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Structural Health Monitoring for the Assessment of Cracking Potential in Concrete Structures

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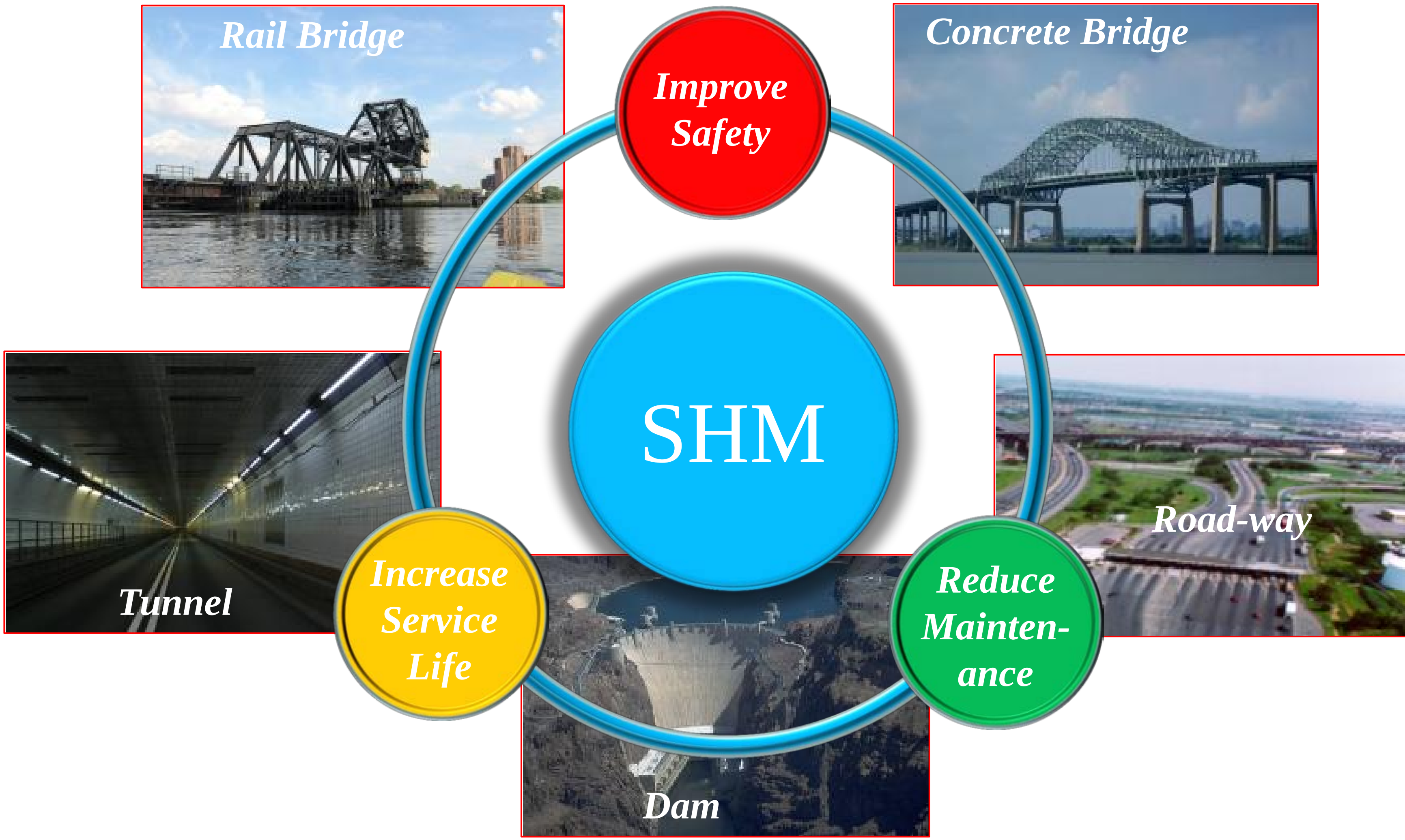
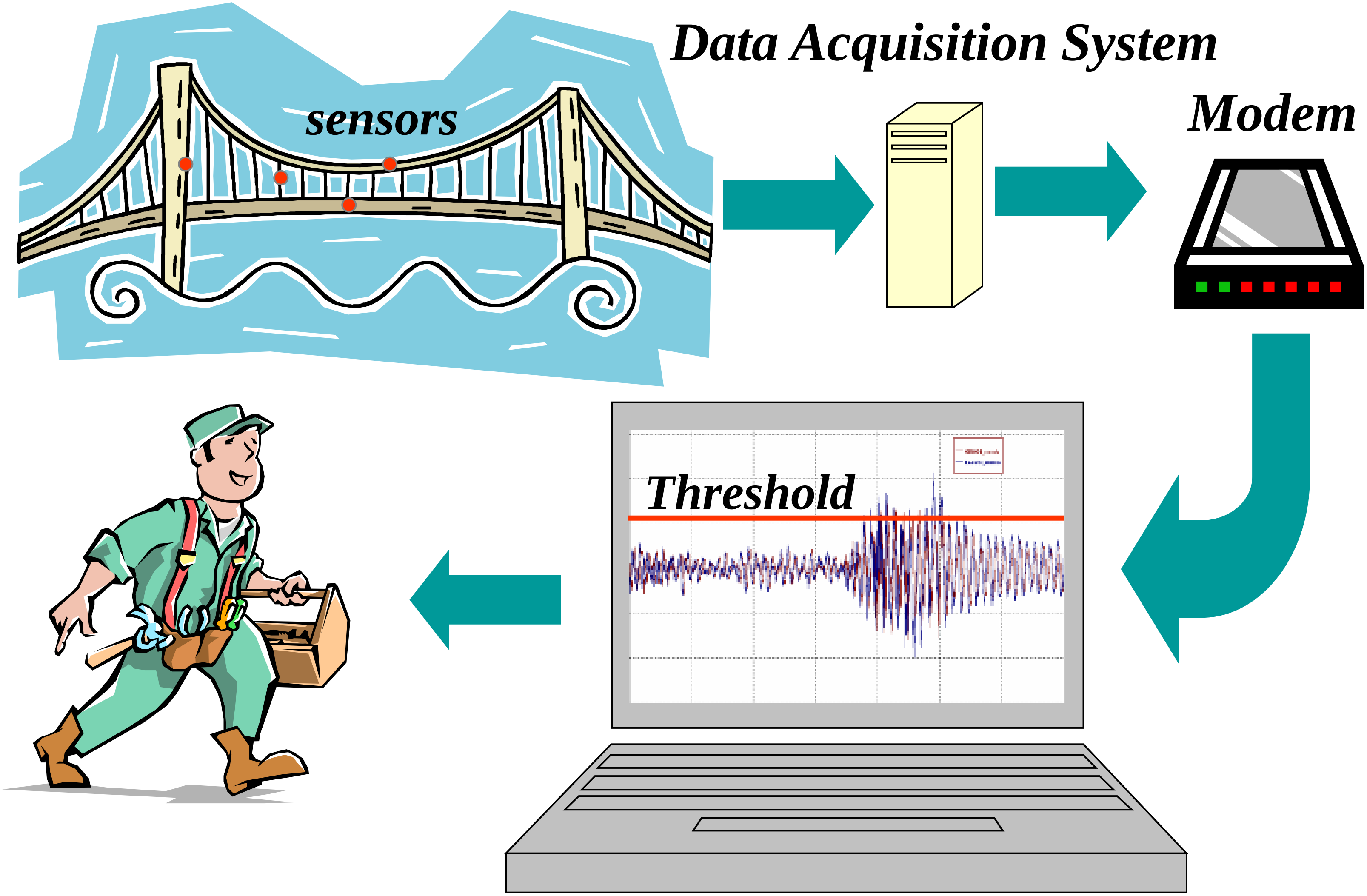
Introduction

- Structural health monitoring (SHM) and field-testing are becoming increasingly popular in the U.S. and Europe:
  - Evaluation and remaining life of aging structures.
  - Performance of new and advanced materials, e.g., high performance and self-compacting concretes, fiber reinforced polymer & advanced composites, etc.
  - Calibration and validation of Design Codes.
  - Monitoring the safety and security of various civil infrastructures, such as Bridges, Buildings, Tunnels, Dams, Traffic Roads, etc.

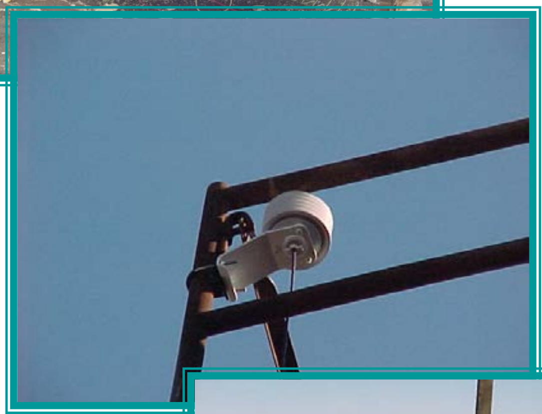
Structural Health Monitoring (SHM)

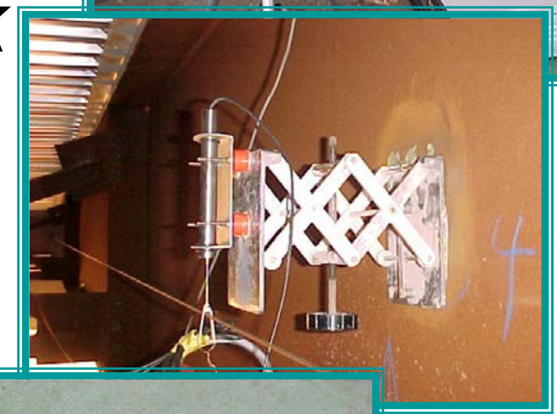


Structural Health Monitoring (SHM)



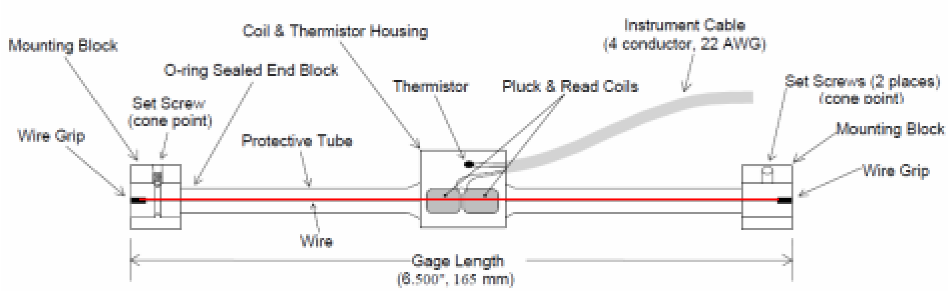
Sensor Network





Sensors for SHM

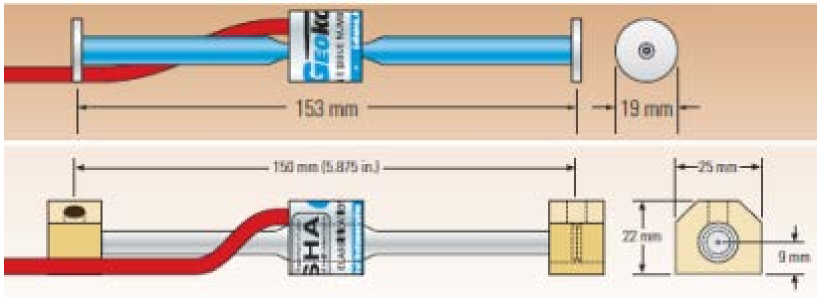
- Structural Testing System (STS)
  - Strain transducer is for long-/short-term and dynamic strain measurement.
  - Strains are measured using a full Wheatstone bridge configuration.
  - The STS is wireless system and capable of sampling up to 16 sensors at 100 Hz.



Digits (Reading, R) = Frequency² / 1000

Deformation = ($R_1 - R_0$) x G x F

where R_1 is the current reading in digit
R_0 is the initial reading obtained at installation in digit
G is the calibration factor or gauge factor
F is an optional engineering units conversion factor

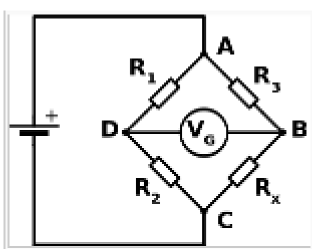


Strain Gauge – Embedment/Weldable

Crackmeter

Sensors for SHM

- Vibrating Wire Strain Gauge
  - For long-/short-term and static strain measurement.
  - Strains are measured using the vibrating wire principle.
  - The strain in tension (or compression) of the wire is measured by resonant frequency of vibration.



Full Wheatstone Bridge

$$V_G = \left(\frac{R_x}{R_3 + R_x} - \frac{R_2}{R_1 + R_2} \right) V_s$$

where V_G is the voltage of node B relative to node D.

Base Station (wireless)

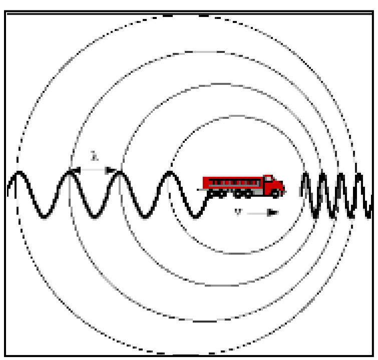
Junction Box (wireless)

Strain Transducer

STS System

Sensors for SHM

- Laser Doppler Vibrometer (LDV)
  - LDV is a on-contact sensor to measure displacement and velocity of a remote point.
  - The displacement and velocity are measured by the Doppler shift principle in the light frequency.
  - A change in distance between the laser head and the reflective target will be measured.

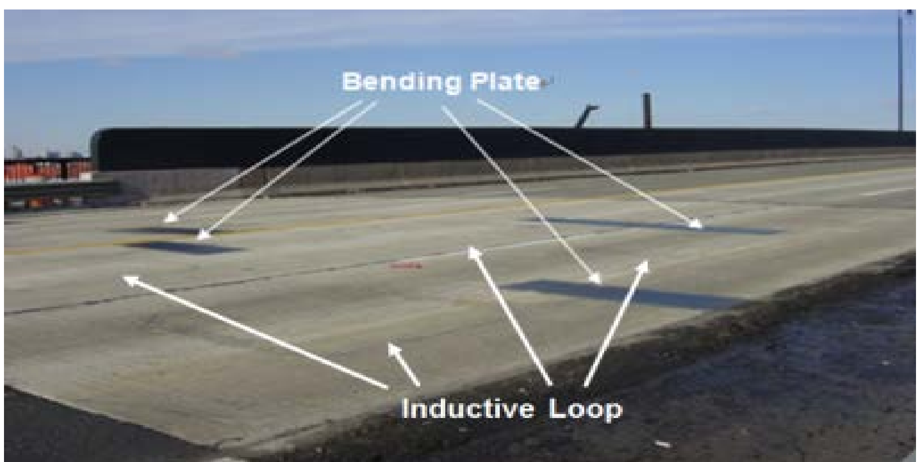


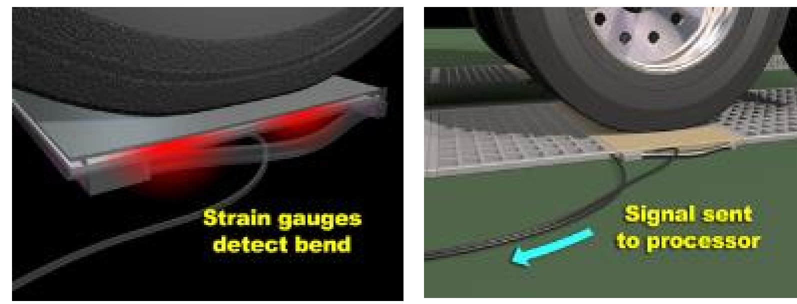
Doppler Shift Principle

LDV System and Reflective Tape

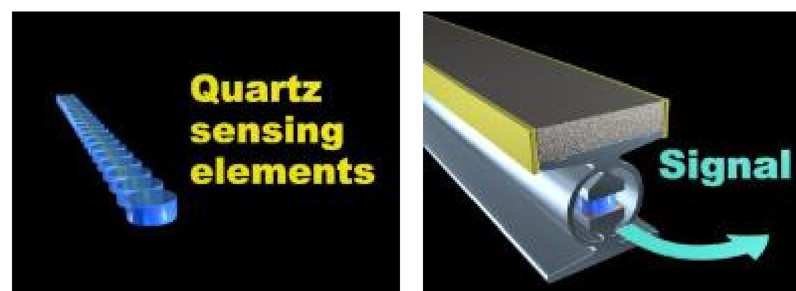
Sensors for SHM

- Weight-In-Motion (WIM)
  - WIM is the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle (ASTM Specifications E 1318-94)
  - Inductive loop detects the vehicle and triggers a sequence of event.
  - Bending plate measures GVW, axle weight and number of axle.





__Bending Plate__



__Piezo-Electric__

Sensors for SHM

- V2000 Corrosion Sensor
  - It is a permanent passive electrode to measure the potential difference between the electrode and steel reinforcement (counter electrode).
  - It detect the chloride ion presence by measuring the voltage.

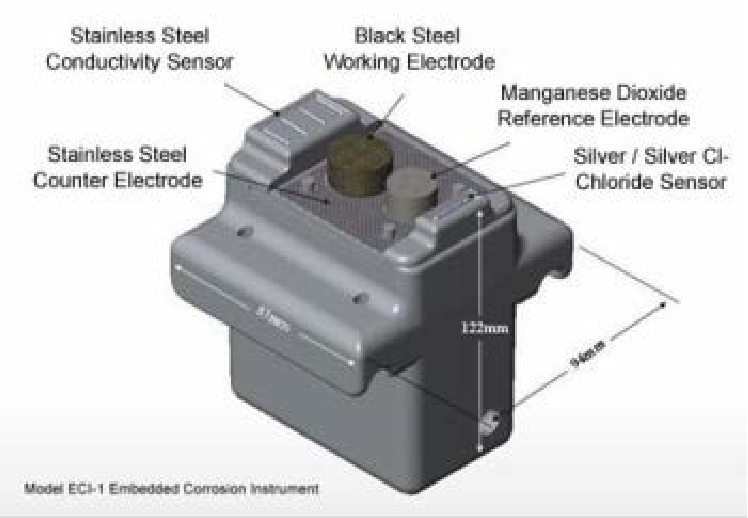
V2000 Electrode

Counter Electrode

Range	Comment
< 300 mV	No corrosion activity is present.
300 ~ 400 mV	The passivation layer of steel is being damaged, and corrosion has begun.
> 400 mv	Corrosion is fully active on the rebar.

