Representative work by over 25 Engineers , technical staff, and graduate students at the
Department of Civil & Materials Engineering
University of Illinois at Chicago

Infrastructure Monitoring and Assessment: State of the Art and Future

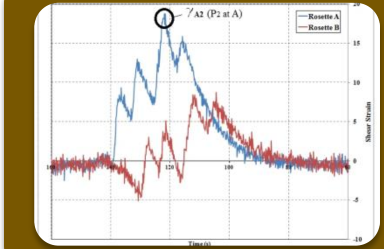
Why Monitor Infrastructure?

Assure safety

- Warn of impending failures
- Rapid post-disaster assessment
- Save lives

Maintenance and Management

- Detect damage at early stages of formation
- Automate, simplify and provide real time access to data
- Reduce life-cycle costs



In-service Structural and Materials behavior

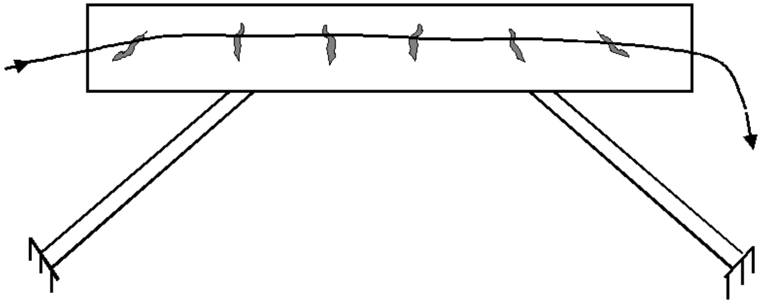
- Quantitative assessment of structural response
- Data for development of innovative materials and structural designs
- Determine Construction quality

Civil structures are large and complex

Many sensors, and lead lines

Too much data

Why Optical Fiber Sensors

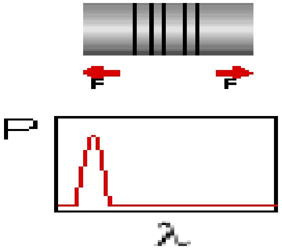


- **Flexible and geometrically versatile** for embedment or adhesion to structural elements.
- Serve the **dual purpose** as the sensor and pathway for the signal.
- **Distributed** measurements or **serial multiplexing**
- Extremely small and lightweight.
- **Immune** to electrical and electromagnetic interference.
- Resist corrosion and fatigue.
- **Safe** (incapable of initiating fire or explosions).
- Capable of making **high resolution** measurements

Localized and Distributed FOS Sensor Types

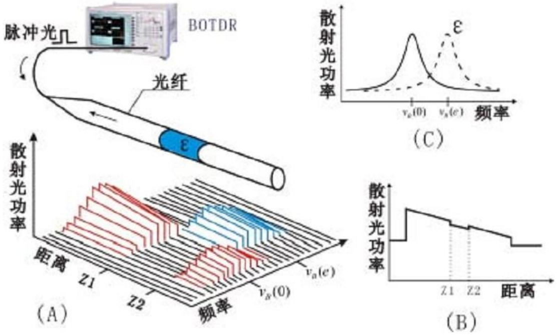
Fiber Bragg Gratings (FBG) –wavelength change

- Discrete/strain/Temperature

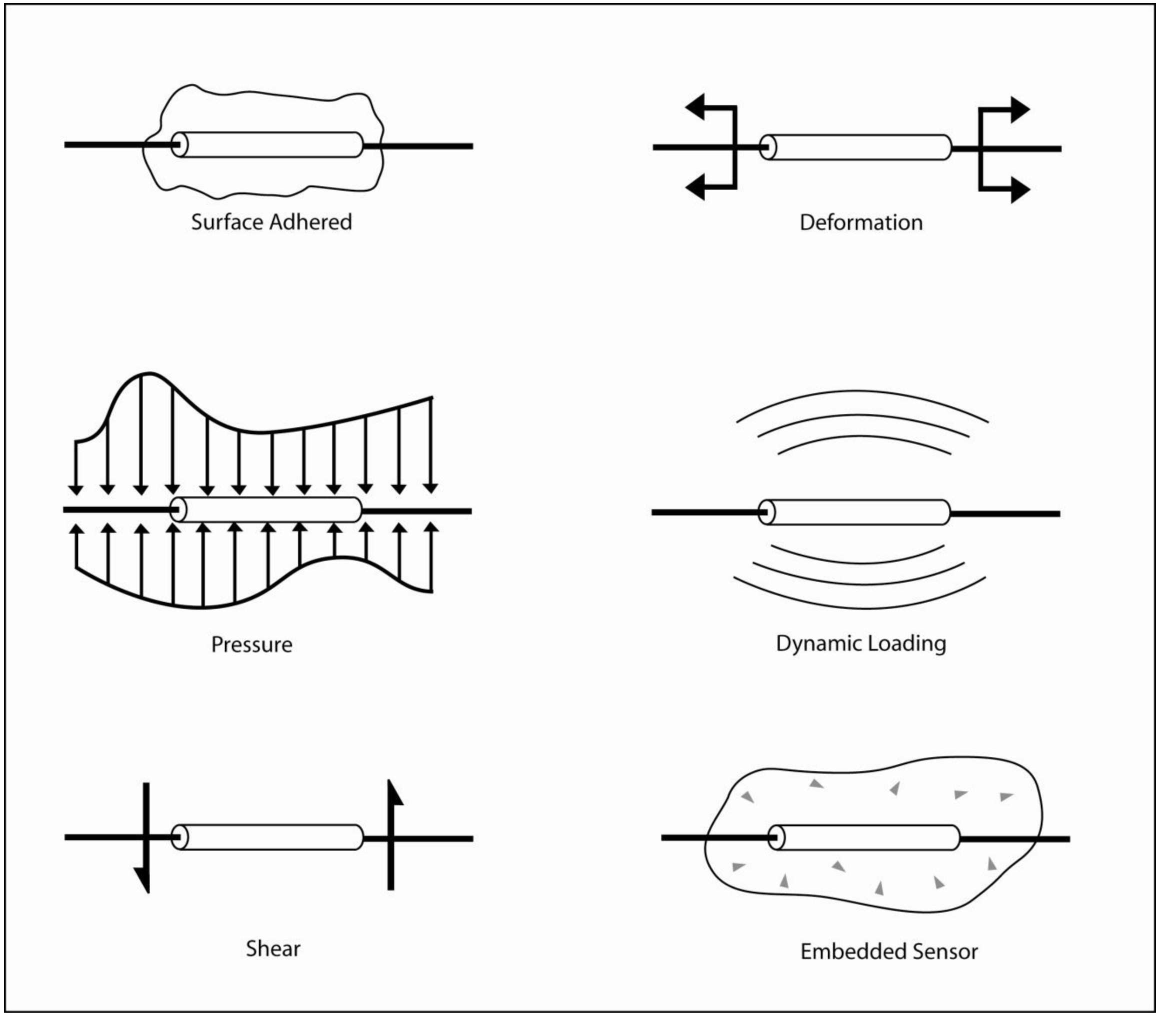


BOTDA/BOTDR- Brillouin Frequency shift

- Distribute Strain/Temperature



Sensor Configurations



Surface Adhered

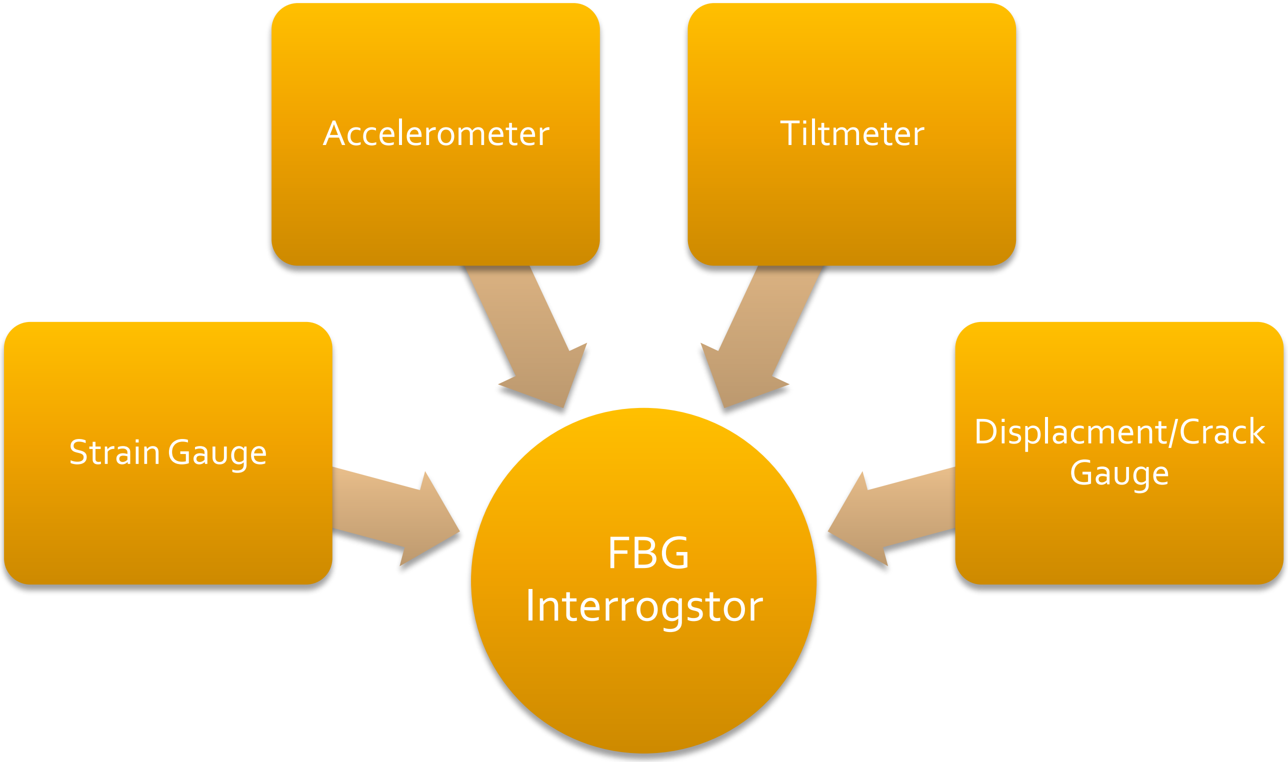
Deformation

Pressure

Dynamic Loading

Shear

Embedded Sensor



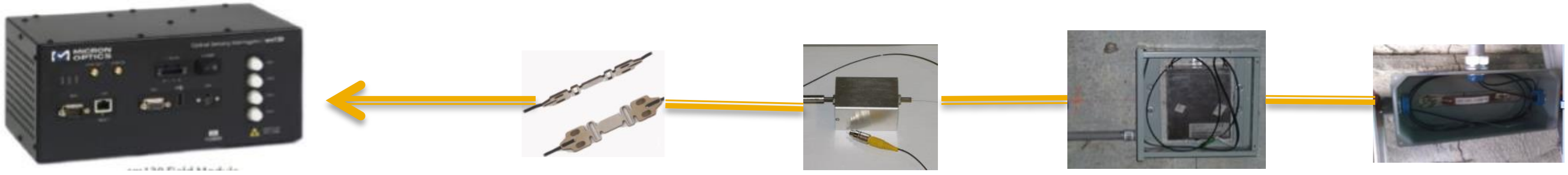
Accelerometer

Tiltmeter

Strain Gauge

Displacment/Crack Gauge

FBG Interrogstor



Distributed Monitoring Strategies

- Use a Single Sensor to monitor the entire infrastructure
- Develop simplified analysis techniques

Optical Fiber Sensors

30 years ago

Applications in Aeronautics

Composite Materials

Today

FBG sensors widely employed in many infrastructure applications

Tomorrow

Distributed Sensors will practically replace FBG

sensors

Example Applications for FBG Sensors

- Shear Force Based BWIM system
  - **Specific application to monitor loads in real time in Bridges**
- Monitoring of vault cracks in Brooklyn Bridge
  - **Specific application to determine the cause for cracking and to assure safety**

Shear Force Based Method for Bridge Weigh-in-Motion System

U.S. Department of Transportation
Federal Highway Administration

Long-Term
Bridge Performance
Program

Existing BWIM Systems

- The BWIM systems are primarily :
  - Based on Bending Capacity of Girders
  - Calibrated against the flexural response of the bridge
  - Instrumentation involves installation of sensors on sections of bridge girders with higher flexural strain responses

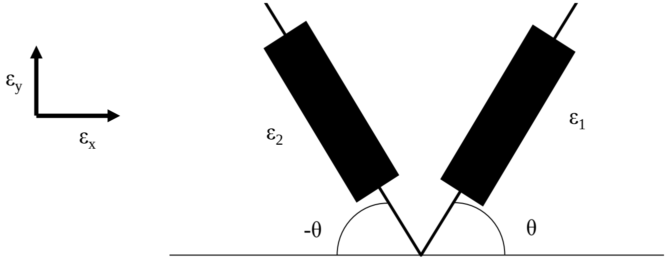
Simplified Approach

- Develop a simple and cost effective WIM system for widespread usage in highway bridges
- Overcome the existing limitations of BWIM systems in terms of installation rigors, Bridge span lengths, geometry, computational time, and monitoring costs

- **Shear Force Based BWIM system:**
  - Sensors are installed below bridge deck.
  - Sensors are installed near abutments.

Rosette Theory

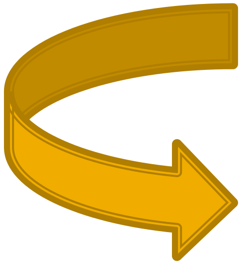
- Since the two strain gages that form the rosette sensor are in such close proximity

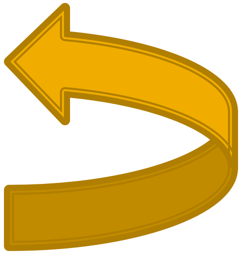


- Thermal variations are automatically cancelled by subtraction of one strain from the other:

$$\gamma_{xy} = \frac{\varepsilon_1 - \varepsilon_2}{2\sin\theta\cos\theta}$$

Shear Force





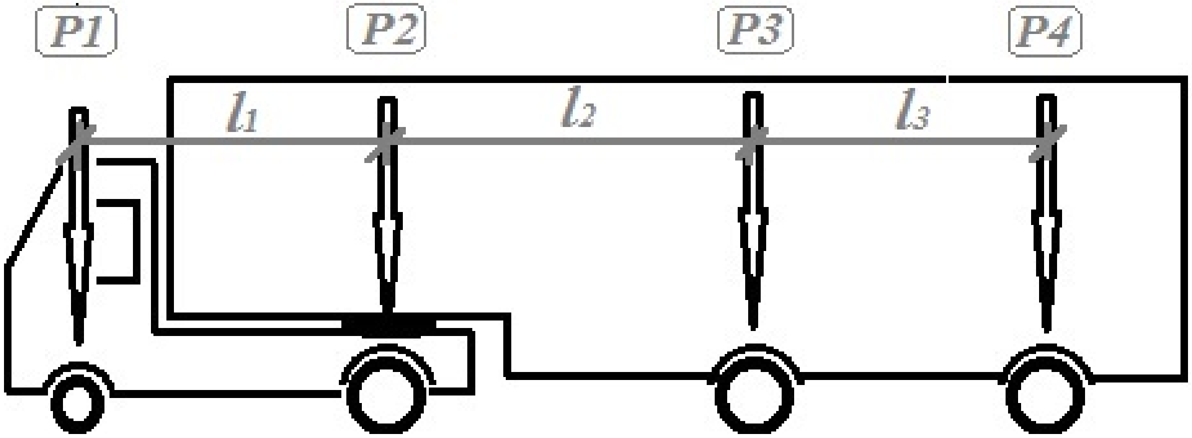
$$\tau = \gamma G$$

$$V = \frac{GIt\gamma}{Q}$$

16

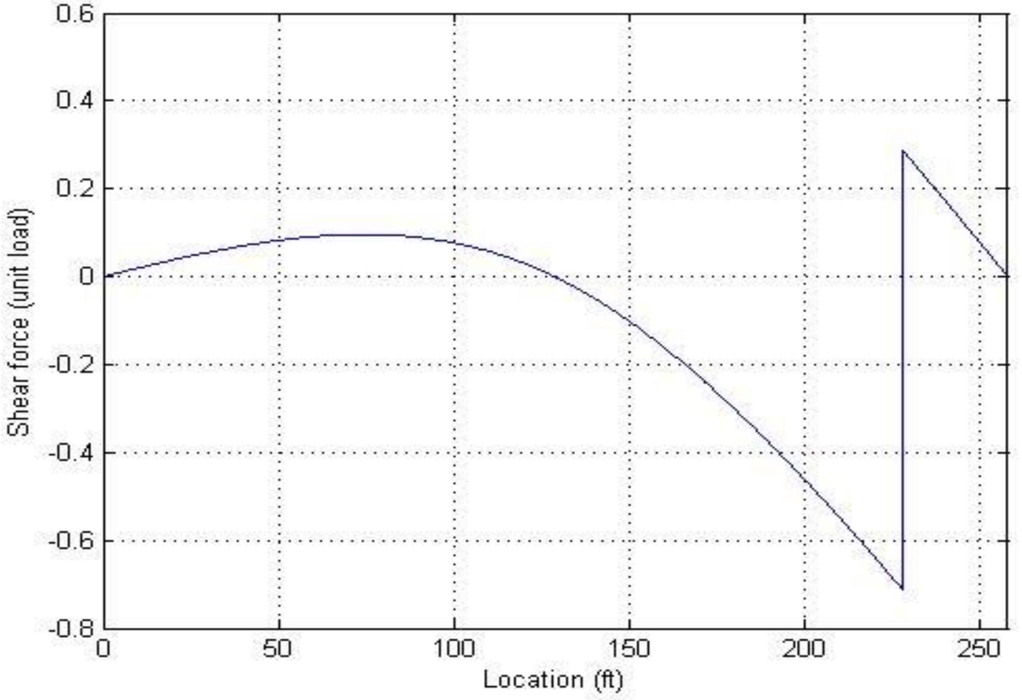
Bridge WIM Method Theory

- Consider a truck, with arbitrary number of axles, passing over a bridge system as shown below:



- As the truck passes over the bridge, each axle imposes a shear force to the bridge relative to its weight. The influence line for the shear force at any location can be constructed using analytical procedures.

