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SUMMARY OF RECENT BRIDGE RESEARCH IN IOWA

PowerPoint Presentation - May 14, 2008

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Summary of Recent Bridge Research in Iowa

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Collaboration with ISU-CTRE Bridge Engineering Center (BEC)

- An agreement with CTRE (Center for Transportation Research and Education) that provides the equivalent of a half-time faculty position dedicated for helping the Iowa DOT Bridges & Structures in various research activities. The research is conducted by the Bridge Engineering Center (BEC) which is part of CTRE

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Overview of Research Program Description

- FHWA Innovative Bridge Research & Construction/Deployment (IBRC/IBRD) and Highways for Life (HFL) programs
- Iowa Highway Research Board (IHRB)
- Special Investigations
- Load Testing program

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LIST OF PROJECTS BY PROGRAM

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IBRC/IBRD & HFL PROJECTS

- Accelerated Bridge Construction Using Prefabricated Elements
- Ultra High Performance Concrete (UHPC)
- Fiber Reinforced Polymer (FRP)
- Corrosive Resistant Reinforcing Steel (MMFX)
- Steel Free Concrete Deck
- High Performance Steel (HPS)

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IOWA HIGHWAY RESEARCH BOARD (IHRB) PROJECTS

- Load Rating through Diagnostic Load Testing
- Investigation of Fatigue Cracks due to Out-of-Plane Bending
- Investigation of Light Pole Failure

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SPECIAL INVESTIGATIONS

- Monitoring of the Iowa River Bridge Launching
- Monitoring of Various Structural Elements (drilled shafts, arch hangers, sign support structures, light poles, etc.)
- Load Testing of Bridges

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DETAILS OF PROJECTS FOLLOW

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IBRC/IBRD & HFL PROJECTS

- Accelerated Bridge Construction Using Prefabricated Elements
- Ultra High Performance Concrete (UHPC)
- Fiber Reinforced Polymer (FRP)
- Corrosive Resistant Reinforcing Steel (MMFX)
- Steel Free Concrete Deck
- High Performance Steel (HPS)

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Chapter 1

Accelerated Construction using Prefabricated Elements

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a) Prefabricated Bridge Elements

Boone County

Madison County

24^{th} Street

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Project Goal

- Using high performance precast concrete bridge components to reduce construction time by 60%.

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Boone County IBRC Project

- Type:
  - PPC beam bridge
  - Steel H piling and pipe piling foundation
  - Approach roadway surface – gravel

- Size:
  - Span: 151’-4 three span 47’-5, 56’-6, 47’-5
  - Width: 33’-2 out to out
  - Roadway: 30’ gutter-line to gutter-line

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Replacement Structure Details

- Superstructure
  - Modified LXA beams - spacing 8'-4
  - Deck full-depth precast deck panels
    - Pre-stressed transversely
    - Post-tensioned longitudinally
- Substructure
  - Precast abutment footing
  - H-pile foundation
  - Precast pier cap
  - Pipe pile foundation

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Substructure Construction

- Integral Abutment
- Precast Abutment Footing (Pile Cap)

- P10A Pier (Pipe Piling)
- Precast Pier Cap

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Superstructure Construction

- Pretensioned Prestressed Concrete Beams
- Precast Deck Panel Fabrication
- Deck Construction

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Deck Panel Fabrication

- Pretensioned Transversely
- Post-tensioned longitudinally
- 32 Interior deck panels
- 4 End panels with PT anchorage zones

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Deck Panel Erection

- Setting Panels
- Leveling Panels
- Casting Transverse Joints
- Post-Tensioning
- Casting Longitudinal Joints and Abutment Diaphragms

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DANGER




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b) Panels and Paving Notch

US 63

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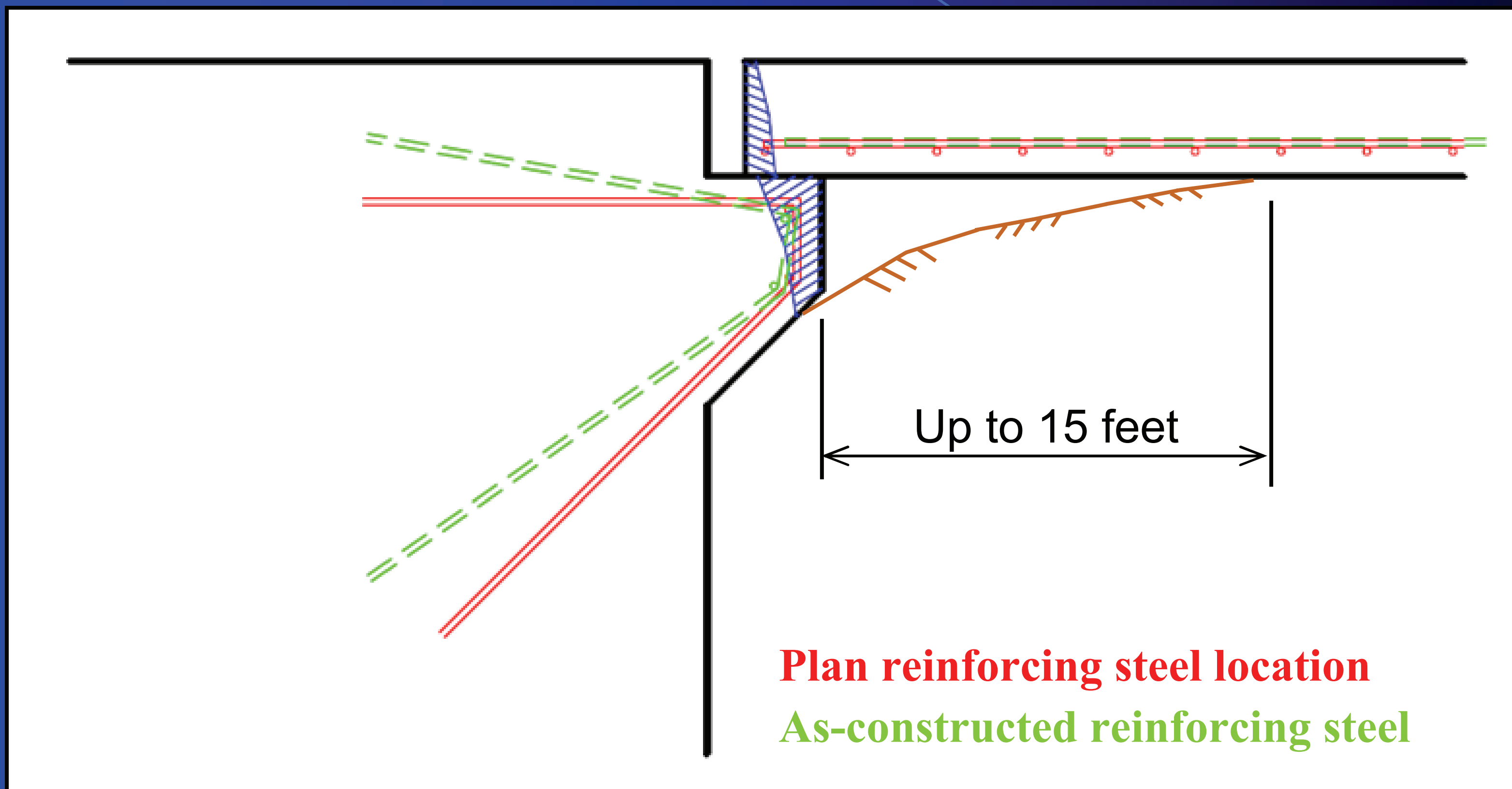
Bridge Approach Settlement Problems

Causes of Approach Settlement



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Conventional repair

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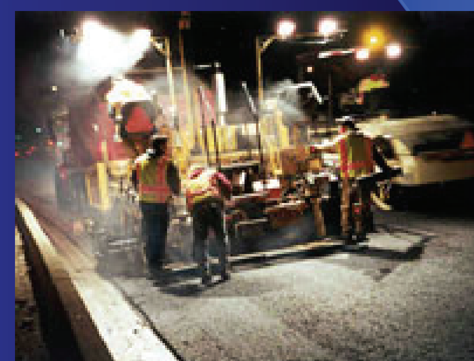
Why Precast Concrete?

- How do you replace failed approach slabs under traffic?
- Night or Weekend construction?



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Lab testing precast paving notch

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c) Precast Bridge Approach
Iowa 60

Iowa Demonstration Project

- Precast Prestressed Bridge Approach Slabs
  - ~77 ft at either end of a skewed bridge
  - Tied to integral bridge abutment
- 2-way Post-Tensioning
- Partial-width panels (lane-by-lane construction)
- Installed over crushed aggregate base graded to crown
- Panels: 14 ft x 20 ft x 12 in.

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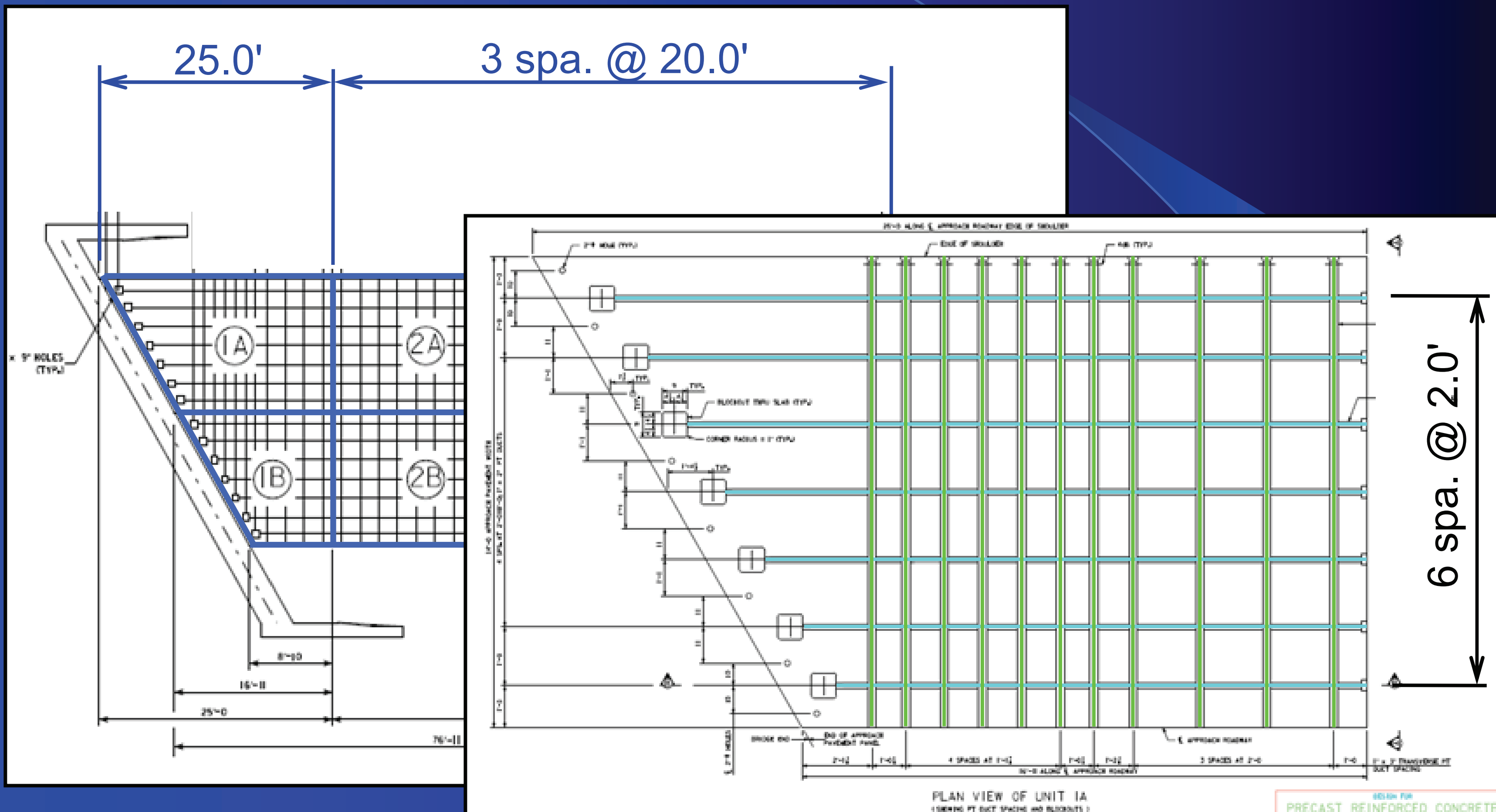
Precast Approach Slab Layout



Longitudinal PT (1 - 0.6" dia. strands)

Transverse PT (1 - 0.6" dia. strands)

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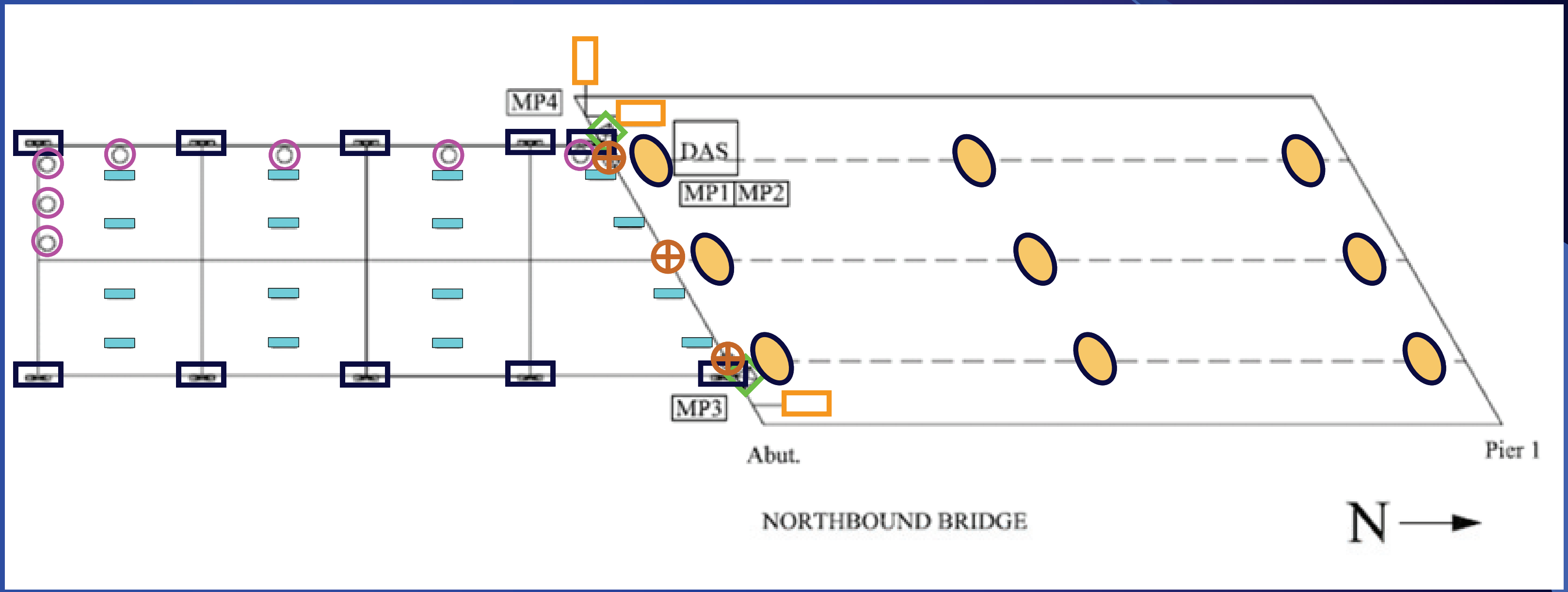
Instrumentation Plan
NB Bridge
(Iowa State University)



- Joint movement crackmeters (10)
- PT strandmeters (7)
- Embedded strain sensors (16)
- Displacement transducers (3)
- Tiltmeters (2)
- Girder strain sensors (18)
- Pile strain sensors (12)

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Chapter 2

Ultra High Performance Concrete (UHPC)

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What is UHPC?

- Produced by Lafarge in North America
- Fine Sand/Cement/Silica Fume
- Low water/cement ratio (0.15)
- Super plasticizer
- Steel Fibers (2% by volume)
- No traditional mild reinforcing steel is required

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Ductal®

Why UHPC?

- High Compressive Strength (up to 30 ksi)
- High Durability
- Low Permeability
- Remove Mild Reinforcement
- More Efficient Sections

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a) Mars Hill Bridge in Wapello County

- 110 ft single span
- 3 beam cross section
- Modified Iowa Bulb-Tee
- 0.6-inch diameter strands
- Integral Abutments
- High Performance Concrete Deck

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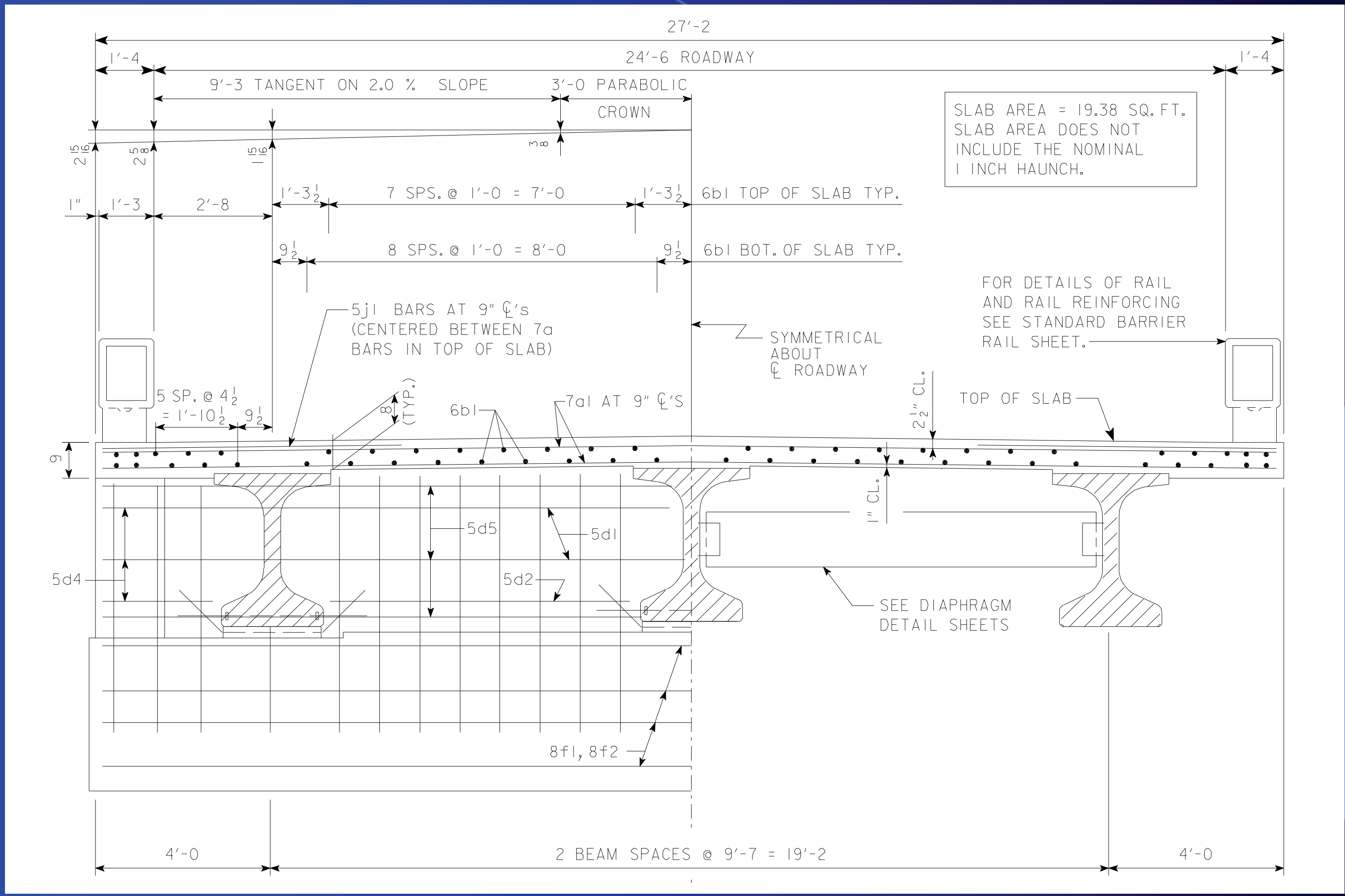

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Design Based on

- Release comp strength 12,000 psi
- Final comp strength 24,000 psi
- Allowable service tension 1,000 psi
- LRFD HL-93 loading
- Grillage analysis for live load distribution

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Test Mix Proportions

Test Mix Proportions	
Description	Quantity
Ductal Mix	137 lbs
Water	8.03 lbs
3000NS (Super Plasticizer)	850 g
Steel Fibers	9.7 lbs

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Adding Steel Fibers

Mixing of UHPC

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Results of Test Mix

Cylinder	Compressive Strength (psi)
1	15,896
2	16,123
3	20,004
4	15,943

Cylinder	Compressive Strength (psi)
1	23,820
2	24,570
3	22,510

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UHPC Issues

- Batching Time
- Equipment
- Placing
- Shrinkage
- Curing Time

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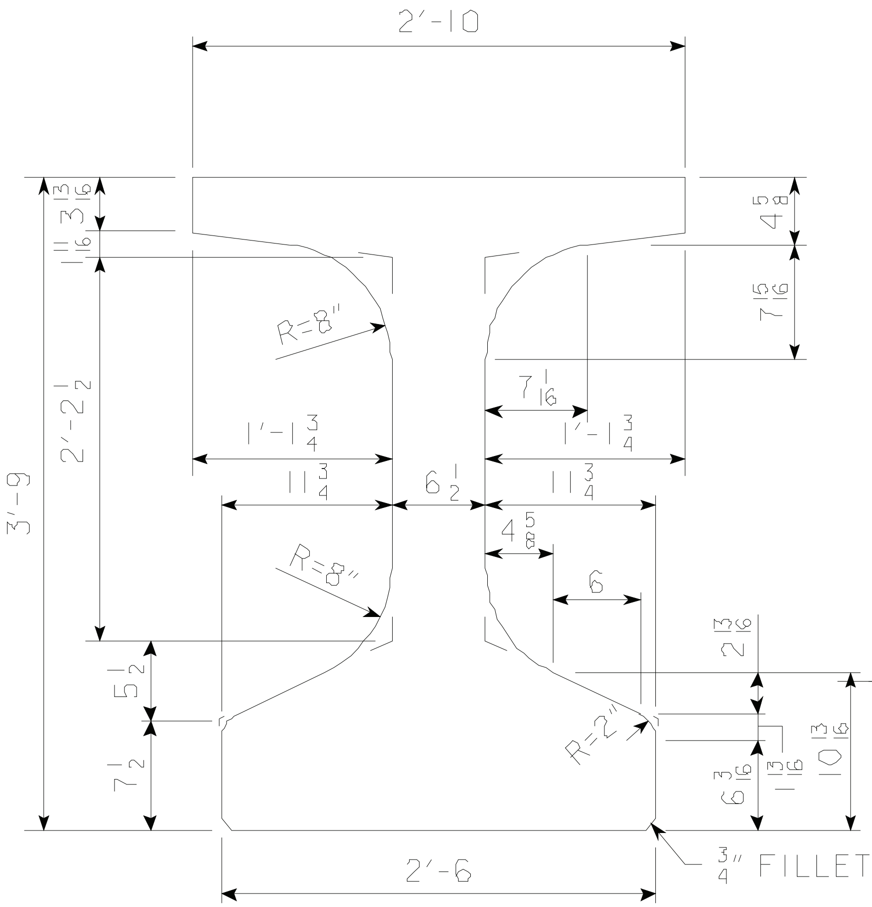
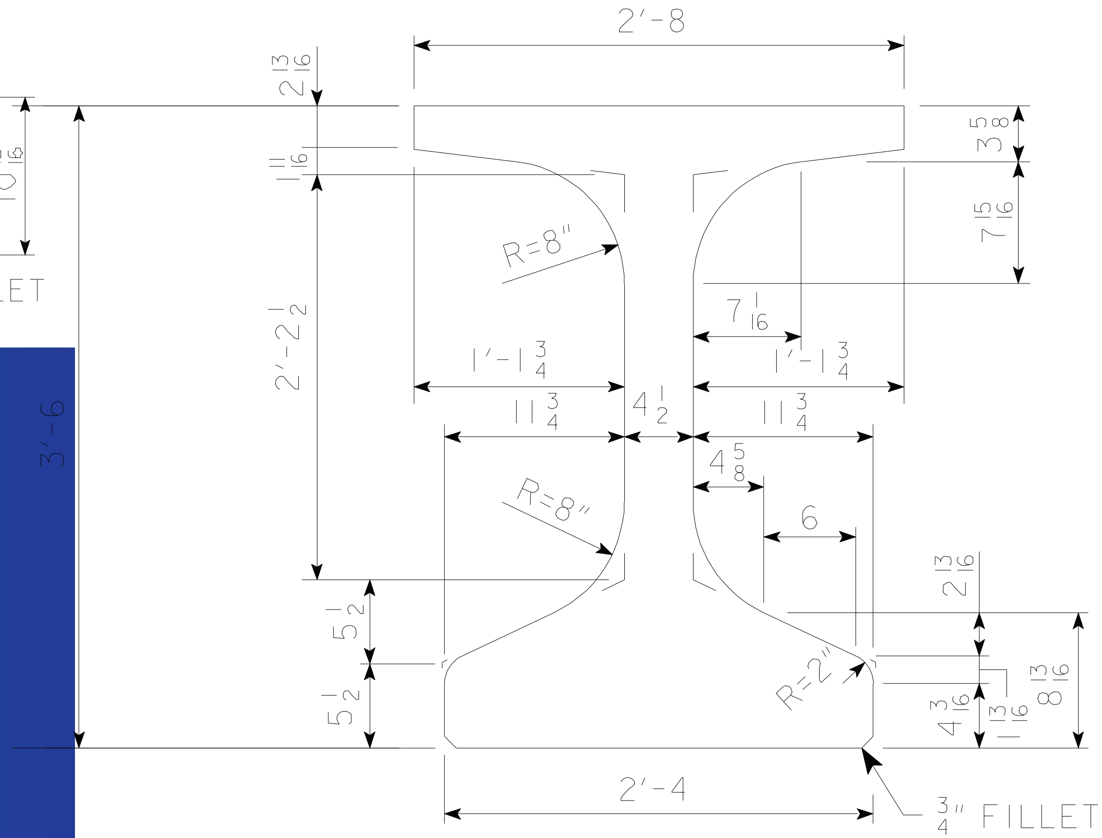


Iowa 45 inch Bulb-Tee

Modified Section



110' Beam Casting

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110' Beam Casting

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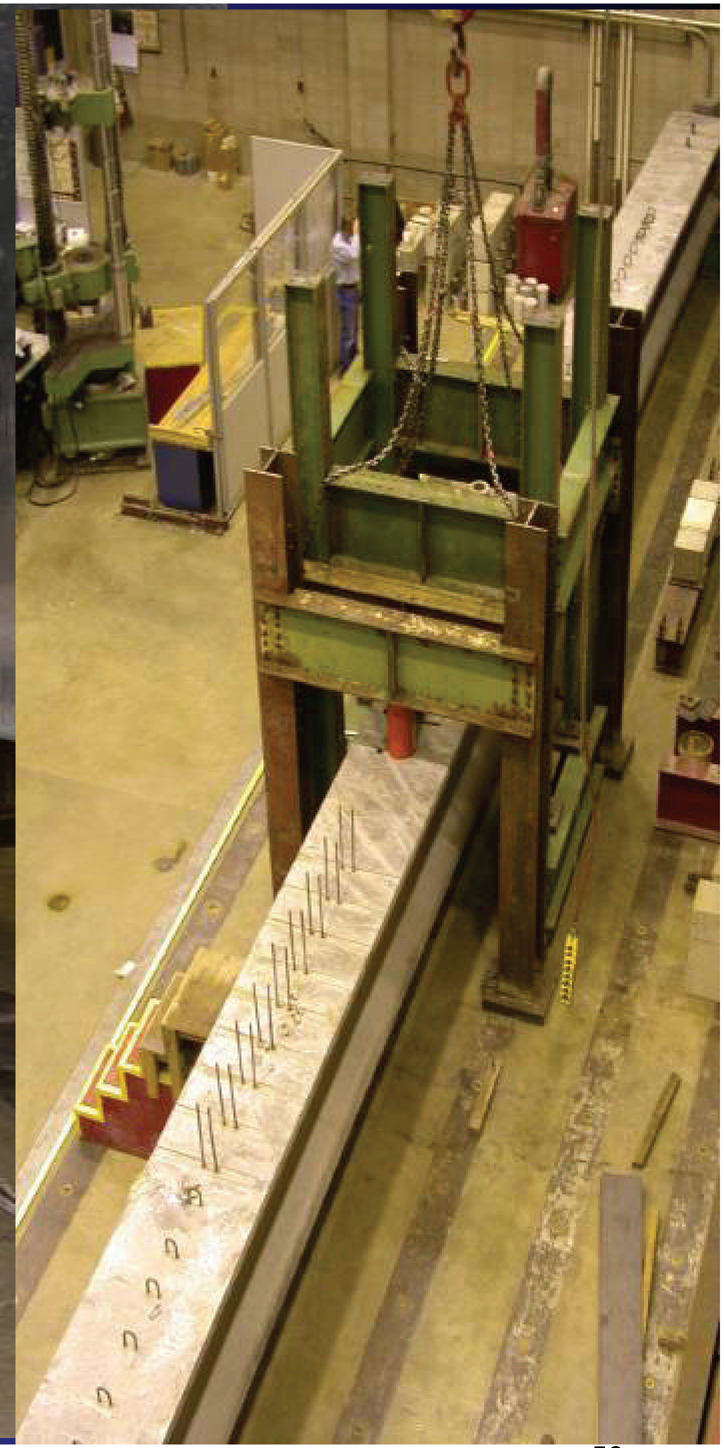

Construction

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Completed Structure

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b) Buchanan County

- 51 ft single span unit
- 3 beam cross section
- π shape sections
- 0.6-inch diameter strands
- Prestressed longitudinally

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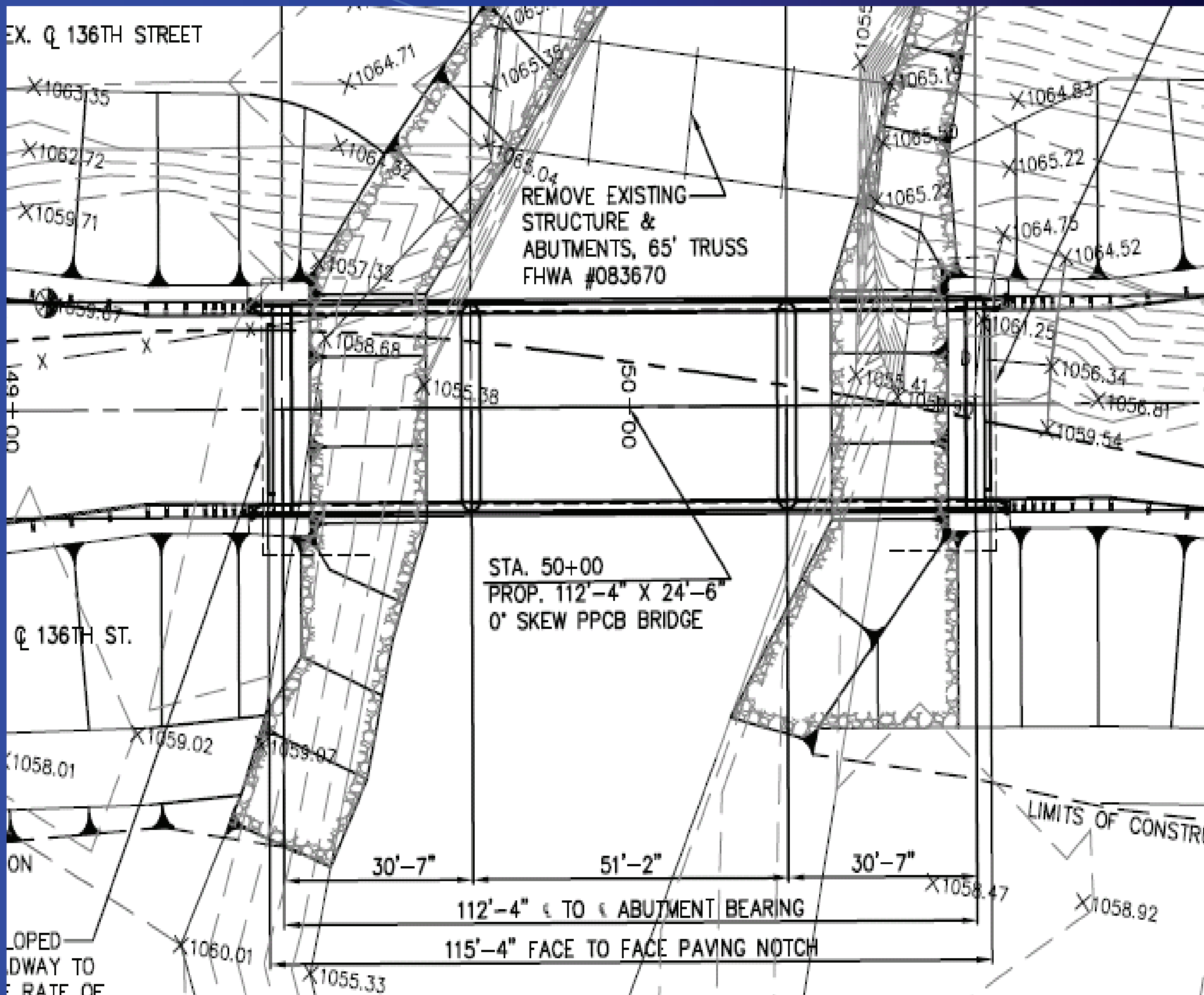
Plan View



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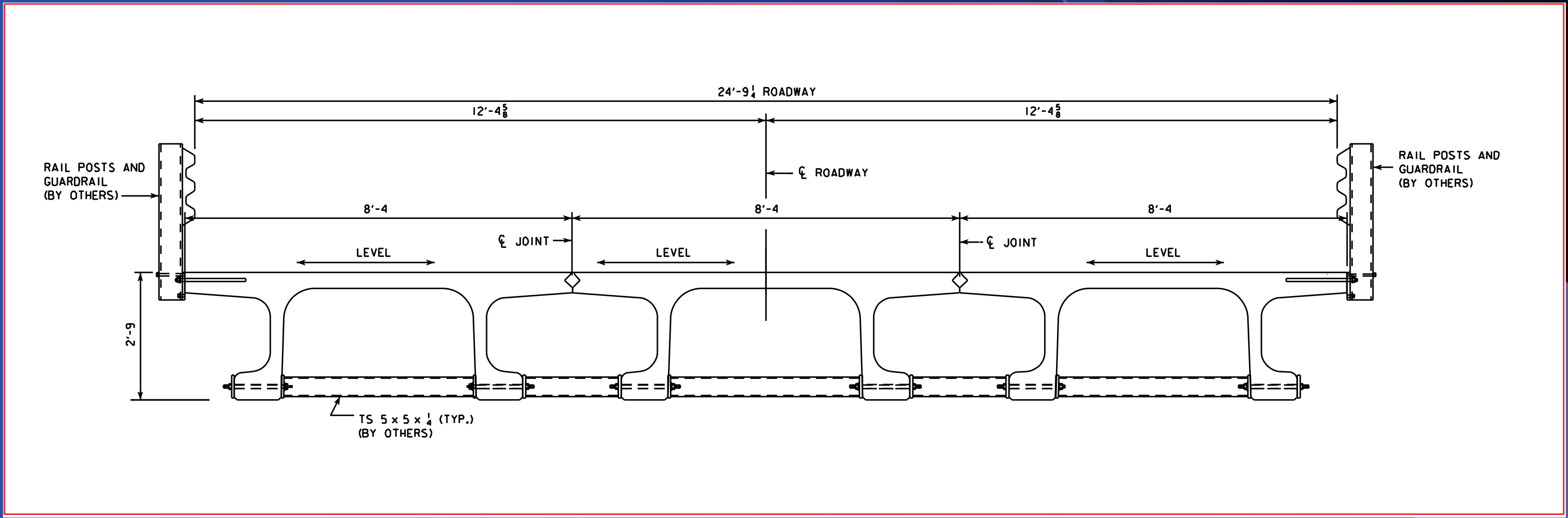
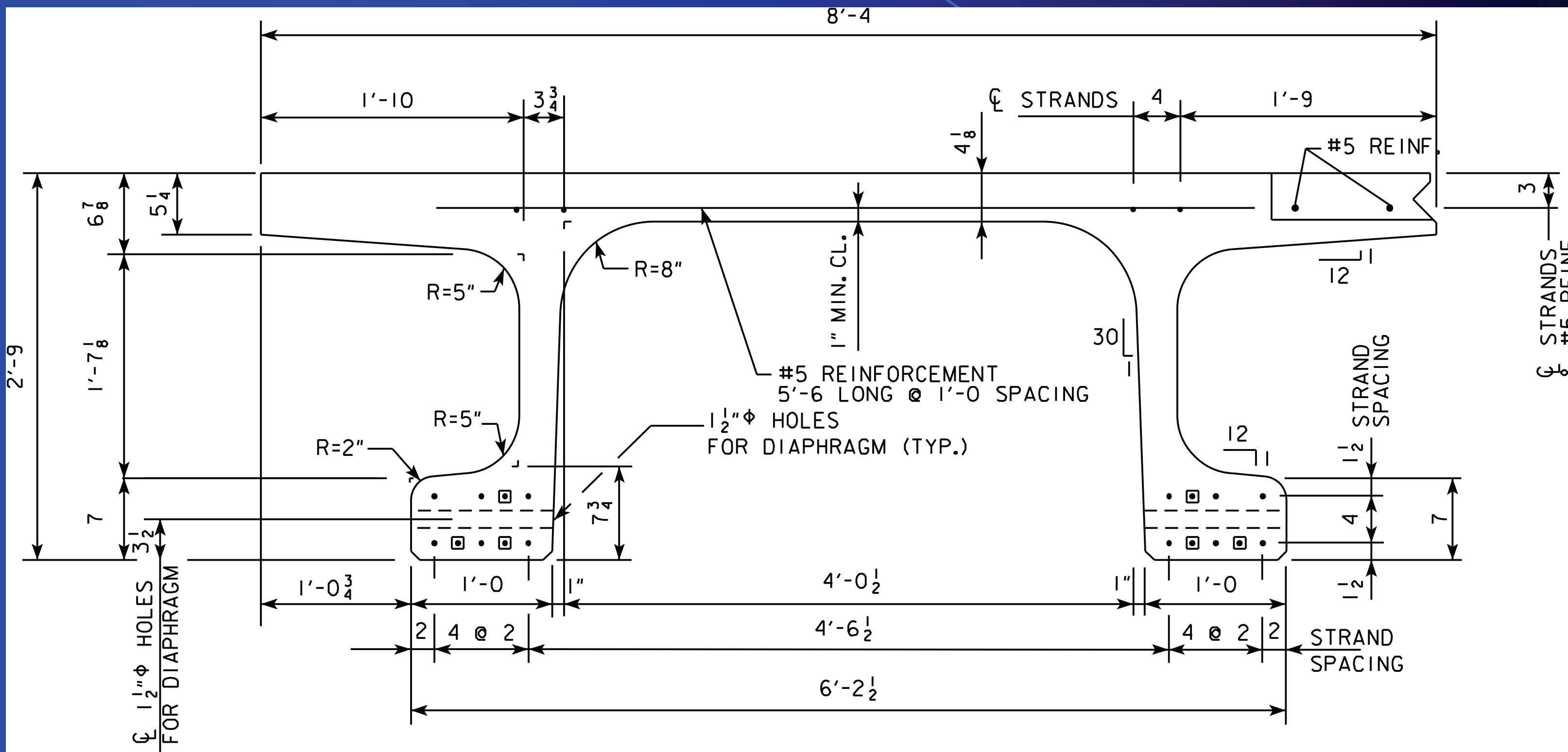
Cross Section



Revised π Section



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UHPC π-Girder

Advantages:

- Corrosion resistant
- Light weight
- High strength with a high fatigue life
- Can be installed with a minimal crew and common equipment

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FRP Projects

- Post-Tensioned FRP Rods
- FRP Strengthening of Steel Beams
- FRP Strengthening of Prestressed Concrete Beams
- FRP Reinforced Glued-Laminated Timber Girders
- FRP Deck
- FRP Superstructure System

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Chapter 3

Fiber Reinforced Polymer

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a) Post-tensioned FRP Rods

- Concept: Use CFRP rods to post-tension a structurally deficient steel girder bridge.
- On Iowa 141 in Guthrie County.

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Strengthening System

- CFRP bars
  - 3/8 inch in diameter
  - Fiber Content : 65 % by volume
  - Tensile Strength : 300 ksi (33 kips per bar)
  - Tensile Modulus : 20,000 ksi

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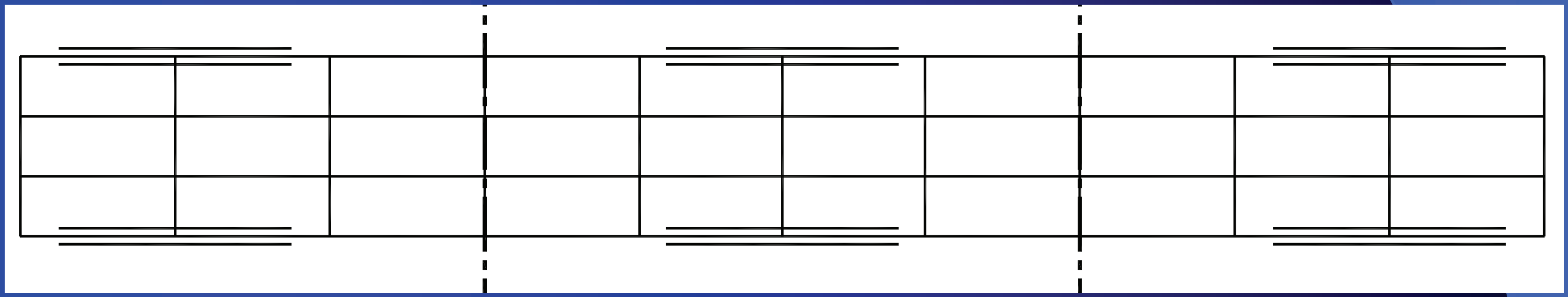
Strengthening System

- Positive moment region of Exterior girders in all three spans



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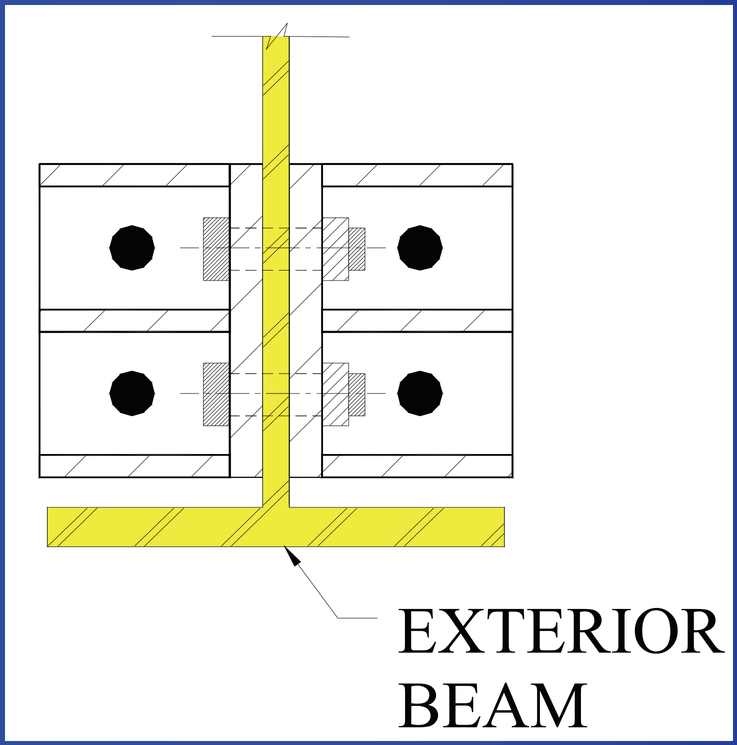
Strengthening System

- Design force of 12 kips per rod, 48 kips per location



- Anchorage assemblies
  - 5 in.x 5 in.x ¾ in. stiffened angles

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Application of P-T force

End Span

Center Span

Completed CFRP P-T System

End Span (Exterior)

End Span (Interior)

Center Span

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Slip of CFRP bar shortly after application of P-T force

- Slip observed at the bar to steel tube anchor interface
- Laboratory testing
  - Slippage phenomenon
  - Material characteristics

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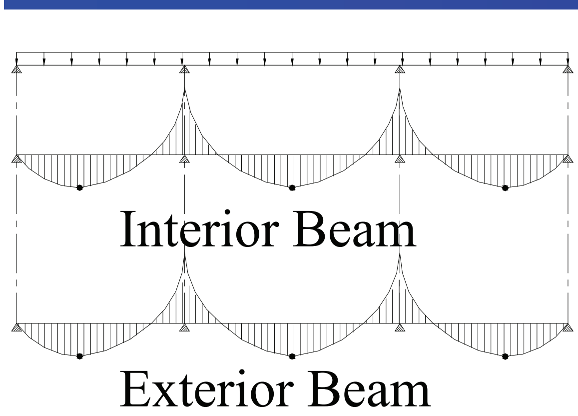
Beam Analysis

- DL, LL, and P-T induced moments
- All combined to illustrate maximum moment reduction

DL



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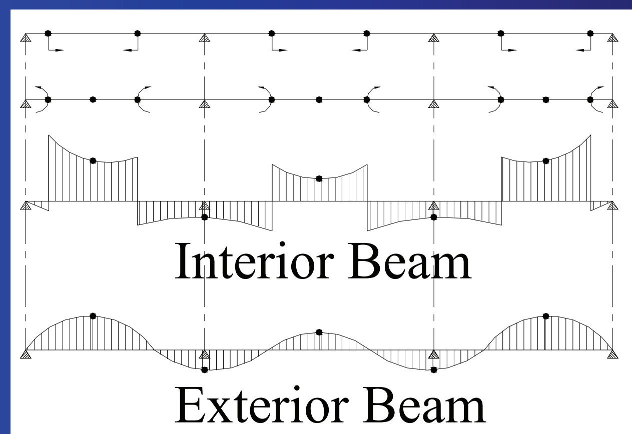
P-T



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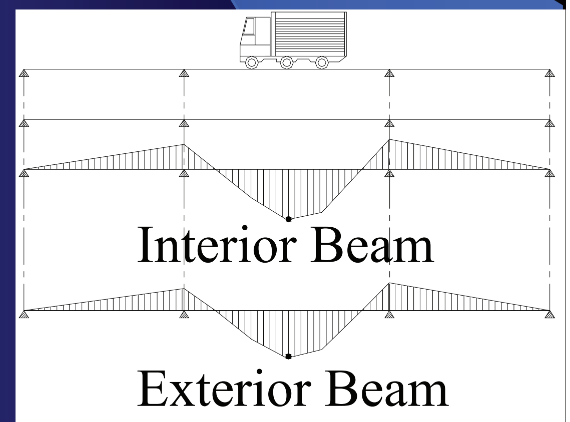
LL



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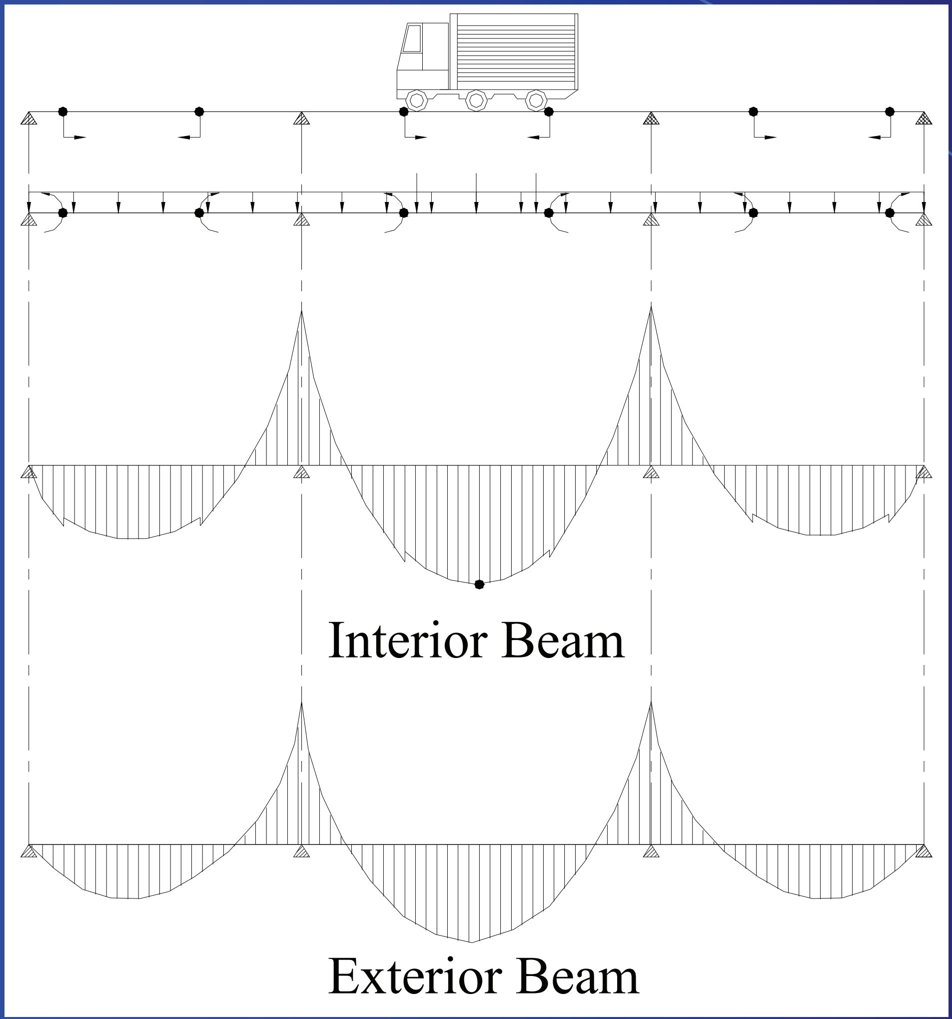
Max Moments Reduction

=



- Center Span
  – 3%
- End Span
  – 5%

b) CFRP Plate Strengthening

- Concept: Strengthen a structurally deficient steel girder bridge by bonding CFRP plates to overstressed regions.
- Located on Iowa 92 in Pottawattamie County.

