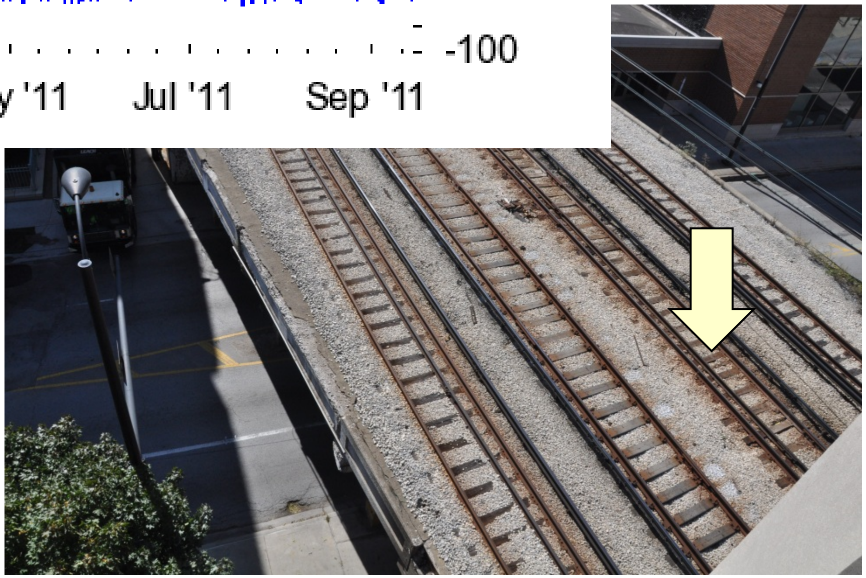


Max. Zero-to-Peak Response vs Temperature

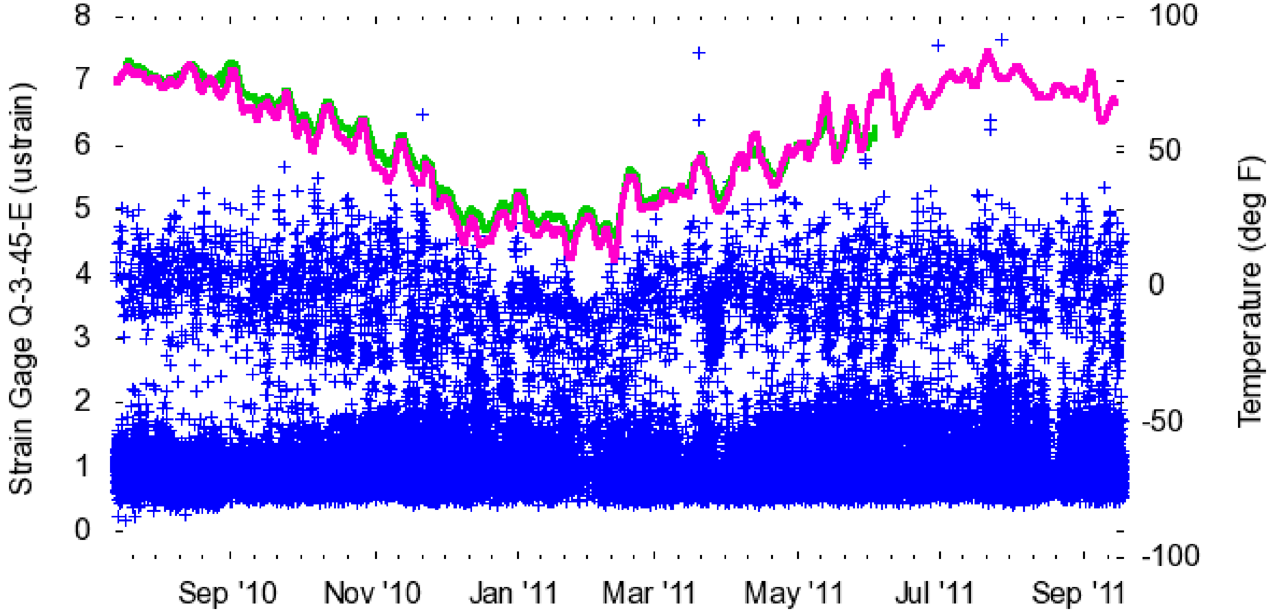


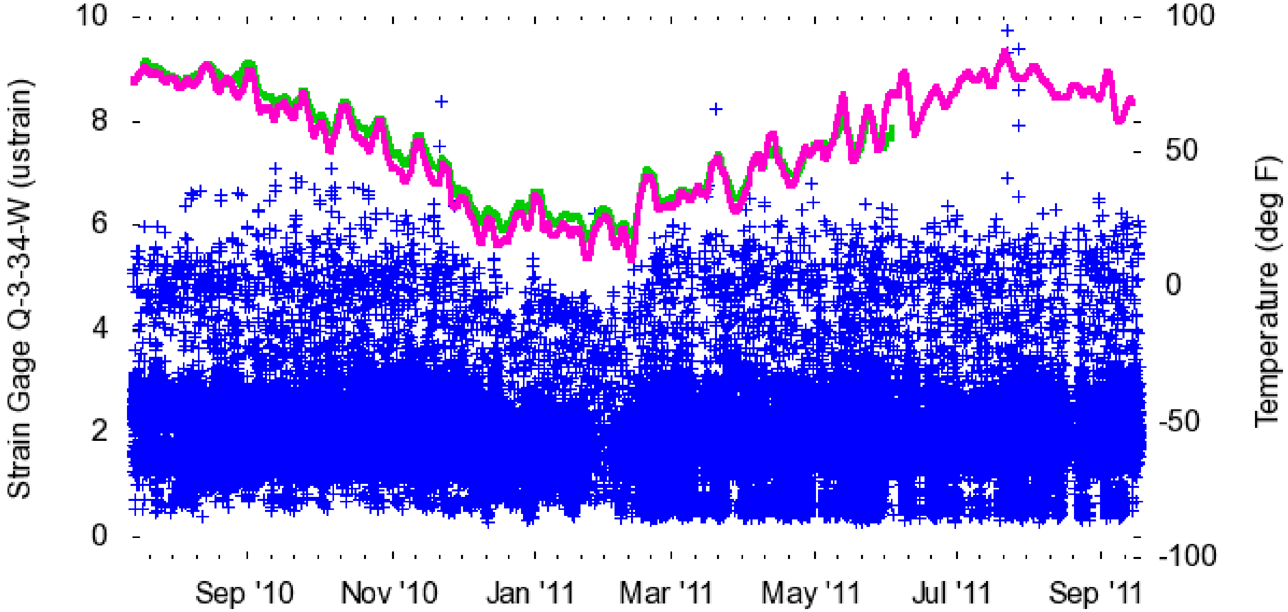
Max. Zero-to-Peak Response vs Temperature: SB Red Line Only

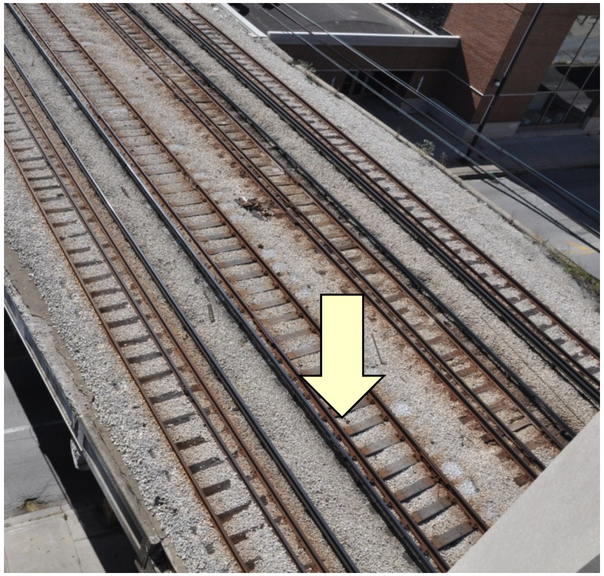




Max. Zero-to-Peak Response vs Temperature: NB Red Line Only







Conclusions

- In general, the live loads on the steel columns are very small, indicating that the concrete columns are still able to carry most of the load

- The live loads on the steel columns decrease with temperature, indicating that thermal contraction causes the steel to disengage from the concrete – another indicator that the concrete columns are mostly OK