Shear force influence line



Method

Shear strain recorded from Rosette is the sum of the products of axle loads and the shear influence line of the girder

$$\text{Shear Strain at Rosette}\ \gamma = \sum_{i=1}^{n} P_i\ f_{(x)}$$

$$\text{GVW} = \sum_{i=1}^{n} P_i$$

$f_{(x)}$ = Influence line for shear strain

(comes from Calibration Procedure)

Definition of Terms

$\mathbf{g}_A$ or $\mathbf{g}_B$: The Peak Shear Strain in a Rosette (set A or B)

$P_1 \ldots P_n$: Individual Axle Weights

GVW : Gross Vehicle Weight

$l_1 \ldots l_n$: Individual Axle Spacing

$f_{(x)}$: The Shear Strain Influence Line Function (from Calibration)

$f'_{(x)}$: The Shear Force Influence Line Function (from Mechanics)

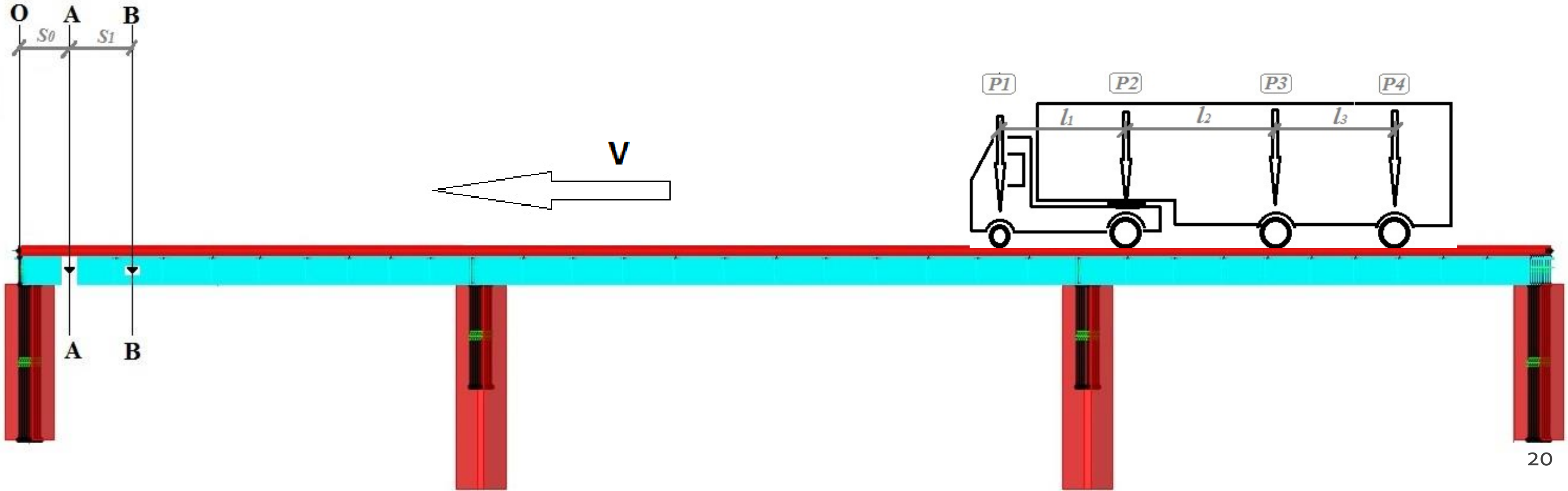
V: Shear Force

v: Velocity of the Vehicle

x : Distance from the Beginning of Span (point O) to the location of the axle.

S_0 : Distance from the Beginning of Span to Rosette set A

S_1 : Distance between Rosette set A and Rosette set B

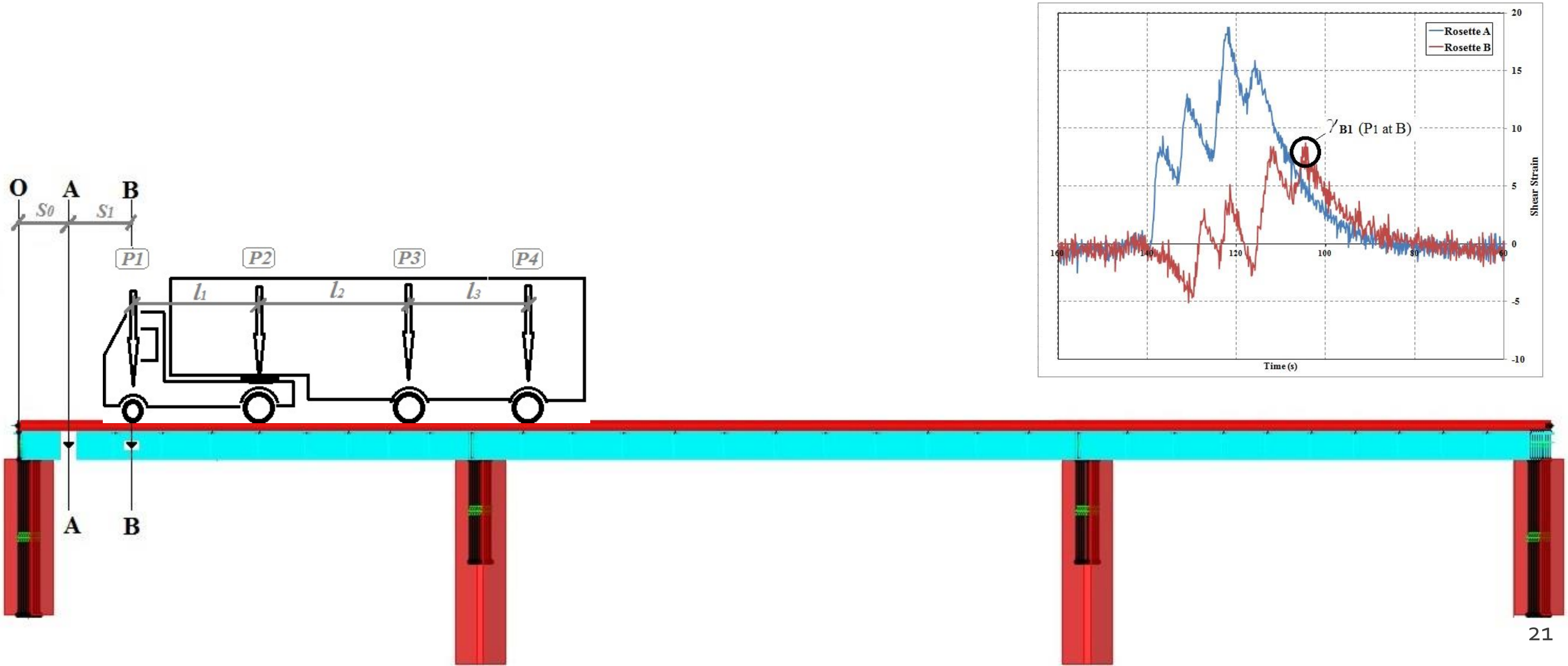


At t = t_1

$$\mathbf{g}_{B1} = P_1 * f_{(S0 + S1)} + P_2 * f_{(S0 + S1 + l1)} + P_3 * f_{(S0 + S1 + l1 + l2)} + P_4 * f_{(S0 + S1 + l1 + l2 + l3)}$$

Generally

$$\mathbf{g}_{B1} = P_1 * f_{(S0 + S1)} + P_2 * f_{(S0 + S1 + l1)} + \;.\;.\;.\;. + P_n * f_{(S0 + S1 + l1 + \ldots + l\,n\text{-}1)}$$



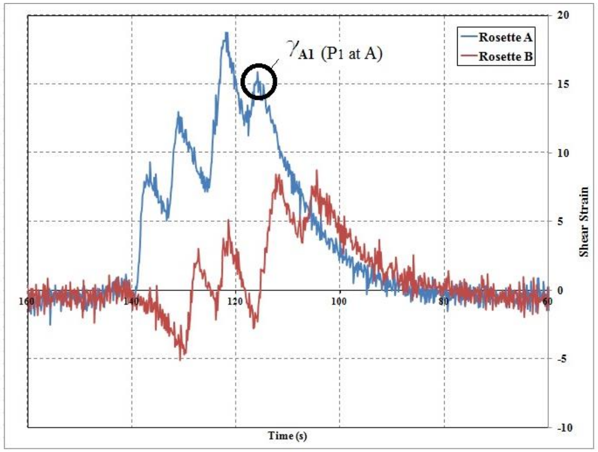
At $t = t_1'$

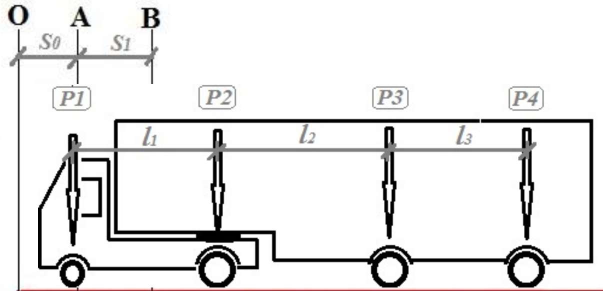
$$\mathbf{g}_{A1} = P_1 * f_{(S0)} + P_2 * f_{(S0 + l1)} + P_3 * f_{(S0 + l1 + l2)} + P_4 * f_{(S0 + l1 + l2 + l3)}$$

Generally

$$\mathbf{g}_{A1} = P_1 * f_{(S0)} + P_2 * f_{(S0 + l1)} + \;.\;.\;.\;. + P_n * f_{(S0 + l1 + \ldots + l\,n\text{-}1)}$$

$\Delta t_1 = t_1' - t_1 \qquad v = S_1 / \Delta t_1$



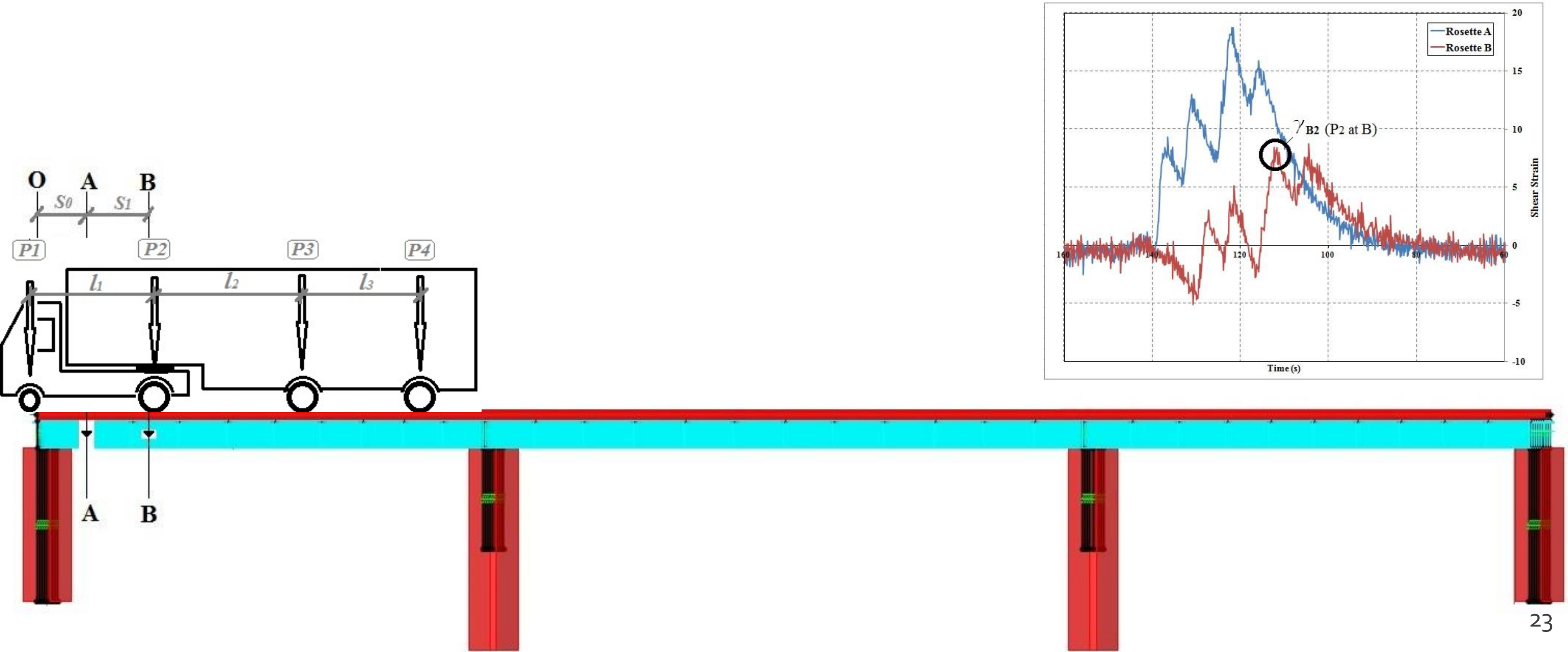


At $t = t_2$

$$\mathbf{g}_{B2} = P_2 * f_{(S0 + S1)} + P_3 * f_{(S0 + S1 + l2)} + P_4 * f_{(S0 + S1 + l2 + l3)}$$

Generally

$$\mathbf{g}_{B2} = P_2 * f_{(S0 + S1)} + \;. \;. \;. \;. + P_n * f_{(S0 + S1 + l2 + \ldots + l\,n\text{-}1)}$$

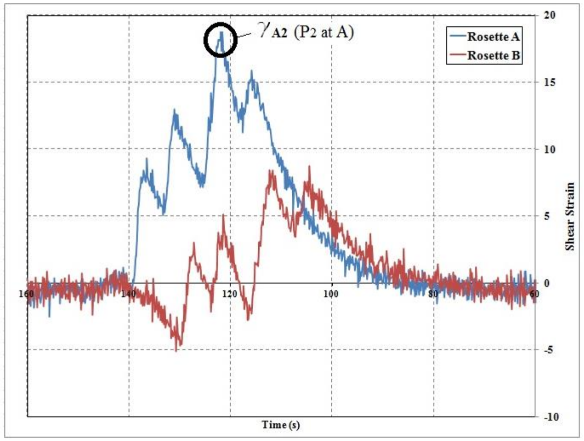


At $t = t_2'$

$$\mathbf{g}_{A2} = P_2 * f_{(So)} + P_3 * f_{(So + l2)} + P_4 * f_{(So + l2 + l3)}$$

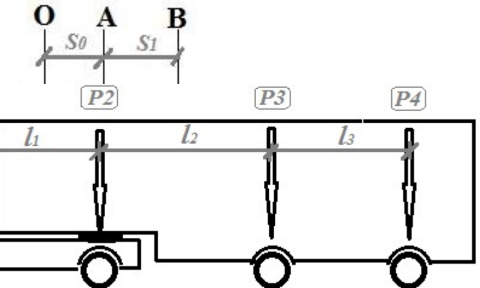
Generally

$$\mathbf{g}_{A2} = P_2 * f_{(So)} + \;.\;.\;.\;.\; + P_n * f_{(So + l2 + \dots + l\, n\text{-}1)}$$



$$\Delta t_2 = t_2' - t_2 \qquad v = S_1 / \Delta t_2$$

$$l_1 = v\,(\,t_2 - t_1\,) \text{ or } l_1 = v\,(\,t_2' - t_1'\,)$$

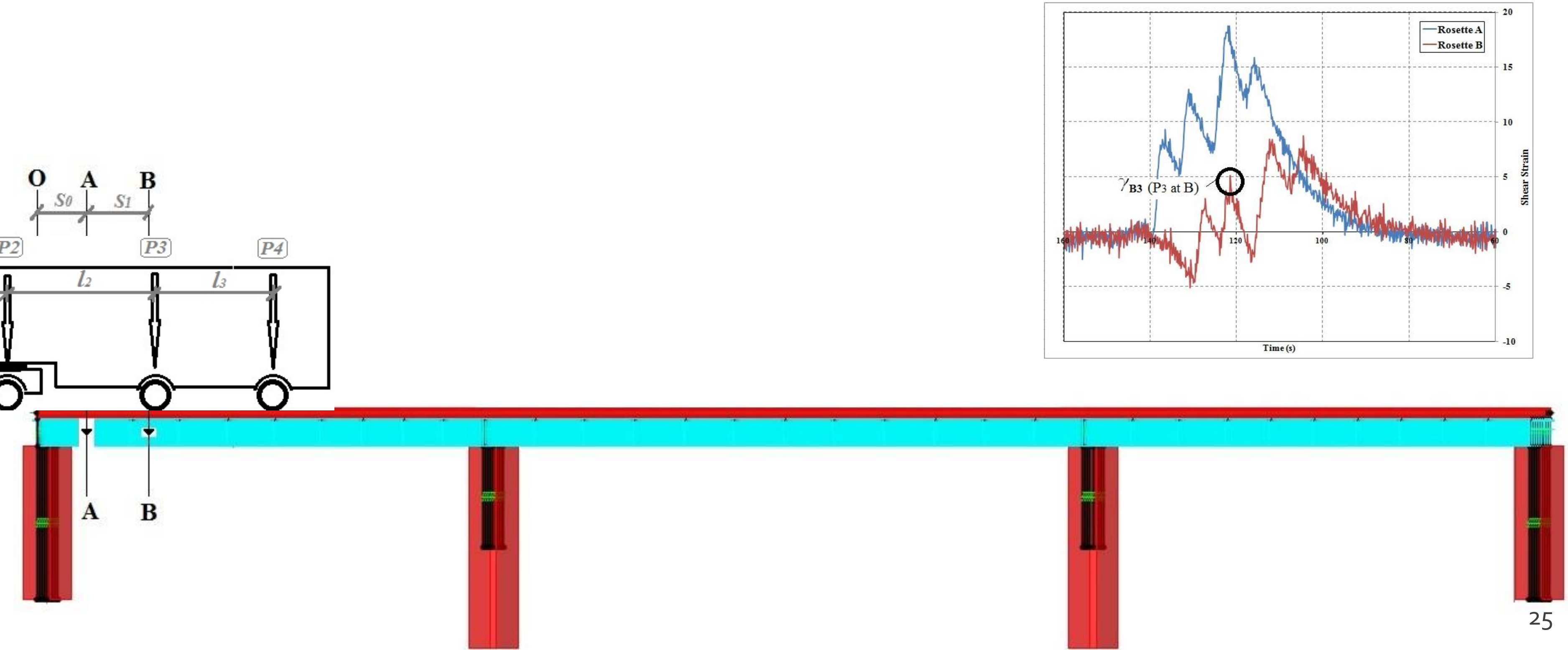


At $t = t_3$ or t_{n-1}

$$\mathbf{g}_{B3} = P_3 * f_{(S_0 + S_1)} + P_4 * f_{(S_0 + S_1 + l_3)}$$

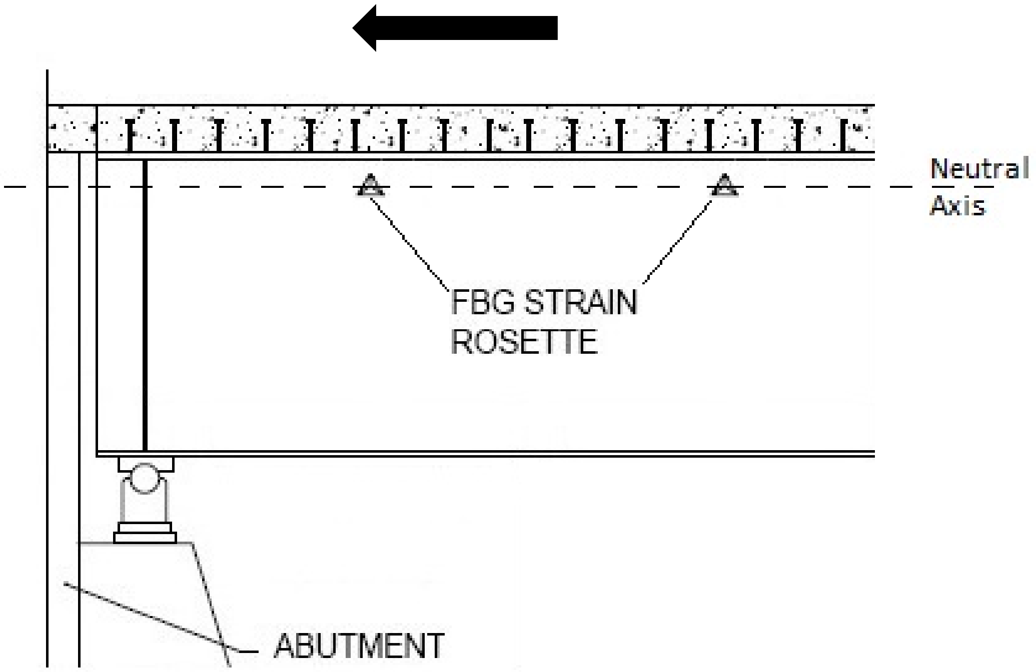
Generally

$$\mathbf{g}_{B3} = P_{n-1} * f_{(S_0 + S_1)} + \ . \ . \ . \ . + P_n * f_{(S_0 + S_1 + l_{n-1})}$$



for the calculation of vehicle speed and is redundant for the first rosette.

