Complementing Visual Inspection with Technology Tools and Heuristics for Bridge Condition Evaluation and Asset Management

FHWA EARP Program Research: Virtual Laboratory for Technology Leveraging

STATE OF NEW JERSEY

NEW JERSEY DEPARTMENT OF TRANSPORTATION
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STRUCTURE NO. 1618-150

US 202 & NJ 23 OVER US 202 (MOUNTAIN VIEW BLVD.), RAMPS M & N, AND NORFOLK SOUTHERN RAILROAD

WAYNE TOWNSHIP, PASSAIC COUNTY

12TH CYCLE

APRIL 18, 2008

Objectives of the Study:

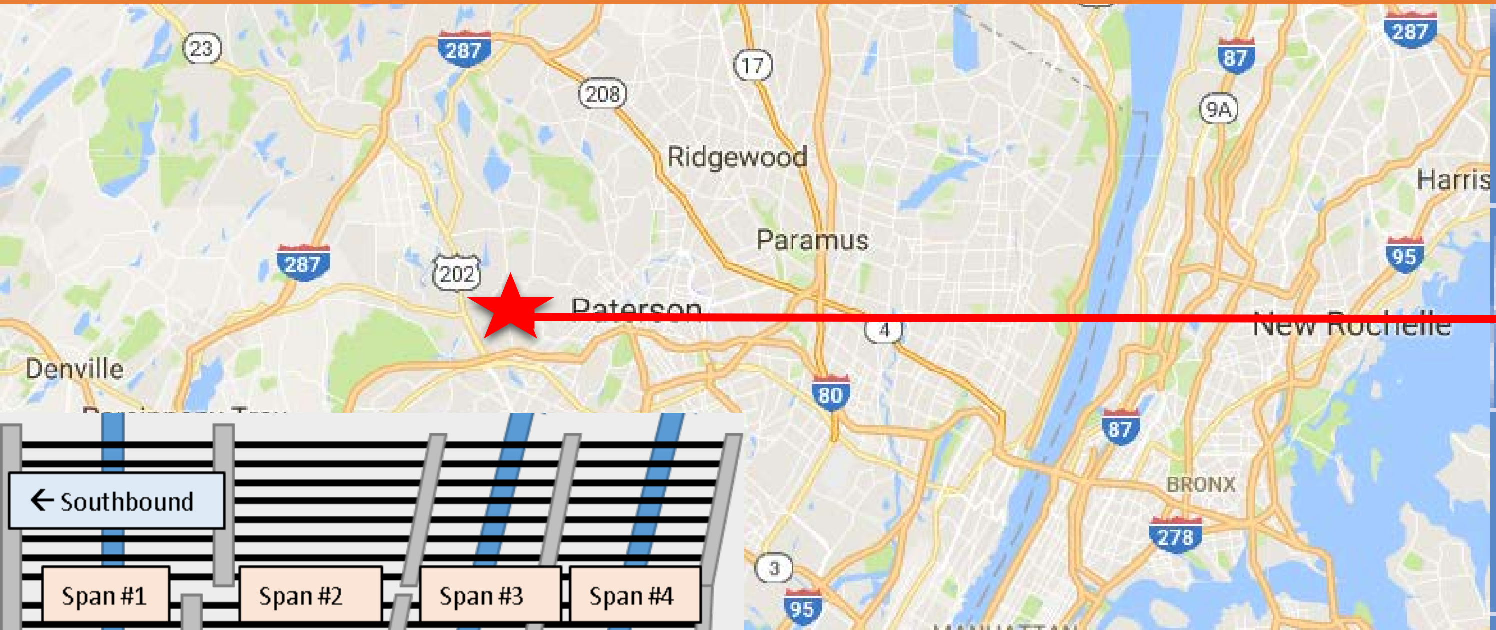
- IBS was conducted as part of the FHWA LTBP Pilot Program during 2010-2012.
- The goal was to explore the effectiveness and best practices for integrating and leveraging NDE+SHM technology for objective bridge condition and performance evaluation and asset-management.
- The principal objective was to explore how various "**information**, **field experimentation**, **modeling-simulation** and **decision-making**" technology tools that have been developed and demonstrated by various parties maybe applied in an integrated manner for the identification of a digital-twin to enable scenario analyses for designing retrofits and eliminate the critical performance deficiencies effectively.
- The US202/NJ23 Bridge was identified by NJDOT as a critical but "nightmare" bridge with many performance concerns, leading to questions for designing effective maintenance and corrective actions.
- The International Bridge Study is therefore considered as an excellent case study for the Virtual NDE+SHM Laboratory for FHWA.

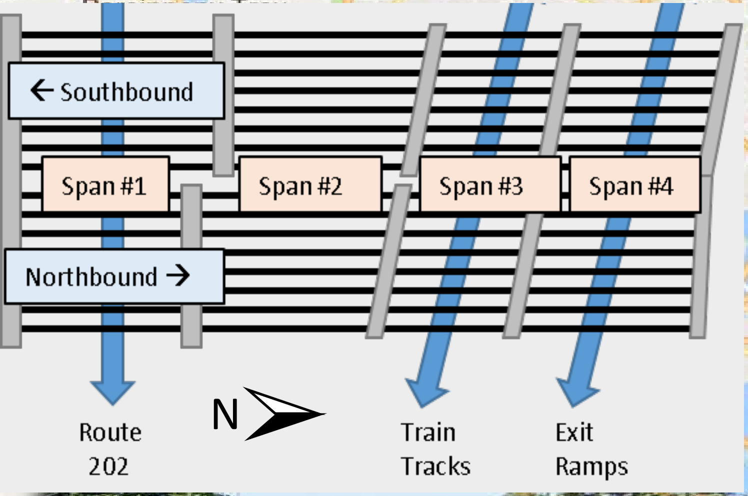
Objectives of the Webinar

- This webinar is prepared by Drexel University researchers under contract to FHWA EARP's "Virtual Bridge Technology (NDE+SHM) Laboratory" for presenting a case-study for integrated NDE and SHM technology applications to a NJ bridge.
- Technology applications were made by many invited participants and technology providers representing "the best practices" in bridge engineering technology leveraging for providing actionable recommendations to a bridge owner.
- The webinar intends to inform bridge owners as well as the bridge consulting and technology services industry regarding the importance of integrating "**heuristics**" and technology tools from several domains (**Information, Computing and Data; Visualization/Modeling/Simulation**; **Sensing/Field Experimentation; Scenario Analysis and Asset Management Decision-Making**) in order to make prudent asset management decisions.
- The state-of-practice to provide similar technology tools is coming of age but the real need is to create a market pull for technology and quantitative data-based decision-making.

The S202/NJ23 Bridge @ Wayne, NJ.

A major artery near the junction of I-80, US-202/NJ-23, and US-46





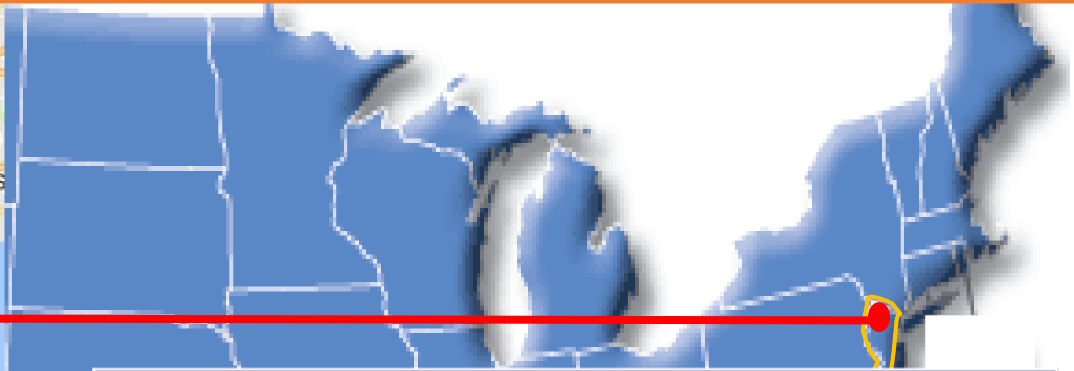


Table of Statistics - International Bridge Study Test Structure									
Year Built	1983-1984								
# of Spans	4								
Span #	Span 1		Span 2		Span 3		Span 4		Overall
Direction	NB	SB	NB	SB	NB	SB	NB	SB	-
Length	105'	130'	130'	130'	70'	70'	130'	114'	429'
Width	61.75'	61.75'	61.75'	61.75'	61.75'	61.75'	61.75'	61.75'	123.5'
Skew Angle	0°	0°	0°/66°	0°/66°	66°	66°	66°/80°	66°	-
Clearance	22+'	22+'	22+'	22+'	22'	22'	22+'	22+'	-
Lanes	3	4	3	4	3	4	3	4	7
Deck Condition Rating			7 – Good (2008)						
Superstructure Condition Rating			5 – Fair (2008)						
Substructure Condition Rating			7 – Good (2008)						

Research Collaborators

- University of Tokyo (Japan)
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- University of Sheffield (United Kingdom)
  - Dr. James Brownjohn
- EPFL | École polytechnique fédérale de Lausanne (Swiss)
  - Dr. Ian Smith
- Vienna Consulting Engineers and University of Vienna (Austria)
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- NEXCO-West Inc. (Japan)
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- Rutgers University NDE
  - Dr. Nenad Gucunski
- Utah State University
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  - Dr. Larry Olsen

Visual Inspection Findings

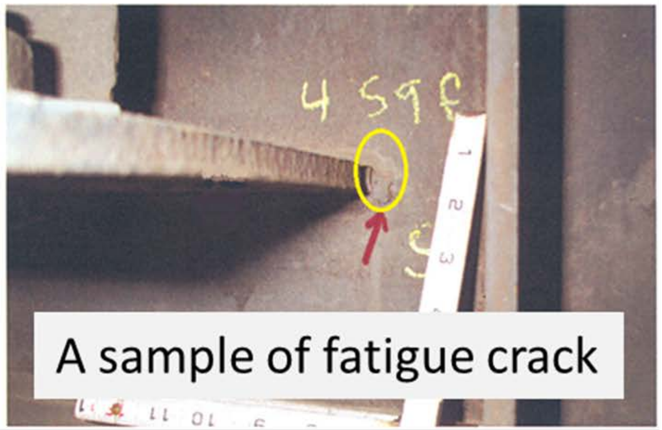
by CHERRY WEBER & ASSOCIATES

- The superstructure is in fair condition due to the common cracks in the welds connecting the lateral bracing horizontal gusset plates to the girder webs in spans 1, 2, and 4. Cracks propagating into the girder webs observed in previous cycles have been arrested by drilling holes and installing bolts. During this inspection, a crack was observed originating at the north gusset plate of lateral brace point "B" and extending approximately *Y."* into the web of girder 8 from west in span 2 from south (See Priority Letter and Memorandum).
- The approaches are in fair condition due to erosion at the southeast embankment, 2"± settlement of the southbound center through lane slab, up to 7"± settlement of the northwest approach sidewalk, and 3"± settlement of the southeast approach sidewalk.

Superstructure: FAIR
Approaches: FAIR
Substructures: Satisfactory
2008 Inspection

RATINGS:

N	Not applicable
9	Excellent Condition
8	Very Good Condition – no problems noted.
7	Good Condition – some minor problems.
6	Satisfactory Condition – some minor deterioration of structural elements.
5	**Fair Condition – minor section loss of primary structural elements.**
4	Poor Condition – advance section loss of primary structural elements.
3	Serious Condition – seriously deteriorated primary structural elements.
2	Critical Condition – facility should be closed until repairs are made.
1	Imminent Failure Condition – facility closed. Study of repairs is feasible.
0	Failed Condition – facility is closed and beyond repair.


A sample of fatigue crack

Cracks arrested by drilling holes and installing bolts

Visual Inspection Findings

Bridge conditions

A. ***Inspection reports***

B. Performance limit states

C. Performance concerns considering all limit-states

IBS researchers performed their own visual inspections coupled with operational monitoring. Teams from Japan and Austria included highly experienced bridge engineers who identified and recorded in detail many additional performance concerns.

Findings of the IBS researchers are summarized in the following in accordance with each performance limit-state. **Although fatigue cracks appeared to be the main concern for typical bridge inspectors, researchers identified additional concerns which were not recorded in the bridge inspection reports.**

INFRASTRUCTURE PERFORMANCE LIMIT-STATES FOR LIFECYCLE PERFORMANCE & ASSET MANAGEMENT

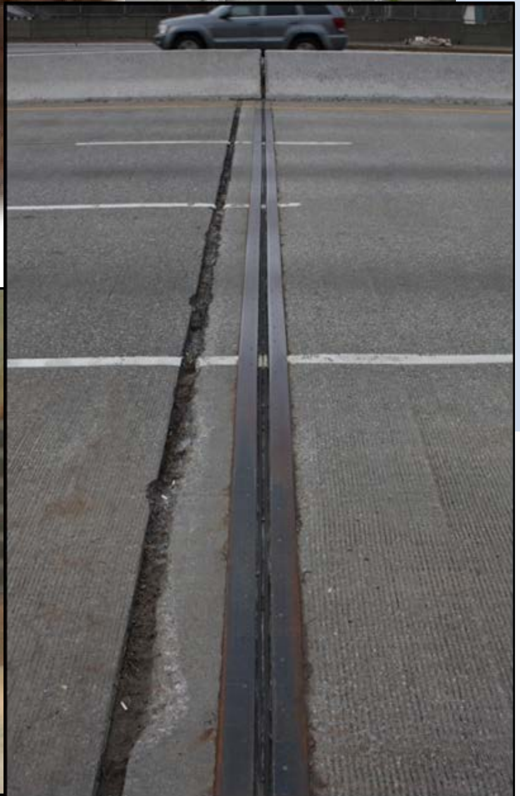
Infrastructure Life-Cycle Performance Management

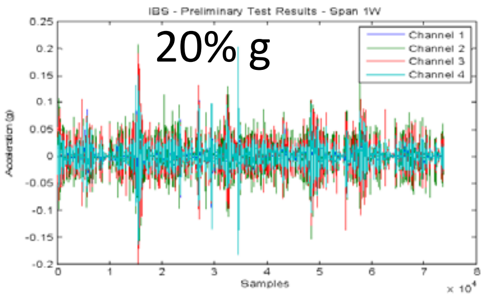
Limit State *Return Period*	**Utility and Functionality** Everyday	**Serviceability and Durability** 5 -20 Years	**Life Safety and Stability of Failure** 50–750 Years	**Resilience** In the case of extremely rare catastrophic events >1000 Years
Asset Management	**Operational Management**	**Maintenance Management**	**Multi-hazard Risk Reduction and Management**	**Disaster Response Planning and Emergency Management**
Performance Criteria	Minimize Disruptions Maximize Reliability • Relative Importance for Network, GDP, National Security, other • Operational efficiency, Safety and Security • Robust and predictable revenue	Effective & Economical : • Inspection • Maintenance • Repair • Rehabilitation Assurance of Lifecycle Revenue for Effective Preservation	Assurance of Life- Safety, Control of Failure Mode, & Reparable Damage: • Quick recovery of normal operations following any hazard (days-months)	Minimize Casualties and Sustain an Acceptable Level of Function for: Society, Economy, Ecology, Government and Critical Infrastructures • Resourceful and Adaptive Society, Economy, Public Health and Emergency Response • Adaptable and flexible lifeline systems • Protected escape and evacuation capacity • Non-Fragility of Interdependent Infrastructures
	Throughout entire lifecycle			

Summary of Performance Concerns

Functionality	Serviceability	Safety	Resilience
• Insufficient Drainage • Bump @ entry	• Fill erosion led to settlement and movement of the approach slabs • Excessive vibrations • Deck cracking • Joint failures • Bearing corrosion • Cracking of Abutments and Piers	• Gas Utility pipe • Water Trunk-line • Fractured Bearings • Pier cap corbel **shear crack** • Fatigue cracks on girder webs	• Bridge serves over 100,000 vehicles per day • Major link to GWB to NY City and NE • Major impacts to regional GDP if bridge has to be closed







Visual Inspection Findings

It appears that the professional bridge inspectors spent most of their effort in recording the fatigue cracks on girder webs. Experienced bridge engineers in the research team observed that these cracks were caused by the forces/displacements exerted by wind bracing on the gusset plates at girder webs
for connections.