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Overview

- Laboratory Investigation:
  - Evaluated the feasibility of using CFRP plates in strengthening steel-concrete composite bridges
  - Tested ten small-scale, steel-concrete beams
    - Two different arrangements of CFRP and two different levels of damage were investigated
- Field Investigation:
  - Used CFRP plates to strengthen an existing, structurally deficient steel girder bridge
  - Investigating short- and long-term effectiveness
  - Identified changes in structural behavior due to the addition of the strengthening system

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Description of Bridge:

- Three-span continuous steel girder bridge
- Roadway width = 30 ft [allowing two traffic lanes]
- Total length = 150 ft
  - Two 45.5 ft end spans and a 59 ft center span

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Strengthening System

- Positive moment region of exterior girders and two of interior girders.
- One layer (0.04" x 8") in West end span, two layers in Center span, and three layers in East end span).
- Half CFRP on the top of bottom flange on one exterior girder.

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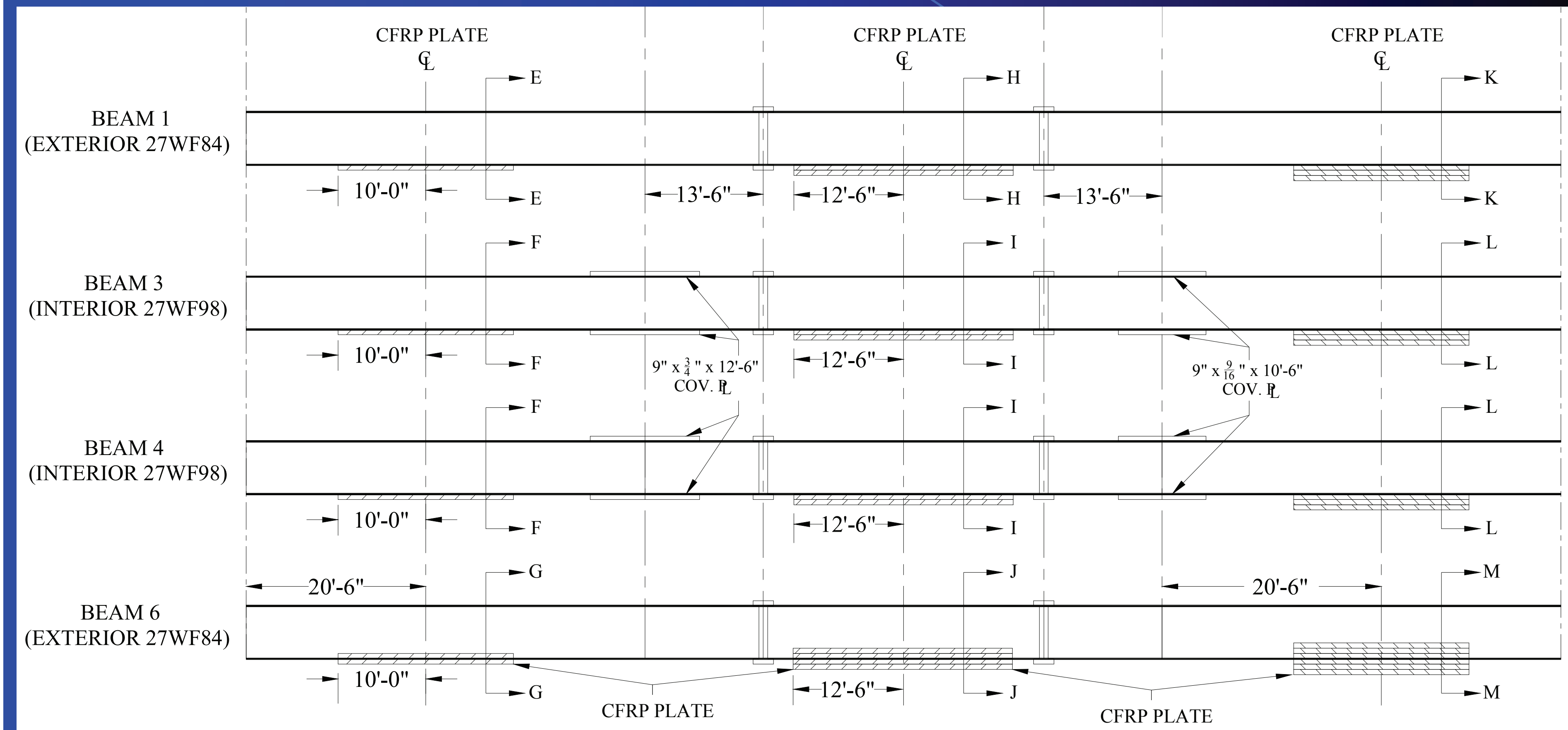
Strengthening System



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Cutting FRP Strips to Desired Lengths

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Removal of Paint from Beams – Stage 1

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Removal of Paint from Beams – Stage 2

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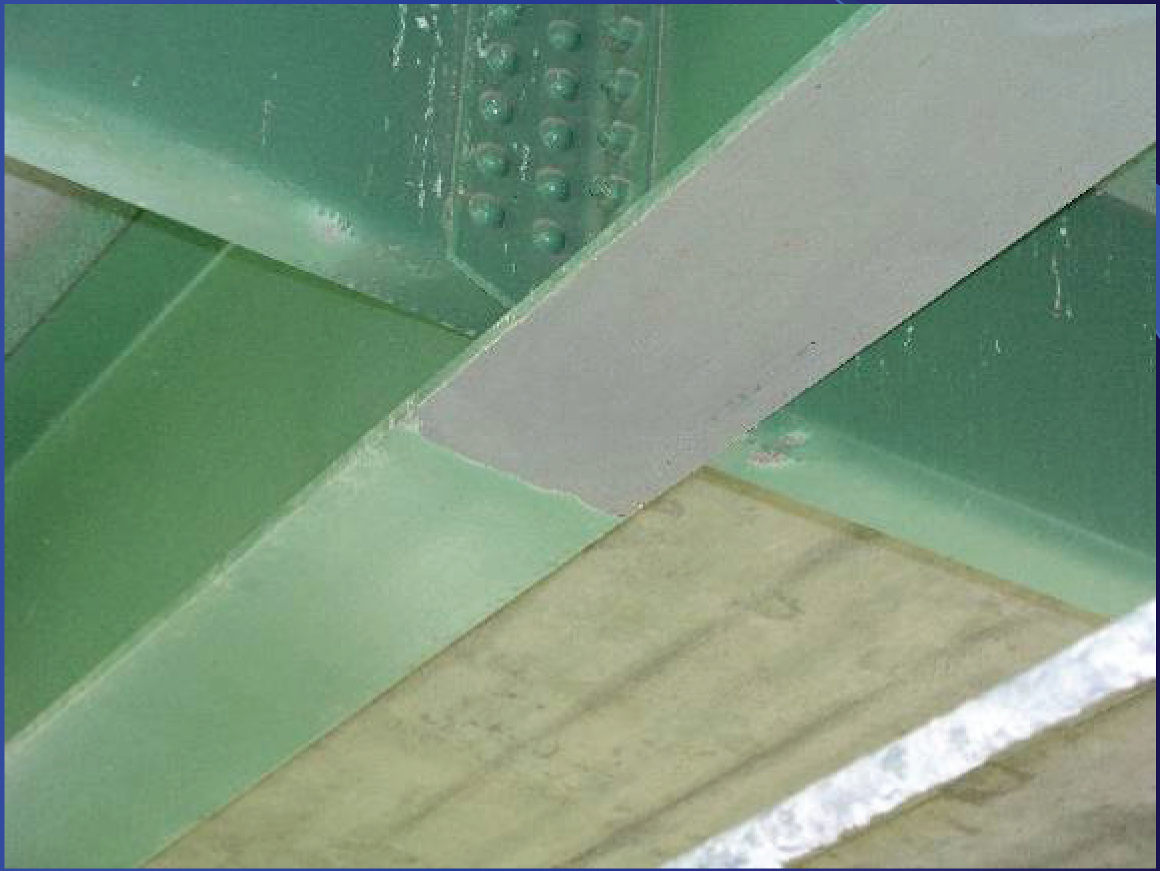
Cleaned Surface



Cleaning of FRP Strips

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Field Cleaning of FRP Strips

Final Cleaning of Beam Flanges

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Installation of FRS Primer

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Application of ECS 104 Structural Epoxy – Long Strips

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Application of ECS 104 Structural Epoxy – Short Strips

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Obtaining Desired Thickness of Epoxy

Application of Epoxy to Beam Flanges

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Installation of FRP Strips to End Span Beams

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Installation of FRP Strips to End Span Beams (continued)

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Installation of FRP Strips to Center Span Beams

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Installation of FRP Strips to Center Span Beams (continued)

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Rolling of installed FRP Plates

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Completed Installation of FRP Plates

One layer (West end span)

Three layers (East end span)

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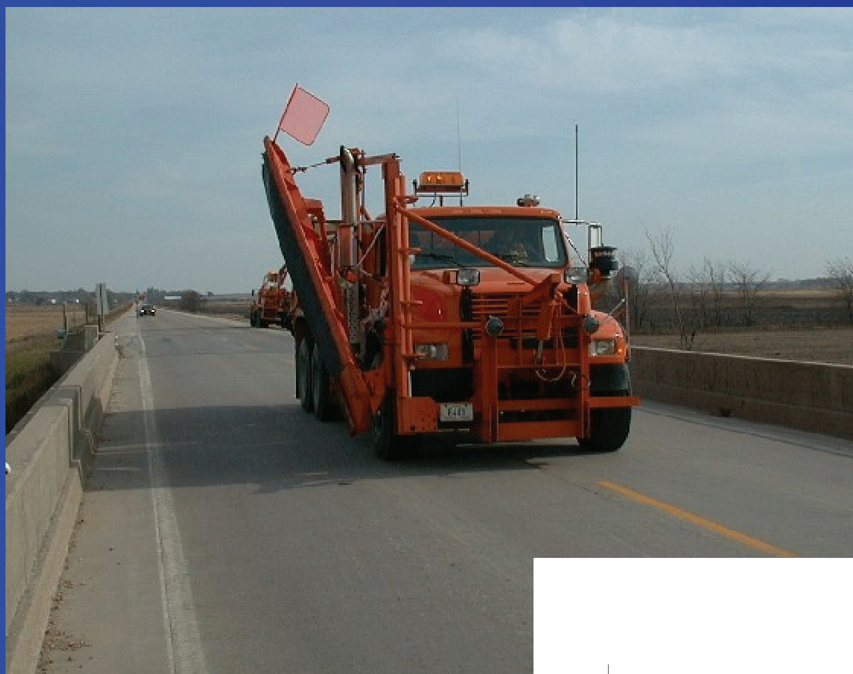
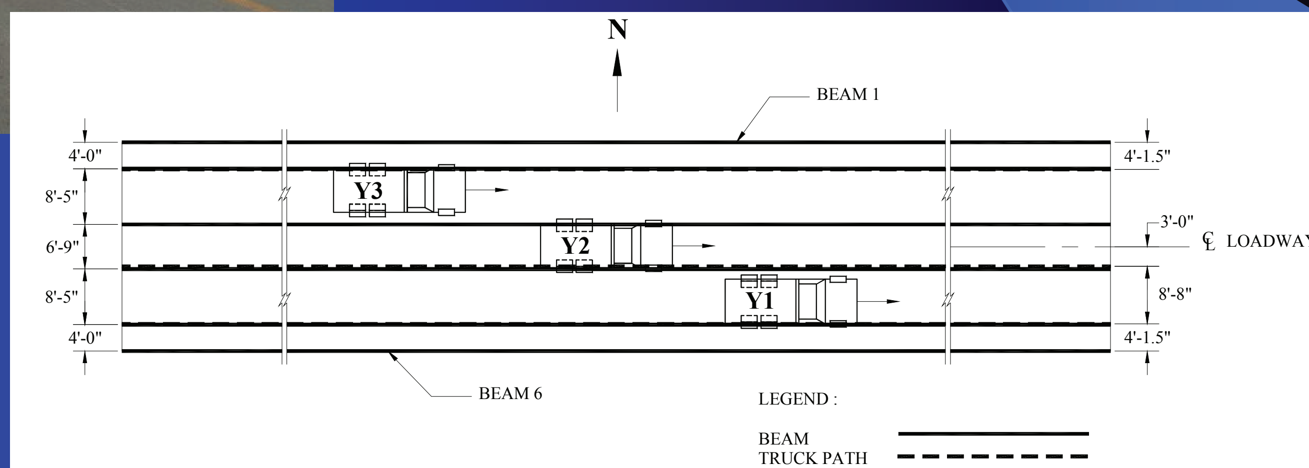
Load Testing



- Half of bridge was instrumented
- 3-axle truck used in three different load paths
- Data collected continuously as truck crossed the bridge
- Initial test and two follow-up tests completed to date



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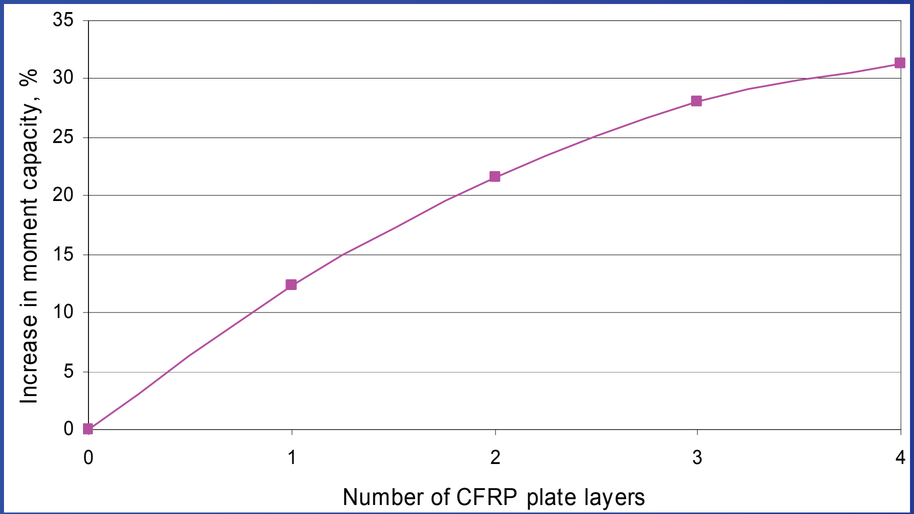
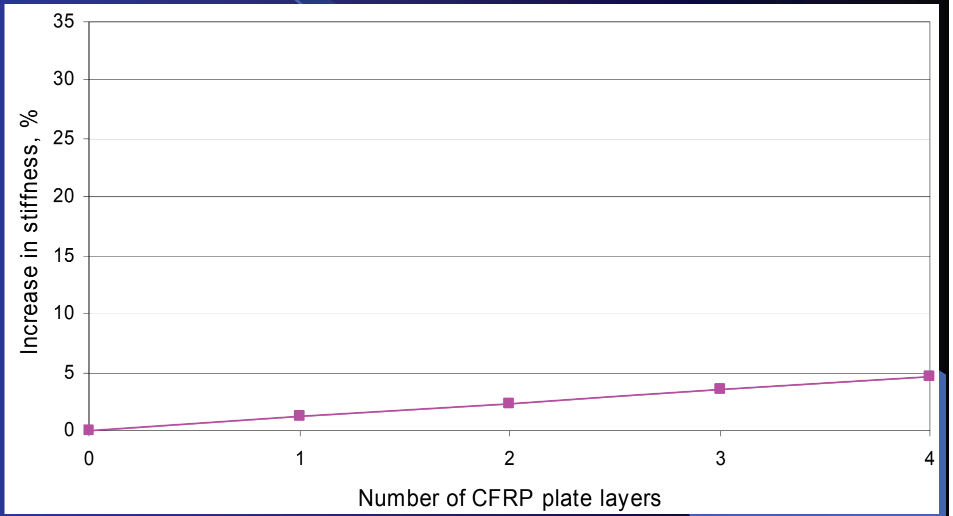
Strength and Stiffness



Change in moment capacity



Change in stiffness

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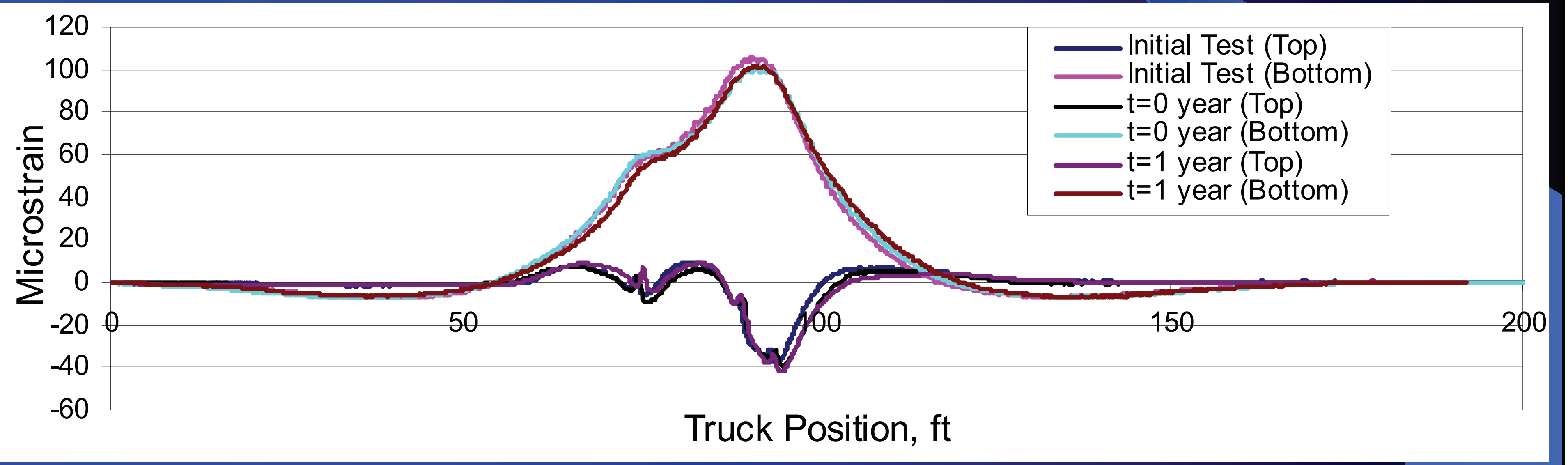
Live-load Flexural Response

- Elastic behavior
- Consistency in strains with time



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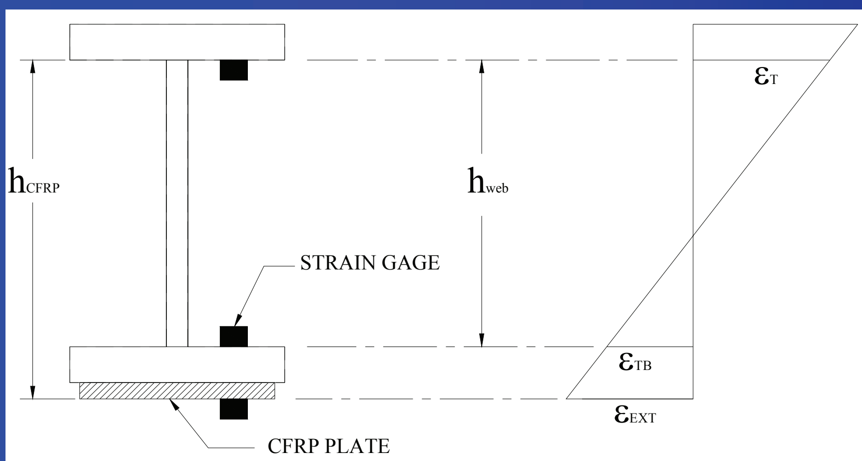
Bond Performance



$$\varepsilon_{EXT} = \frac{(\varepsilon_{T} + \varepsilon_{TB}) * h_{CFRP}}{h_{web}} - \varepsilon_{T}$$

- Critical to have adequate bond for force transfer
- Gages installed on CFRP plate to investigate the bond performance
- Analytical model developed based on strain compatibility relation
- Extreme fiber strains were predicted and compared with experimental data

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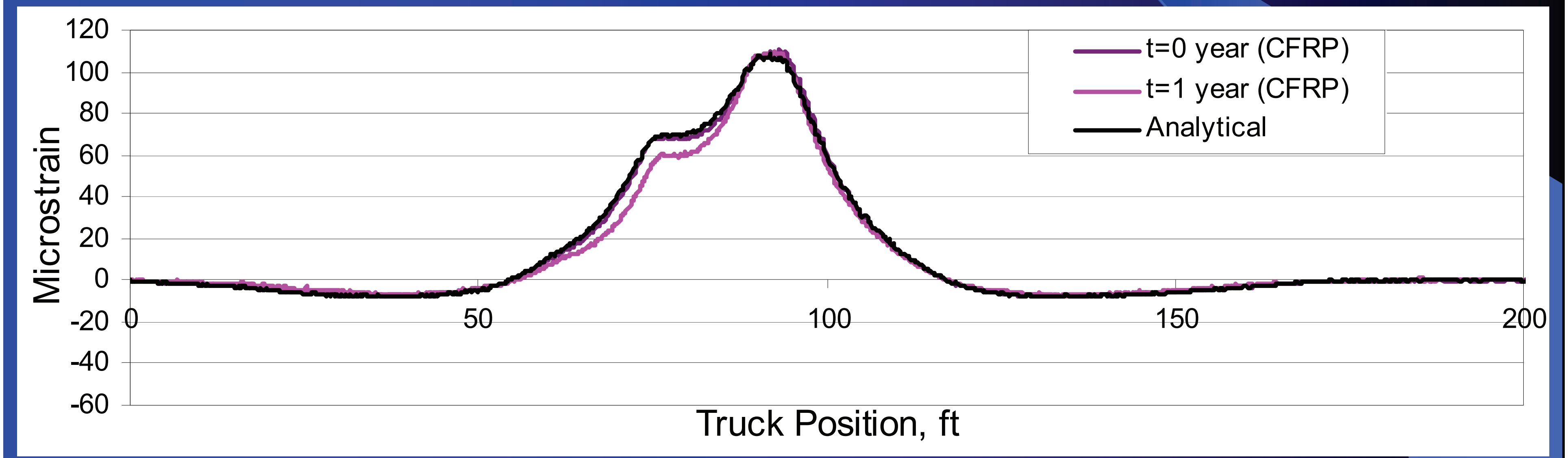
Bond Performance



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Conclusions

- Approximately 10%/layer theoretical increase in moment capacity was attainable.
- CFRP plates strengthening system did not significantly change the behavior of the bridge
- At least initially, there was good bond between the beam and CFRP plates.

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Concluding Remarks….

- Strength of damaged steel girders can be fully restored with the use of CFRP plates
- Stiffness of repaired steel girders is greater than that of the damaged girder, however not fully restored to that of the undamaged girder

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Concluding Remarks [continued]…

- CFRP plates have minimal impact on changing the member stiffness but can have a relatively large impact on changing member strength, ……if properly designed
- Bond performance after one-year of service was good

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Concluding Remarks [continued]….

- The use of CFRP plates appears to be a viable strengthening alternative for steel girder bridges
- Handling and installation of CFRP plates was initially relatively labor intensive and required some training

A three-man crew was needed to install the system

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c) FRP Strengthening of Prestressed Concrete Beams

- Concept: Utilize FRP plates and wrap to strengthen collision damaged prestressed concrete beams.
- US 65 in Polk County.

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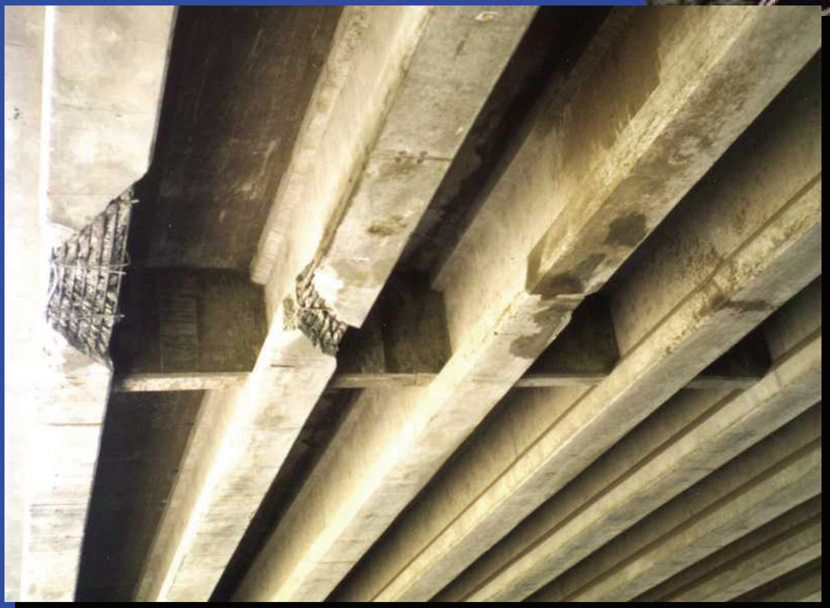

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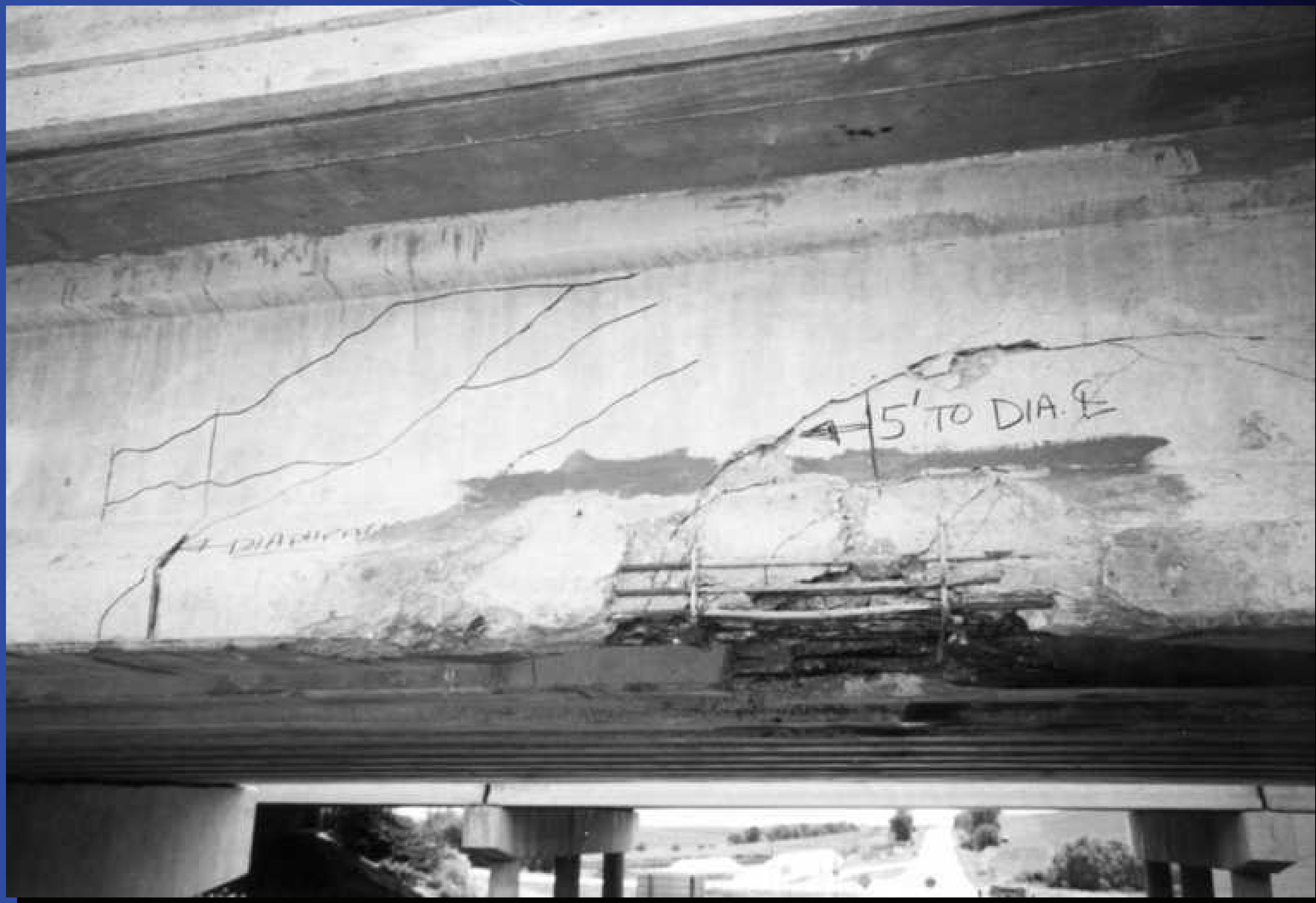

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d) FRP Reinforced Glued-Laminated Timber Girders

- Concept: Utilize glued-laminated timber girders with an FRP bottom laminate.
- In Delaware County.

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Bridge Description

- FRP reinforced glued-laminated girders
  – Eight girders, 64 ft c-c bearings
- Transverse glued-laminated deck
  – 28 ft – 3 in. roadway
  – Longitudinal deck stiffener beams between girders
- Asphalt wearing surface
- Note: short section of FRP delaminated during bridge construction

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FRP Installation

- Epoxy application

- Finished girders

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FRP Deck Panels

- Concept: Utilize GFRP deck panels in a pre-stressed concrete girder bridge.
- In the City of Bettendorf .

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e) Temporary FRP Detour Bridge

- Concept: Construct a FRP bridge superstructure as a replacement for current temporary steel detour bridge superstructure.

Iowa Department of Transportation

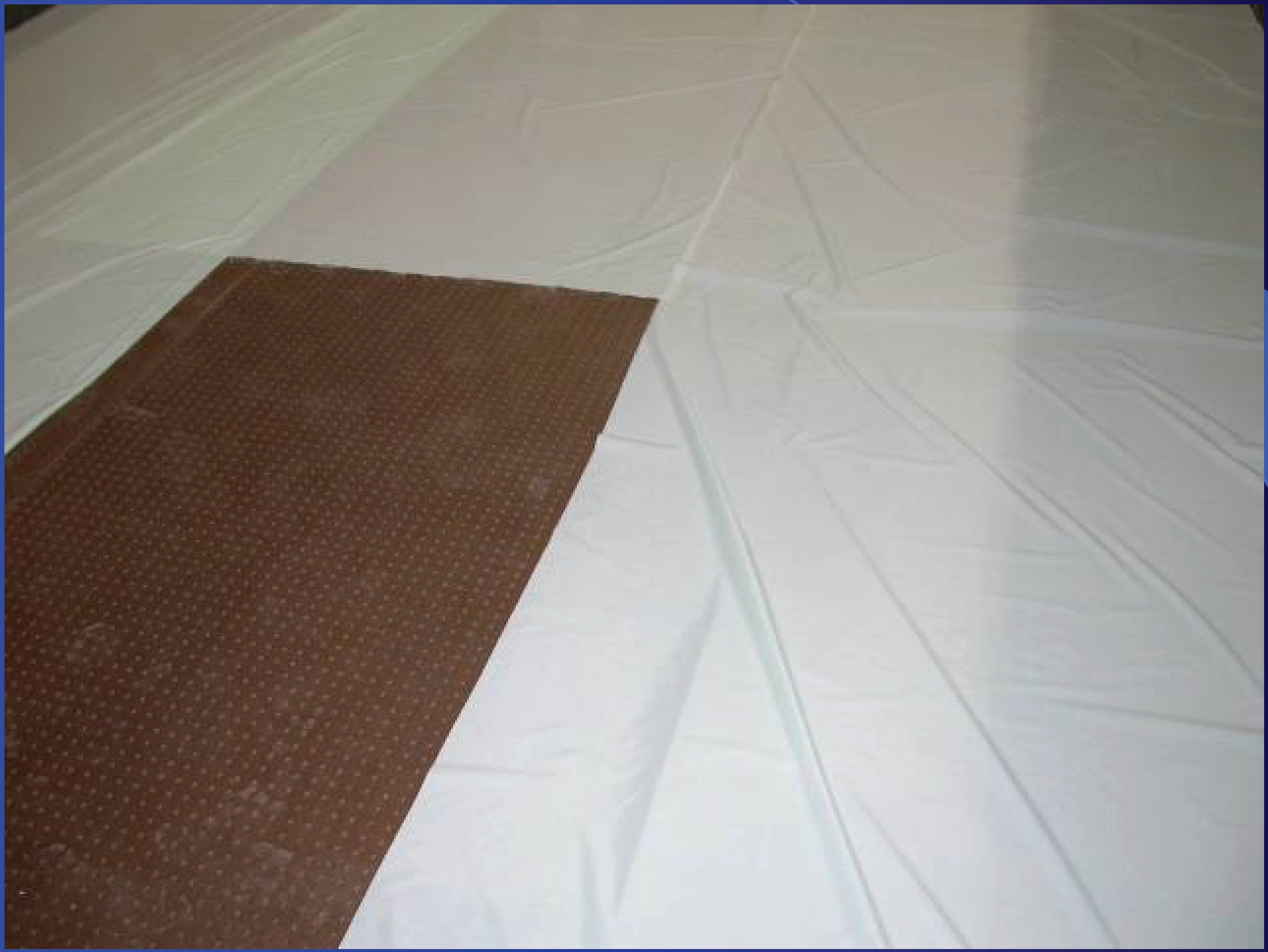
Temporary Detour Bridge

Iowa Department of Transportation

FRP Bridge

Iowa Department of Transportation

Peg Board and Peel Ply



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Bottom Skins

First Bottom Skin

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Rolling Out Skin

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First Skin Layer Complete

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Second Skin Layer

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Placing Skins …

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Bottom Skins Layer Complete

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Bottle Installation

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Bottle Installation

Iowa Department of Transportation

Mixing Resin

Vacuum Assisted Resin Transfer Molding

Resin Infusion

Resin Infusion

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Resin Infusion

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Installing Lifting Lugs

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Panel Storage

Iowa Department of Transportation

Chapter 4

Corrosive Resistant Reinforcing Steel (MMFX)

Iowa Department of Transportation

MMFX Reinforcing Steel

- Concept: Utilize MMFX reinforcing steel, a proprietary steel with high corrosion resistance, in a concrete bridge deck.

Iowa Department of Transportation

Objective and Scope

- Investigate and evaluate the field performance of new reinforcing steel and compare with conventional reinforcing steel
- Corrosion sensors embedded in deck slab to be monitored
- Data collected occasionally to assess performance in terms of corrosion resistance

Iowa Department of Transportation

MMFX vs. Epoxy coated steel

- Micro-composite Multi-structural Formable Steel (MMFX)
  - Relatively new form of corrosion resistant material
- Epoxy coated steel (ECS)
  - Conventional black steel coated with epoxy

Iowa Department of Transportation

Bridge Description

MMFX bridge

Epoxy bridge

- Twin 83.5m x 12m three-span prestressed concrete girder bridges constructed in May 2002, and open to traffic in Aug 2003
- Located in Grundy County, IA carrying relocated Highway U.S. 20
- Each bridge deck constructed with different types of reinforcing steel
  - East bound : MMFX steel (MMFX bridge)
  - West bound: Epoxy coated steel (Epoxy Bridge)

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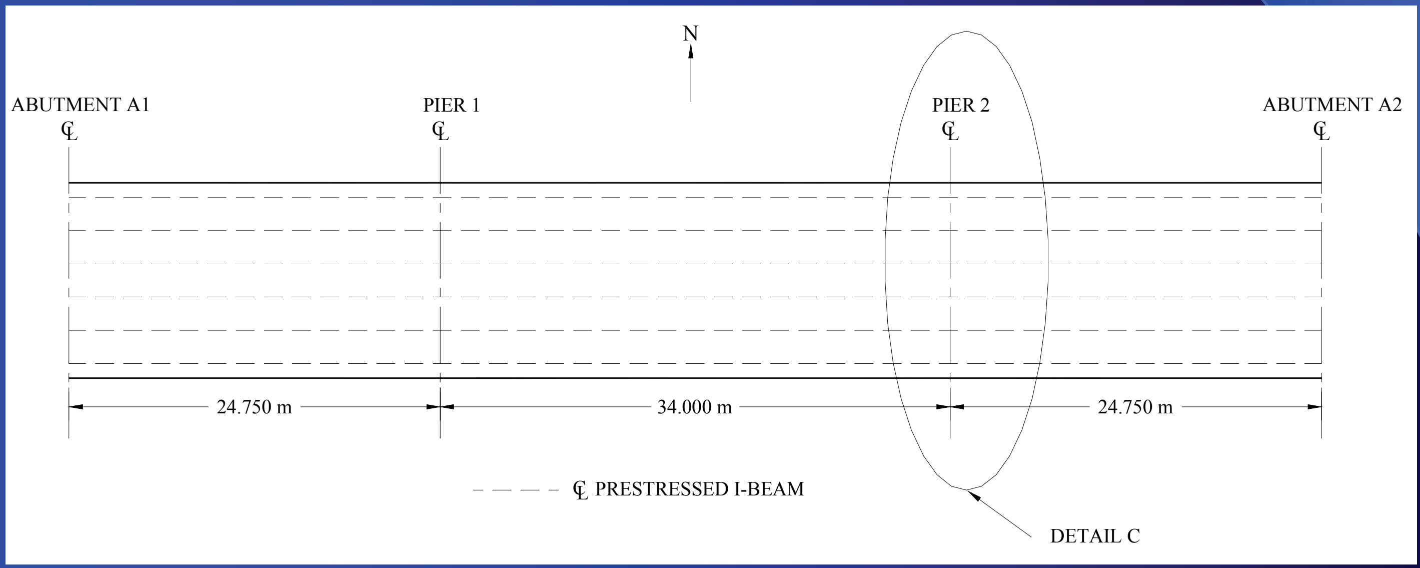
Instrumentation

- Sensors on Ten bars in each bridge deck
- Negative bending moment region near the eastern drainage points



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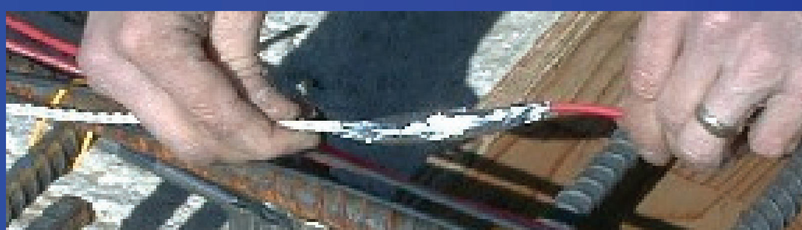
Instrumentation



- Lead wires run out of deck to measure voltage and electric current

Completed installation

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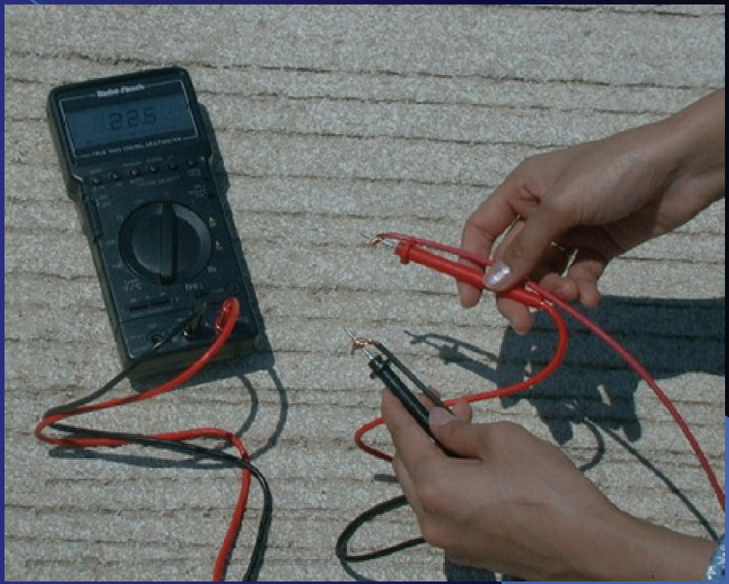
Monitoring Concept

- Increase in electric potential and internal voltage with presence of active corrosion
- DC voltage and DC current measured with a Voltmeter



Voltmeter

Monitoring Concept

- Output dependent on conditions of concrete after placement
- Normal to expect high voltage levels with fresh and uncured concrete (could be over 1000 mV)
- Initial "spike" subsides back to within the "normal" range of less than 400 mV
- Corrosion indication
  - Electric Current above 0.100 mA (1000 µA)

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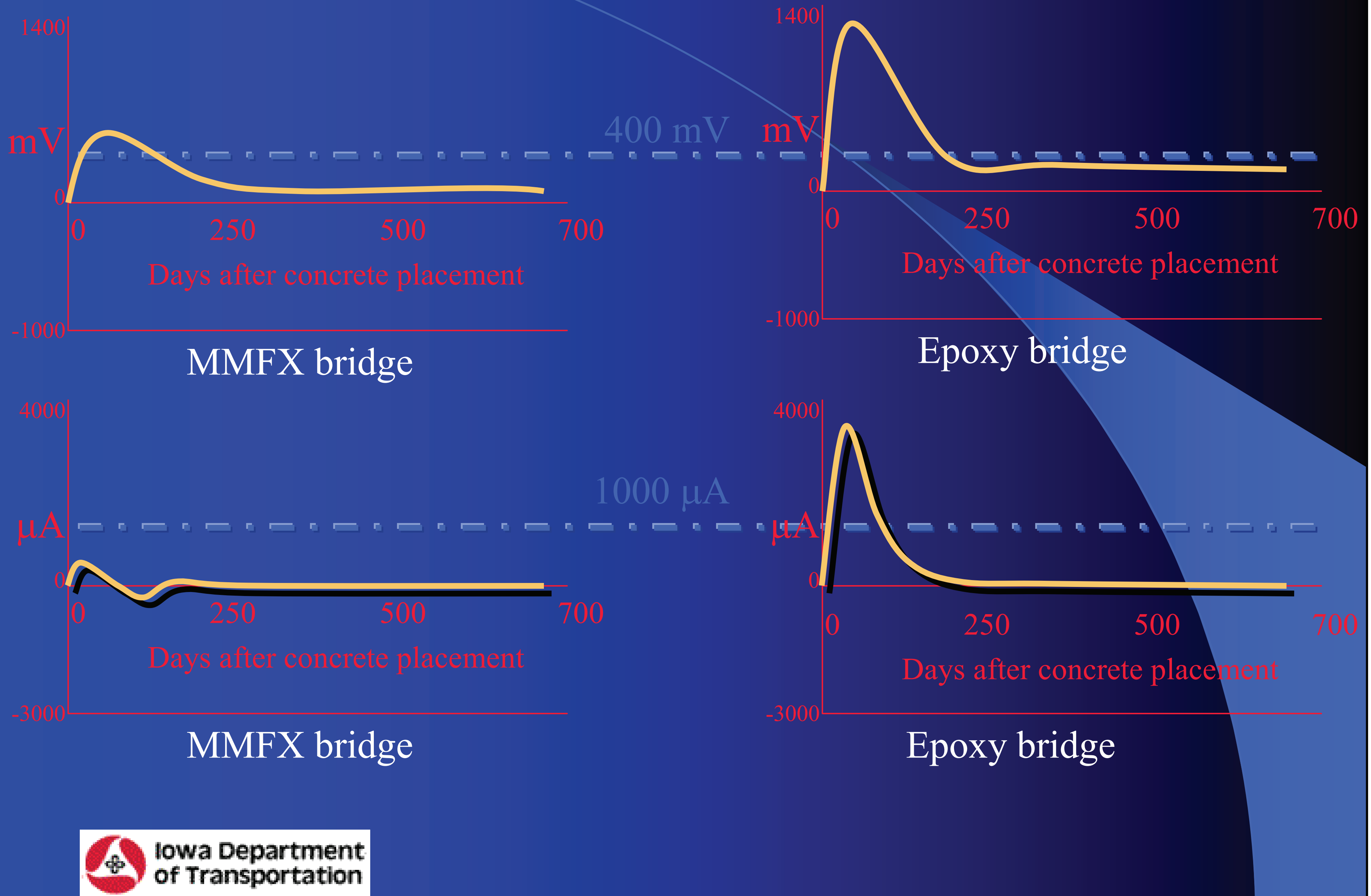
Field Monitoring



Overall to date

- In general, Readings on MMFX bridge lower than Epoxy bridge
- No significant active corrosion
  - Electric Current reading close to zero
- On-going investigation
  - More Data to be collected

Iowa Department of Transportation

Chapter 5

Steel Free Concrete Deck

Iowa Department of Transportation

Steel Free Concrete Deck

- Concept: Utilize fiber reinforced concrete with no deck reinforcing steel.
- Note: First bridge of this type in the US.

Iowa Department of Transportation

Deck Deterioration Due to Steel Corrosion

Iowa Department of Transportation

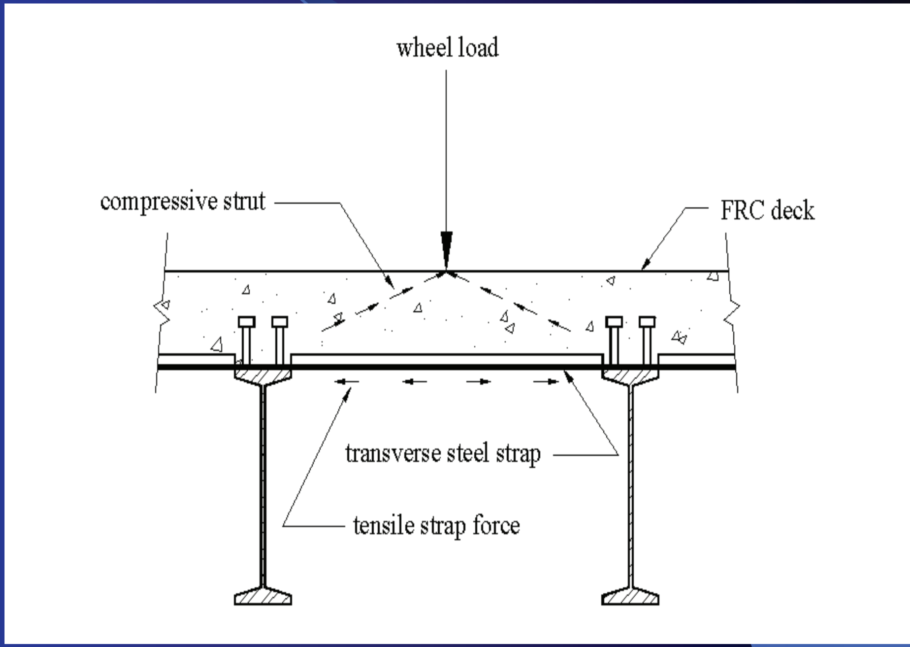
Background Information for a Steel Free Deck (SFD)

- Developed by Canadian researchers.
- Published in the Canadian Highway Bridge Design Code (CHBDC).
- No internal steel reinforcement.
- Internal arching action of the deck concrete.
- Improved durability and increased life cycle
  .

Iowa Department of Transportation

Internal Arching Action of Bridge Decks

- Punching shear behavior.
- Steel straps provide lateral girder restraint.
- Development of compressive strut.



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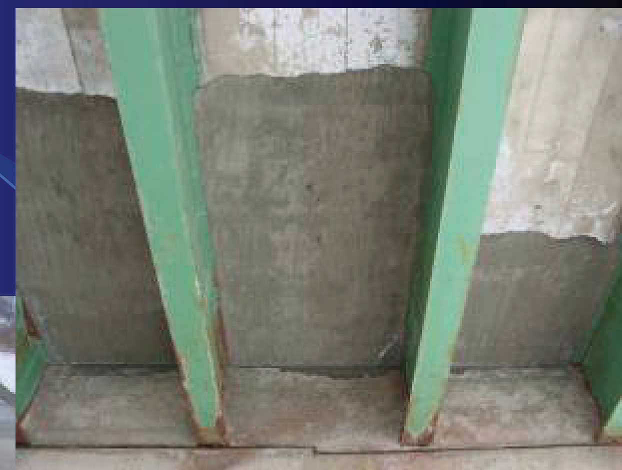
Tama County Bridge (TCB) Information

- 1st known SFD in the United States
- 41 ft simple span.
- 24 ft roadway
  - Increased to 28 ft.
- 7 steel girders on 3 ft – 8 in. centers
  - Exterior girder spacing increased to 5 ft.