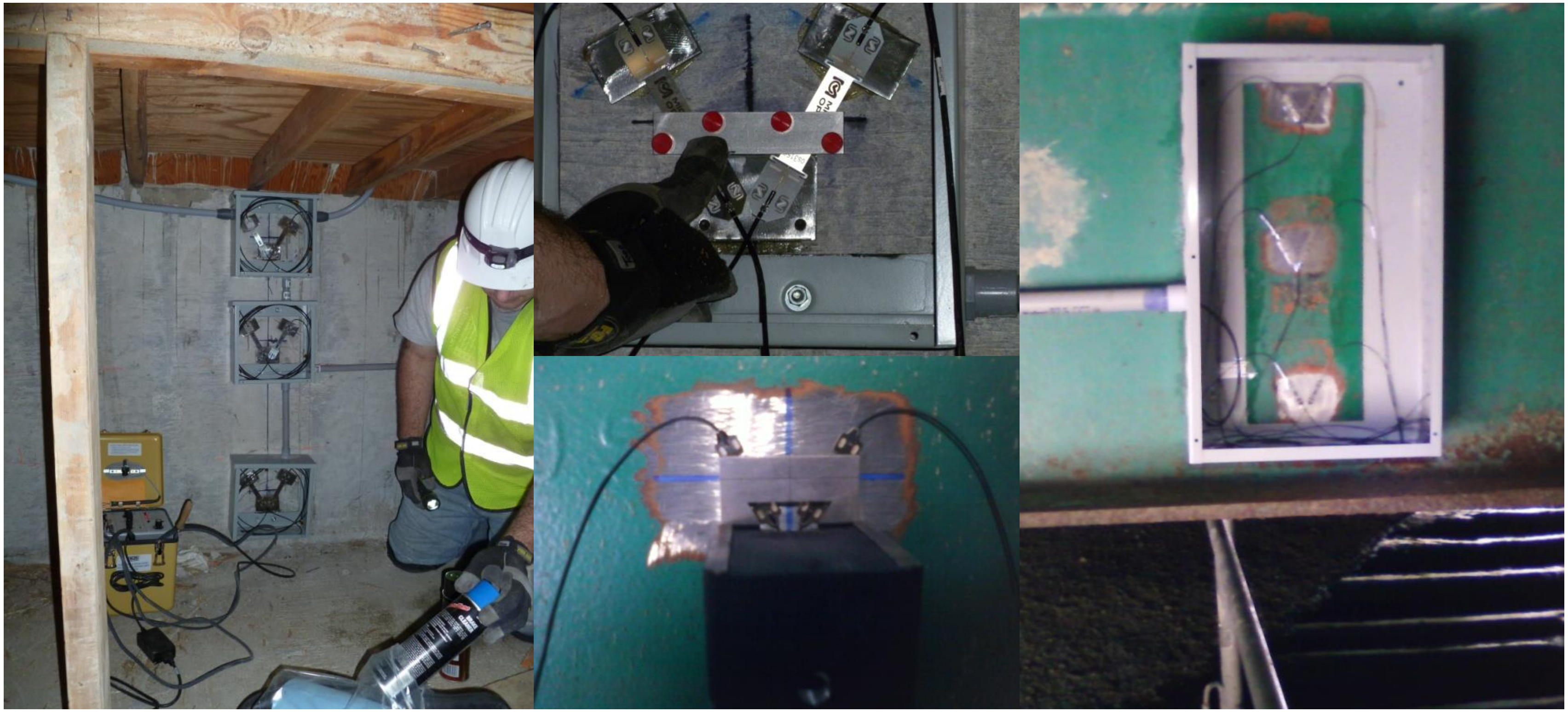
Direction of Traffic



System Control Enclosures

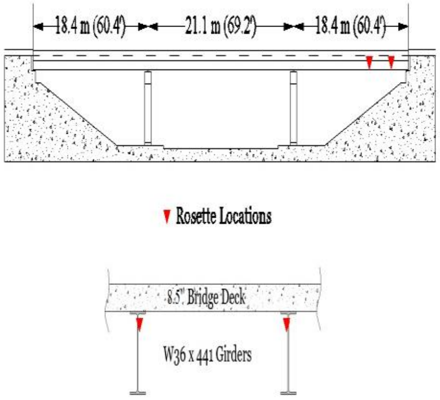
NEMA 4X rated outdoor enclosures for control system protection.

Rosette Sensors for Shear Strain Measurement



Rosette sensor installation with alignment guides to maintain proper 60° angle.

Calibration Vehicles



I-55 Chicago, IL
Composite Section
Span Lengths (60ft, 69ft, 60 ft)

Min Error= 0.6 ft
Max Error= 1.7 ft

Axle Weights Error

Min Error= Individual (1.8%), GVW (2.8%)
Max Error= = Individual (9.7%), GVW (5.2%)

Axle Spacing Error

		Actual Weight kN (lb)	Measured Axle Weight kN (lb)	Error (%)
Run #2	P1	87.1 (19580)	95.5 (21469)	+9.7
	P2	165.0 (37100)	149.7 (33654)	-9.3
	GVW	252.1 (56680)	245.2 (55123)	-2.8
Run #3	P1	87.1 (19580)	84.3 (18953)	-3.2
	P2	165.0 (37100)	179.6 (40365)	8.8
	GVW	252.1 (56680)	265.2 (59627)	5.2
Run	P1	87.1 (19580)	93.3 (20970)	7.1
	P2	165.0	168.0	

		Actual Axle Spacing m (ft)	Measured Axle Spacing m (ft)	Difference m (ft)
Run#2	L1	6.2 (20.5)	6.03 (19.93)	0.17 (0.57)
Run#3	L1	6.2 (20.5)	6.03 (19.93)	0.17 (0.57)
Run#6	L1	6.2 (20.5)	5.69 (18.80)	0.51 (1.7)
Run#7	L1	6.2 (20.5)	6.01 (19.86)	0.19 (0.64)

Channel Select

2

Axle Spacing (feet)

Axle Weights (lbs)

Date	Time	Lane	Class	Speed(mph)	Space 1	Space 2	Space 3	Space 4	Space 5	Group 1	Group 2	Group 3	Group 4	Group 5	GVW
6/19/2015	11:55:16 AM	4	6	57.4	21.0	4.8	0.0	0.0	0.0	11149	21548	0	0	0	32697
6/19/2015	11:54:59 AM	3	9	42.5	16.4	4.4	34.8	3.9	0.0	6991	29685	15068	0	0	51744

Brooklyn Bridge

- Location : NYC (Manhattan–Brooklyn)
- Design: Suspension/Cable-stay Hybrid
- Span Length: 486.3 m
- Total Length: 1825 m
- Width: 26 m
- Clearance below: 41 m at mid-span
- AADT: 145,000

Impetus for Monitoring

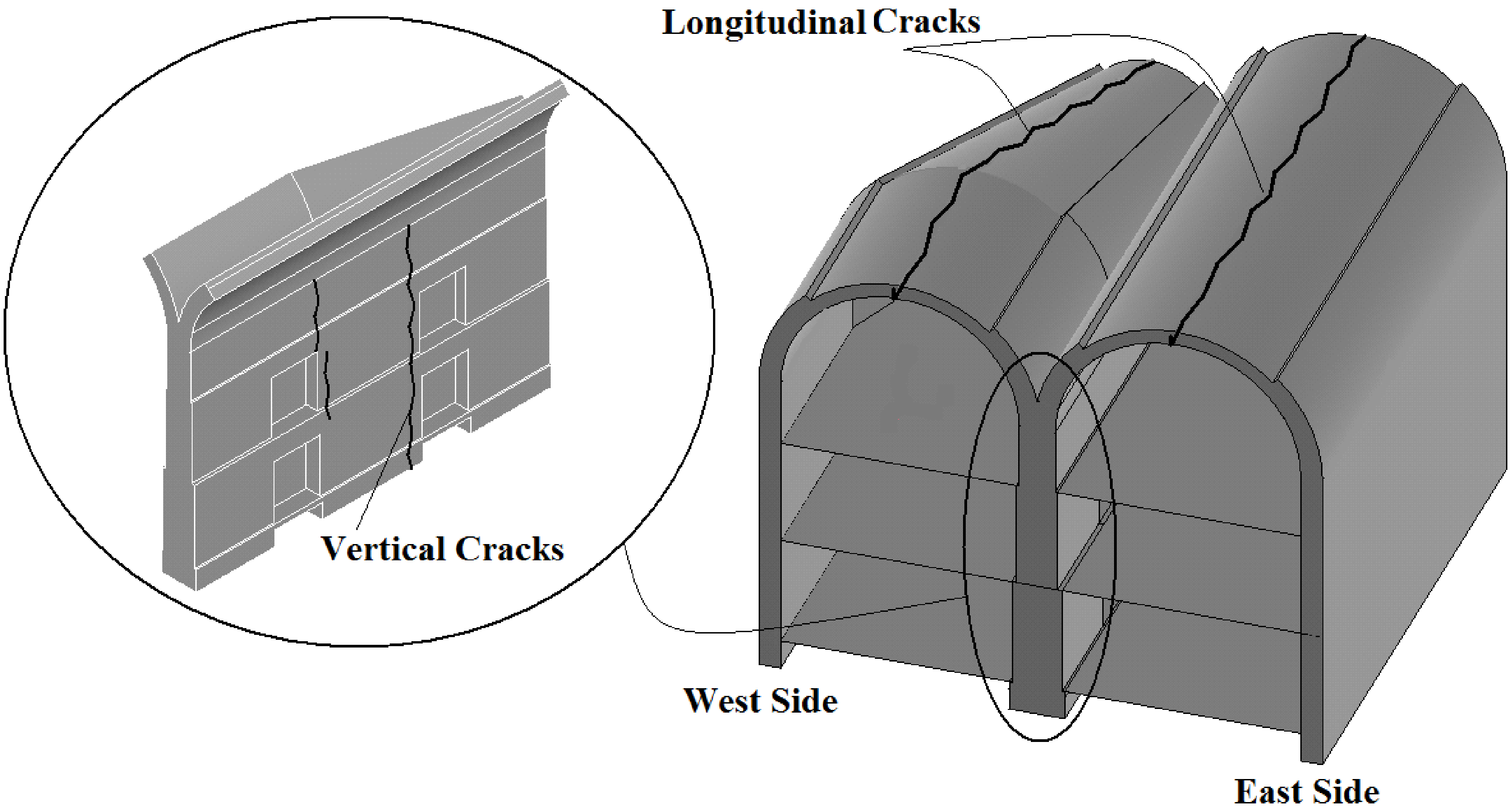
- Approach structure - a series of brick masonry vaults.
- Double-span vaults are seated on the walls of two three-story masonry buildings.
- Damage: crown cracks developed along the entire length of double spans
  - Is the structure safe?
  - How did these cracks develop?

BROOKLYN BRIDGE REMOTE MONITORING

MASONRY ARCH APPROACH SPANS

Crown Crack

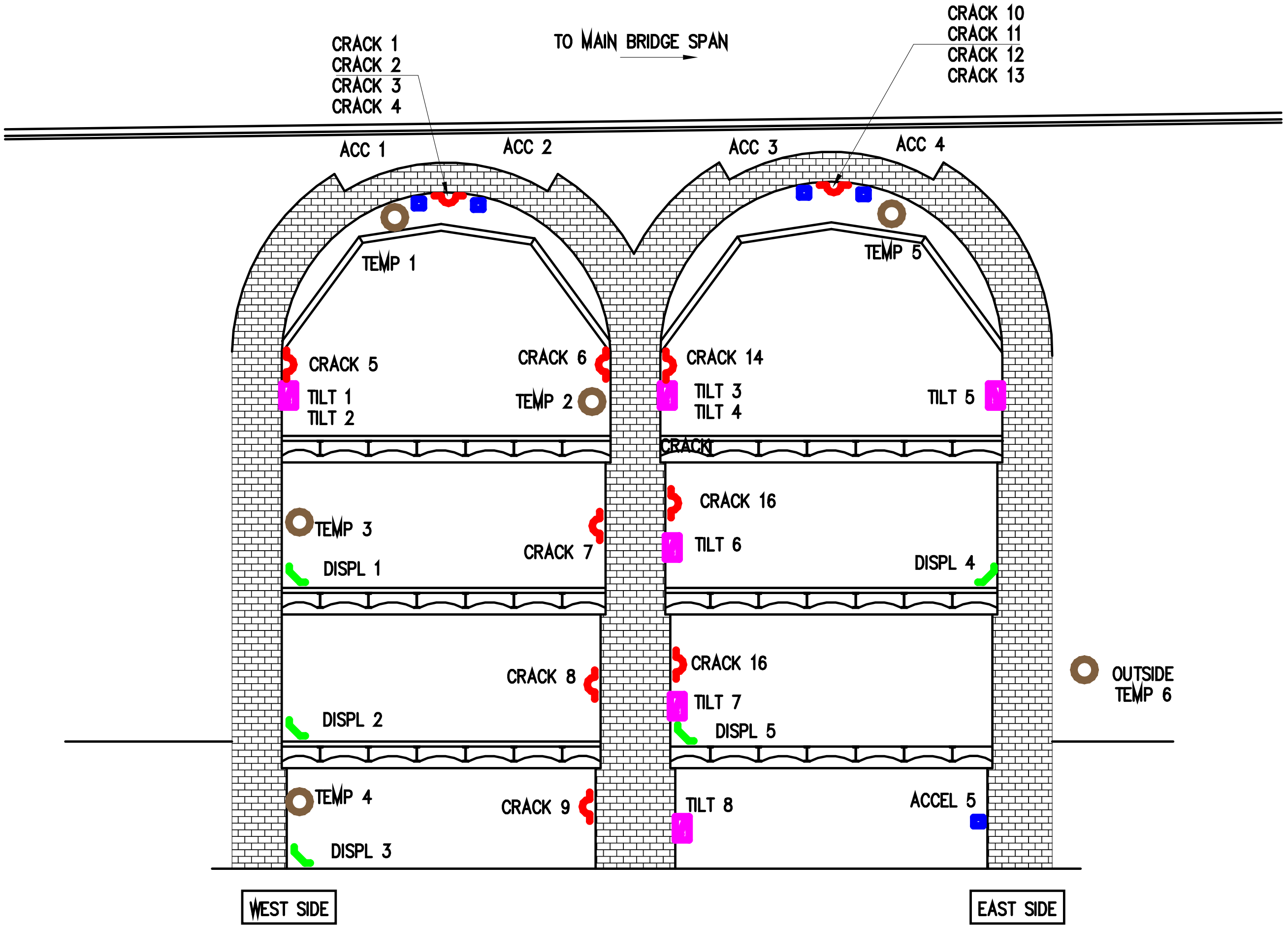
Visual Inspection



Considerations for Monitoring Strategy – Optimal Sensor locations

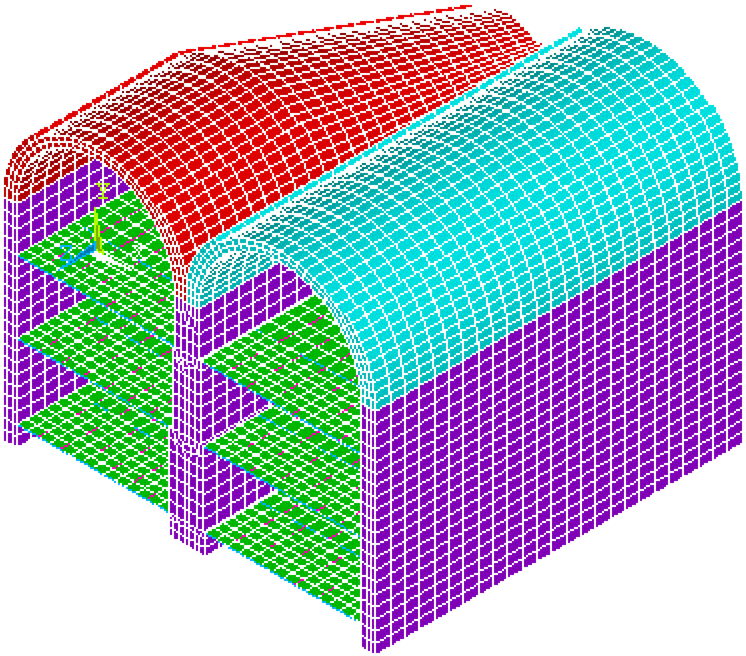
- Bedrock is very near the ground surface in Manhattan area. The fact that the east wall was not cracked was attributed to confinement by the anchorage structure.
- The west wall was partially confined by the steel truss supports but likely to move by excessive loads or thermal gradients.