Sensors for SHM

- ECI-2 Corrosion Sensor
  - A long-term corrosion monitoring device with 5 sensors.
  - (1) Linear Polarization Resistance (LPR)
  - (2) Open Circuit Potential (OCP)
  - (3) Resistivity
  - (4) Chloride Ion Concentration (Cl-)
  - (5) Temperature



(1) Black Steel Electrode - LPR, OCP

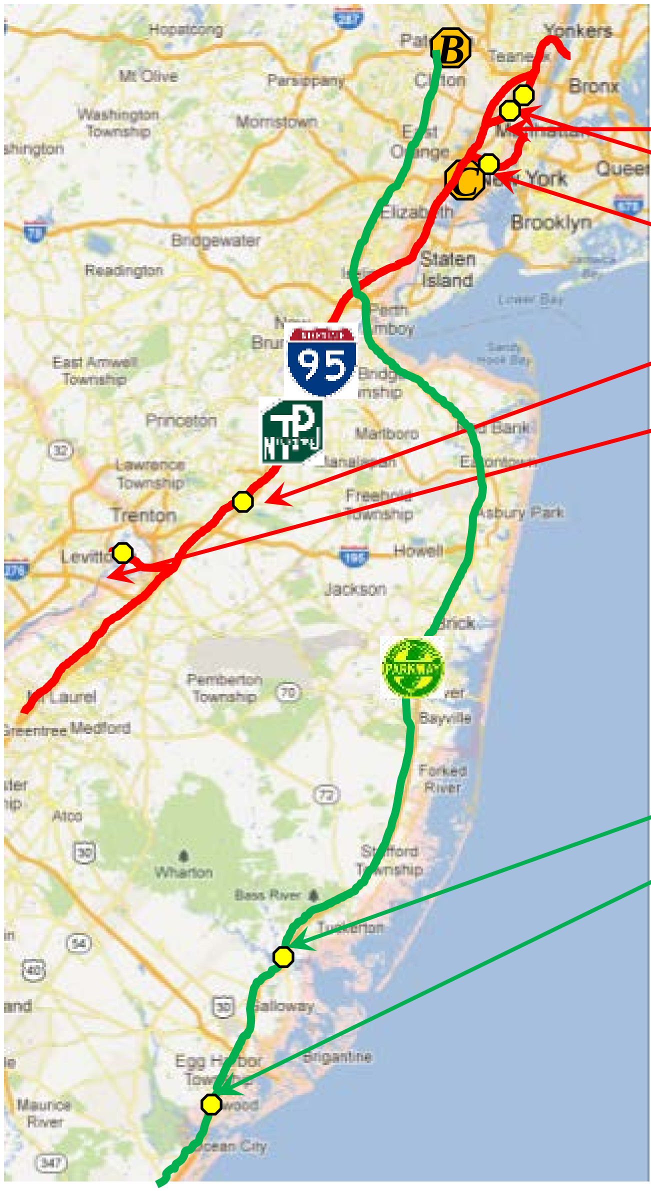
(2) Manganese Dioxide Ref. Electrode - LPR, OCP

(3) Stainless Steel Counter Electrode - LPR

(4) Four Stainless Steel Wire Electrode - Resistivity

(5) Silver-Silver Chloride Wire Electrode - Chloride Level

List of Bridges



New Jersey Turnpike Projects

- *Exit 16E Bridge*
- *Hackensack Bridge*
- *Newark Bay Bridge*
- *Str. 60.51I & 59.05*
- *Delaware River Bridge*

❖ **NJDOT Projects**

Ⓐ *Rt. 18 Bridge*

Ⓑ *Doremus Ave. Bridge*

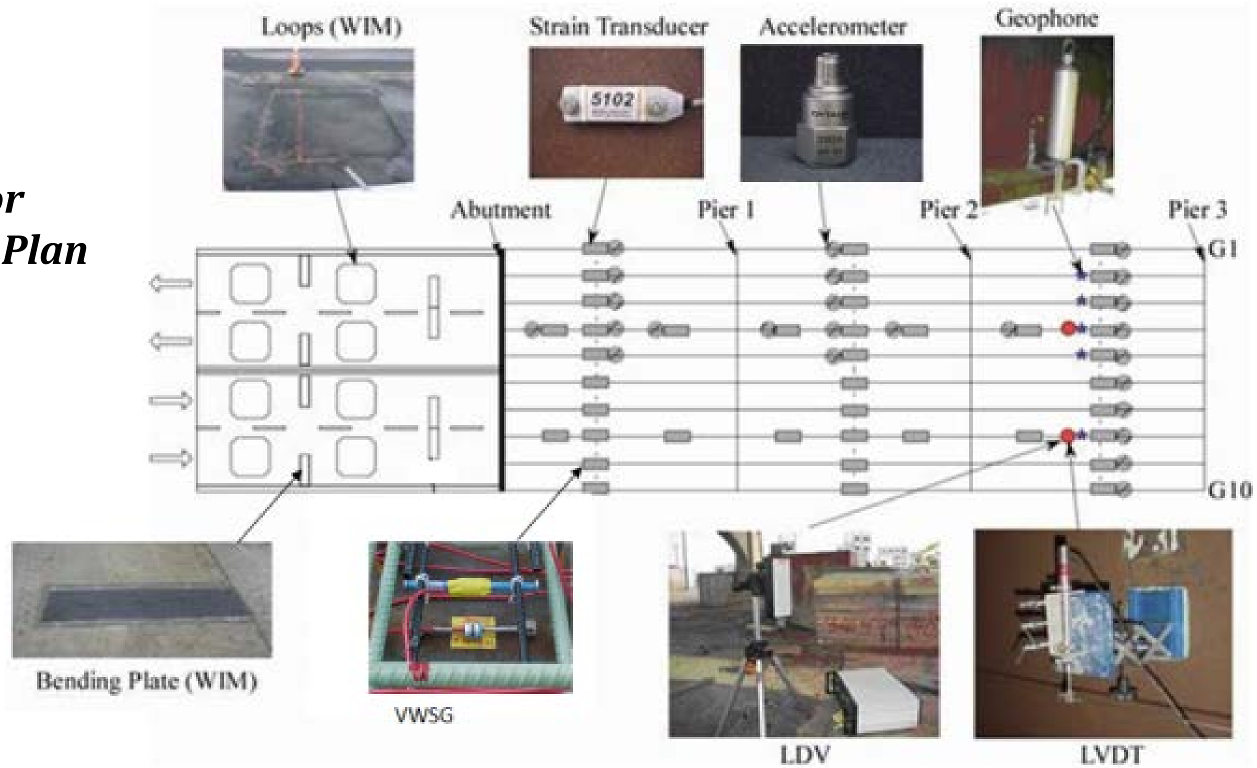
❖ **Garden State Parkway**

- *Mullica River Bridge*
- *Patcong Creek Bridge*

Case Study 1 – Doremus Avenue Bridge (NJDOT)

- Objective
  - To validate the LRFD Specifications.
  - To develop a truck-load model and a fatigue load model

Various Sensor Instrumentation Plan



Material Properties

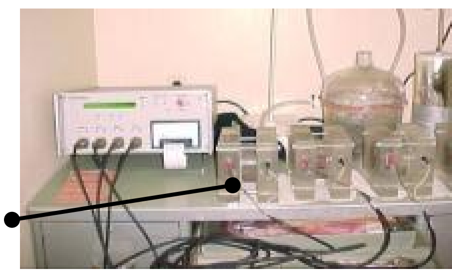
Concrete Samples from the Field

Compressive Strength
Tensile Strength
Modulus of Elasticity

Creep and Shrinkage

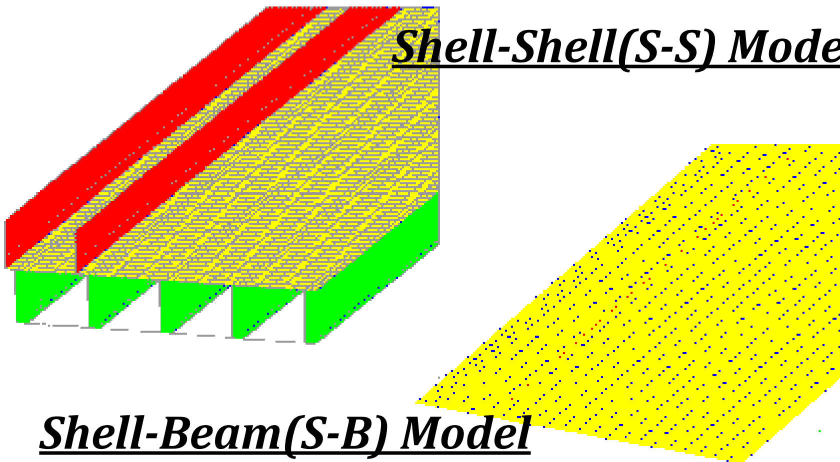
Freeze-Thaw

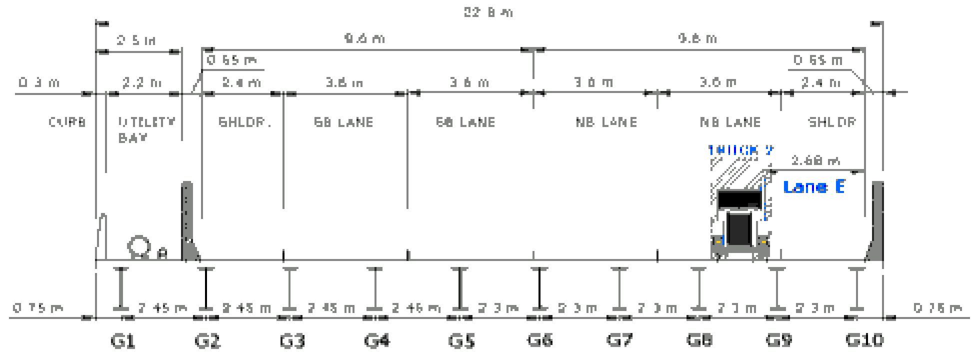
Rapid Chloride Permeability

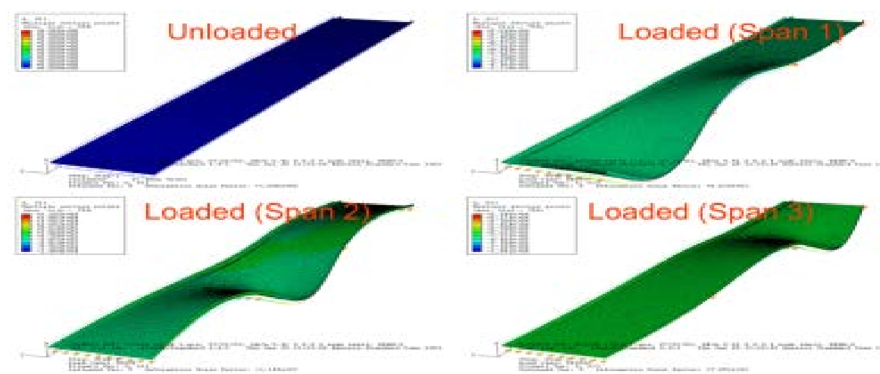


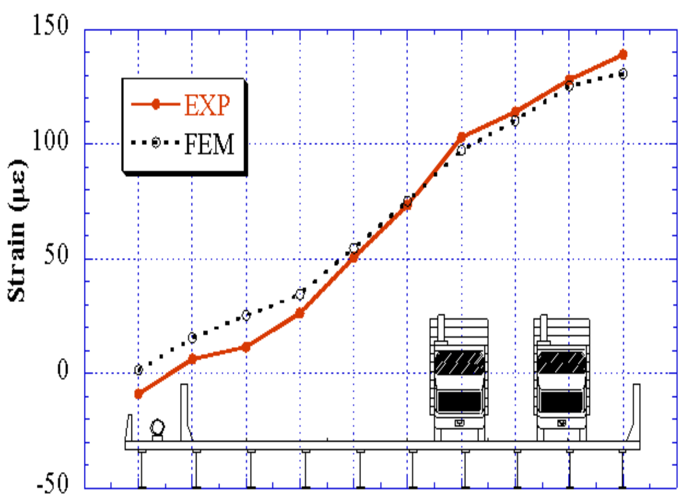
Free Shrinkage
Restrained Shrinkage

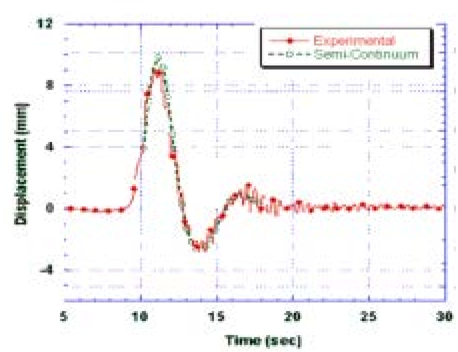
Finite Element Model and Calibration Test

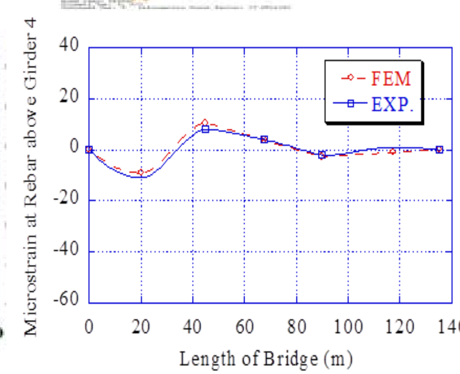




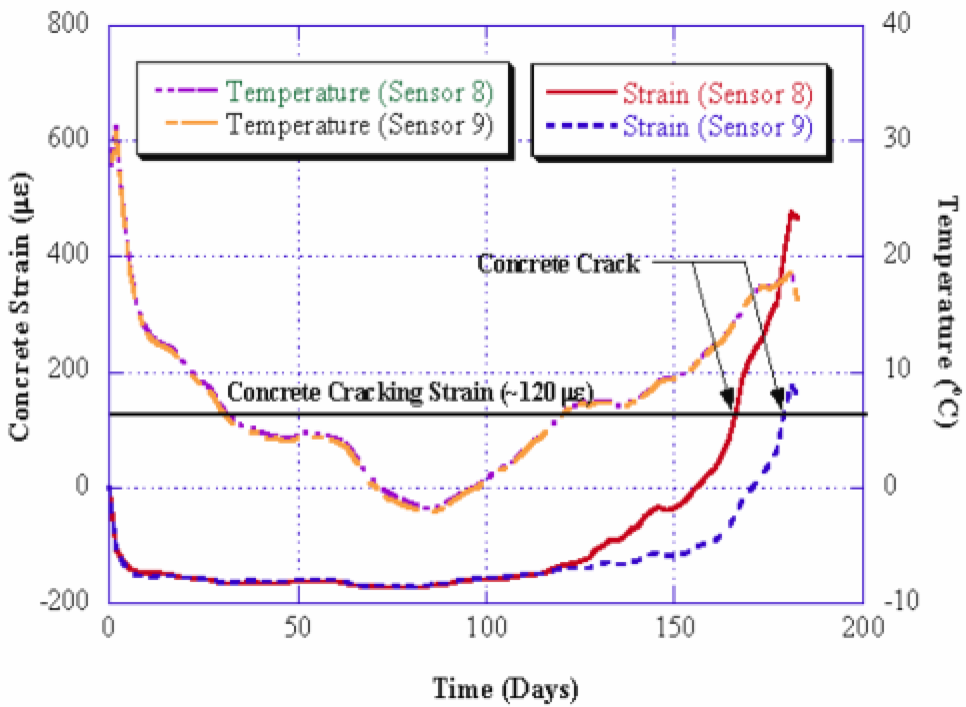




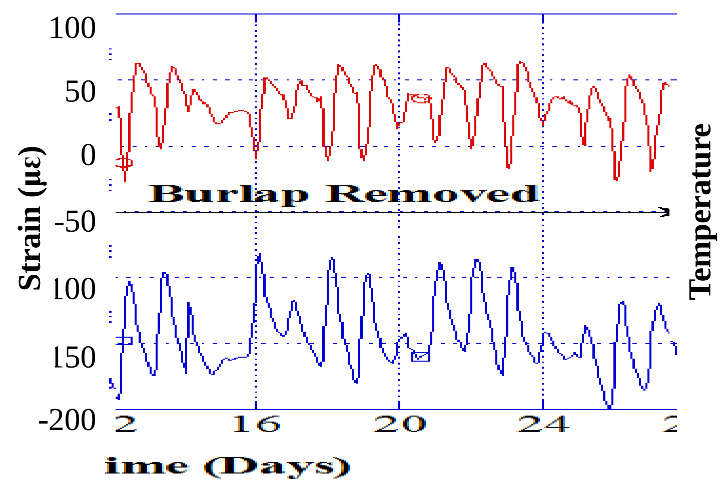




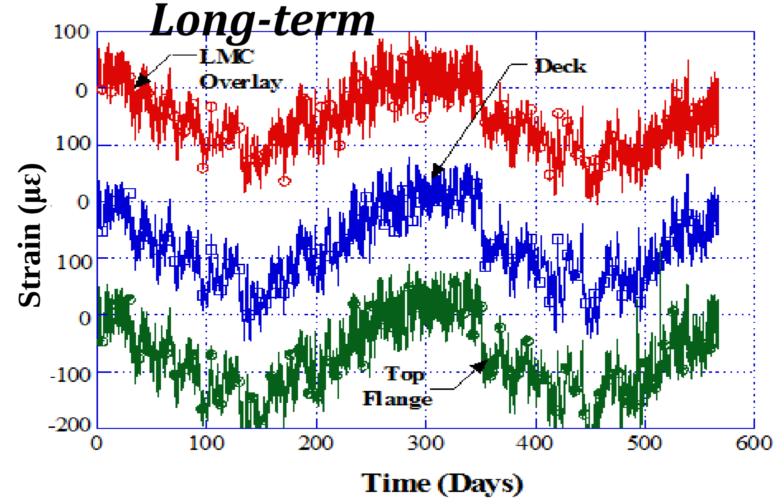
Short-&Long-Term Performance of Concrete Deck



Short-term



Long-term



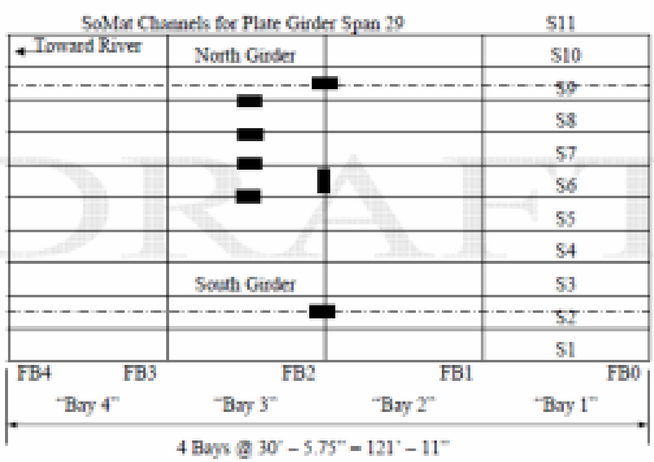
- ***Concrete deck cracks when the tensile strain exceed its strain capacity.***

Case Study 2 – Delaware River Bridge (NJTA)

- Objective
  - To evaluate the performance of HPC mixes at various stages.
  - To understand the cause of cracks.