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Design of the TCB deck using the CHBDC

Code Requirements

1. Composite bridge deck.
2. Maximum girder spacing of 9 ft – 8 in.
3. Required transverse edge stiffness.
4. Maximum diaphragm spacing of 26 ft – 2 in.

TCB Design Solutions

1. Add shear stud connectors.
2. Maximum spacing of 5 ft.
3. End concrete diaphragms used.
4. In place diaphragm spacing of 21 ft.

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Design of the TCB deck using the CHBDC (cont'd)

<u>Code Requirements</u>

5. Minimum area of the transverse strap.
6. Strap to girder connection strength.
7. FRC requirement.
8. Other requirements.

<u>Design Solutions</u>

5. 2 in. x 0.5 in. steel strap on 4 ft centers used.
6. Requirement satisfied.
7. 9.2 lb/yd^3.
8. All requirements satisfied.

Iowa Department of Transportation

Fibrillated Polypropylene Fibers

- Sufficient fiber volume fraction is required to prevent early plastic cracking.
- 5 denier fibrillated polypropylene fibers specified at a rate of 9.2 lb/yd^3.
- Special Provision required.
- Specification of material requirements, concrete batching and testing techniques.

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Deck Overhang Design

- Deck overhang negative moment region was designed using standard reinforced concrete practices.
- American Association of State Highway Transportation Officials (AASHTO) Standard Specifications used.

Iowa Department of Transportation

Proposed Construction Documentation and Bridge Evaluation

- Written and photographic documentation of the construction process.
- Be available to provide technical assistance.
- A series of structural health monitoring tests over the next 2 years.
- Study structural performance and durability of the steel free deck.

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Chapter 6

High Performance Steel

Iowa Department of Transportation

HPS Characteristics

- Viable and economical option for many bridge applications.
- Improved weldability.
- Increased toughness for use in fracture critical or non-redundant members.
- Better corrosion resistance to protect from exposure to de-icing chemicals.

Iowa Department of Transportation

First HPS Bridge in Iowa E 12th Street over I-235

- 91.0 m x 15.3 m CWPG.
- Two spans: 44.3 m and 46.7 m.
- HPS 50W (345) in the positive moment region.
- HPS 70W (485) in the negative moment region.
- Completed in 2004.
- Includes post construction continuous monitoring for two years and performance evaluation.

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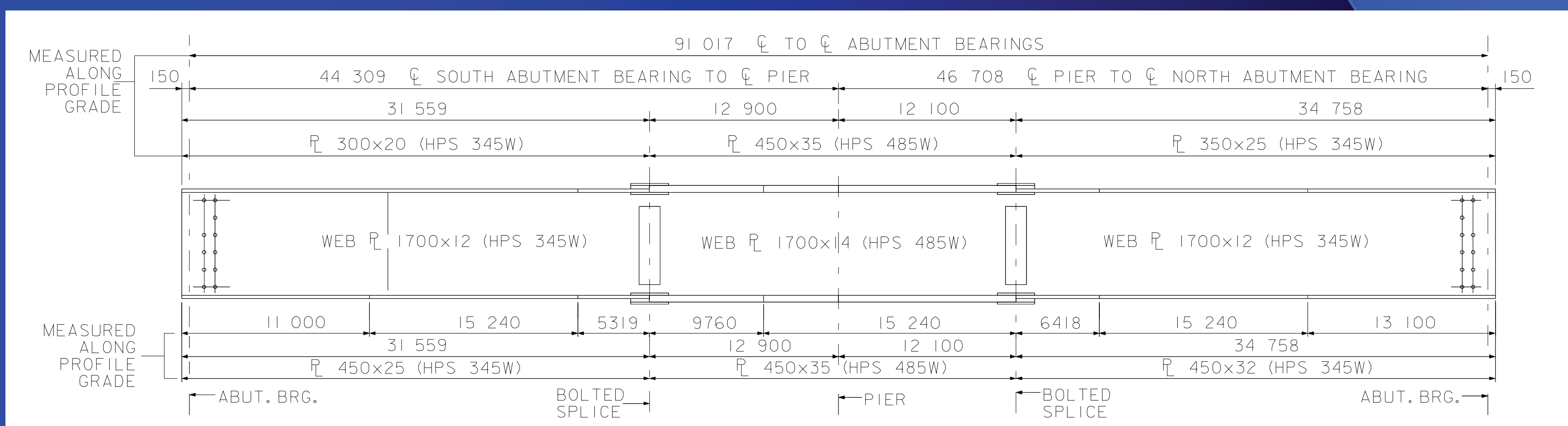

MEASURED ALONG PROFILE GRADE
91 017 ℄ TO ℄ ABUTMENT BEARINGS
150
44 309 ℄ SOUTH ABUTMENT BEARING TO ℄ PIER
46 708 ℄ PIER TO ℄ NORTH ABUTMENT BEARING
150
31 559
12 900
12 100
34 758
℘ 300x20 (HPS 345W)
℘ 450x35 (HPS 485W)
℘ 350x25 (HPS 345W)
WEB ℘ 1700x12 (HPS 345W)
WEB ℘ 1700x14 (HPS 485W)
WEB ℘ 1700x12 (HPS 345W)
MEASURED ALONG PROFILE GRADE
11 000
15 240
5319
9760
15 240
6418
15 240
13 100
31 559
12 900
12 100
34 758
℘ 450x25 (HPS 345W)
℘ 450x35 (HPS 485W)
℘ 450x32 (HPS 345W)
ABUT. BRG.
BOLTED SPLICE
PIER
BOLTED SPLICE
ABUT. BRG.

Health Monitoring of HPS at East 12th Street

- Purpose of monitoring”
  - Assess long-term performance
    - Changes with time.
    - Structural characteristics.
  - Measure and quantify fatigue loadings and examine fatigue behavior of various connection details.
  - Assess serviceability issues associated with “lighter” design such as live-load deflection.

Iowa Department of Transportation

Health Monitoring of HPS at East 12th Street

- Both point-in-time tests (under static and dynamic loading) and continuous data collection will be performed under ambient traffic using remote monitoring.
- Performed by the Bridge Engineering Center, Center for Transportation Research and Education at Iowa State University.

Iowa Department of Transportation

Health-Monitoring System at East 12th Street

- Components:
  - 30 FBG optical sensors.
  - Swept laser interrogator (Unix based).
  - Web server.
  - Data collection server(DSS).
  - Video camera.
  - Wireless networking components.

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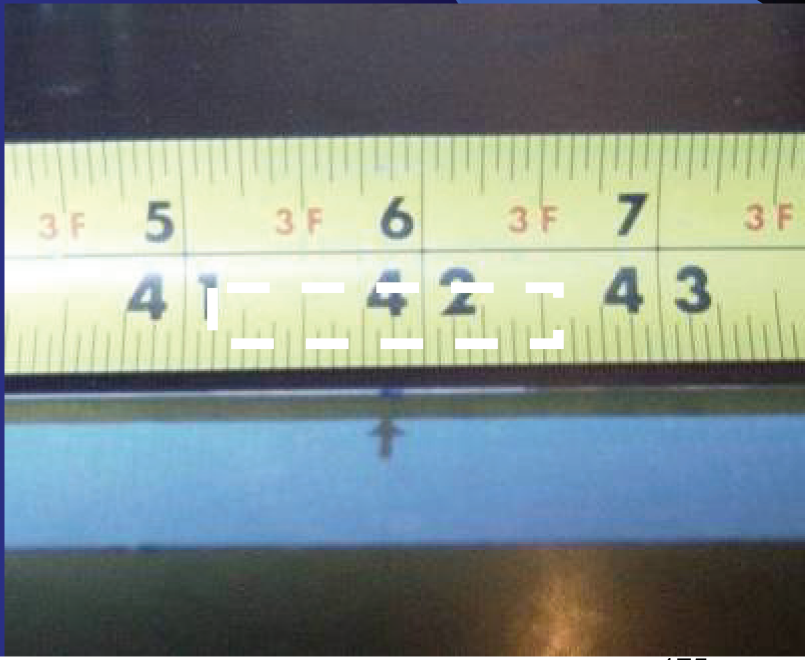
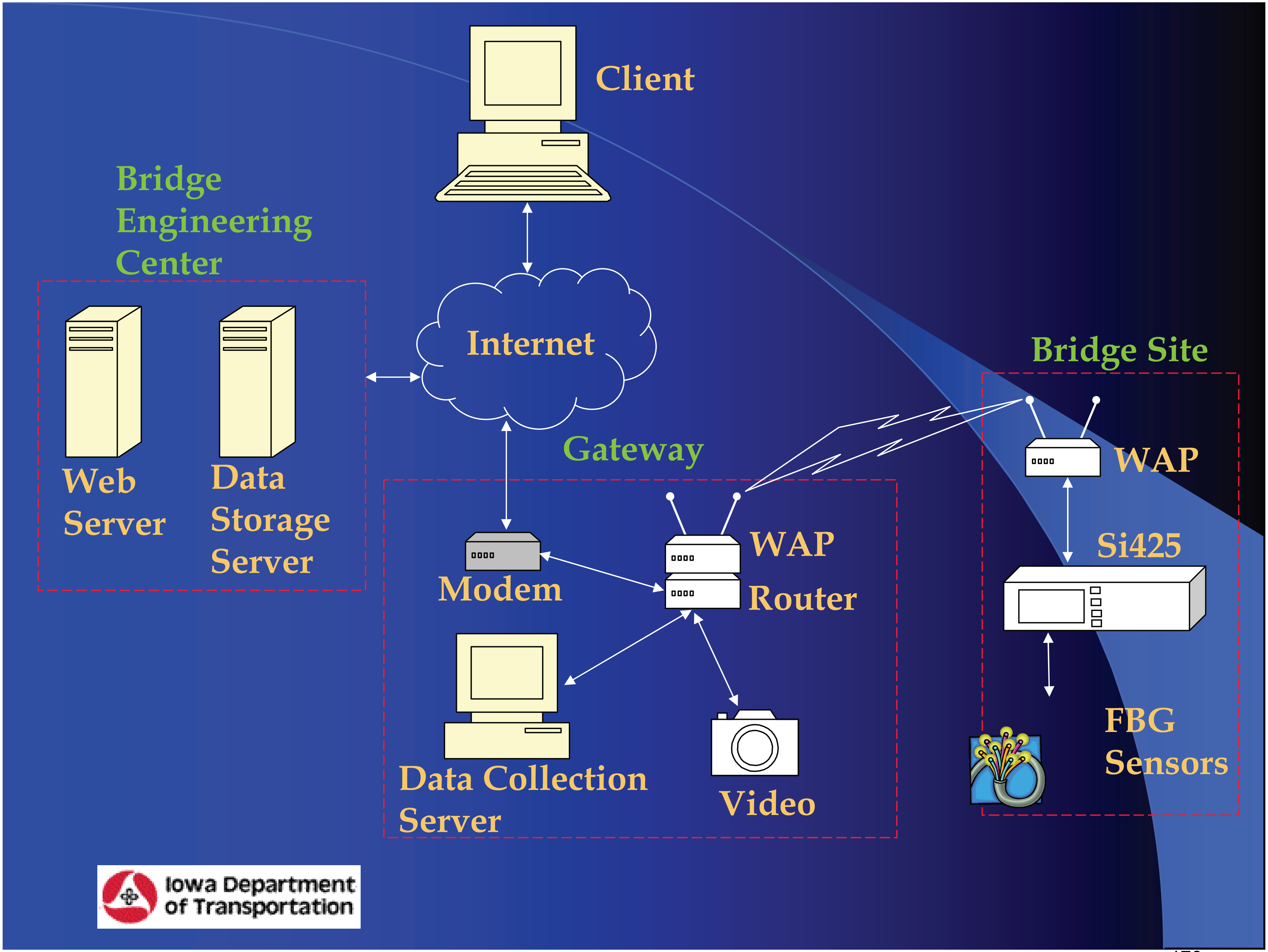
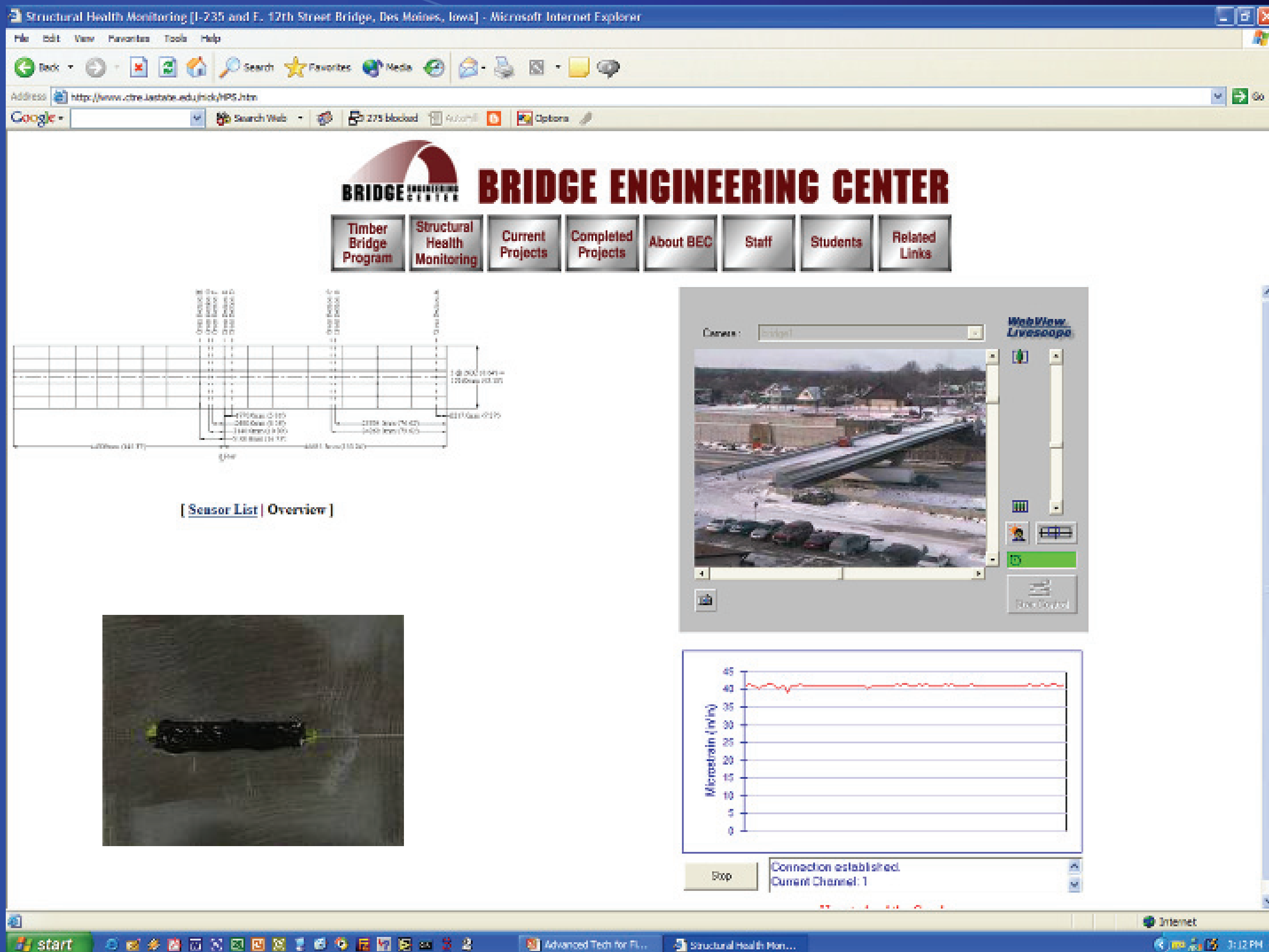
- Fiber Bragg Grating (FBG) Sensors


Client
Bridge Engineering Center
Internet
Web Server
Data Storage Server
Gateway
Bridge Site
WAP
Modem
WAP
Router
Si425
Data Collection Server
Video
FBG Sensors
Iowa Department of Transportation



Iowa Department of Transportation

IOWA HIGHWA RESEARCH BOARD (IHRB) PROJECTS

- Load Rating through Diagnostic Load Testing
- Investigation of Fatigue Cracks due to Out-of-Plane Bending
- Investigation of Light Pole Failure
- Structural Health Monitoring of Steel Bridges

Iowa Department of Transportation

Chapter 7

Load Rating Through Diagnostic Testing

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The Problem

- Posted bridges and bridges with unknown strength and behavior.
- Limited financial resources.
- Code equations that are usually <u>very</u> conservative at predicting bridge behavior.

Iowa Department of Transportation

The Problem

- Unknown bridge conditions
  - Load distribution.
  - End restraint.
  - Edge stiffening.
  - Composite action.
  - Effectiveness of specific bridge details.
  - Other details contributing to bridge capacity.

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The capacity of damaged bridges to determine the need for imposing temporary load restrictions

Iowa Department of Transportation

The capacity of damaged bridges before and after strengthening

Iowa Department of Transportation

The Solution

- Use physical testing to understand the specific characteristics of each bridge.
- Use field collected data to calibrate a computer constructed model of the bridge.
- Use the accurate, calibrated computer model to determine bridge response to rating vehicles and other loads.

Iowa Department of Transportation

An Integrated Testing System

- Hardware and software suite.
- Integrated and seamless through all steps
  - Field testing.
  - Data presentation.
  - Model generation.
  - Model calibration.
  - Rating.

Iowa Department of Transportation

Data Collection Hardware

- Hardwired strain gages with variable gage lengths.

Iowa Department of Transportation

Data Collection Hardware

- Strain gage junction box
  - Balance and control strain gages.
  - Collect and temporarily store data.
  - Communicate with PC.

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Data Collection Hardware

- Wireless truck position indicator.

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Data Collection Hardware

- Power unit and PC
  - Power and control entire system.

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Software Suite

- WinGRF
  - Relates truck position with strain data.
  - Prepare visual summaries of data
    - Strain.
    - Neutral axis location.
    - Curvature.
  - Allows engineer to study the data for behavioral interpretation.

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Software Suite

- WinGEN
  - Construct bridge model
    - Overall geometry.
    - Material characteristics.
    - Section properties.
    - Support conditions.
  - Define loading conditions.
  - Establish optimization parameters.
  - Create analysis file.

Iowa Department of Transportation

Software Suite

- WinSAC
  - Performs analysis.
  - Performs optimization calculations
    - Linear least squares method of error reduction.

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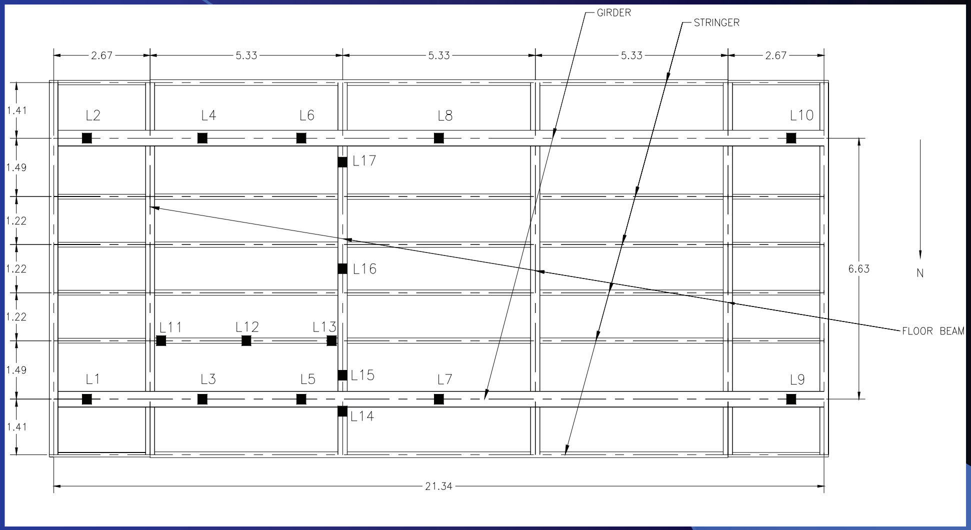
Diagnostic Testing of a bridge

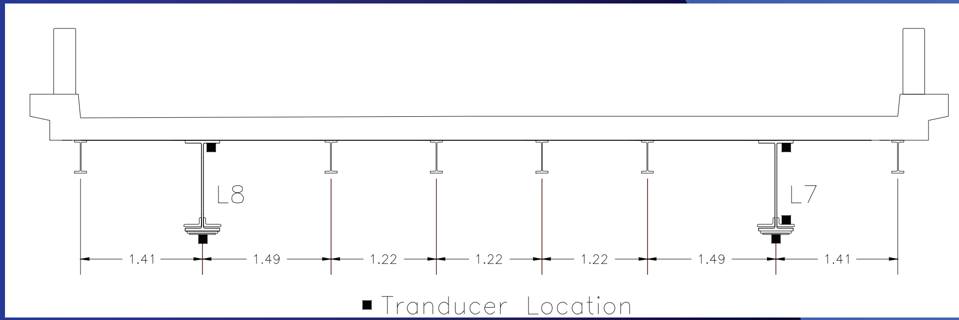
- Carries US 6 over a small stream.
- 21.34 m single span.
- Two main girders w/ floor beams & stringers.
- Welded plates & strengthening angle on girders.

Iowa Department of Transportation

Instrumentation

- 36 Intelliducers at 17 locations used.
- Focused on:
  - Effectiveness of angles.
  - End restraint.
  - Load distribution.
- Instrumented:
  - Both girders
  - Typical floor beam and stringers.





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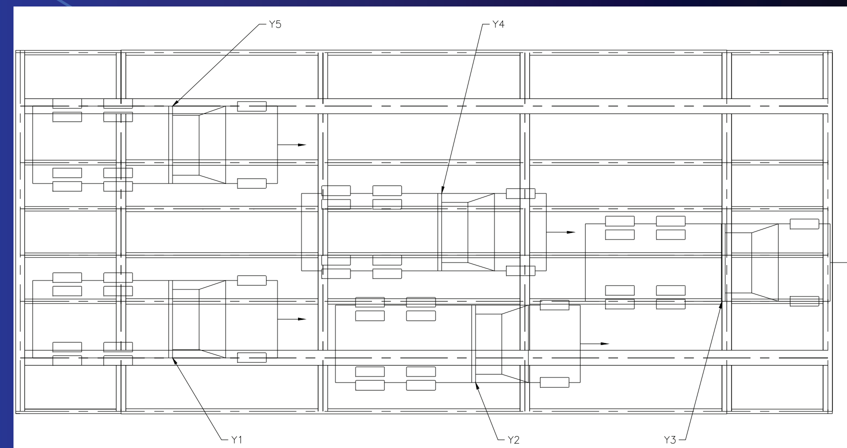
Load Position

- 5 different load paths defined.
- Each addressing a key concern of the bridge.
- Paths marked out with paint on deck and position recorded using the AutoClicker.



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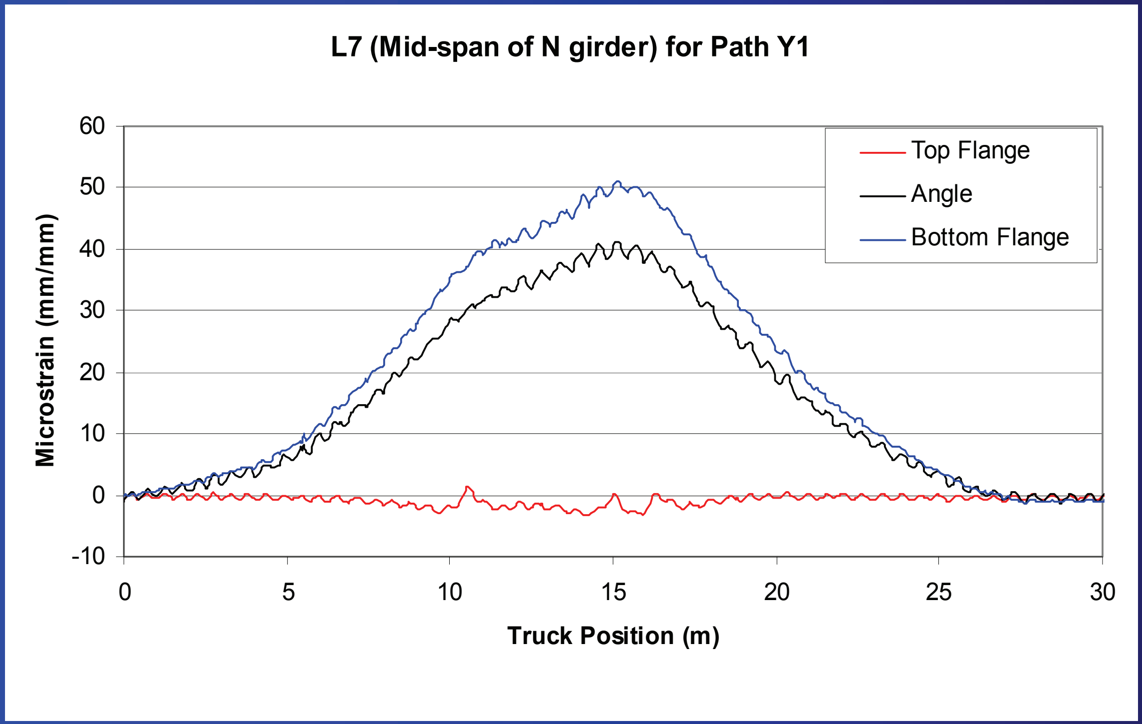
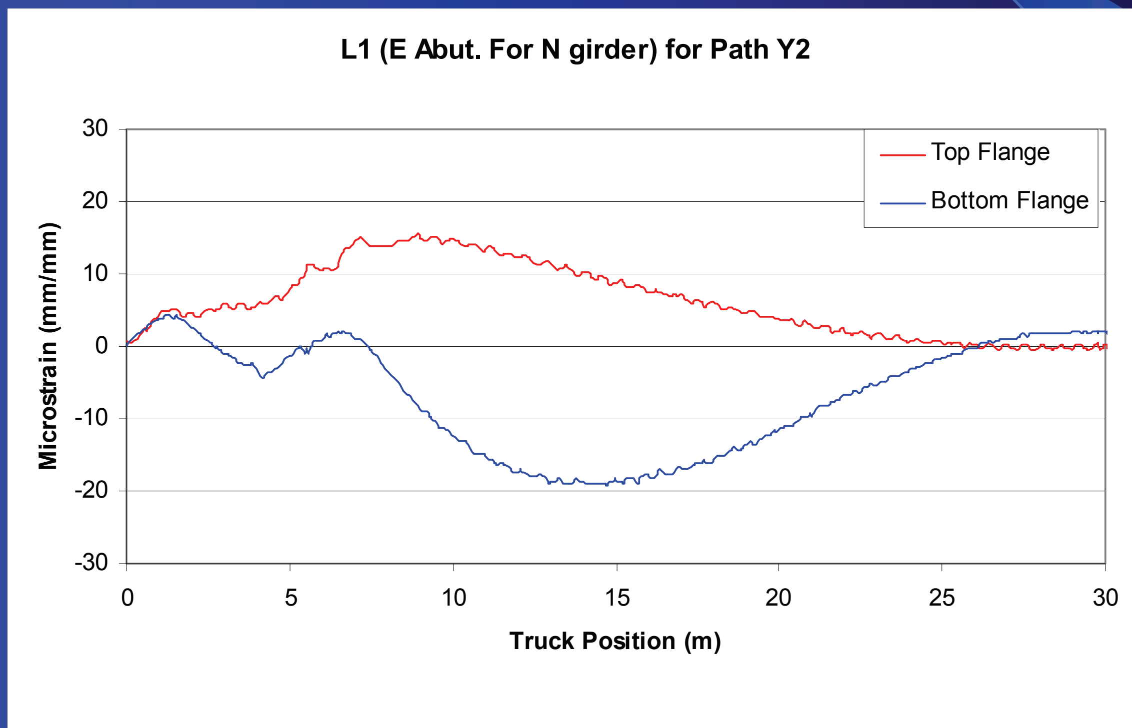
Test Results

- Strengthening angles shown effective.



Test Results

- Significant end restraint identified.



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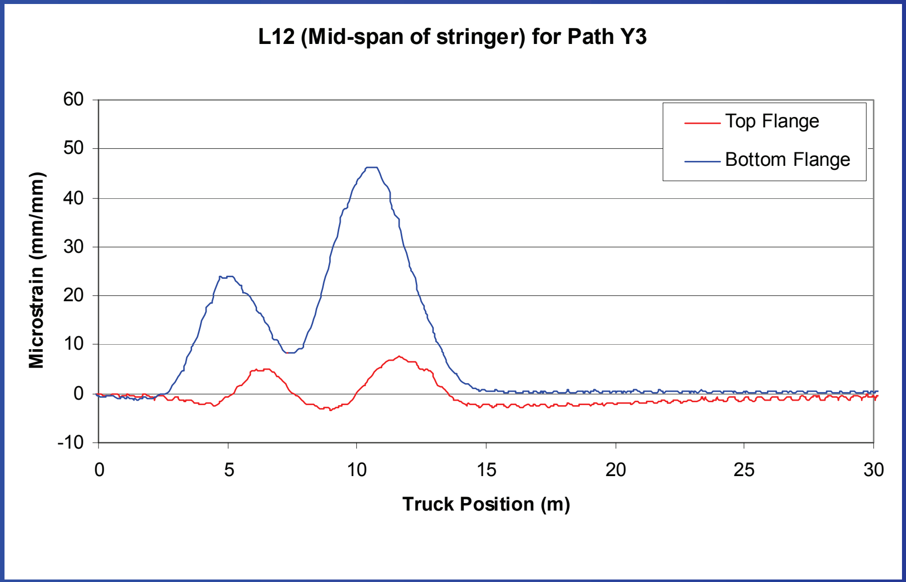
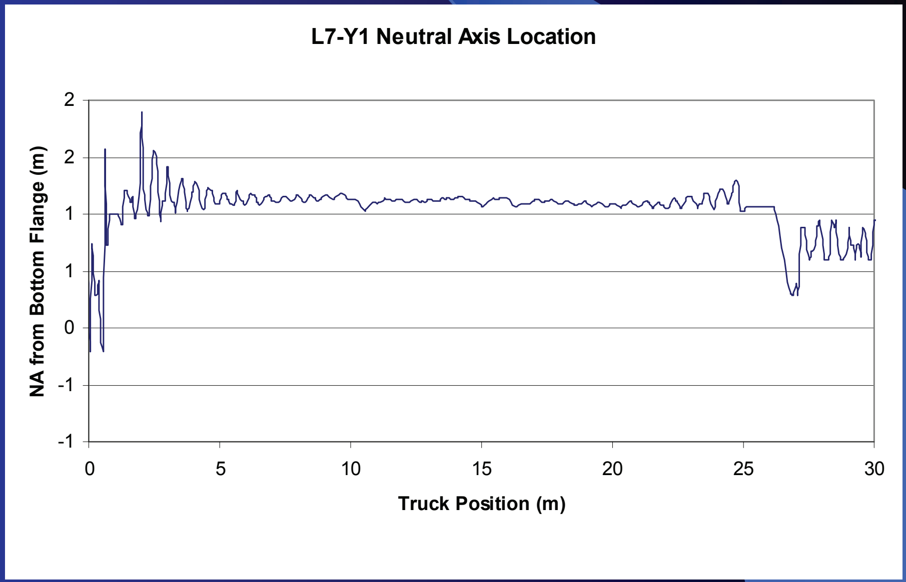
Test Results

- Composite action determined.





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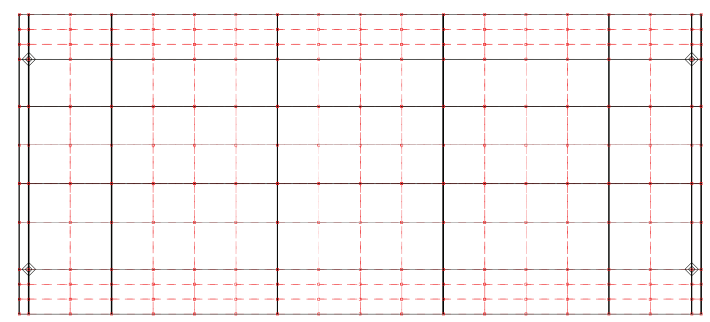
Modeling

- Created using WinGen.
- Based on plan geometry.
- 19 total element groups.
- 16.3% initial error with spring.



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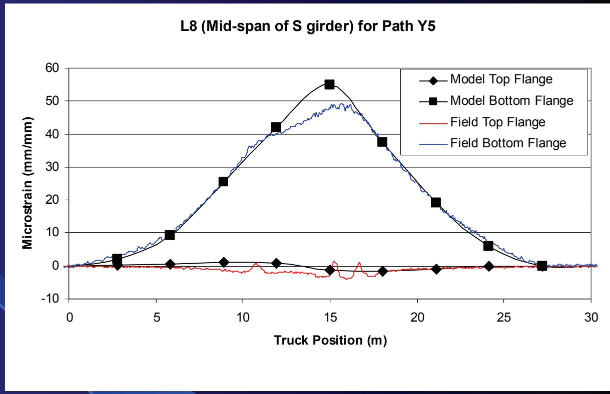
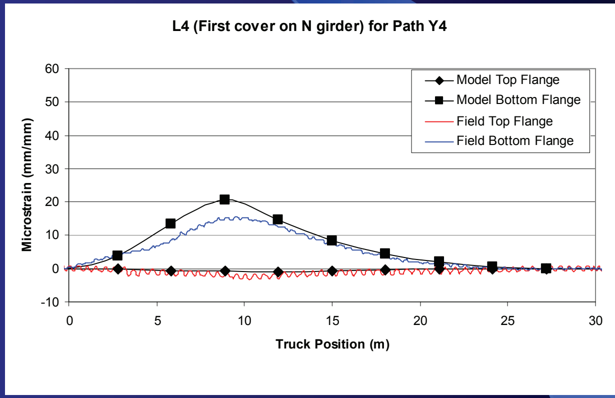
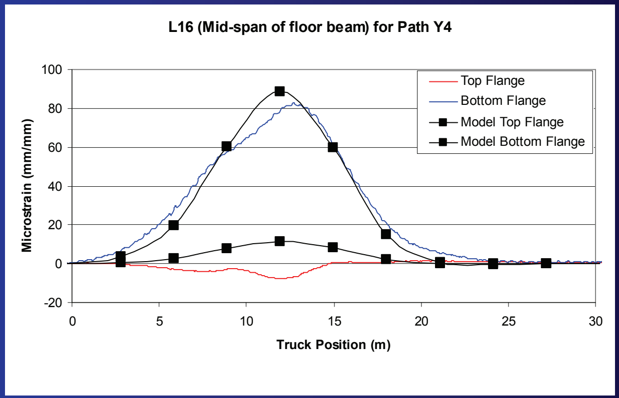
Modeling Results

- 11 Optimized element groups:
  - 4 girder sections
  - 3 floor beam sections
  - 2 stringer sections
  - 1 rotational spring
  - Deck stiffness
- Resulting in 9.1% error when optimized.







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Rating

- Traditional AASHTO LFD Calculations
- HS-20 Load Vehicle
- Shear limit:
  – Small stringer
  – 1.46 Inventory
  – 2.44 Operating
- Flexural limit:
  – Girder at Mid-span
  – 1.43 Inventory
  – 2.39 Operating

- WinSAC LFD Calculations
- HS-20 Load Vehicle
- Shear limit:
  – Small stringer
  – 1.07 Inventory
  – 1.79 Operating
- Flexural limit:
  – Floor beam
  – 2.20 Inventory
  – 3.67 Operating

Iowa Department of Transportation

Results of testing

- General increase in flexural rating of all members.
- Shear rating decreased and controlled for this bridge.
- Effectiveness of unknown structural elements studied.

Iowa Department of Transportation

Conclusions

- System is well suited to rating "typical" highway bridges.
- Inclusion of AutoCad allows for modeling more complex structures.

Iowa Department of Transportation

Chapter 8

Investigation of Fatigue Cracking due to Out-of-Plane Bending

New Bridges

-Weld or bolt to top flange

Existing Bridges

-Loosen Bolts in connection

Iowa Department of Transportation

Overview

- In Iowa, fatigue cracking in web gaps of multiple steel girder bridges in negative bending region becoming more common.
- Retrofit to relieve strain in web gap originally developed in coordination with Iowa DOT, but not tested long-term and only tested on X-type bracing.

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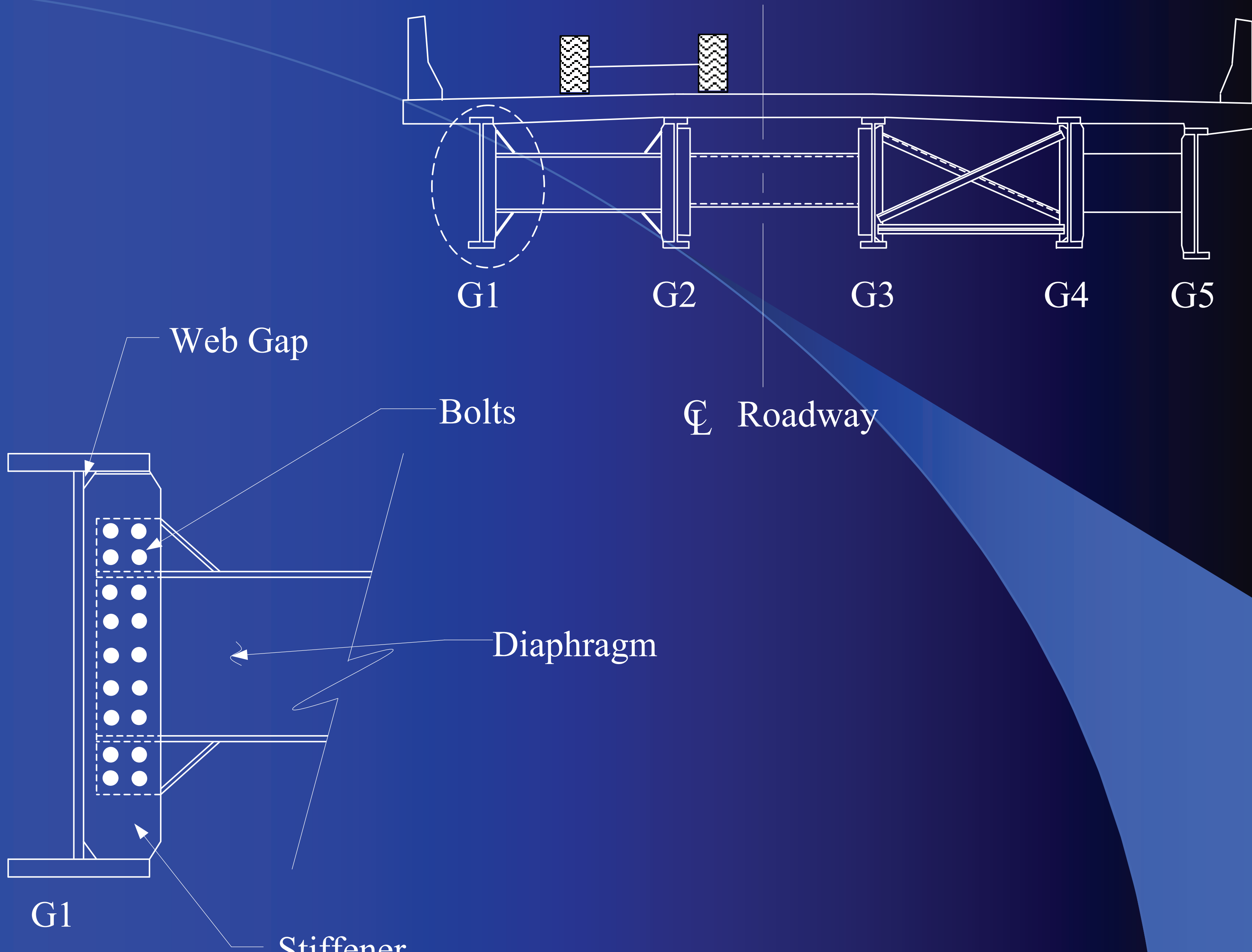

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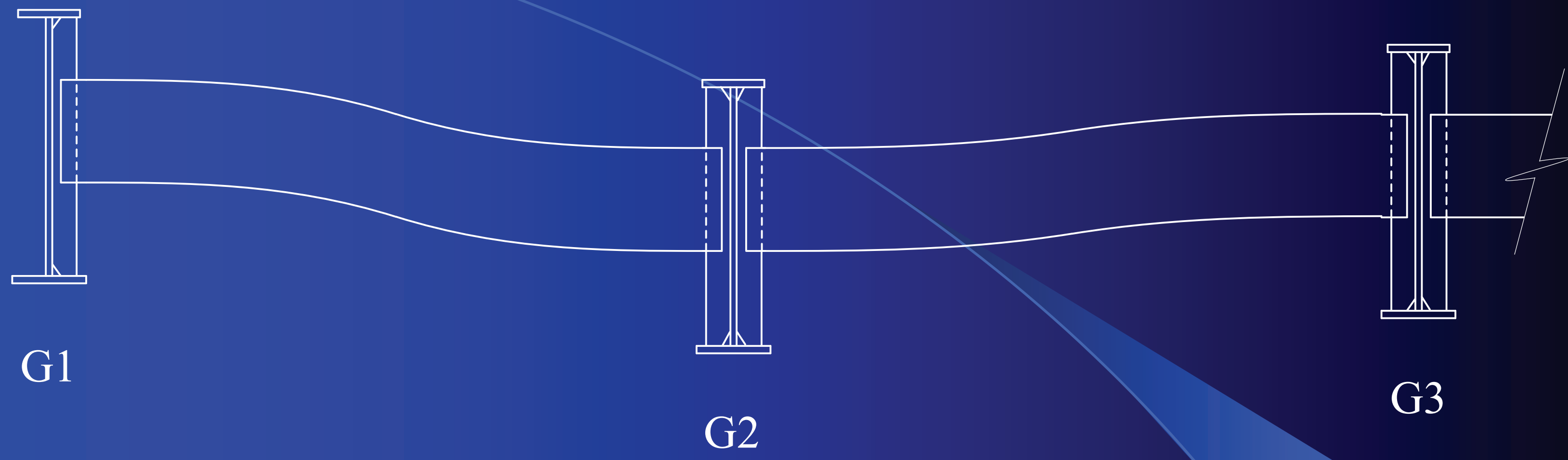
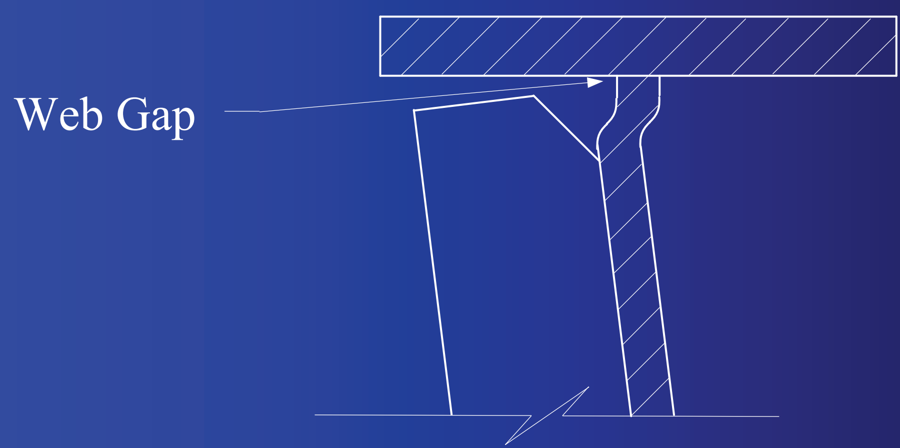

G1
G2
G3


Web Gap

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The Retrofit

- Loosen bolts in diaphragm/girder connections.
- Leave diaphragms in place to support girders.

Iowa Department of Transportation

Scope

- 3 bridges instrumented
  - Channel diaphragm.
  - I-section diaphragm.
  - X-type bracing
- Tested before and after retrofit
  - Short-term.
  - Long-term.

Iowa Department of Transportation

Interstate-35 Bridge

- Three span, five girder bridge with channel diaphragms.
- Short-term testing.

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Interstate-35 Bridge

Iowa Department of Transportation

Instrumentation

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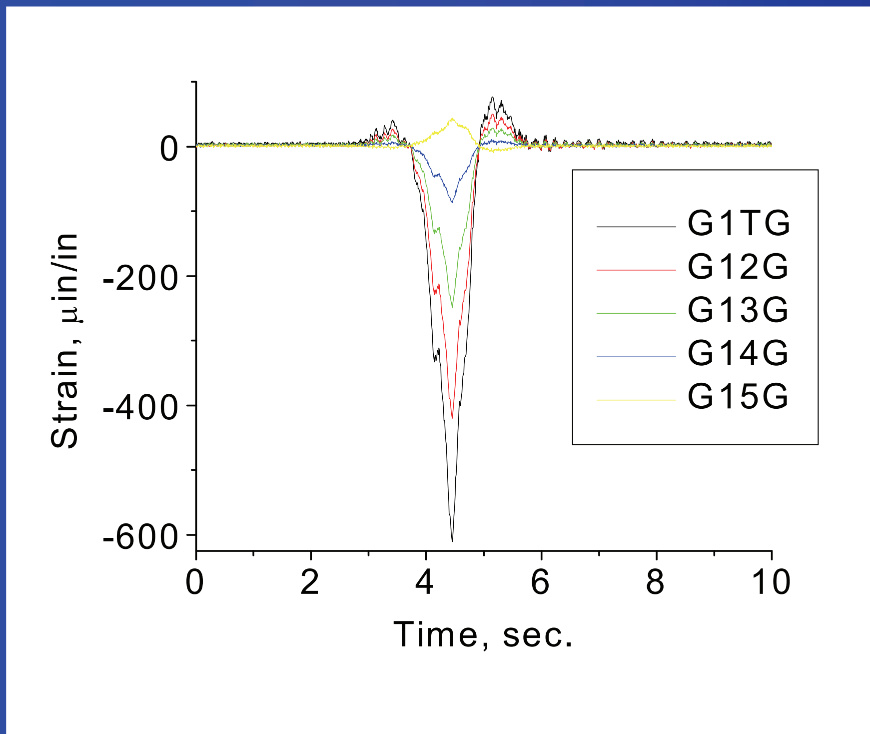
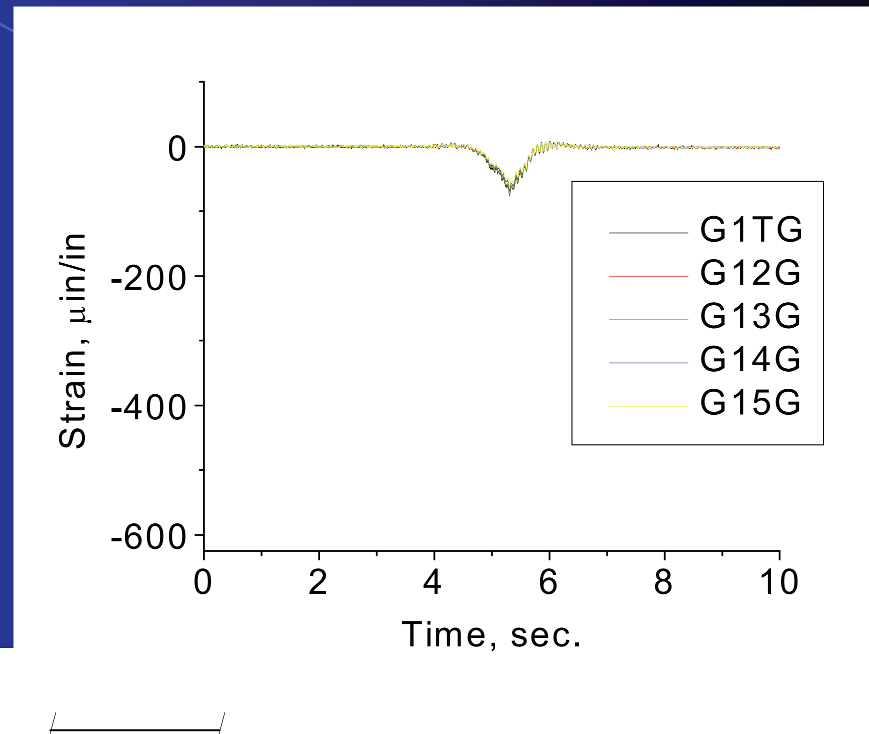
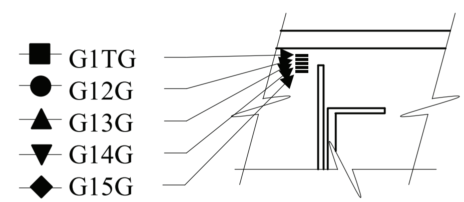
Web Gap Strain







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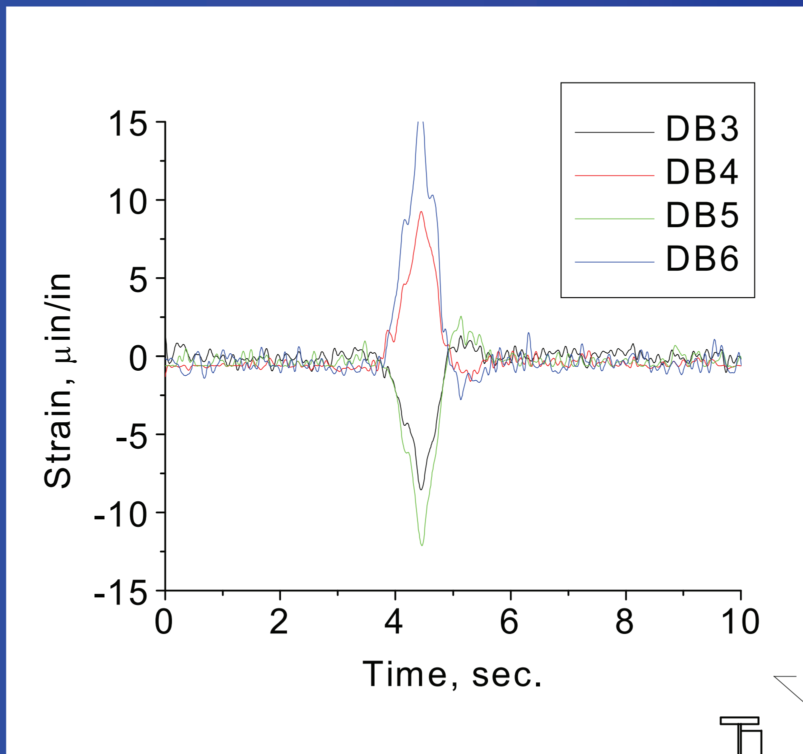
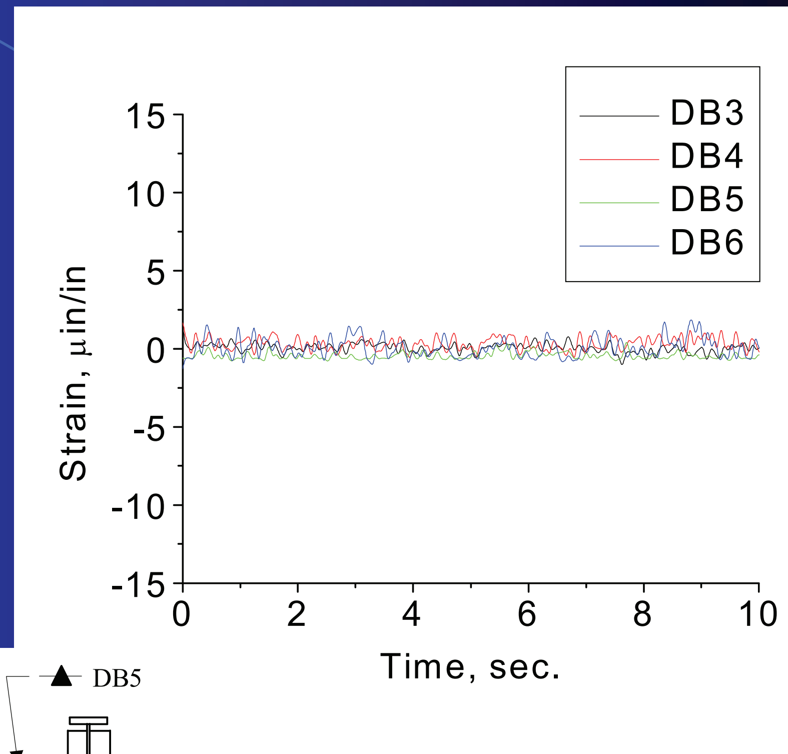
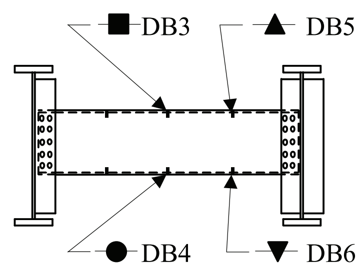
Diaphragm Strain







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Iowa-17 Bridge

- Three span, five girder bridge with X-type cross-bracing.
- Long-term testing.