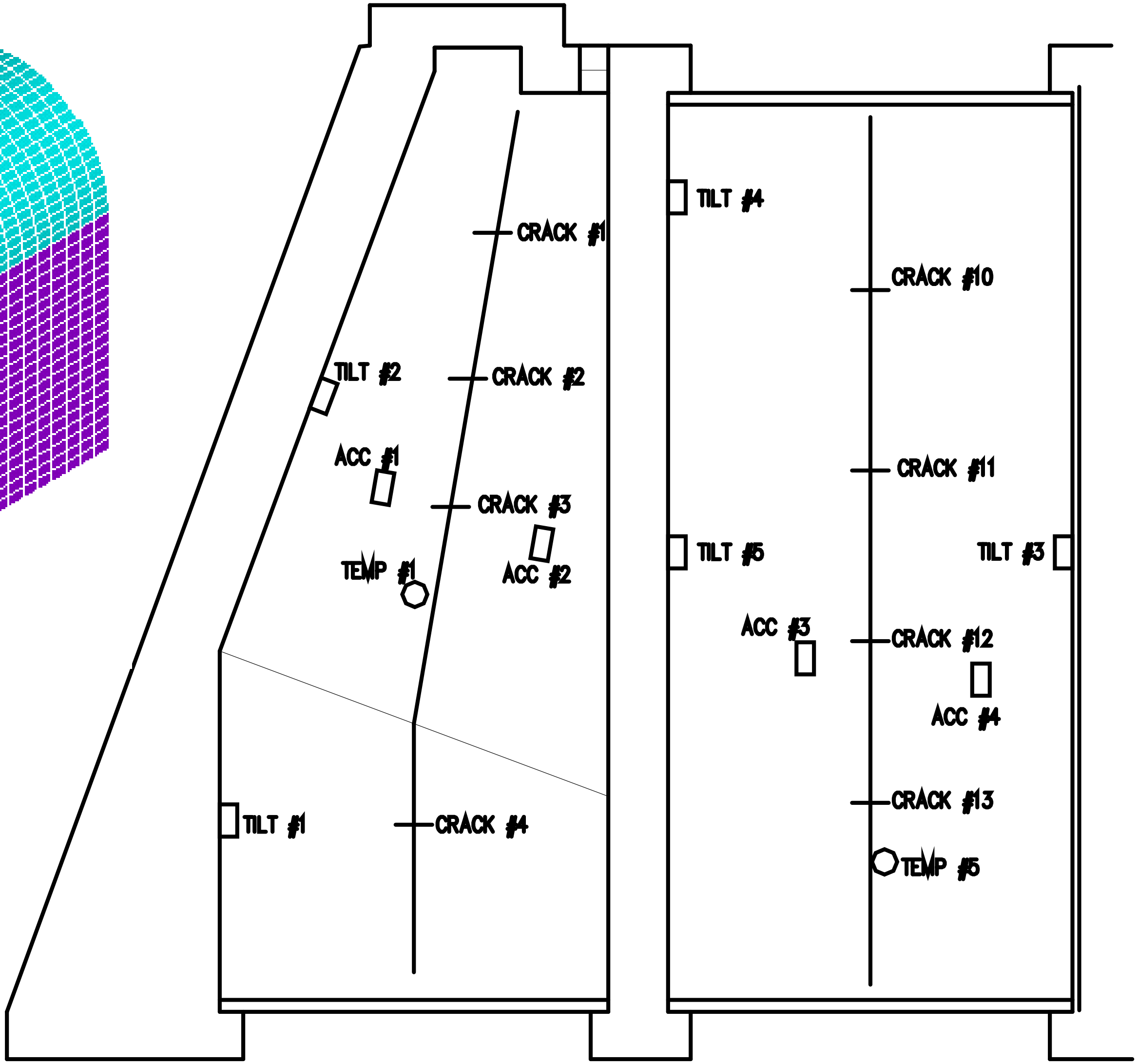
Sensor Types and Locations



BROOKLYN BRIDGE REMOTE MONITORING

SENSOR LAYOUT





Typical Fiber Optic Based Crack and Tiltmeter

Typical FBG crack sensor (vault crown

Typical FBG Tilt meter (wall supporting the two vaults

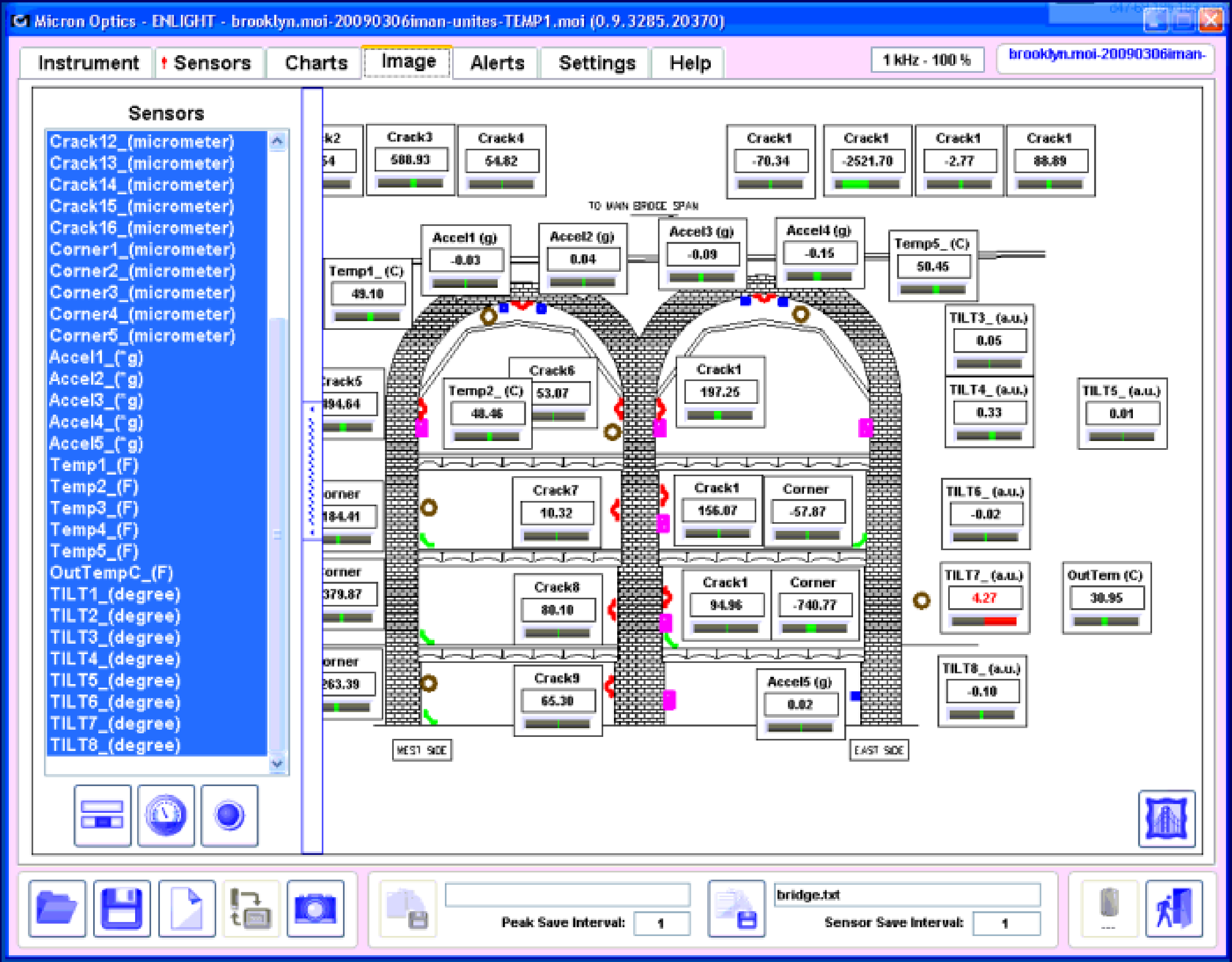
BROOKLYN BRIDGE REMOTE MONITORING

SMART SENSORS AND NDT LABORATORY

BROOKLYN BRIDGE REMOTE MONITORING

REMOTE MONITORING

UIC
UNIVERSITY
OF ILLINOIS
AT CHICAGO



Sensors

- Crack12_(micrometer)
- Crack13_(micrometer)
- Crack14_(micrometer)
- Crack15_(micrometer)
- Crack16_(micrometer)
- Corner1_(micrometer)
- Corner2_(micrometer)
- Corner3_(micrometer)
- Corner4_(micrometer)
- Corner5_(micrometer)
- Accel1_(g)
- Accel2_(g)
- Accel3_(g)
- Accel4_(g)
- Accel5_(g)
- Temp1_(F)
- Temp2_(F)
- Temp3_(F)
- Temp4_(F)
- Temp5_(F)
- OutTempC_(F)
- TILT1_(degree)
- TILT2_(degree)
- TILT3_(degree)
- TILT4_(degree)
- TILT5_(degree)
- TILT6_(degree)
- TILT7_(degree)
- TILT8_(degree)

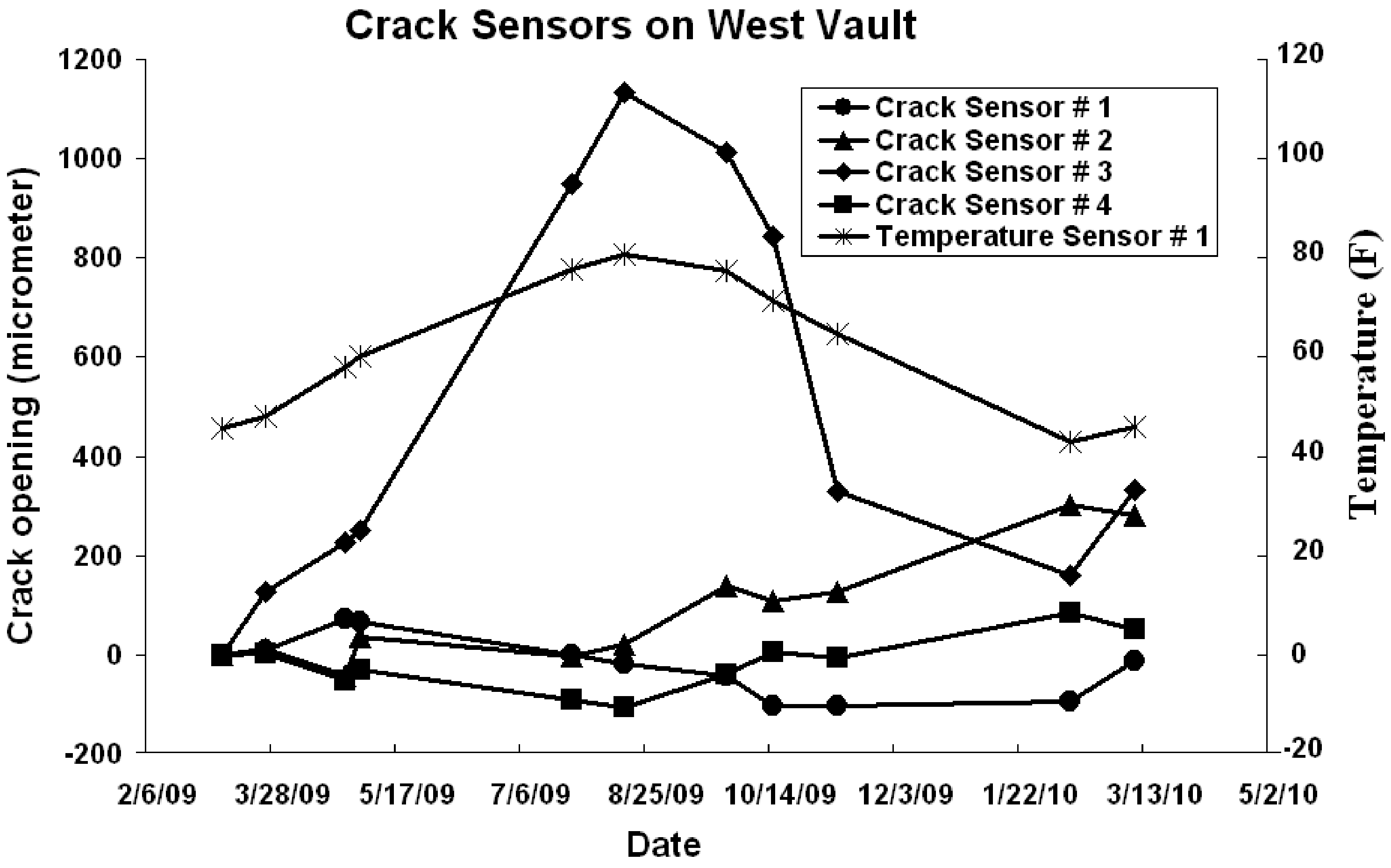
k2: 54
Crack3: 588.93
Crack4: 54.82
Crack1: -70.34
Crack1: -2521.70
Crack1: -2.77
Crack1: 88.89
Accel1 (g): -0.03
Accel2 (g): 0.04
Accel3 (g): -0.09
Accel4 (g): -0.15
Temp5_ (C): 50.45
Temp1_ (C): 49.10
TILT3_ (a.u.): 0.05
rack5: 494.64
Crack6: 53.07
Temp2_ (C): 48.46
Crack1: 197.25
TILT4_ (a.u.): 0.33
TILT5_ (a.u.): 0.01
orner: 184.41
Crack7: 10.32
Crack1: 156.07
Corner: -57.87
TILT6_ (a.u.): -0.02
orner: 379.87
Crack8: 80.10
Crack1: 94.96
Corner: -740.77
TILT7_ (a.u.): 4.27
OutTem (C): 30.95
orner: 263.39
Crack9: 65.30
Accel5 (g): 0.02
TILT8_ (a.u.): -0.10

Peak Save Interval: 1

bridge.txt

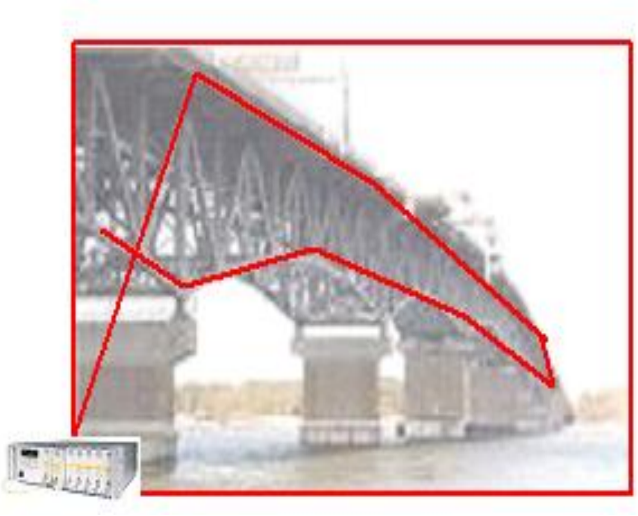
Sensor Save Interval: 1

Year long crack sensors and temperature sensor data (west vault)



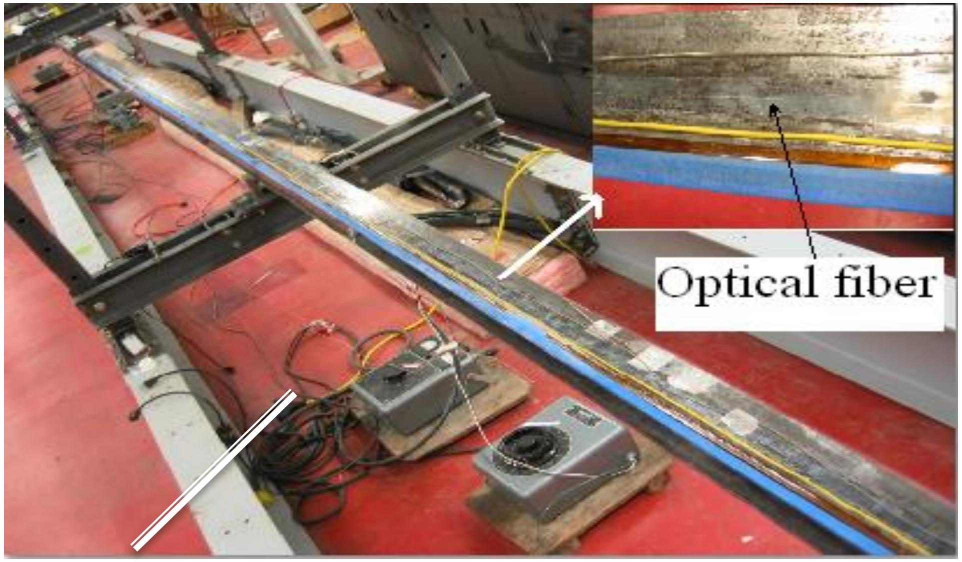
Distributed Monitoring – Capability for monitoring over 30 kilometers of infrastructure with a single fiber

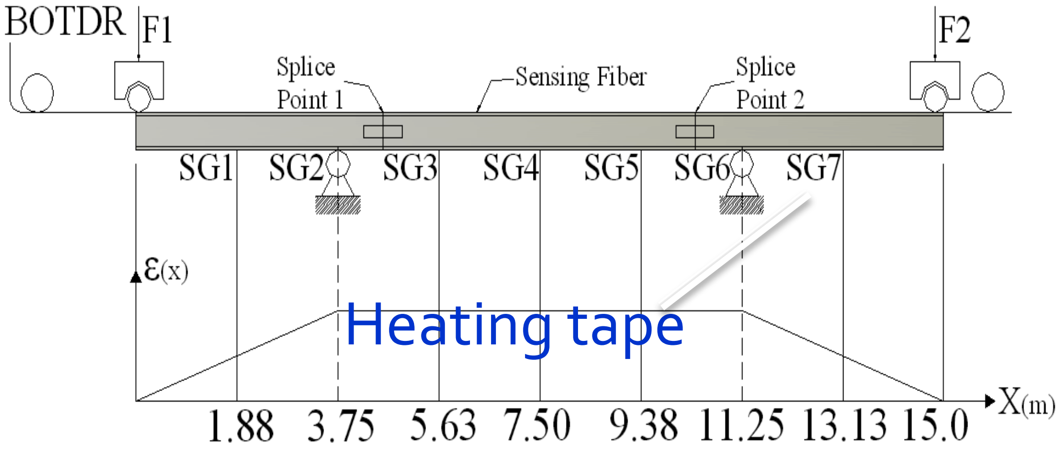
Multiplexed Single Point Sensing



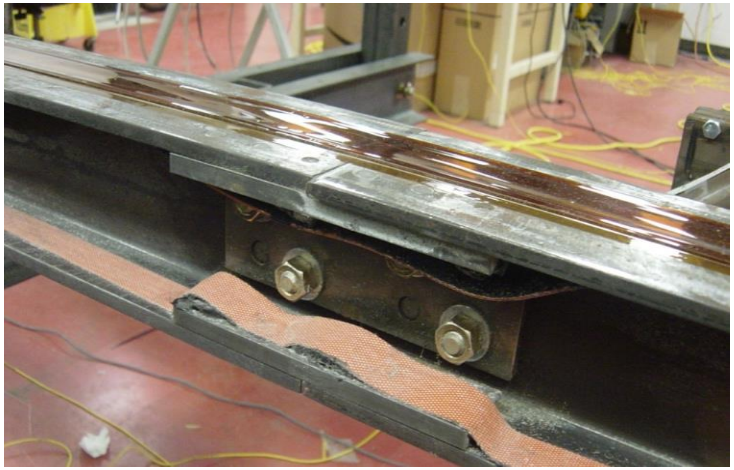
Distributed Sensing

Laboratory Evaluation

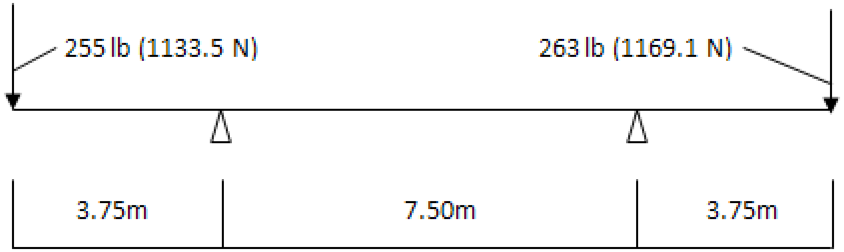




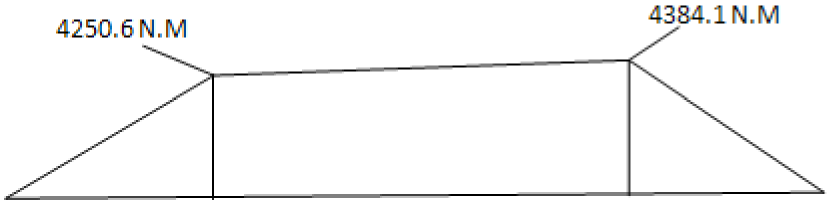
Heating tape



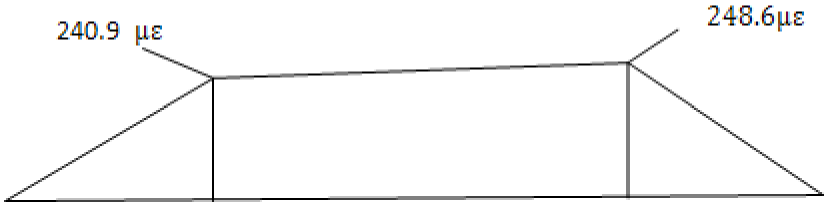
Load Tests – Room Temperature Test Results