- Bridge remains in service

Acknowledgements

We gratefully acknowledge the kind assistance of the **Chicago Transit Authority**

This work was done by at the **Northwestern University Infrastructure Technology Institute**, a multidisciplinary laboratory dedicated to improving transportation infrastructure

SHM-based lifetime extension of 70-year old bridge in Gothenburg, Sweden

Presenter: Branko Glišić

Associate Professor of Civil and Environmental Engineering
Princeton University

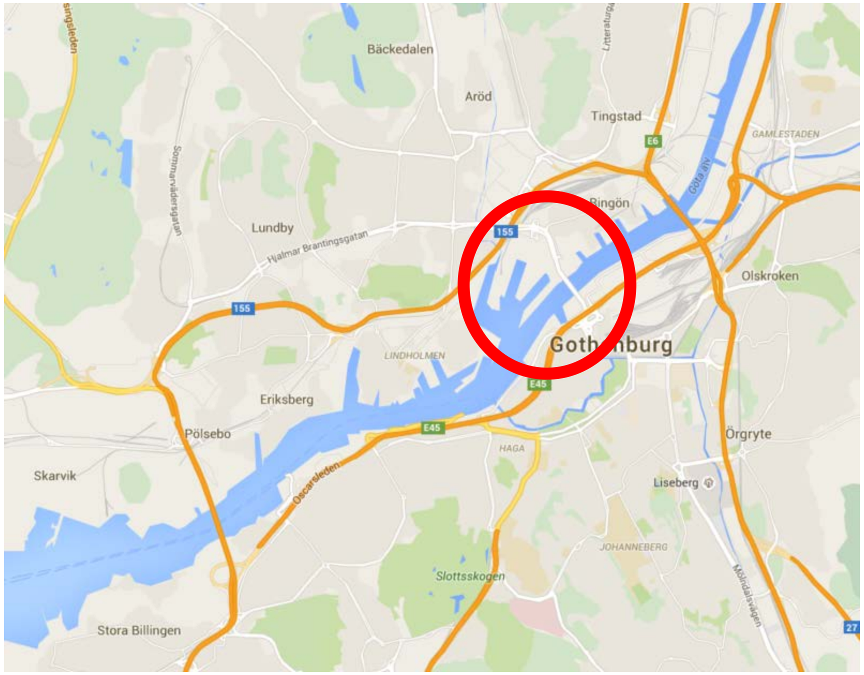
Project partners: **Trafikkontoret Gothenburg, Sweden**
Norwegian Geological Institute, Norway
SMARTEC SA, Switzerland
Royal Institute of Technology, Sweden
Various subcontractors