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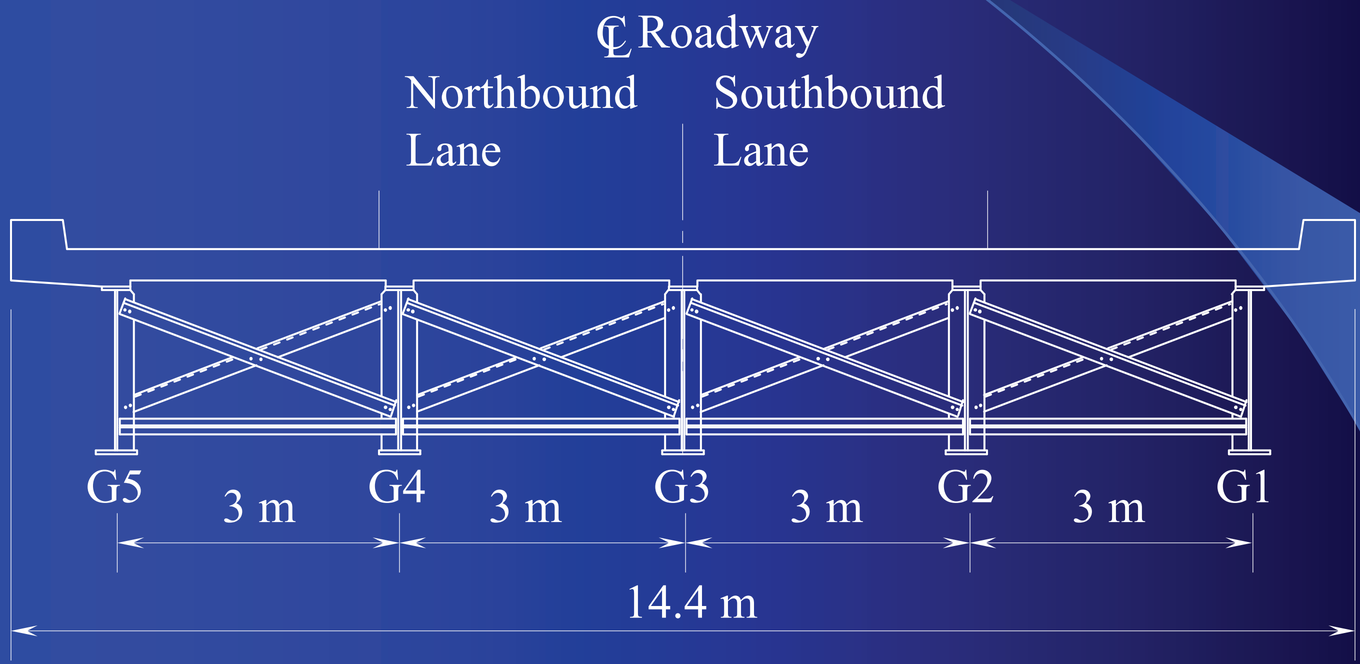
Iowa-17 Bridge

Iowa Department of Transportation

Bridge Cross-Section



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Health Monitoring System

- A Campbell Scientific CR 9000 was selected for remote monitoring of ambient truck traffic on the bridge.
- Strain gages, displacement transducers, and thermocouples were installed and connected to the CR 9000.

Iowa Department of Transportation

Health Monitoring System

- 24 input channels.
- Connected to local power grid for continuous operation.
- Phone line installed to allow data acquisition and program adjustments.
- Trigger programmed into system to collect only data larger than a designated threshold set to register truck loads.

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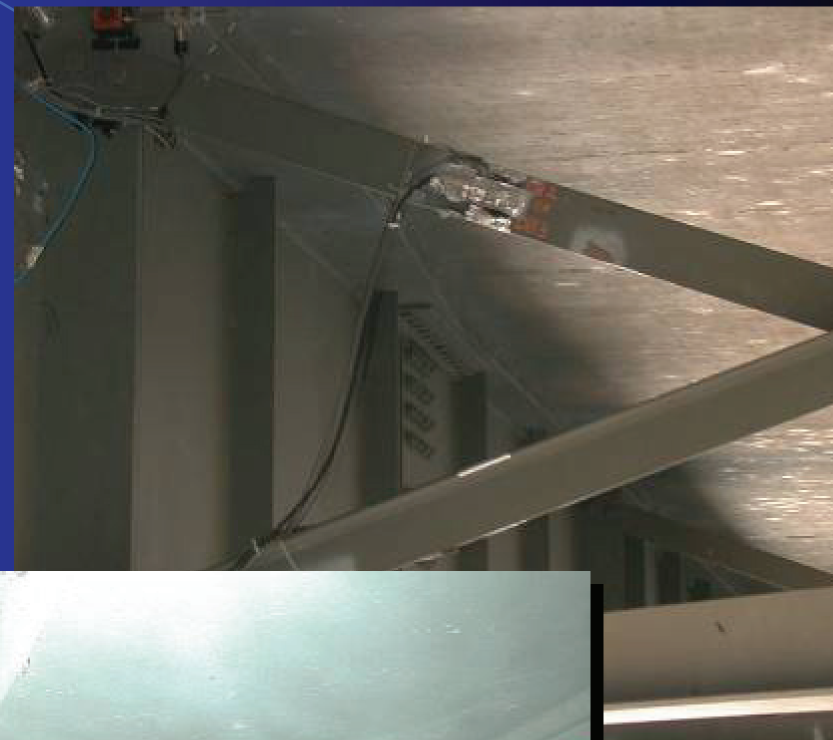
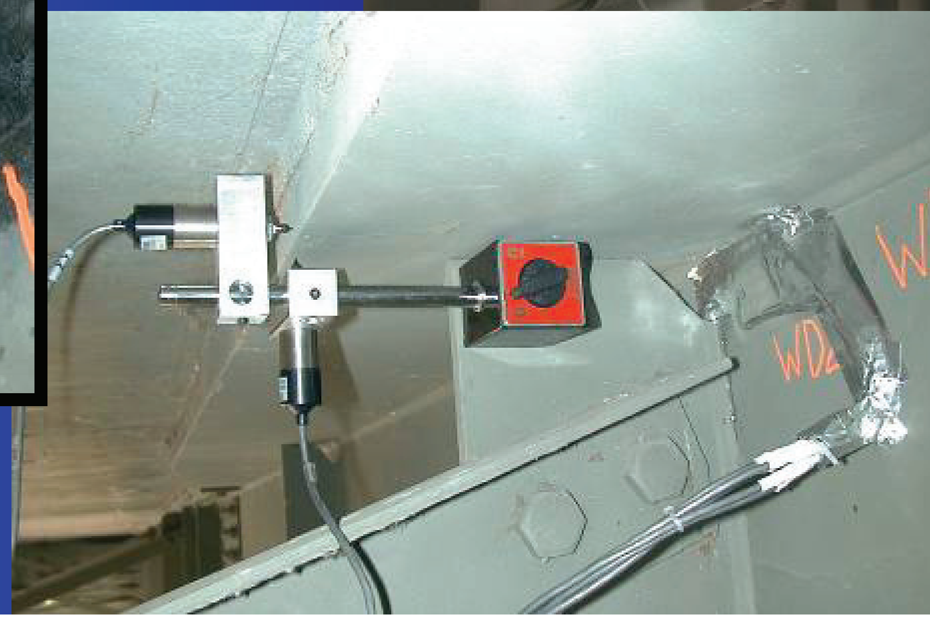
Health Monitoring System

Iowa Department of Transportation

Instrumentation





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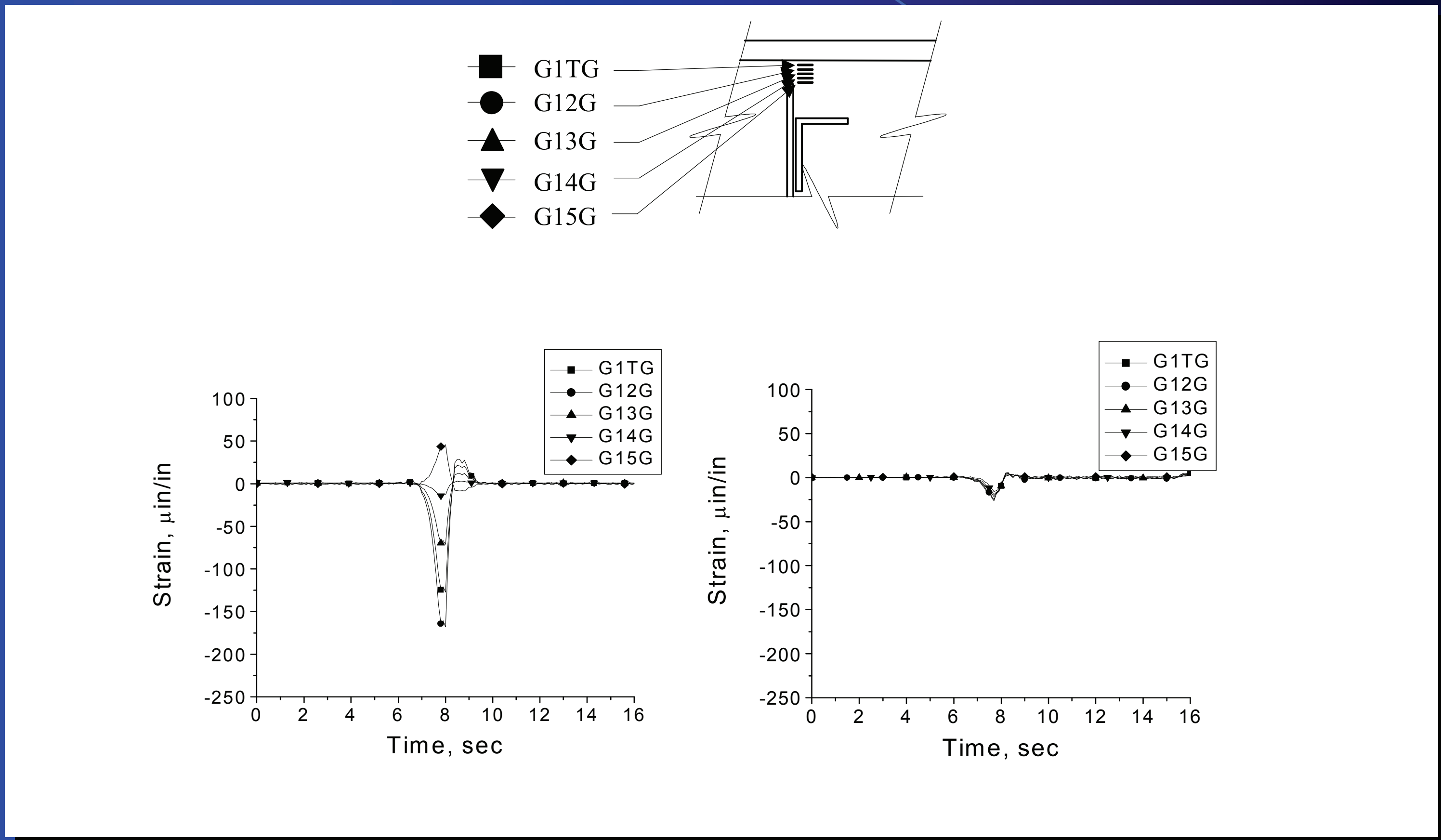
Web Gap Strain Gradient- Close to Pier



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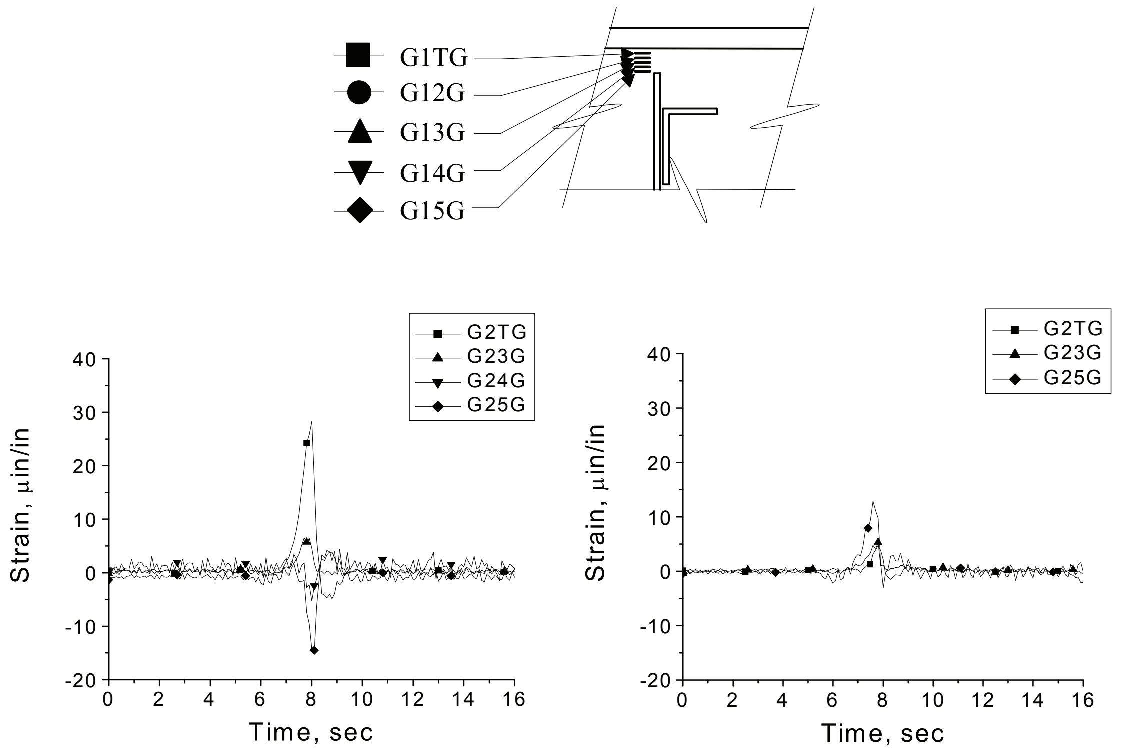
Web Gap Strain Gradient- Away From Pier



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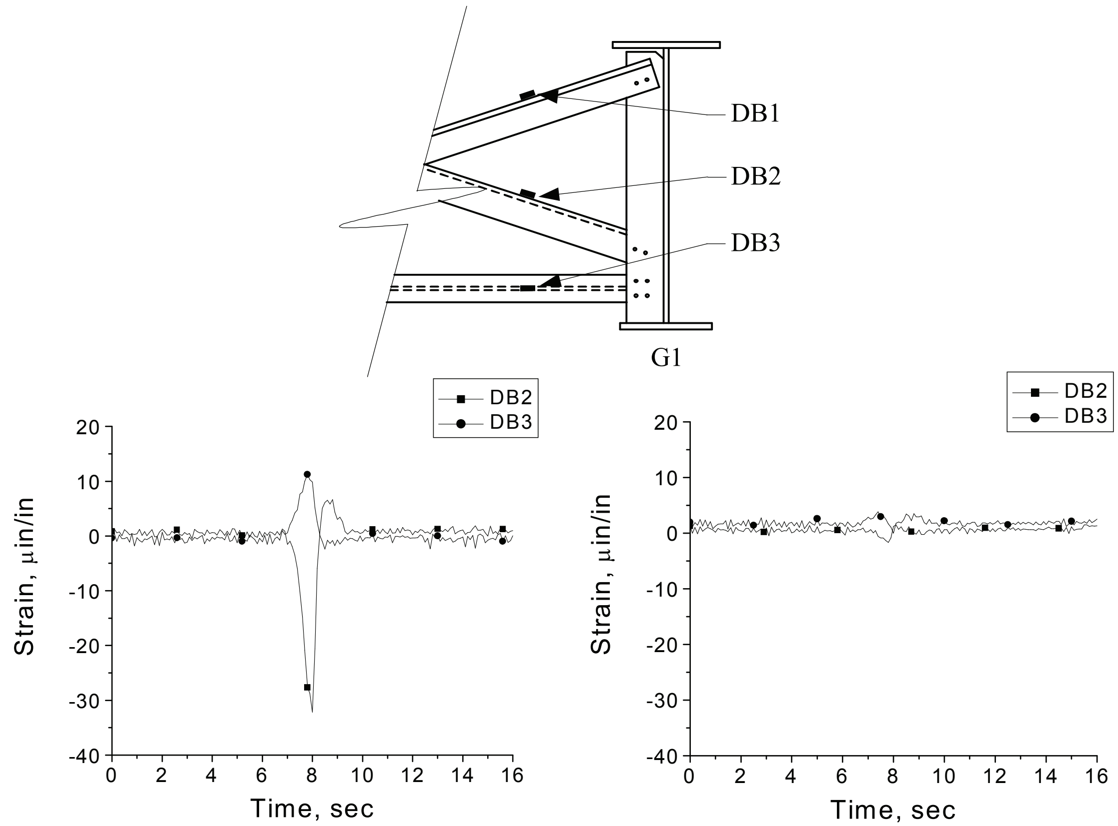
Cross-Frame Behavior



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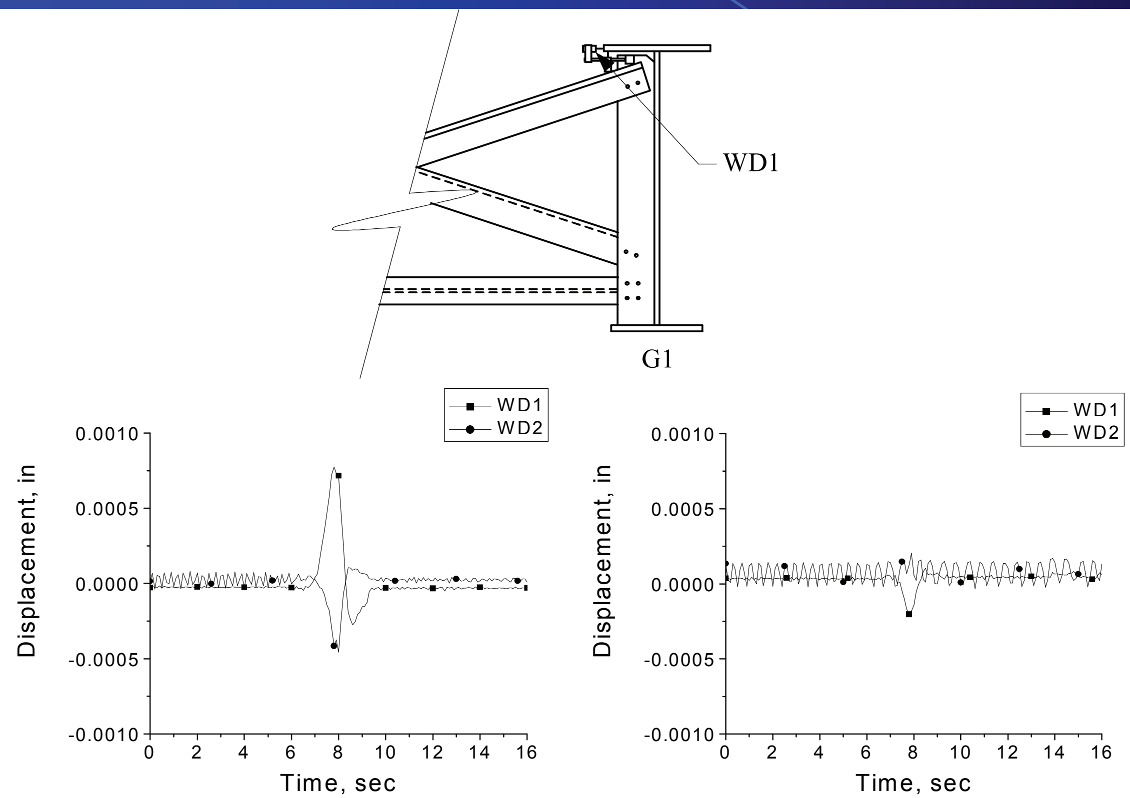
Out-of-Plane Displacement



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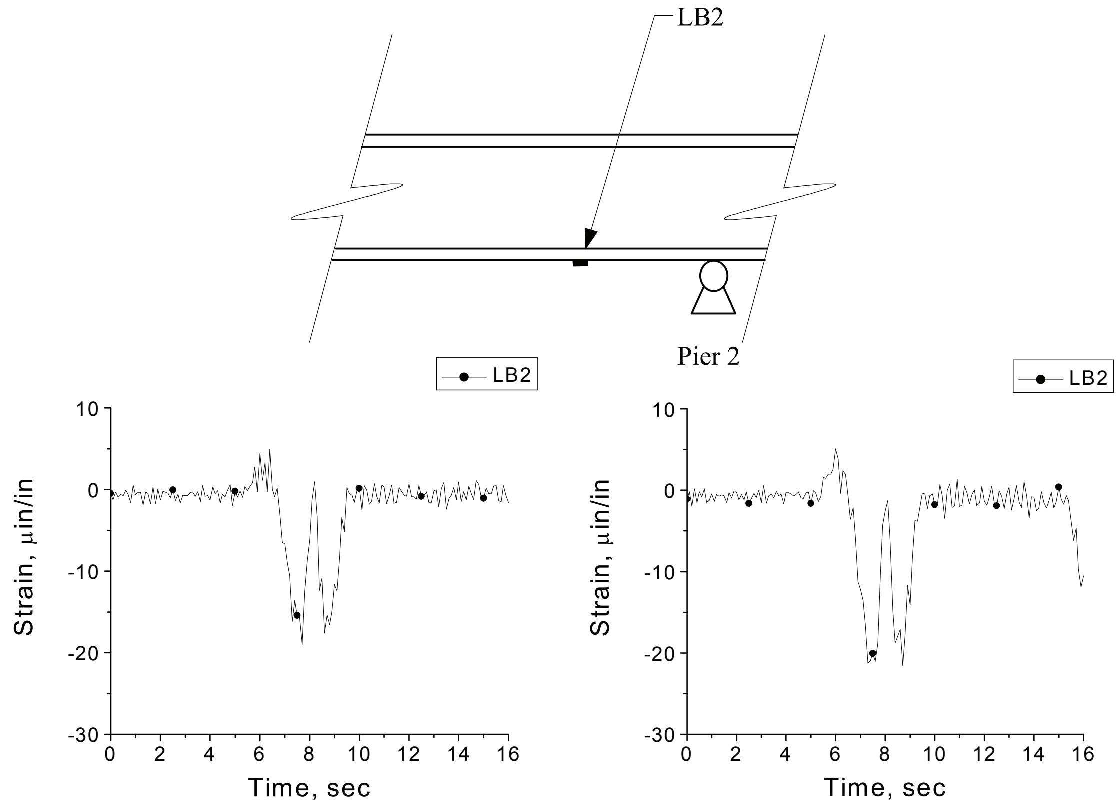
Bottom Flange-Trigger Data



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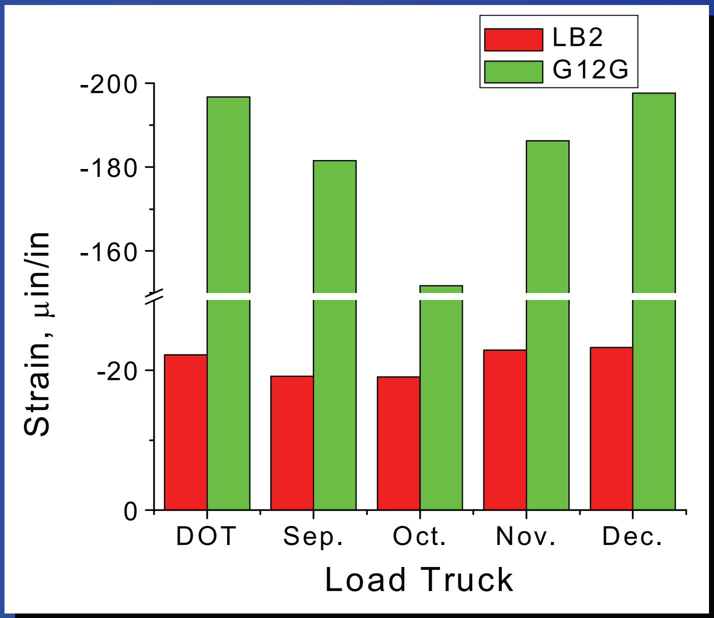
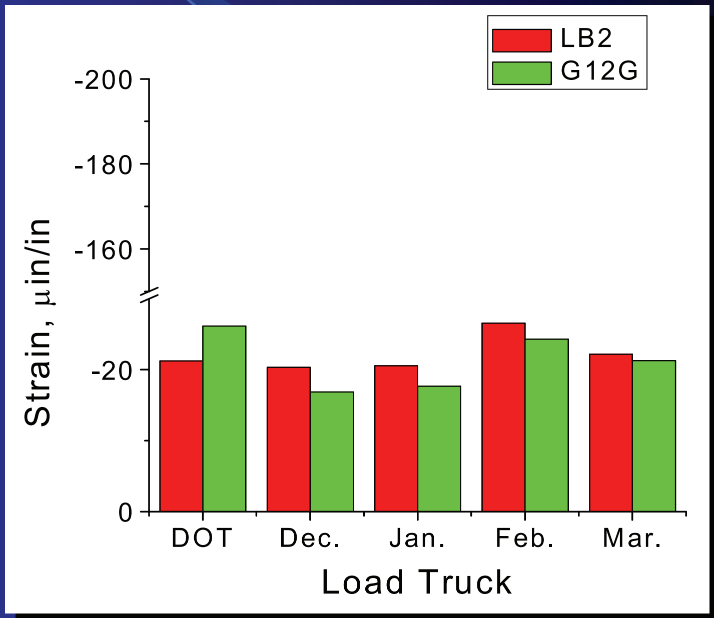
Loading Variability





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Conclusions

- Collected data showed a reduction in strain in the web gap resulting from the retrofit of approximately 75%.
- Long-term data trends suggest the effectiveness of the retrofit is not affected over time by vibrations and temperature changes.

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Chapter 9

Investigation of High Mast Light Pole Failure

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Investigation of High Mast Light Pole Failure

- Monitor wind-induced strains and accelerations in high mast light pole
- Record strains, accelerations, and video during an "event"
- Perform fatigue evaluation
- Recommend retrofit to existing designs, recommendations for new design

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Development of Fatigue Design Loads for Slender Structures/Highway Luminaries Subject to Wind-Induced Excitation

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Introduction

- There have been several failures of support structures - likely due to fatigue
- There are deficiencies in the understanding of the impact of dynamic wind loadings on support structures
- Thus, a more representative and comprehensive design procedure for the AASHTO Specifications is needed

HML Support Base Failure - IA

HML Support Base Failure - WI

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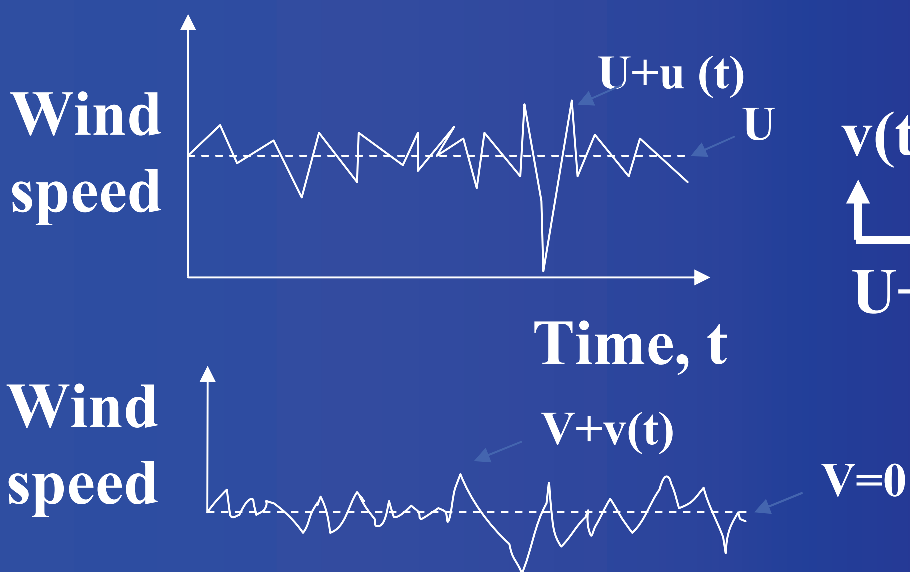
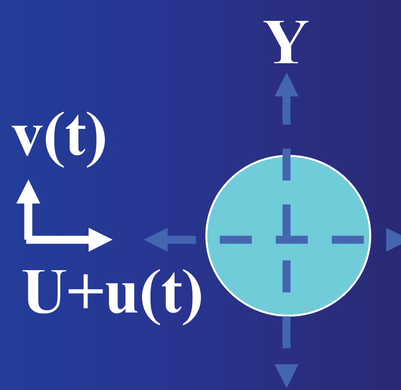
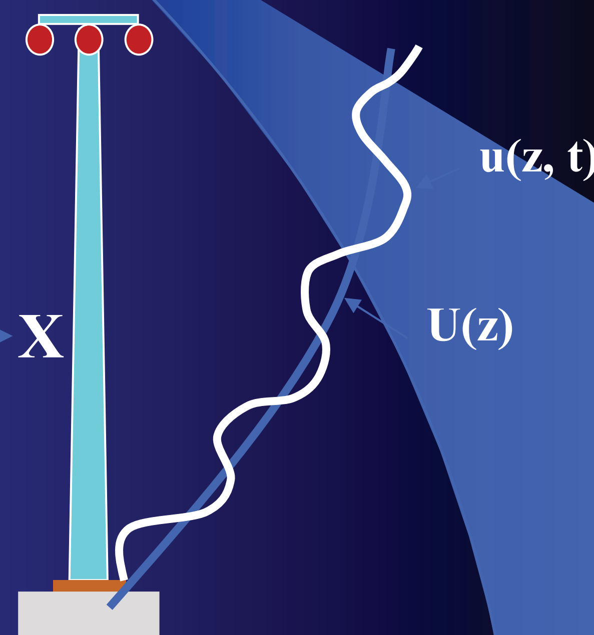
Background

Buffeting

- Buffeting forces are aerodynamic forces acting on structures due to wind fluctuations about the mean







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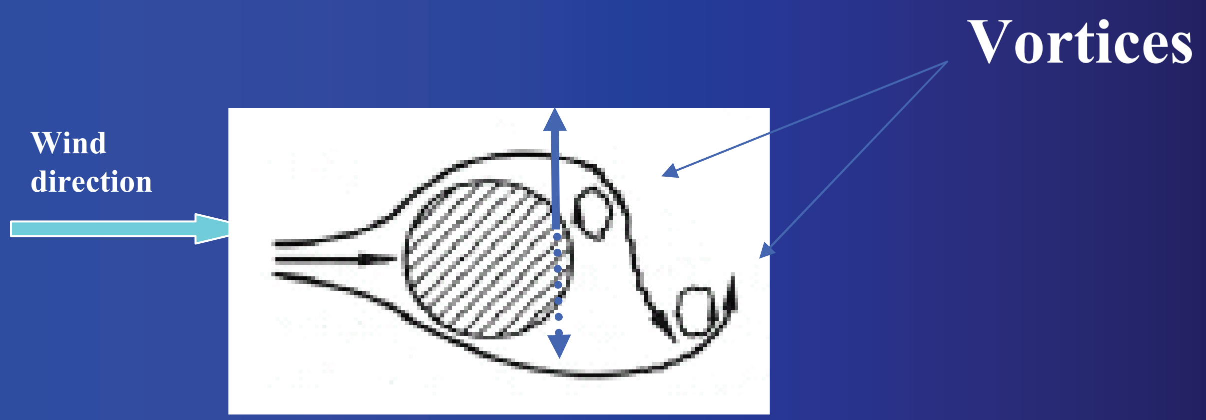
Background
Vortex shedding

- Vortex shedding induces unsteady pressures on the structure, in the direction perpendicular to the wind direction (i.e., across-wind), causing transverse motion



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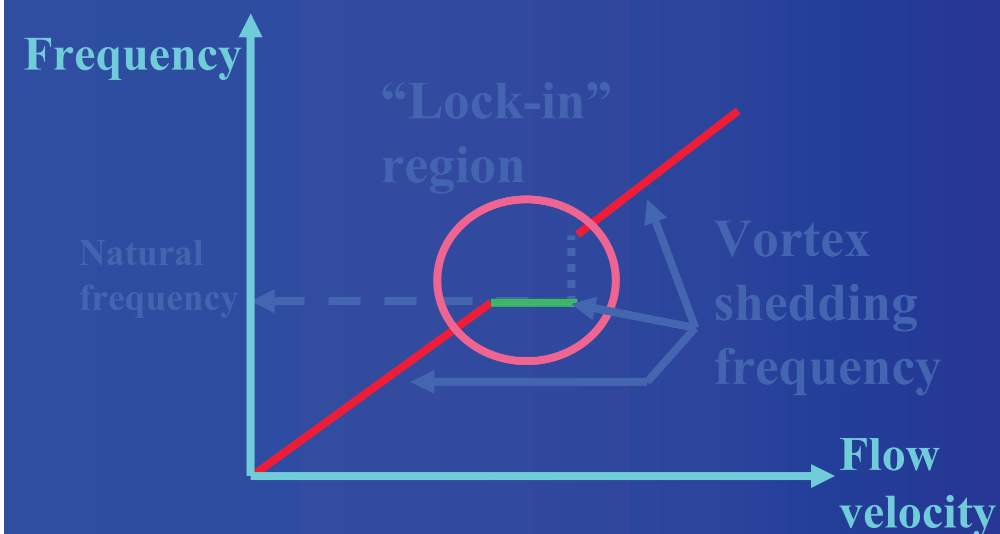
Background

Vortex shedding

- "Lock-in" phenomenon: $f_n = f_s$
- Strouhal number, $S_t = \dfrac{f_s B}{U}$



B: Body dimension

U: Flow velocity

f_s: Vortex shedding frequency

Circular: St = 0.2

Square: St = 0.11 ~ 0.13

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Background

Current Loading Recommendations

2001 AASHTO

$$P_{vs} = \frac{0.00118 \cdot V_{cr}^{2} \cdot C_{d} \cdot I_{F}}{2 \cdot \zeta}$$

ξ: 0.005

C_d: drag coefficient

V_{cr}: $f_n \cdot D / S_t$

f_n: 1st mode frequency

S_t: 0.11 ~ 0.18

I_F: importance factor

L_e: height of structure

Ontario Code

$$P_{t} = \frac{0.3 \cdot C_{s} \cdot V_{cr}^{2}}{\zeta} (Pa)$$

ξ: 0.0075 for steel

C_s: RMS lift coefficient

V_{cr}: $f_n \cdot D / S_t$

f_n: 2nd mode frequency

S_t: 0.11 ~ 0.18

C_s: 0.71 ~ 0.85

L_e: ±10% of critical diameter

NCHRP 469

$$P_{vs} = \frac{0.00118 \cdot V_{cr}^{2} \cdot C_{d} \cdot I_{F}}{2 \cdot \zeta}$$

ξ: 0.005

C_d: drag coefficient

V_{cr}: $f_n \cdot D / S_t$

f_n: 2nd mode frequency

S_t: 0.11 ~ 0.18

I_F: importance factor

L_e: ±10% of critical diameter

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Objectives

- Develop a coupled mathematical model for:
  - Vortex shedding
  - Buffeting
- Refine mathematical model parameters based upon wind tunnel testing, long-term monitoring, and a parametric study results
- Formulate a procedure and a more realistic equation for determining fatigue design loads due to vortex shedding and buffeting for slender support structures

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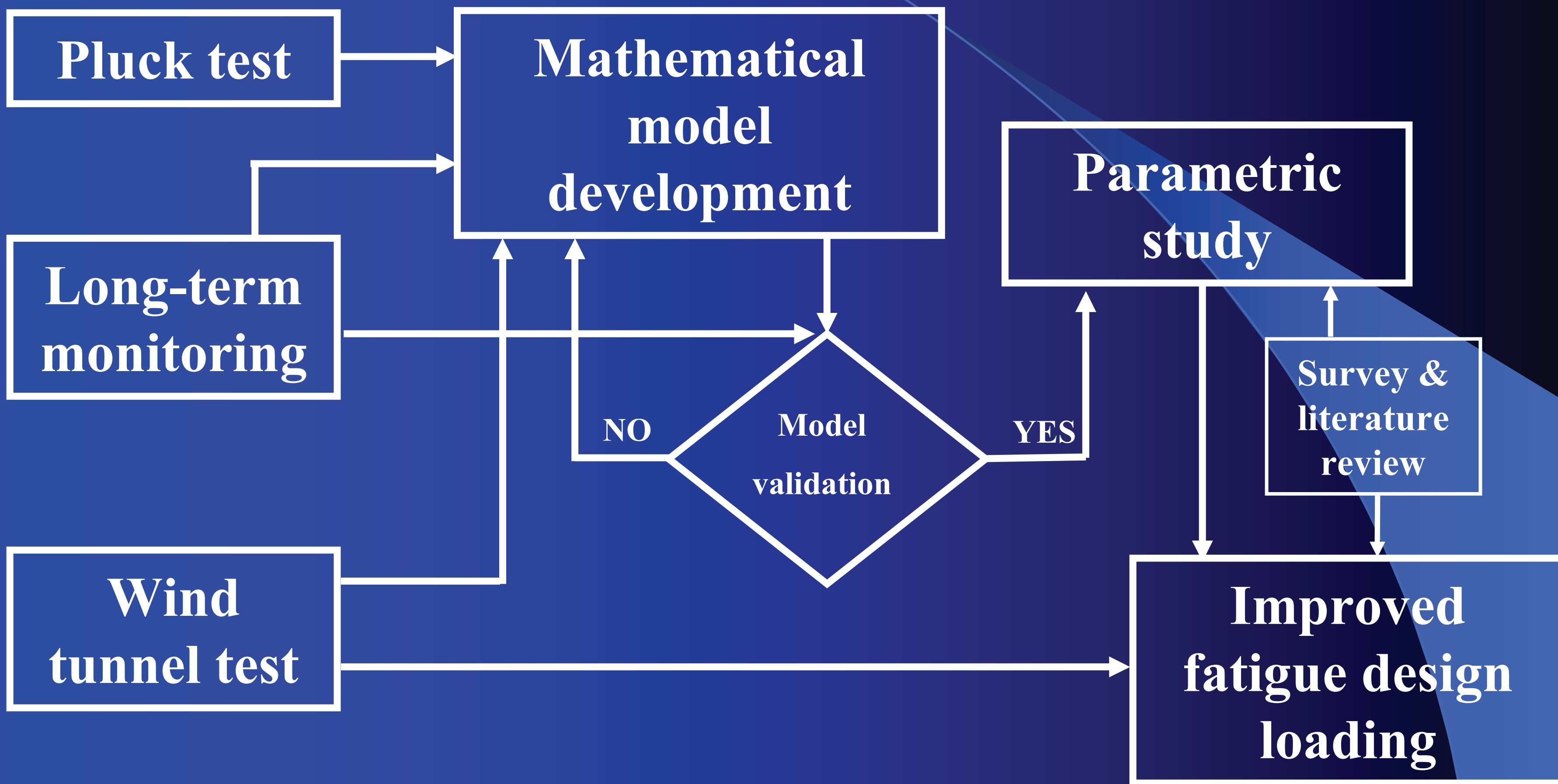
General approach



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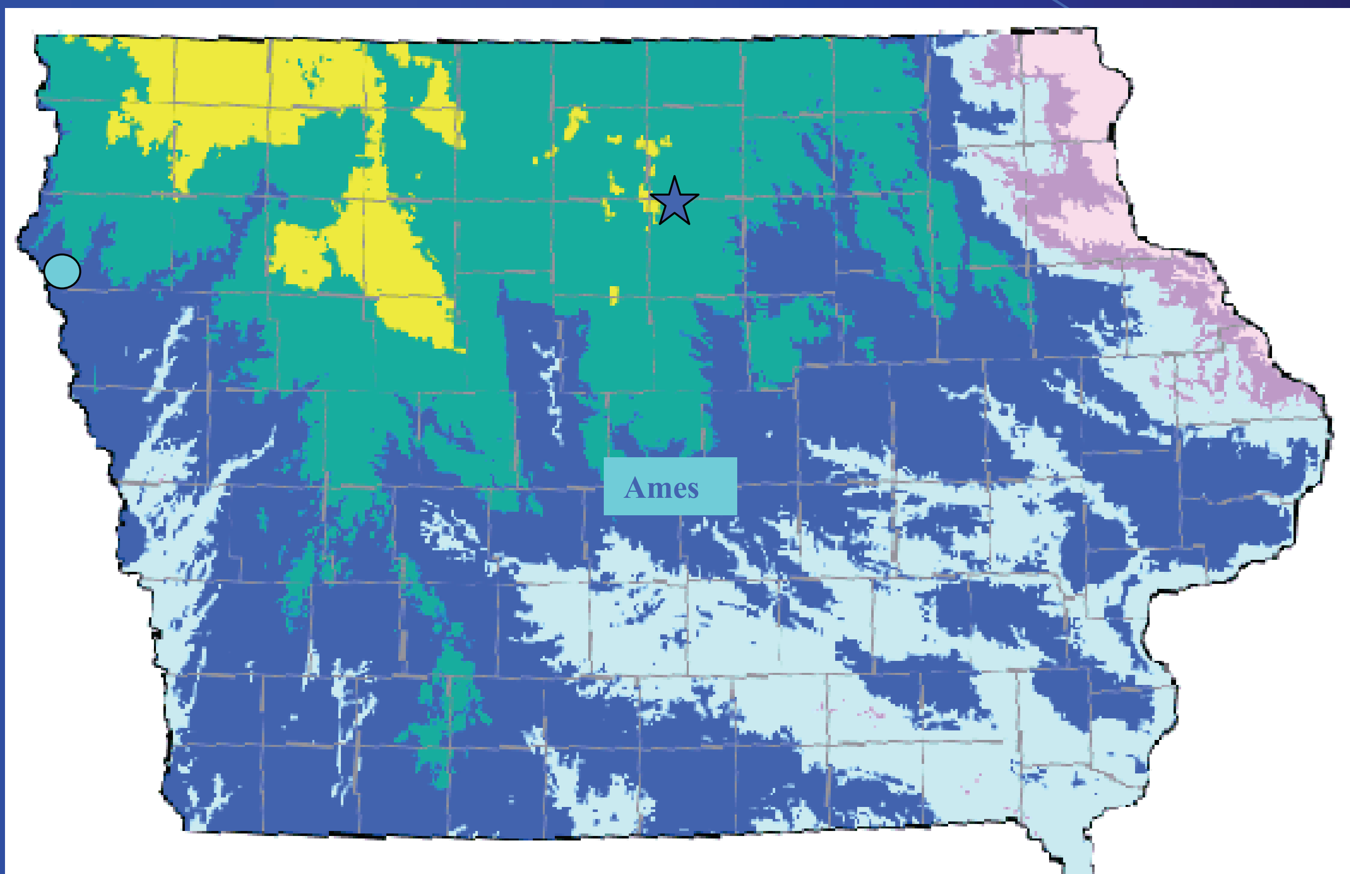
Long-term monitoring



MPH		m/s
>19.0		>8.5
17.9-19.0		8.0-8.5
16.8-17.9		7.5-8.0
15.7-16.8		7.0-7.5
14.5-15.7		6.5-7.0
13.4-14.5		6.0-6.5
12.3-13.4		5.5-6.0
<12.3		<5.5

Near Sioux City: Location of collapsed high-mast light pole

Near Mason City: Location of long-term field monitoring

<http://www.energy.iastate.edu/renewable/wind/maps-index.html>

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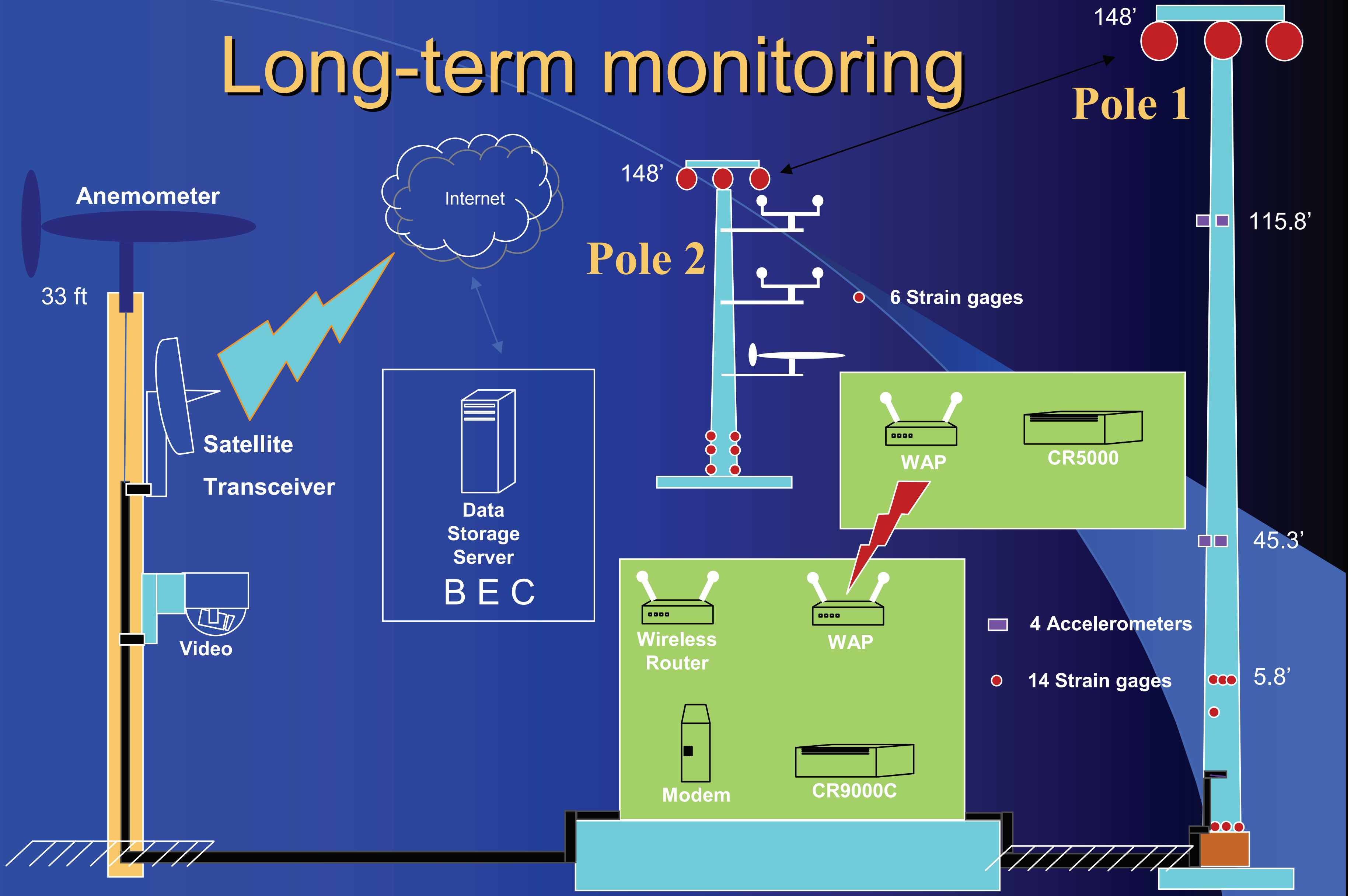
Long-term monitoring