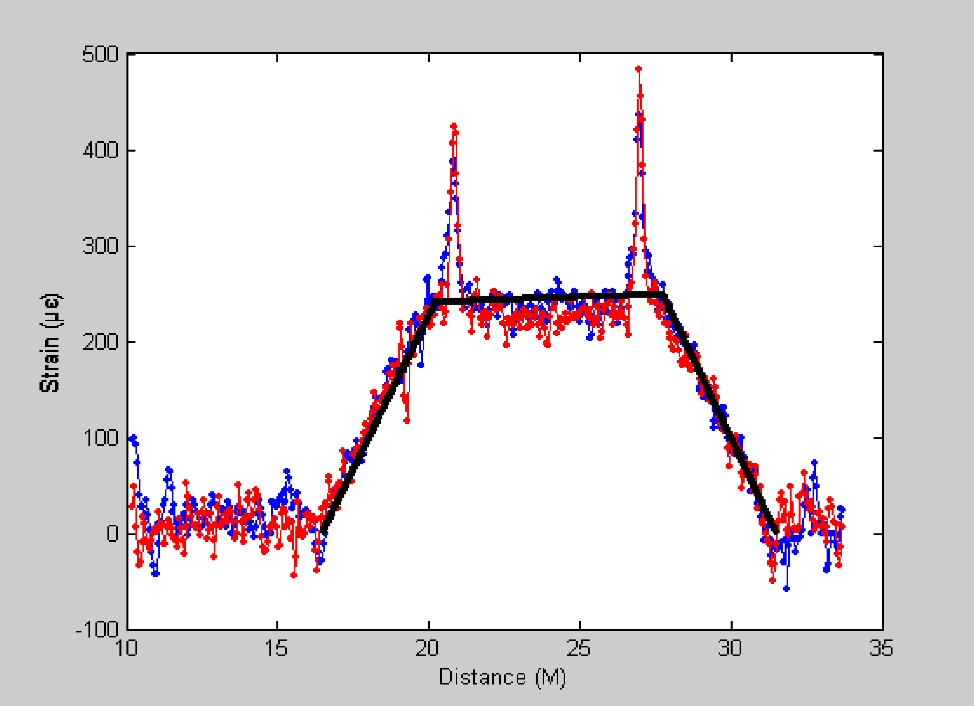
the loading plot



the moment plot



the axial strain distribution along the beam



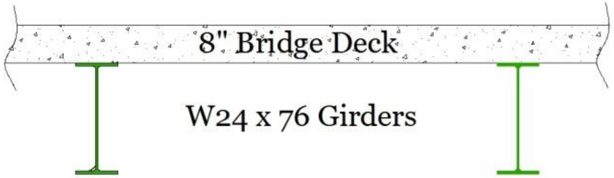
SMF28 – Blue

PM fiber – Red

<u>20cm spatial resolution;</u>

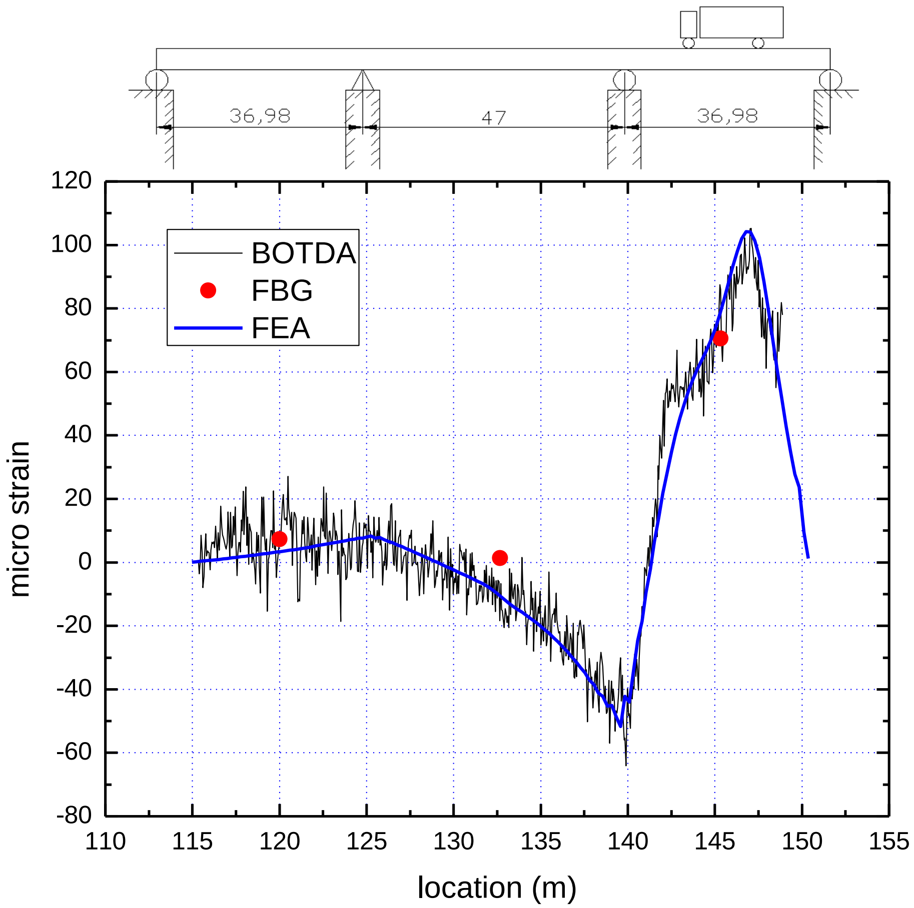
Load Testing of Salt Creek Bridge

Rt-83 Elmhurst, IL
Composite Section
Span Lengths (37ft, 47ft, 37 ft)

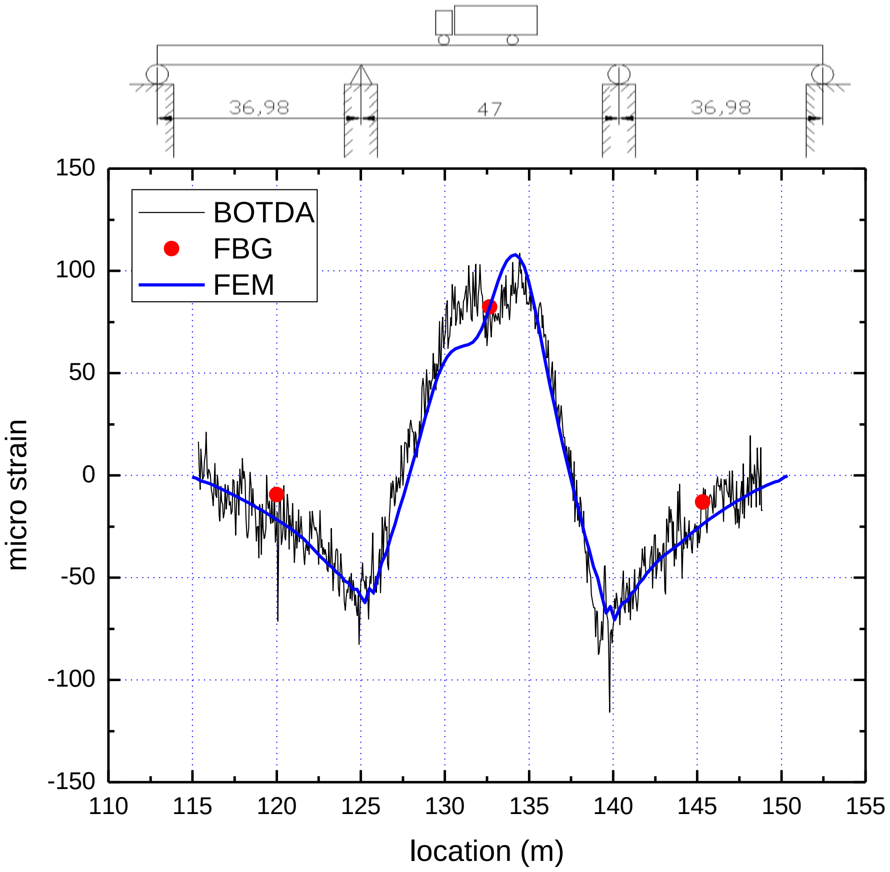


Field Tests – Distributed Sensor - Salt Creek Bridge

Load Case 1


36,98
47
36,98
BOTDA
FBG
FEA
micro strain
location (m)
120
100
80
60
40
20
0
-20
-40
-60
-80
110
115
120
125
130
135
140
145
150
155

Load case 2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47
36,98
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-150
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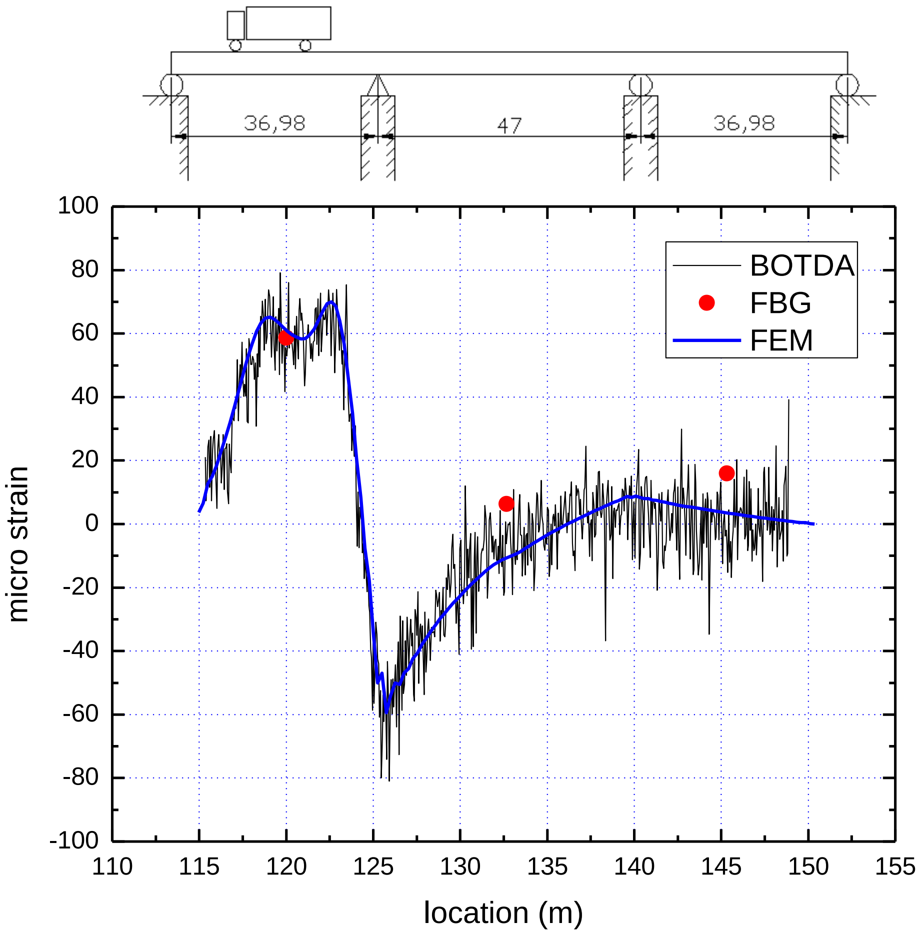
115
120
125
130
135
140
145
150
155
micro strain
location (m)
BOTDA
FBG
FEM

Load case 3:


36,98
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36,98
micro strain
location (m)
100
80
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20
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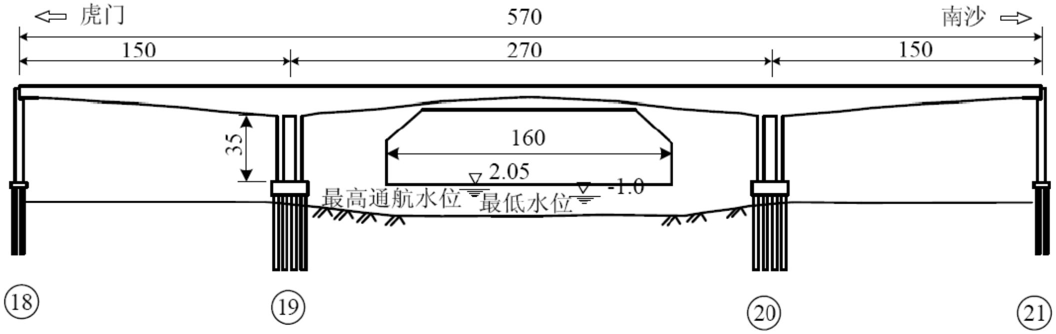
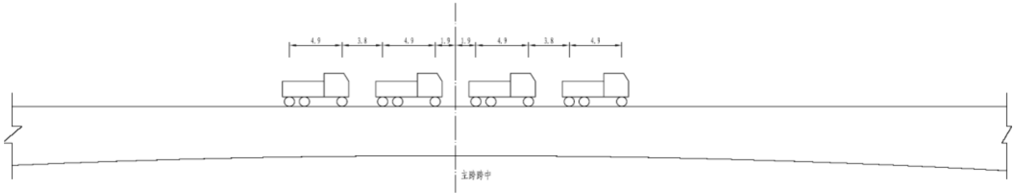
-20
-40
-60
-80
-100
110
115
120
125
130
135
140
145
150
155
BOTDA
FBG
FEM

Load Testing of Sub-Navigational Channel Crossing of the Humen Bridge in China

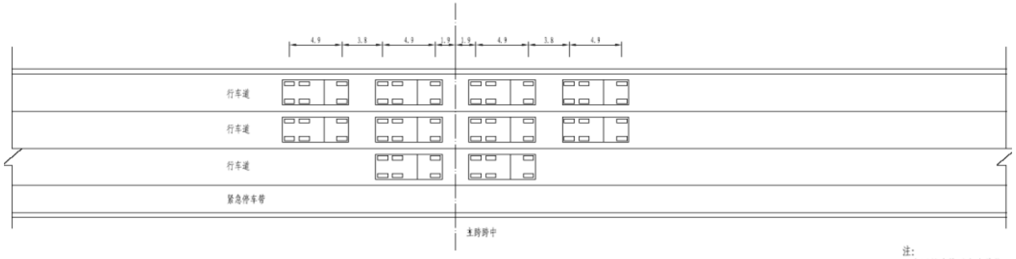
Sub-navigation channel bridge
(150m+270+150m)



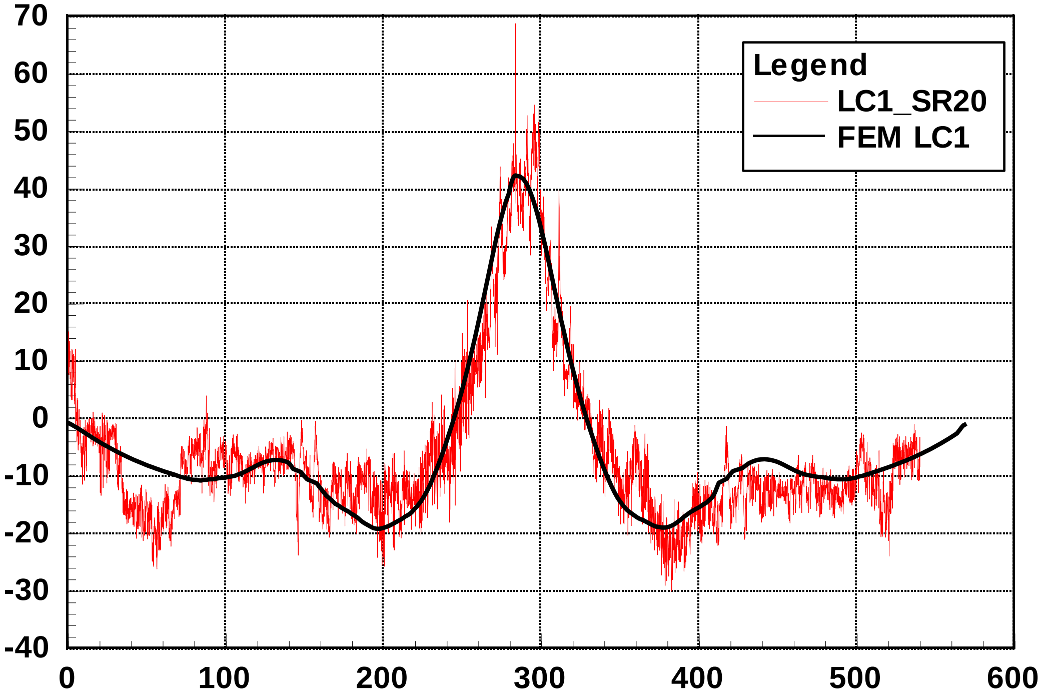
立面



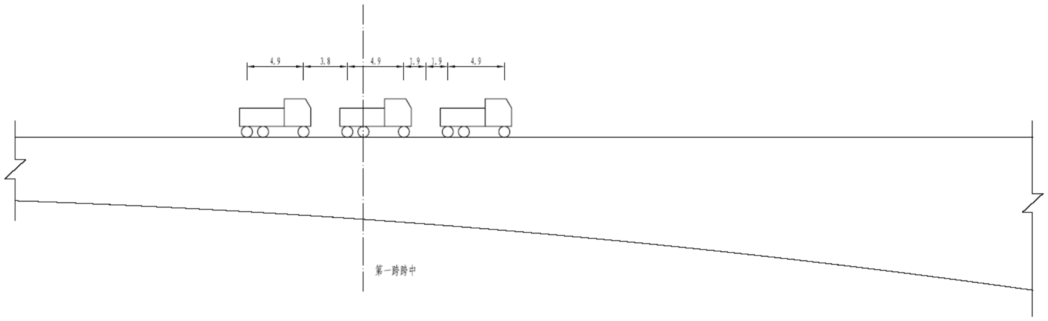
平面



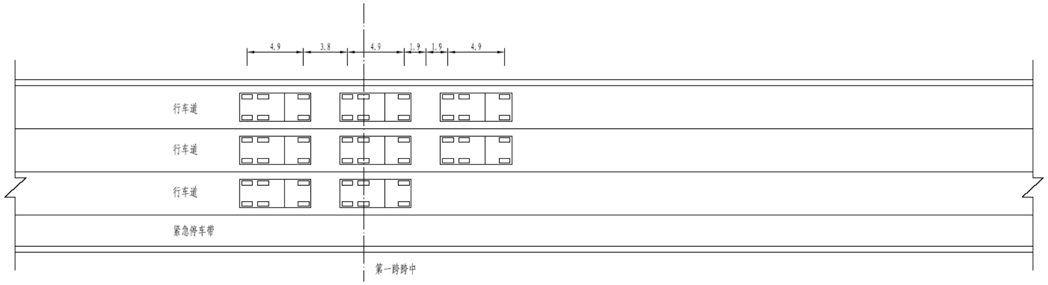
注：
1.本图尺寸均以米为单位



立面



平面



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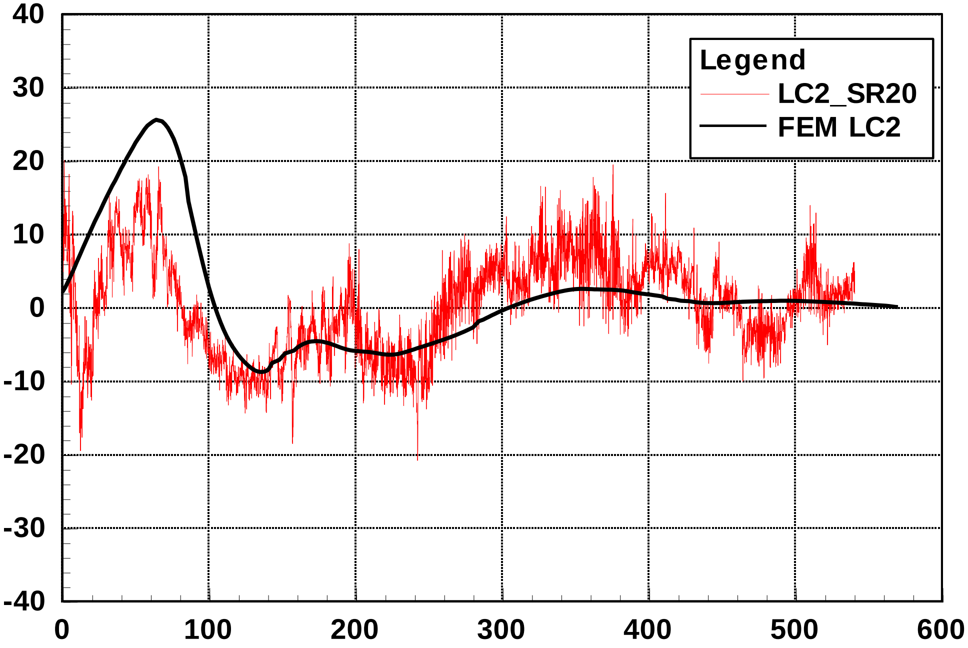
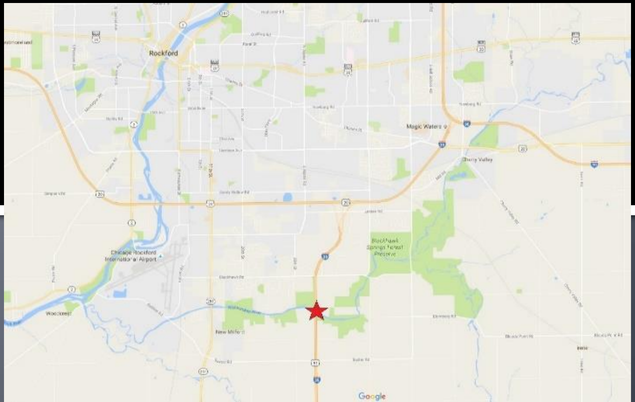
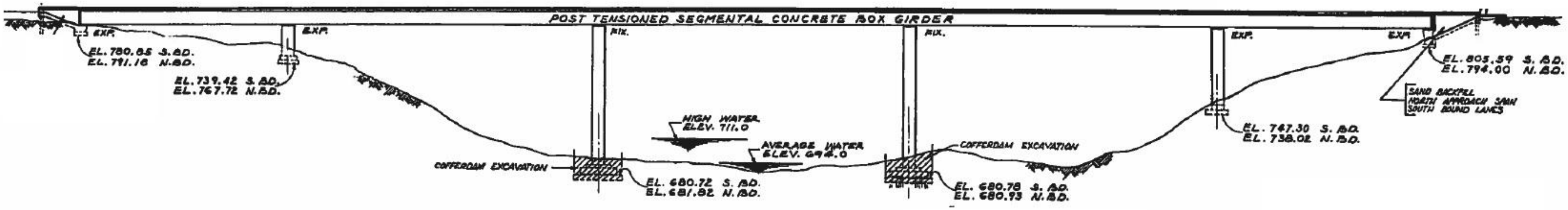