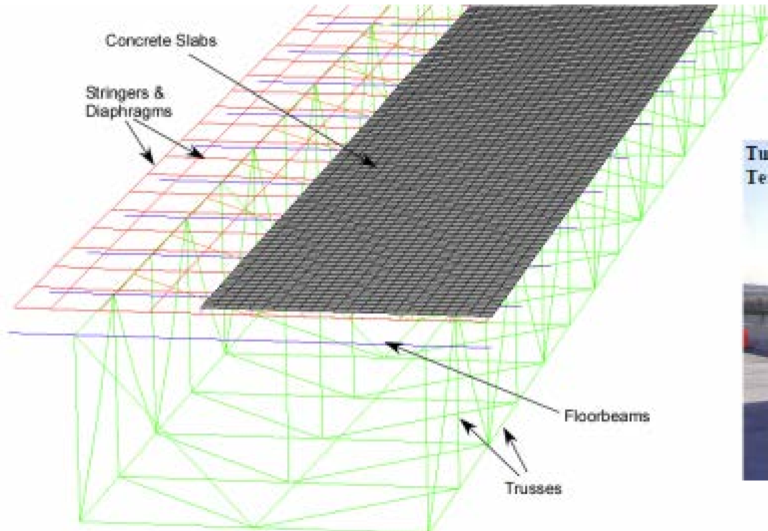
Construction

Observed Crack

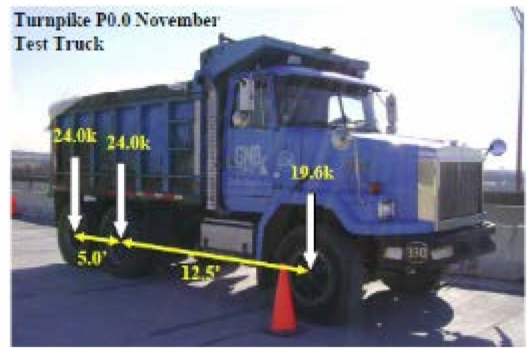


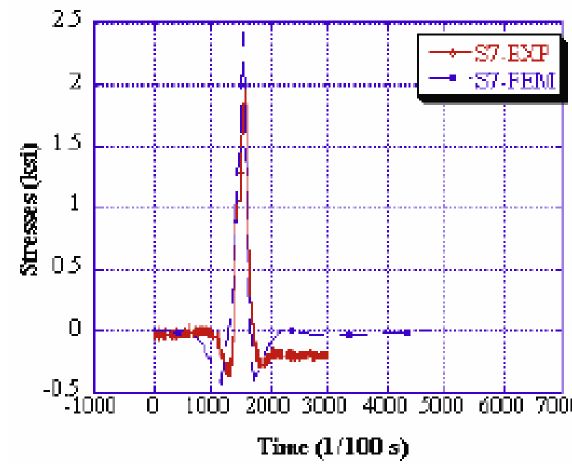
Sensor Location

Finite Element Model and Calibration Test

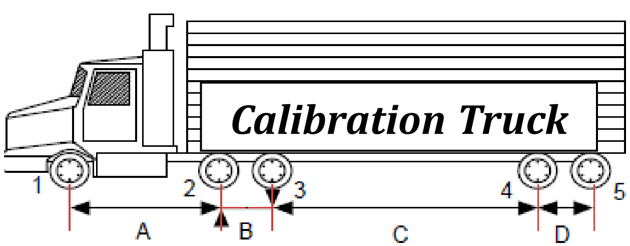


Static Test

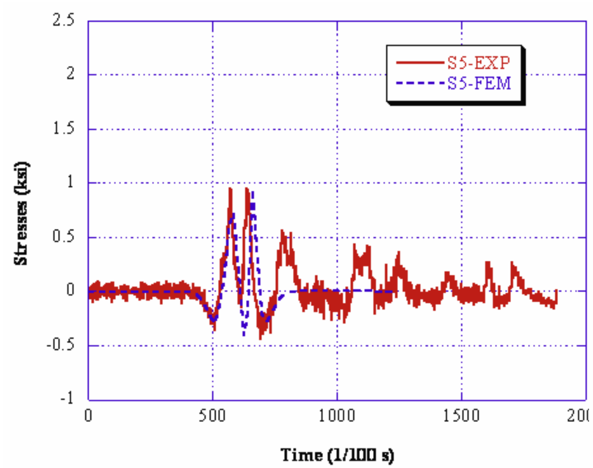


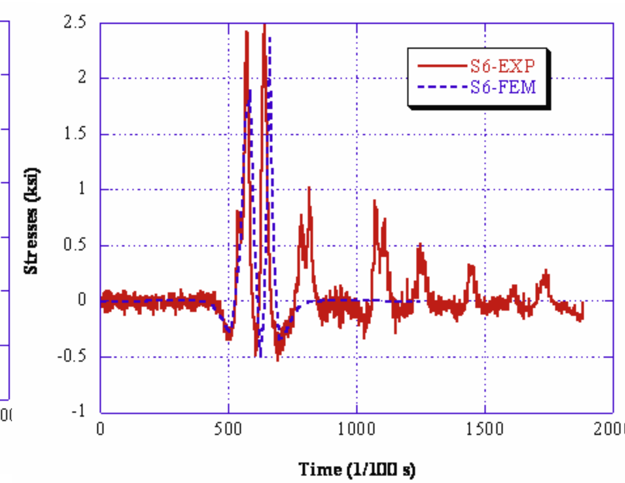


Dynamic Test



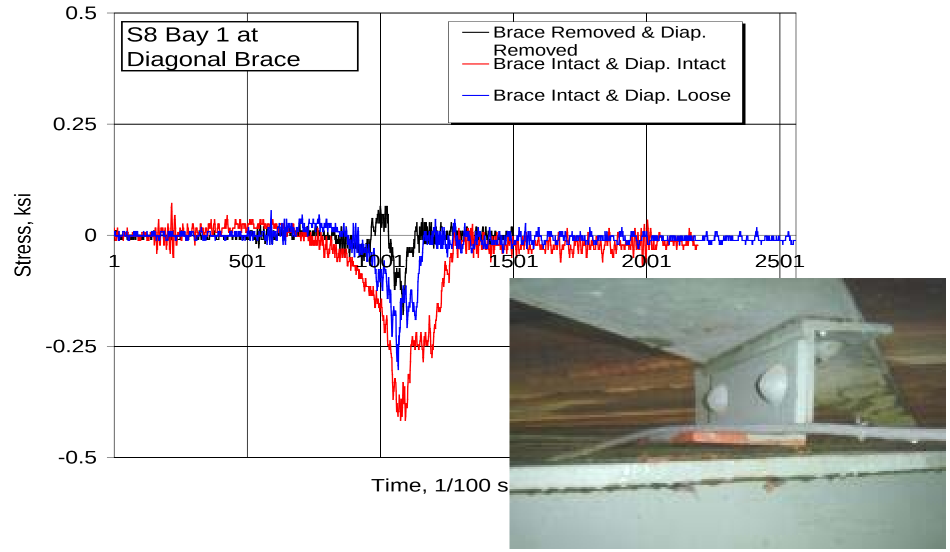
Truck GWV (kips)	65.2
Axle 1 (kip)	9.2
Axle 2 (kip)	13.3

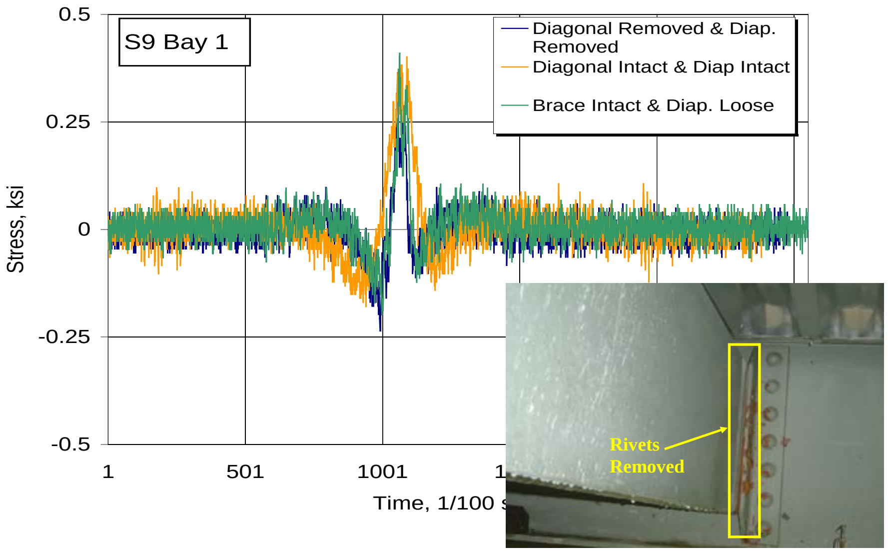


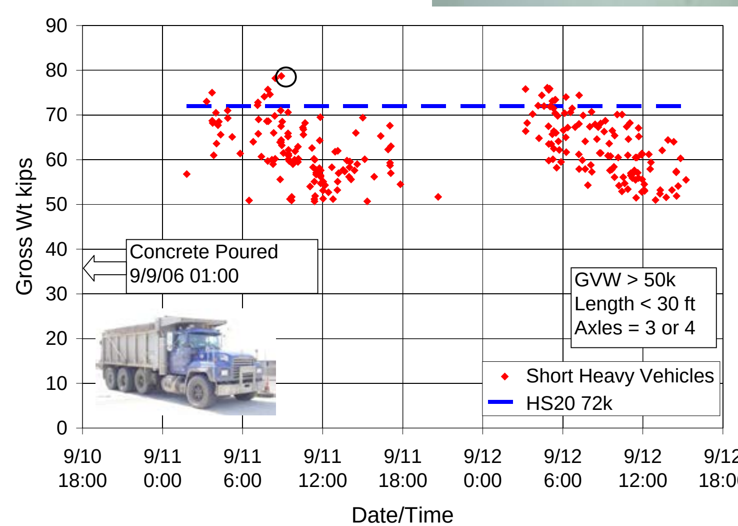


Field Test

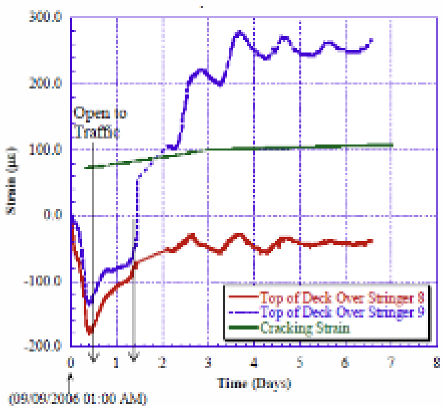

S7
Diag. Wind Brace
S8
FB11'
FB12
S9
S10

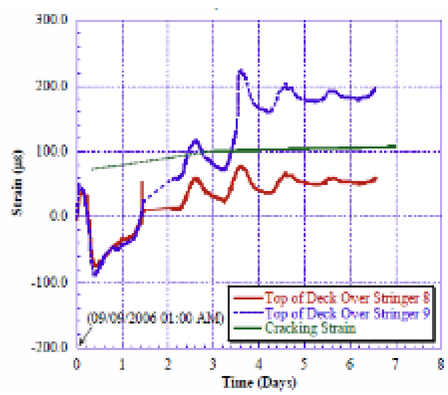

S8 Bay 1 at Diagonal Brace
Brace Removed & Diap. Removed
Brace Intact & Diap. Intact
Brace Intact & Diap. Loose
Stress, ksi
0.5
0.25
0
-0.25
-0.5
1
501
1001
1501
2001
2501
Time, 1/100 s

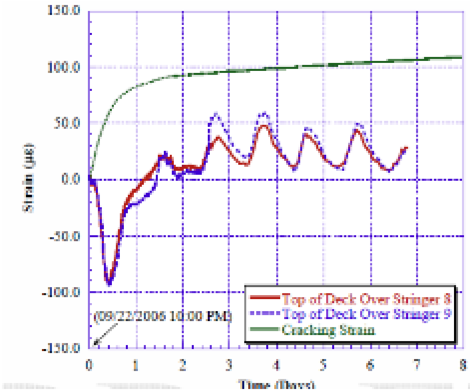

S9 Bay 1
Diagonal Removed & Diap. Removed
Diagonal Intact & Diap Intact
Brace Intact & Diap. Loose
Stress, ksi
0.5
0.25
0
-0.25
-0.5
1
501
1001
Time, 1/100 s
Rivets Removed


Gross Wt kips
90
80
70
60
50
40
30
20
10
0
Concrete Poured 9/9/06 01:00
GVW > 50k
Length < 30 ft
Axles = 3 or 4
Short Heavy Vehicles
HS20 72k
9/10 18:00
9/11 0:00
9/11 6:00
9/11 12:00
9/11 18:00
9/12 0:00
9/12 6:00
9/12 12:00
9/12 18:00
Date/Time

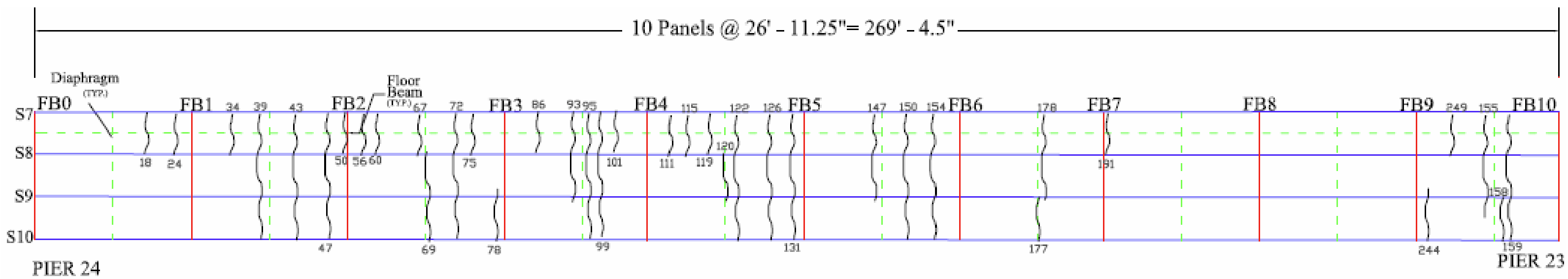
Field Monitoring Results

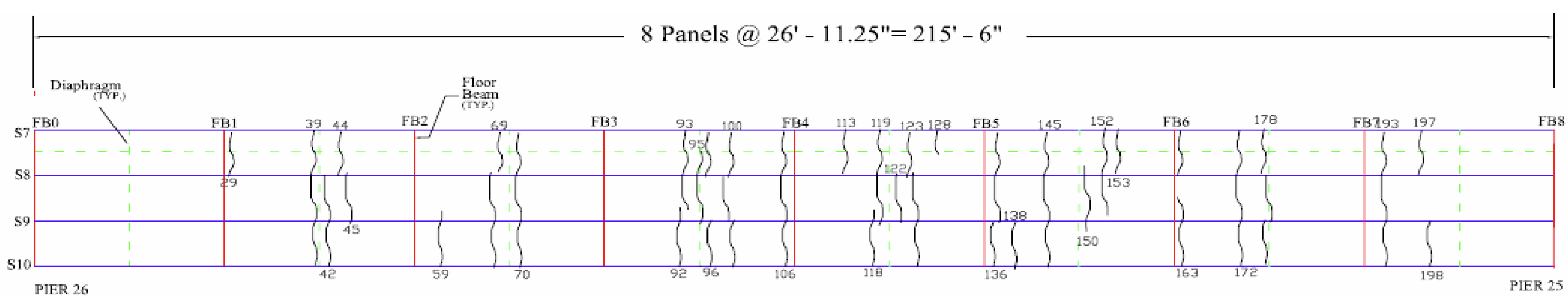






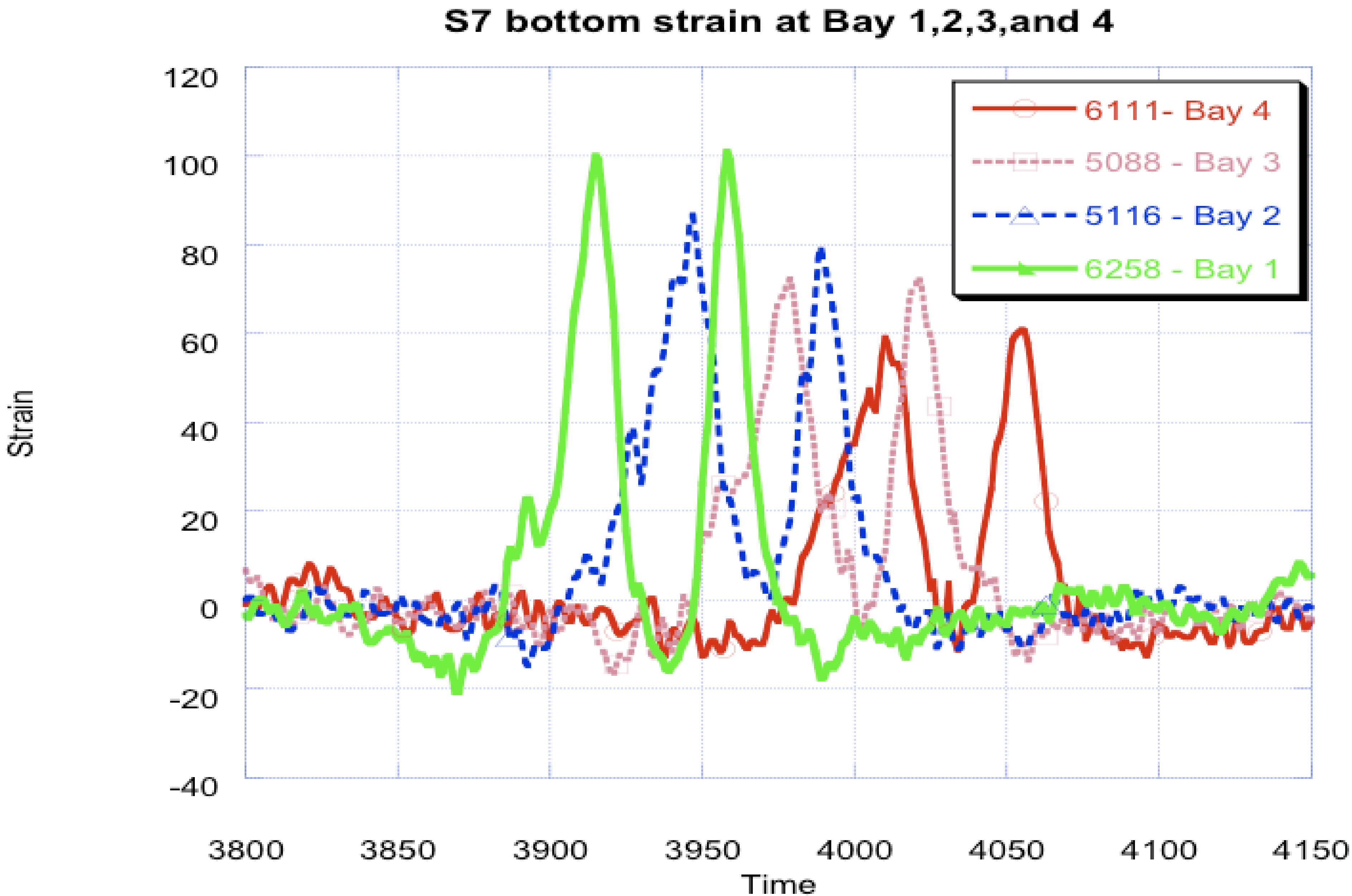
Cracks were observed as early as 7 days prior to burlap removal





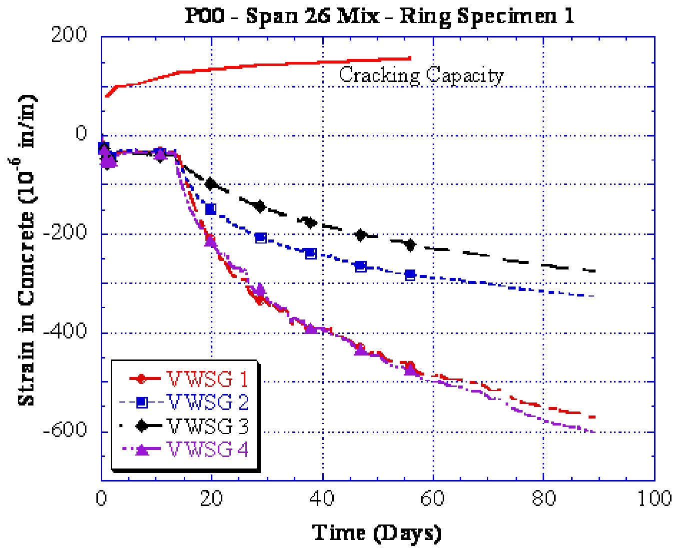
Strain Records

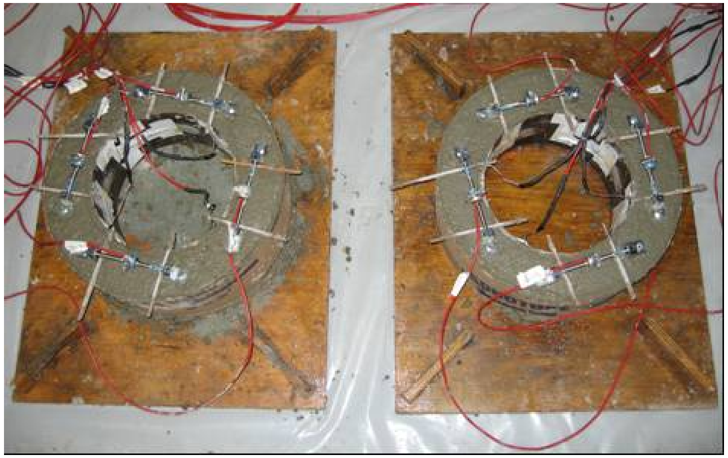
- Structural Testing System
  - Clamp-on gages
  - 100 Hz Data Sampling