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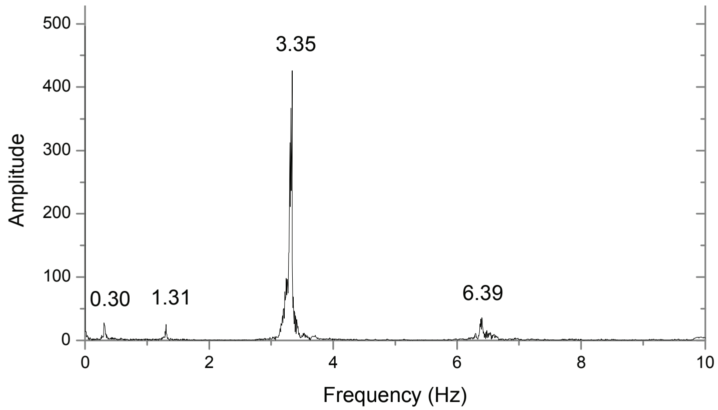
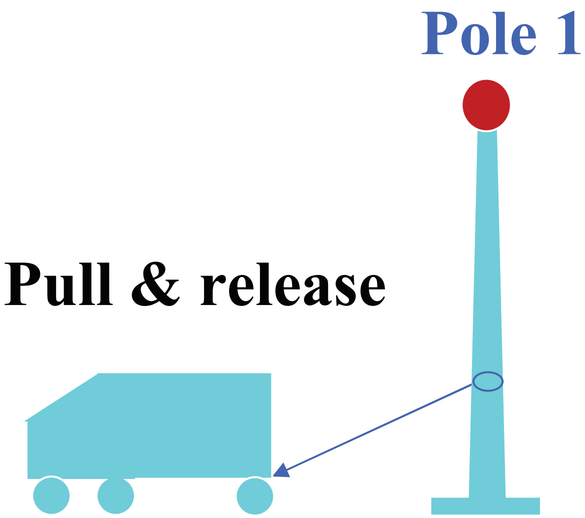
Long-term monitoring

Pluck-test – Pole 1



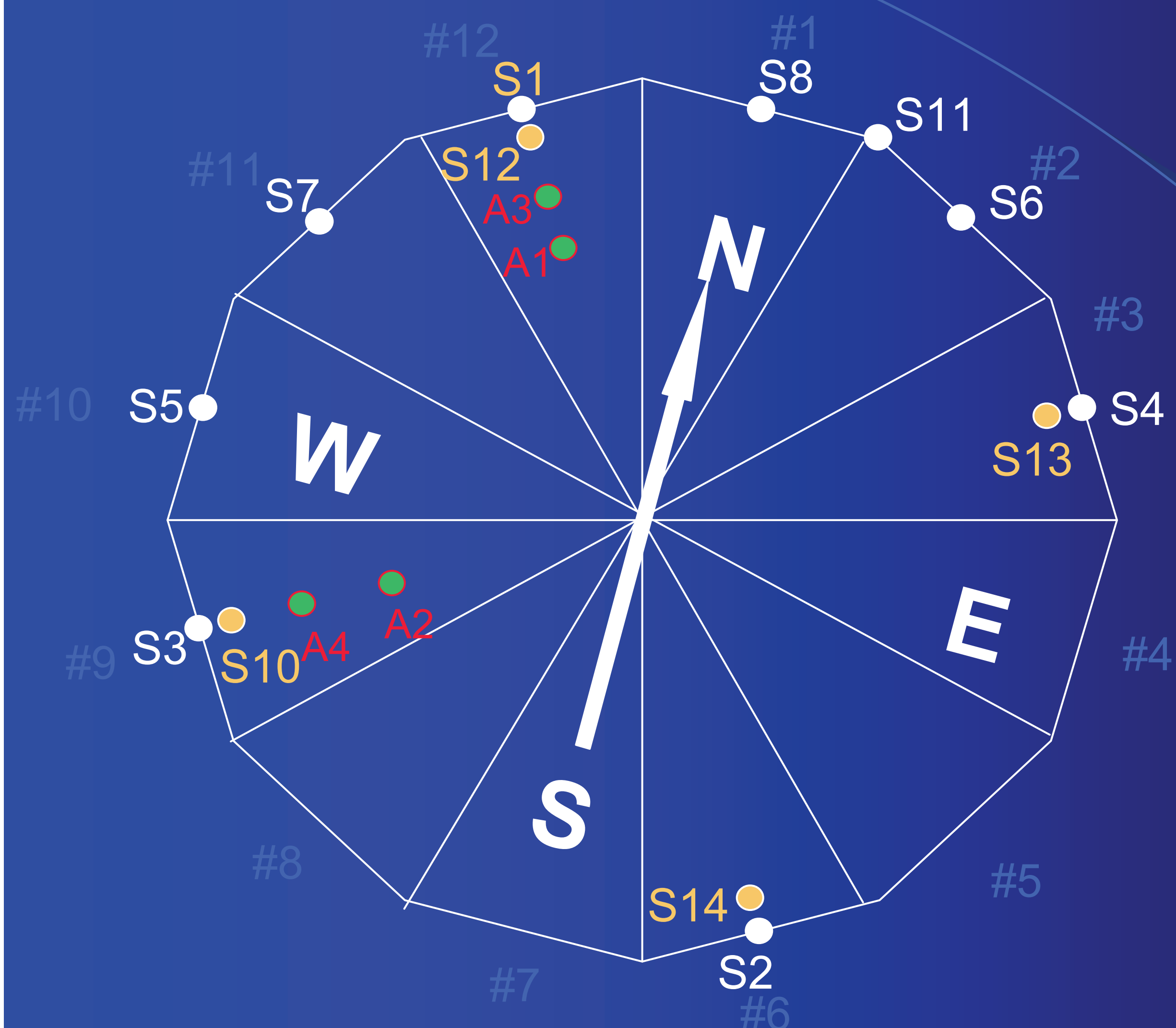


Mode	Frequency (Hz) using FEA		Field test	% Difference	
	Linear geometry	Nonlinear geometry		Linear	Nonlinear
1	0.33	0.32	0.31	10.33%	5.67%
2	1.34	1.33	1.31	2.52%	1.37%
3	3.45	3.43	3.33	2.87%	2.39%
4	6.64	6.62	6.39	3.88%	3.62%

Damping ratio = 0.26% (logarithmic decrement method)

of Transportation

Long-term monitoring



Pole 1

- 12-sided section
- 4 Accelerometers
- 14 Strain gages
- 1 Anemometer

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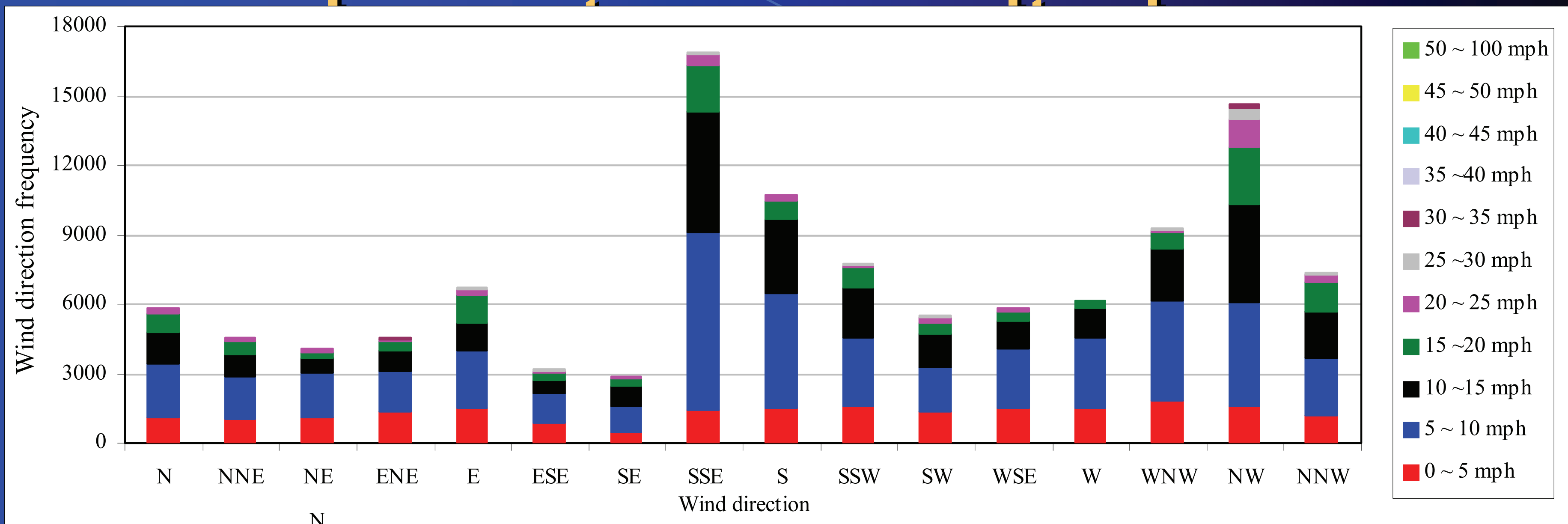
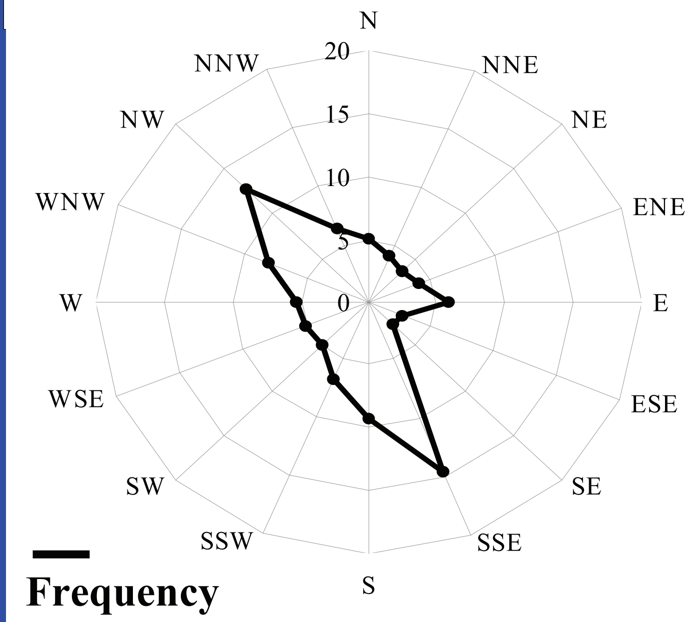




Wind speed and direction frequency

Long-term monitoring

Wind profile parameters – Pole 2

Roughness length, Z_0

Terrain factor, α

Log Law

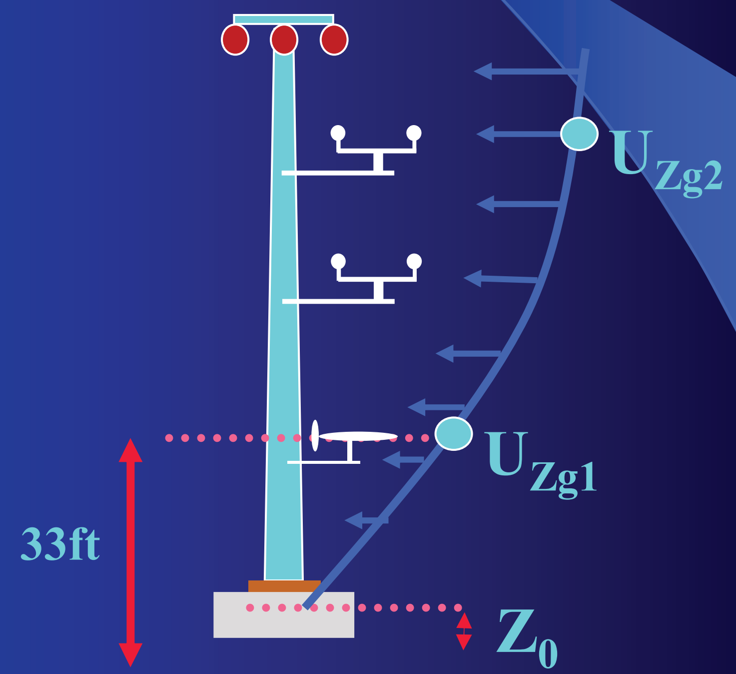
$$U(Z_g, Z_{g0}) = 2.5u^{*}\ln(Z_g / Z_0)$$

Z_0 = 3.3 cm (Ref: 2 ~ 7 cm)

Power Law

$$U_{Zg1}/U_{Zg2} = (Z_{g1} / Z_{g2})^{\alpha}$$

α = 0.13 (Ref: 0.10 ~ 0.14)



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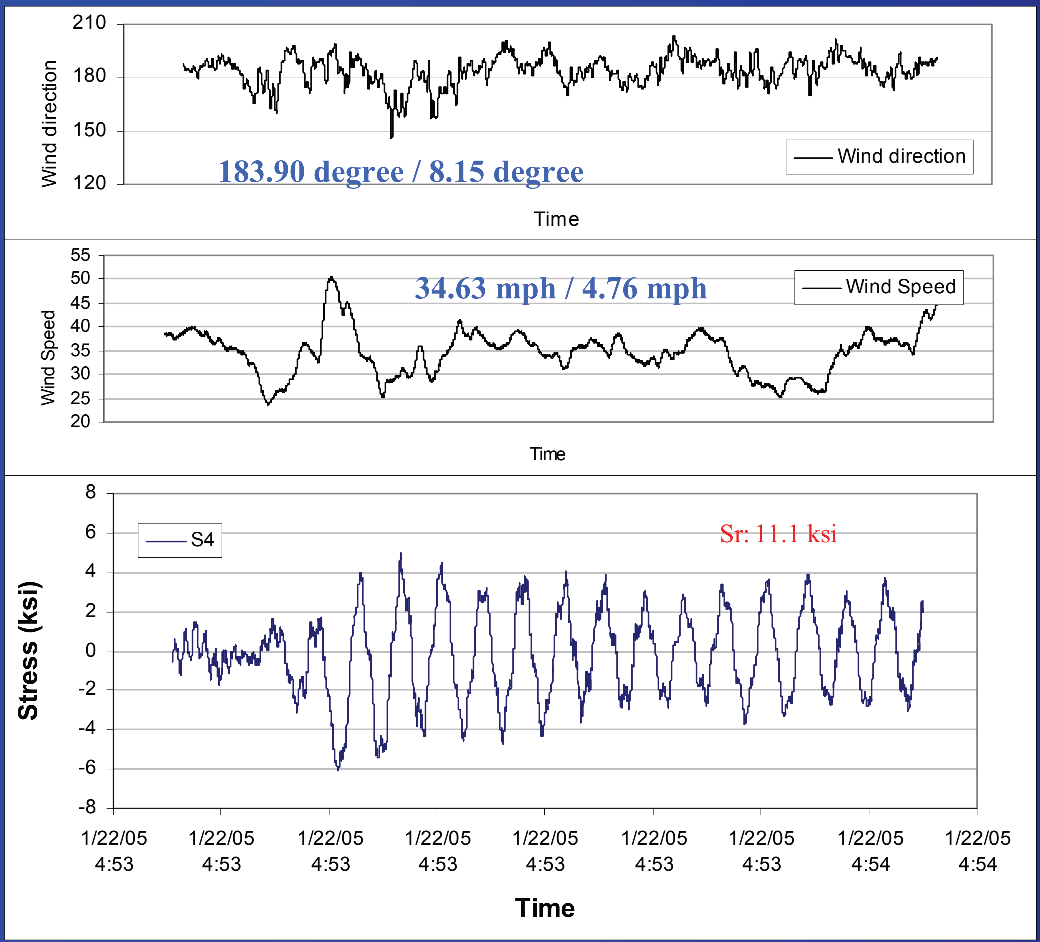
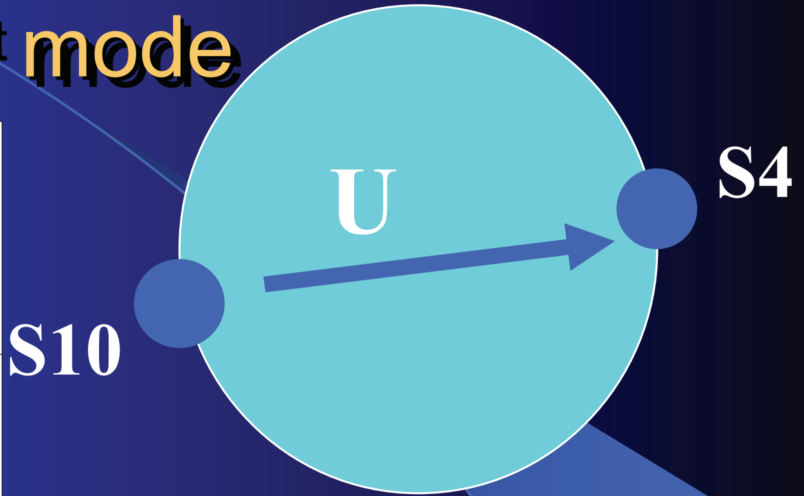
Long-term monitoring

Buffeting – 1st mode





Frequency = 0.3 Hz
~Mode 1

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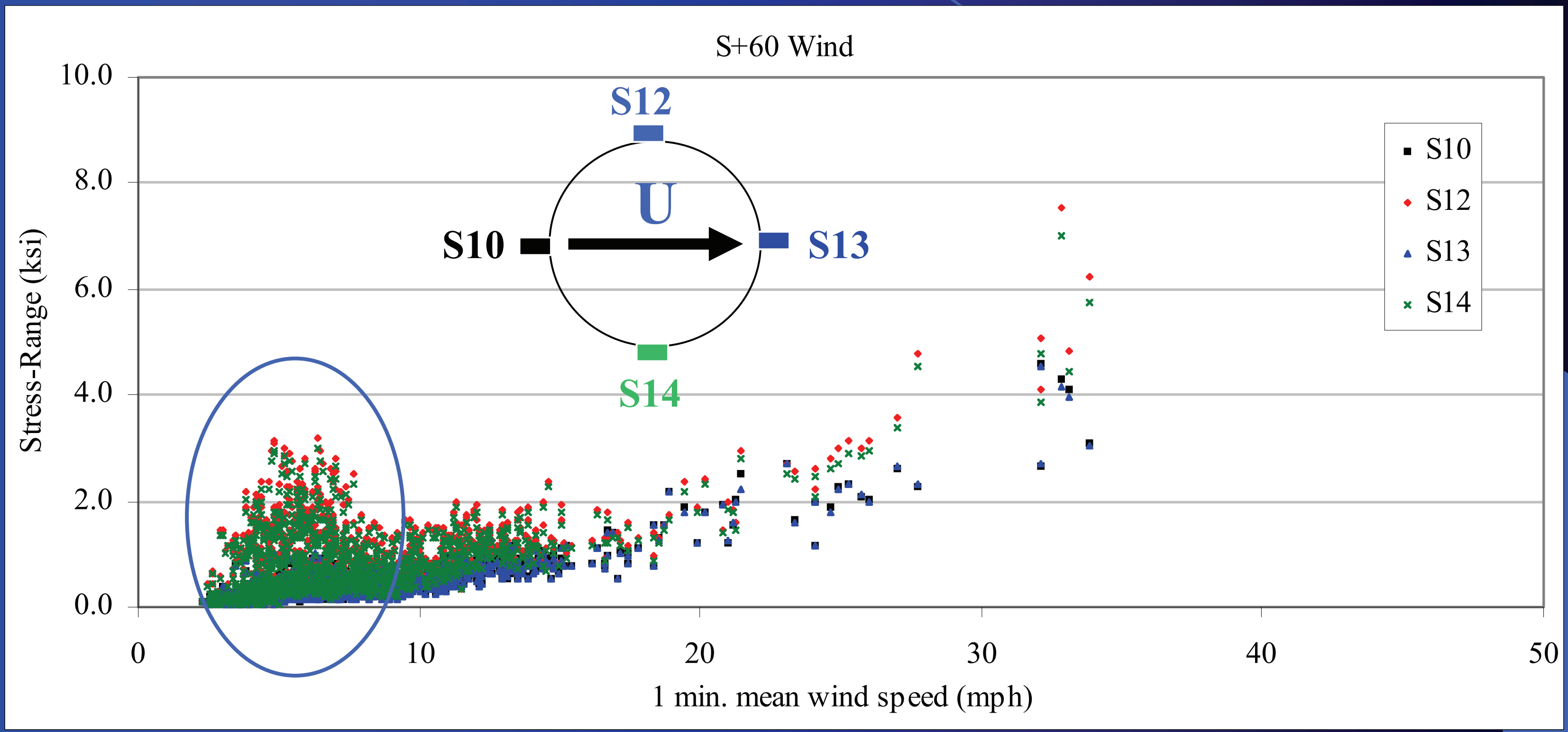
Long-term monitoring

Vortex shedding –Pole 1



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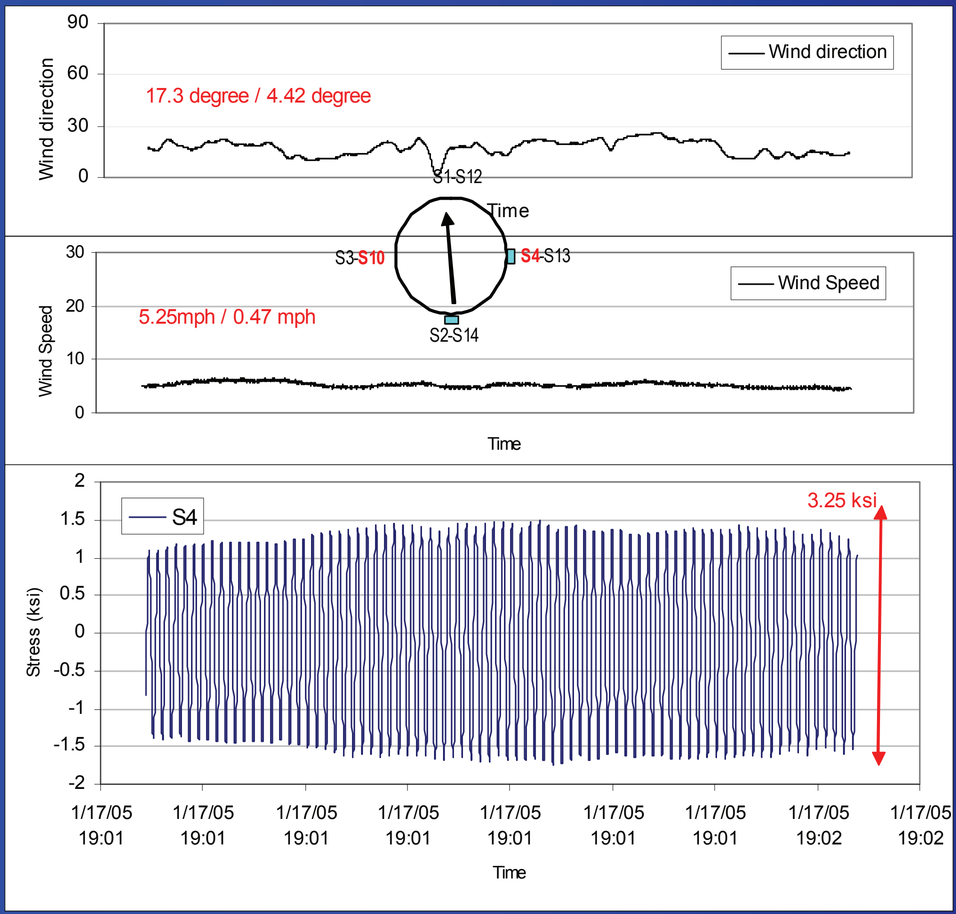
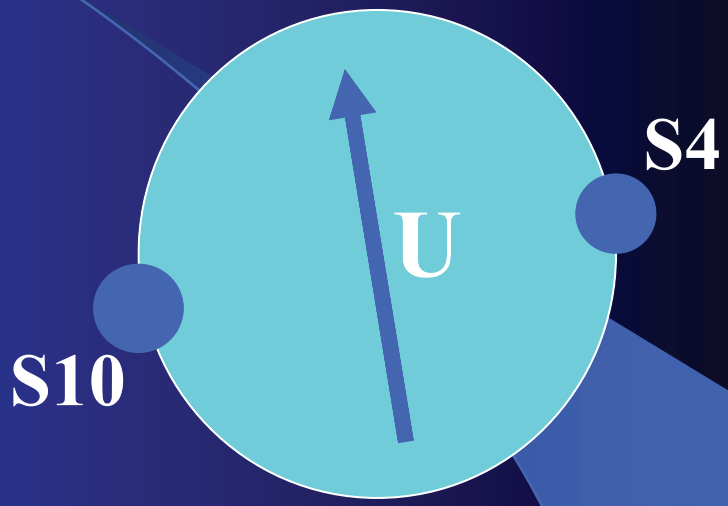
Long-term monitoring

Vortex shedding – 2nd mode





Frequency = 1.3 Hz
~Mode 2

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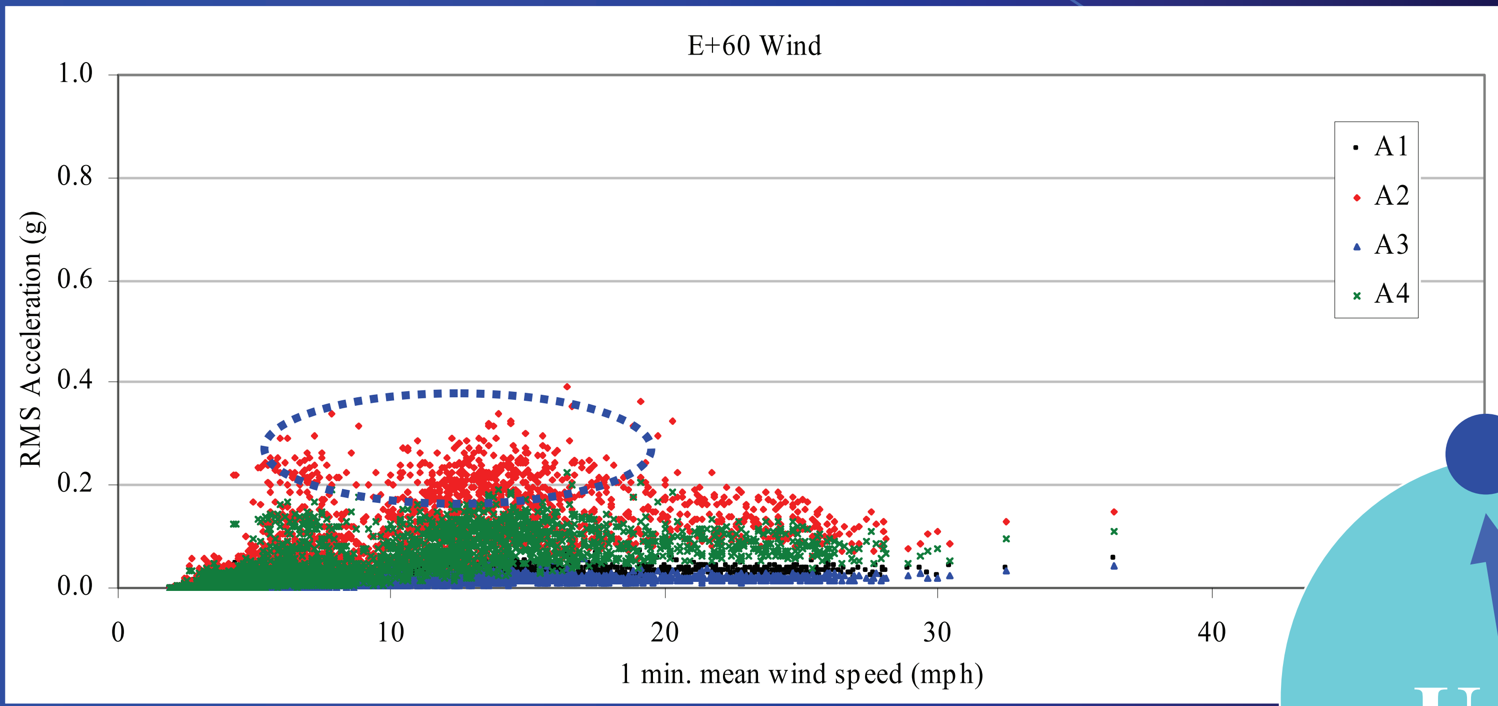
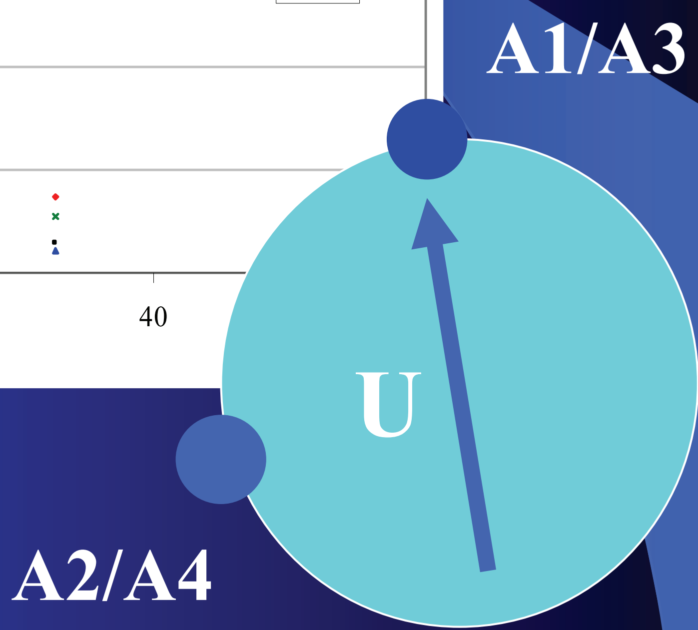
Long-term monitoring
Vortex shedding





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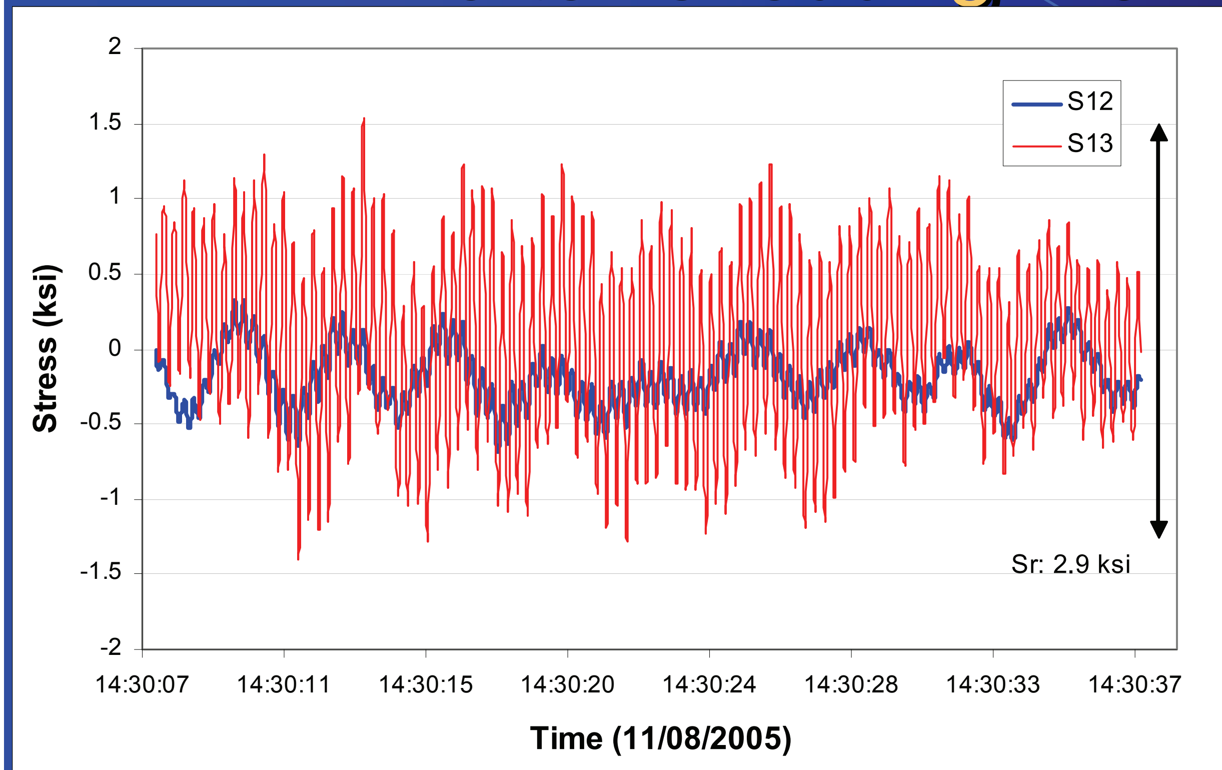
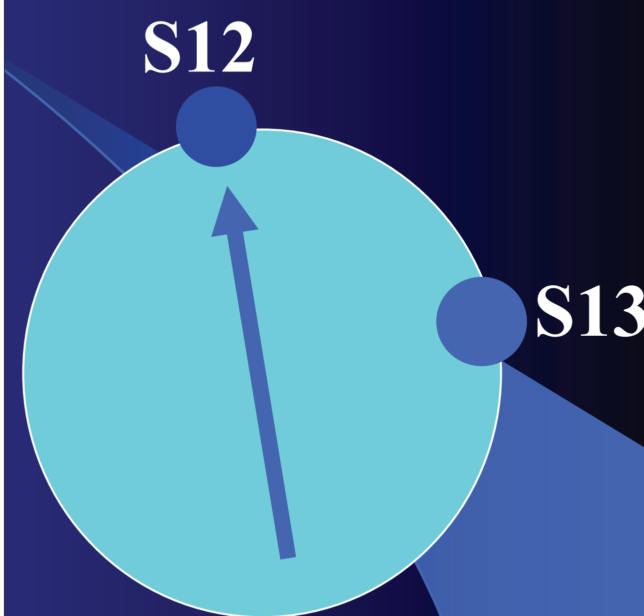
Long-term monitoring
Vortex shedding – 3rd Mode





Mean wind Speed: 20. 4 mph
Mean wind direction: 16.1 deg.

Frequency = 3.3 Hz
~Mode 3

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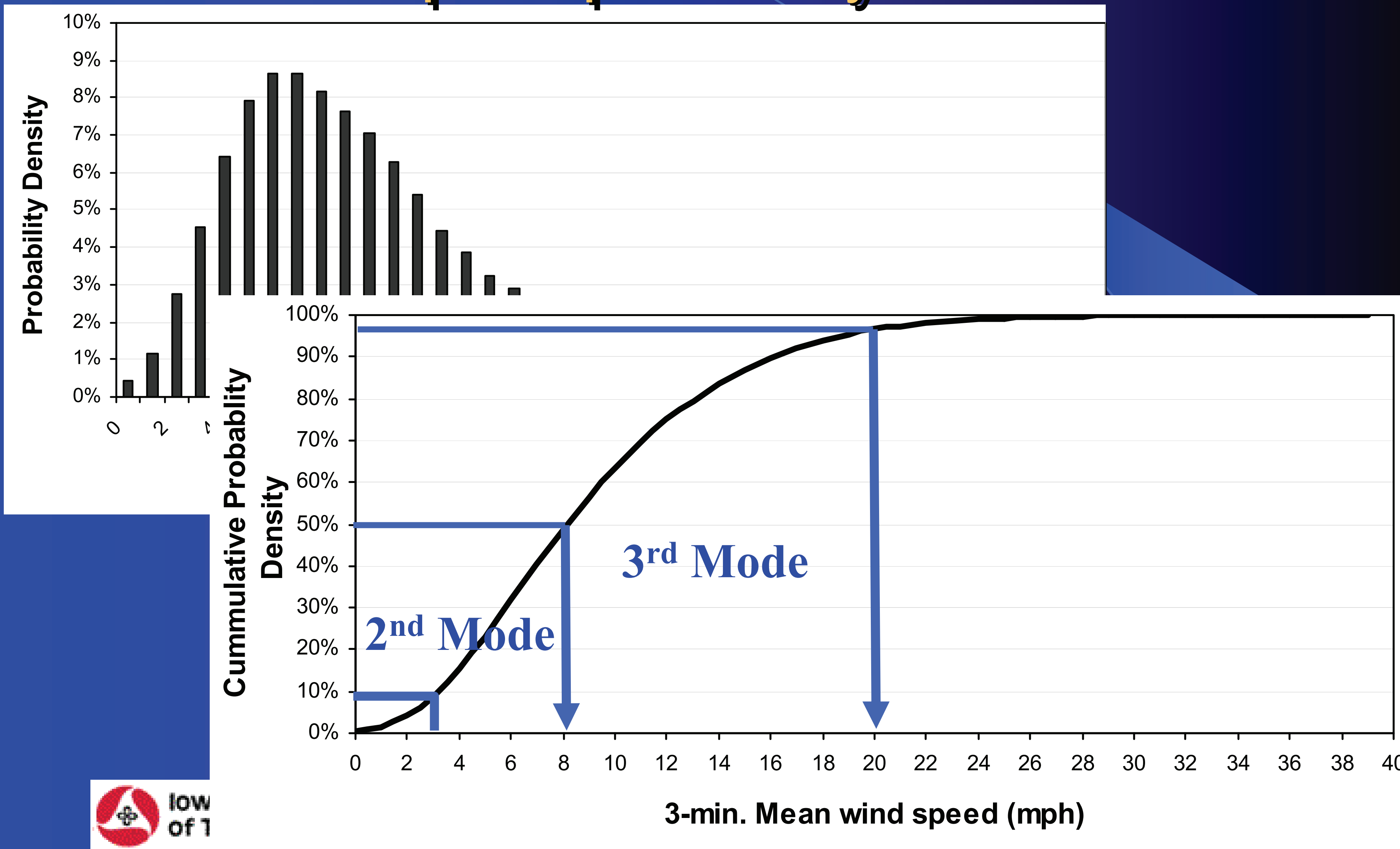
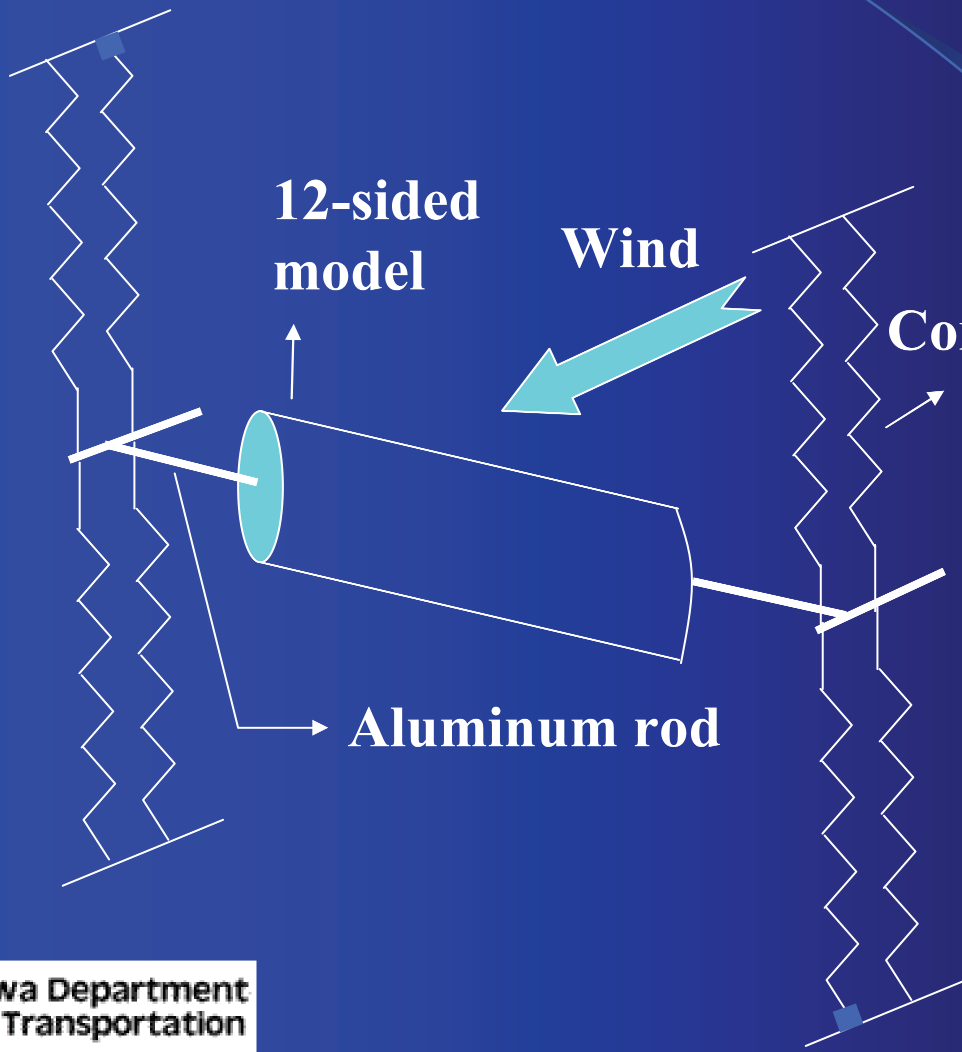
Long-term monitoring

Wind speed probability – Pole 1



Wind tunnel test

Dynamic test



- Transducers

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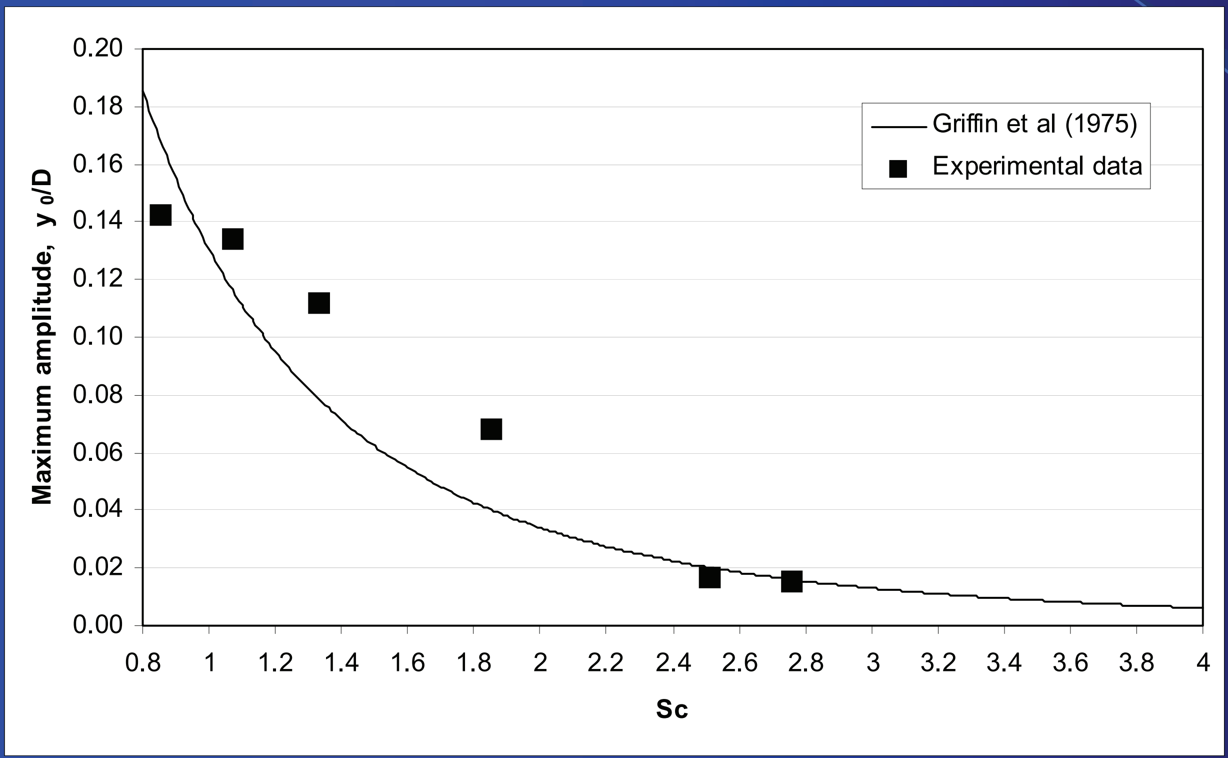
Wind tunnel test