Introduction

- Götaälvbron (Gota Bridge): structural condition and performance issues
- Owner concerns and reasoning for decision to use SHM technology
- Technical SHM solution, including: SHM method, selected technology, activities and challenges
- Involved parties (e.g., agencies, industry, academia), their responsibilities and mutual relationships
- Outcomes of the SHM, including: deliverables, recommendations and benefits

Götaälvbron (Gota Bridge)

- Constructed 1936-1939
- The main communication line across the Göta River
- 26000 vehicles per day in 2008
- Expected: 40000 per day in 2020



Götaälvbron (Gota Bridge)

- Material: concrete deck slab resting on nine continuous steel girders
- Supported by more than 50 steel columns with various span lengths
- Total length: 950 meters (0.6 mi)
- The bridge has a central bascule that allows boats to sail along the river

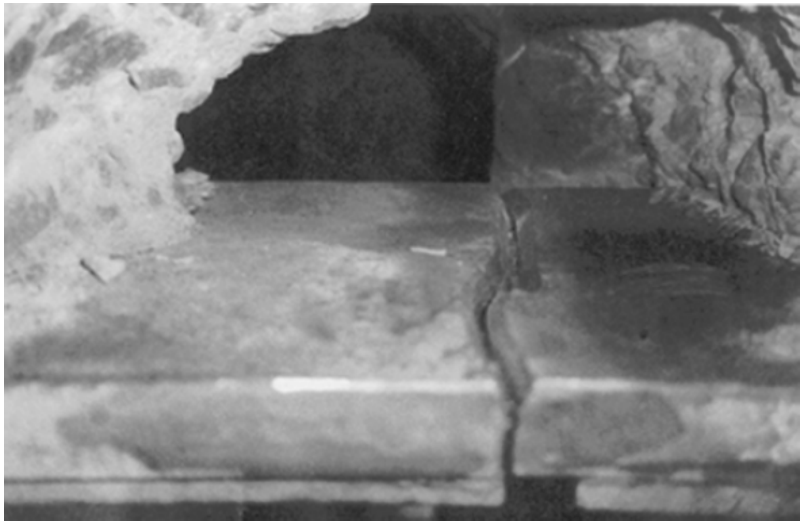
Götaälvbron (Gota Bridge)

- Originally, four lanes accommodating vehicles and city trams and two lanes for pedestrians and bicycles

- Due to increasing traffic the bridge was reconstructed and widened in 1958 to six lanes for vehicles

Issues

- The steel quality low (Thomas steel): brittle and varies along the length of the girders ⇒ **prone to fatigue cracking**
- The design and construction of connections between the steel columns and the girders is unfavorable ⇒ **prone to failure under repeated loads and/or corrosion**
- Risks amplified during the cold winter weather (record low temperature of −26.0°C = −14.8°F)
- Routine inspection in 1999 ⇒ **large cracks in flanges** of steel girders above the support columns
- **Cause:** fatigue over many years of service and the low quality of steel



Decision to implement SHM

- The cracks repaired, structural improvements implemented
- The bridge should be **kept in service until 2020** to allow sufficient time to plan and build new crossing (bridge or tunnel)
- **Owner, Trafikkontoret** (The Gothenburg City Traffic Authority) made a comprehensive study: material testing, determination of failures modes, analyses of fatigue, simulations of damage propagation
- Restrictions of acceptable axial load of vehicles were imposed
- The need for **integrity monitoring** of the bridge up to 2020 was recognized
- **Aim:** create **an early warning system** for any unusual structural behavior to allow **emergency preventive actions**