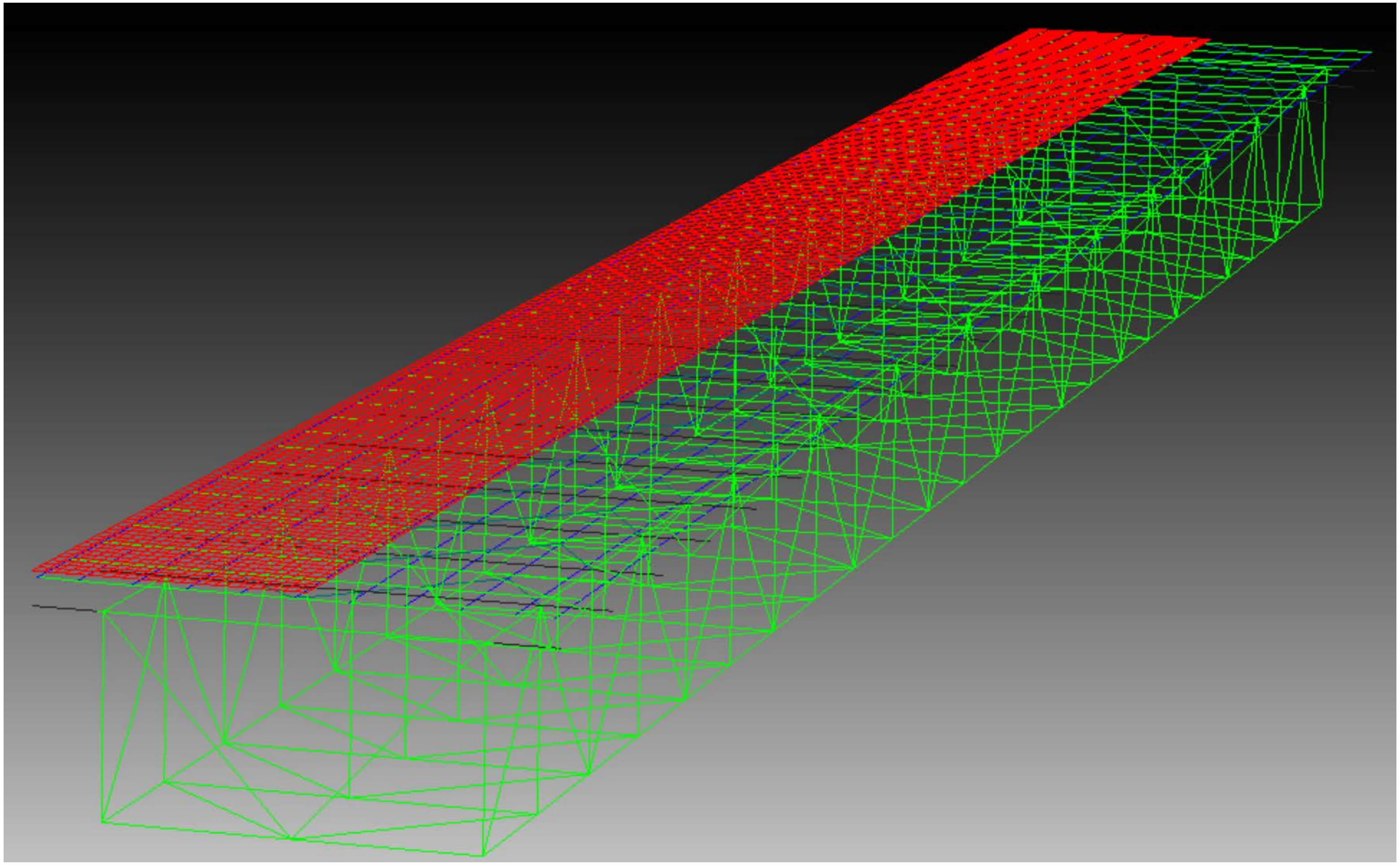

S7 bottom strain at Bay 1,2,3,and 4
6111- Bay 4
5088 - Bay 3
5116 - Bay 2
6258 - Bay 1
Strain
120
100
80
60
40
20
0
-20
-40
3800
3850
3900
3950
4000
4050
4100
4150
Time

RESTRAINED SHRINKAGE

- This was rule out because the concrete were properly cured as indicate by the restrained ring test performed in the laboratory.





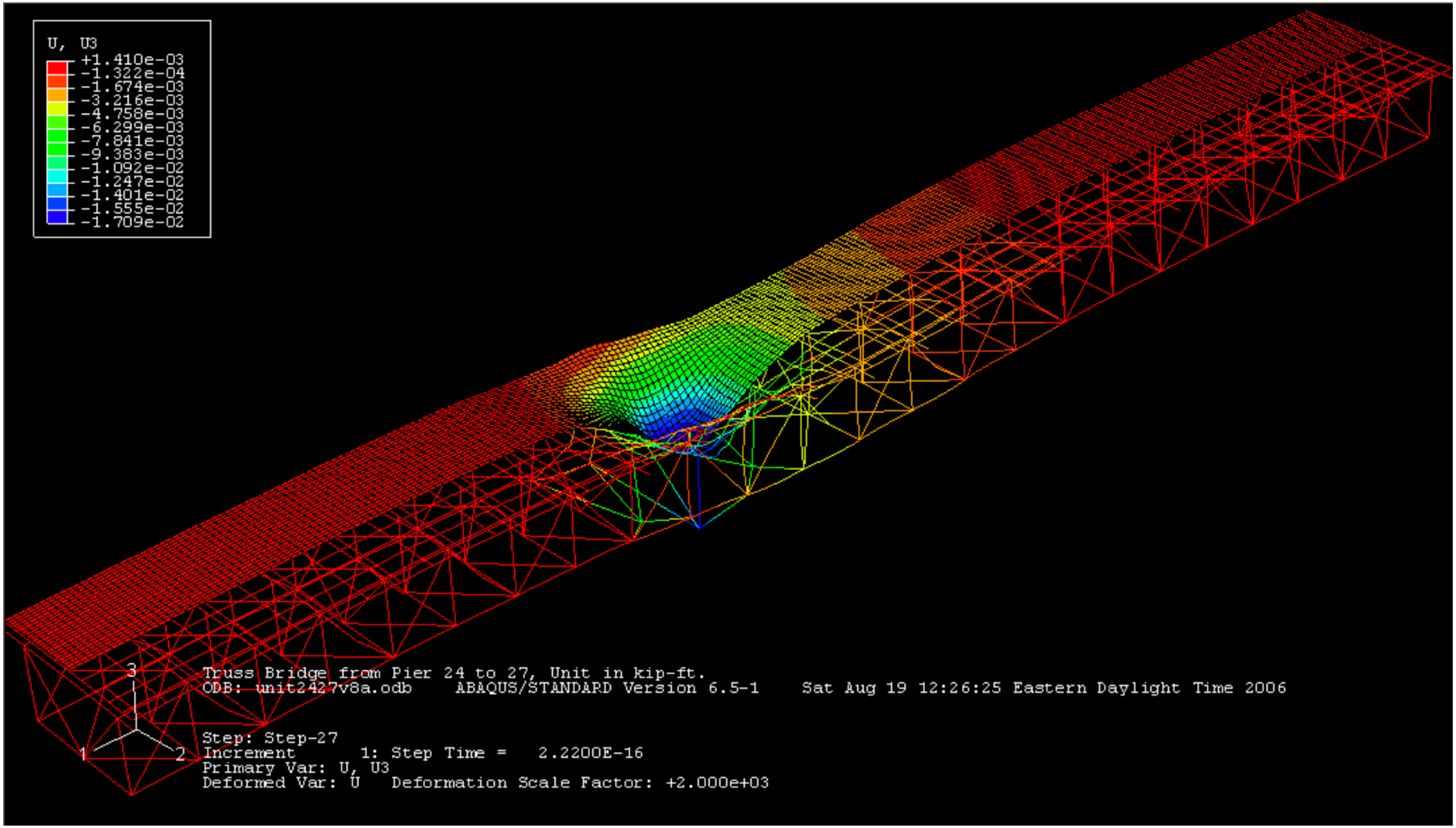


- ***Only existing deck is modeled to simulate actual behavior***

Model Validation and Analysis

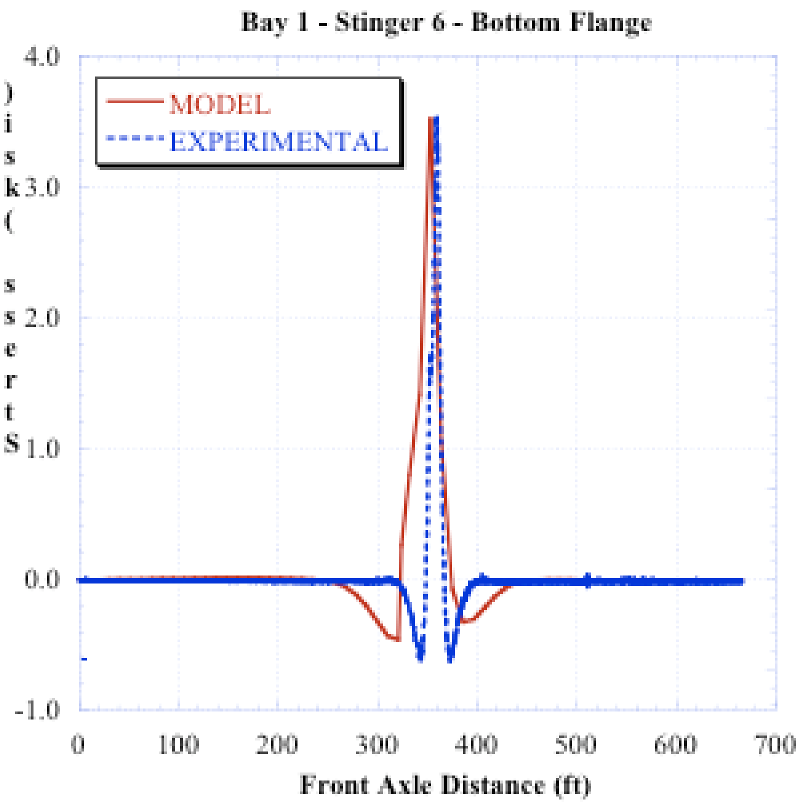
- Each test case was run on the model using the truck weight and dimensions obtained in the field