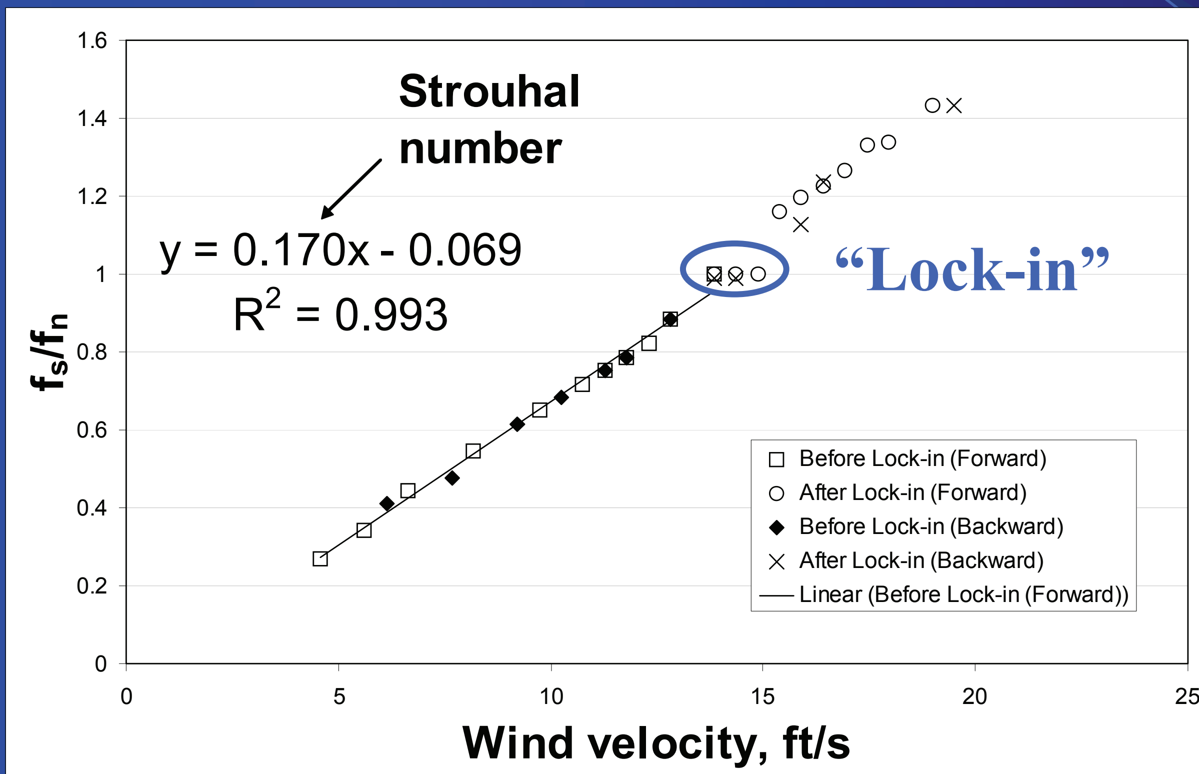
Dynamic test

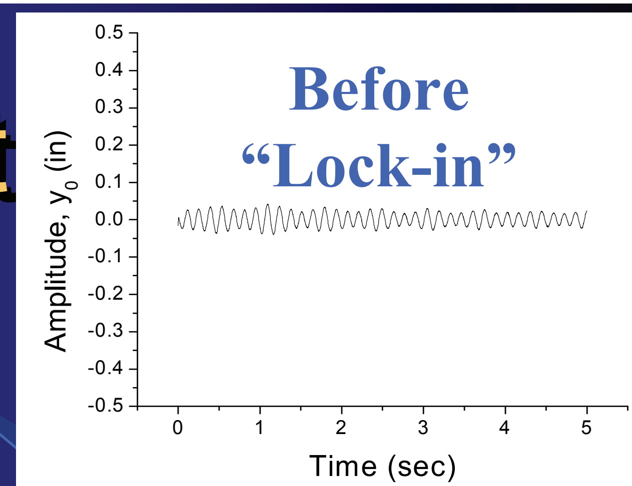


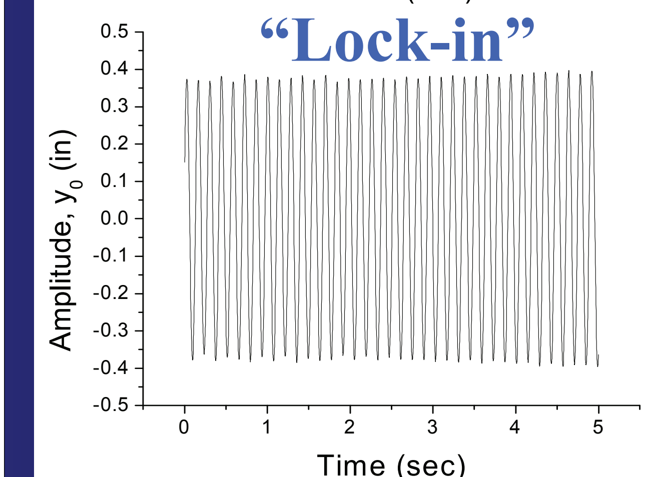
$$S_c = \frac{m_e \zeta}{\rho D^2}$$

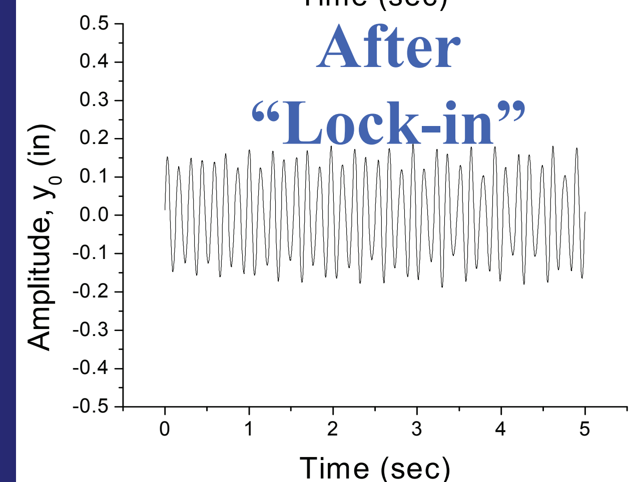
Wind tunnel test

Dynamic test









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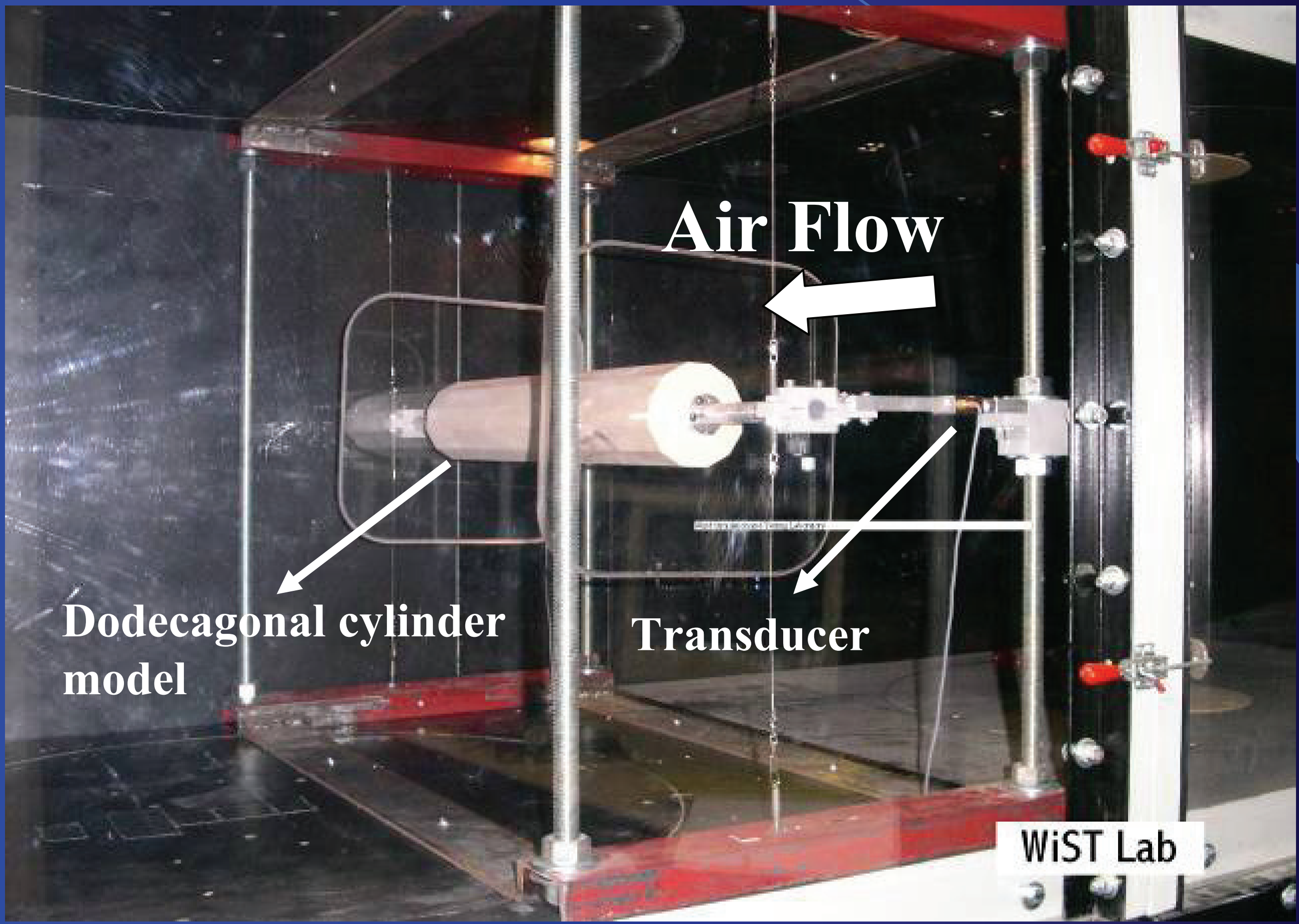
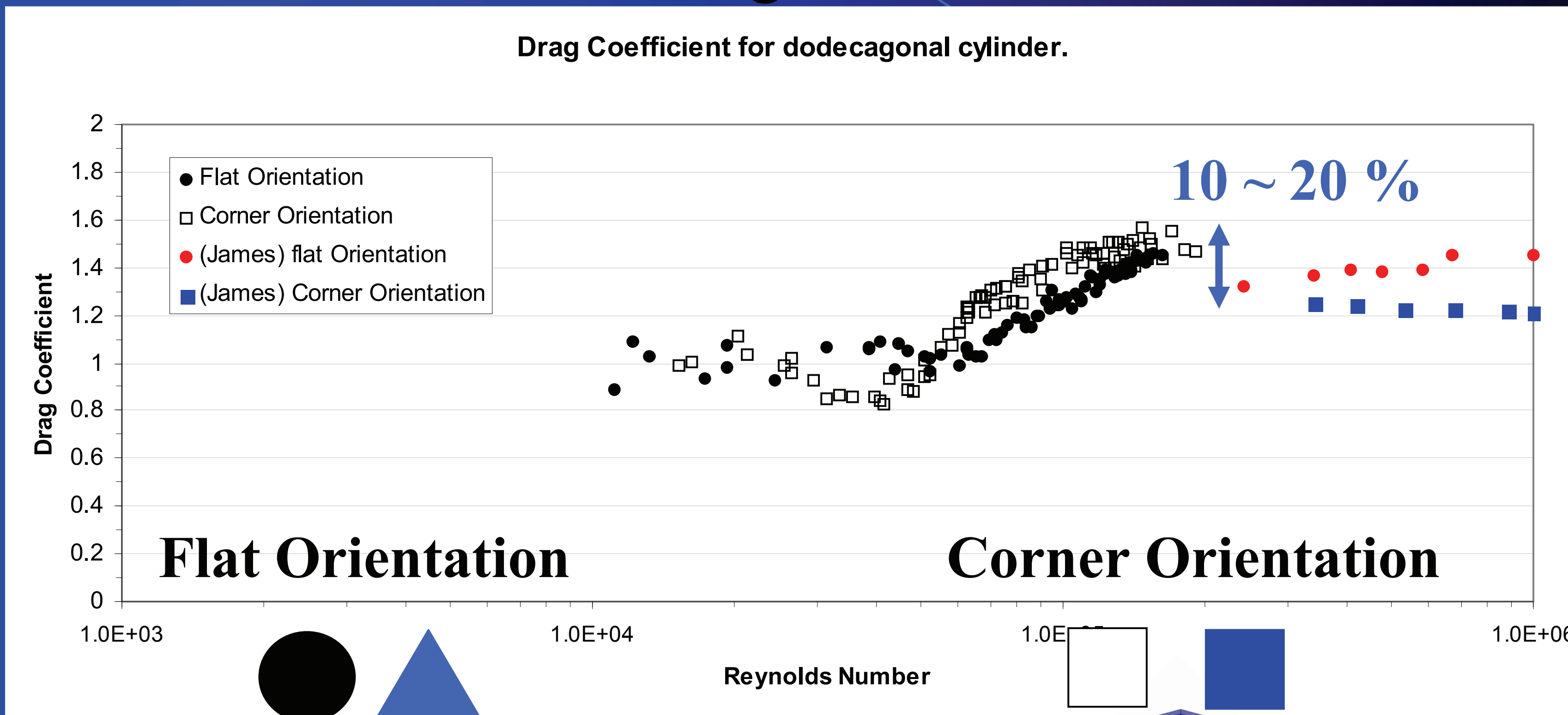
Wind tunnel test

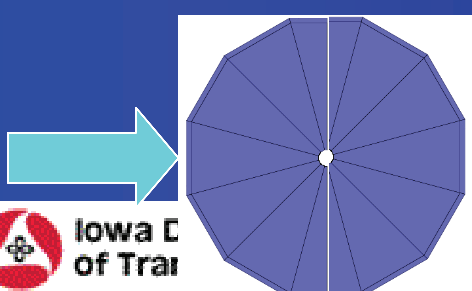
Drag measurement

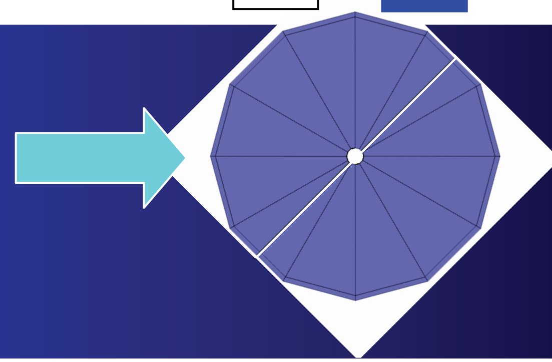


Wind tunnel test

Drag measurement







Wind tunnel test

Test video

C:\Documents and Settings\BChang\My Documents\Desktop\Project\Wind tunnel\Lift Wind Tunnel Testing\Lock-in.Avi

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Comments

- Significant step in the ability to effectively monitor and remotely manage infrastructures
- Each SHM system tailored to monitor specific behaviors
- Benefits must exceed the costs

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Chapter 10

Structural Health Monitoring of Bridges

Iowa Department of Transportation

a) Monitoring the Structural Condition of Fracture-Critical Bridges

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Background

- Iowa has more than 50 fracture-critical bridges (FCB) on the primary roadway system
- Iowa DOT requested development of structural health monitoring (SHM) system
- Demonstration bridge: East-bound US Highway 30 (US30) bridge over Skunk River near Ames, IA

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Scope of Research

- SHM system specifications
  - Aid in detection of damage
  - Autonomous data collection, reduction, evaluation, and storage
  - Understandable reports that summarize and support evaluations
  - Implementable by DOT work forces on any Iowa FCB

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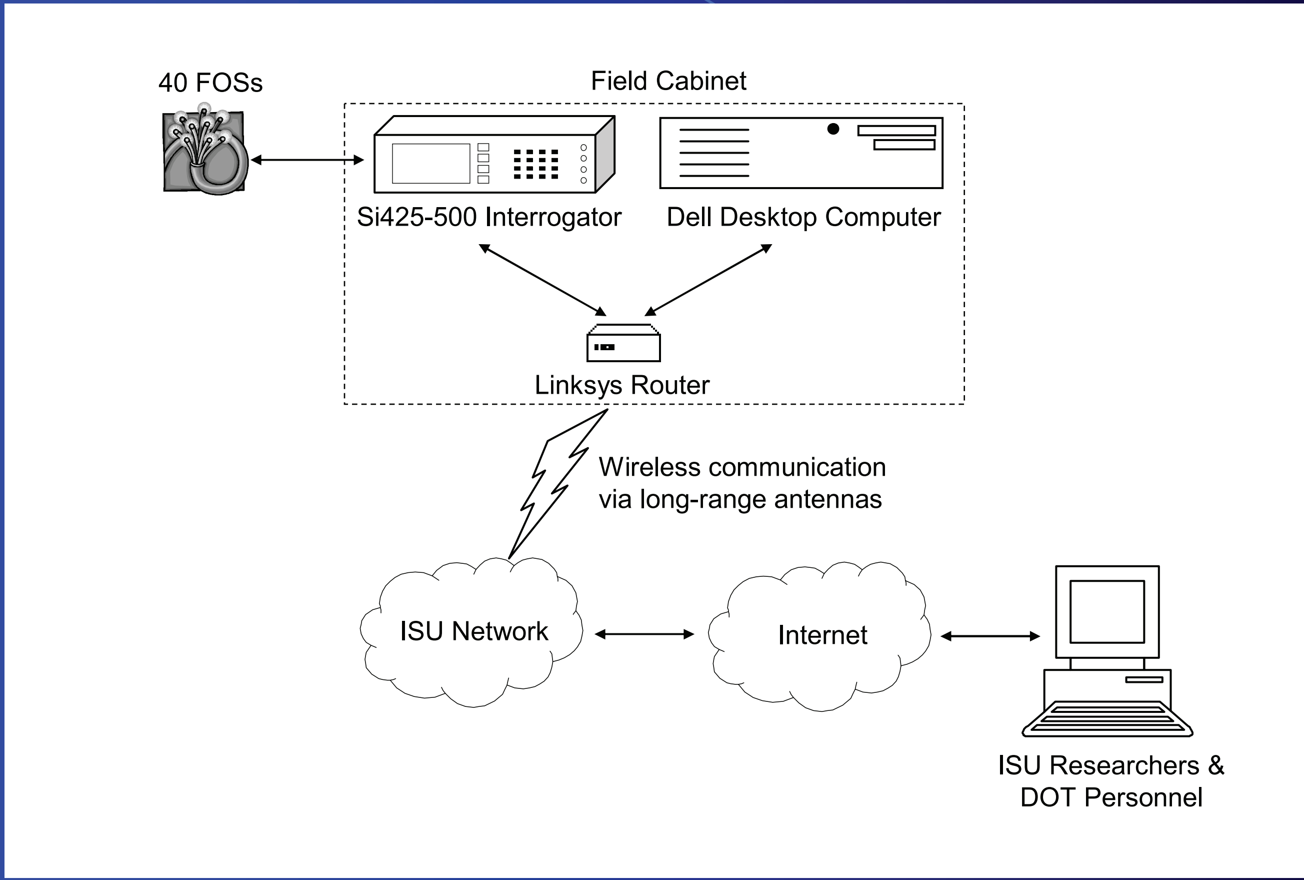
SHM Hardware Configuration



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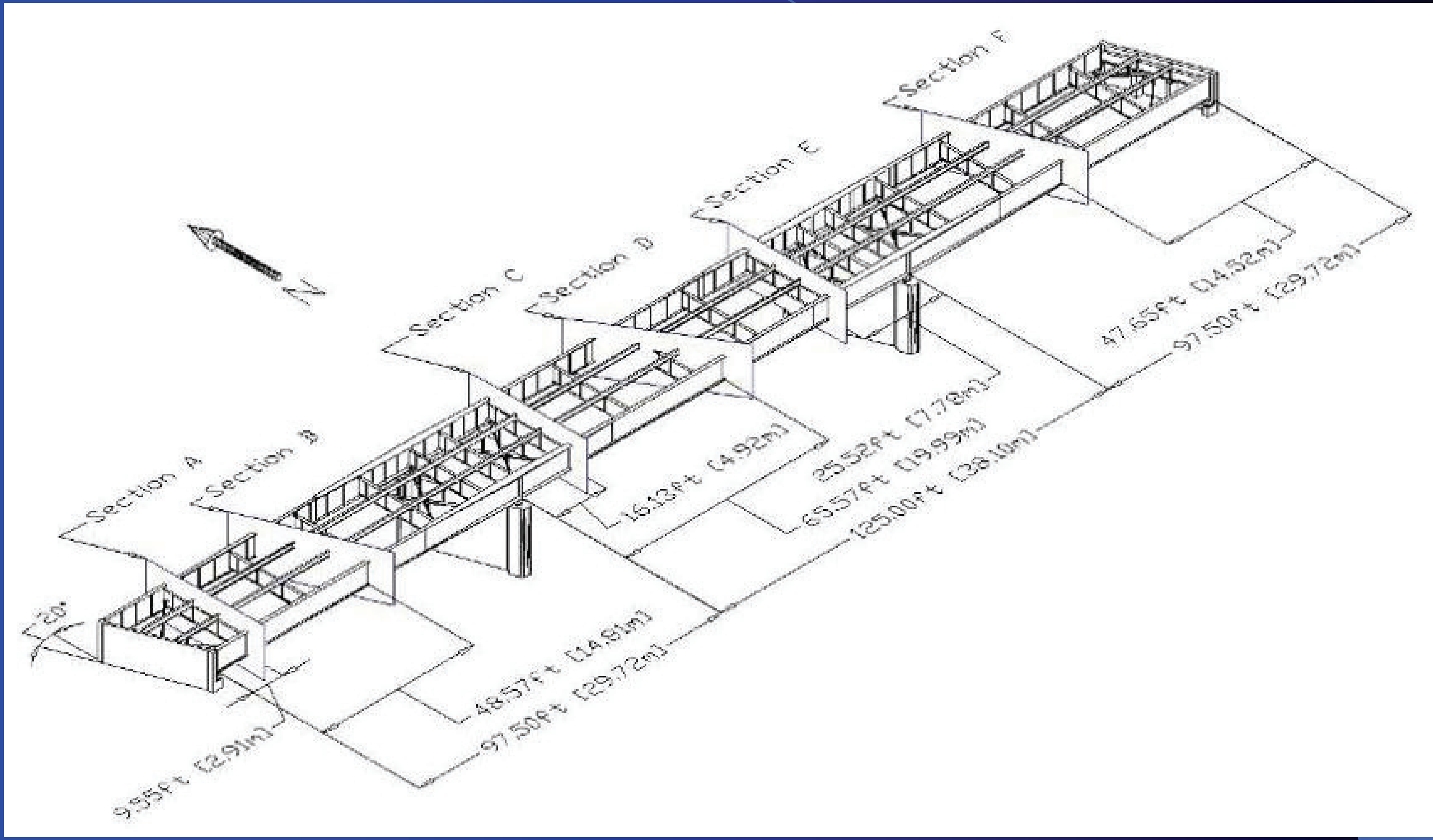
FOS Locations and Orientations



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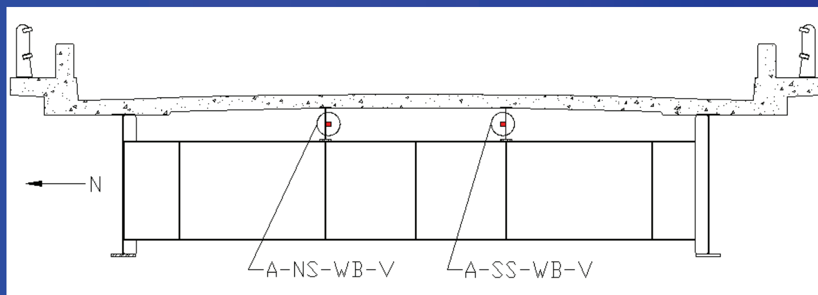
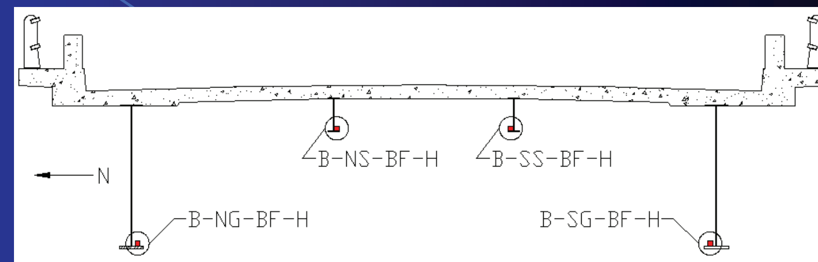
FOS Locations and Orientations

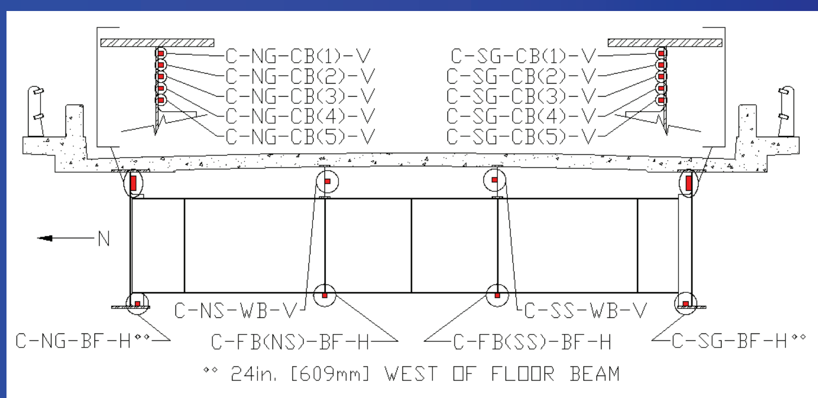
Section A:



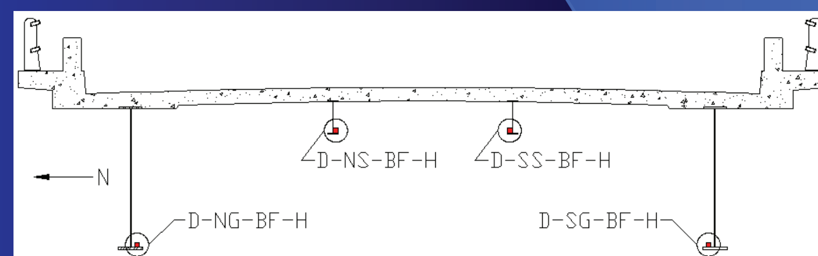
Section B:



Section C:



Section D:



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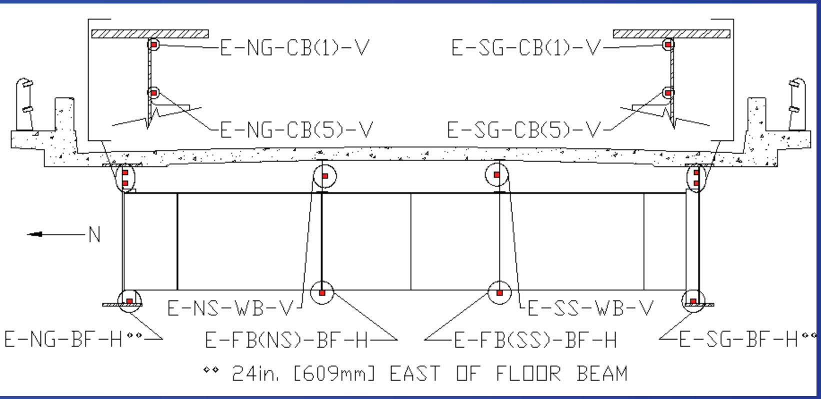
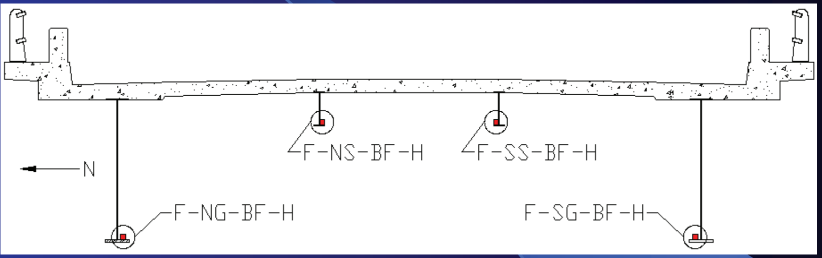
FOS Locations and Orientations

Section E:



Section F:



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FOS Locations and Orientations

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SHM System Software

- Unknowns in autonomous SHM:
  - Vehicle weight and geometry
  - Traffic density and position
  - Dynamic impacts and variability of suspension systems

∴ Conventional structural analysis difficult to perform

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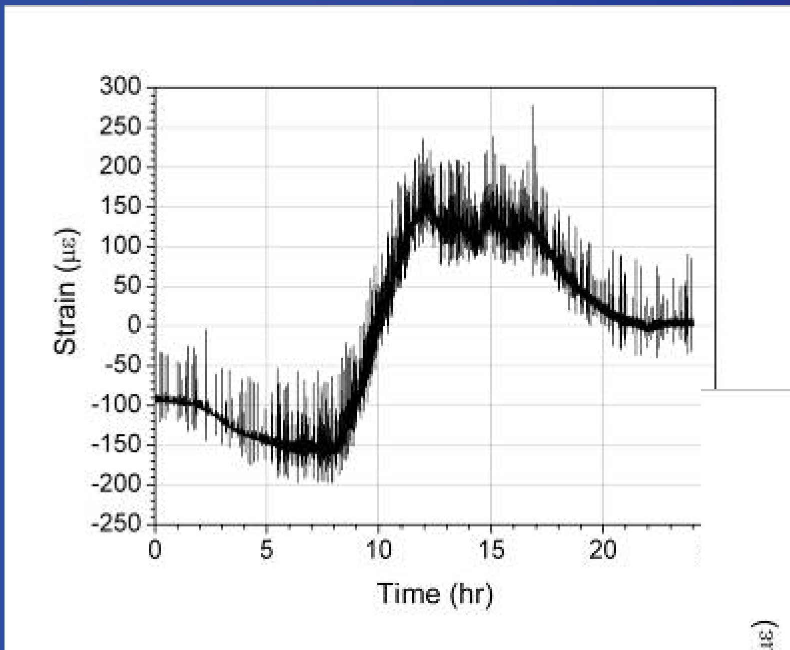
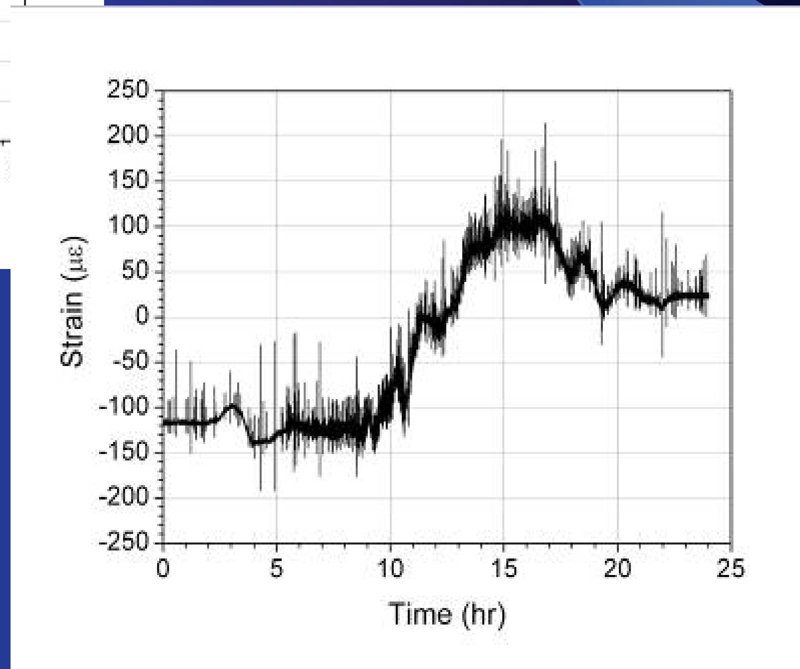
SHM System Software



B-SG-BF-H

F-SG-BF-H



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SHM System Software

- Solution: pattern recognition
  - Train the SHM system to recognize and develop relationships among the sensors that are indicative of typical bridge performance
  - Deviations from trained relationships are indicators of damage formation
  - Relationships are similar to bivariate control charts in statistical process control

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SHM System Software

- Extrema Matching
  - Each traffic event leaves a "footprint" with distinct shape and magnitude in the strain history record of each sensor
    - Significant: static vehicular weight, bridge geometry, sensor location and orientation
    - Noticeable: vehicle geometry, transverse location on bridge, dynamics, etc.
  - Static extrema for corresponding events between two sensors form distinct relationships

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SHM System Software

- Extrema Matching
  - Sensors classified as target sensor (TS) or non-target sensor (NTS)
    - TS = Sensor in location prone to damage
    - NTS = Sensor not in location prone to damage
  - Relationships:
    - TS maxima with NTS maxima (MAMAR)
    - TS maxima with NTS minima (MAMIR)
    - TS minima with NTS maxima (MIMAR)
    - TS minima with NTS minima (MIMIR)

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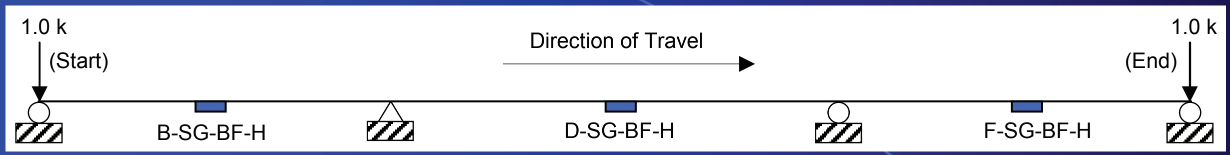
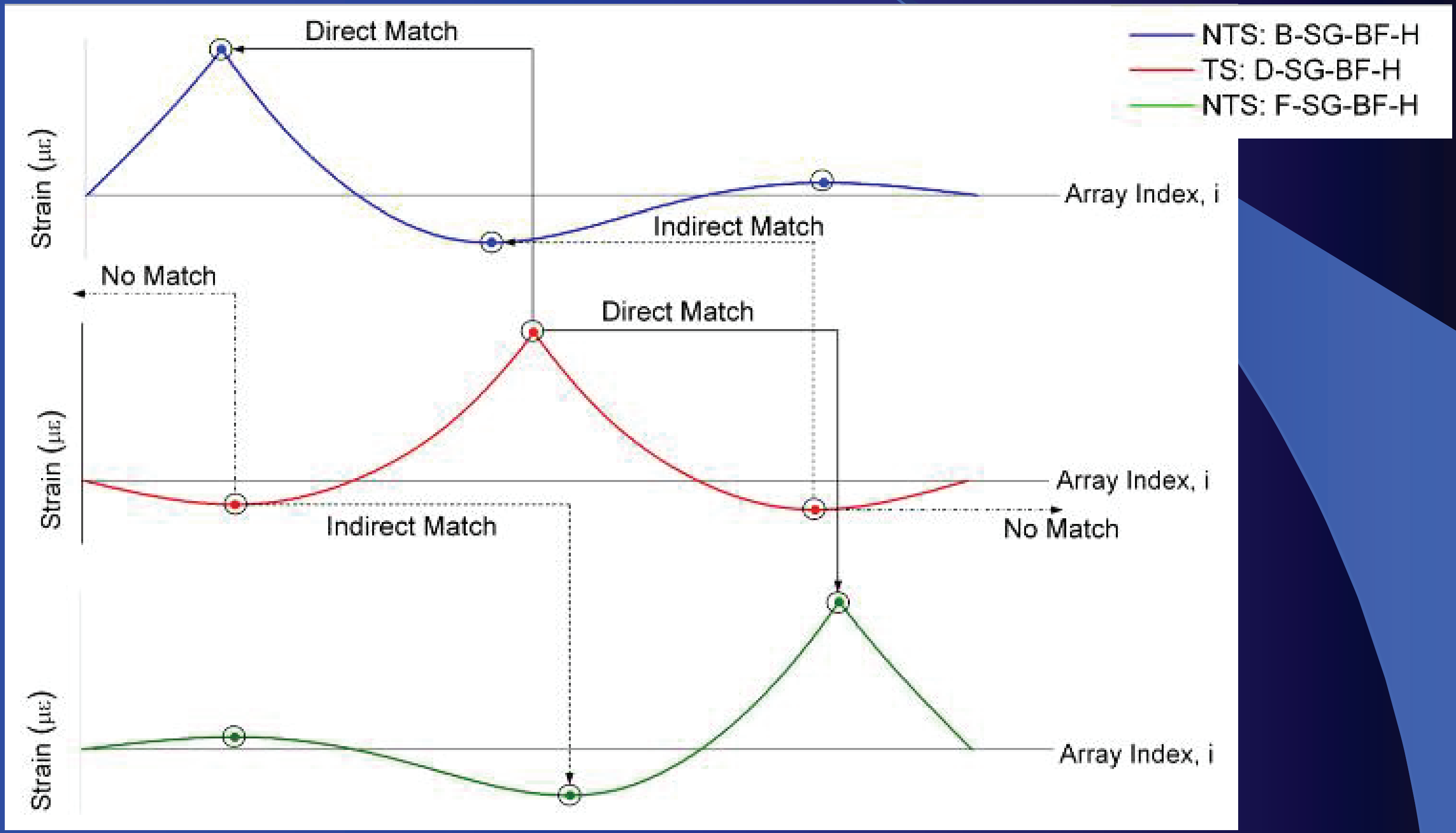
Extrema Matching Procedure





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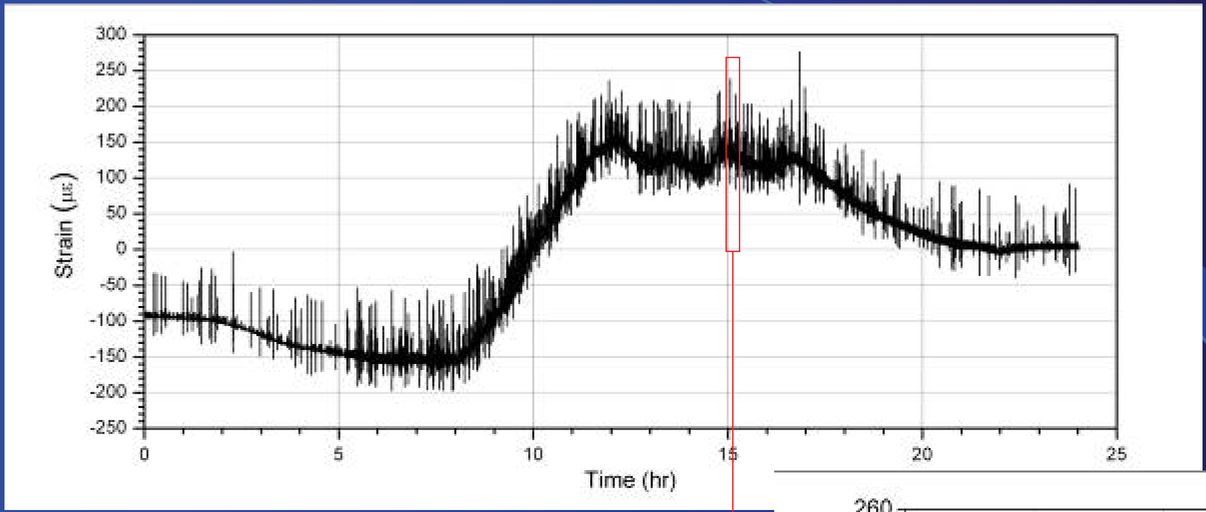
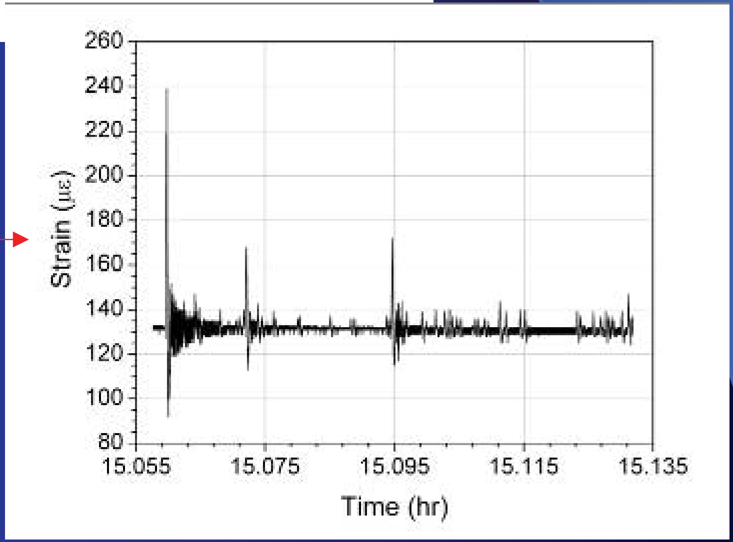
Data Reduction and Extraction



B-SG-BF-H



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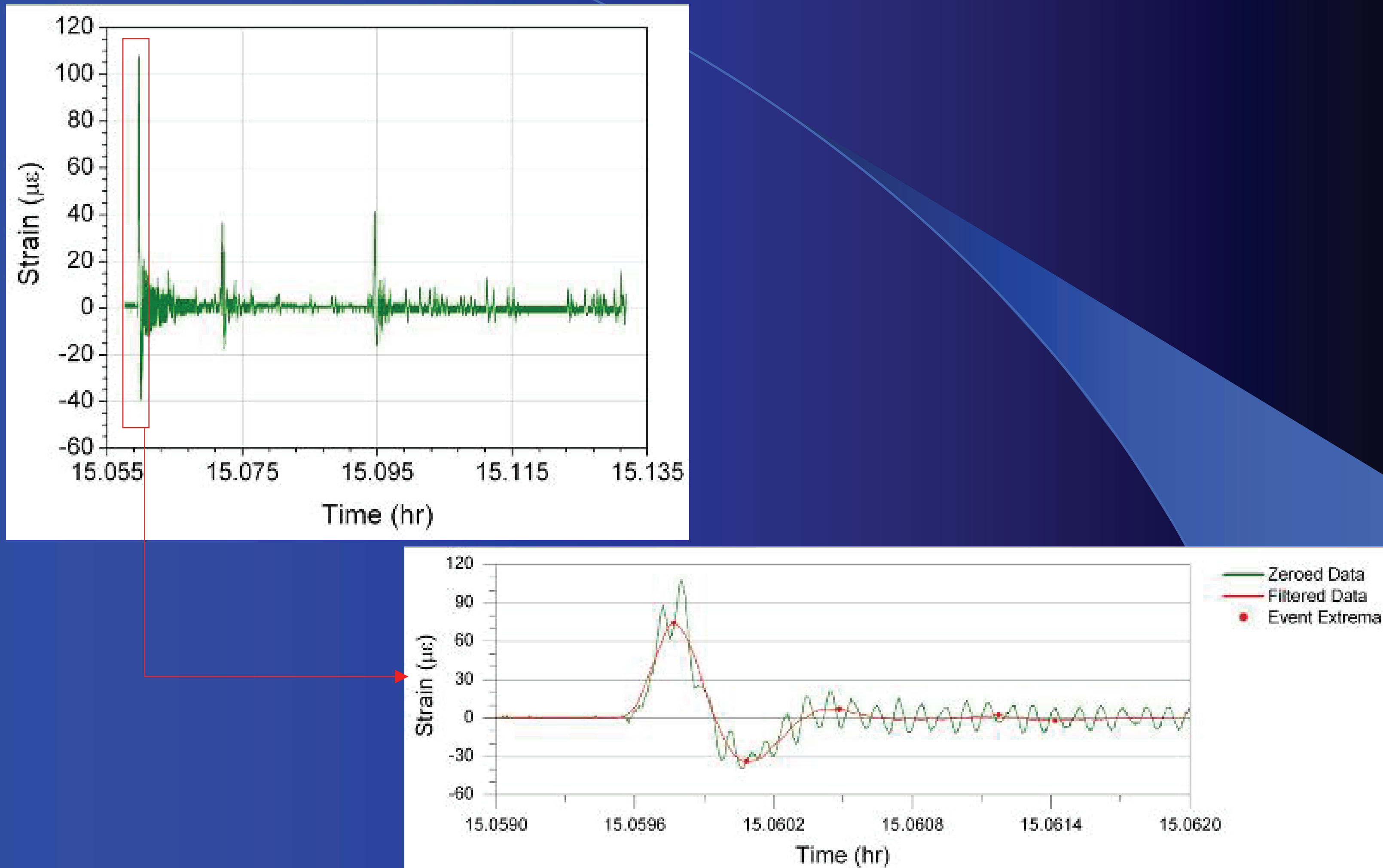
Data Reduction and Extraction



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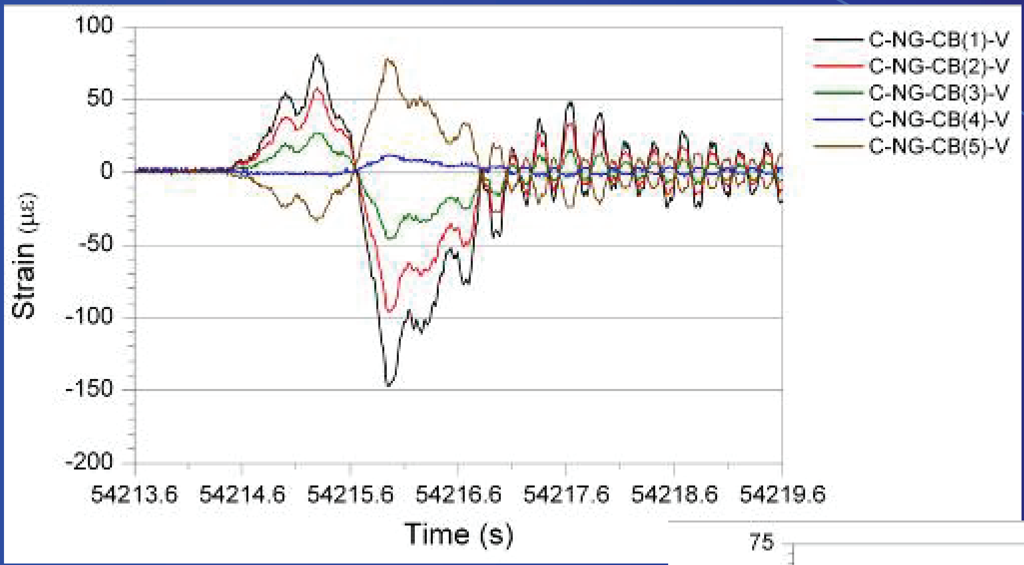
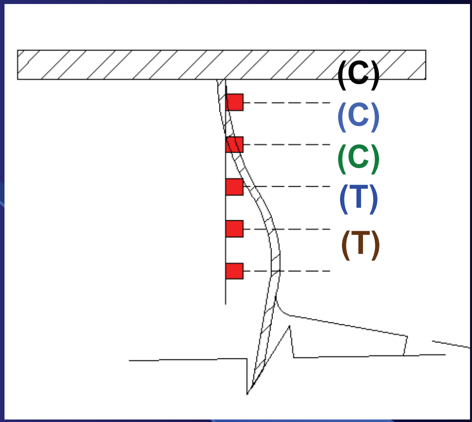
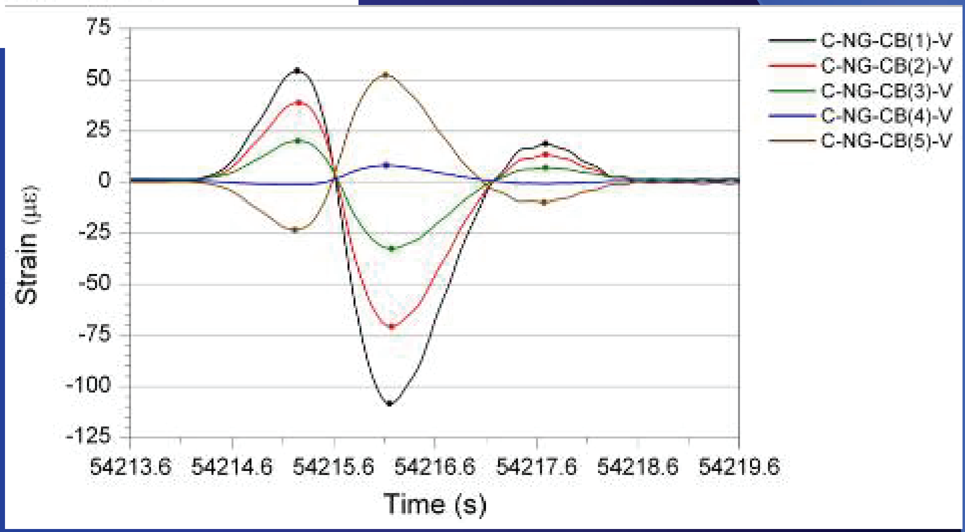
Data Reduction and Extraction





N. Cut-Back Region



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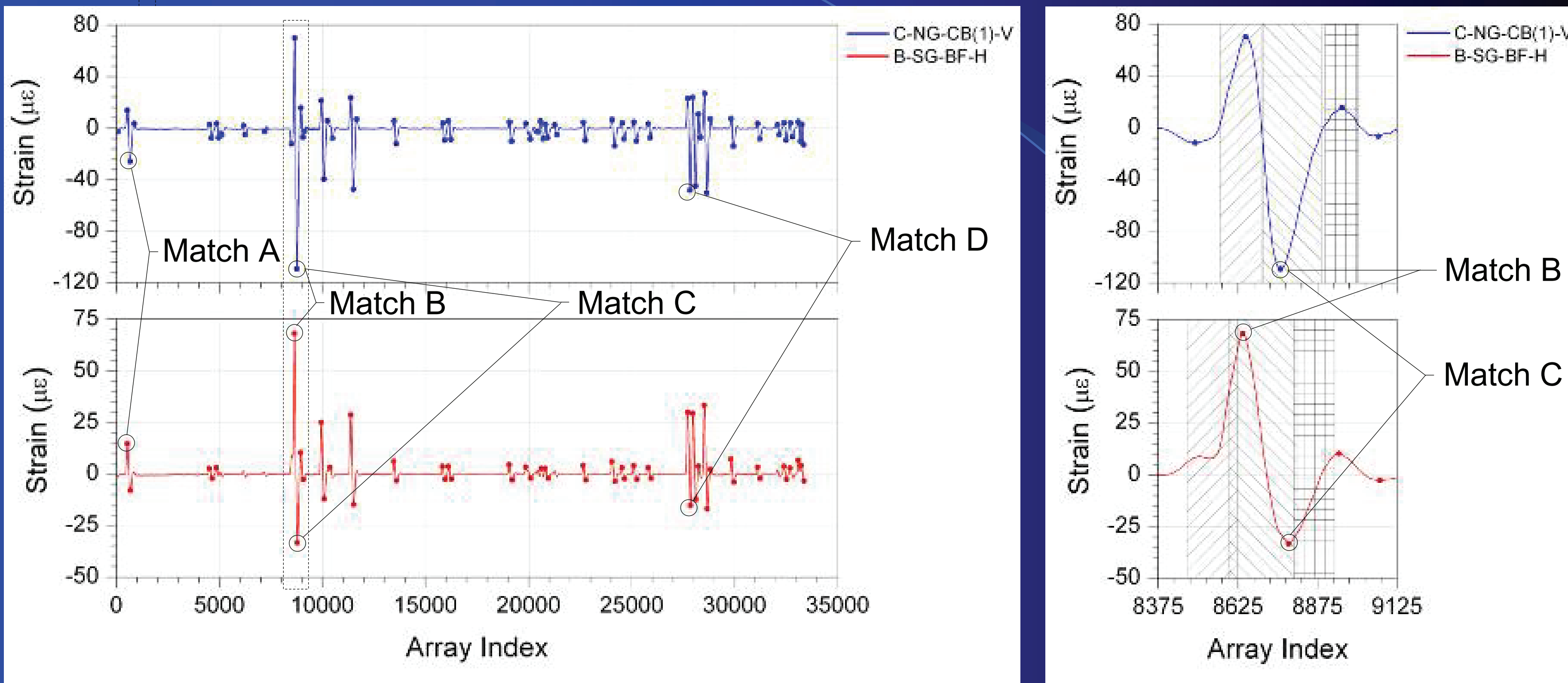
Extrema Matching Procedure