Reasoning behind the design of wind bracing with fatigue-prone details is unclear. The bracing may have been omitted or connections to girder webs may have been detailed differently.

Additional performance concerns include the pier-cap corbel shear crack, vibrations, deck cracking, bearing failures and fill erosion leading to bumps at the entries to the bridge. Each of these were found to be significant performance concerns.

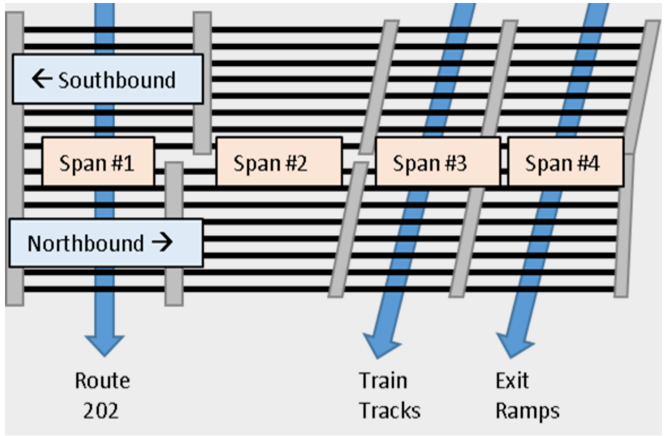
CONCLUSION: The 33-Year old bridge serves a critical route and the performance deficiencies at each of the functionality, serviceability, safety and resilience limit-states are reducing its life-span significantly.
What are the most effective repair/retrofits?
How can we identify and implement these? Is heuristics sufficient for designing retrofits and management decisions?

Technology Integration Strategy for Bridge Management

1. Next Generation Visual Bridge Inspection	2. Measure Geometry; Materials: In-situ; sampling & lab testing	3. Characterizing the Structure, Foundation & Soil via a Digital Twin	4. Diagnosis, Prognosis and Risk Evaluation;	5. Health and Performance Monitoring; Asset Management
Wireless tablets and camera/glasses for effective inspection (by sharing images in real-time consultation with a senior bridge engineer)	Surveying and GPS: coordinates of discrete points – for as-is geometry, conditions and validation of as-built plans	A-Priori FE Modeling, simulations for identifying critical regions & failure modes for experiment design	Scenario Analyses by FE Model: Critical demand/ capacity envelopes, identifying mechanisms causing performance concerns	ITS technology, WIM, open-road tolling, adverse driving conditions alert & actions (de-icing), speed limit adjustment
Operational monitoring by quick-deploy wireless sensors, local NDE scans as needed	Non-contact geometry capture: photogrammetry, 3D Laser, Lidar and Digital Image Processing (DIP)	Systematic wide-area NDE applications – for rebar detailing, deck concrete conditions and deck surface and camber profiles	Identify site-specific hazards, vulnerabilities & consequences to assess disutility risk & sources of uncertainty – Resilience?	Automated speed limit, aggressive driver ID; Security, Truck Weight enforcement technologies
3D CAD and BrIM for visualization and documentation of performance deficiencies	In-situ material characterization; sampling & lab testing of materials	Controlled Testing: Truck load; Excitation; Impact; Operational Monitoring	Identify risk mitigation measures and any emergency actions	Structural health monitoring to drive special hazard & vulnerability-based customized inspections
Bridge type-specific Heuristic Knowledge repository	Updated 3D CAD for capturing as-is geometry and any signs of damage and deterioration	Parameter Id; A-Priori FE model improvement, calibration and validation	Identify if technology may help mitigate risk, ensure redundancy of transportation routes for resilience	Asset management based on projected lifecycle demands, capacity & cost – operational and capital financing & revenue needs

Experimental Tools Selected for Application to IBS

1. Operational Monitoring of vibrations (Drexel, Tokyo, Austria, Utah State)
2. Forced Excitation testing (Drexel – Impact Testing, Sheffield - Multiple Harmonic Exciters)
3. Controlled Proof-Level Load Testing (Drexel)
4. Long-Term Monitoring (Princeton)
5. Multi-Modal NDE Scanning of the RC Deck (Rutgers)
6. Remote Vibration Monitoring by Laser (WMU)



FEM Simulations helped to design instrumentation (Sensor Type, Location, Range, Bandwidth) and loading for the experiments applied to SB Span 2 (and some also to NB Span 2) in conjunction with a complete application of the **Column 3 of the Tech Integration (Slide 10).** In addition, by calibrating the FE Model, scenario analyses for designing reliable measures to correct performance concerns were conducted.

In addition to providing data for FE model calibration, the experimental results also offered direct insight into the bridge’s behavior. These are summarized in the following.

Summary of IBS tests and data

Test Type	Time	Team	Location	Sensors (Equipment)
Operational Monitoring	April, 2010	Drexel	Span 1-4	Accelerometer (PCB 393C)
	Sep., 2010	Austria (VCE)	Span 1-4	BRIMOS Sensor
	July, 2010	Sheffield	Span 1,2,3	Wireless sensors (outer 41 nodes=123 channels) and wired accelerometers (inner)
	June, 2011	Utah State University	span 1-4	20 sensors. Sensor: Sercel L4C 1.0Hz. Seismometer
	2010	KEC & Sejong University, Korea	Span 2 (Southbound)	15 Accelerometer (Model 393B12 (PCB))
Forced Excitation Testing	June, 2011	Drexel	Span 2	Accelerometer, Impulse Hammer, Load Cell, NI cRIO (Hammer test)
	July, 2010	Sheffield	Span 1,2,3	Wireless sensors (outer 41 nodes=123 channels) and wired accelerometers (inner)
Truck Load Testing	Sep., 2010	Drexel	Span 1 &2 (@ lane 1-3)	Strain gages, displacement gages
NDE Scanning of the deck	June, 2011	Rutgers	Span 1-4	IE, ER, HCP, USW, GPR
Laser tracking	Oct., 2011	Western Michigan University	Span 2 (Southbound)	Laser tracker, 1.5” and 0.5” Reflectors
Long-term Monitoring	2011-2016	Princeton University	Girder 2 &5 (southbound)	Fiber Bragg Grating (FBG) Sensors

1. Operational monitoring: High dynamic amplification

Three Events Monitored:

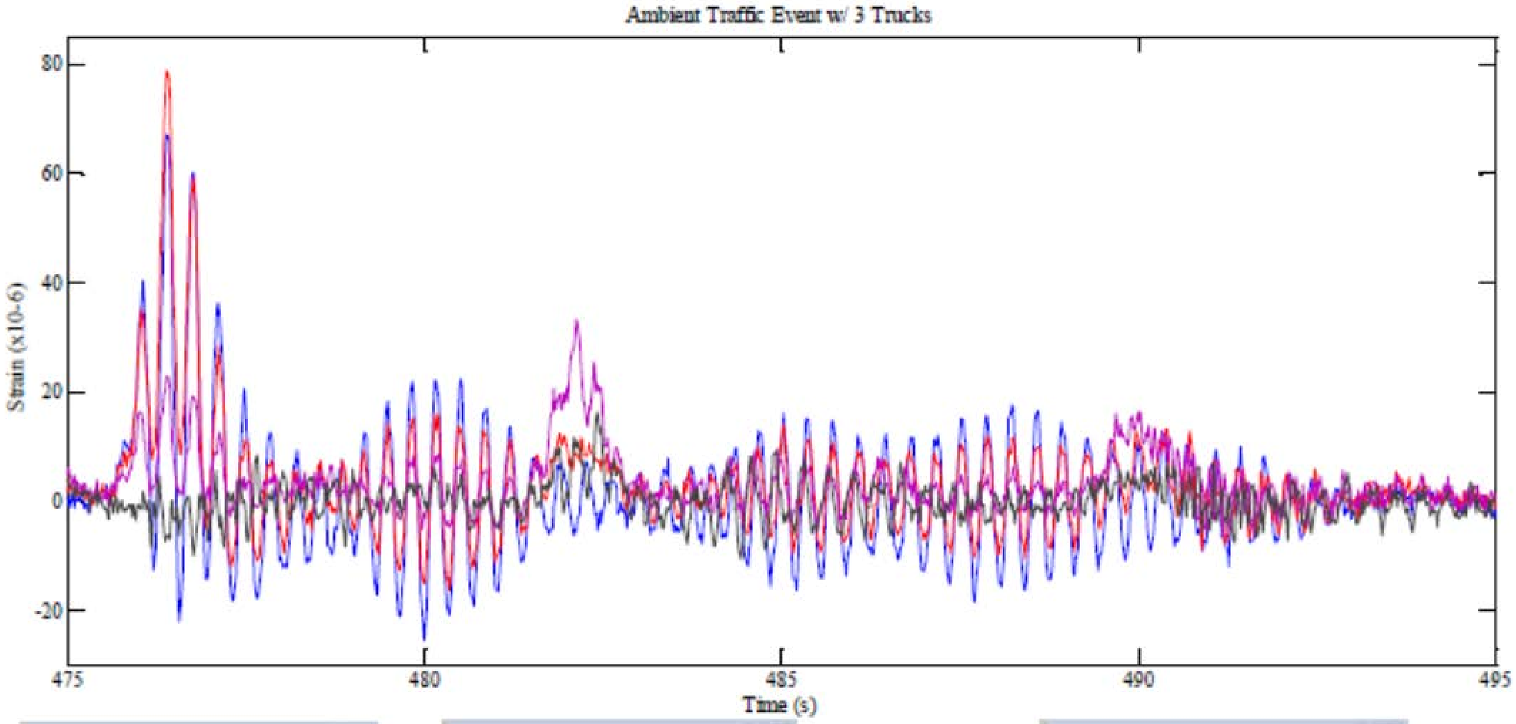
Recording length: 10 minutes

Sensors: Strain gauges installed on Girders 1, 3, 6, and 8

Conclusion: the type of truck, speed of truck, and position on the bridge can all have an effect on the excess vibration experienced by the bridge.

Identified Frequencies - Preliminary Data

Span 2 NB	**Span 2 SB**
3.699	2.808
5.261	3.174
5.981	5.249
9.595	9.167
12.380	14.880
15.150	15.440
20.860	

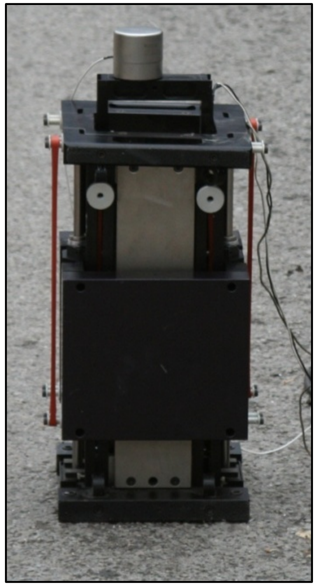


Truck #1 – Lane 1:
80us response in Girder #3, followed by four vibration cycles where Girder #1 shows larger response

Truck #2 – Lane 3:
37us response in Girder #6, followed by traffic excitation causing 20us response in Girder #1

Truck #3 – Lane 3:
15us response in Girder #6 which does not excite Girder #1 at all

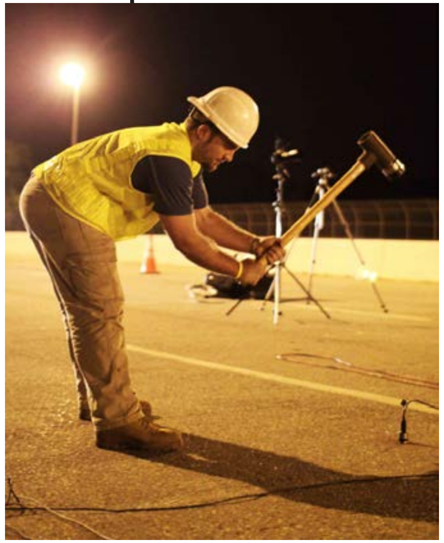
2. Examples of Forced Excitation by Linear Mass Shaker or Impact Hammer

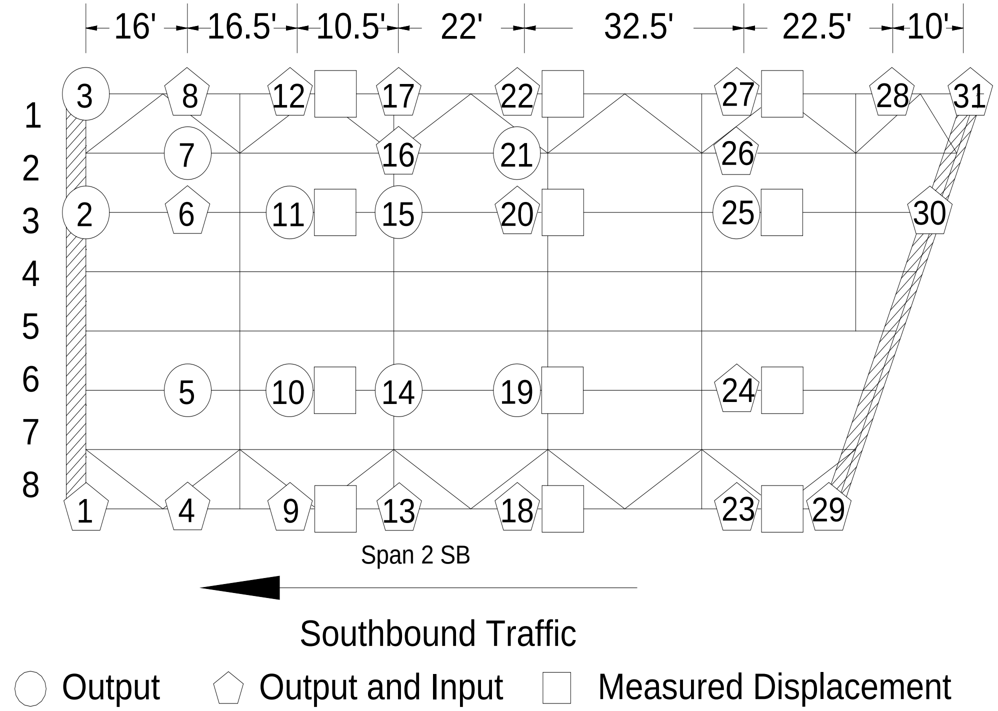


- Low amplitude harmonic force input
- Controlled Impact input
- Measured input and output at grid locations

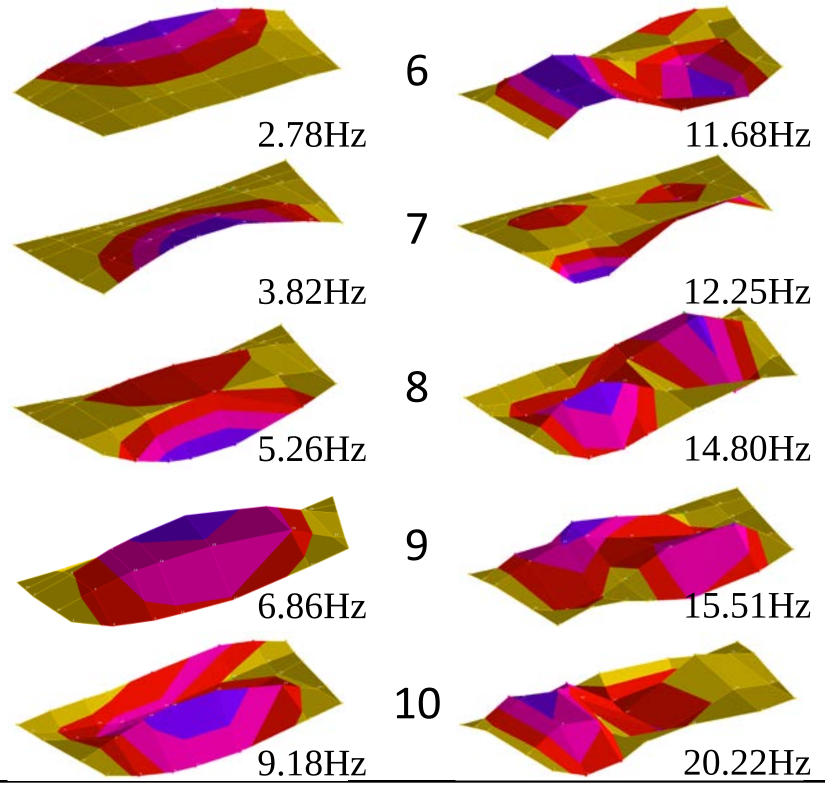
Forced vibration test by impact: Freq & mode shapes


Drop hammer test


Impact hammer test



31 PCB 393A03 seismic accelerometers were used to capture the response of the bridge to the input forces. The accelerometers were installed on the bottom flange of girders six and eight, while the remainder of the sensors were installed on the top of the deck.