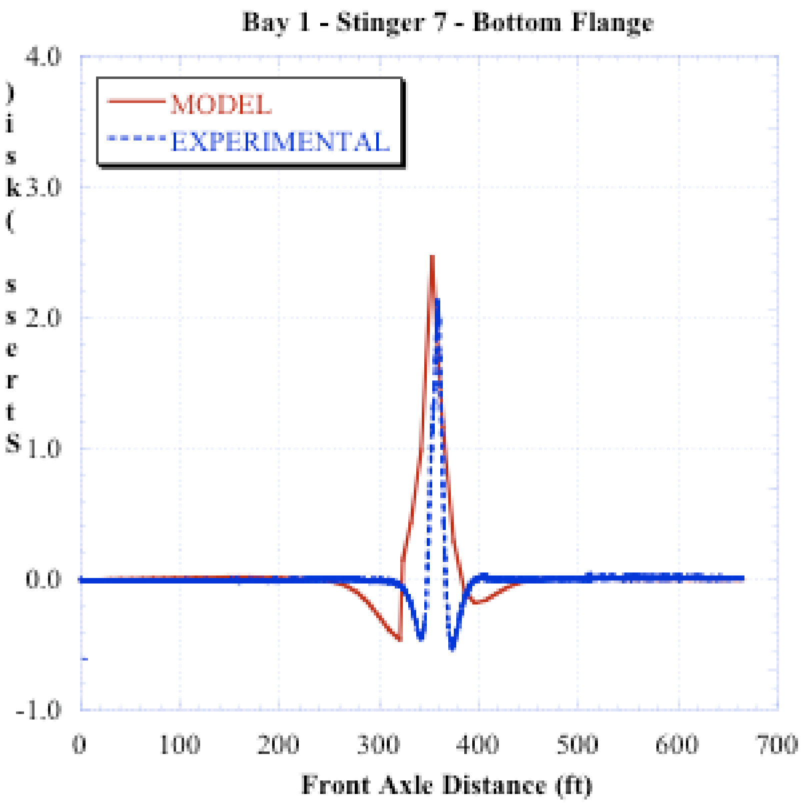
Figure: Deformation Contours

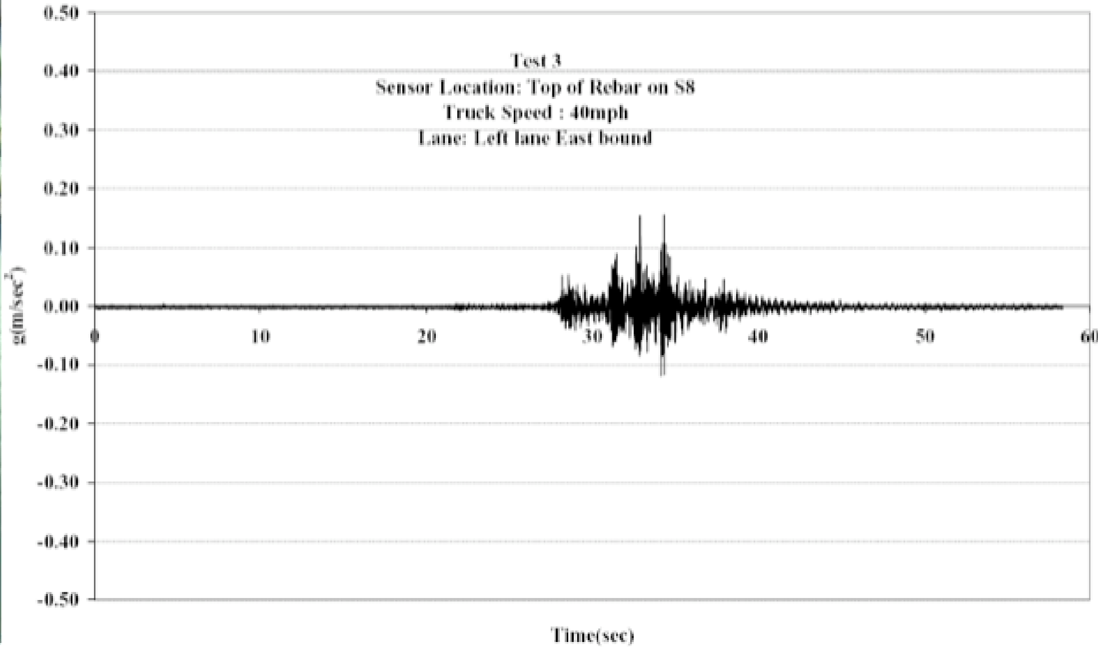


Results and Comparison

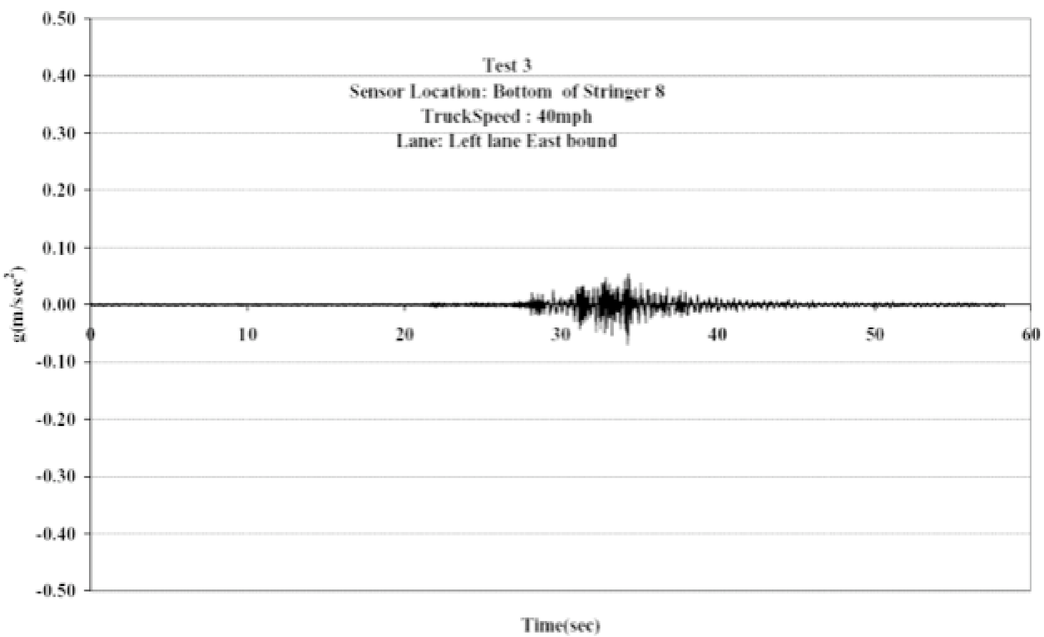
- West Bound Right Lane Runs



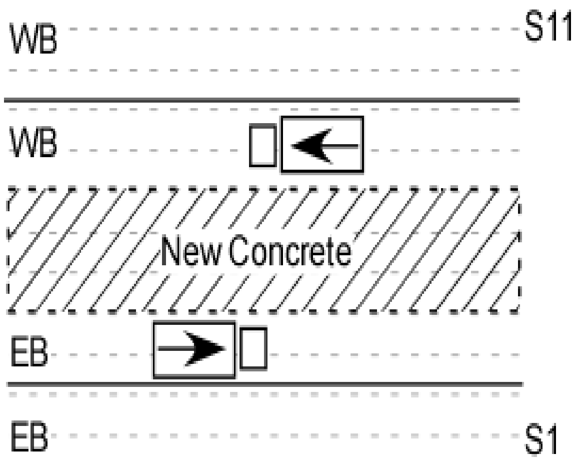




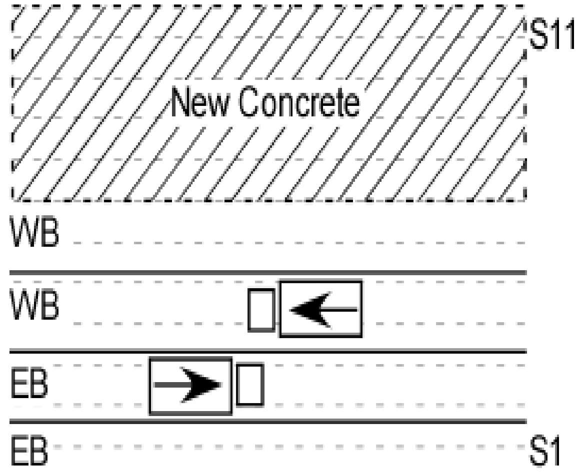
Rebar Vibration



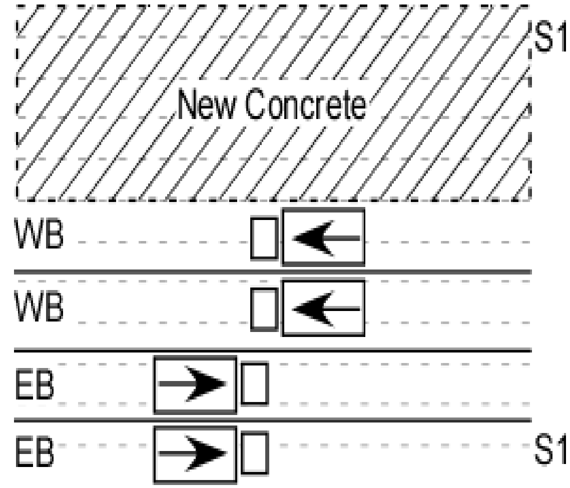
LOAD CASES



Case 1

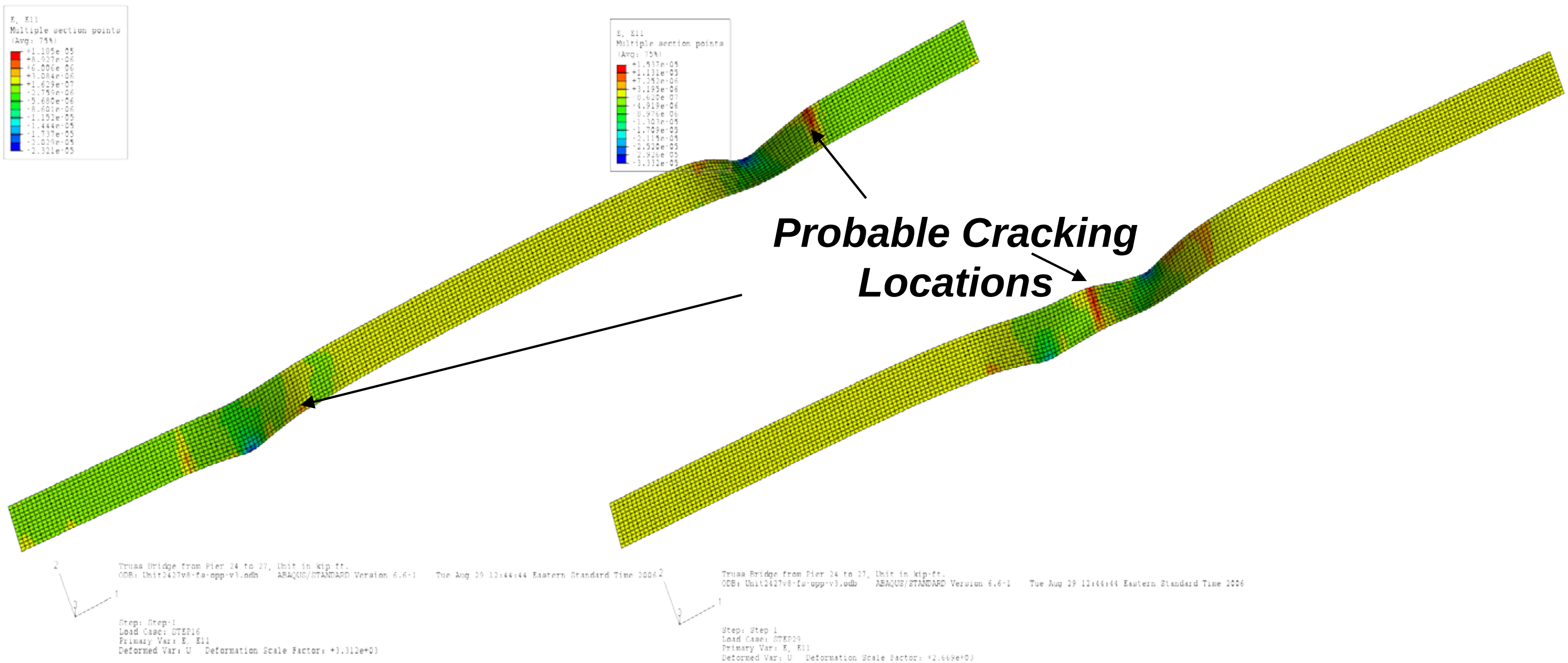


Case 2

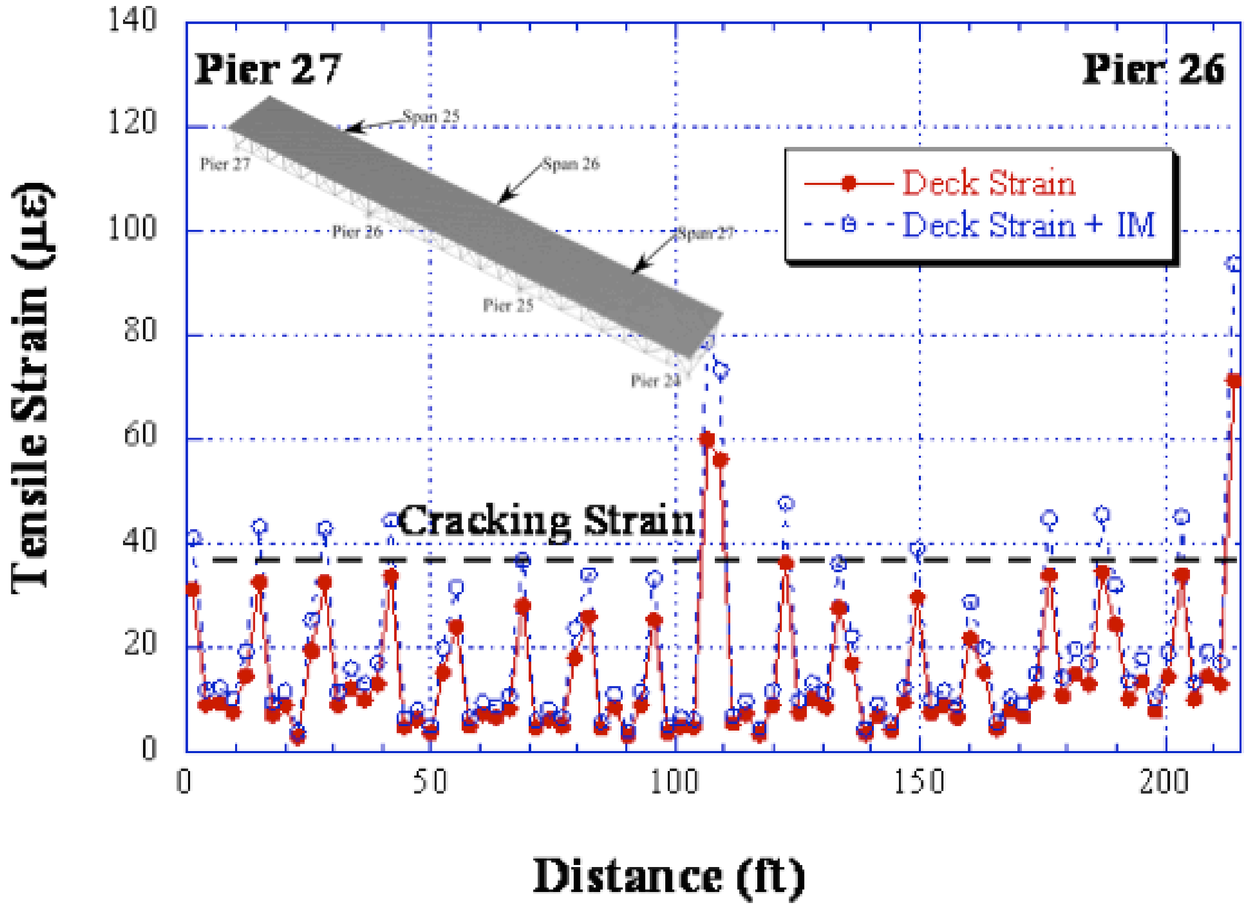


Case 3

CASE 1



Superimposed concrete deck strain on Span 27 at 12 hours when one 78.7 kips 4-axle and one 50 kips 3-axle dump trucks travel westbound side-by-side; and one 50 kips 3-axle dump truck travels eastbound on the left lane



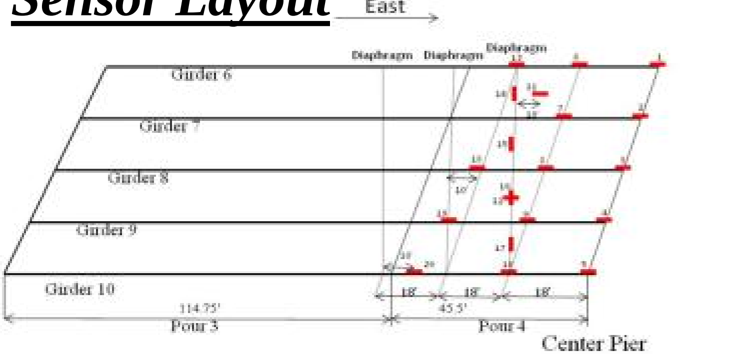
SUMMARY (P0.00 Bridge)

- Based on results, the cracks on the bridge could be attributed to the truck traffic adjacent to the fresh concrete.
- Closing traffic to adjacent lanes of the pour could significantly reduce cracking.
- The cracking could be controlled by increasing the compressive strength at early-age (namely at 8 hours).
- It is recommended that the concrete should have at least a minimum of 2000 psi compressive strength at 1 day or more specifically 1000 psi at 8 hours.

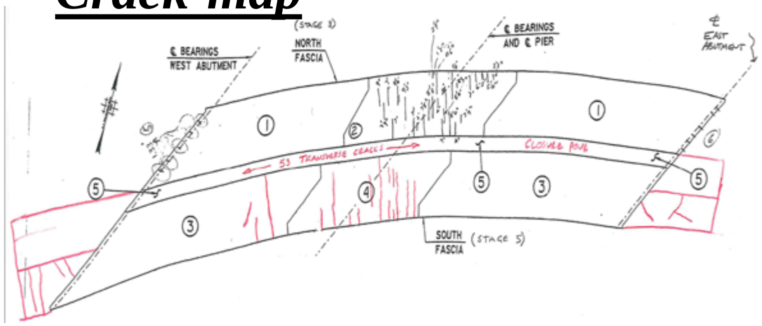
Case Study 3 – Exit 16E Bridge (NJTA)

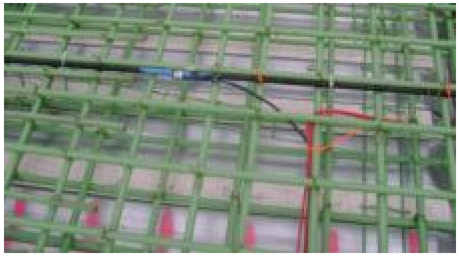
- Objective
  - To monitor strain and temperature during and after placement and under traffic loads