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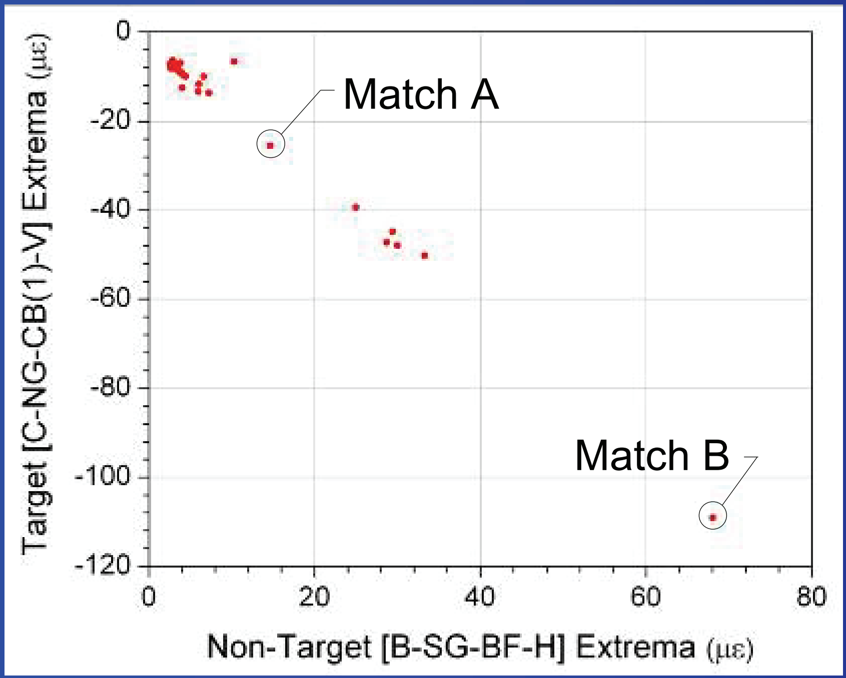
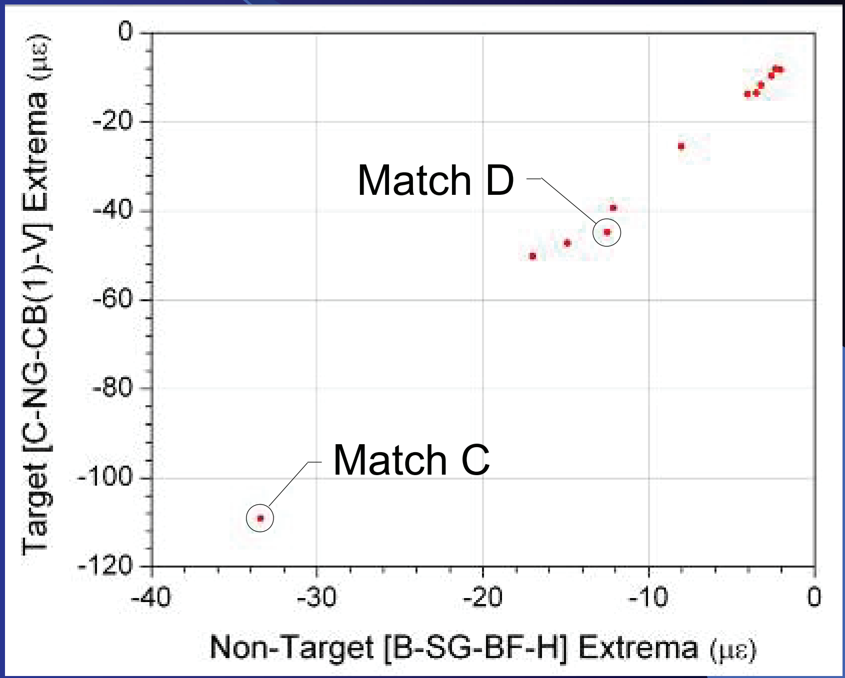
Relationship Development

MIMAR: Direct Match



MIMIR: Indirect Match



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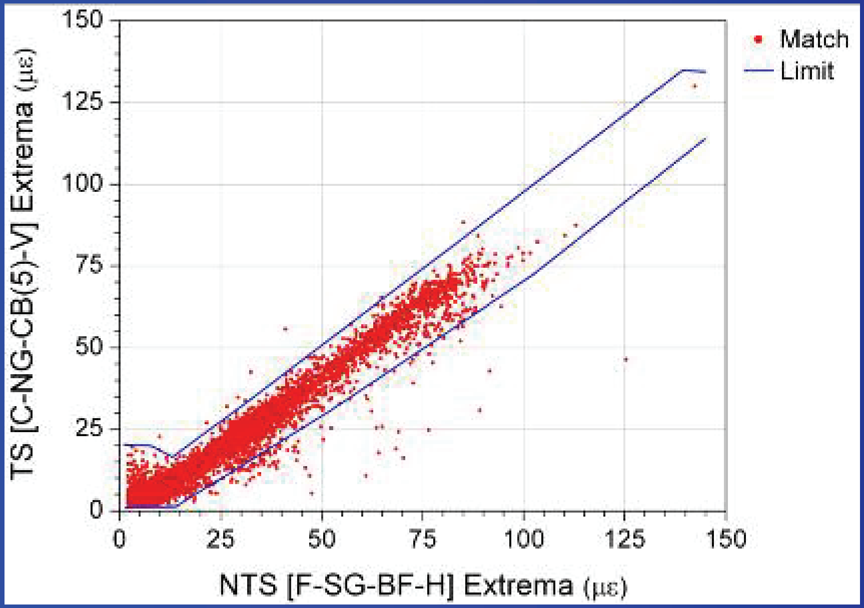
Training Relationships

MAMAR:



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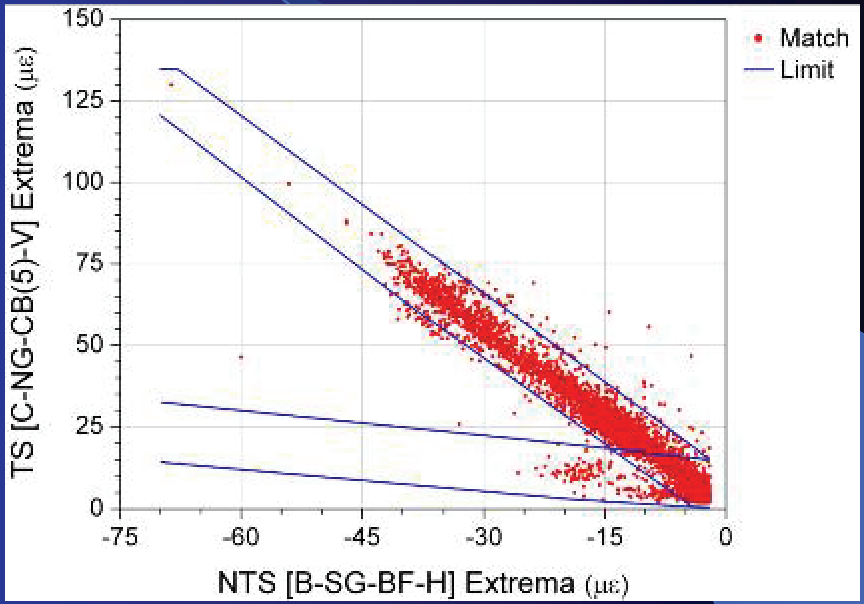

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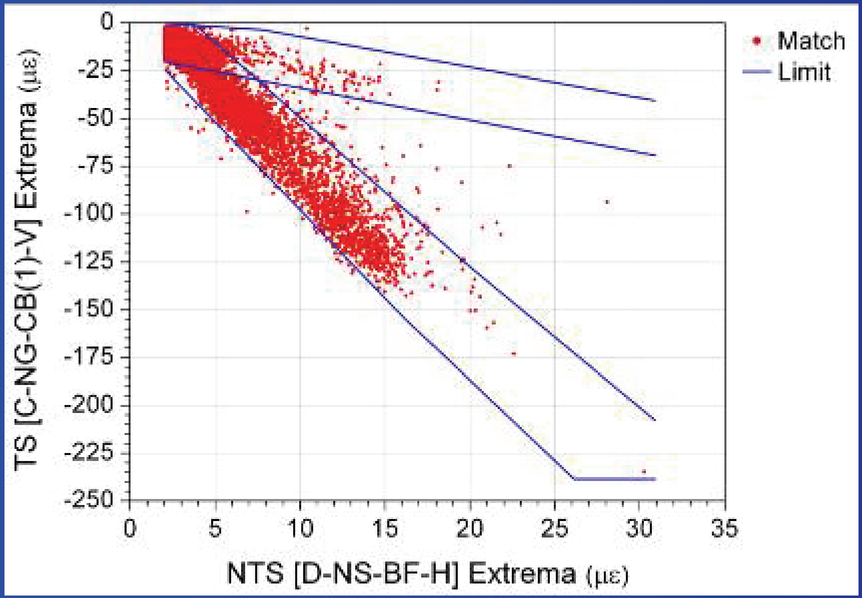
Training Relationships

MIMAR:



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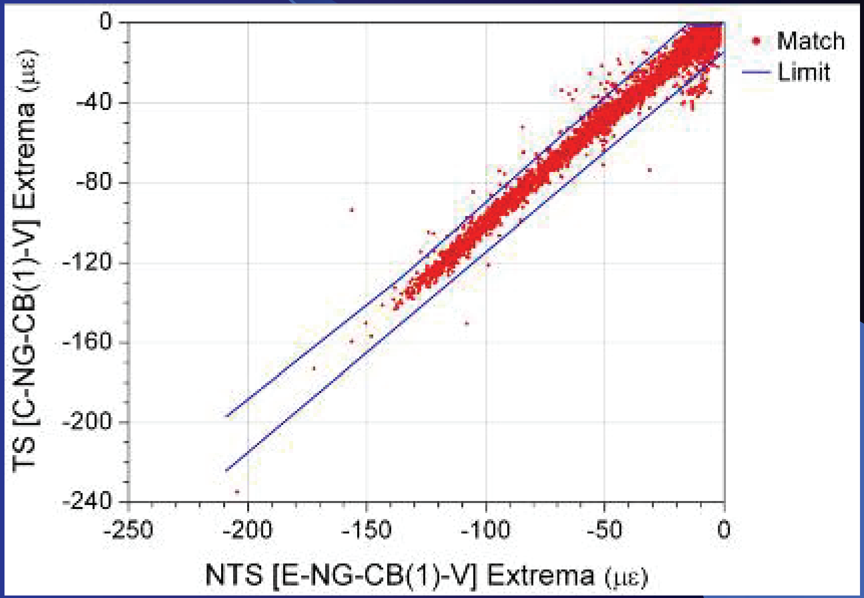

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Training Relationships

Non-Target Sensor	Target Sensor: C-SG-CB(5)-V	C-SG-CB(4)-V	C-SG-CB(3)-V	C-SG-CB(2)-V	C-SG-CB(1)-V	C-NG-CB(5)-V	C-NG-CB(4)-V	C-NG-CB(3)-V	C-NG-CB(2)-V	C-NG-CB(1)-V
B-NG-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR	MAMAR MAMIR	MAMAR	MIMAR MIMIR	MIMAR MIMIR	MIMAR MIMIR
B-NS-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
B-SS-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR	MAMAR MAMIR	MAMAR	MIMAR	MIMAR MIMIR	MIMAR MIMIR
B-SG-BF-H	MAMAR MIMAR MIMIR	MAMAR	MIMAR	MAMAR MIMAR	MAMAR MAMIR MIMAR	MAMAR MAMIR	MAMAR	MIMAR MIMIR	MIMAR MIMIR	MIMAR MIMIR
C-SG-BF-H	MAMIR MIMIR	MAMIR	MIMIR	MAMIR MIMIR	MIMIR	MAMIR MIMIR	MAMIR	MAMIR MIMIR	MIMIR	MAMIR MIMIR
C-FB(SS)-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
C-SS-WB-V	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR
A-NS-WB-V	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR
A-SS-WB-V	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR
D-SG-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MAMAR MIMAR	MAMAR MAMIR	MAMAR	MIMAR MIMIR	MIMAR MIMIR	MIMAR MIMIR
D-SS-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
D-NS-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
D-NG-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR MIMIR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR MIMIR
C-NG-BF-H	MAMIR	MAMIR	MIMIR	MIMIR	MIMAR MIMIR	MAMAR MIMIR	MAMAR	MAMIR MIMAR	MAMIR MIMAR	MAMIR MIMAR
C-FB(NS)-BF-H	MAMAR MIMAR	MAMAR	MIMAR	MIMAR	MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
C-NS-WB-V	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR
E-NG-BF-H	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR
E-NG-CB(5)-V	MAMAR MIMIR	MAMAR	MAMIR MIMAR	MAMIR MIMAR	MAMAR MAMIR MIMAR	MAMAR MAMIR	MAMAR	MAMAR MAMIR MIMAR MIMIR	MAMAR MAMIR MIMAR MIMIR	MAMAR MAMIR MIMAR MIMIR
E-NG-CB(1)-V	MAMAR MAMIR MIMAR	MAMIR	MAMAR MIMIR	MAMAR MIMIR	MAMAR MAMIR MIMAR MIMIR	MAMAR MAMIR	MAMIR	MAMIR MIMAR MIMIR	MAMAR MAMIR MIMAR MIMIR	MAMAR MAMIR MIMAR MIMIR
E-NS-WB-V	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR
E-FB(NS)-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
E-FB(SS)-BF-H	MAMAR MIMAR	MAMAR	MIMAR	MIMAR	MAMAR MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
E-SS-WB-V	MAMIR	MAMIR	MIMIR	MIMIR	MAMIR MIMIR	MAMIR	MAMIR	MIMIR	MIMIR	MIMIR
E-SG-CB(5)-V	MAMAR	MAMAR	MAMAR MIMAR	MAMAR MIMAR	MAMAR MIMAR	MAMAR MAMIR MIMAR MIMIR	MAMAR	MAMAR MAMIR MIMAR MIMIR	MAMAR MAMIR MIMAR MIMIR	MAMAR MAMIR MIMAR MIMIR
E-SG-CB(1)-V	MAMIR MIMIR	MAMIR	MAMIR MIMIR	MAMIR MIMIR	MAMIR MIMIR	MAMAR MAMIR MIMAR MIMIR	MAMIR	MAMAR MAMIR MIMAR MIMIR	MAMAR MAMIR MIMAR MIMIR	MAMAR MAMIR MIMAR MIMIR
E-SG-BF-H	MIMIR	MAMIR	MAMIR	MAMIR MIMIR	MAMIR	MAMIR	MAMIR	MIMIR	MAMAR MIMIR	MAMAR MIMAR MIMIR
F-SG-BF-H	MAMAR MAMIR MIMAR	MAMAR	MIMAR MIMIR	MAMAR MIMAR MIMIR	MIMAR MIMIR	MAMAR MIMIR	MAMAR	MAMIR MIMAR	MAMIR MIMAR	MAMIR MIMAR
F-SS-BF-H	MAMAR	MAMAR	MIMAR	MAMAR MIMAR	MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
F-NS-BF-H	MAMAR	MAMAR	MIMAR	MAMAR MIMAR	MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
F-NG-BF-H	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR	MAMAR	MAMAR	MIMAR	MIMAR	MIMAR
Totals by Type (MAMAR / MAMIR / MIMAR / MIMIR)	19 / 12 / 5 / 5	18 / 12 / - / -	2 / 3 / 18 / 12	6 / 4 / 18 / 13	6 / 6 / 20 / 13	21 / 17 / 2 / 5	19 / 11 / - / -	3 / 7 / 21 / 16	5 / 6 / 21 / 17	5 / 7 / 22 / 18
Overall Totals	41	30	35	41	45	45	30	47	49	52

Note: MAMAR, MAMIR, MIMAR, MIMIR

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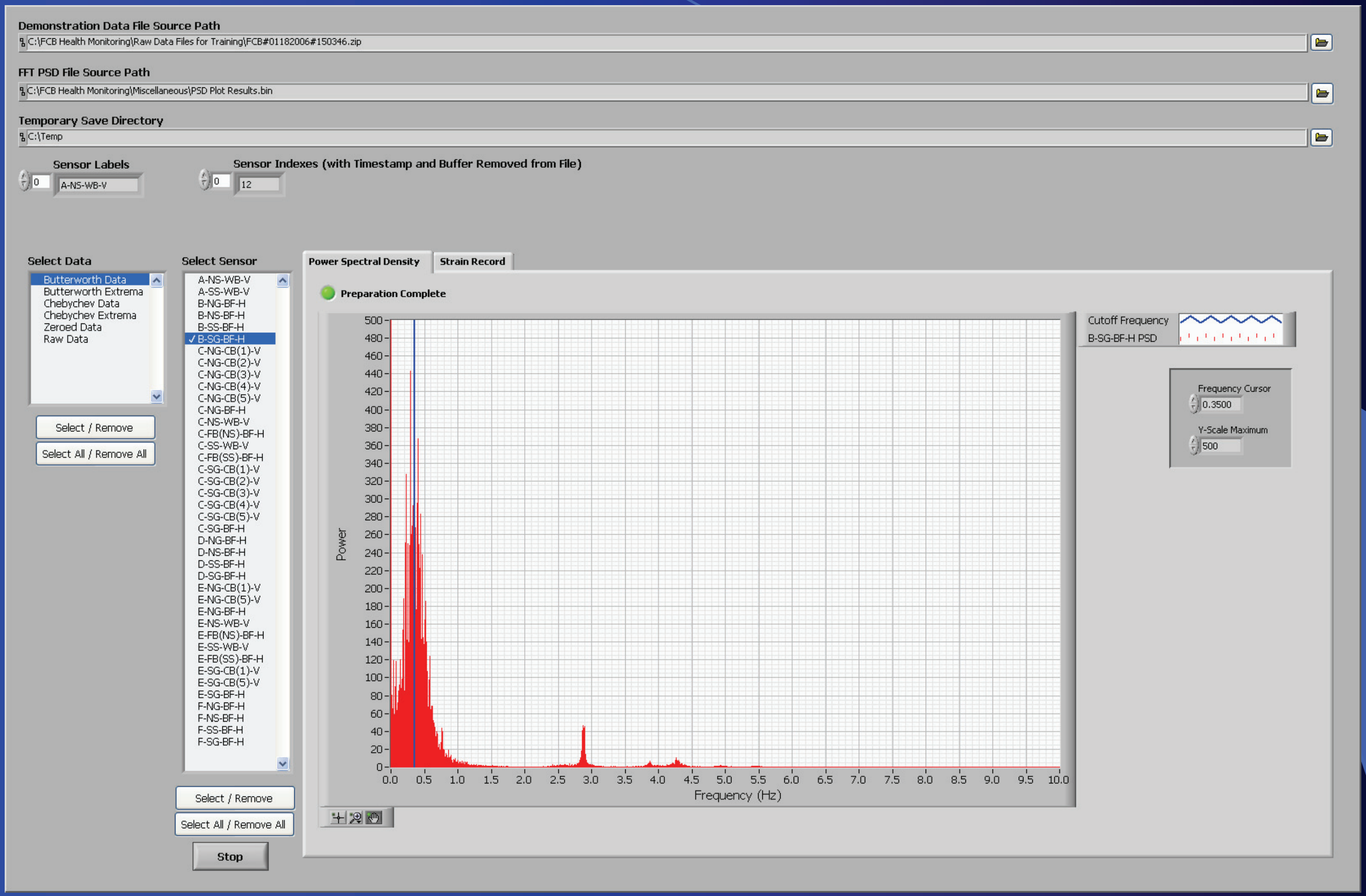
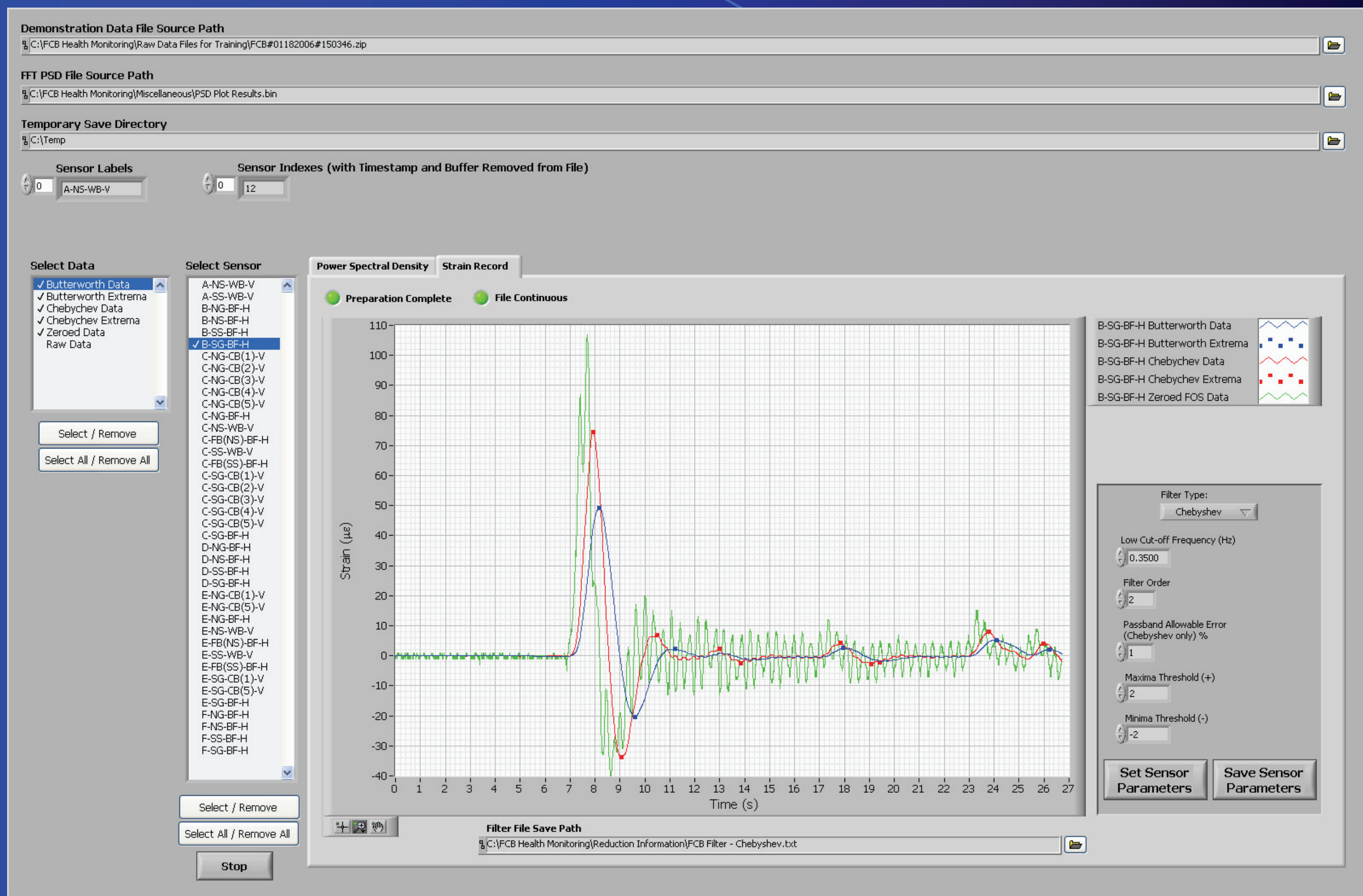
Training Software



Training Software



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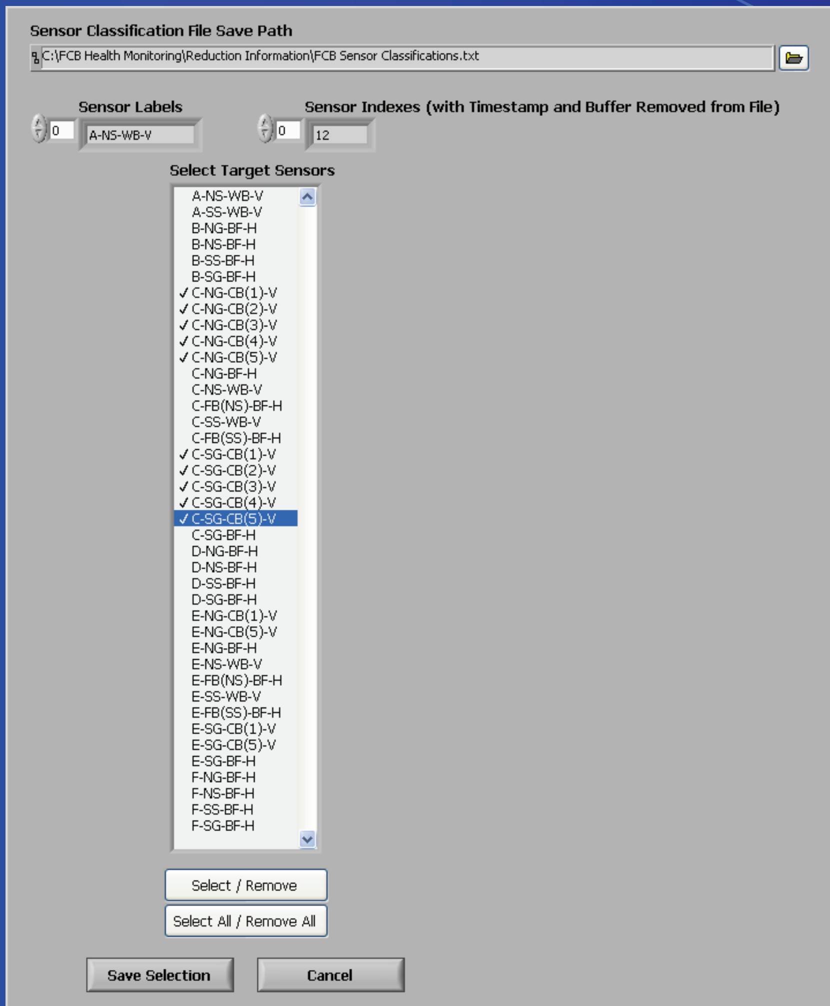
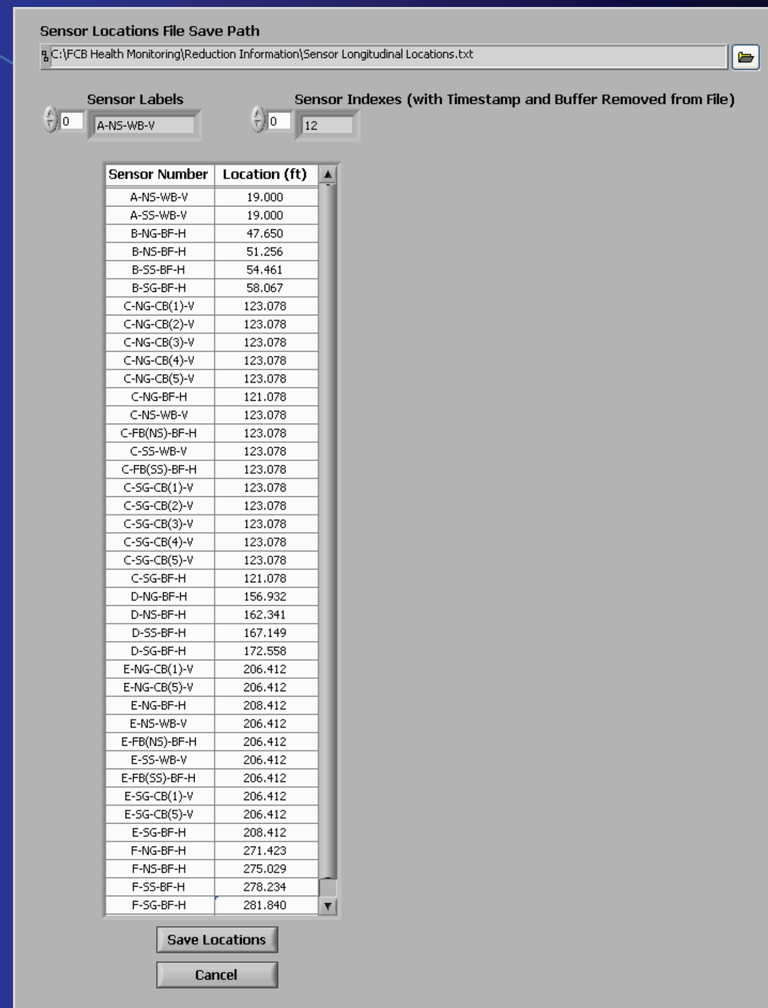
Training Software





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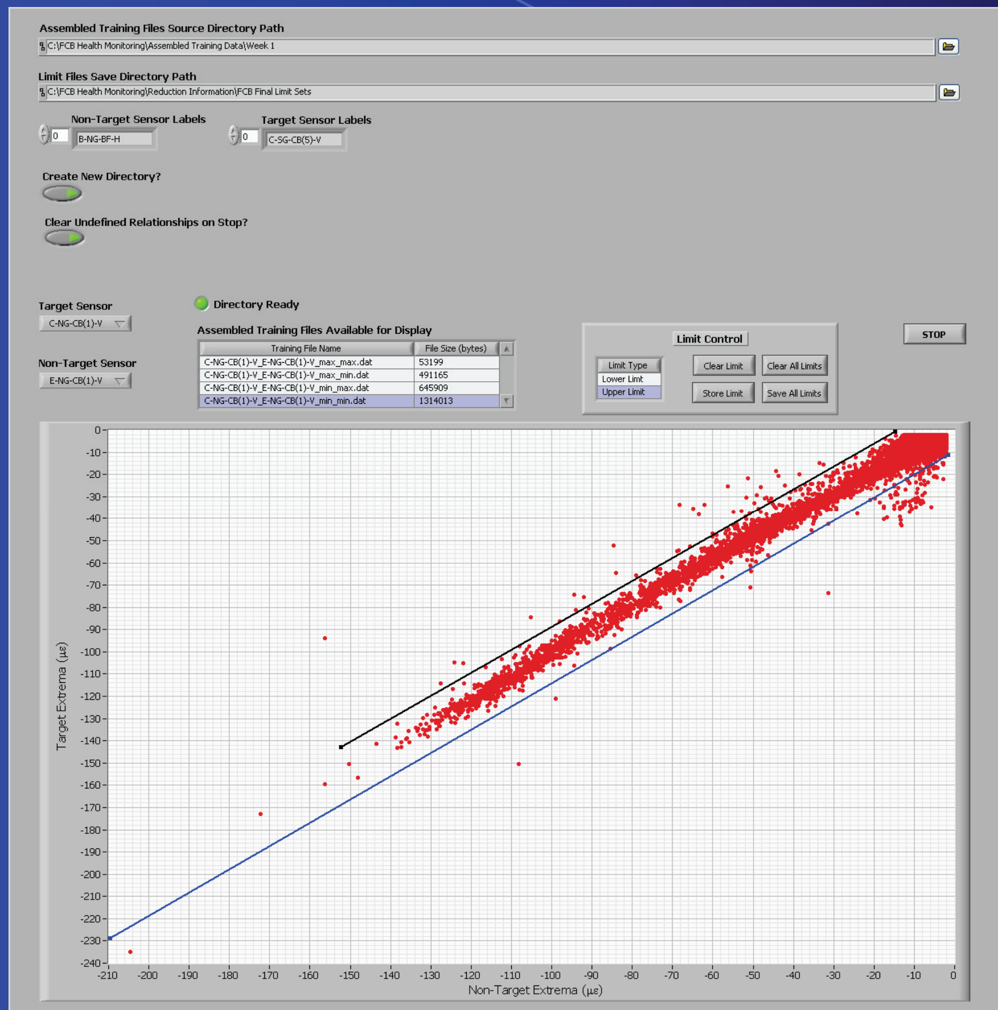
Training Software



SHM System Procedures

- Six phases in monitoring process:
  - Data collection
  - Preliminary reduction
  - Primary reduction
  - Extrema matching
  - Extrema evaluation
  - Report generation

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SHM System Procedures

- Preliminary reduction
  - Data file is checked for sensor count and continuity; baselines are established
- Primary reduction
  - Data are zeroed and filtered; extrema information is extracted
    - Filter = digital lowpass Chebyshev infinite impulse response (IIR)
- Extrema matching

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SHM System Procedures

- Evaluation
  - Each TS extrema is evaluated using matched NTS extrema
    - All applicable relationships are assessed
    - Result from each relationship assessment is “Pass” or “Fail”
    - Relationship Pass Percentages (RPPs) are computed for each applicable relationship:

$$\text{RPP (\%)} = \frac{\text{Number of "pass" assessments}}{\text{Total number of assessments}}(100)$$

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SHM System Procedures

- Report generation
  - For a specified time period, the pass percentage rates are displayed in a histogram (5% bin widths)
  - Two graphs are generated for TS
    - Evaluations (Count) vs. Relationship Pass Percentage (%)
    - Evaluations (%) vs. Relationship Pass Percentage (%)

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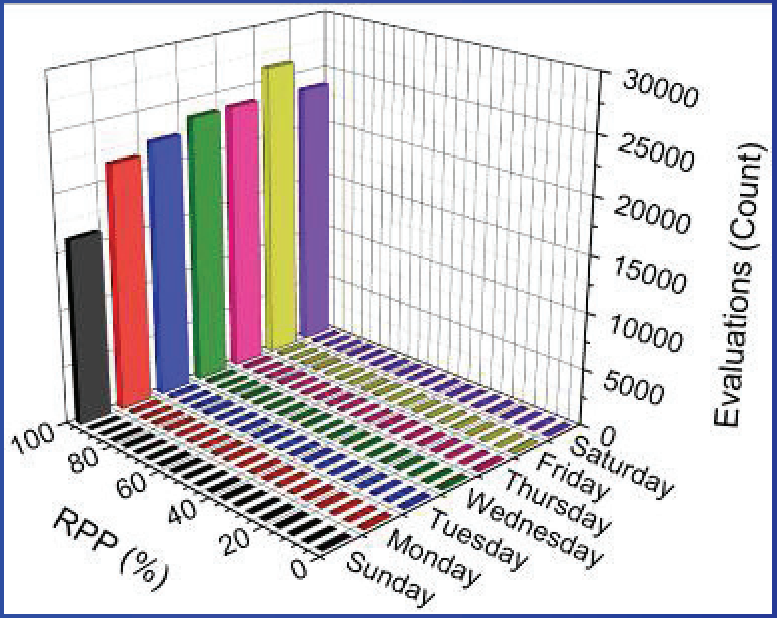
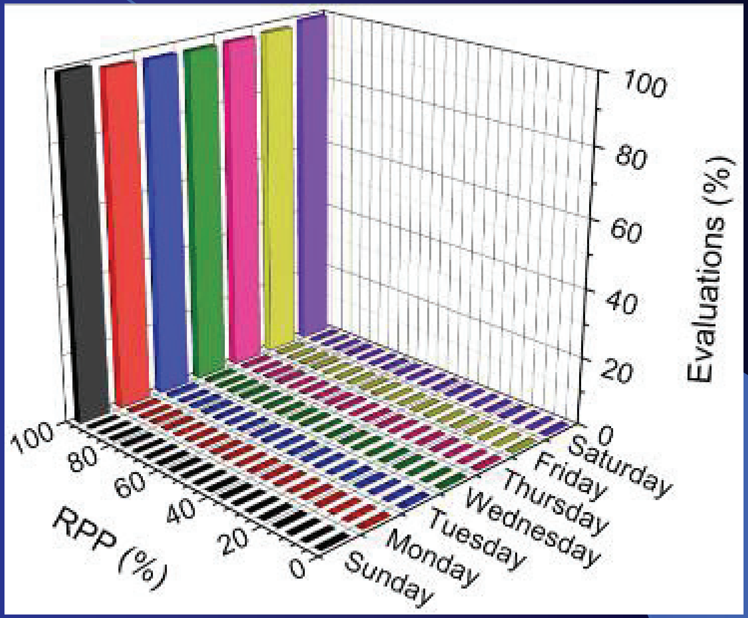
Evaluation Reports





Daily Evaluation Reports for C-SG-CB(1)-V

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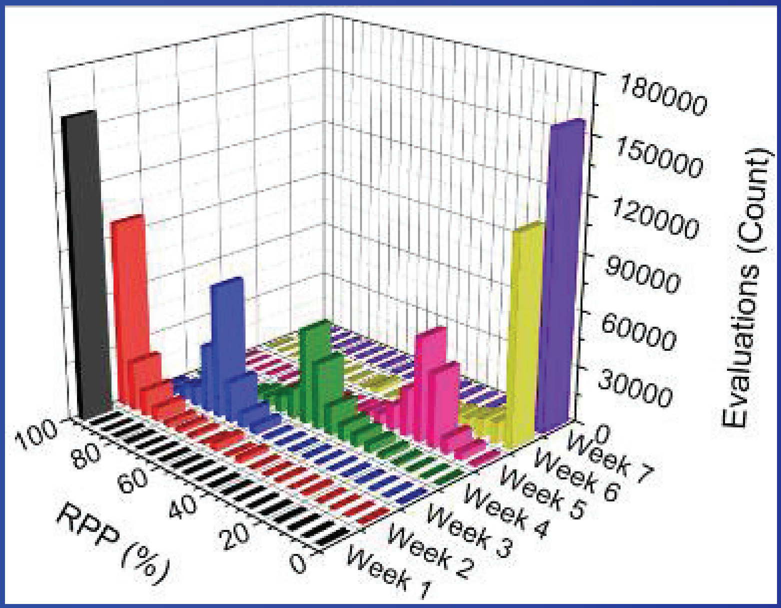
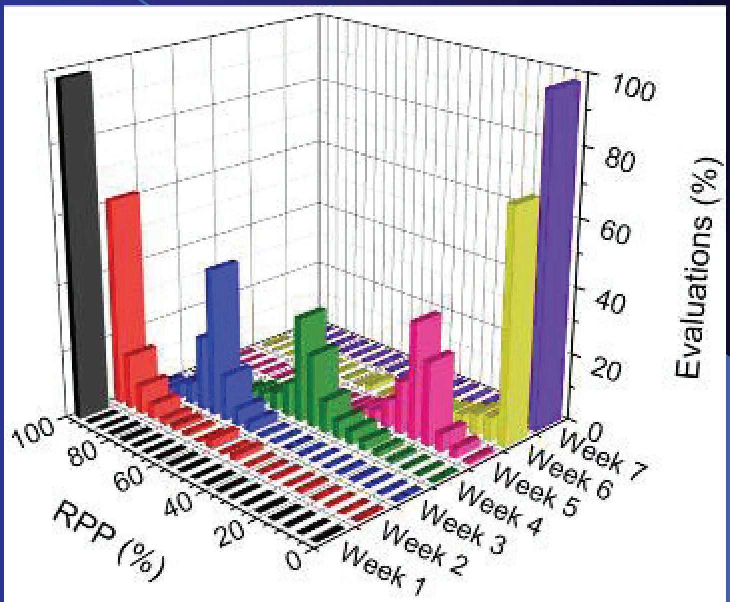
Evaluation Reports





Gradual damage: distribution changes

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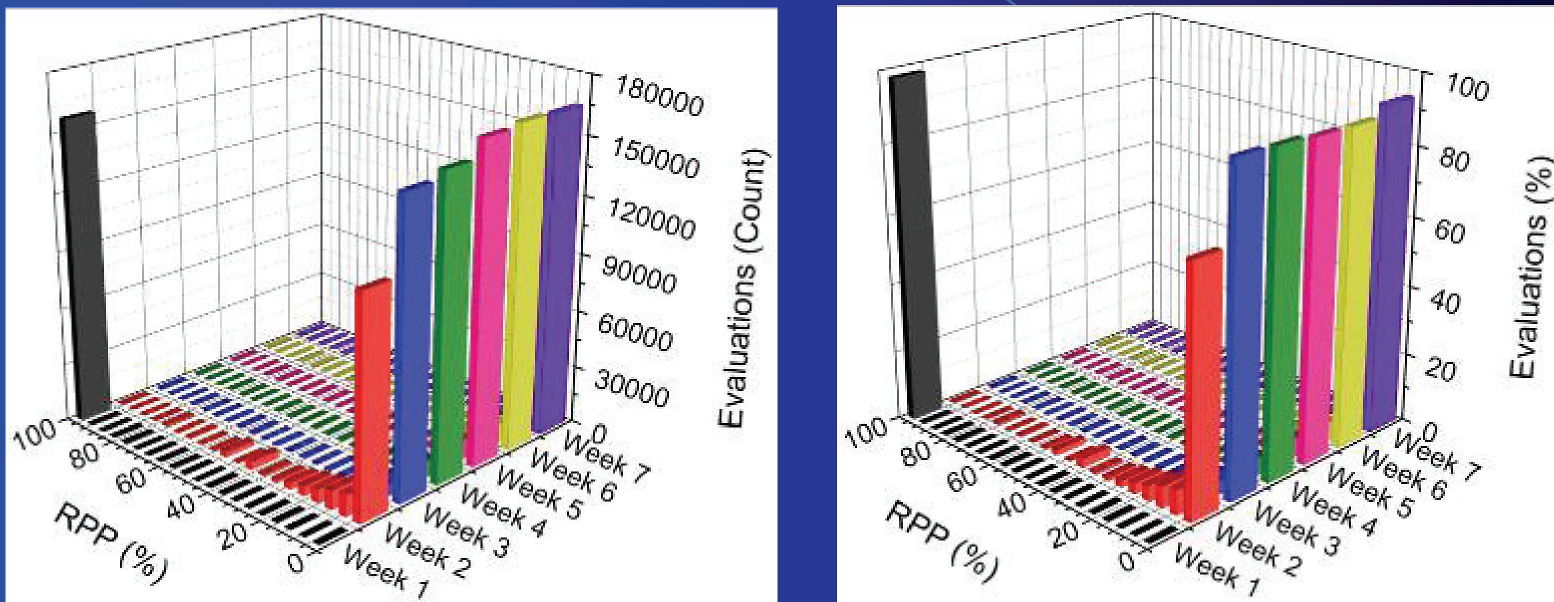
Evaluation Reports



Sudden damage: distribution changes

SHM System Performance

- Data saved in 1 MB files (27 s/sensor)
- Phases 2 – 5 average 1.7 seconds (total)
  - Evaluated extrema average 0.13% of raw data that is collected
- Phase 6 averages 8.7 seconds (daily)
- 3.4 GB continuous data per day
  - Save only matched extrema, save 95% storage space

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Summary and Conclusions

- SHM system allows bridge owners to monitor bridge behavior for signs of damage
  - Success depends on ability to identify and install sensors in damage-prone areas
- System is trained with measured performance data, and thus, monitors preexisting condition of a structure
  - Unsupervised learning

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Summary and Conclusions

- System ability to identify and evaluate repeatable bridge behavior has been proven
  - Damage detection ability not proven
- Evaluations are based on extracted information from each data file
  - Rapid evaluations
  - Saved storage space

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Summary and Conclusions

- Evaluation reports summarize continuous monitoring results into a familiar, graphical format for bridge owner/manager interpretation
- Project addressed criticisms of SHM

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b) Low-Cost, Continuous Structural Health Monitoring System for Secondary Road Bridges

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Objective

- Develop a low-cost structural health monitoring (SHM) system
  - Continuously monitor typical girder bridge
  - Detect overload vehicles/vehicle collision
  - Identify changes in structural behavior
- System specifications
  - Autonomous data collection/processing
  - Alarm/warning capability
  - Reports summarizing evaluation

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SHM System

- Hardware components
  - Sensors
  - Data acquisition/processing
  - Communication system
- Live load structural analysis software
  - Bridge specific system configuration
- Field monitoring software
  - Data collection/processing/reporting

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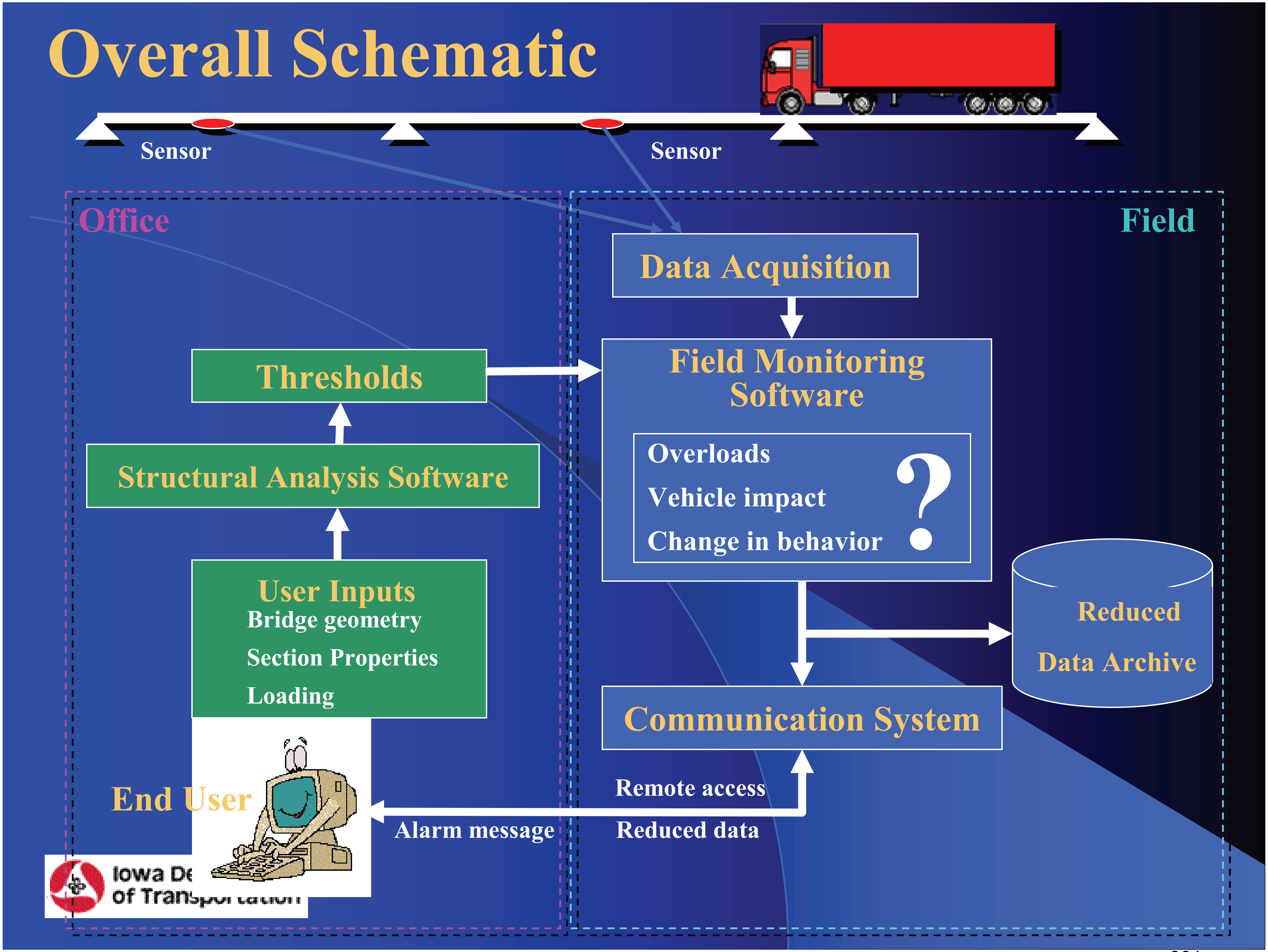
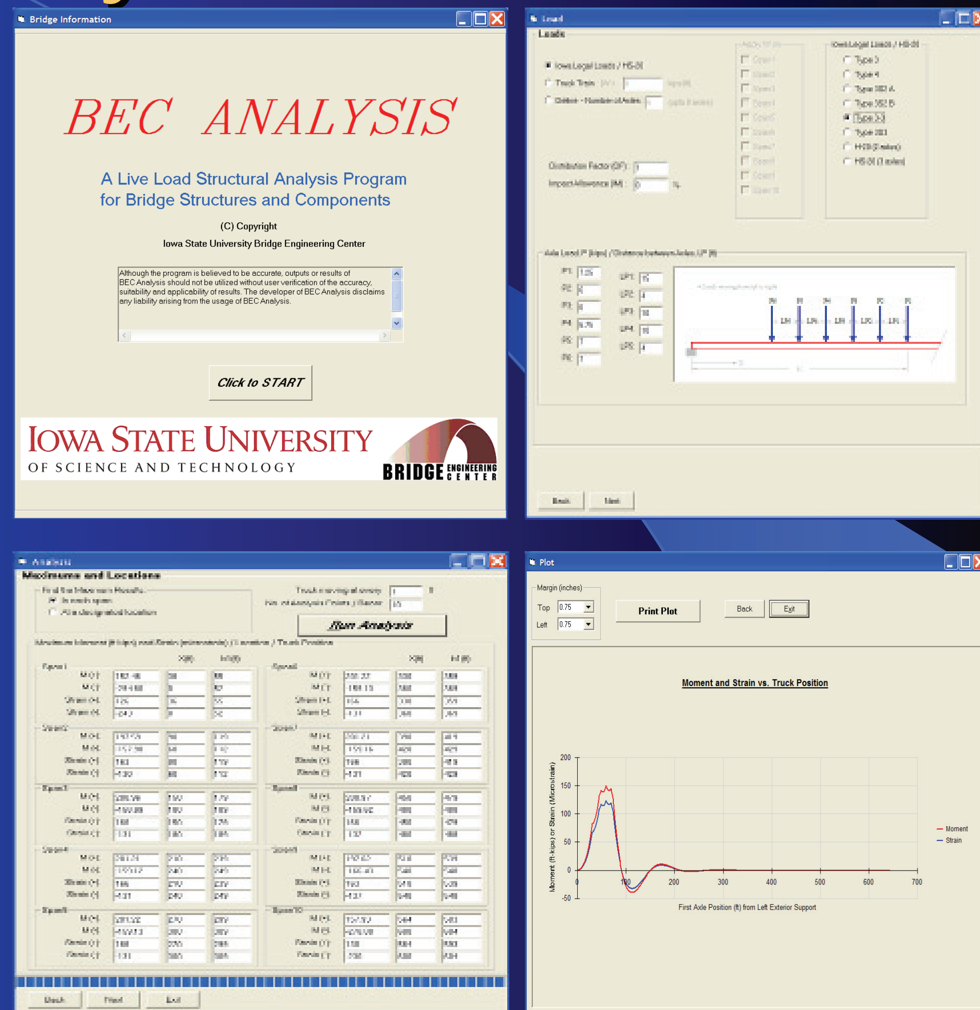