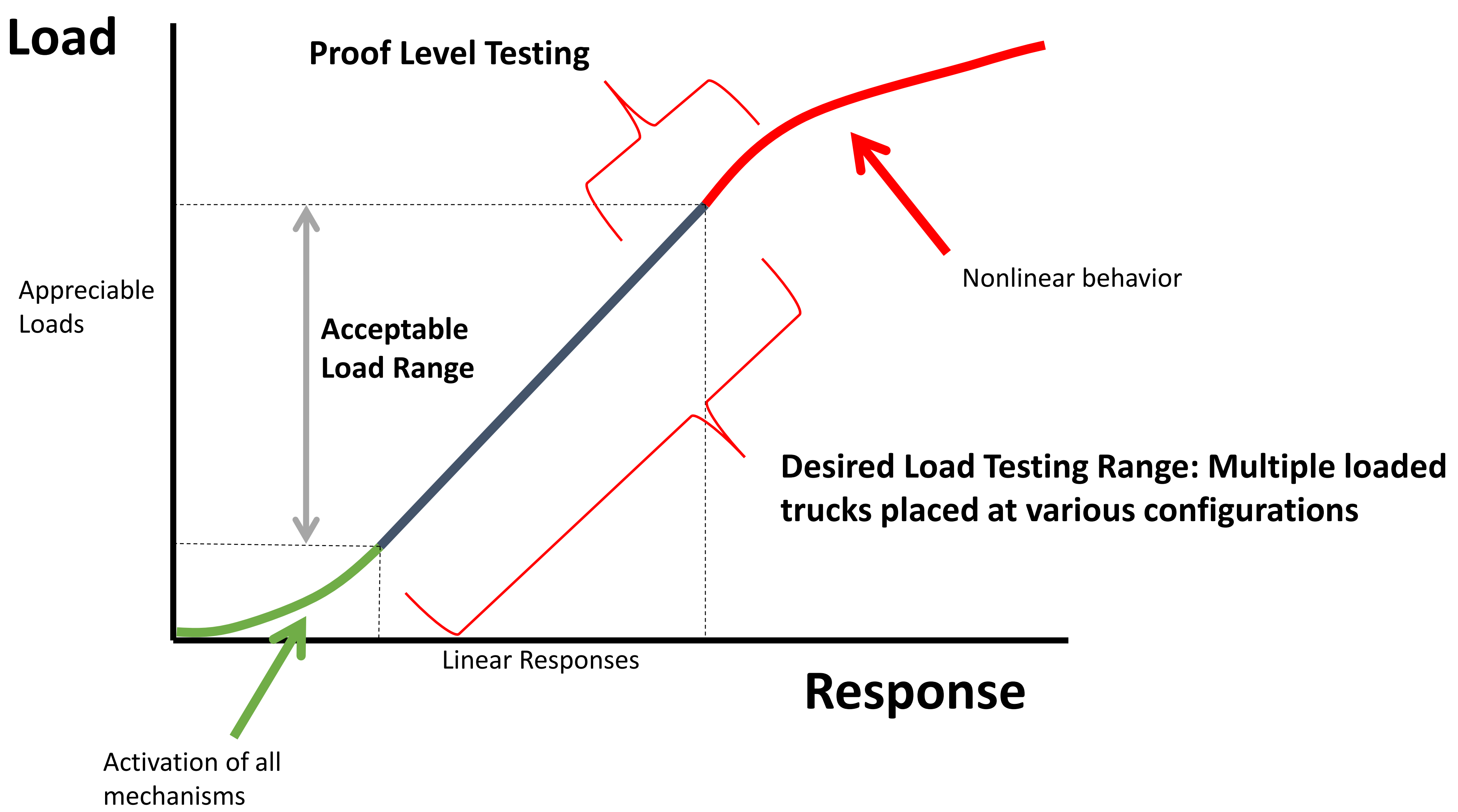
No.	Mode Shape	No.	Mode Shape
1	2.78Hz	6	11.68Hz
2	3.82Hz	7	12.25Hz
3	5.26Hz	8	14.80Hz
4	6.86Hz	9	15.51Hz
5	9.18Hz	10	20.22Hz

The first mode resembles flapping of the deck like a wing along girder 8 while in the second mode the wing is flapping along girder 1. 2-10 Hz frequency band coincides with the input frequency band of trucks.

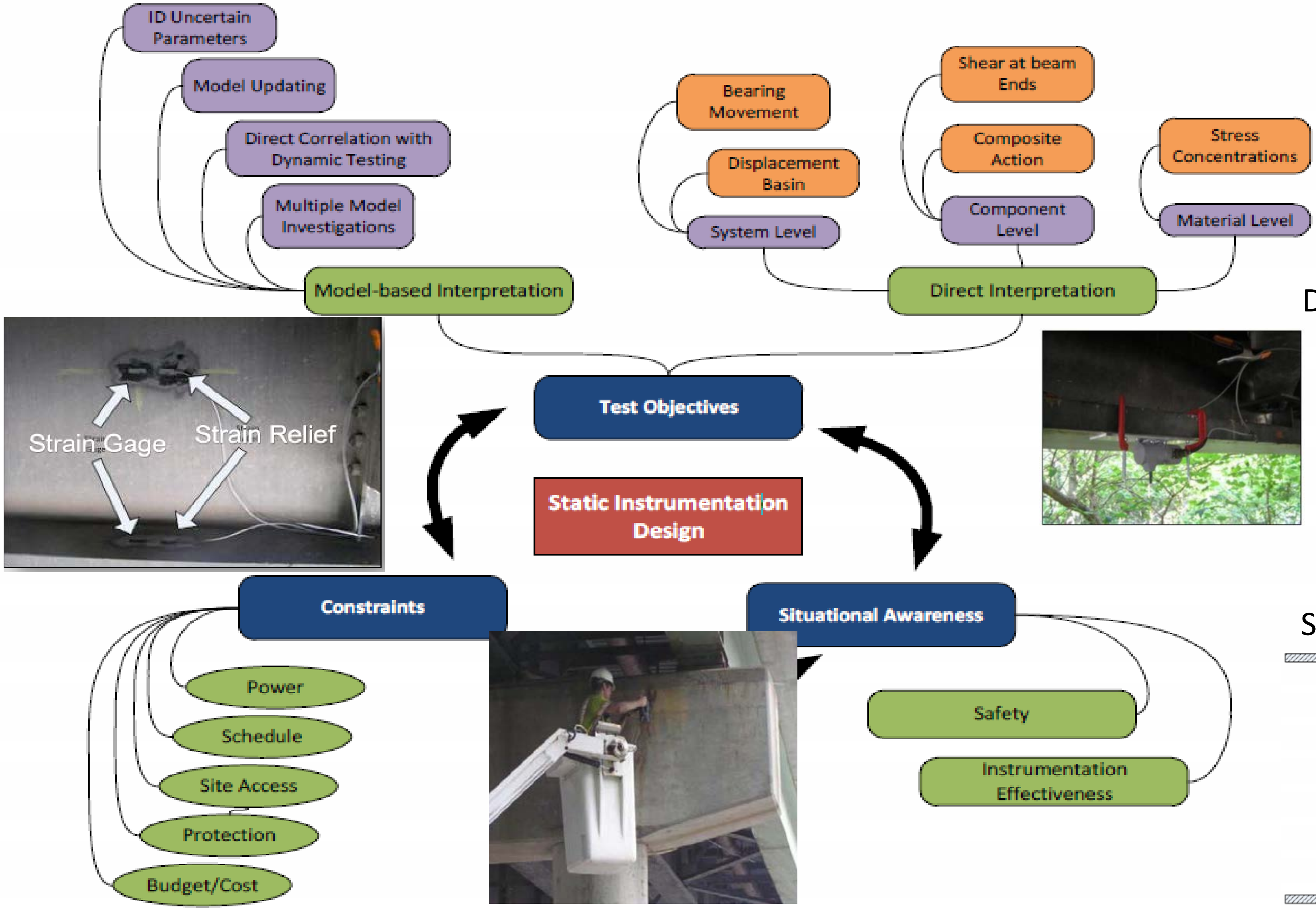
Frequency (Hz) and Modal Order from all vibration tests

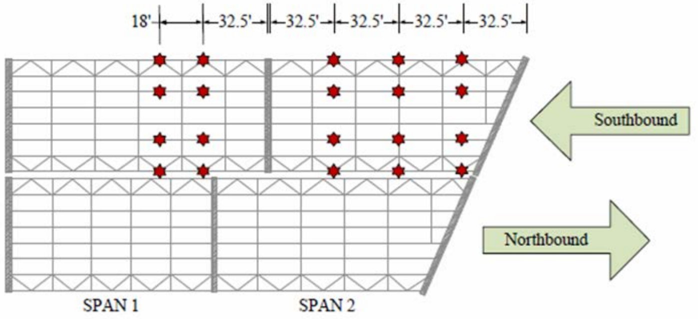
Mode	Ambient Vibration					Forced Excitation		Integrated Results	
	Drexel University	Austria (VCE)	KEC & Sejong University	Utah State University	University of Sheffield	Drexel University	University of Sheffield	Average	Range
1	2.89 (2.79%)		2.72 (-3.25%)	2.856 (1.58%)		2.78 (-1.12%)		2.81	2.72-2.89
2				3.1 (0%)				3.10	3.1
3	3.79 (1.96%)	3.75 (0.88%)	3.52 (-5.3%)	3.7 (-0.46%)	3.75 (0.88%)	3.82 (2.77%)	3.69 (-0.73%)	3.72	3.52-3.82
4		4.47 (1.06%)		4.5 (1.73%)	4.3 (-2.79%)			4.42	4.3-4.5
5	5.23 (0.11%)		5.14 (-1.61%)		5.27 (0.88%)	5.26 (0.69%)	5.22 (-0.08%)	5.22	5.14-5.27
6					5.96 (-7.02%)	6.86 (7.02%)		6.41	5.96-6.86
7			7.75 (0%)					7.75	7.75
8	9.47 (1.8%)	9.18 (-1.32%)	8.92 (-4.12%)	9.38 (0.83%)	9.5 (2.12%)	9.18 (-1.32%)	9.49 (2.01%)	9.30	8.92-9.5
9	11.61 (0.06%)	11.79 (1.61%)	11.14 (-3.99%)		11.7 (0.83%)	11.68 (0.66%)	11.7 (0.83%)	11.60	11.14-11.79
10	12.25 (-0.24%)			12.3 (0.16%)	12.4 (0.98%)	12.25 (-0.24%)	12.2 (-0.65%)	12.28	12.2-12.4
11		14.81 (-0.54%)		14.94 (0.34%)	14.9 (0.07%)	14.8 (-0.6%)	15 (0.74%)	14.89	14.8-15
12	15.12 (-1.98%)			15.6 (1.13%)	15.1 (-2.11%)	15.51 (0.54%)	15.8 (2.42%)	15.43	15.1-15.8
13		16.51 (0%)						16.51	16.51
14	20.64 (1.03%)					20.22 (-1.03%)		20.43	20.22-20.64

3. Load Testing: What should be the load level? Typical Load vs. Response of Bridges

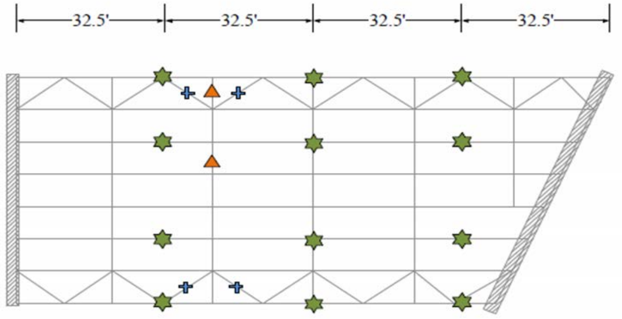


Load Testing Instrumentation Design Fundamentals

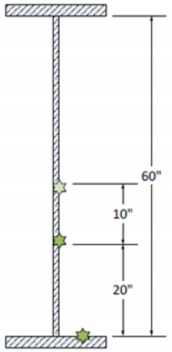




DISPLACEMENT MEASUREMENTS



STRAIN MEASUREMENT LOCATIONS



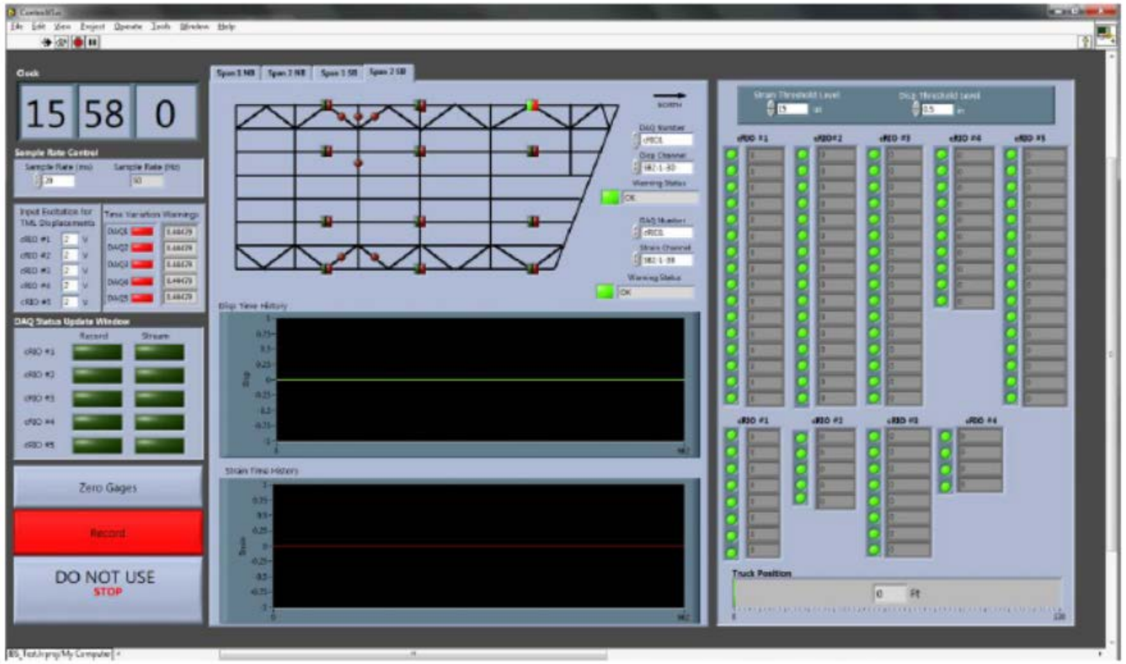
- ★ Longitudinal strain gauge
- ✚ Wind brace sensor
- ▲ Diaphragm Strain Gage

Load Testing (Drexel University)

Closure of three of the four lanes permitted after mid-night, one lane remained open to traffic

Three configurations of Truck loading:

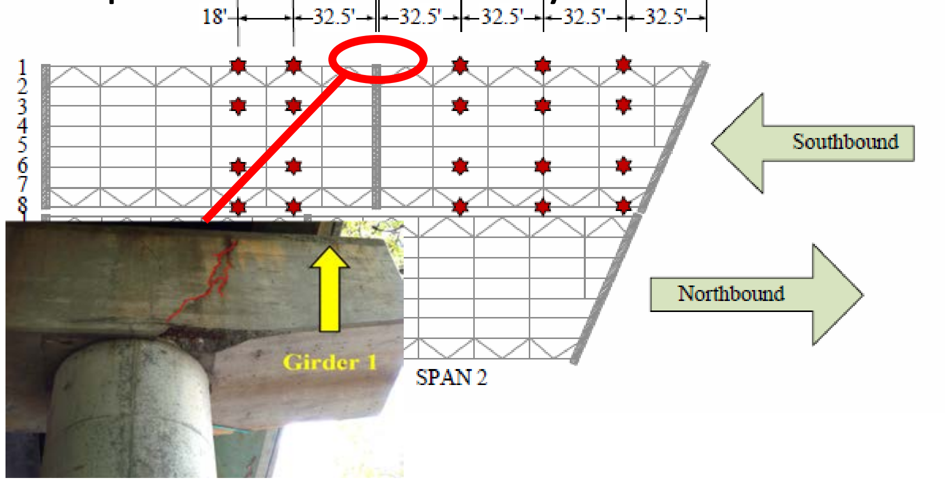
1. Total load of 3 Empty trucks: 86.7 Kips
2. Total load of 3 Full trucks: 230 Kips
3. Total load of 6 Full trucks: 460 Kips



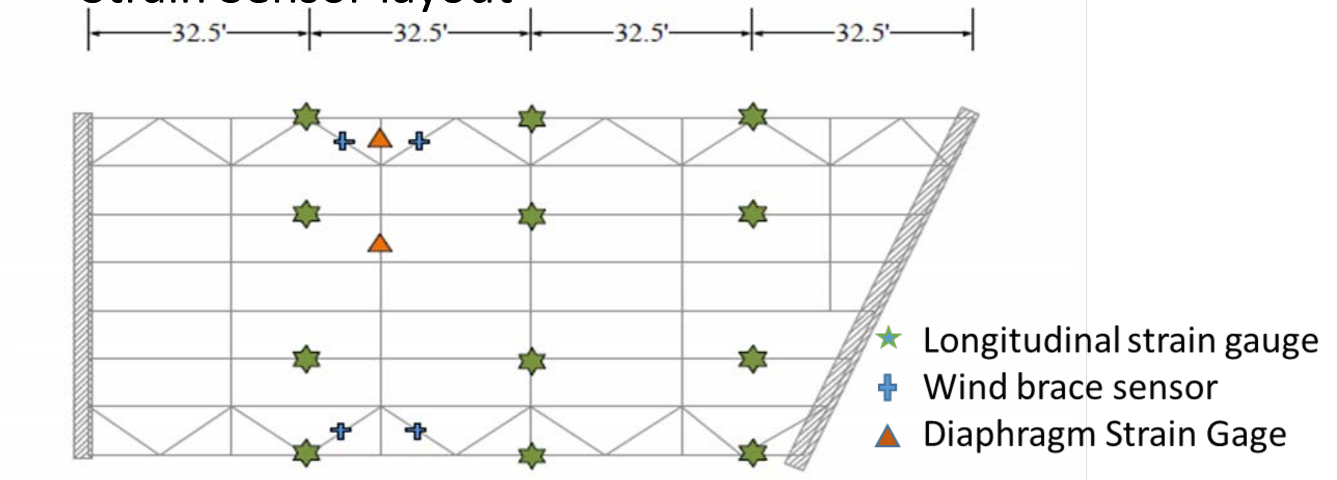
Real Time Data Display For Test Control Screen

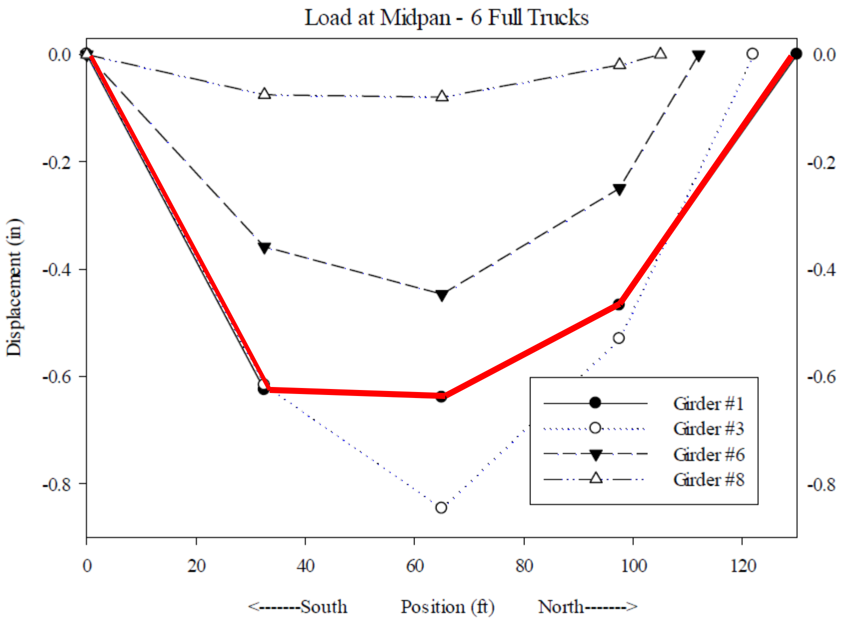
Load Testing: Typical Measurements

Displacement Sensor layout

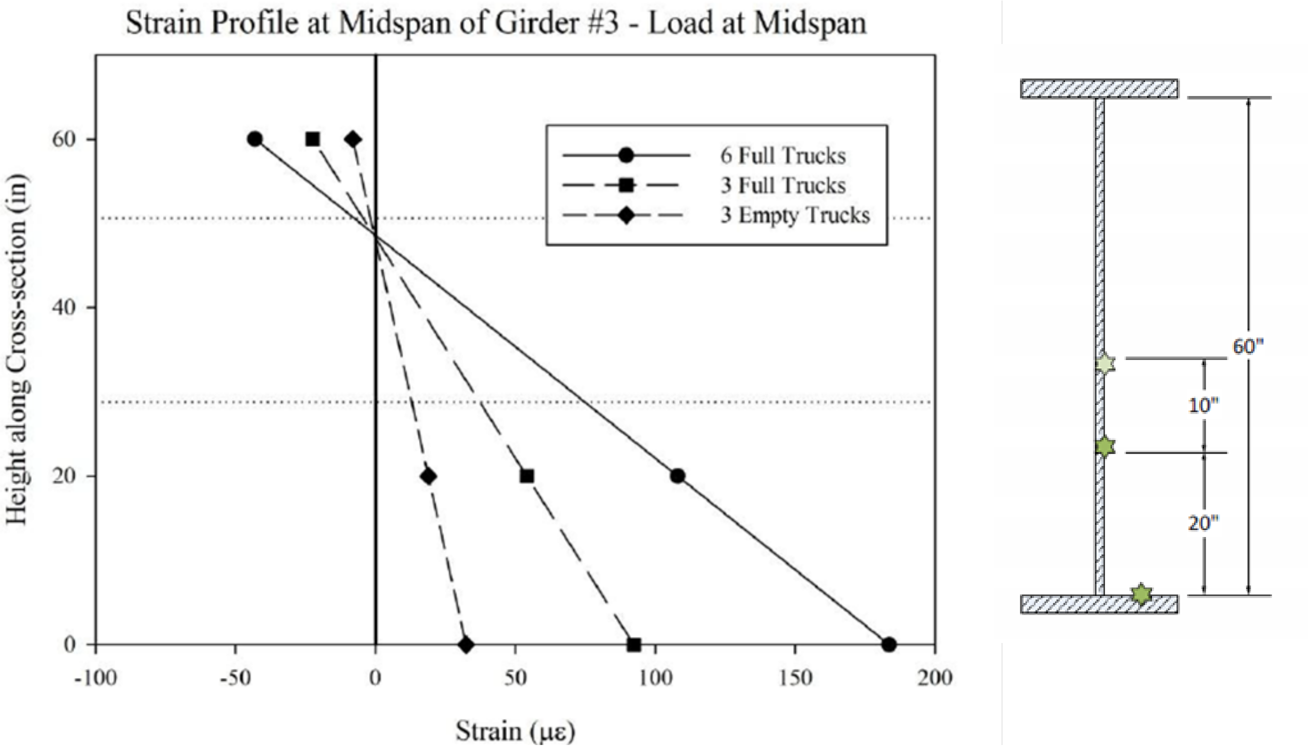


Strain Sensor layout

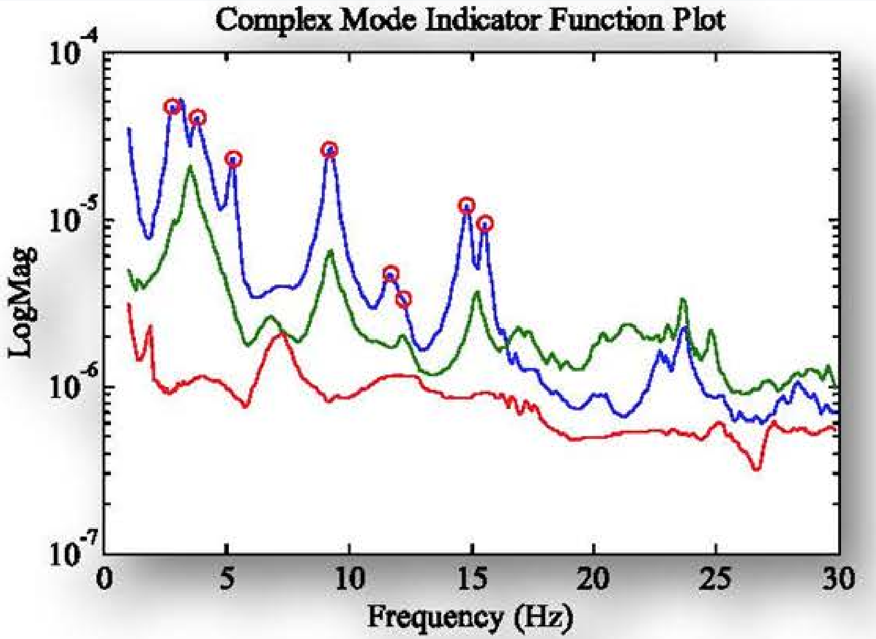


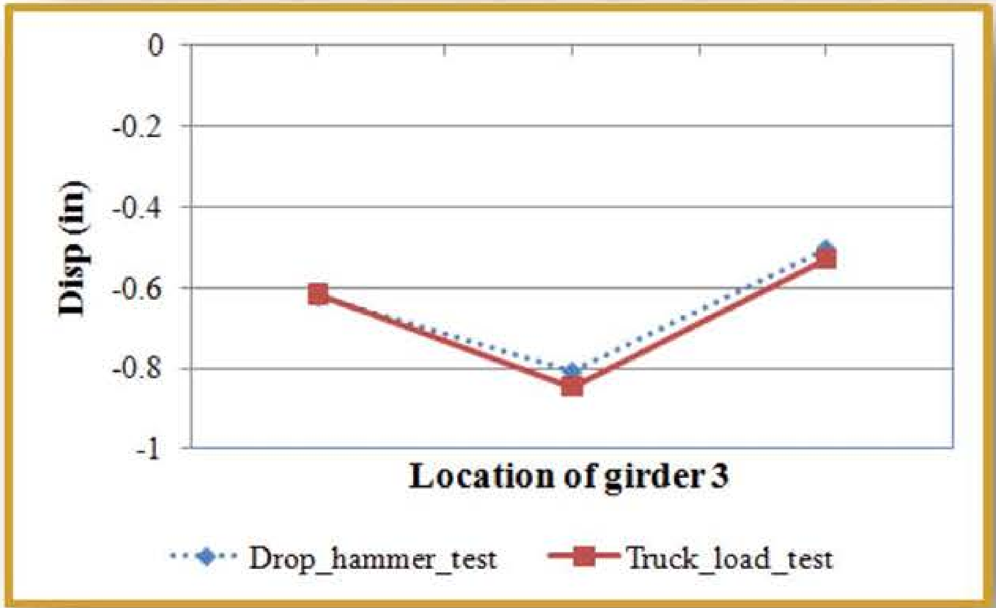


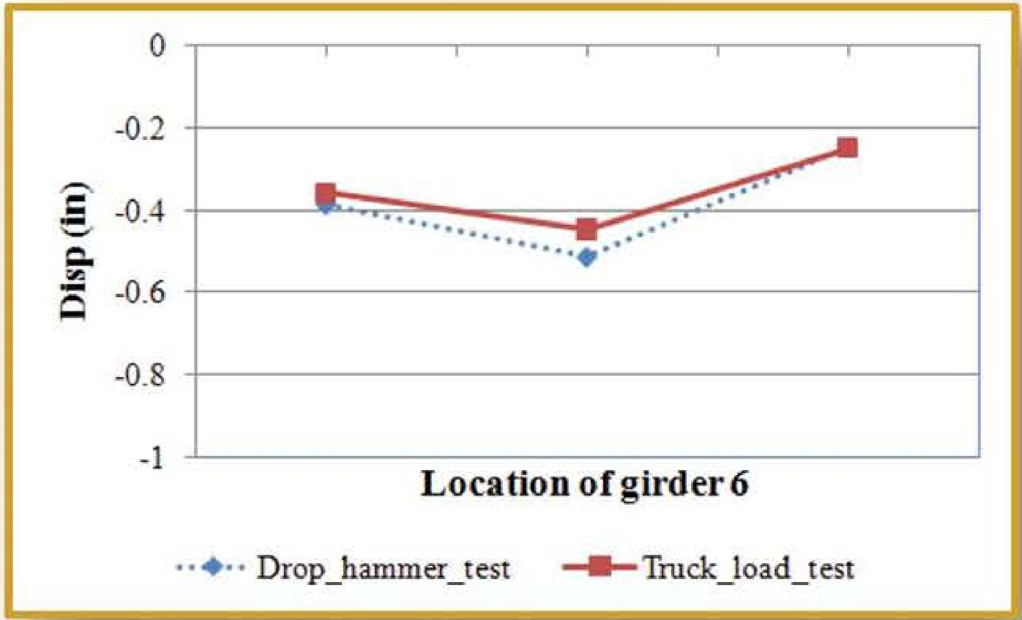
Girder Displacement Profiles under 6 Full trucks



VALIDATION OF EXPERIMENTS BY CORRELATING FLEXIBILITY FROM STATIC and DYNAMIC TESTS







4. Long-term Strain Monitoring (Princeton University)

Six cross-sections are equipped with long-gauge FBG sensors in parallel topology
(12 strain sensors and 12 temperature sensors)

Long-term Strain Monitoring (Princeton University)

Sensors were installed in girders #2 and #5 of Span 2 Southbound

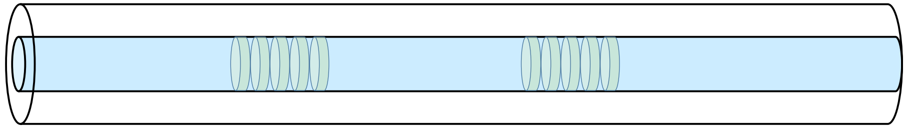
Girder #2:

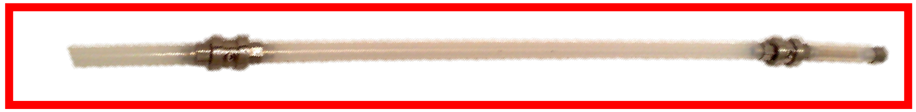
- Gauge length at quarter span = 1m
- Gauge length at mid span = 2m
- 6 strain + 6 temperature sensors