Sensor Layout



Crack-map

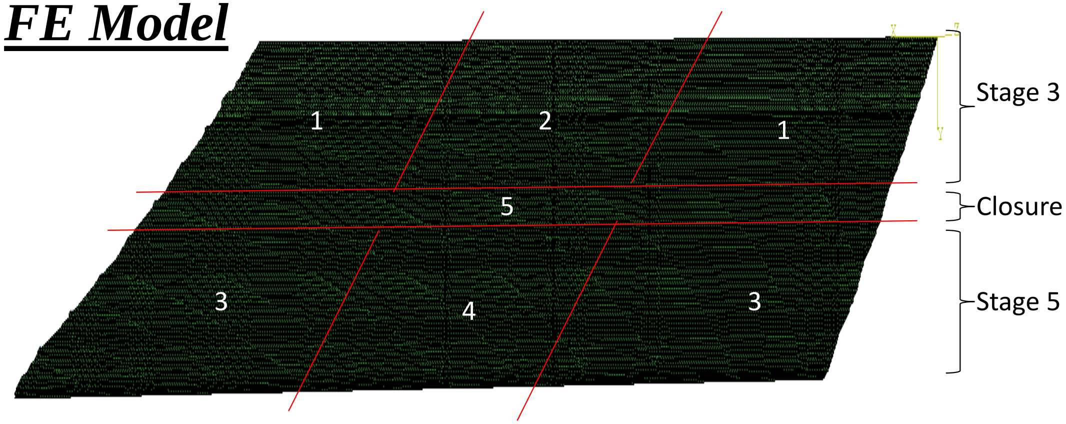


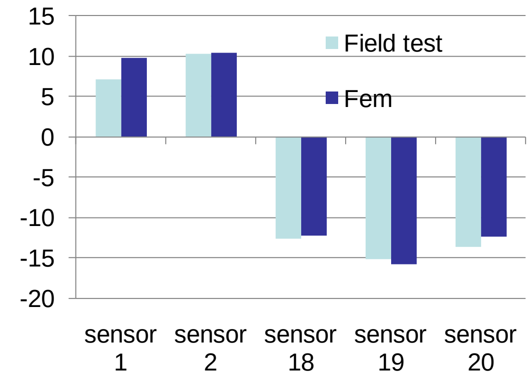


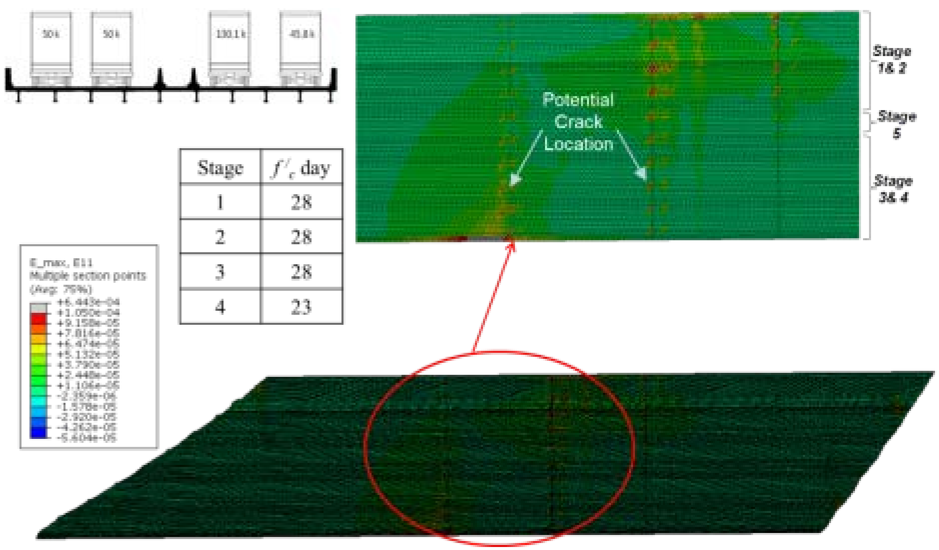
Sensor Instrumentation

Finite Element Analysis and Calibration Test

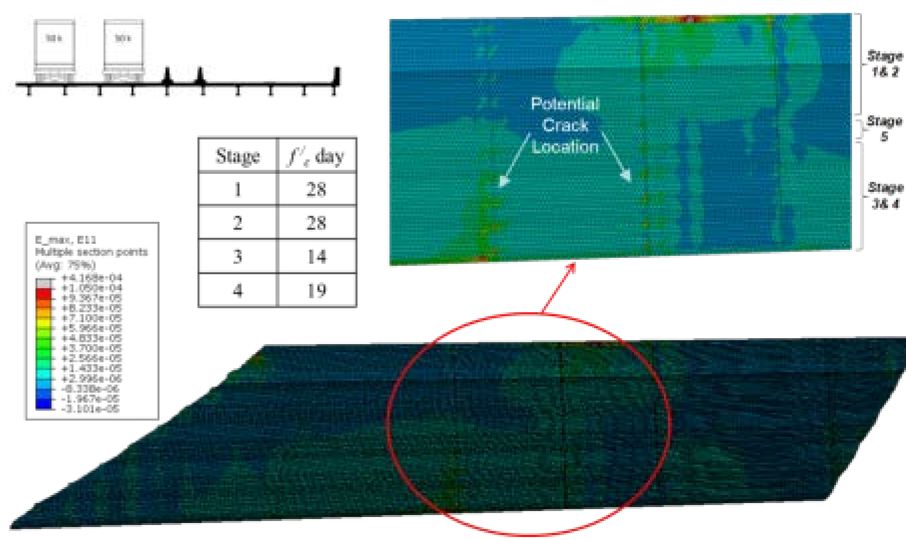
FE Model





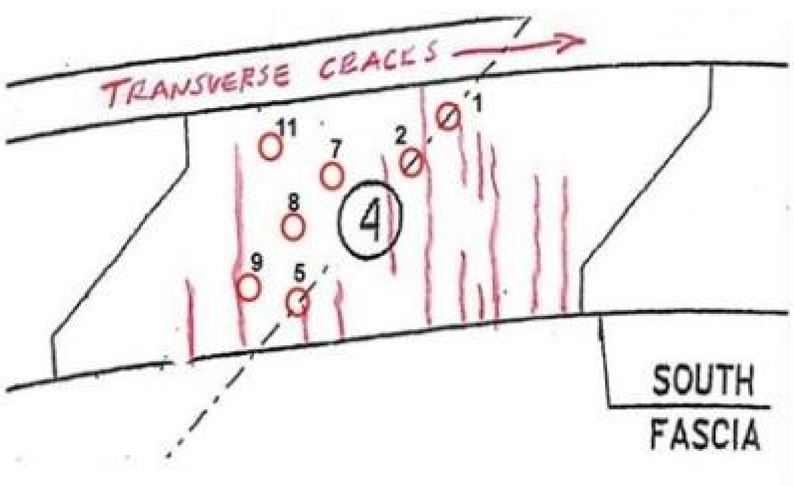


Stage	f'_c day
1	28
2	28
3	28
4	23

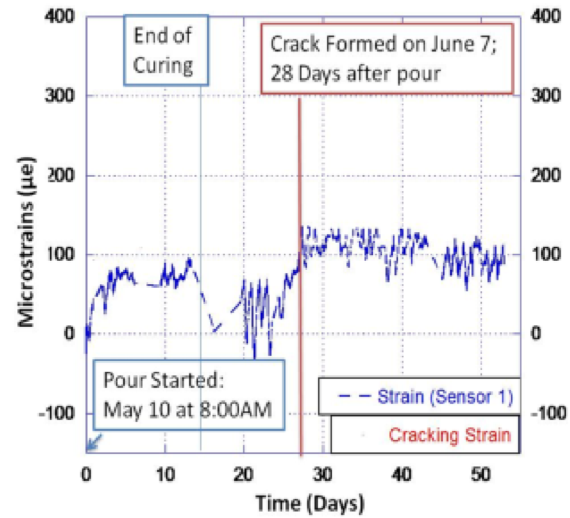


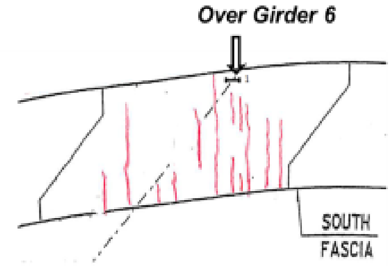
Stage	f'_c day
1	28
2	28
3	14
4	19

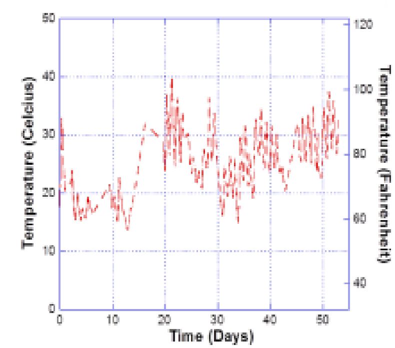
Field Monitoring Results

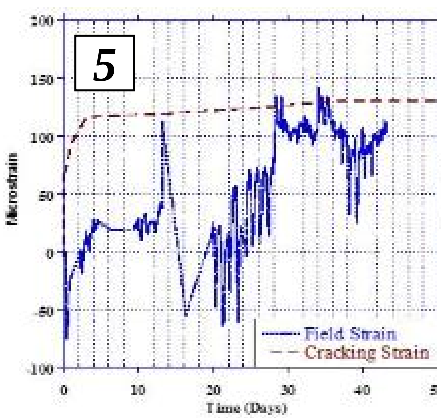


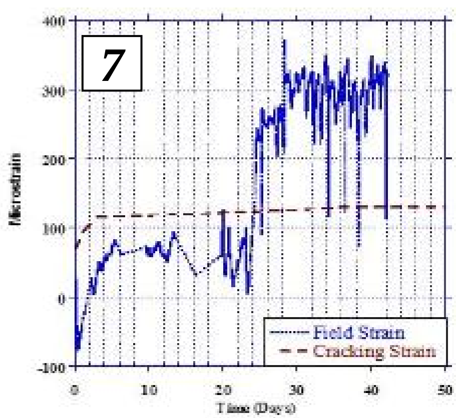
Crack map and sensor location

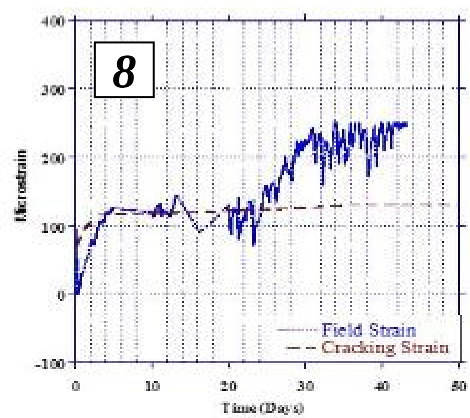


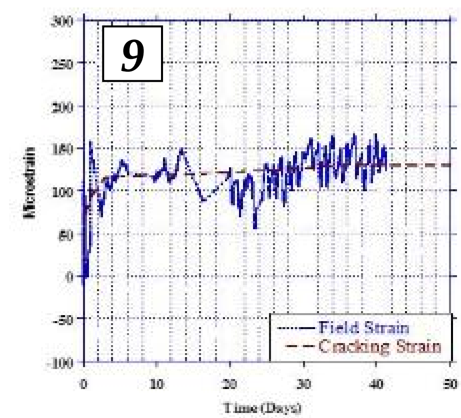






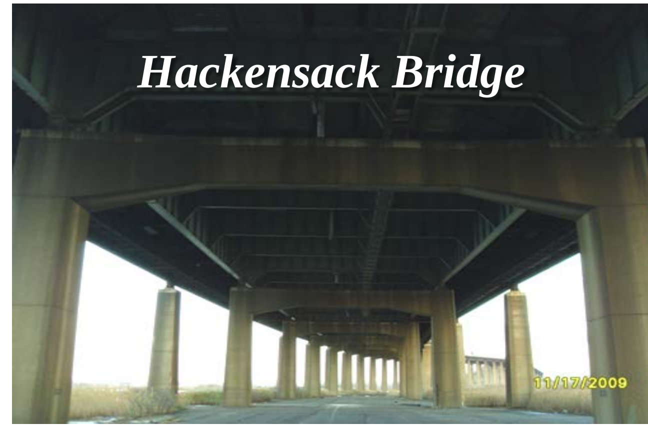




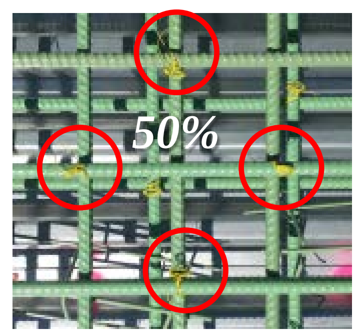


Case Study 4 – Easterly Hackensack Bridge (NJTA)

- Objective
  - Rebar tie-down reduces the relative movement of mats (top/bot.).
  - To monitor the effect of tie-down on bridge behavior during pouring.

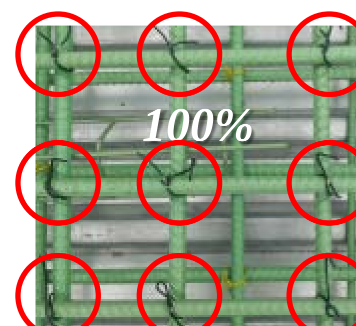


Accelerometers on rebars



50% tie-down

LDV (Laser Doppler Vibrometer)



100% tie-down

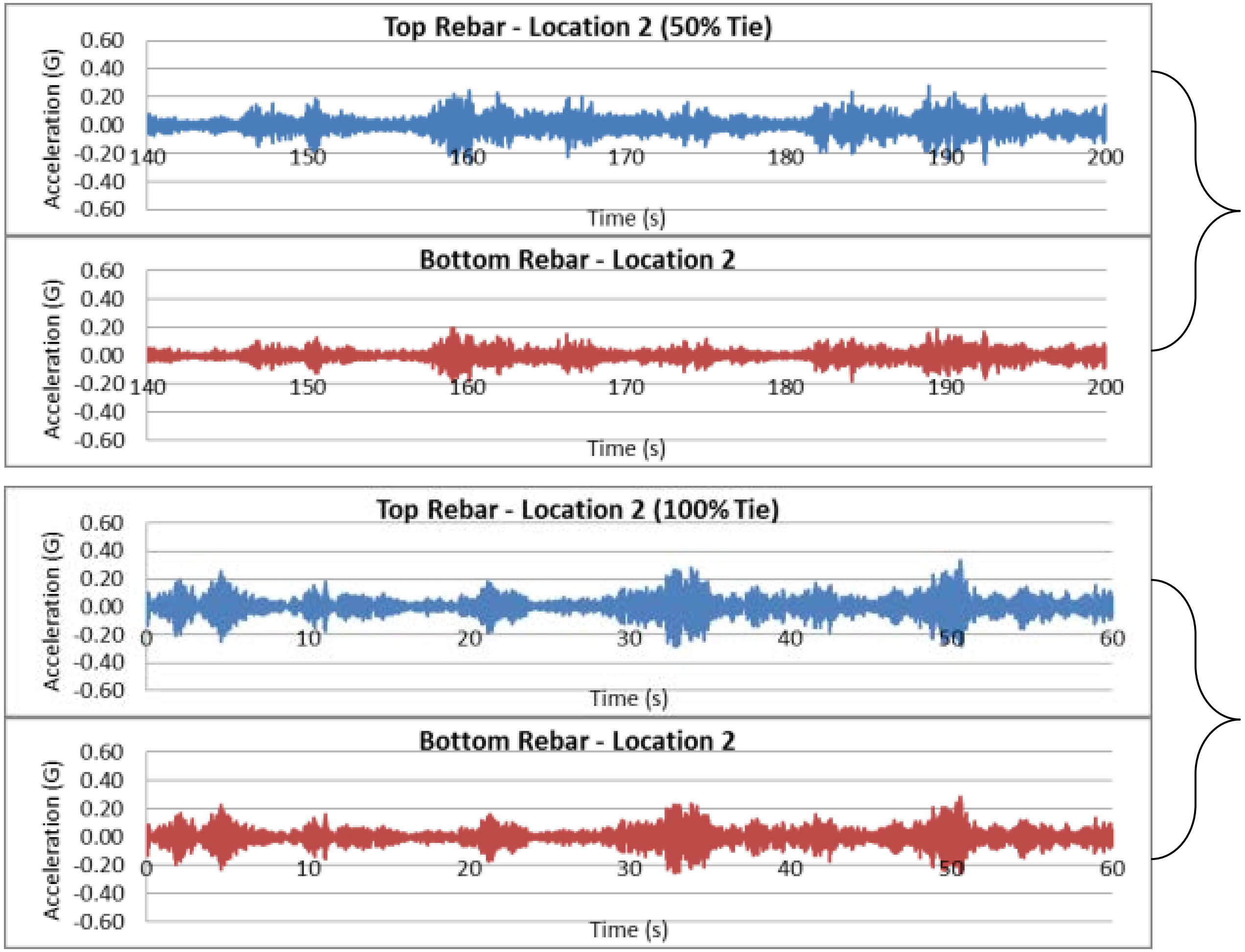
Field Testing and Monitoring

- Part I
  - Accelerometers were attached to rebars on the top and bottom reinforcement layers, at 50% and 100% tiedown locations
  - Acceleration data was collected during a peak traffic period.
- Part II
  - Acceleration was monitored for the rebars and superstructure for following periods:
    1. Immediately before concrete pouring
    2. During pouring
    3. 3-hour curing age
    4. 3-day curing age
  - Velocity and displacement were monitored for Girder WN5 using a portable Laser Doppler Vibrometer (LDV)
  - LDV tests were conducted simultaneously with the rebar and superstructure acceleration tests

Monitoring Results

50% Tiedown

100% Tiedown

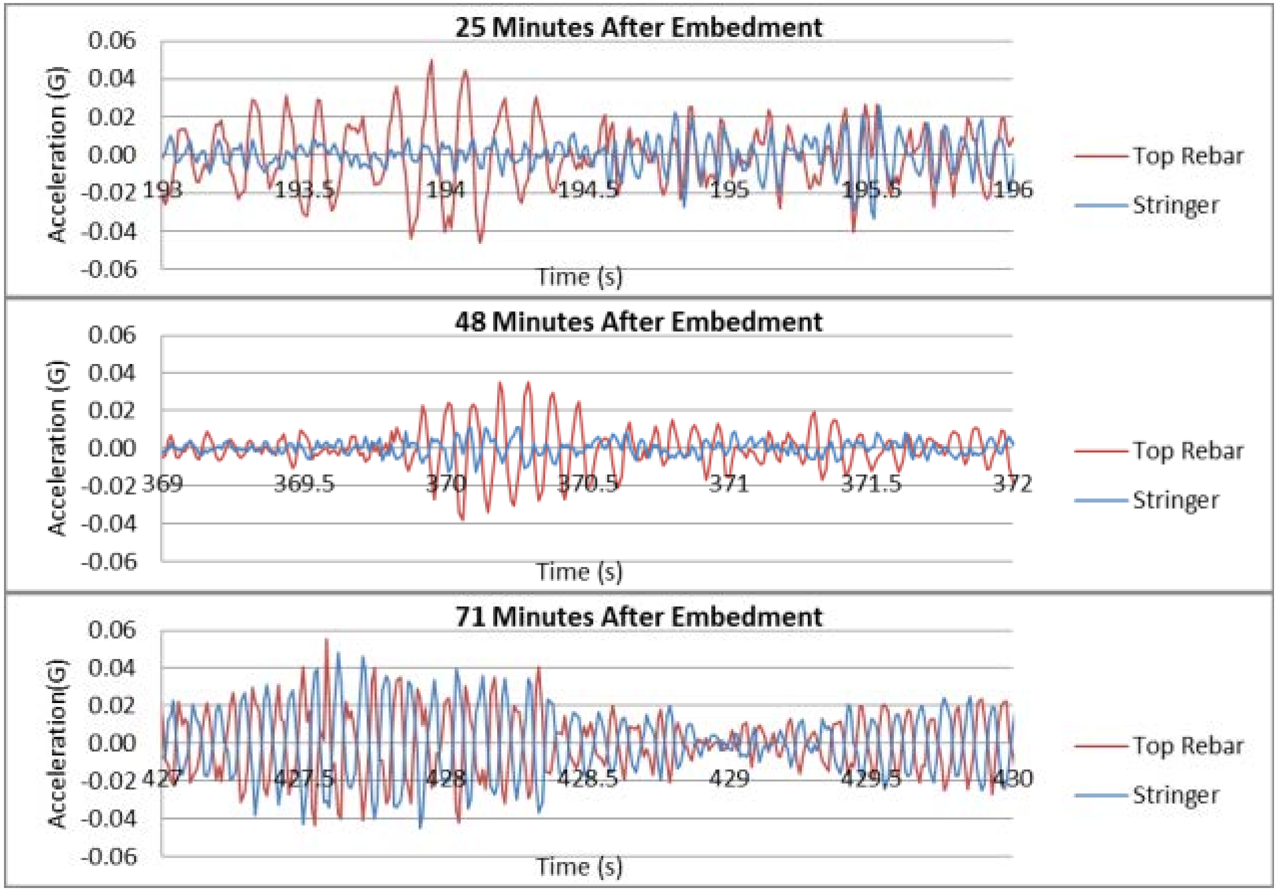


Acceleration Ratio = 70% (bottom/top)

Acceleration Ratio = > 90% (bottom/top)

- All rebar intersections are recommended to tie-down when the rebar spacing is more than 12 inches.

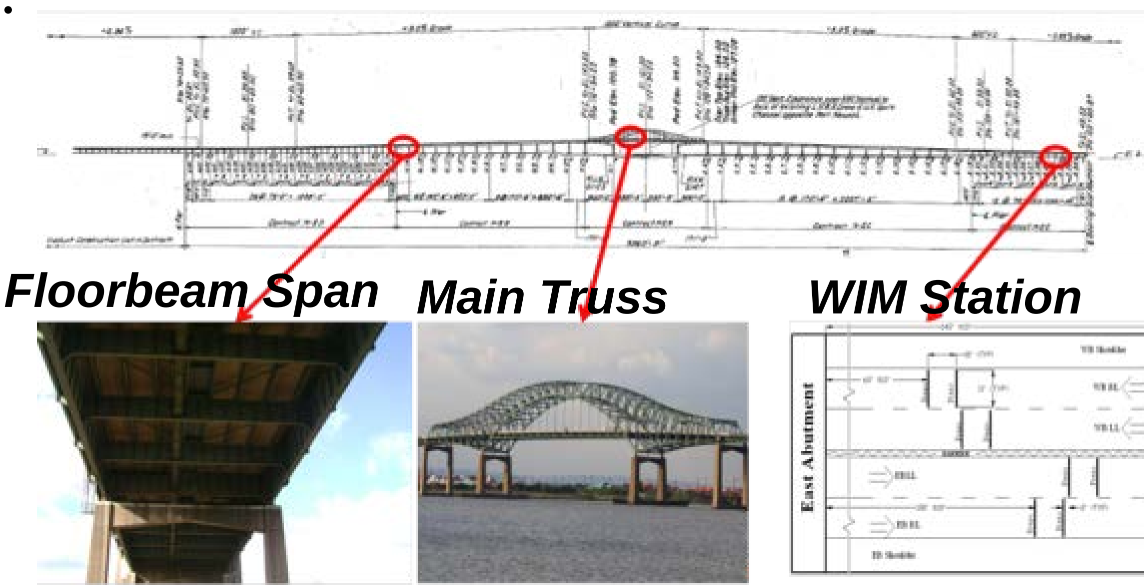
Monitoring Results



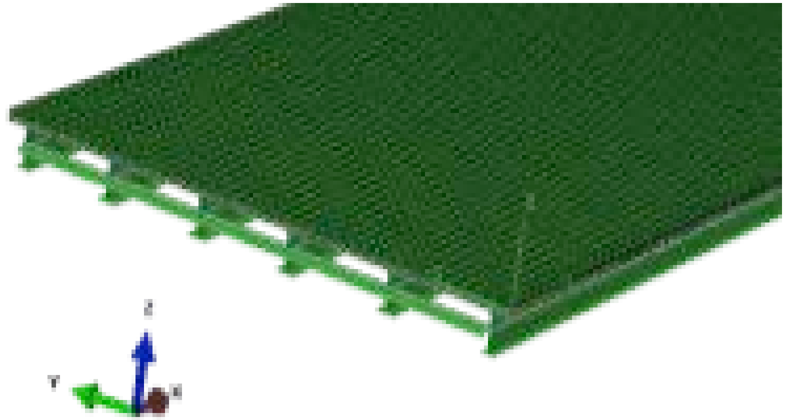
- Stringer vibration was not significant, which confirms that truck loading induces vibration of the rebar relative to the deck.

Case Study 5 – Newark Bay Bridge (NJTA)

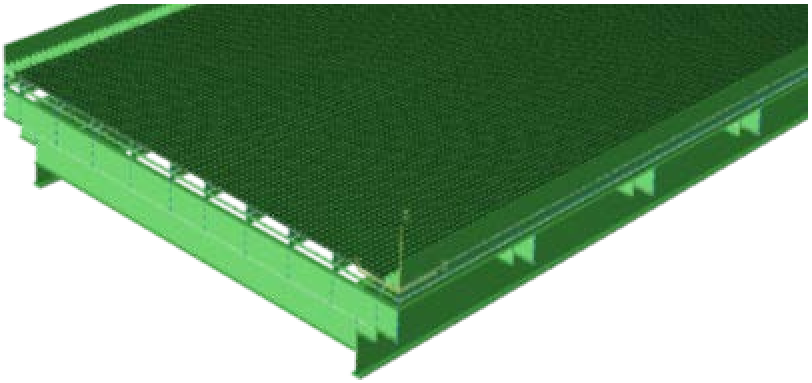
- Objective
  - Monitor the structural behavior during fabrication of pre-cast panel and under live load.
  - Evaluate the shrinkage strain of HPC for precast panel.
  - Evaluate the corrosion of epoxy coated and stainless steel rebars.