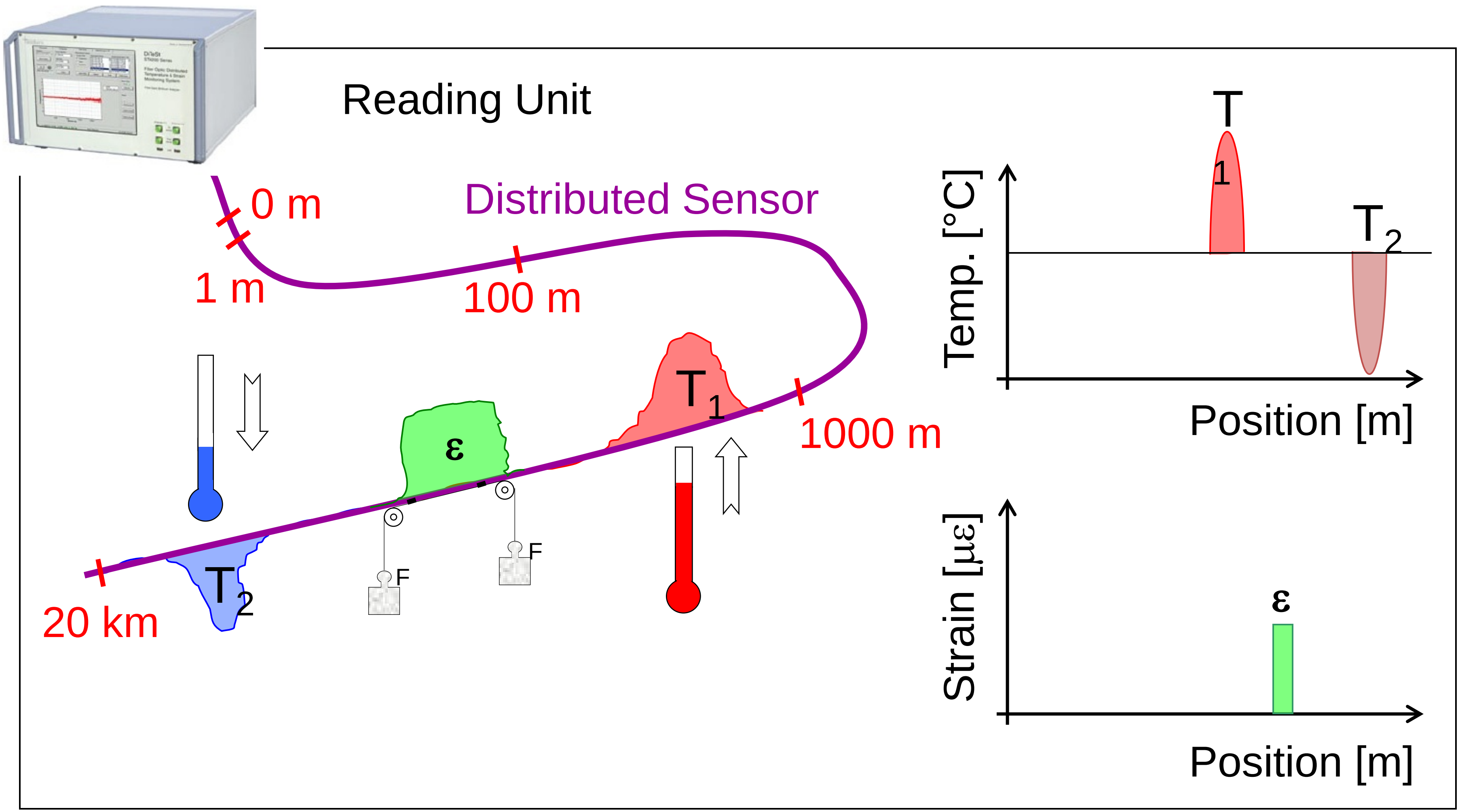
SHM objectives

- Five most loaded steel girders to be monitored
- Automatic monitoring and localization of unusual mechanical strain in monitored girders
- Temperature monitoring
- Detection of cracks that may occur at any point along the monitored girders
- Self-monitoring capability (monitoring of the SHM system for correct functioning)
- Transmission of early warning messages to the responsible operator on the bridge and to responsible engineers and managers at the Tarfikkontoret