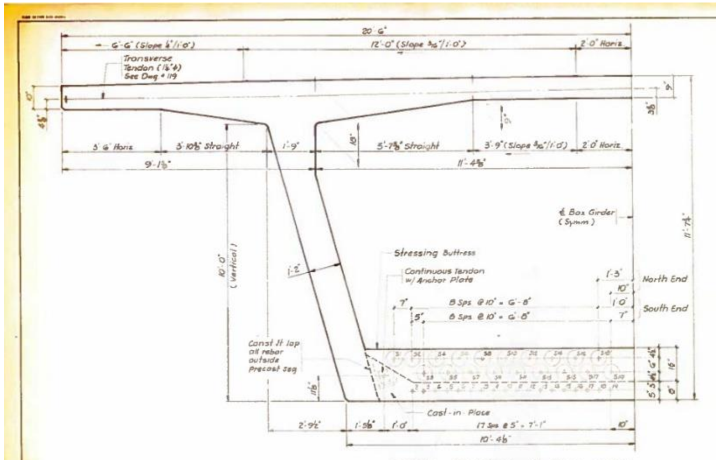
KISHWAUKEE RIVER BRIDGE



ELEVATION AND CROSS-SECTION



ELEVATION



CROSS SECTION AT MID SPAN

SOUTHBOUND BRIDGE

BRIDGE INFORMATION

- Constructed in 1979
- 5 Span Continuous Post-Tensioned Concrete Box Girder Construction. Made from 7ft (2.1m) Precast segments.
- Span Lengths of 170ft, 250ft, 250ft, 250ft, 170ft for a 1090ft (332m) Total Span Length.
- 42ft (12.8m) Wide Supporting 2 Lanes of Traffic.
- In 2008, Post Tensioning Cables were added within the box girder to increase the bridge stiffness.

SENSOR INSTALLATION

- A coated fiber optic sensor was installed along the upper surface of the bridge cell to monitor the strain profile of the entire bridge in a distributed manner. In essence this provides the strain profile along the entire length of the bridge at every single location.

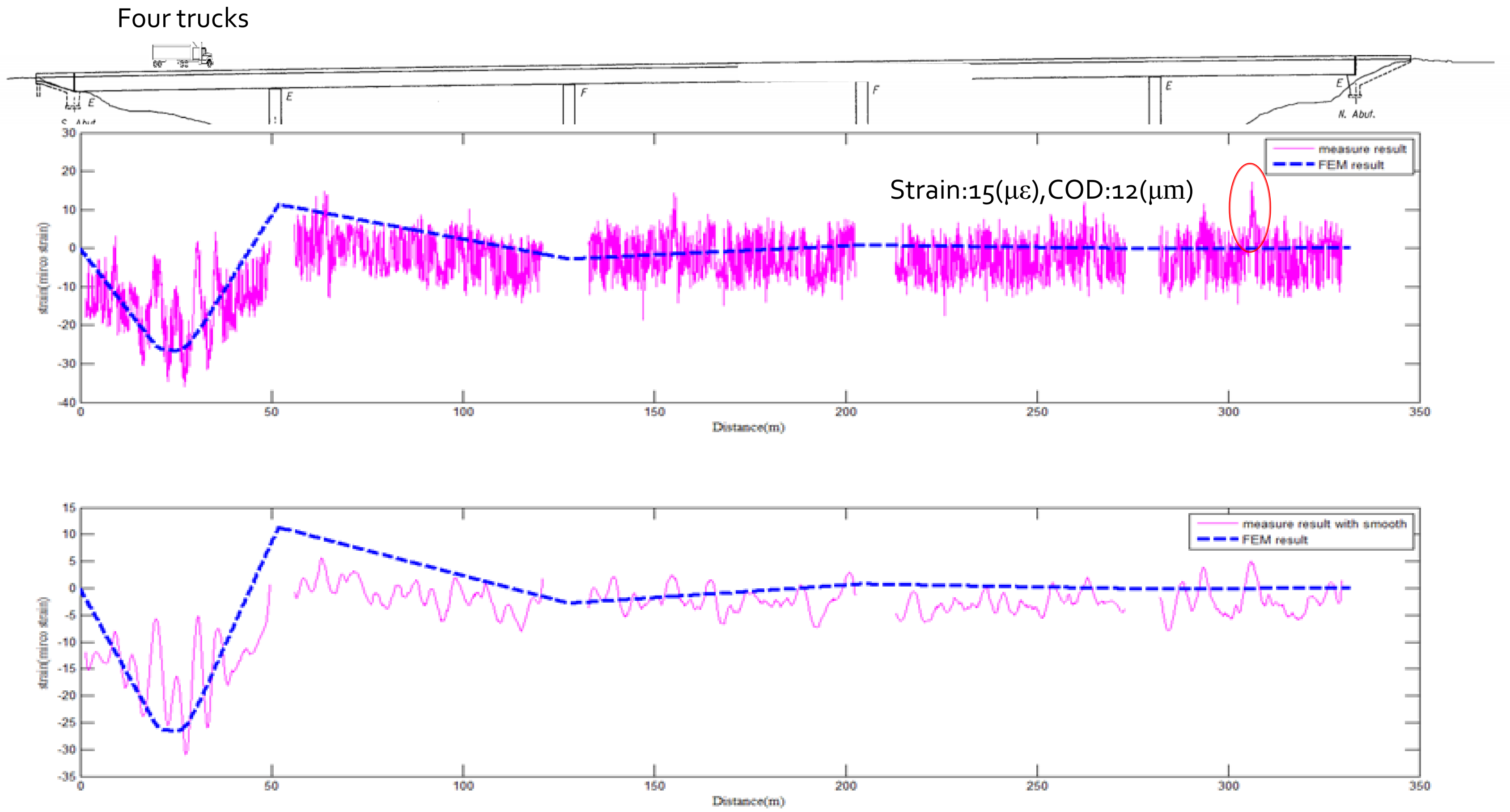
BRIDGE LOADING

- **Four trucks were used for testing the Bridge in October of 2016.**

BRIDGE LOADING

- Each truck (as reported)
  - GVW = 46000 (184000 for four trucks)
  - First axle load ≈ 8000 lb (32000 total for 4 trucks)
  - Second axle load ≈ 20000 lb (80000 pounds for 4 trucks)
  - Third axle load ≈ 18000 lb (64000 for four trucks)

Distributed Strain and Detection of Cracks

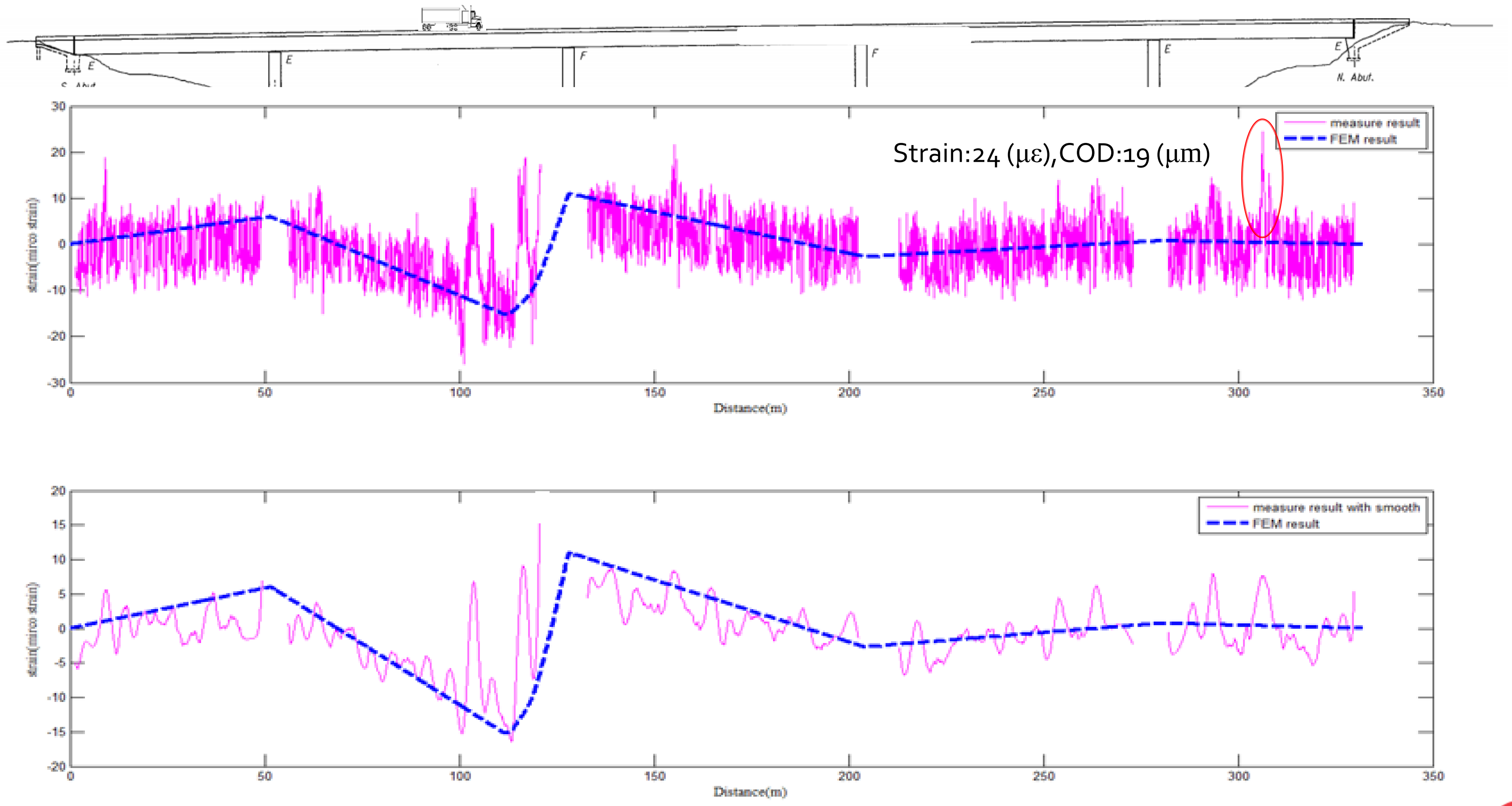


Four trucks

Strain:15(με),COD:12(μm)

Distributed Monitoring

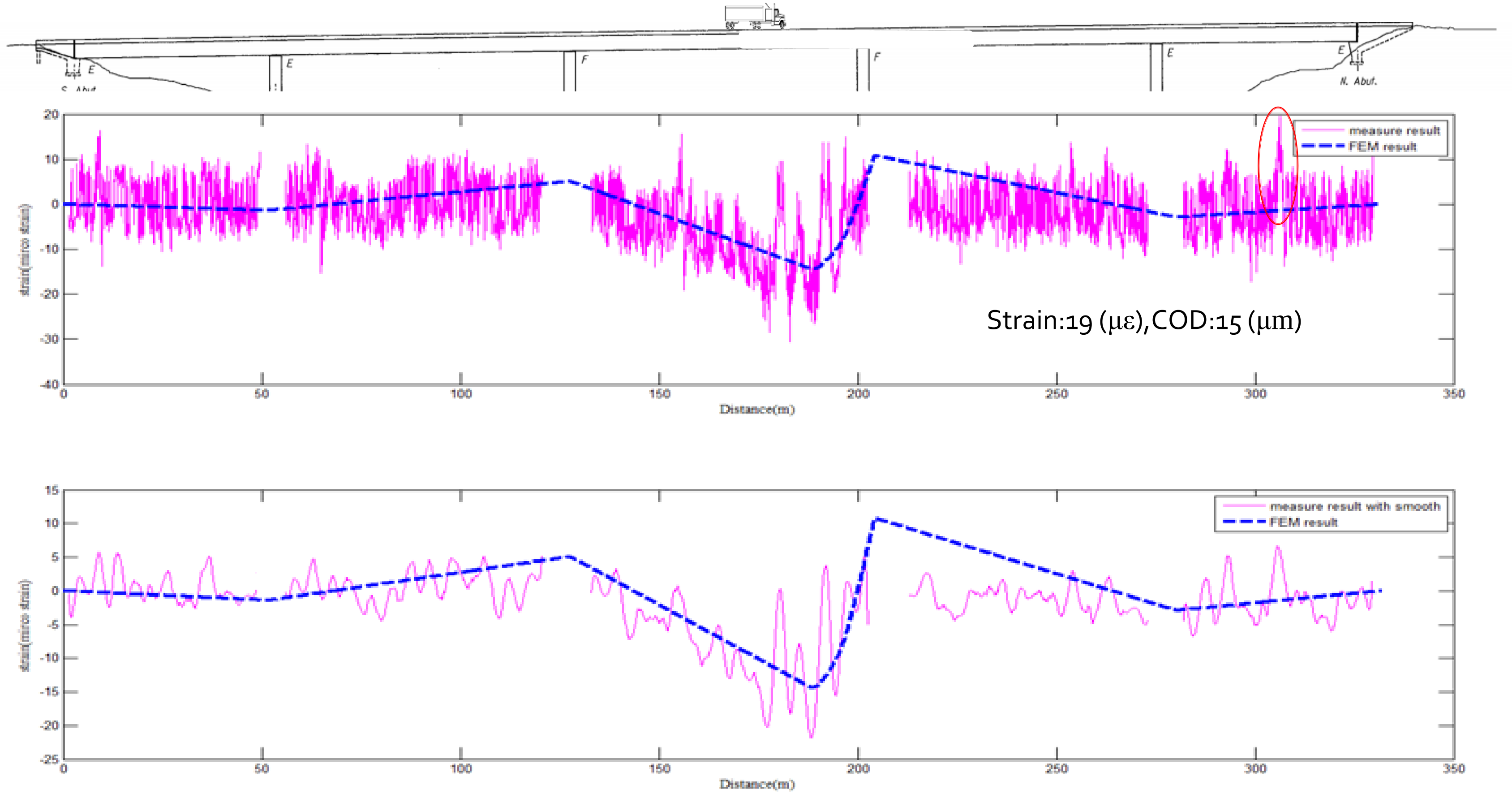
Four trucks



Strain:24 (με),COD:19 (μm)

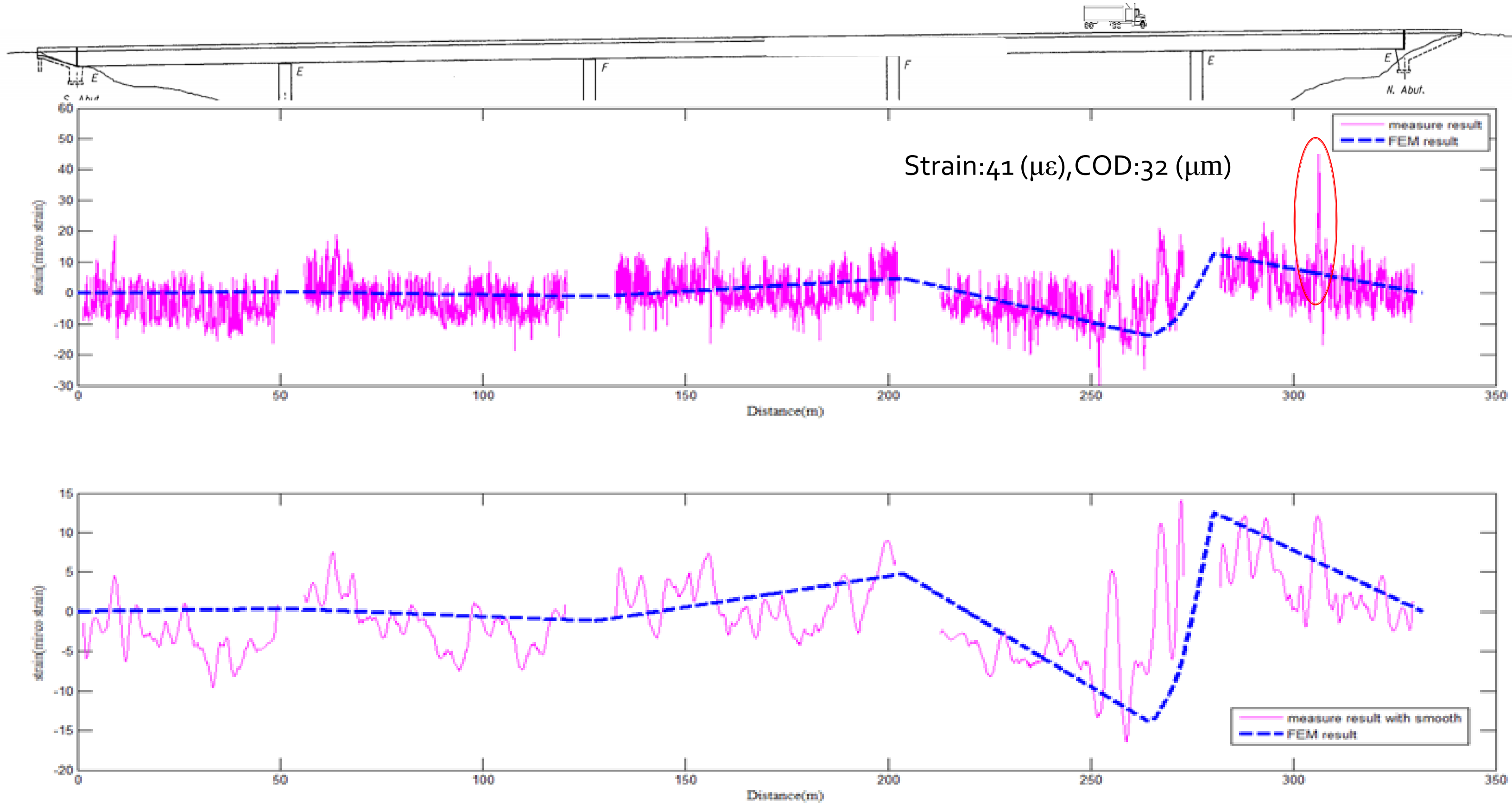
Distributed Monitoring

Four trucks



Strain:19 (με),COD:15 (μm)