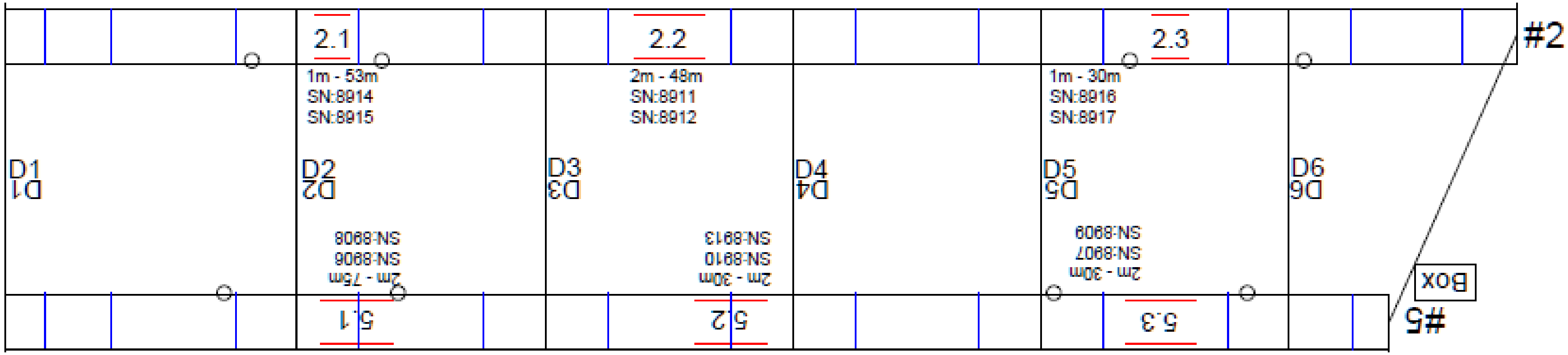
Girder #5:

- Gauge length at quarter span = 2m
- Gauge length at mid span = 2m
- 12 strain + 12 temperature sensors

Long-gauge FBG sensors:

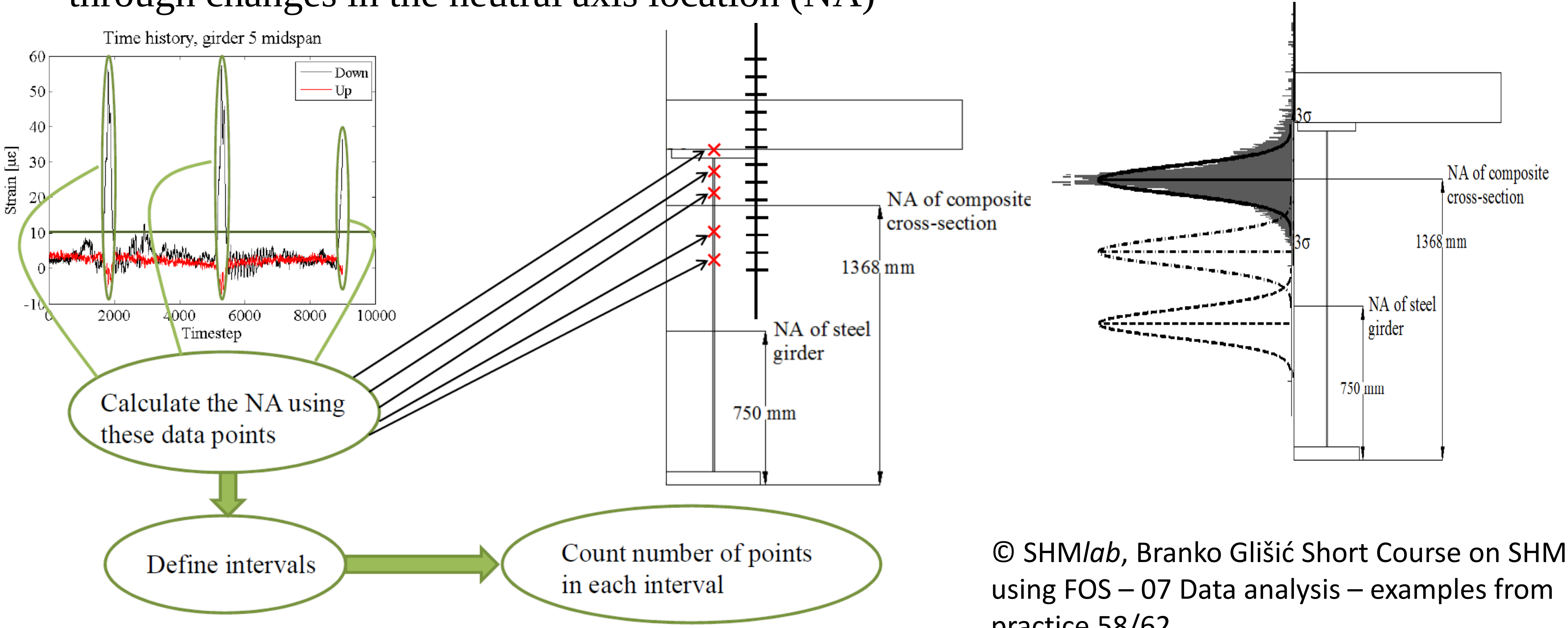






Long-Term Strain Monitoring (Princeton University)

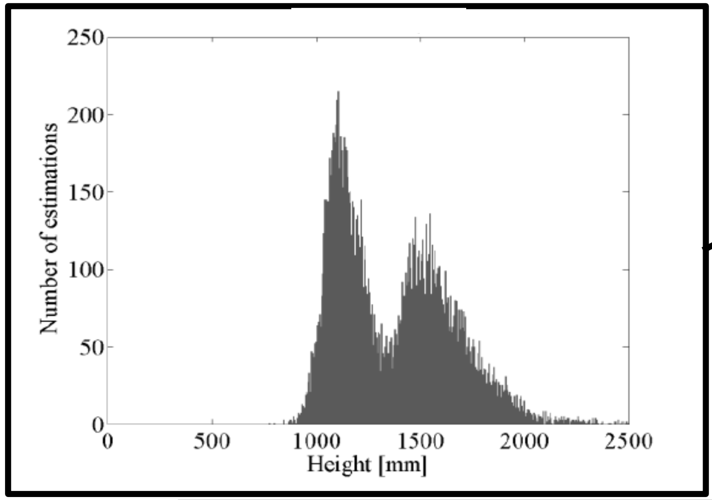
Dynamic strain data from large events is used to evaluate the structural behavior through changes in the neutral axis location (NA)

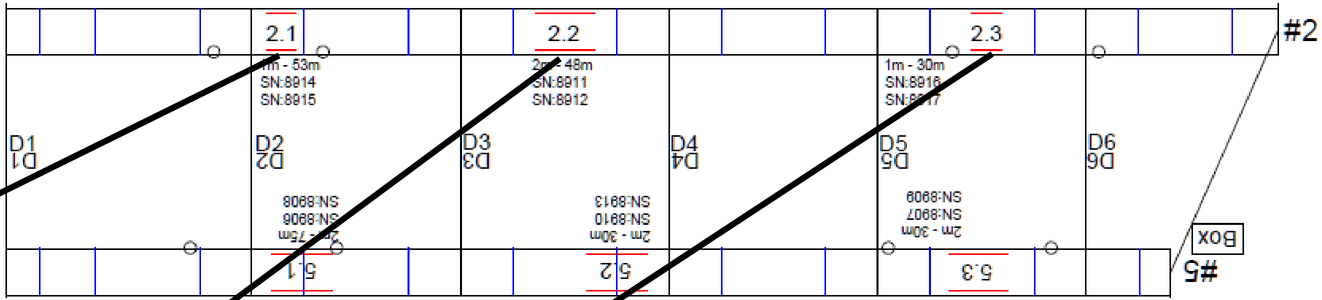


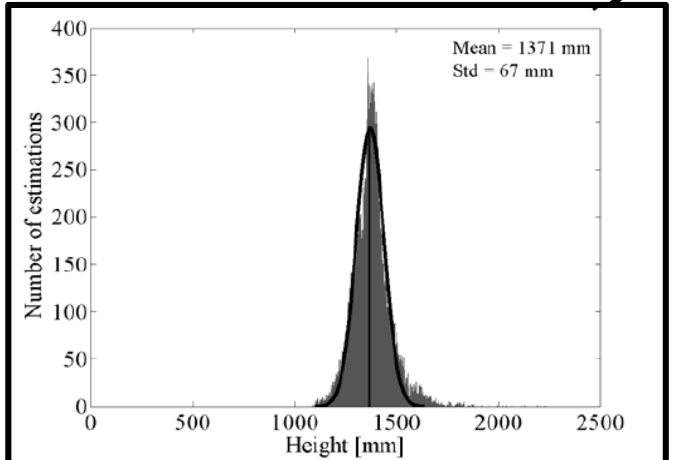
1-Year Strain Monitoring Data Interpretation

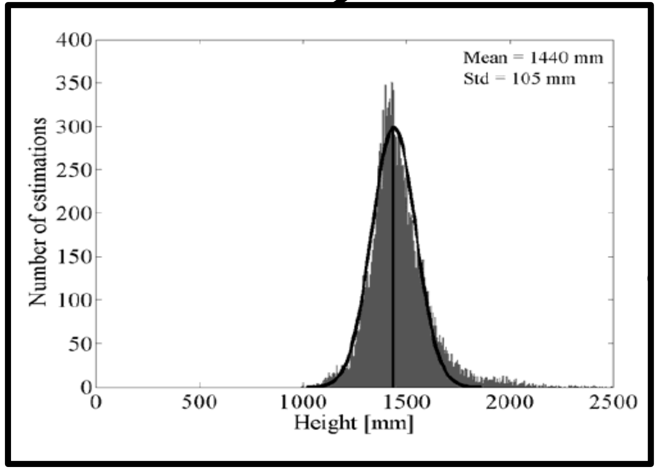
Neutral Axis Analysis

- Histogram, 1 year
- Fit Gaussian curve







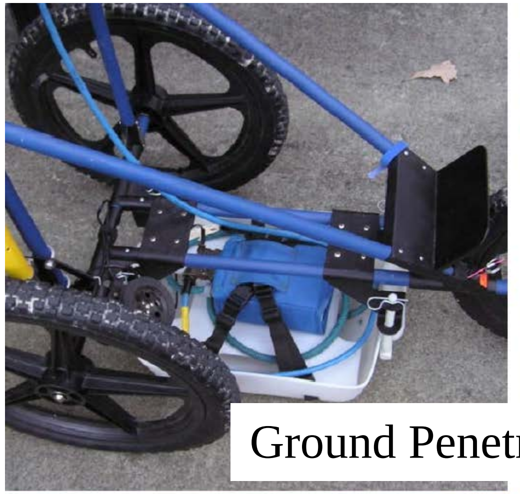


Interpretation:
Two locations show stable neutral axis location, third shows shifting of n.a. over a year, most likely indicating progressive deck delamination

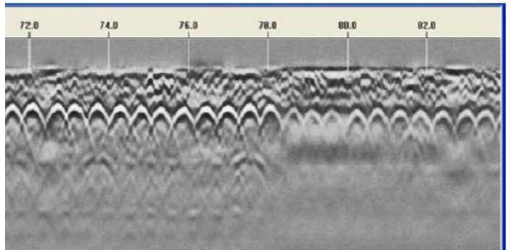
5. Multi-Modal NDE Scanning of Deck by Rutgers University

Ultrasonic Surface Wave

Impact Echo probes carried by Stepper

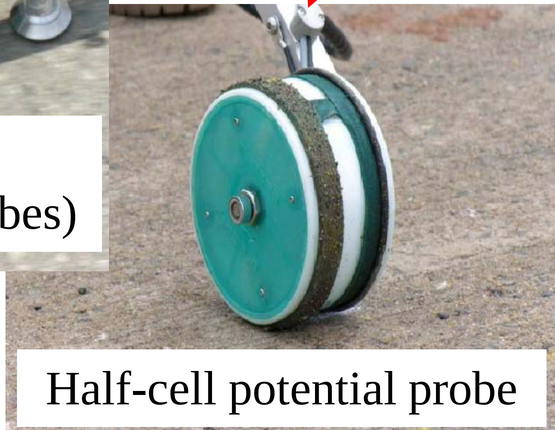


Ground Penetrating Radar



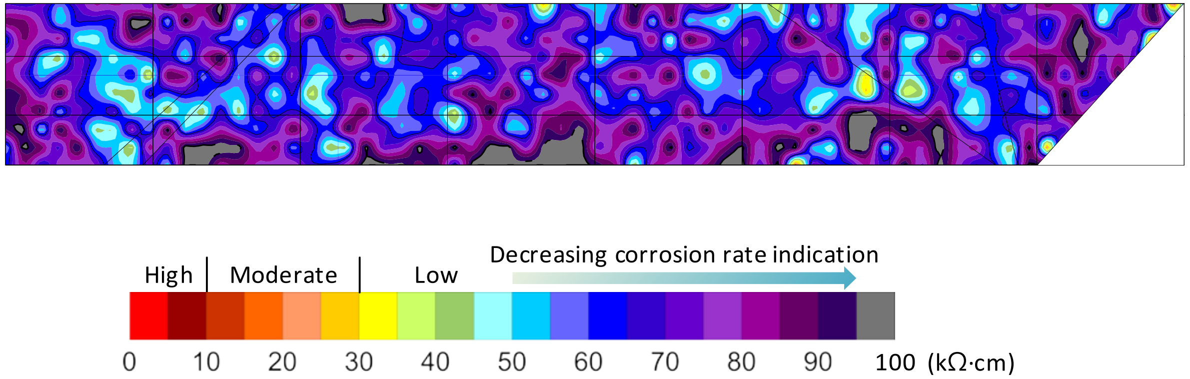
Electrical Resistivity

MicroScan
(Microwave Probes)

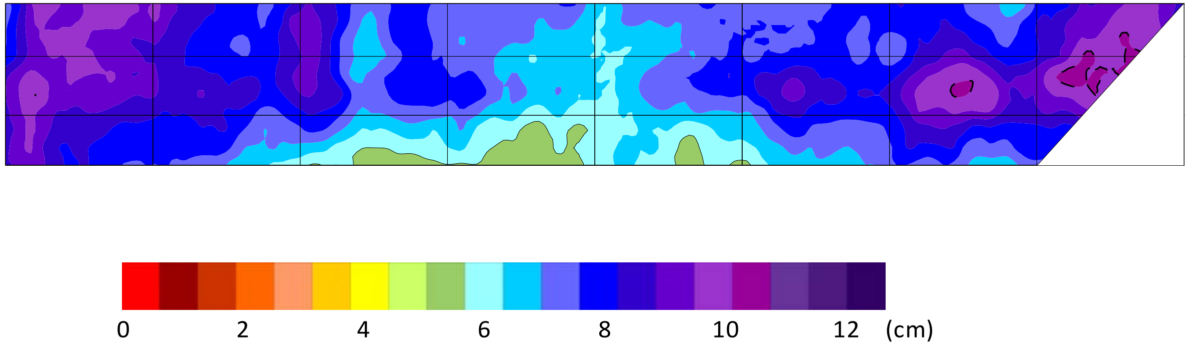


Half-cell potential probe

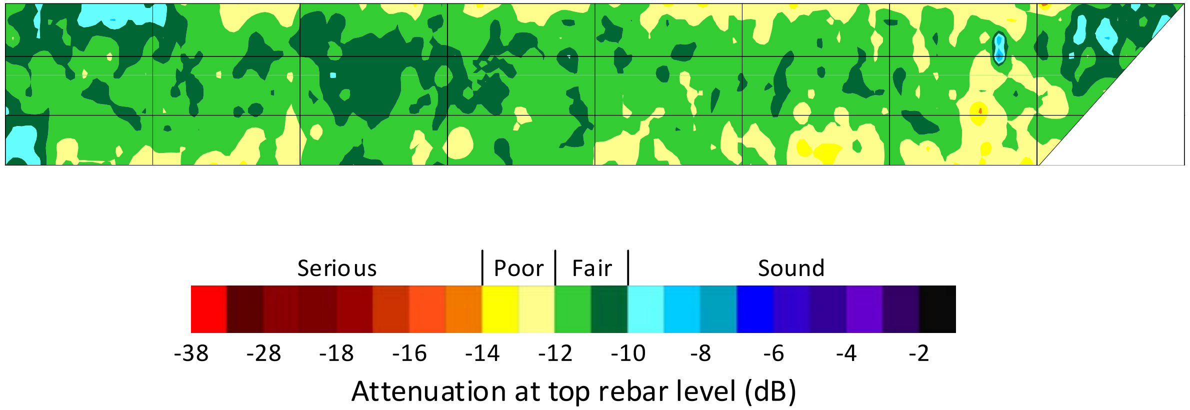
NDE Testing by Rutgers University – MAPPING the DATA