SHM technical solution

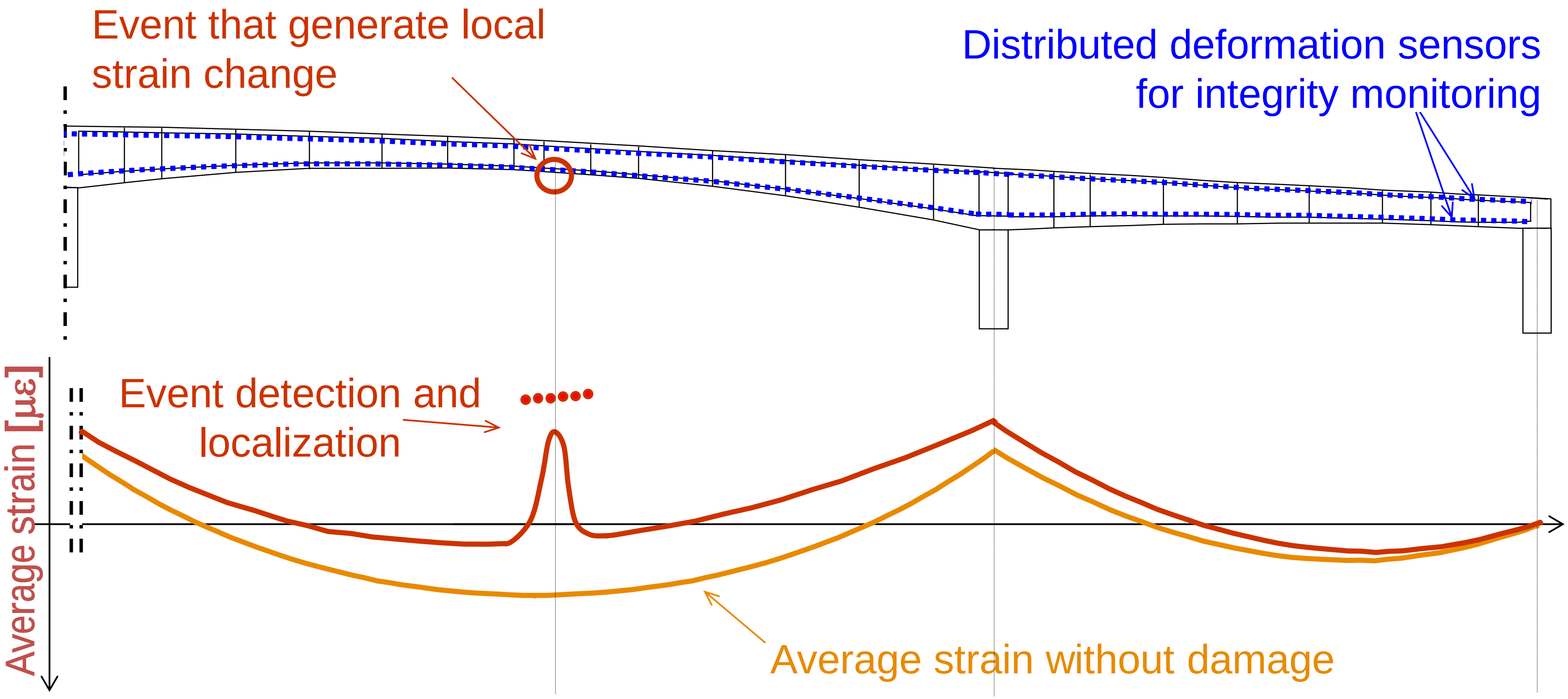
- Traffikkontoret performed comparable studies and cost-benefit evaluations of several SHM techniques (including data management)
- The following techniques were considered:
  - Strain-gauge technologies
  - Automatic optical surveying systems
  - Imaging techniques
  - Fiber optic sensing technologies (FOS)
  - Differential synthetic aperture radar (SAR) interferometry
- **Distributed FOS were selected as the optimal solution**
- **The first large-scale application of distributed FOS for SHM of bridges**

Distributed FOS



Integrity monitoring

- Distributed sensing provides for integrity monitoring
- Event (e.g. damage) detection and localization



Application to Gota Bridge

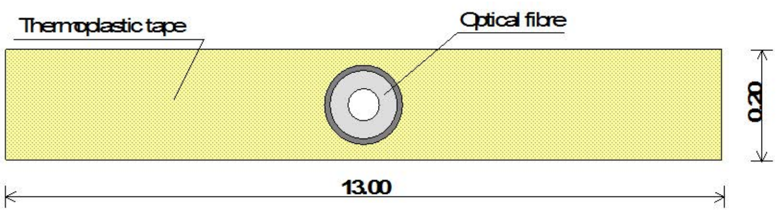
- Five girders monitored, each over full length of ~950 m (~0.6 mi)

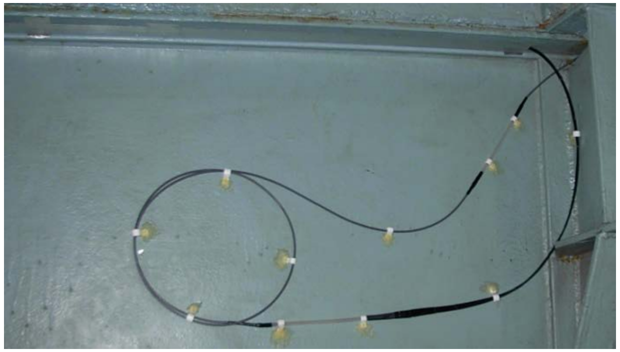
- **Consultant**, Norwegian Geotechnical Institute (**NGI**): specifications (tender) including algorithms for data analysis
- Key specifications:

Resolution:	Strain = ± 3 $\mu\varepsilon$	Temperature = ± 0.1°C
Limit of error:	Strain = ± 21 $\mu\varepsilon$	Temperature = ± 1°C
Crack detection:	0.5 mm (1/5 in) along 10 cm (4 in)	
Measurement time:	2 h	

SHM system

- **Monitoring company, SMARTEC**: SMARTape sensors, Brillouin Optical Time Domain Analysis (BOTDA) interrogator DiTeSt





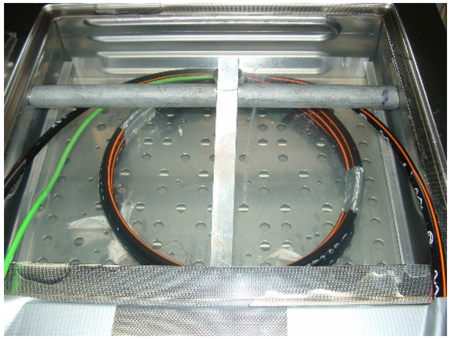
- Single optical fiber per cable embedded in thermoplastic glass fiber reinforced composite tape
- Require separate temperature compensation cable if temperature variations are expected
- Installed on surface by gluing and protected with "aluminum" tape