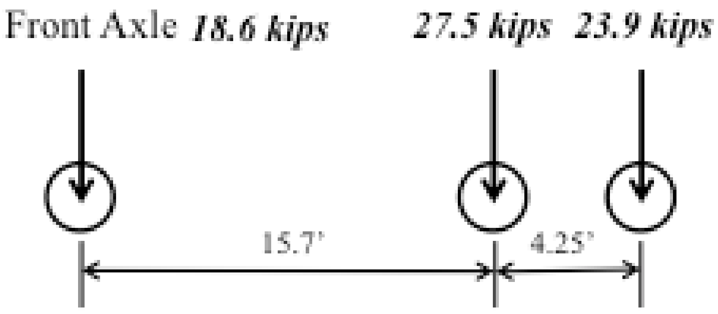
Bridge Calibration



Span W15 Beam Span

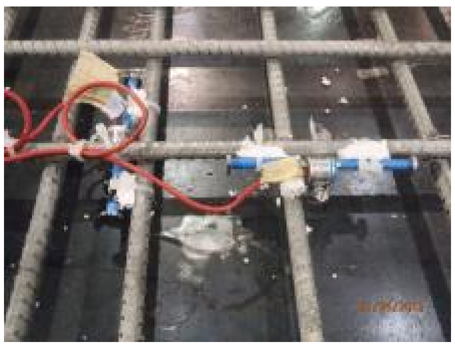


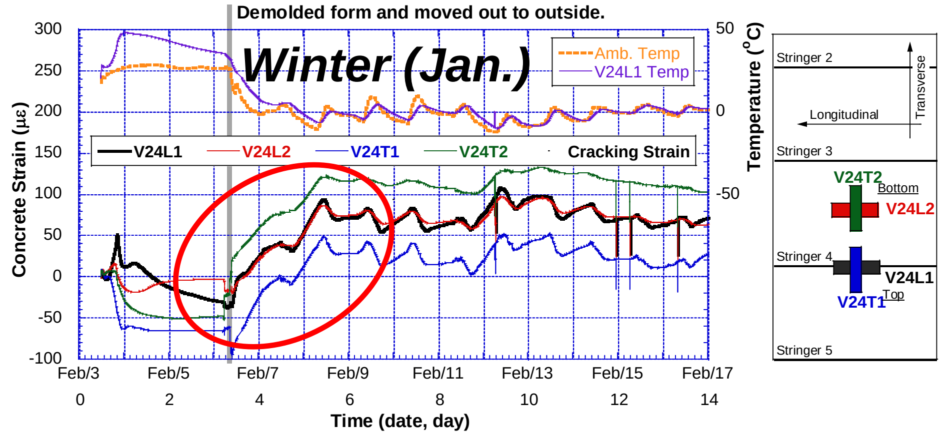
Span W13 and W14 Floorbeam System Span

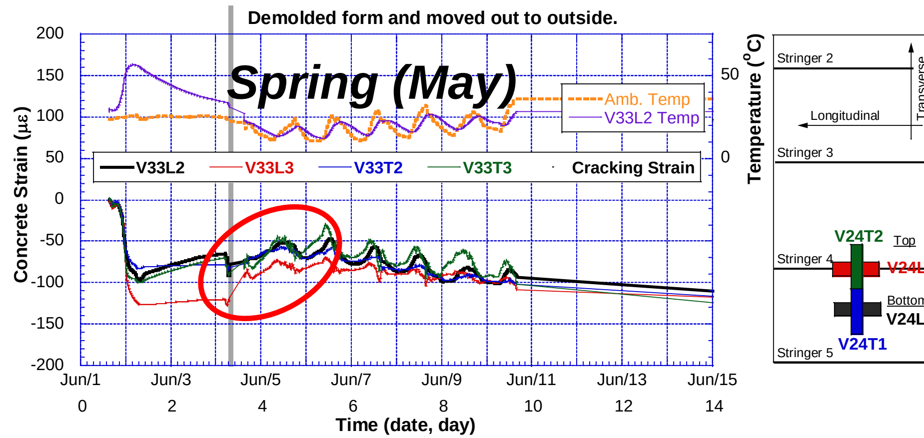


GVW=70kips

Monitoring during Fabrication

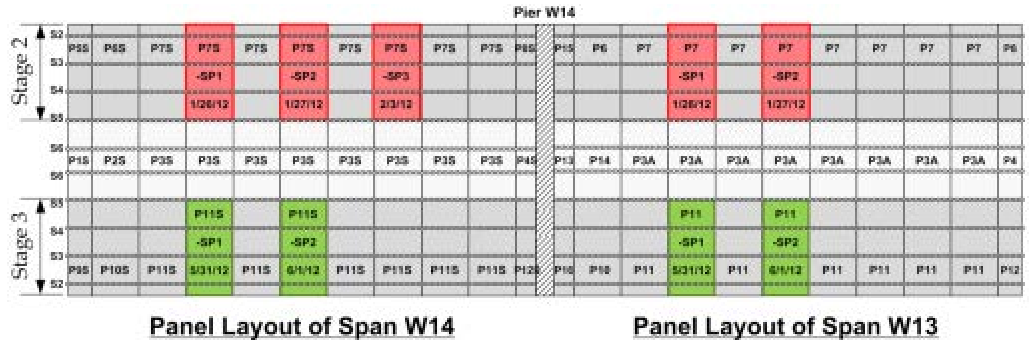


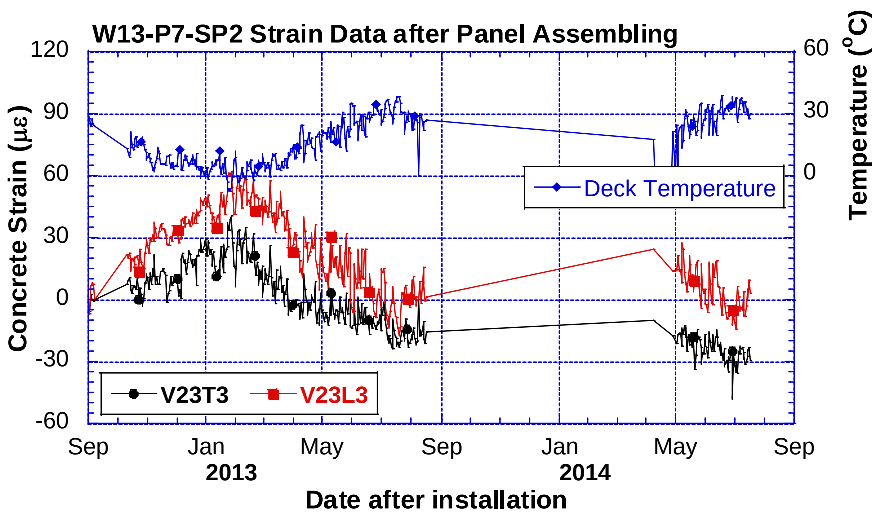


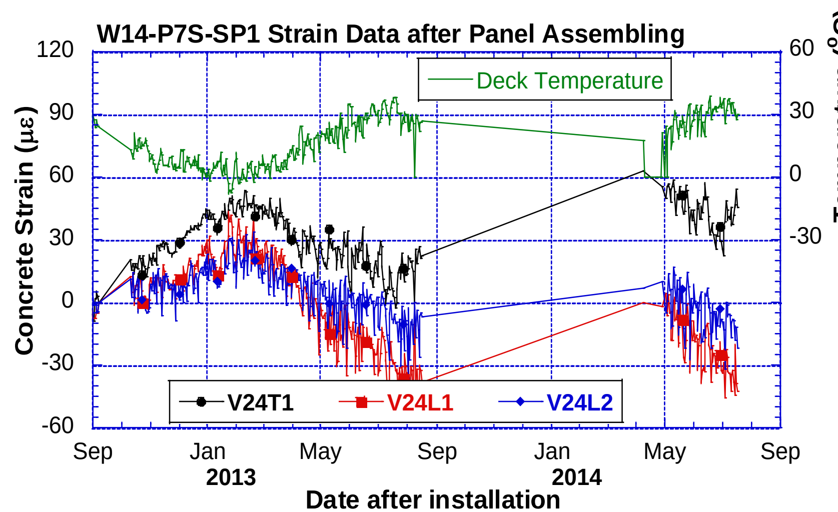


- Higher Strains were observed when precast panels were cast during winter-time, because of the thermal shock.

Monitoring after Fabrication



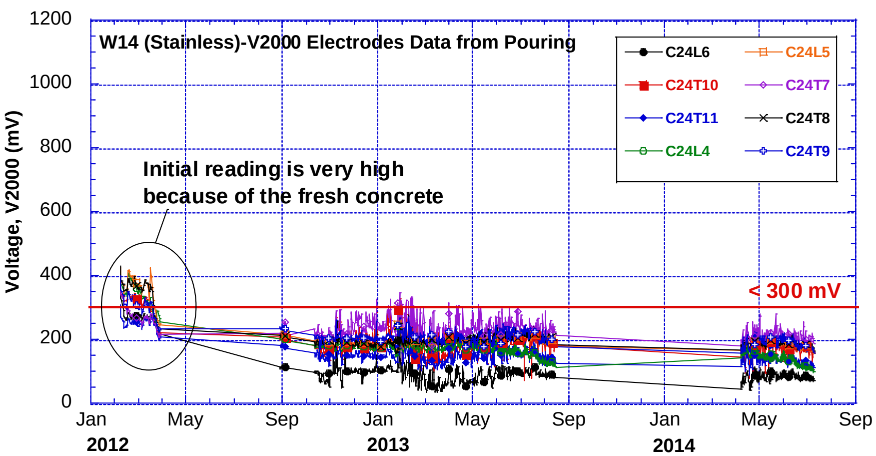




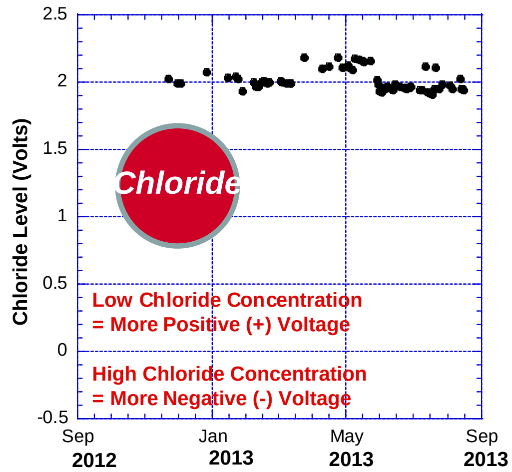
- A gradual change in concrete deck strain was observed, mainly due to seasonal thermal changes.

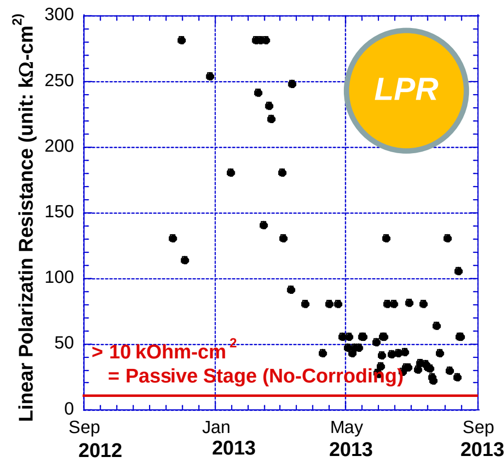
Monitoring after Fabrication

V2000 Sensor



ECI-2 Sensor





Range	Comment
< 300 mv	No corrosion activity is present.
300~400 mV	The passivation layer of steel is being damaged, and corrosion has begun.
> 400 mV	Corrosion is fully active on the rabar.

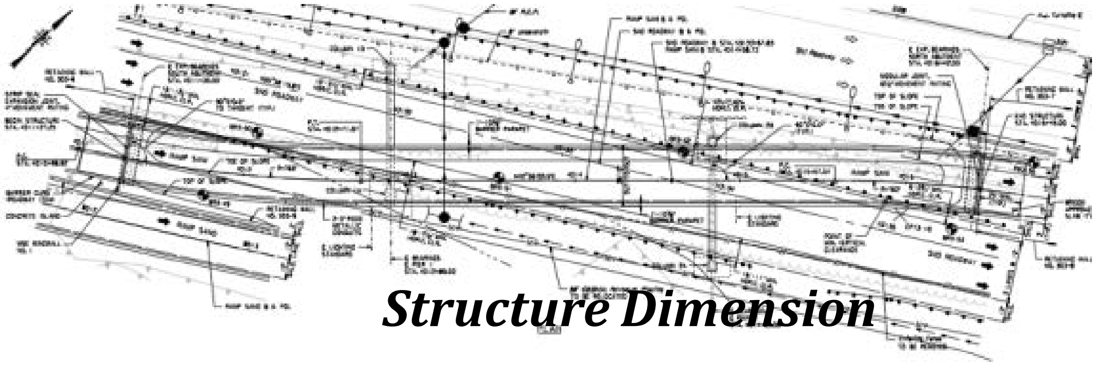
Function	Current Reading	Range no corrosion	Status
LPR	20 ~ 280	> 10 KΩ-cm²	No
Resistivity	100	> 20 KΩ-cm	No
OCP	1.4 ~ 1.8	> – 0.28 V	No
Chloride	1.8~2.3	positive	No

Overall Judge = No Corrosion

Case Study 6 – Structure No. 59.05 (Exit 7A) NJTA

- Objective
  - To identify the Extensive cracks observed on the concrete deck.
  - To determine the causes of cracking.


Str. 59.05, Fly-over ramp at Exit 7A on New Jersey Turnpike


Structure Dimension

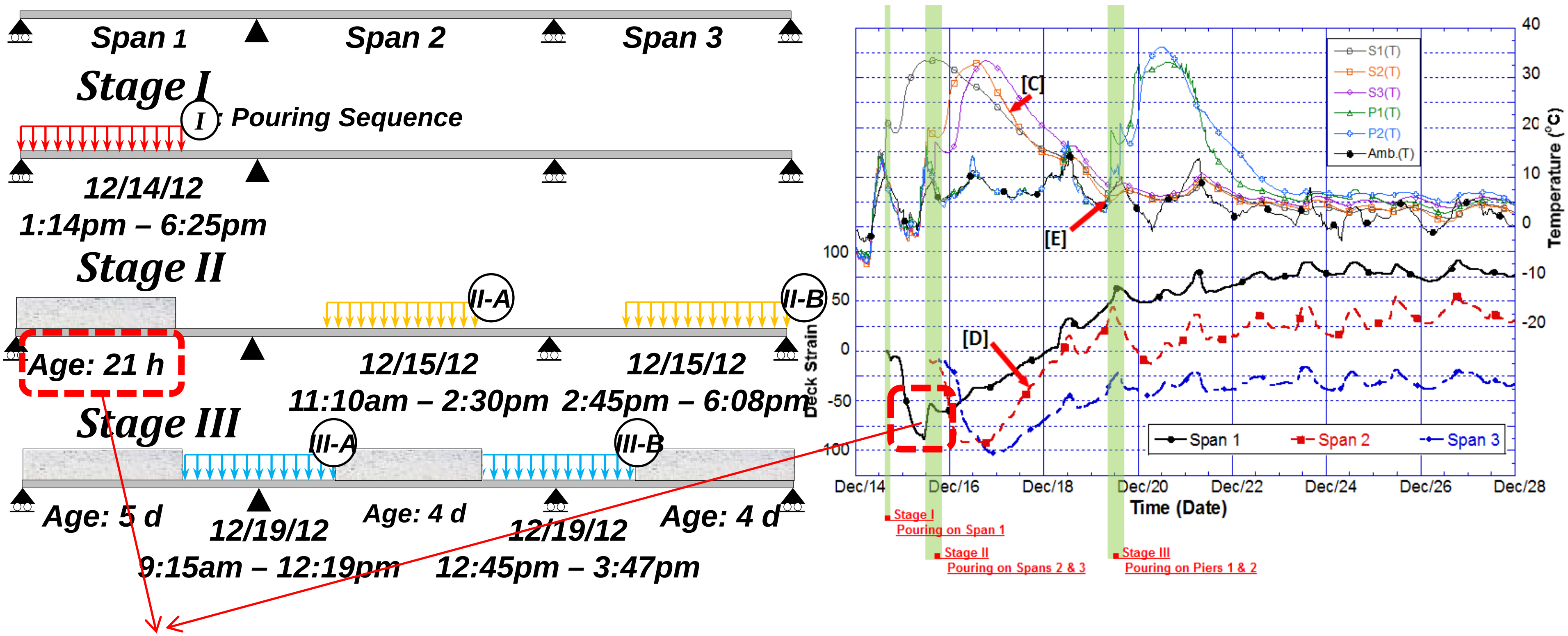

Observed Crack


VWSG in the deck


VWSG on the girder

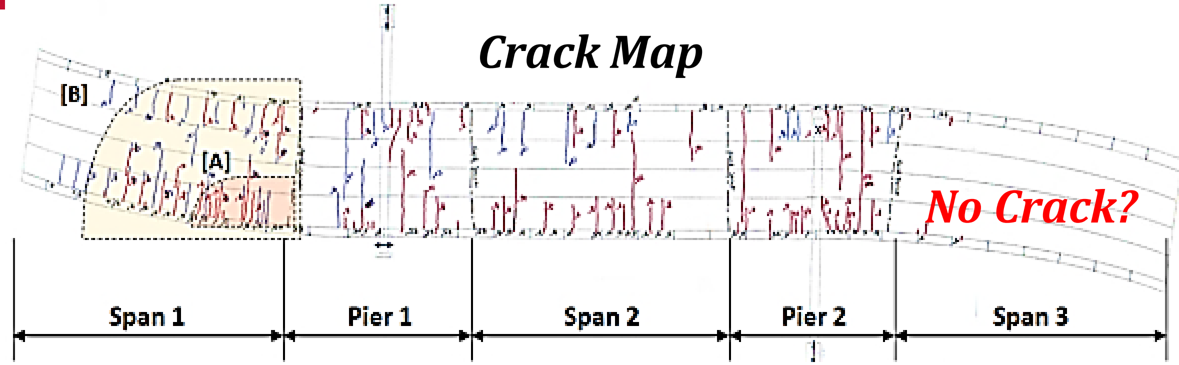
Thermometer

Staging Effect

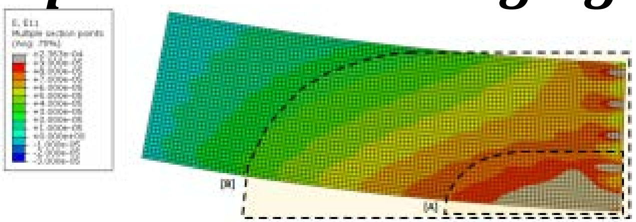


- At Stage II, the concrete deck at Stage I was at 21 hours after pouring, and the estimated strength was less than 2,000 psi.
- The upward camber due to Stage II resulted in sudden increase of deck strain on Span 1.

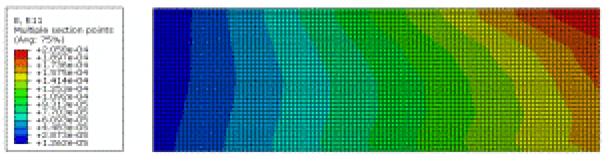
Various Effects



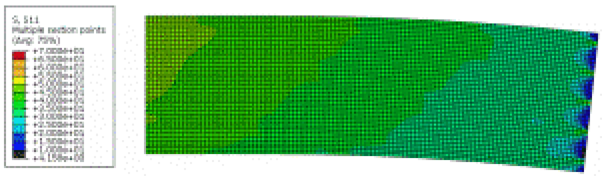
Span 1 : Due to Staging



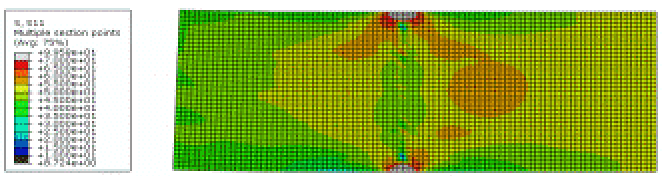
Span 2 : Due to Staging



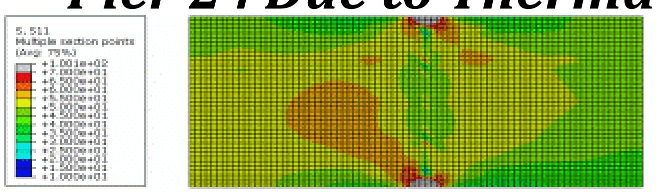
Span 3 : No crack



Pier 1 : Due to Thermal

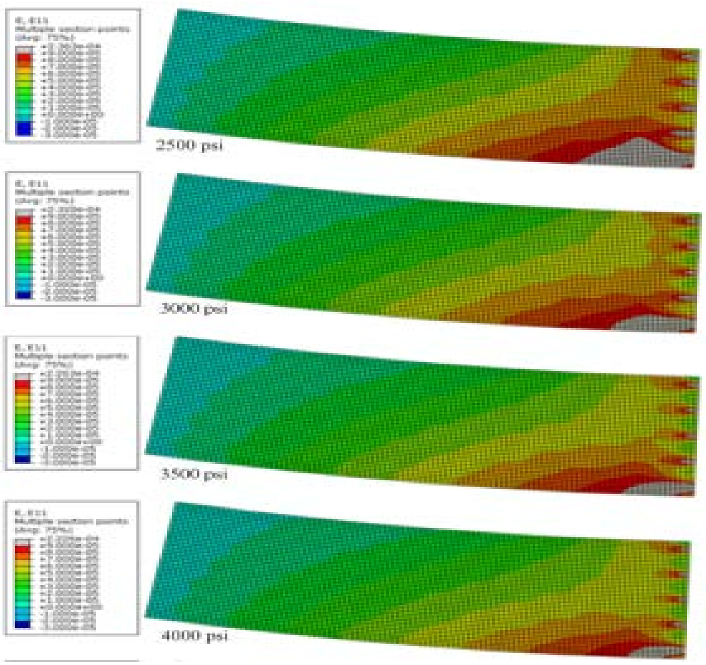


Pier 2 : Due to Thermal

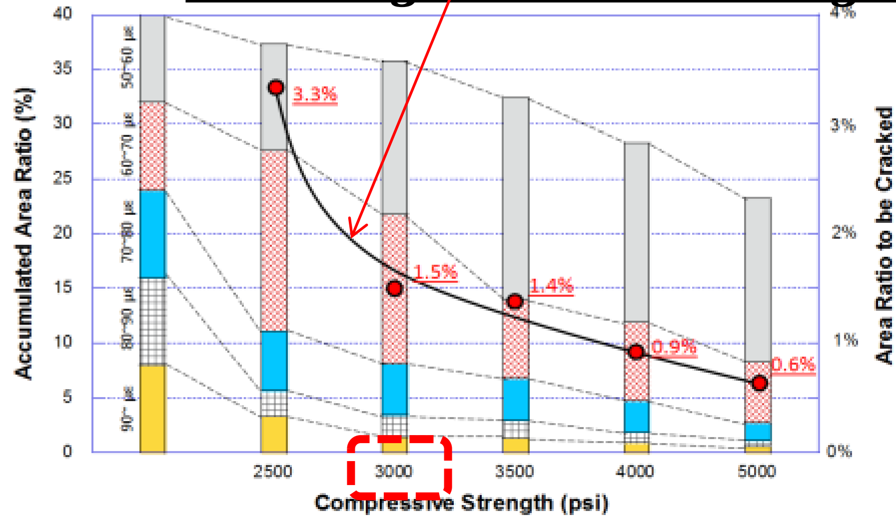


Effects	Maximum Strain (με)				
	Span 1	Pier 1	Span 2	Pier 2	Span 3
Staging	> 100	0	> 100	0	-5
Curing	-	-	25	-	-
Shrinkage	24	24	24	24	24
Thermal	55	85	65	85	54
Parapet	-4	6	-4	6	-3
Summary	**> 175**	**115**	**> 210**	**115**	**70**

Recommendations



Area to be cracked decreases according to concrete strength.