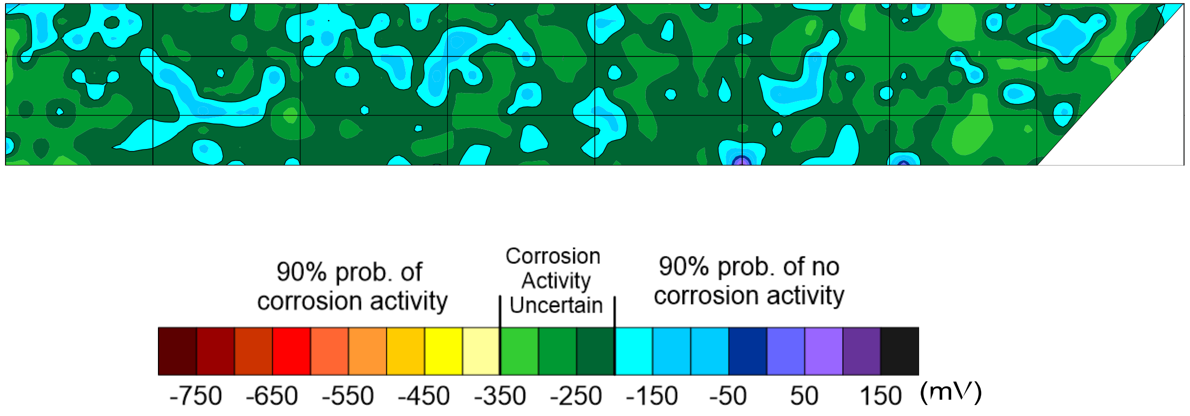
Electrical Resistivity Result of Span 2 SB
showing



Ground Penetrating Radar of Span 2 SB
showing concrete cover

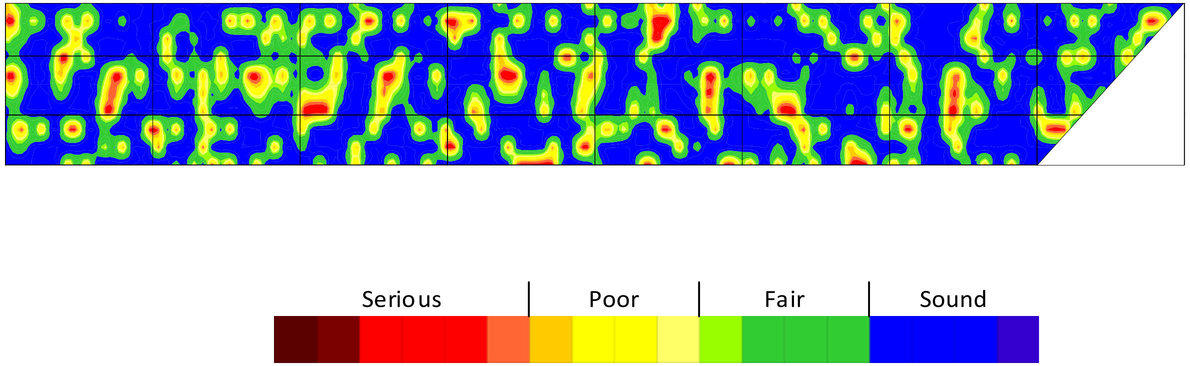


Ground Penetrating Radar Result of Span 2 SB
showing Attenuation at Top Rebar

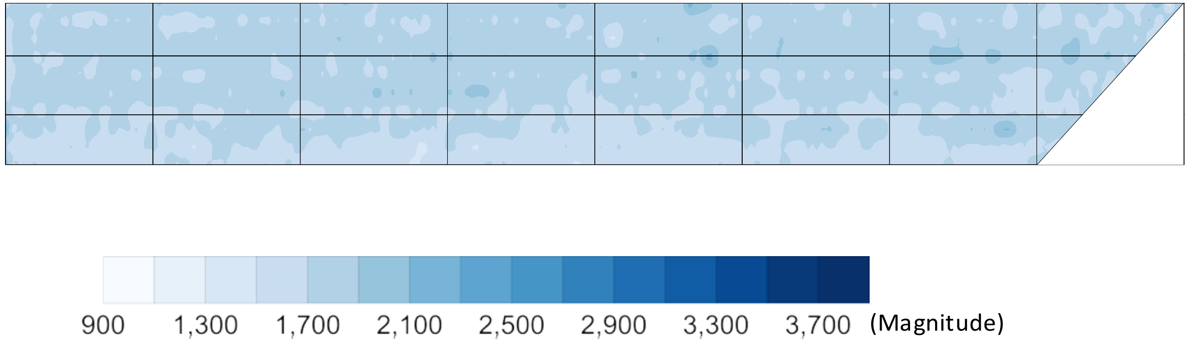


Half Cell Potential Result of Span 2 SB
showing probability of corrosion activity

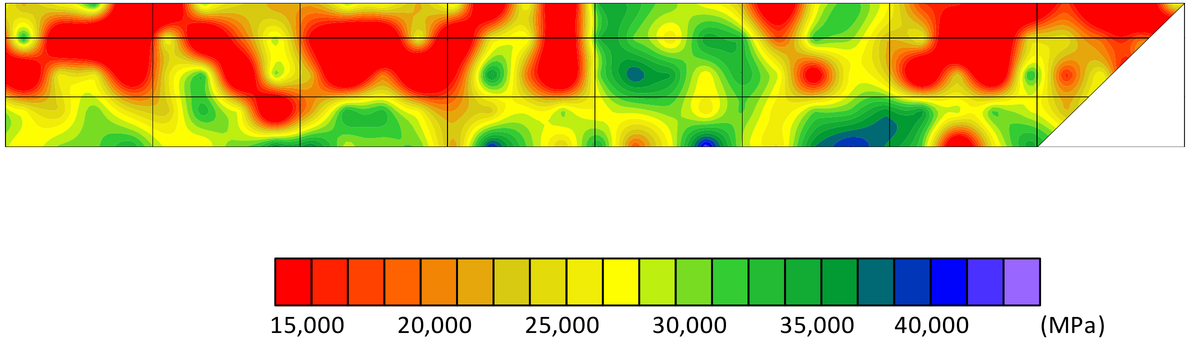
NDE testing by Rutgers University - Interpretation



Impact Echo Result of Span 2 SB
showing delamination



MoistScan (Microwave probes) Result of Span 2 SB
showing areas of higher moisture content



Ultrasonic Surface Wave Result of Span 2 SB
showing concrete modulus

- **There are only minor signs of corrosion activity. The measured electrical resistivity indicates that the deck environment only slightly promotes corrosion.**
- **Concrete modulus is on a lower side, typically between 2500 and 4000 ksi. Lower concrete modulus was primarily measured in the slow lane.**
- **Despite little signs of corrosion activity, a number of delaminated areas were identified. Delamination is possibly a result of repeated high deflections of the deck accentuated by vibrations.**

6. Laser Tracking by West Michigan University

Laser Tracker

1.5" Red-Ring Reflector
acceptance angle of $\leq \pm 30^0$

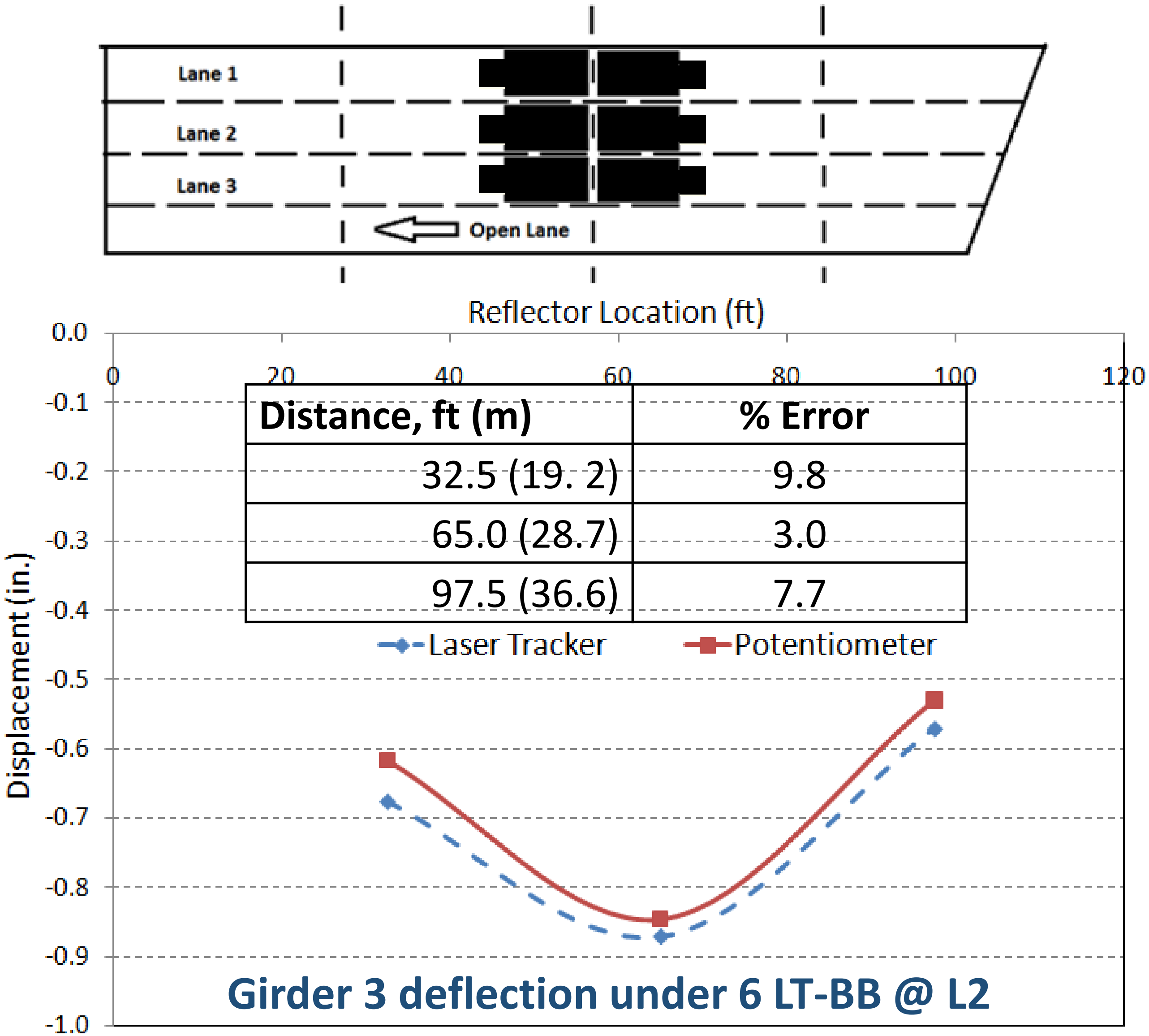
0.5" Reflector
acceptance angle $\leq \pm 50^0$

AT MeteoStation
(Temp., humidity,
and pressure)

Control Unit and Laptop

A reflector is mounted next to a potentiometer

Laser Tracking by West Michigan University

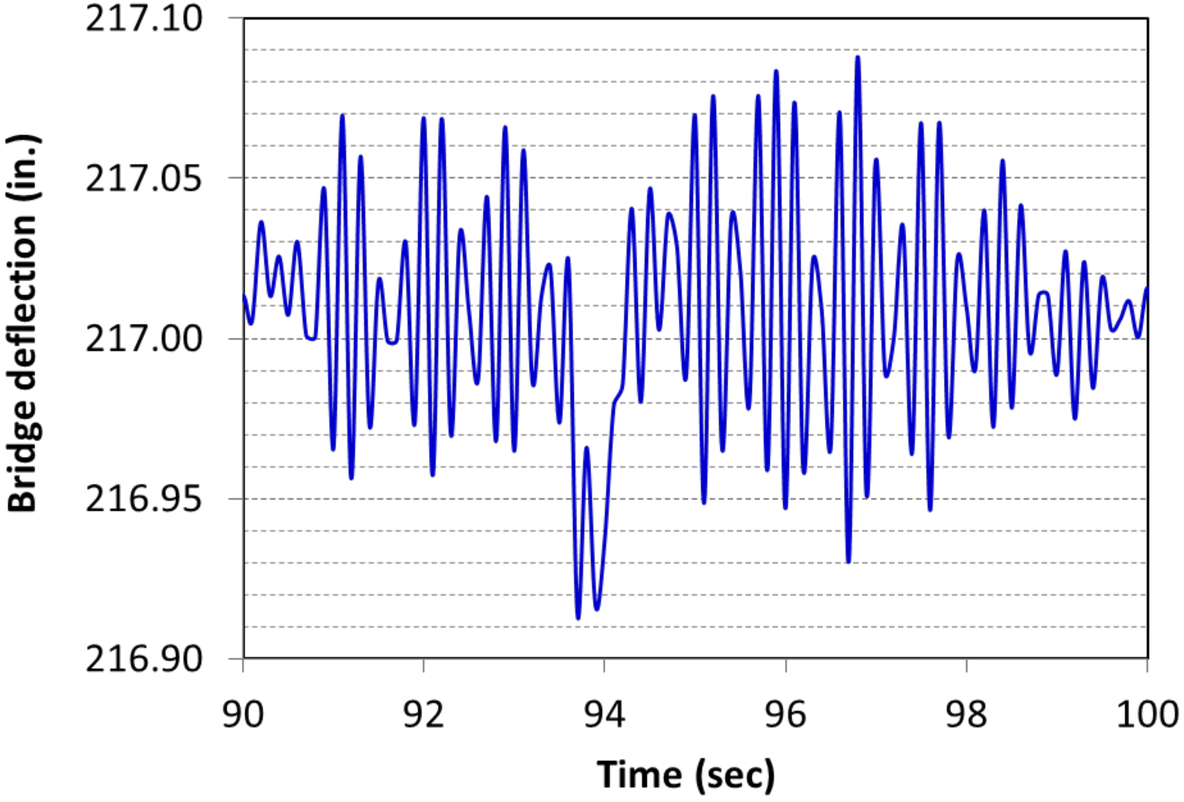


Distance, ft (m)	% Error
32.5 (19. 2)	9.8
65.0 (28.7)	3.0
97.5 (36.6)	7.7

(Oct. 10-11, 2010)

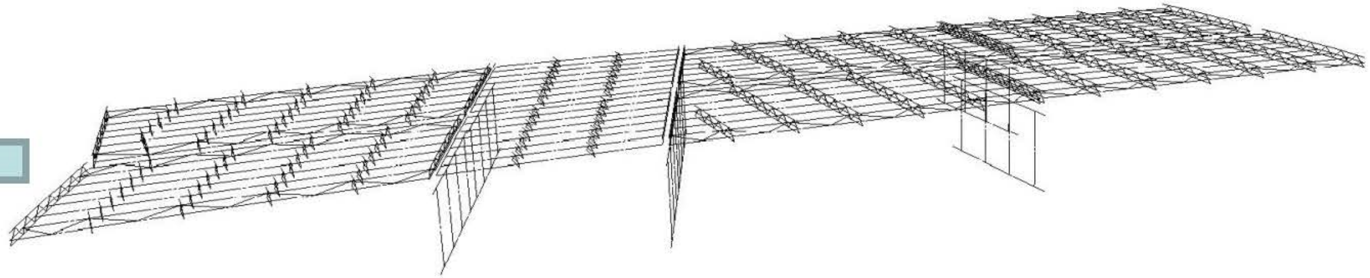
Bridge Displacements Under Operating Loads

Maximum deflection = 0.18 in. OR 4.6 mm



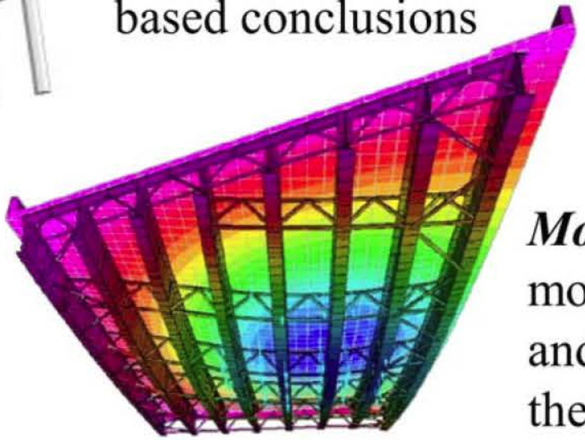
7. STAGES IN the CONSTRUCTION of a FE MODEL