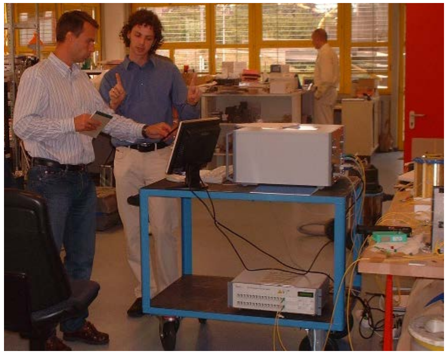
Temperature Cable

Qualification of SHM system (1)

- **NGI** prescribed various factory acceptance tests (FAT) and site acceptance tests (SAT) for qualification and commissioning of the SHM system

- **SMARTEC** and **NGI** developed FAT and SAT procedures with **Trafikkontoret's** approval
  - FAT 1: Specifications of sensors tested
  - FAT 2: Specifications of interrogator (reading unit) tested
  - FAT 3: Full system tested including self-monitoring and alarming capabilities



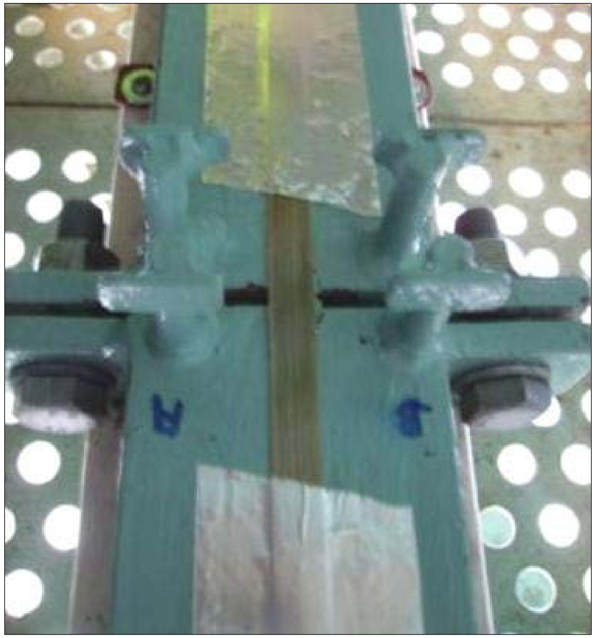


Installation of SHM system

- **SMARTEC** developed installation procedures and tested them in lab and on-site
- Various **contractors** (Bemek, KTH, NGI, SMARTEC) installed SMARTape sensors over 5 main girders
- **NGI** supervised the installation

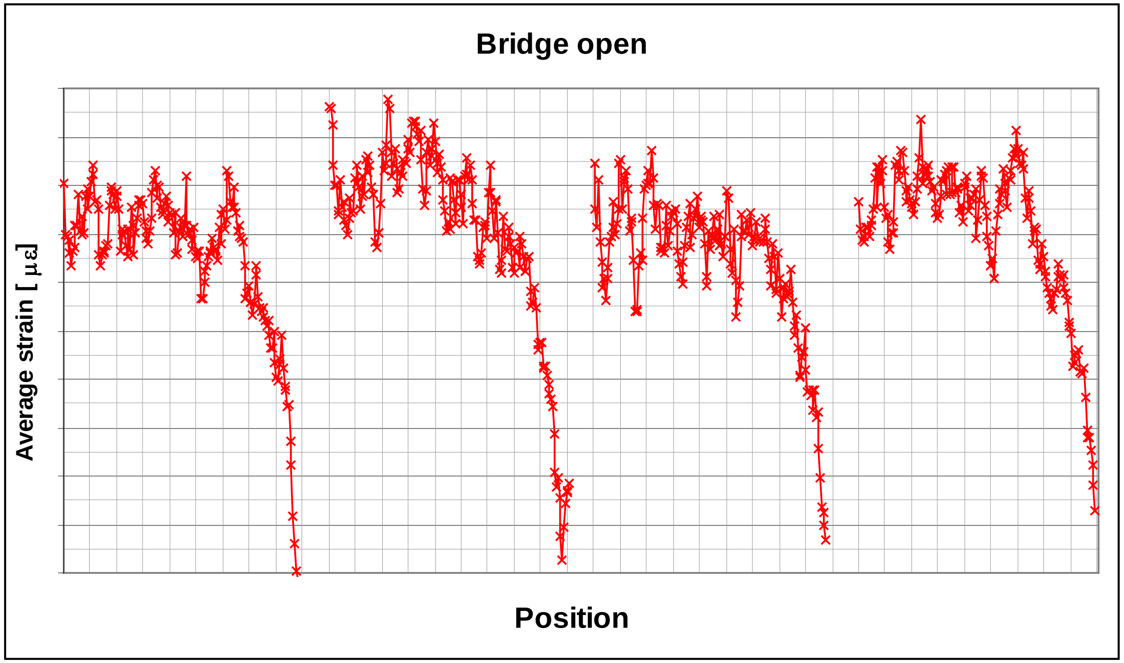
Qualification of SHM system (2)