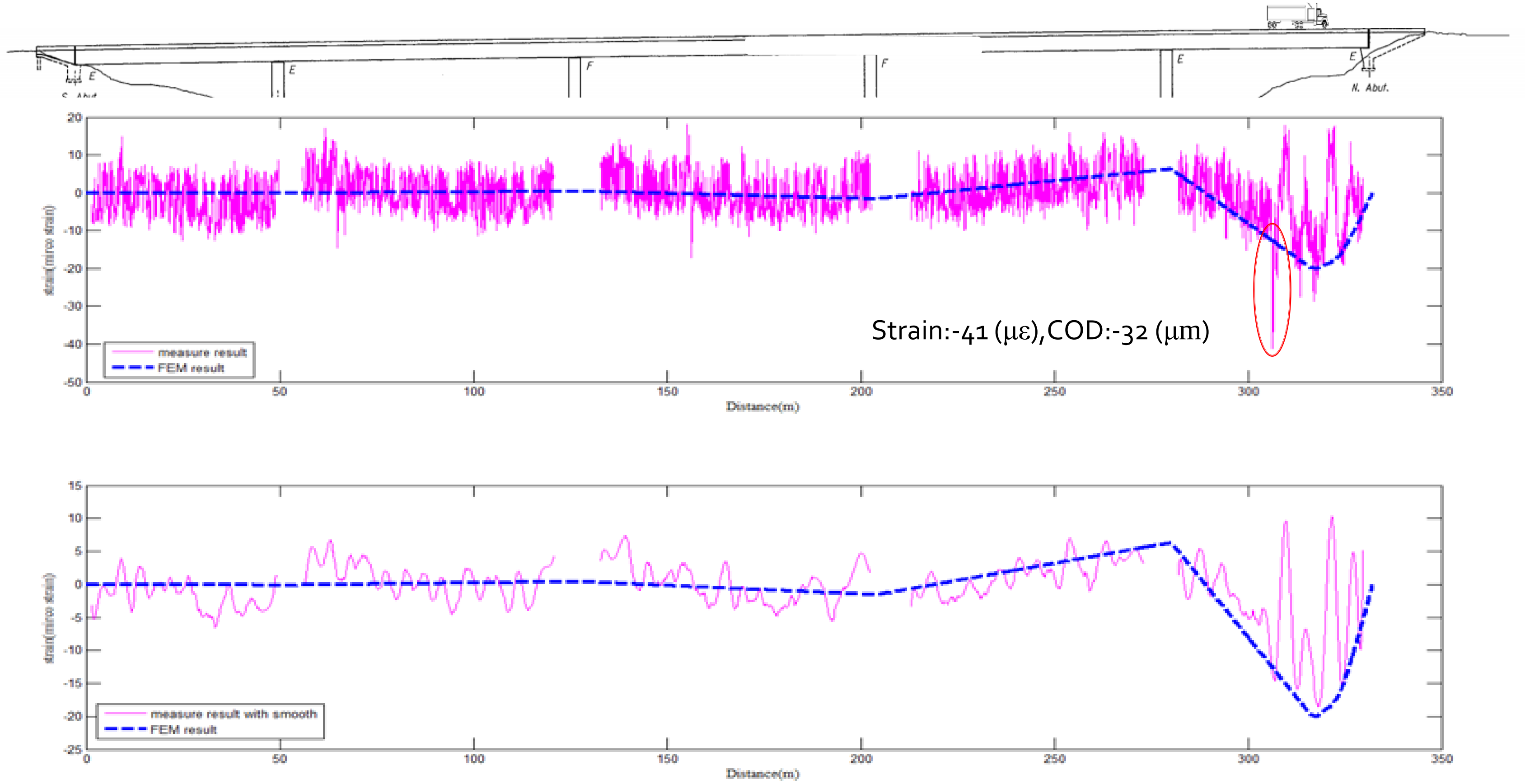
Distributed Monitoring



Four trucks

Strain:41 (με),COD:32 (μm)

Distributed Monitoring



Four trucks

Strain:-41 (με),COD:-32 (μm)

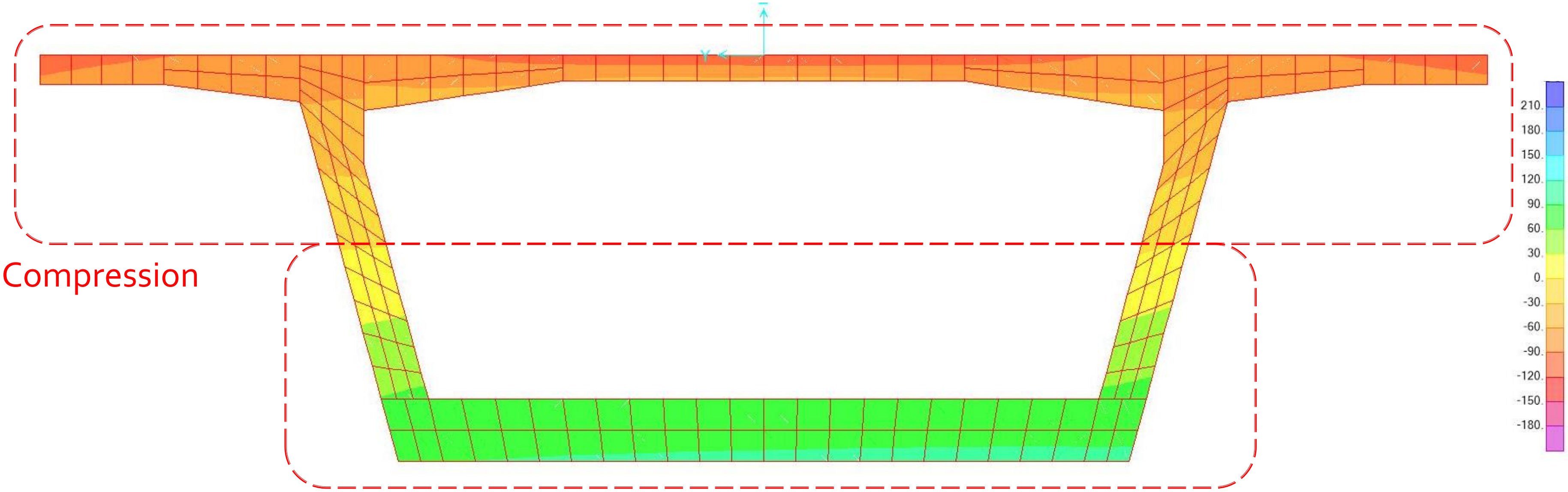
Detected Microcracks

Crack location in 5th span overhead surface near the joint of two segments.

KISHWAUKEE RIVER BRIDGE

CRACK DEVELOPMENT AND FINITE ELEMENT ANALYSIS

LOCAL STRESSES AT CRACKED CROSS SECTION DUE TO WHEEL LOADS

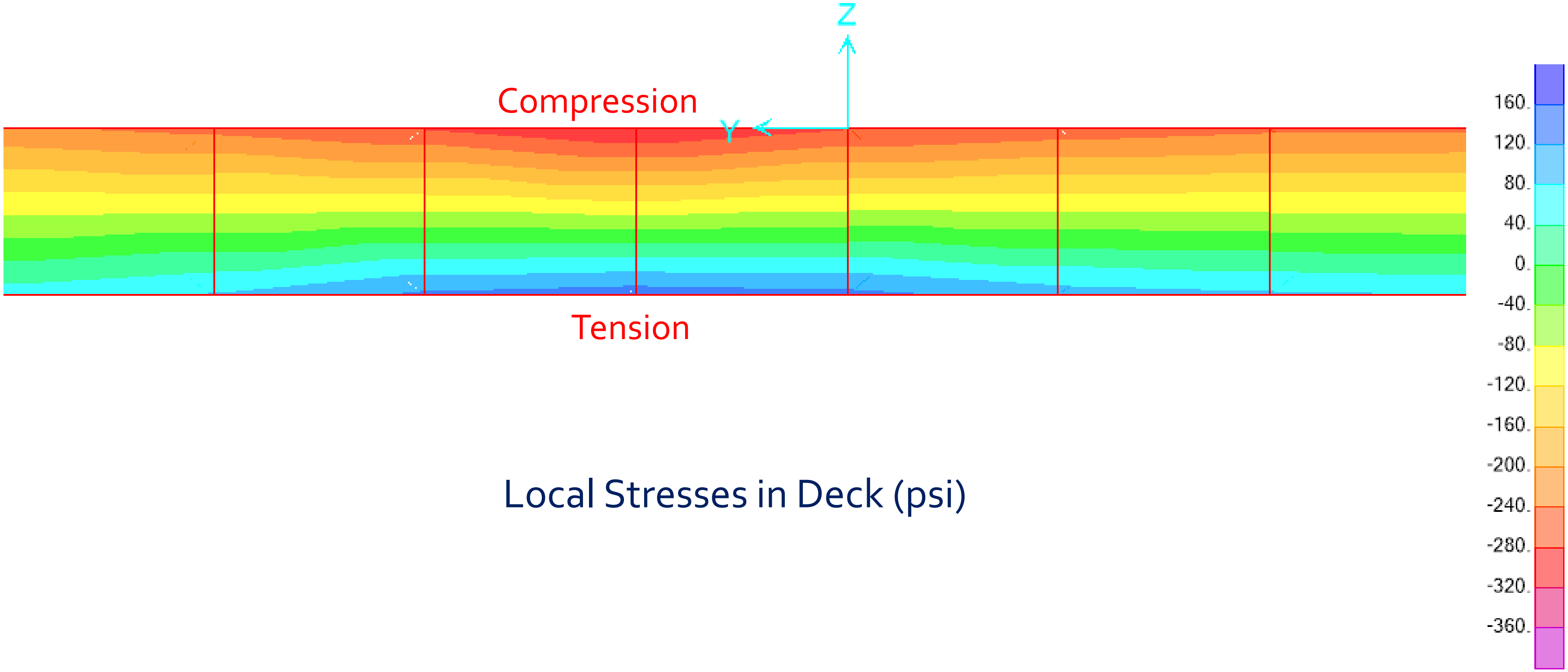


Compression

Tension

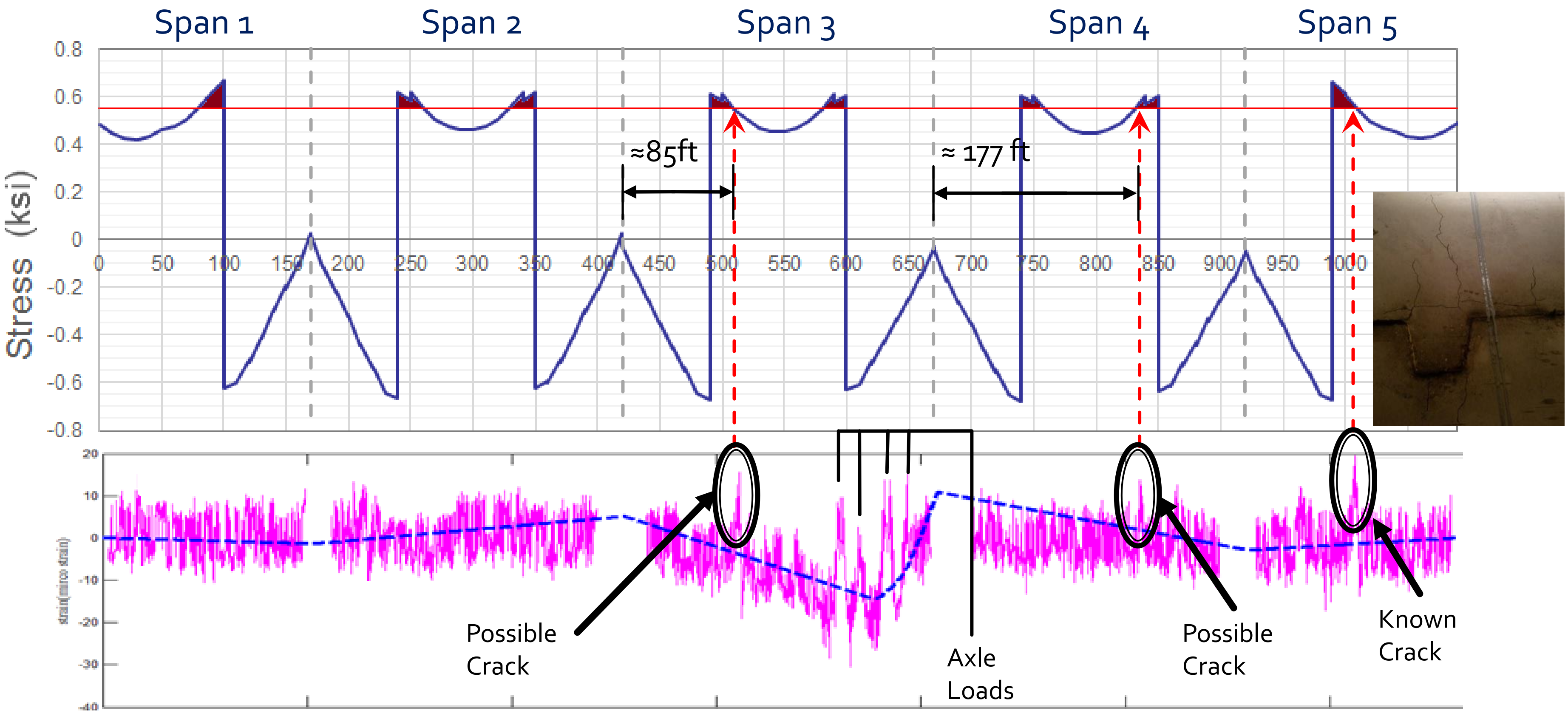
Section Stresses right before wheels get to the section (psi)

LOCAL STRESSES AT CRACKED CROSS SECTION DUE TO WHEEL LOADS



Local Stresses in Deck (psi)

LOCATIONS FOR FURTHER INVESTIGATION

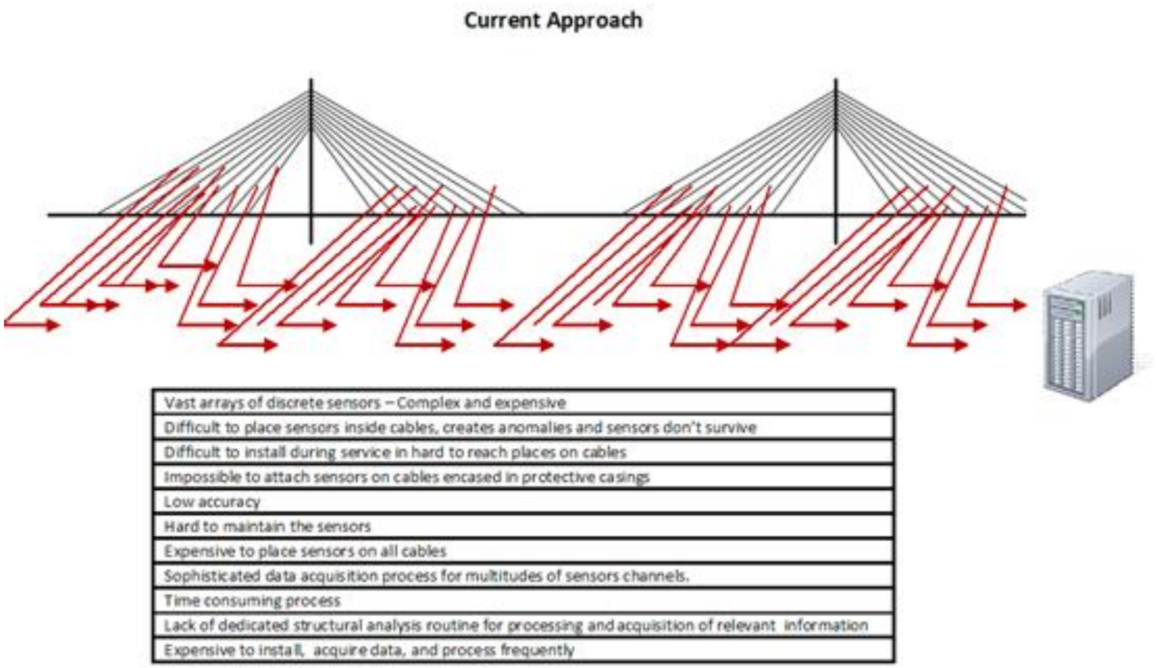


Coincidence of observed peaks within vulnerable areas

Cable-stayed Bridges

Health Monitoring of Cables with localized sensors

Multitudes of discrete sensors require expensive, inefficient and rigorous installations

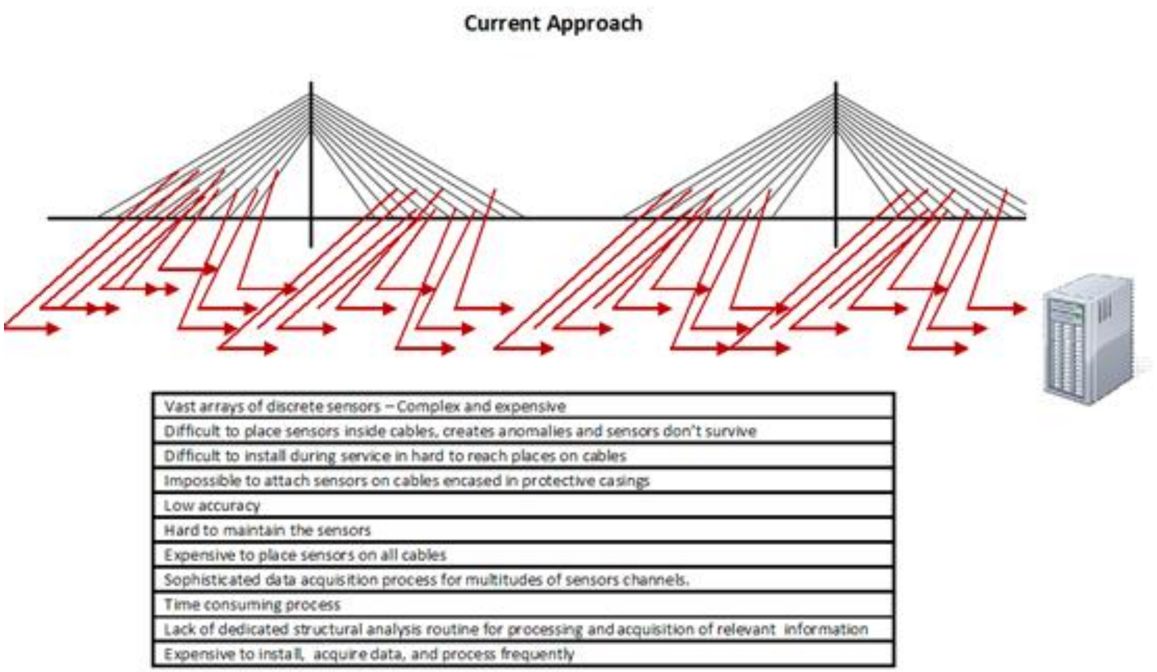


Current Approach

Vast arrays of discrete sensors – Complex and expensive
Difficult to place sensors inside cables, creates anomalies and sensors don't survive
Difficult to install during service in hard to reach places on cables
Impossible to attach sensors on cables encased in protective casings
Low accuracy
Hard to maintain the sensors
Expensive to place sensors on all cables
Sophisticated data acquisition process for multitudes of sensors channels.
Time consuming process
Lack of dedicated structural analysis routine for processing and acquisition of relevant information
Expensive to install, acquire data, and process frequently

Health Monitoring of Cables with localized sensors

Multitudes of discrete sensors require expensive, inefficient and rigorous installations