Conceptualization: The structure was inspected through the viewpoint of a modeler



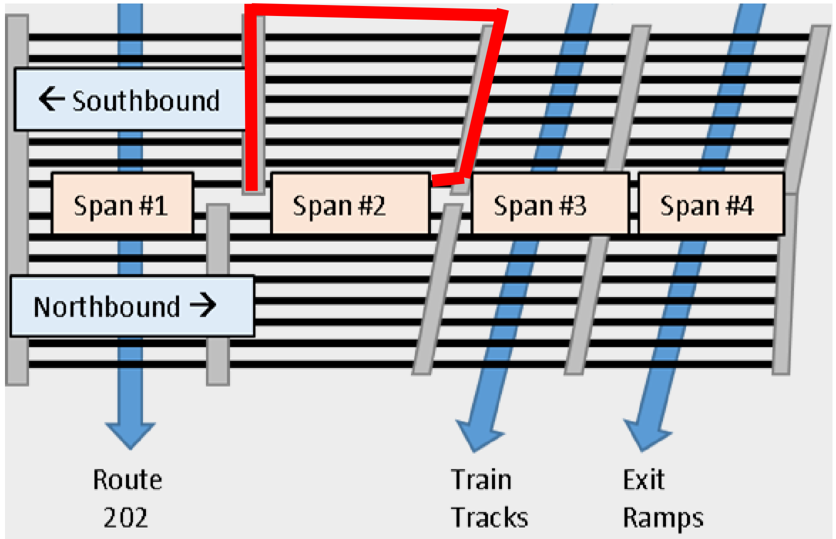
A Priori Model: A global, parameterized model with only minor focus on specific detailing is developed to prepare for experimentation

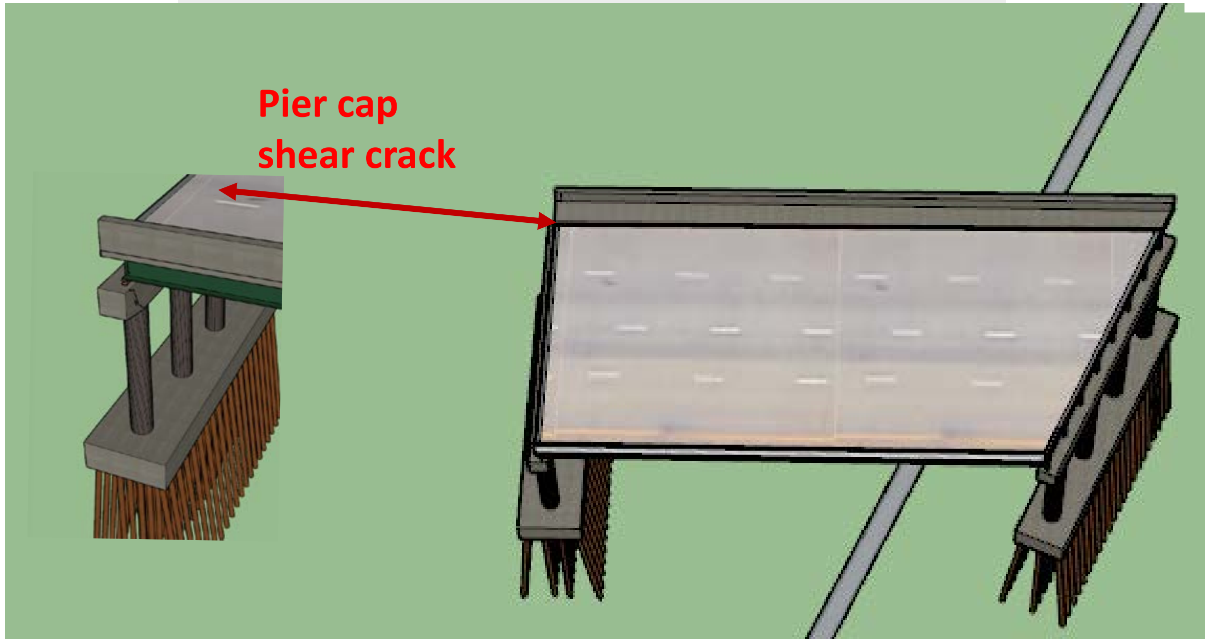
Data Reduction: The model size was reduced and focused on the location of experimentation (Span SB2) to support drawing of data-based conclusions



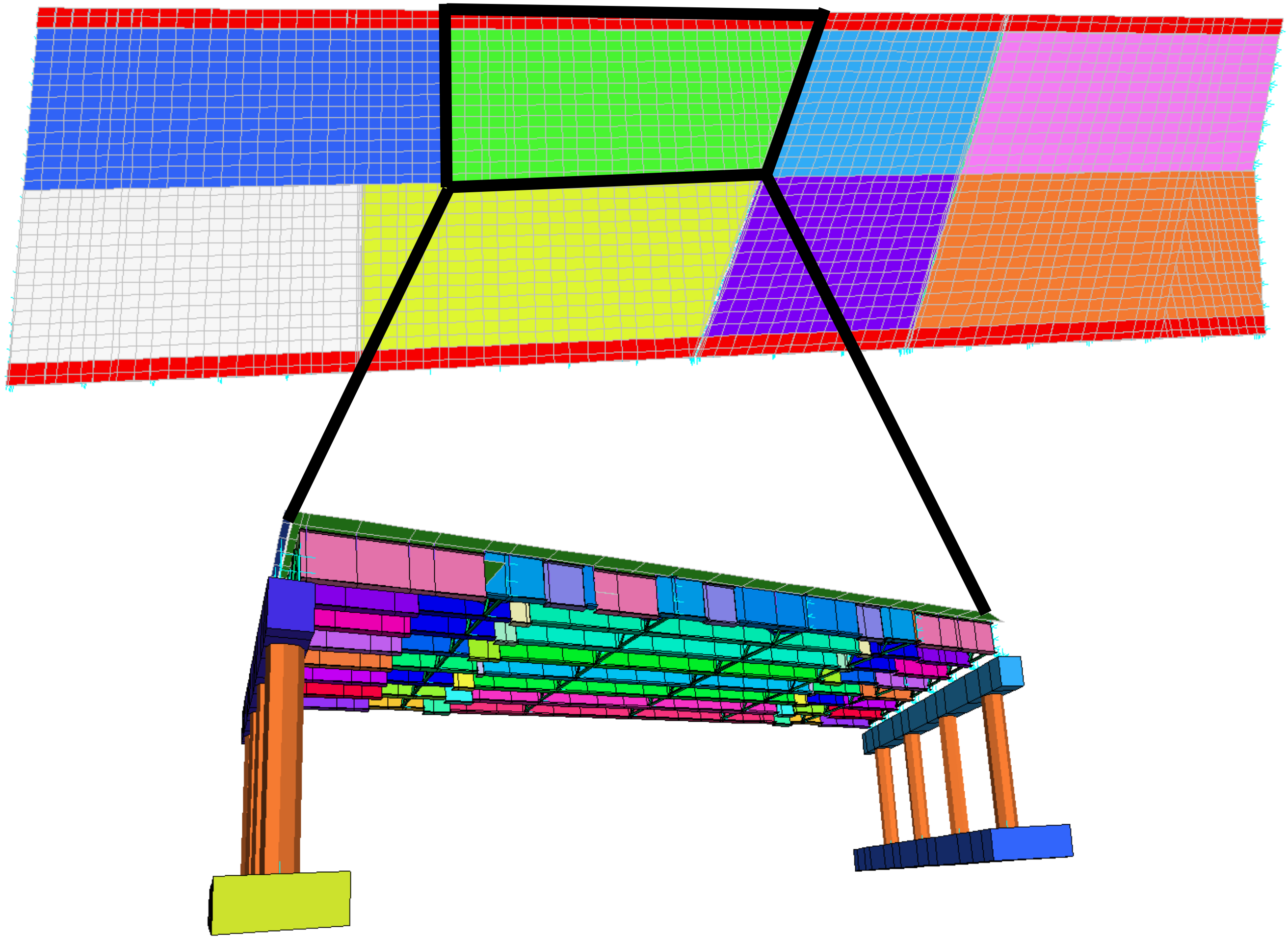
Model-Experiment Correlation: Model was modified in order to represent, parameterize, and update influential factors as indicated by the experimental results

3D Visualization and FE Modeling of the Second SB Span





Global bridge model top view



Southbound Span 2 model

FE Model FREQ Calibration by Static OR Dynamic Test Results

Mode	Experimental Result (Ambient vibration test)	FE model (Calibrated by Operational Dynamic test)	FE model (Calibrated by Static load test)
1	2.89	2.85	2.60
2	3.79	3.71	3.80
3	5.23	5.54	5.21
4			8.69
5	9.47	8.99	9.78
6	11.61	10.61	11.58
7	12.25	13.13	13.06
8	15.12	14.75	
9			16.98
10	20.64	18.13	

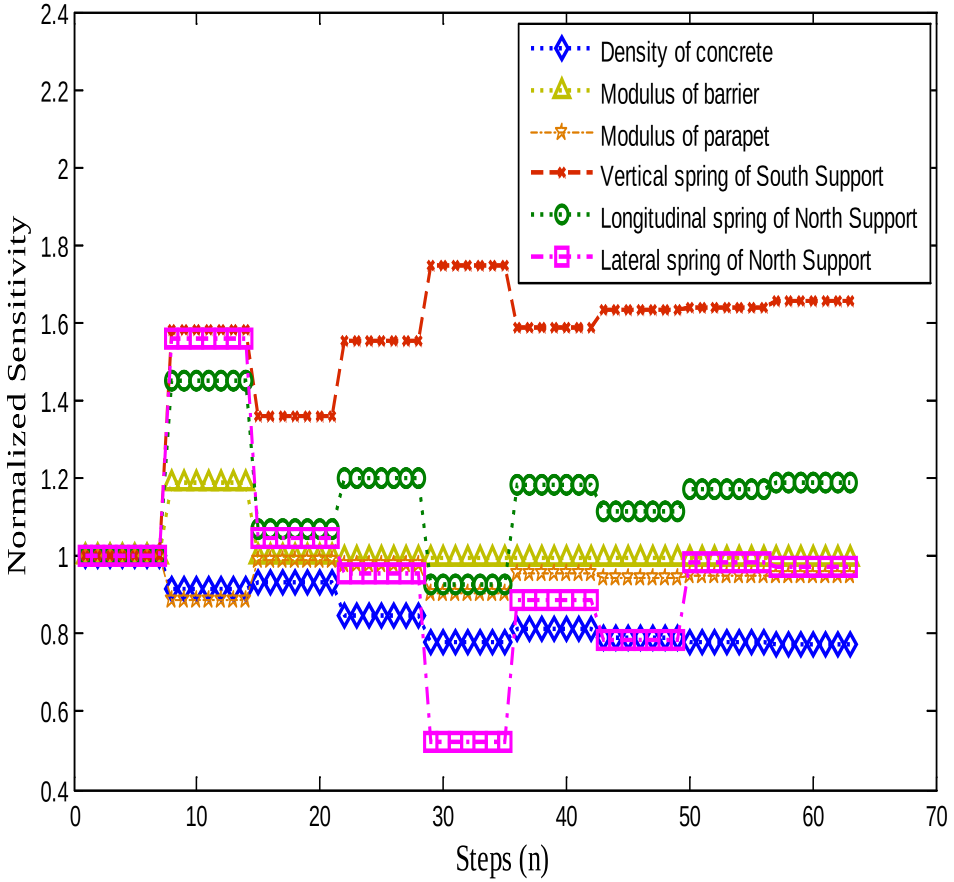
Model calibration by dynamic test results leads to better correlation between experimental and simulated frequencies (Hz).

Correlation between experimental and analytical results decrease if we consider only the static test results for calibration.

FE Model Parameter Identification (Drexel University)

Finite element model for IBS Southbound Span 2 (Strand7)

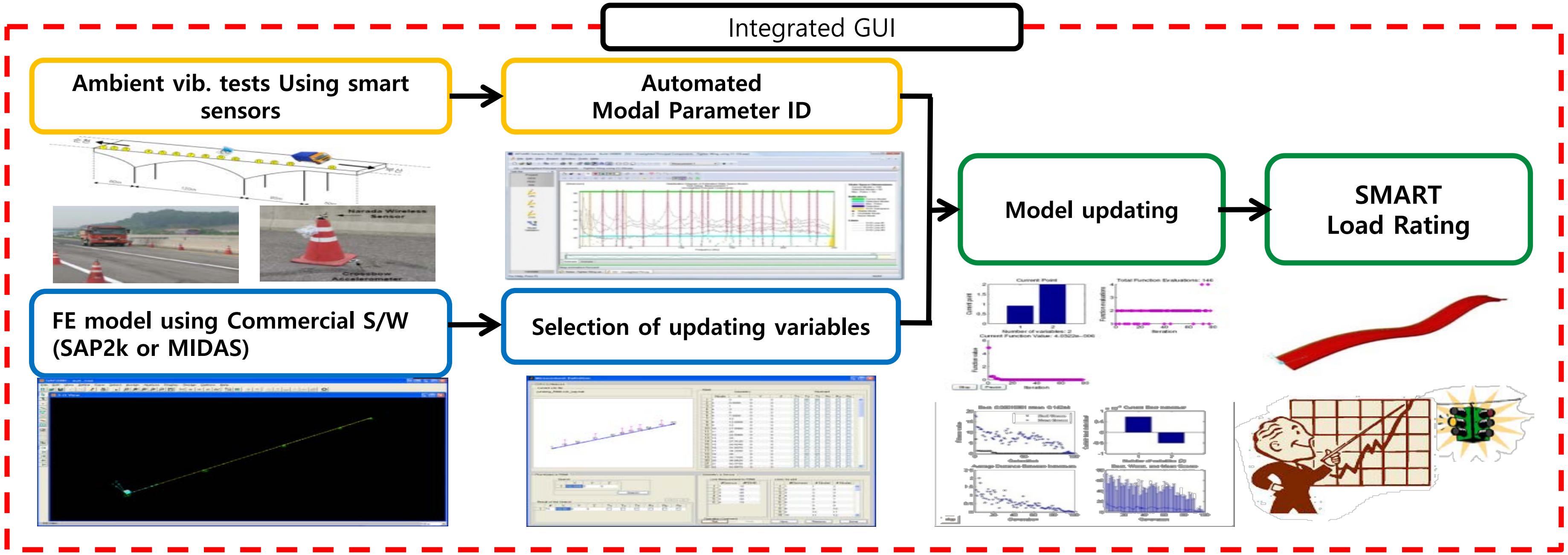
Parameter	Initial	Bounds	Final	Units
Density of concrete	0.095	[0.07,0.1]	0.0734	lb/in^3
Modulus of barrier	3750	[3000,4500]	3733	ksi
Modulus of parapet	3750	[3000,4500]	3555	ksi
Vertical spring of South Support	500	[0,1000]	829	k/in
Longitudinal spring of North Support	500	[0,1000]	594	k/in
Lateral spring of North Support	500	[0,1000]	485	k/in



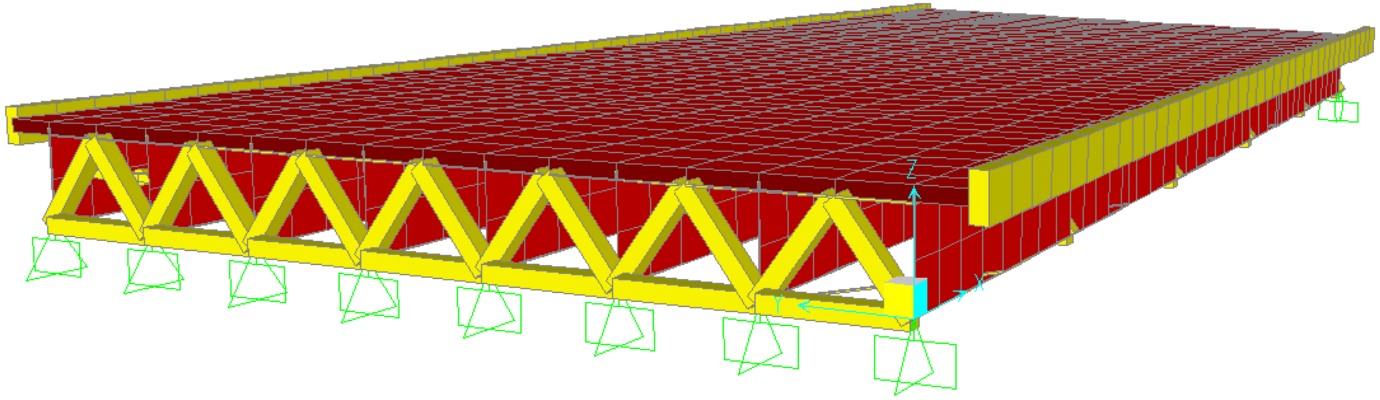
Convergence analysis of five updated parameters