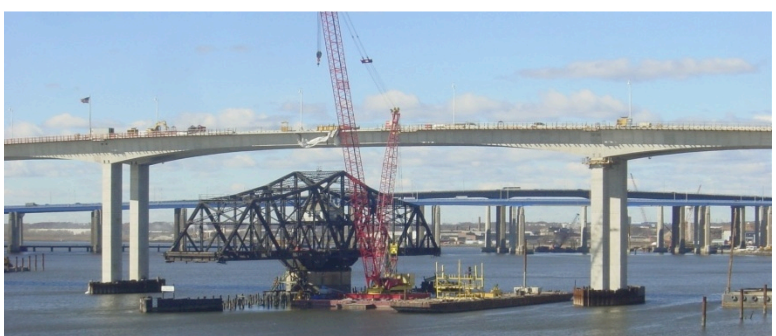


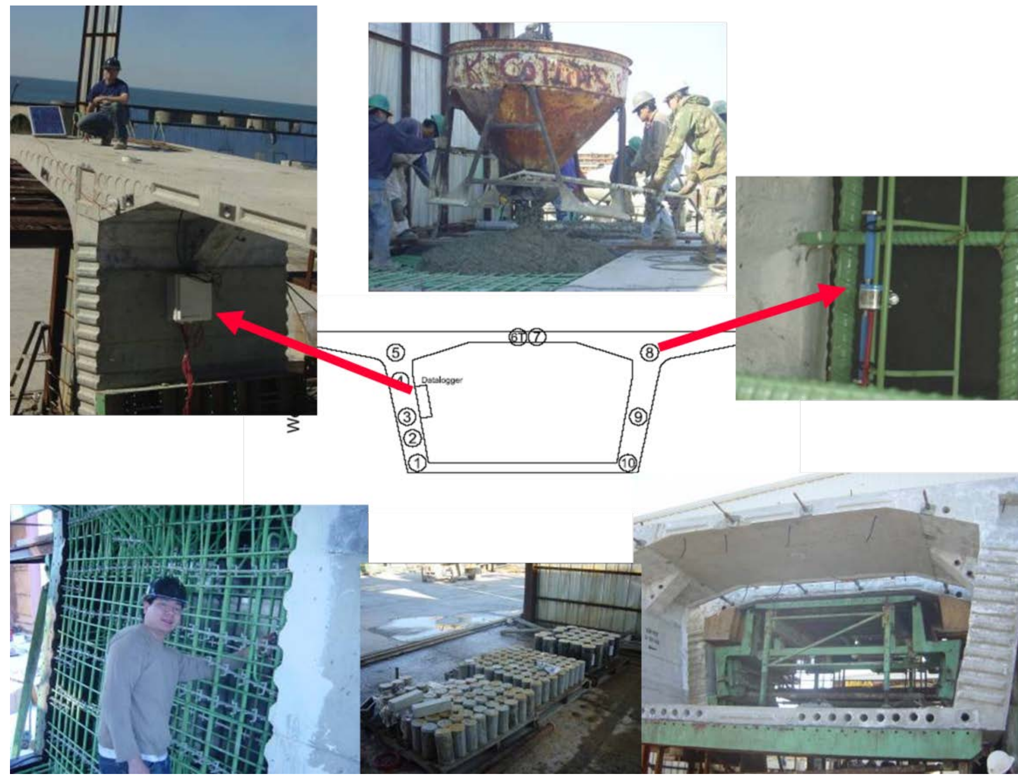
- ***A minimum of 3,000 psi is required to minimize the cracks due to staging.***

- Current Spec. of New Jersey Turnpike Authority.
  - No guideline of pouring sequence or interval.
- Recommended Spec. to NJTA.
  - No concrete pouring will be permitted on any adjacent section until the concrete strength have attained over 3,000 psi.

Case Study 7– Victory Bridge (NJDOT)

Victory Bridge during Construction

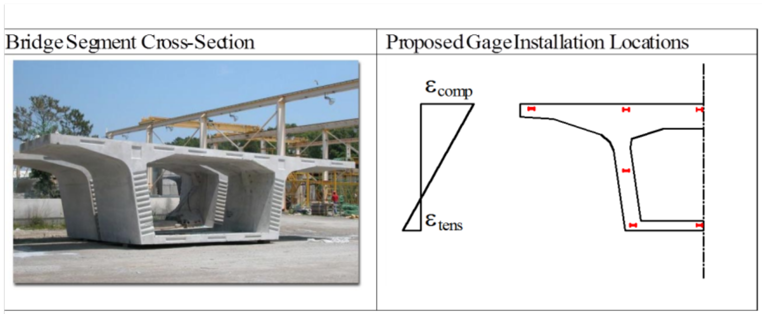


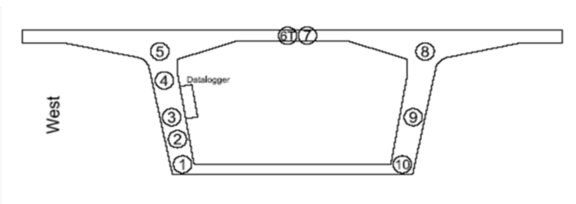


Sensor, datalogger instrumentation, and concrete sample collection

Field Instrumentation and Laboratory Testing

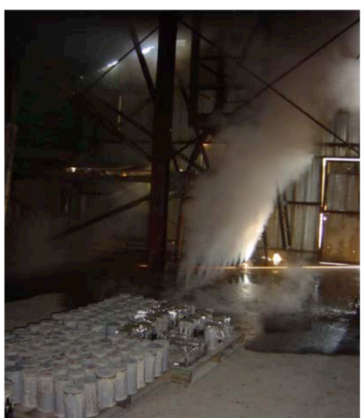
Sensor Locations





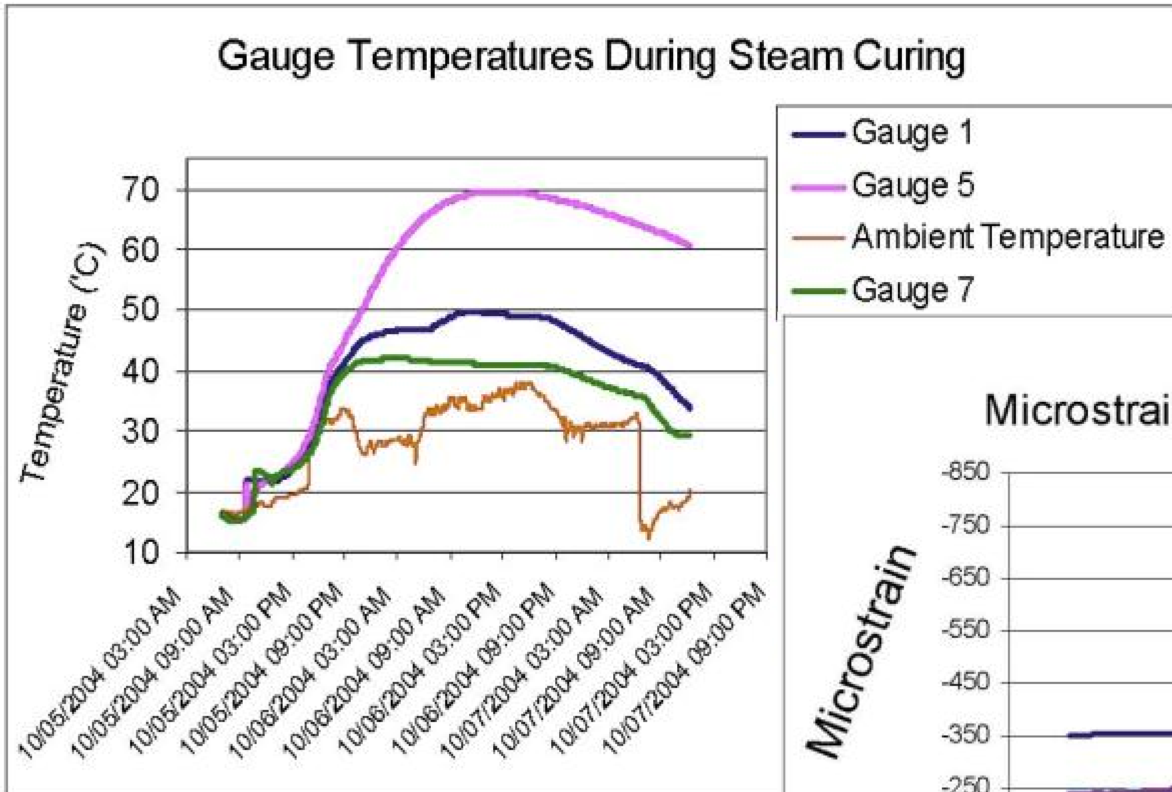
Sampling

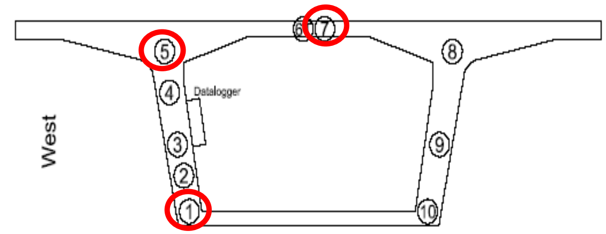
Steam Curing

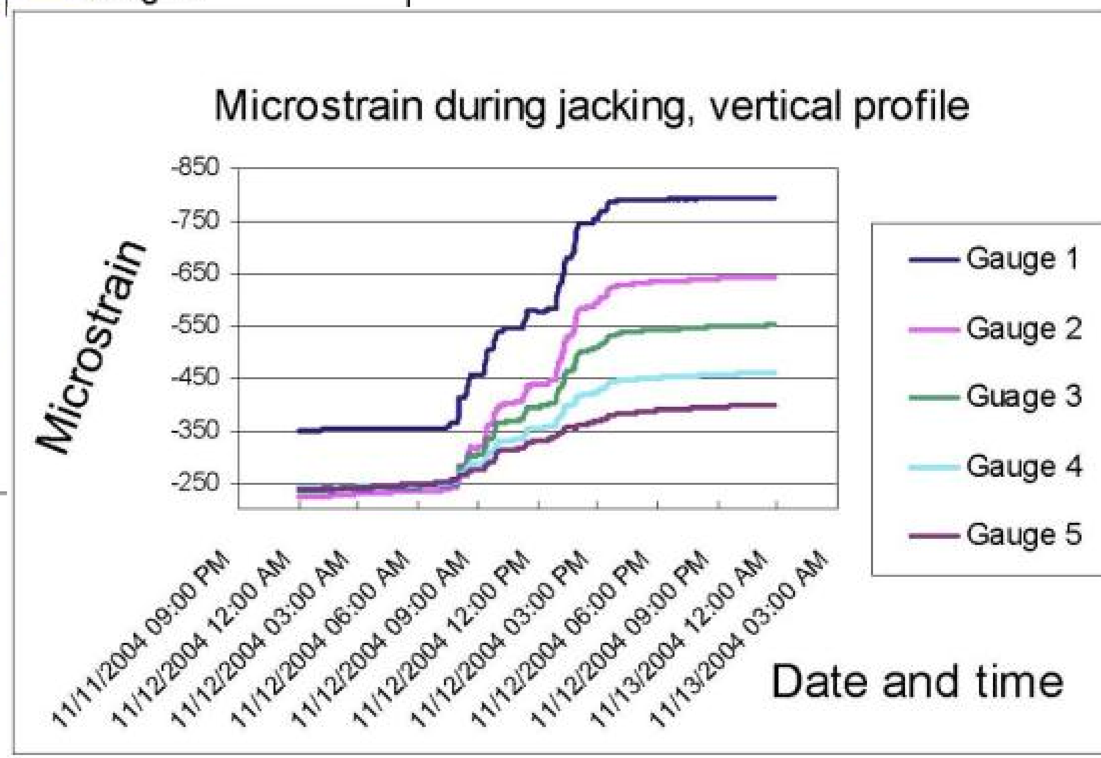


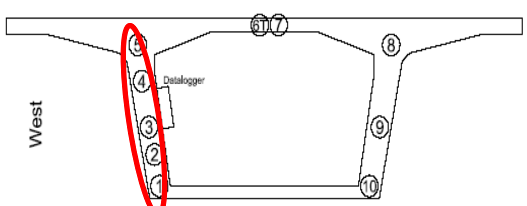
Compressive Creep Test

Temperature during Steam Curing
Concrete Strain during Jacking

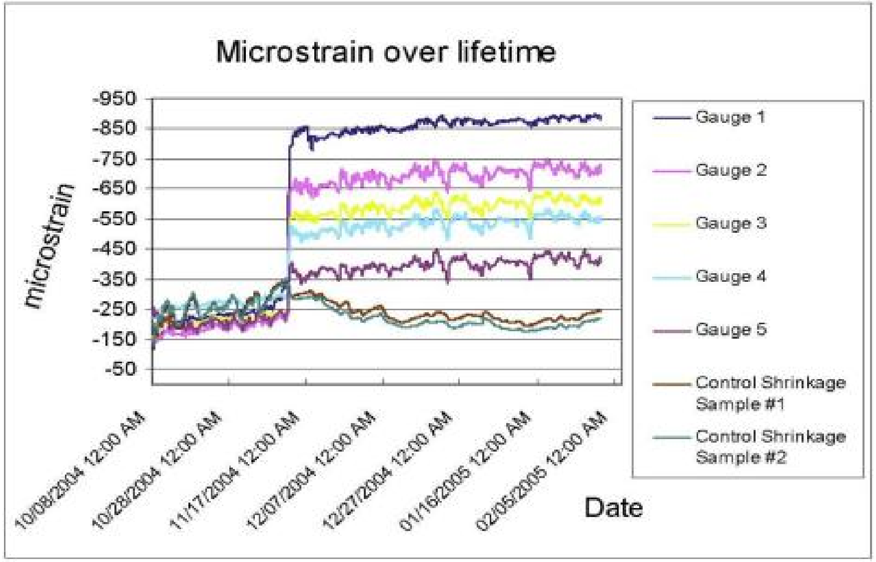


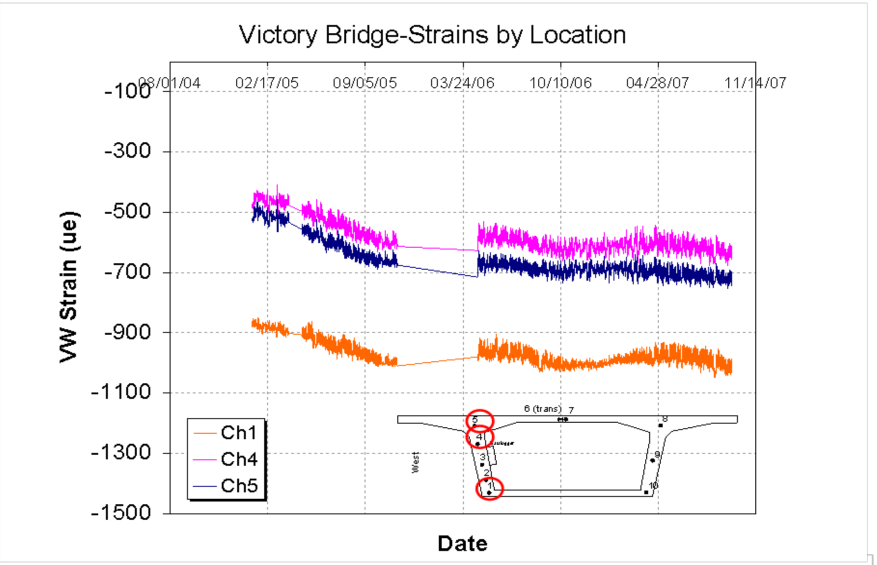


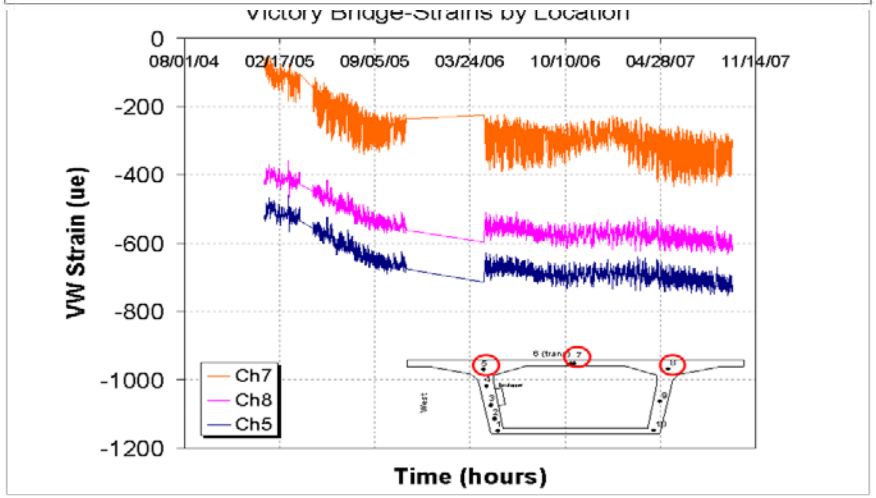


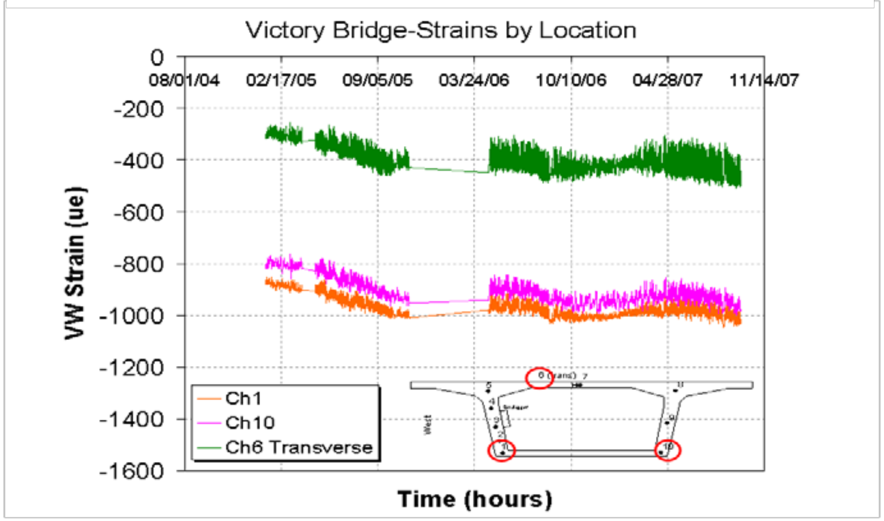


Concrete Strain after Jacking









Summary and Conclusions

- SHM is a good and economical alternative to provide engineers with a better understanding of the structural interaction, as well as the causes of cracking, excessive deflection/vibration, or even structural failure.
- SHM could be used as an early warning system prior to an impending structural failure.
- SHM could also be used for the re-evaluation and load rating, as well as in maintenance, management, and rehabilitation programs of existing structures.

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Thank you !