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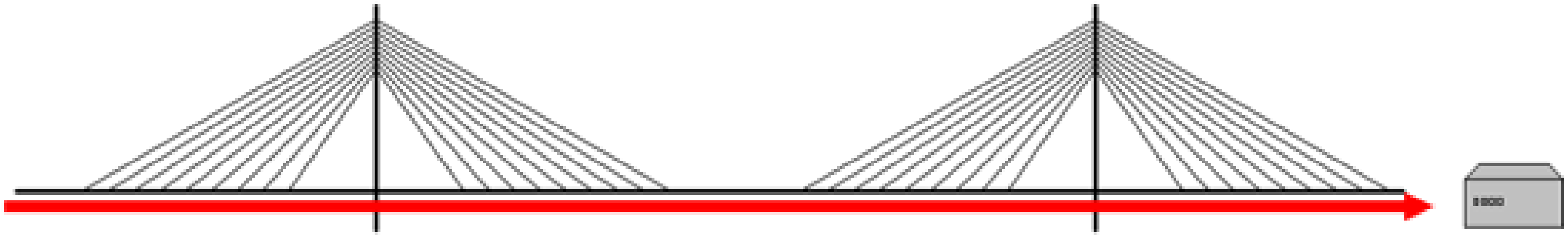
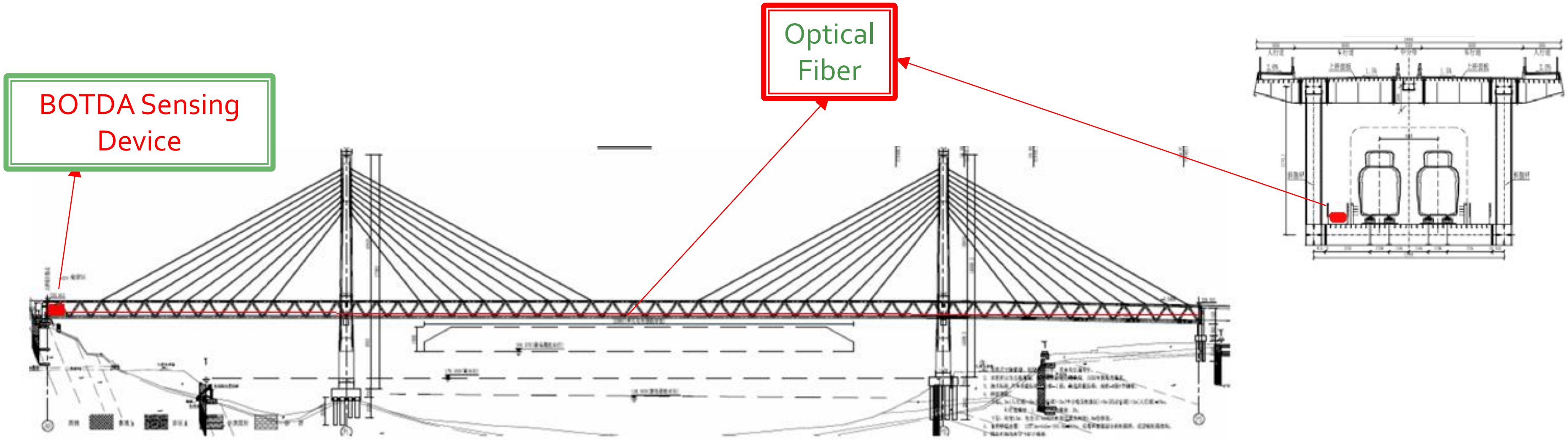
Tension Loss in Cables by Distributed Monitoring of Deck Strains

Cost effective quantifying damage in the cables of cable-stayed bridges



Distributed sensor – Simple to install – Single line of data
High resolution – Cost Effective – Rapid extraction of data
Dedicated innovative method for structural analysis for detection of location and extent of cable tension losses

Model of Two-River Bridge in ChongQing

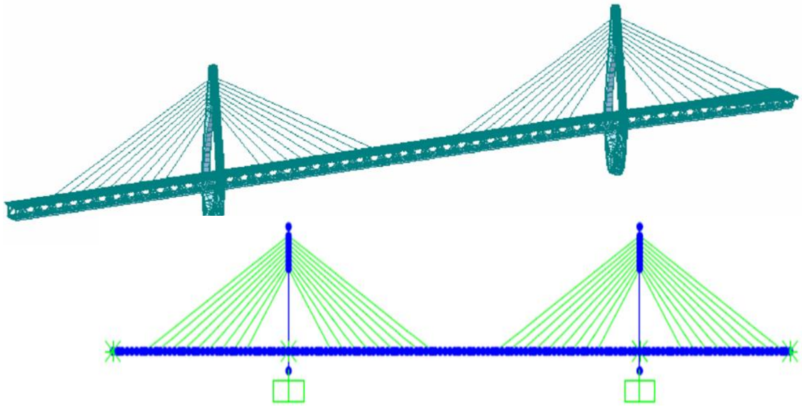


BOTDA Sensing Device

Optical Fiber

立面图

Two River Bridge and 1/68 Laboratory Model



Formulations

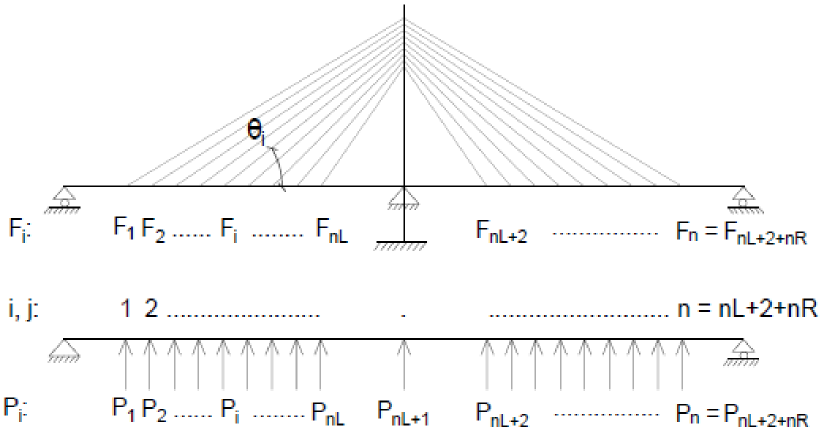
$$M_i = \sum_{j=1}^{n} P_j M_{ij}$$

M_i is the bending moment at location i,

M_{ij} is the bending moment at location i due to a unit vertical force at point j

n is the total number of cables and the interior supports.

$$M_i = \frac{\epsilon_i EI}{C}$$



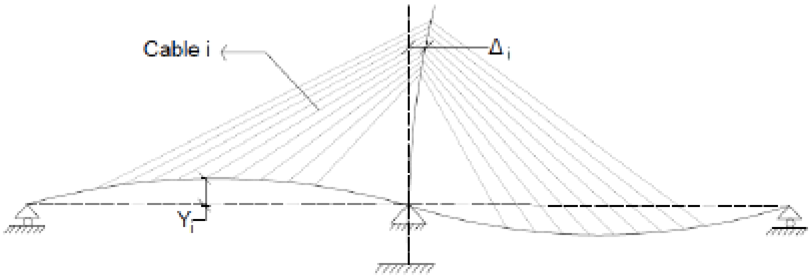
$$\begin{bmatrix} M_{11} & \cdots & M_{1n} \\ \vdots & \ddots & \vdots \\ M_{n1} & \cdots & M_{nn} \end{bmatrix} \begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix} = \begin{bmatrix} M_1 \\ \vdots \\ M_n \end{bmatrix}$$

Effect of Spatial Resolution in Strain Measurements

$$F_i = \frac{E_i A_i}{L_i}(-Y_i \sin\theta_i \pm \Delta_i \cos\theta_i)$$

$$Y_i = \sum_{j=1}^{n} P_j f_{ij}^{b}$$

$$\Delta_i = \sum_{j=1}^{nL} (Q_j - Q_{nL+2-j}) f_{ij}^{p}$$



Y_i is the vertical deflection of the deck at point i

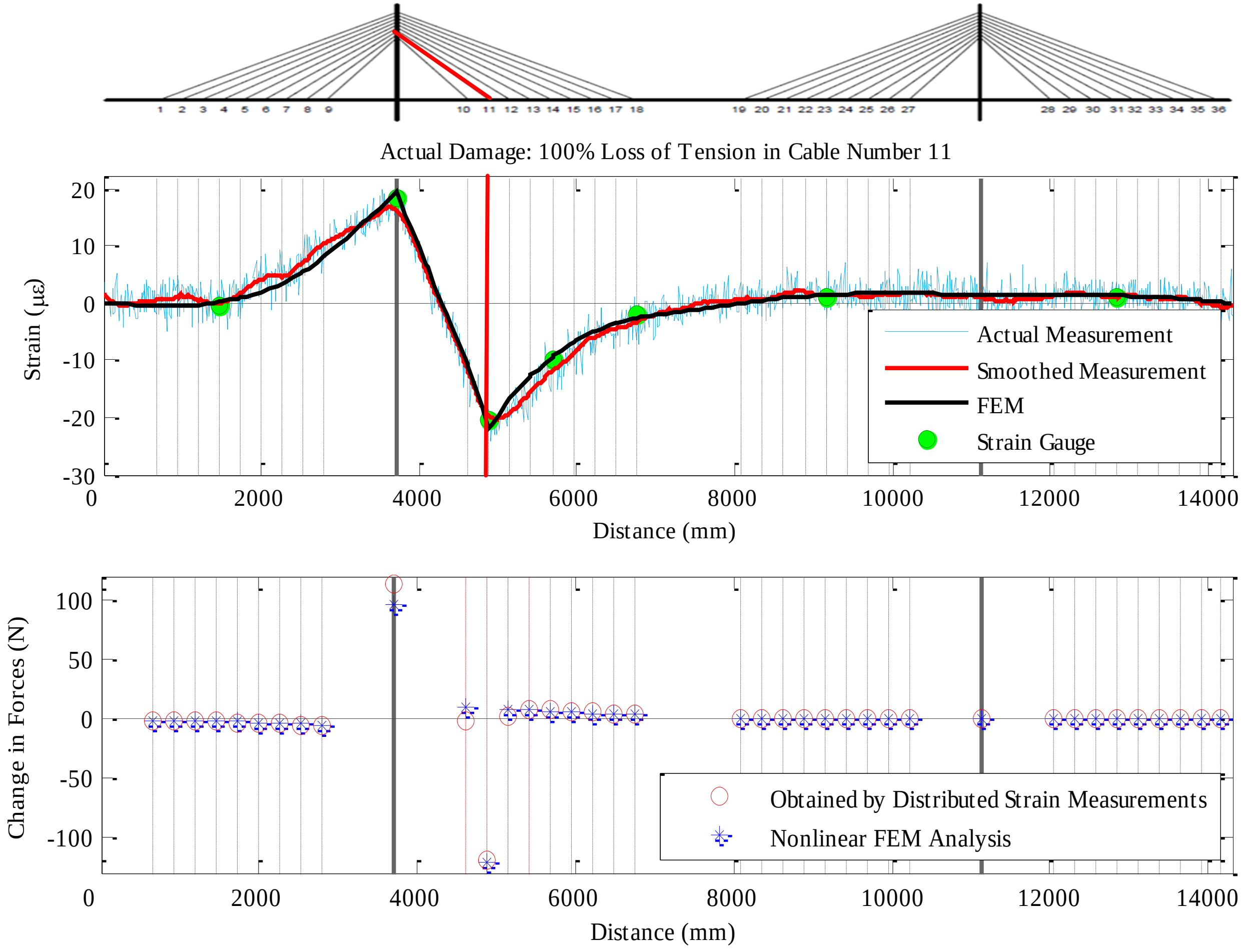
and Δ_i is the pylon horizontal displacement at the connection of cable i

Q_i *is the horizontal component of cable force*

f_{ij}^{b} and f_{ij}^{p} is deflection of the deck and pylon at section i due to a unit force at section j, respectively.

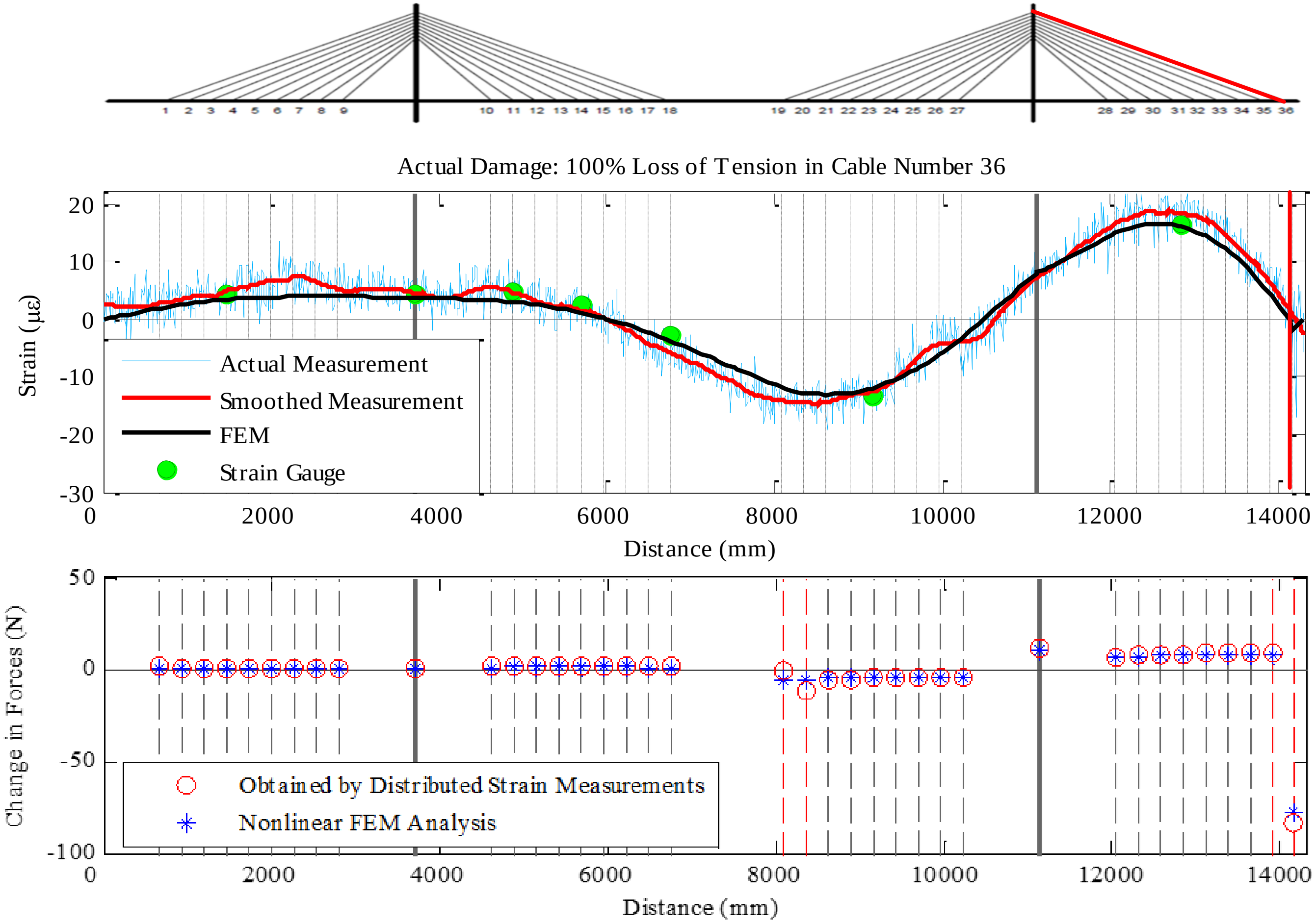
Damage case I.

100% Tension Loss



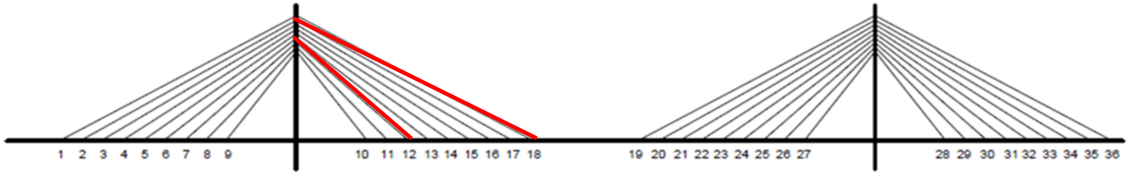
Damage case II.

100% Tension Loss

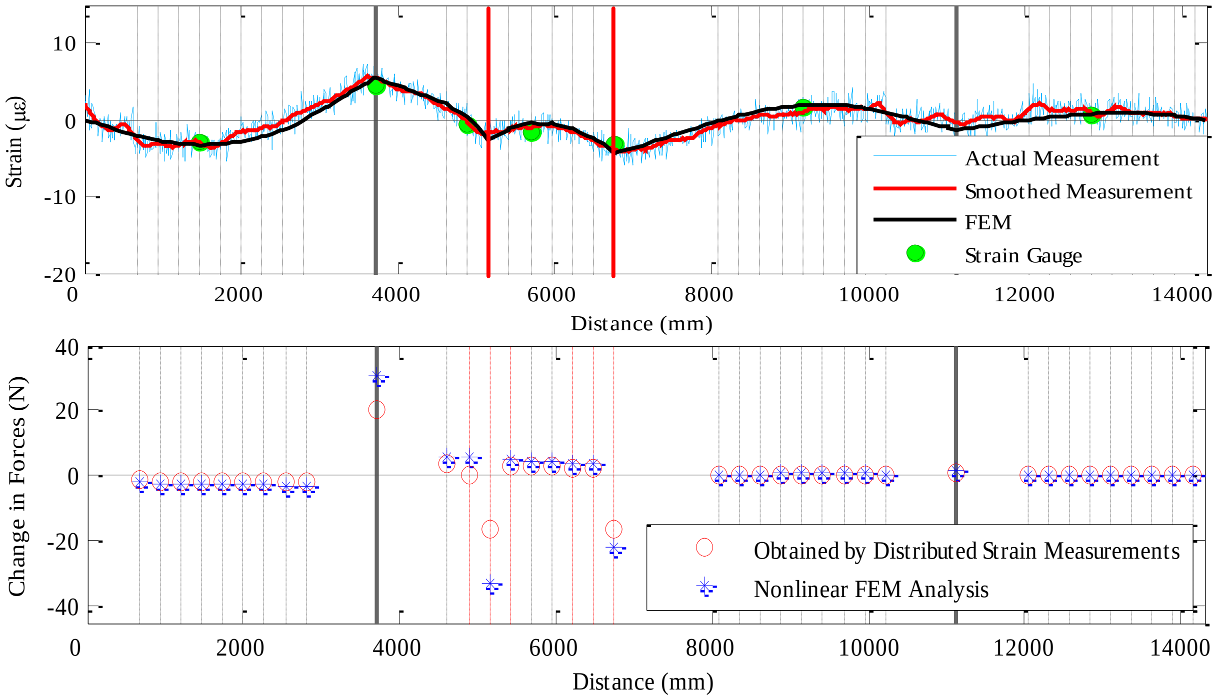


Damage case III.

30% Tension Loss in Each Cable



Actual Damage: 30% Loss of Tension in Each Cable Number 12 and 18



Summary

- Structural monitoring shall begin by a well defined objective and for solving specific problems
- A number of examples pertaining to the application of Fiber Optic Sensors in monitoring of Bridges were provided
- Two types of sensors, discrete and distributed have been prevalent in Civil Structural health Monitoring, FBG, and Brillouin systems.
- FBG sensors have found widespread usage. Distributed sensors will be prevalent in near future