FE modeling (KEC & Sejong University, Korea)

Finite element model for IBS Southbound Span 2 (SAP2000)



Parmeter	Initial	Updated
Slab Stiffness	1	0.523
Cross Beam Stiffness	1	0.505
Spring at Support(Ux)	1	12147ton/m
Web Stiffness	1	1.19



FE Model Frequency Calibration Results

Composite Results for experimental frequencies (Hz)	Drexel- Strand7 Model (calibrated by Drop Hammer test)	Drexel- Strand7 Model (calibrated by Dynamic Impact test)	Drexel-Strand7 Model (calibrated by Static Truck Proof-Load test)	KEC & Sejong University - SAP2000 (calibrated by Operational monitoring test)
2.81	3.05(8.48%)	2.85(1.37%)	2.6(-7.52%)	2.72(-3.25%)
3.72	3.94(6%)	3.71(-0.19%)	3.8(2.23%)	3.57(-3.96%)
4.42	4.21(-4.82%)			
5.22	5.92(13.32%)	5.54(6.05%)	5.21(-0.27%)	5.18(-0.84%)
7.75			8.69(12.13%)	7.93(2.32%)
9.30	9.7(4.27%)	8.99(-3.36%)	9.78(5.13%)	8.09(-13.04%)
11.60	10.65(-8.22%)	10.61(-8.56%)	11.58(-0.2%)	11(-5.2%)
12.28	12.81(4.32%)	13.13(6.92%)	13.06(6.35%)	
14.89	14.76(-0.87%)			
15.43	15.44(0.09%)	14.75(-4.38%)		
16.51			16.98(2.85%)	
20.43	20.84(2.01%)	18.13(-11.26%)		

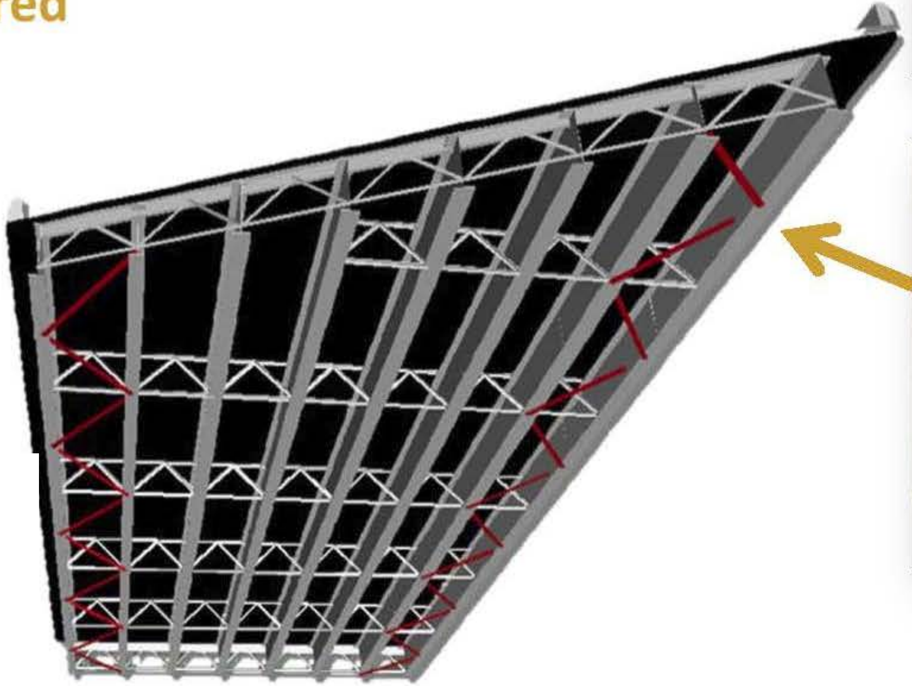
Errors range between 0%-13% whether the FE model is calibrated by Dynamic or Static Test results and used for simulating the Frequencies of the Bridge

8. Scenario analyses by the Digital Twin for Identifying/Confirming Root Causes for Performance Deficiencies

- Once the FE Model is calibrated to simulate measured experimental responses with acceptable errors, we may simulate various loading events to confirm the root causes of performance deficiencies.
- Naturally, causes of deficiencies such as: Fill erosion leading to settlements and Bump at the entrances; and, risks due to the Water and Gas Main do not need simulation. The most important lesson from erosion is to ensure quick and complete drainage of any surface water from the bridge and especially its approaches. The Gas Main poses a major risk and needs to be removed, renewed and routed underground.
- Causes of fatigue cracking, vibrations, deck cracking, bearing distresses and pier-cap crack are NOT OBVIOUS and even though one may hypothesize the causes it is necessary to confirm these before investing into corrective actions.

Findings: Wind Braces are NOT contributing to Structural Stiffness or Strength Capacity

- **Fatigue cracks occur primarily due to distortion of the wind bracing caused by live load deflection**
- **Braces appear to be redundant for lateral loading and irrelevant for vertical loading**
- **Removal of wind bracing elements should be considered**

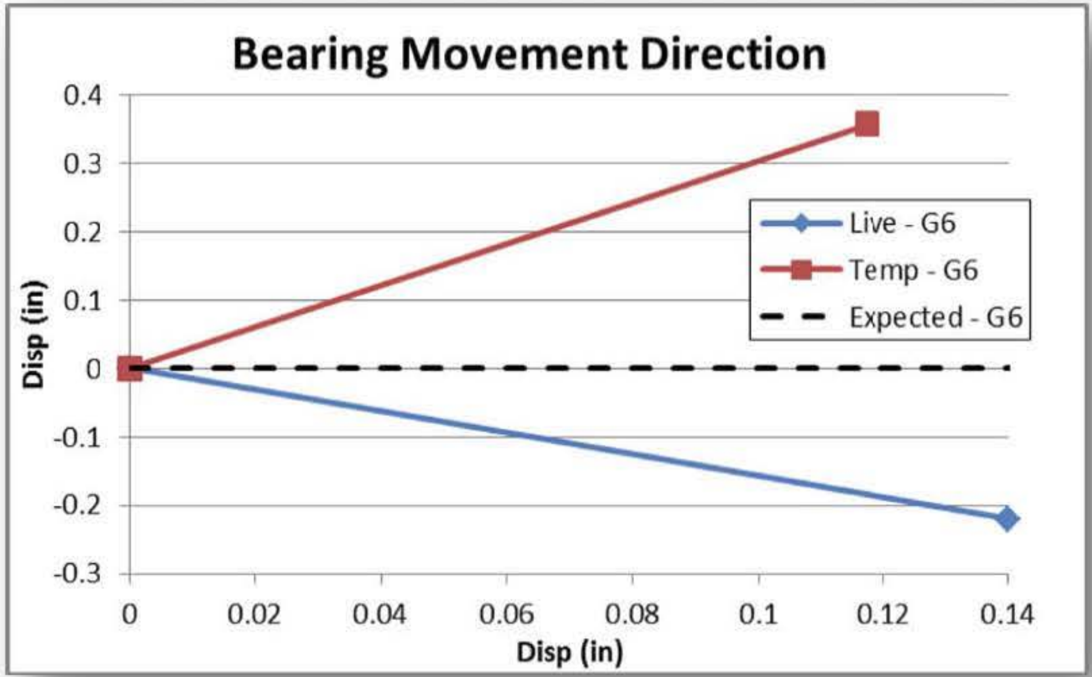


Gusset plates should not be directly welded on girder webs. They may be connected through stiffeners that will stiffen and protect the girder web against distortion-induced fatigue failure.

X-braces are instead highly functional adding to stiffness and strength of the bridge superstructure.

Findings: Fixed-Direction Rocker Bearings

- Original rocker bearings are deteriorated and, in some cases, damaged
- Water drains through joints onto bearings
- Additionally, the calibrated finite element model indicates ideal bearing movements are not uniaxial along span
- Any bearing replacement should explicitly consider bi-directional movement (and its impact on the joints)

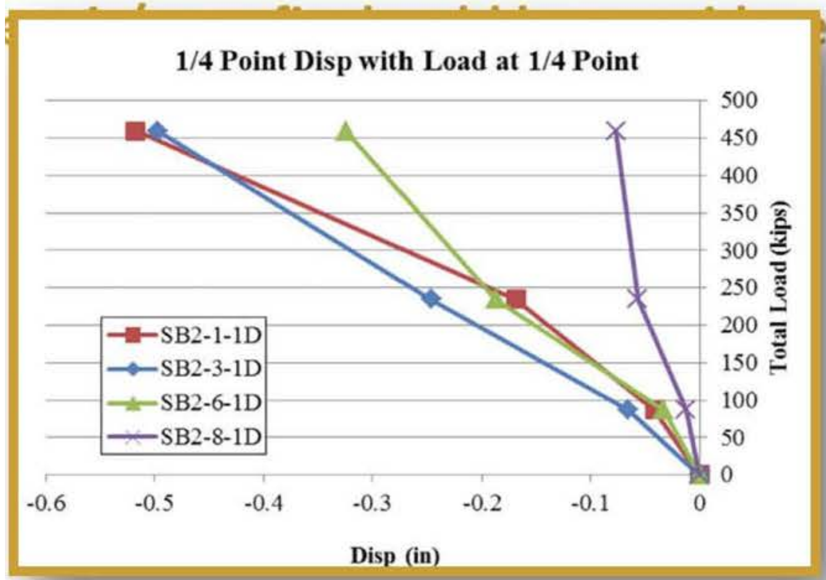


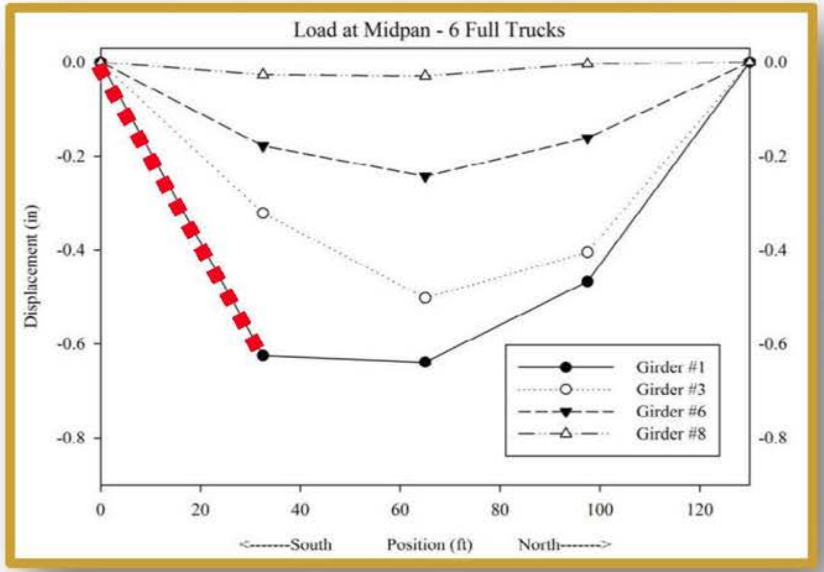
It is recommended to replace all bearings with multi-directional elastomeric bearings

Findings: Pier-Cap Corbel Shear Crack is Active

- **Crack opening was directly measured both during the static test and during normal operations**
- **Static testing indicated nonlinear behavior of girder #1**
- **Significant flexibility of pier cap identified through model updating**
- **Apparent detailing error in the original plans**

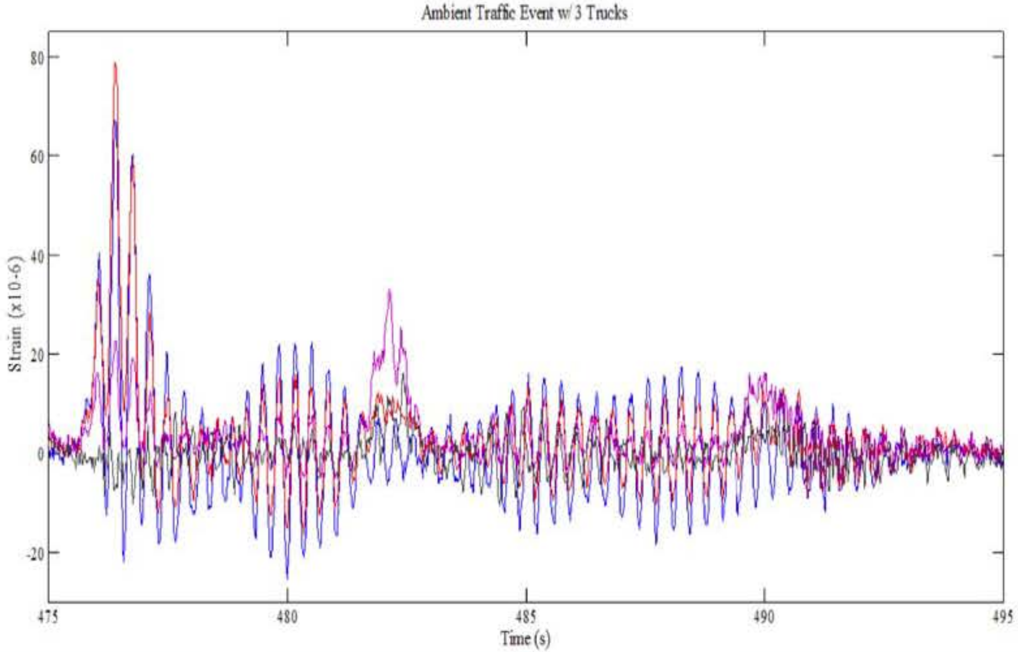
Post-tensioning the Pier-Cap by coring within/thru may be considered for repairs in conjunction with epoxy injection.





Findings: Excessive Vibrations Need Mitigation

- **Excessive vibrations (up to 0.4g under normal operations) were observed**
- **Heavy vibrations likely contributed to:**
  - Bearing/joint deterioration
  - Pier cap cracking
  - Fatigue cracking
- **Mitigation of vibration should be considered to ensure/improve durability and performance.**
- **A potential strategy would be to modify stiffness through modifications to diaphragms, girder cross-sections or through rendering the bridge continuous.**



Truck #1 – Lane 1:
80us response in Girder #3, followed by four vibration cycles where Girder #1 shows larger response

Truck #2 – Lane 3:
37us response in Girder #6, followed by traffic excitation causing 20us response in Girder #1

Truck #3 – Lane 3:
15us response in Girder #6 which does not excite Girder #1 at all

- **Elastomeric Energy Dissipating Bearings may be considered**
- **Bridge Dynamics should be explicitly included in design**

Concluding Remarks on Future of Bridge Engineering

- Current visual inspection practice has to be improved by leveraging technology before and during the inspection, by sharing images in real-time and remotely consulting with senior engineers; by installing sensors and capturing data to quantify operational strains, tilts, displacements and accelerations; and by leveraging properly captured and archived heuristic data about bridge types.
- Inspection results should include documenting performance concerns for ALL PERFORMANCE LIMIT-STATES considering the site geology, geophysics, hydrology, climate and the owner-operators organizational system.
- Technology leveraging requires strategy and integration – the construction of a digital twin of a bridge is an excellent strategy for a mechanistic understanding of how a bridge (or - type of bridge) is performing, the root causes of performance concerns and for developing a maintenance and asset management strategy.
- Identifying the cause of a number of performance deficiencies do not require technology – they require a carefully obtained and archived heuristic knowledge-base – which is worth a coordinated investment by FHWA and States.