- Site Acceptance Test (SAT)
- Long painted specimens instrumented
- Specimens included in bridge monitoring system on-site
- Tests performed on-site, all cracks detected, localized and reported properly

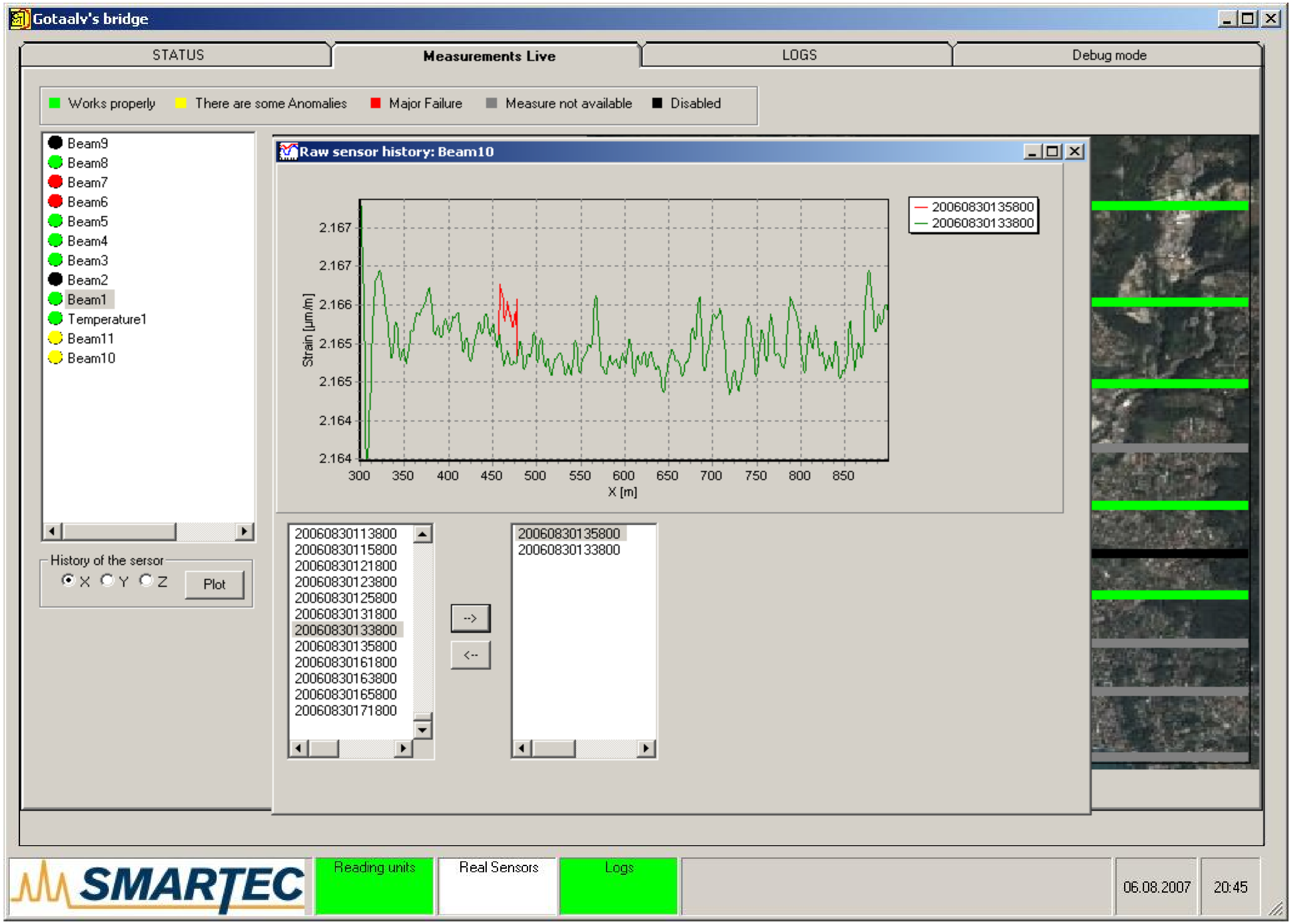


Example of results

- Strain field change in movable part of the bridge when open
- Movable part of the bridge has only four main girders



Interface



Gotaalv's bridge
STATUS
Measurements Live
LOGS
Debug mode
Works properly
There are some Anomalies
Major Failure
Measure not available
Disabled
Beam9
Beam8
Beam7
Beam6
Beam5
Beam4
Beam3
Beam2
Beam1
Temperature1
Beam11
Beam10
History of the sensor
X
Y
Z
Plot
Raw sensor history: Beam10
20060830135800
20060830133800
Strain [µm/m]
X [m]
20060830113800
20060830115800
20060830121800
20060830123800
20060830125800
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SMARTEC
Reading units
Real Sensors
Logs
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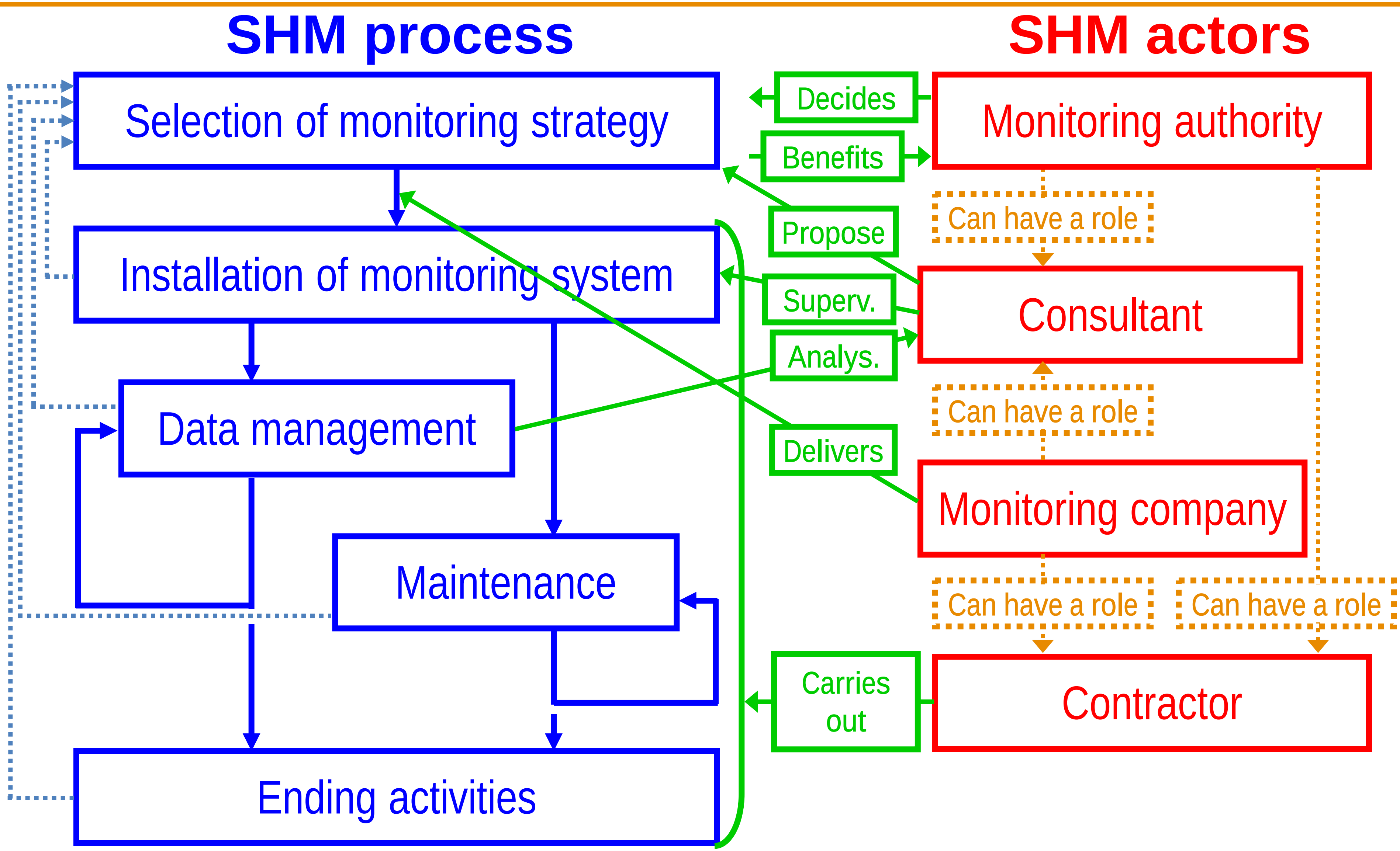
20:45

SHM – core activities

Monitoring strategy	*Installation of SHM system*	*Maintenance of SHM system*	*Data management*	*Closing activities*
Monitoring aim	**Installation of sensors**	**Providing for electrical supply**	**Collecting data (reading of sensors)**	**Interruption of monitoring**
Selection of monitored parameters	**Installation of accessories (boxes, cables…)**	**Providing for com-munication lines (wired or wireless)**	**Storage of data (local or remote)**	**Dismantling of monitoring system**
Selection of monitoring systems	**Installation of reading units**	**Implementation of maintenance plans for hardware**	**Providing for access to data**	**Storage of monitoring components**
Design of sensor network	**Installation of software**	**Repairs and replacements**	**Visualization**	
Schedule of monitoring	**Interfacing with users**		**Export of data**	
Data explo-itation plan			**Interpretation and data analysis**	
Costs			**The use of data**	

Core activities and involved parties



Outcomes of SHM

- Periodic reports to **Trafikkontoret** generated and issued by **NGI**
- Bridge preserved, lifetime extension supported by SHM since 2008 (target is 2020)
- Safety enhanced, procedures for non-scheduled interventions established
- First project of its kind – numerous lessons learned in terms of SHM process, BOTDA based FOS performance in variable on-site conditions, and installation and operation of SHM system

Acknowledgments

- Trafikkontoret, Gothenburg, Sweden
- Norwegian Geotechnical Institute, Oslo, Norway
- SMARTEC SA, Manno, Switzerland
- Royal Institute of Technology (KTH), Stockholm, Sweden
- Omnisens SA, Morges, Switzerland
- Bemek, Sweden

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