Overall Schematic
Sensor
Sensor
Office
Field
Data Acquisition
Thresholds
Field Monitoring Software
Overloads
Vehicle impact
Change in behavior
?
Structural Analysis Software
User Inputs
Bridge geometry
Section Properties
Loading
Reduced Data Archive
Communication System
End User
Remote access
Reduced data
Alarm message

Structural Analysis Software

- Windows-based, live load structural analysis program
- User friendly
- Easy to operate
- Maximum live load moment & strain
- Envelopes
- Moment & Strain
  vs. Truck position
- Numerical results
- Graphic display



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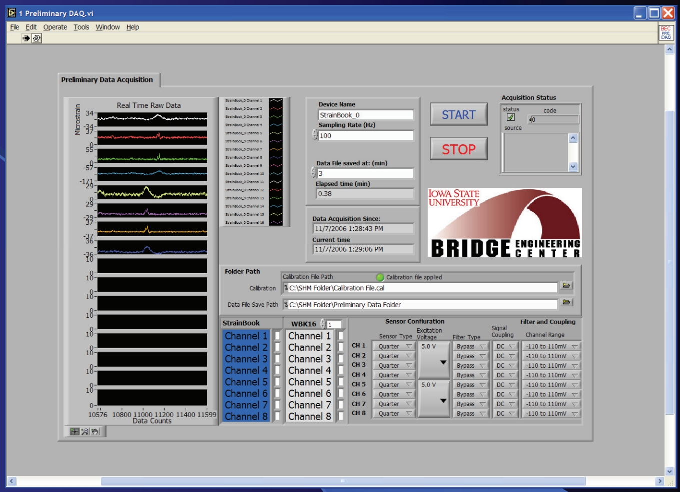
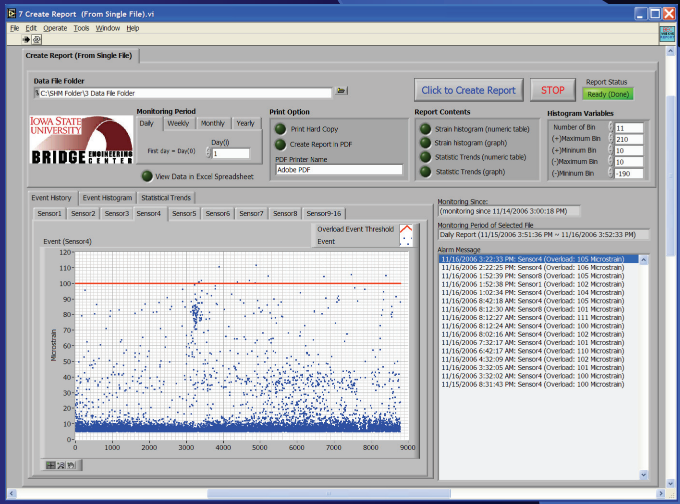
Field Monitoring Software

- Autonomously collect, process and evaluate measured bridge response
- Temperature compensation
- Noise minimization
- Data Reduction
  - Less than 1% saved
- Alarm/warning capability
  - Overload
  - Vehicle impact/collision
- Report contents
  - Event history
  - Event histogram
  - Statistical trend





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Demonstration Bridge Information

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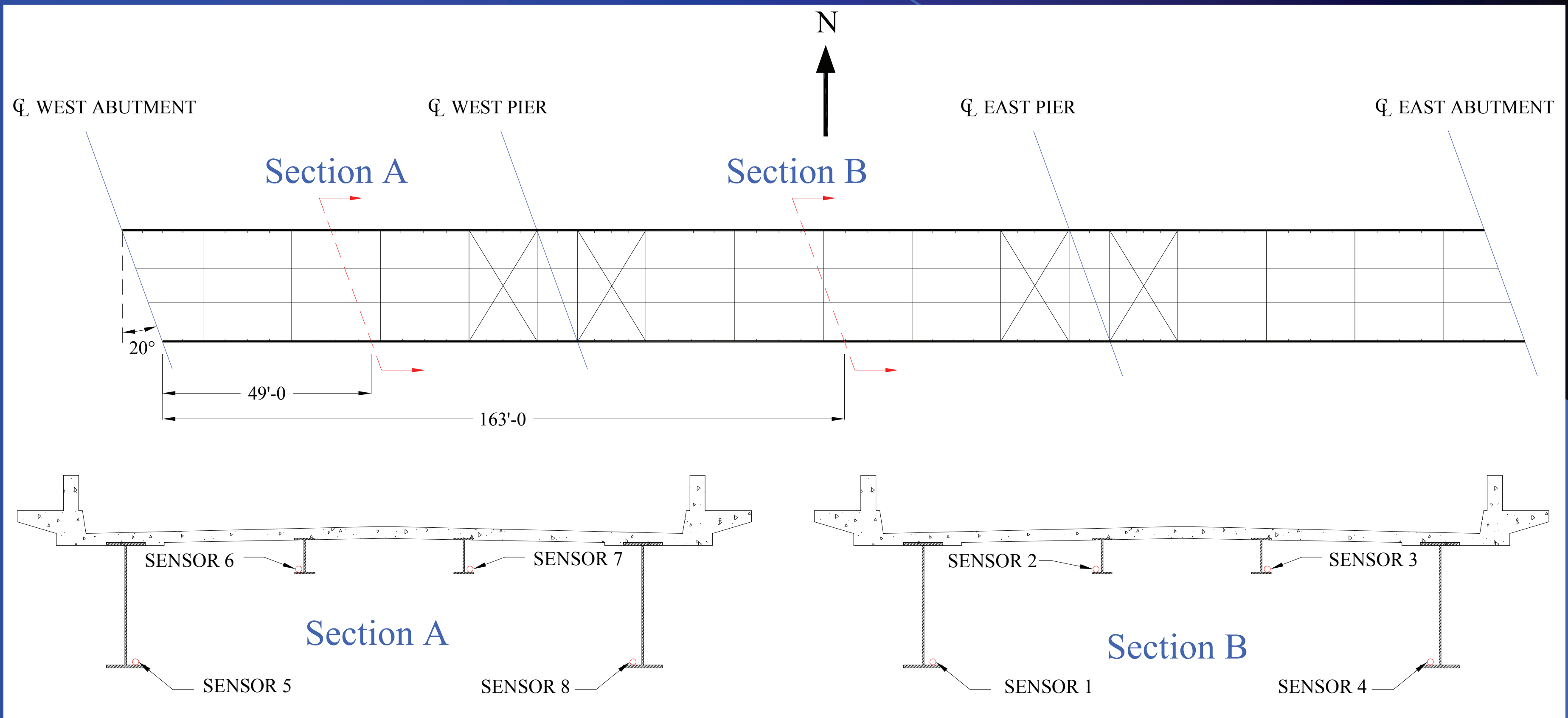
Sensor Location



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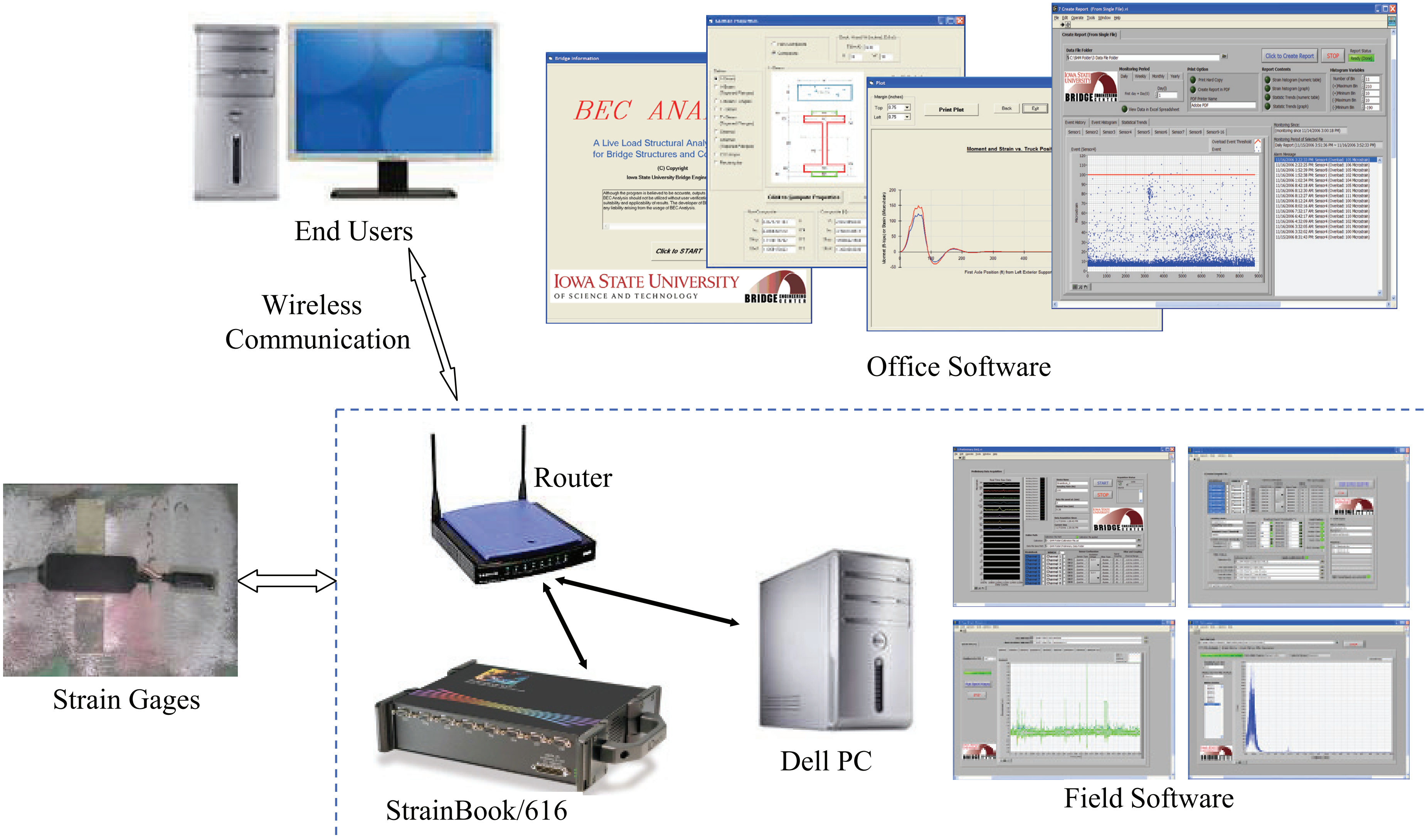
SHM Configuration



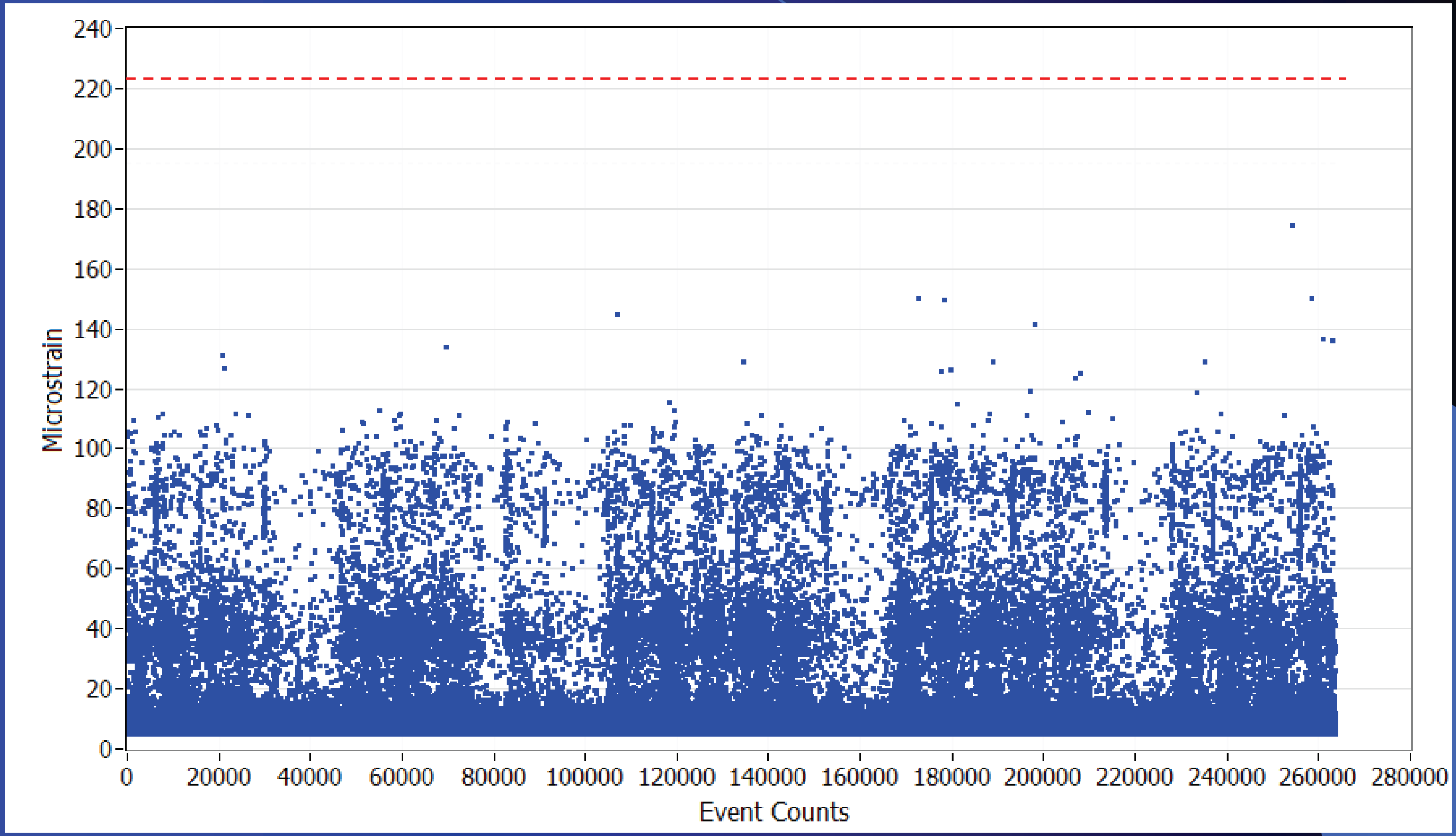
Field Cabinet at US30 Bridge

Evaluation Reports

- Event History (30 days)

Threshold

Identified Events



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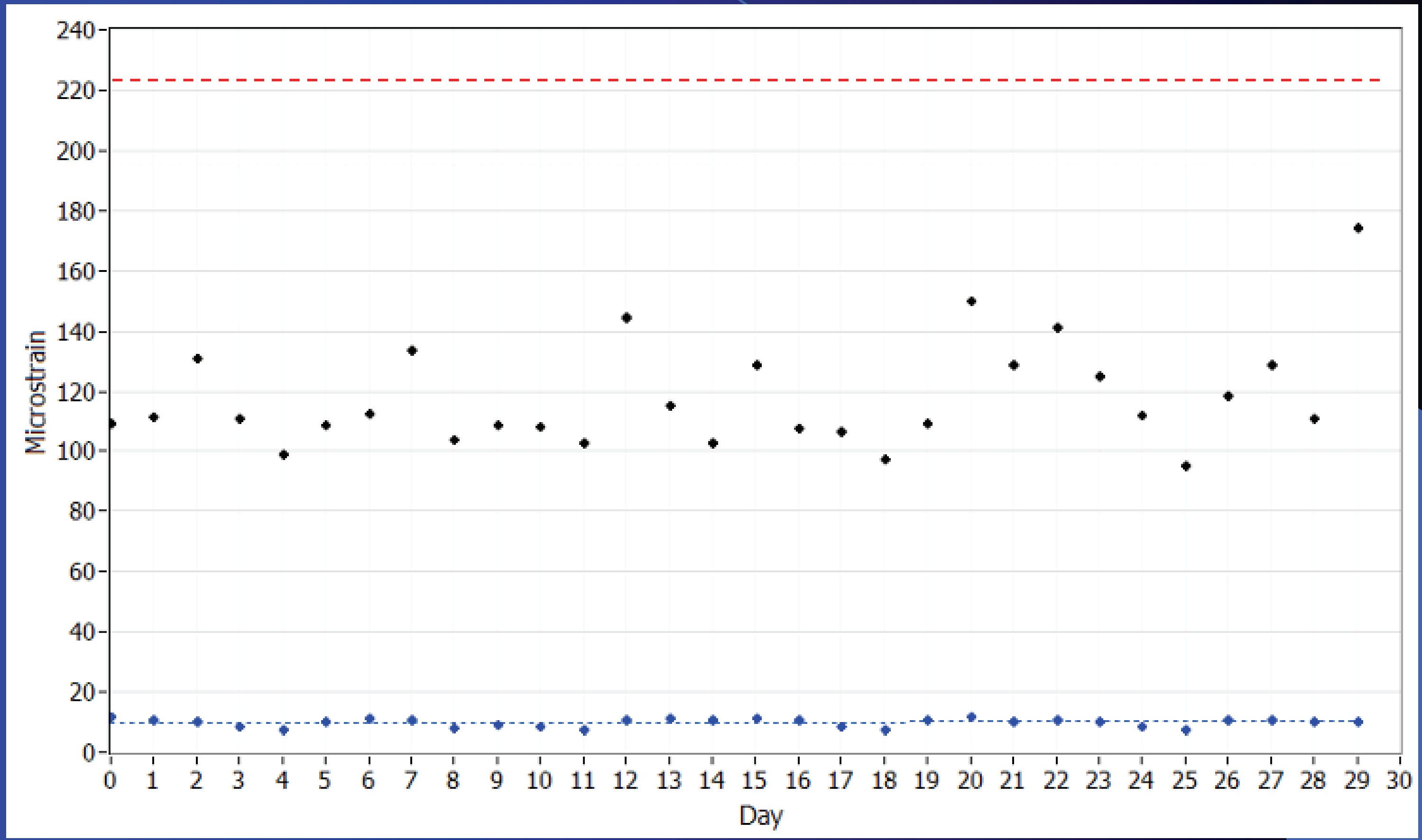
Evaluation Reports

- Statistical Trend (30 days)

Threshold

Daily Max

Daily Average/ Trend Line



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Concluding Remarks

- SHM system allows bridge owners to remotely monitor bridges for
  - Overload/vehicle impact/change in behavior
- Evaluations are based on extracted information: timely generated, reduced data files
- Evaluation reports summarize continuous monitoring results into a format that is clear and easy to interpret
- Suitable for typical girder bridges
- Low-cost
  - Can be implemented for approximately $8,000-$15,000
- The use of the SHM system can help to better manage bridge assets.

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SPECIAL INVESTIGATIONS

- Monitoring of the Iowa River Bridge Launching
- Monitoring of I-235 Pedestrian Bridges
- Deck Overhang Sufficiency for Barrier Rails

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Chapter 11

Monitoring of the Iowa River Bridge Launch

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Monitoring of the Iowa River Bridge Launch

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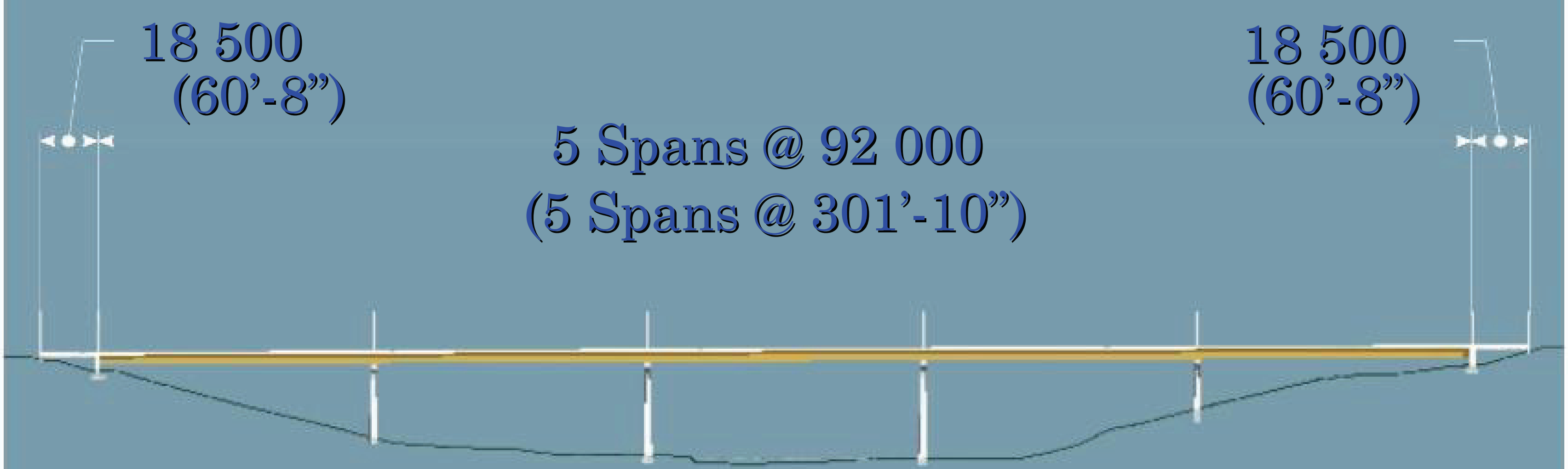
Bridge Details



Longitudinal Section

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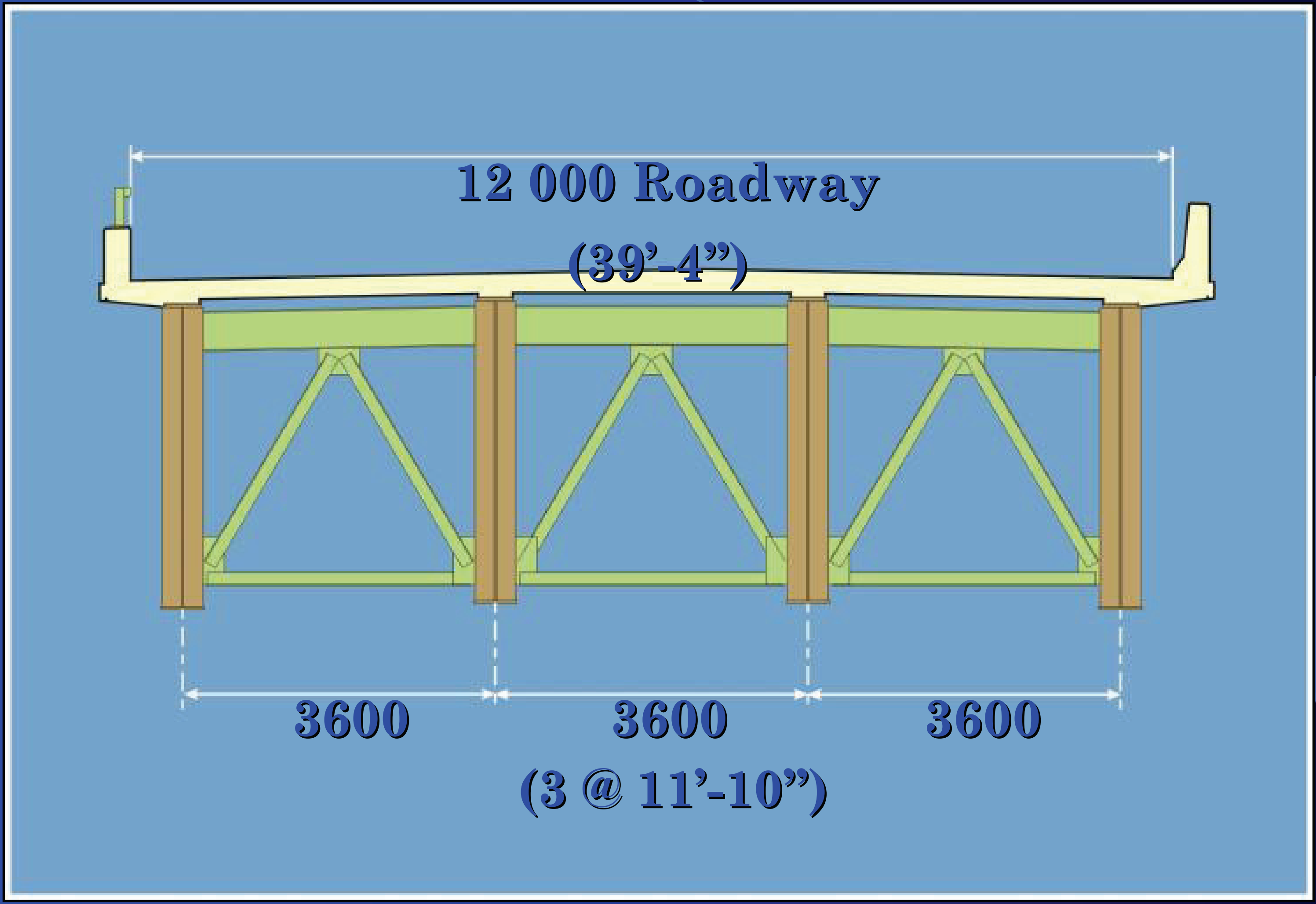
Bridge Details (One Superstructure)



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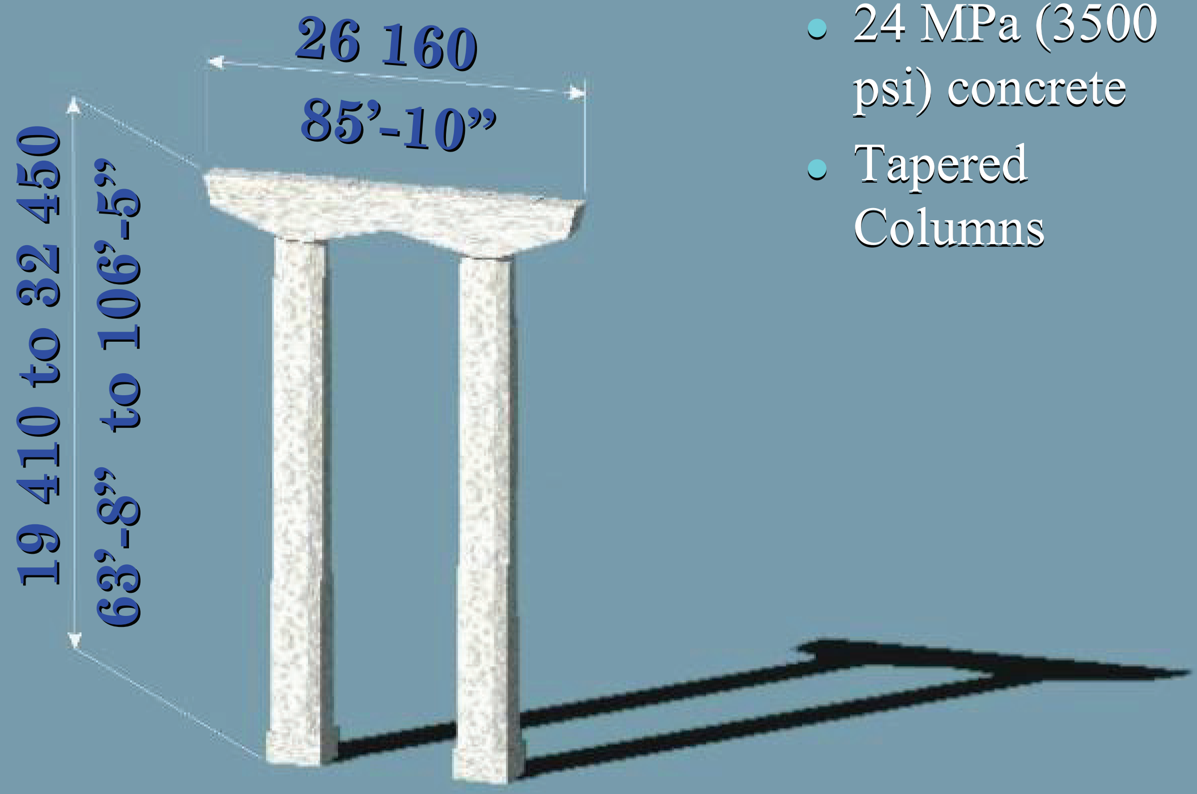
Bridge Details (Piers)



- 24 MPa (3500 psi) concrete
- Tapered Columns

Typical Pier

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Launching Pit Excavated at East Abutment

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Girders Assembled in Launching Pit

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Ramp Plates Aid Transition at Field Splices

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Misalignment of Girders During Launch EB1

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Rotation of Bottom Flange – Launch EB1

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Jacking System Used for Launching

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Jacking System Used for Launching

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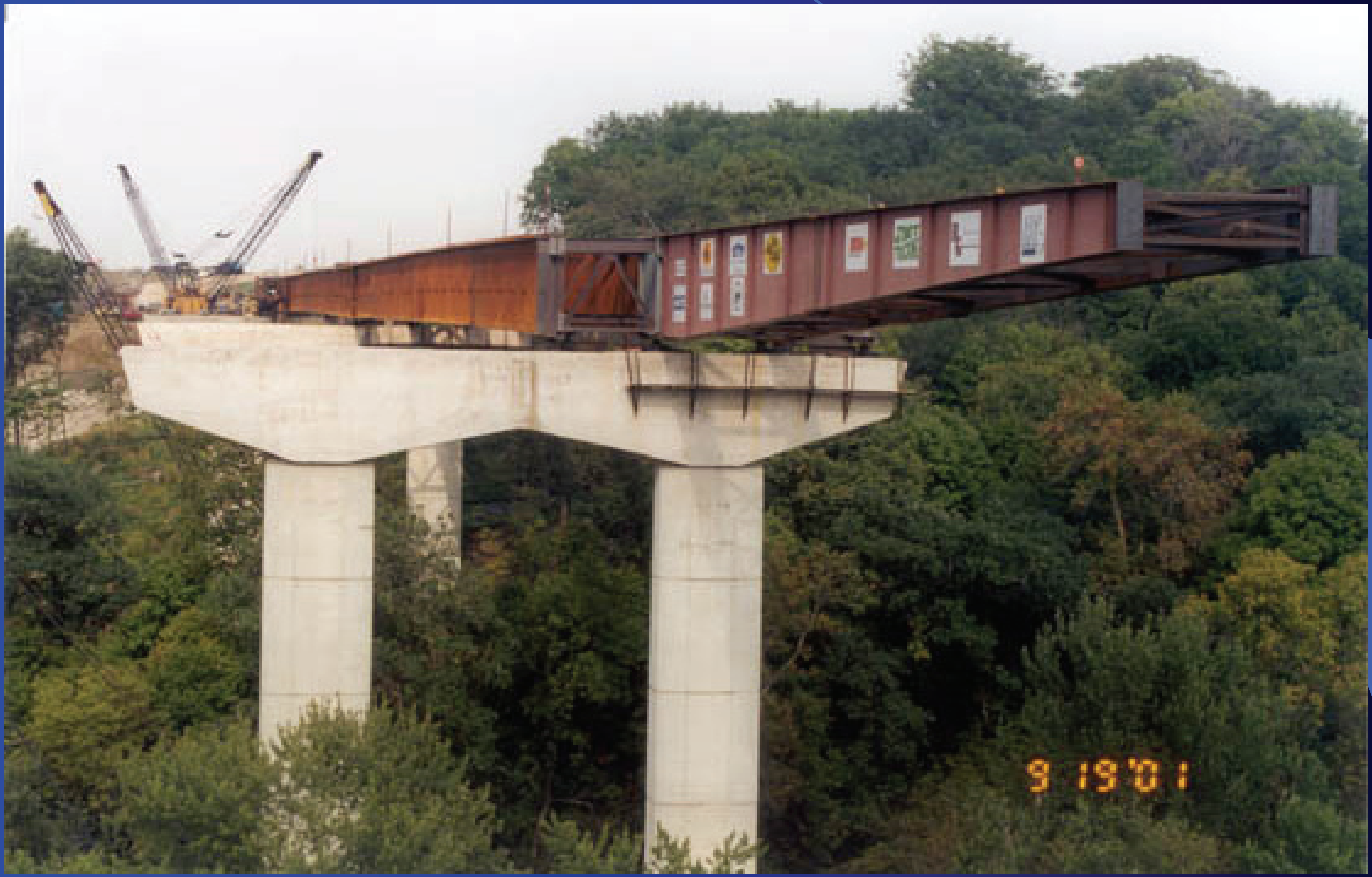
Launching Nose Accommodates Deflection



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Deflection of WB Span 1 During Launch

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Monitoring Program

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Goals of Monitoring Program

- **Gain a more complete understanding of the behavior of launched plate girder bridges**

- **Quantify structural performance and verify assumptions made during design**

- **Identify locations of overstress or other damage**
  - **Immediate repair**
  - **Long-term maintenance concerns**

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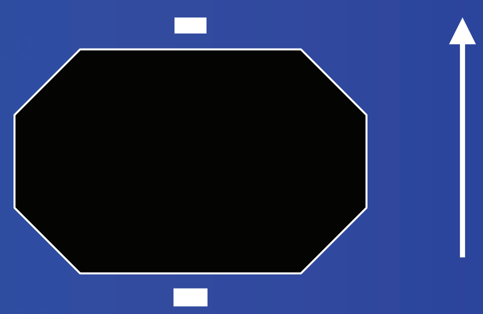
Substructure Monitoring

- General pier behavior
- (drilled shaft and driven pile)
  - Column base strain
  - Column base translation & tilt
  - Cap beam tilt

Near and far column faces



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Substructure Monitoring

Magnitude of launching forces:

- At hydraulic jacks
- At pier cap rollers

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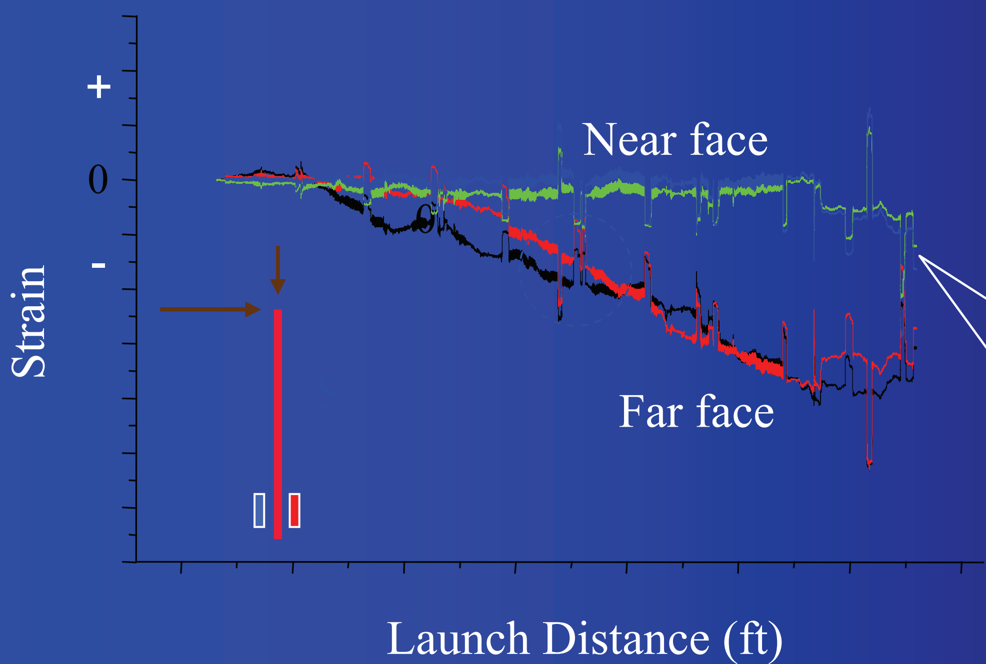
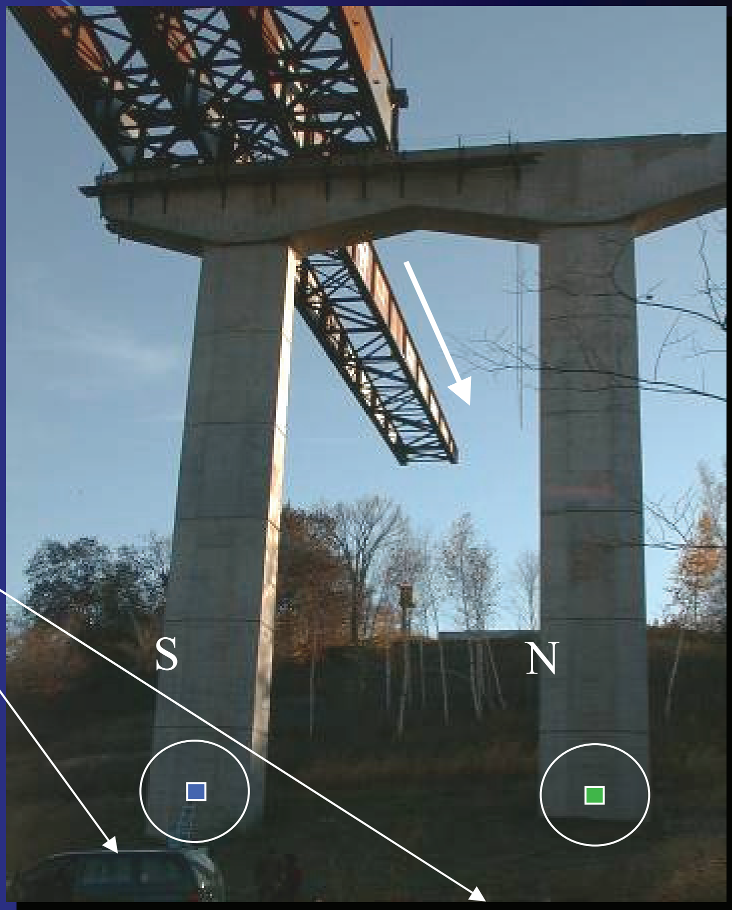
Substructure Monitoring - Results

- Largest one-day cumulative column stress measured was 600 psi
- Residual stress at end of launch day





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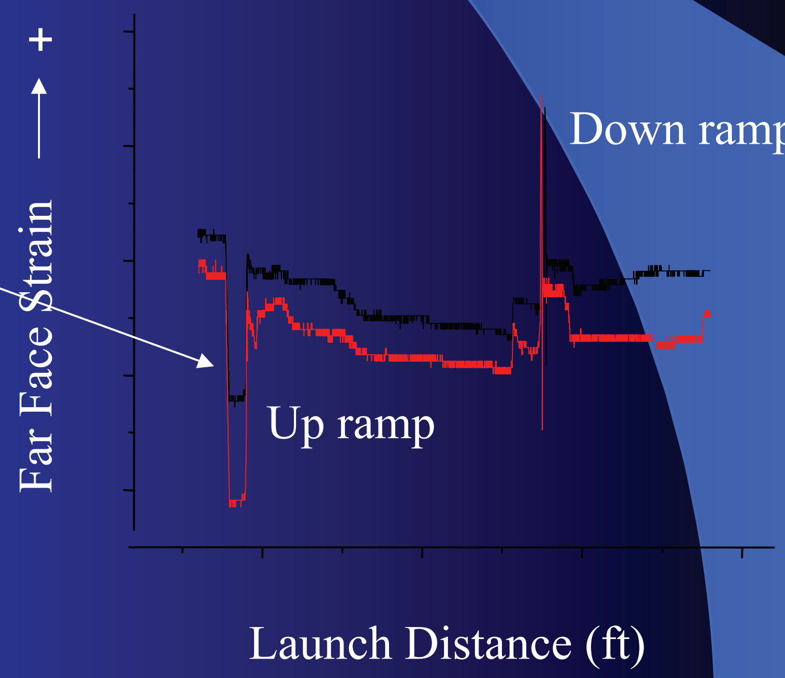
Substructure Monitoring - Results

- Max. measured column stresses of approx. 260 psi due to applied launch force “spikes”; similar to calculated values
- Pier design controlled by AASHTO loads
- (design checks considered ramp crossing loads)



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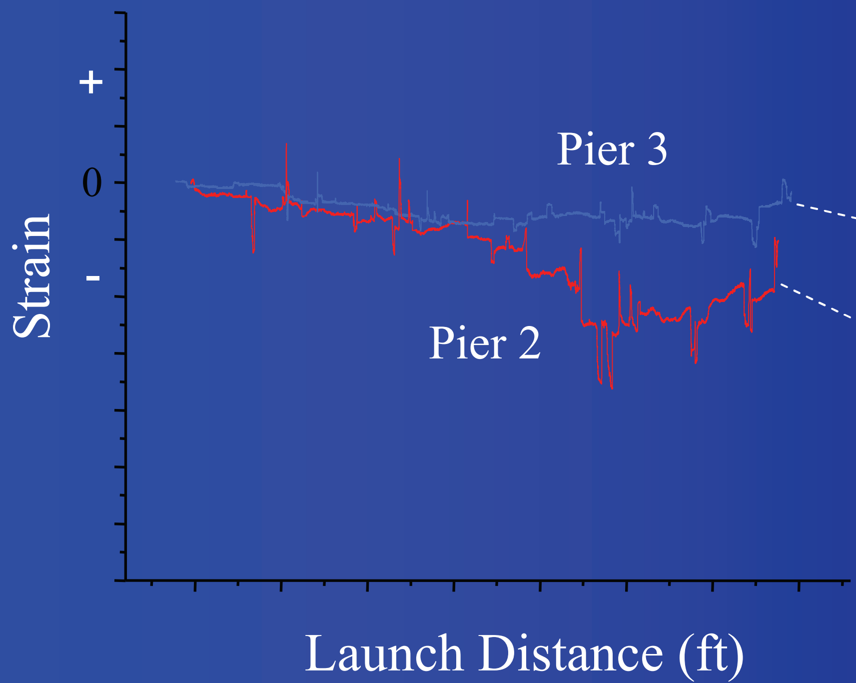
Substructure Monitoring – Results

- Drilled shaft foundation more "flexible" than pile group foundation in resisting launch forces

WB Roadway – North Column:



Pile Group Foundation

Drilled Shaft Foundation

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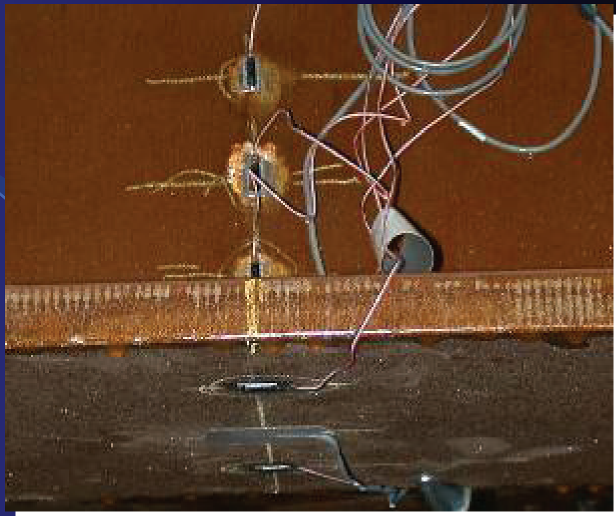
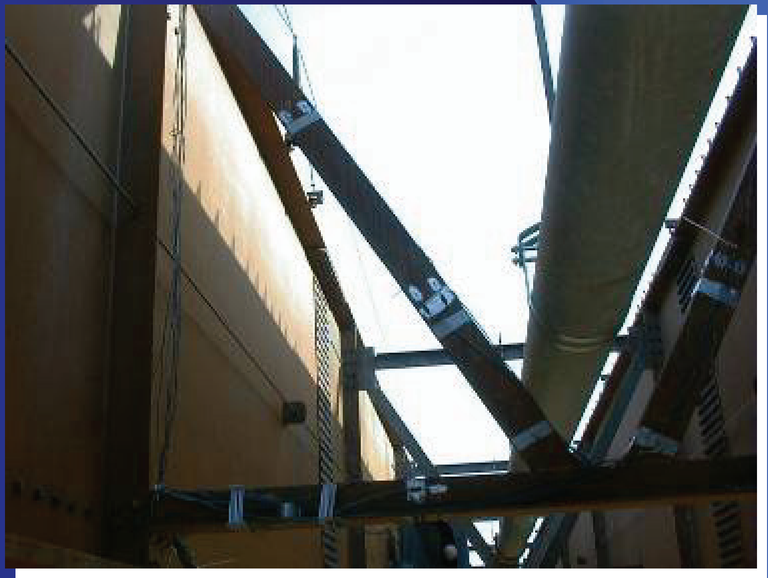
Superstructure Monitoring

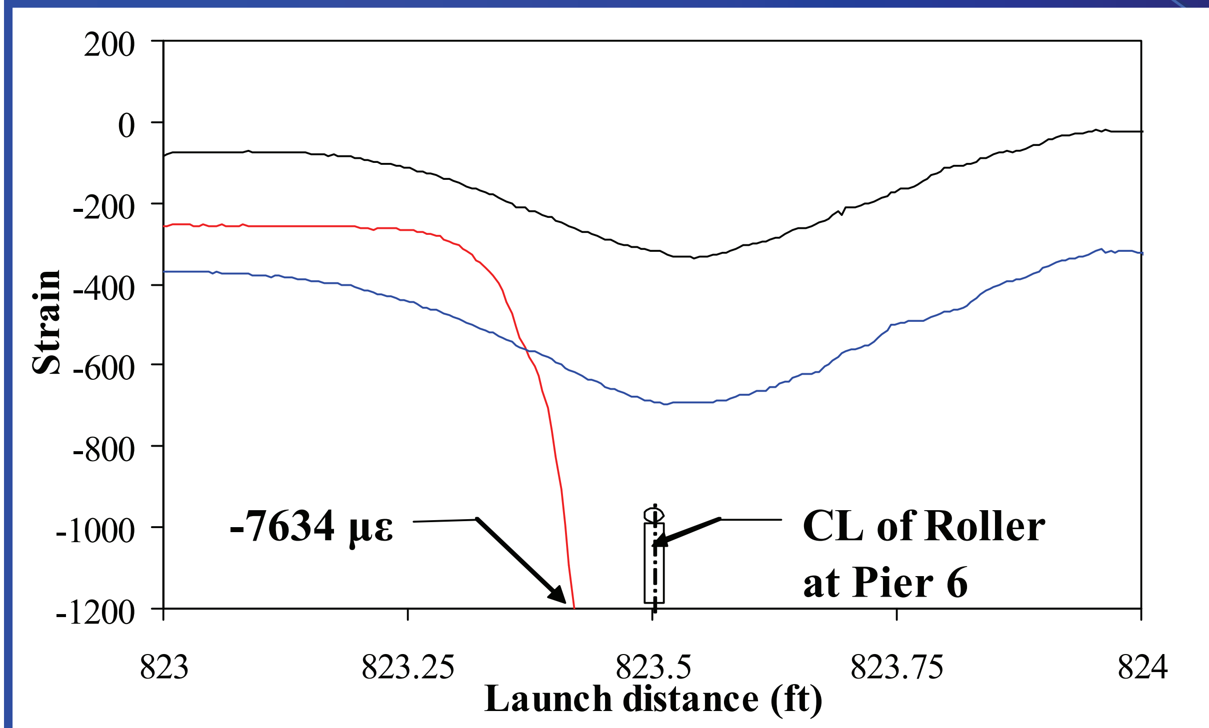
- Girder load distribution (flexure)
- Cross-frame behavior
- Roller contact stresses:
  - Bottom flange
  - Web
  - Flange to web welds

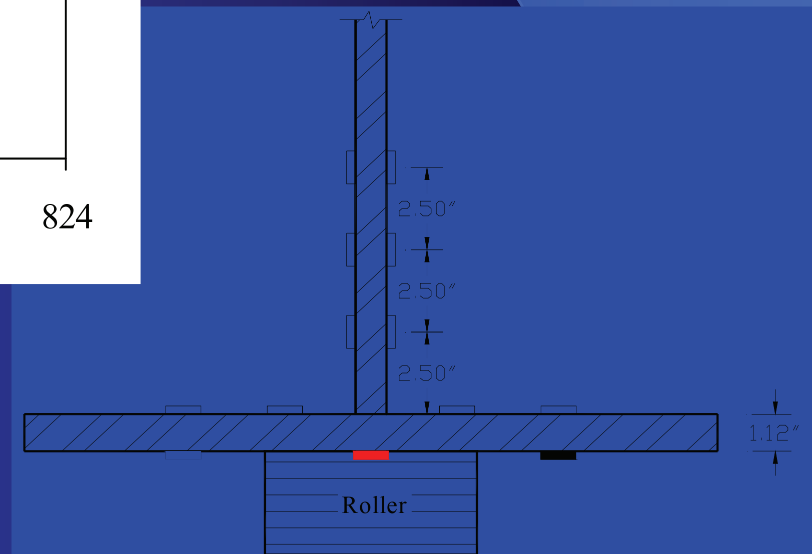




Superstructure Monitoring - Results

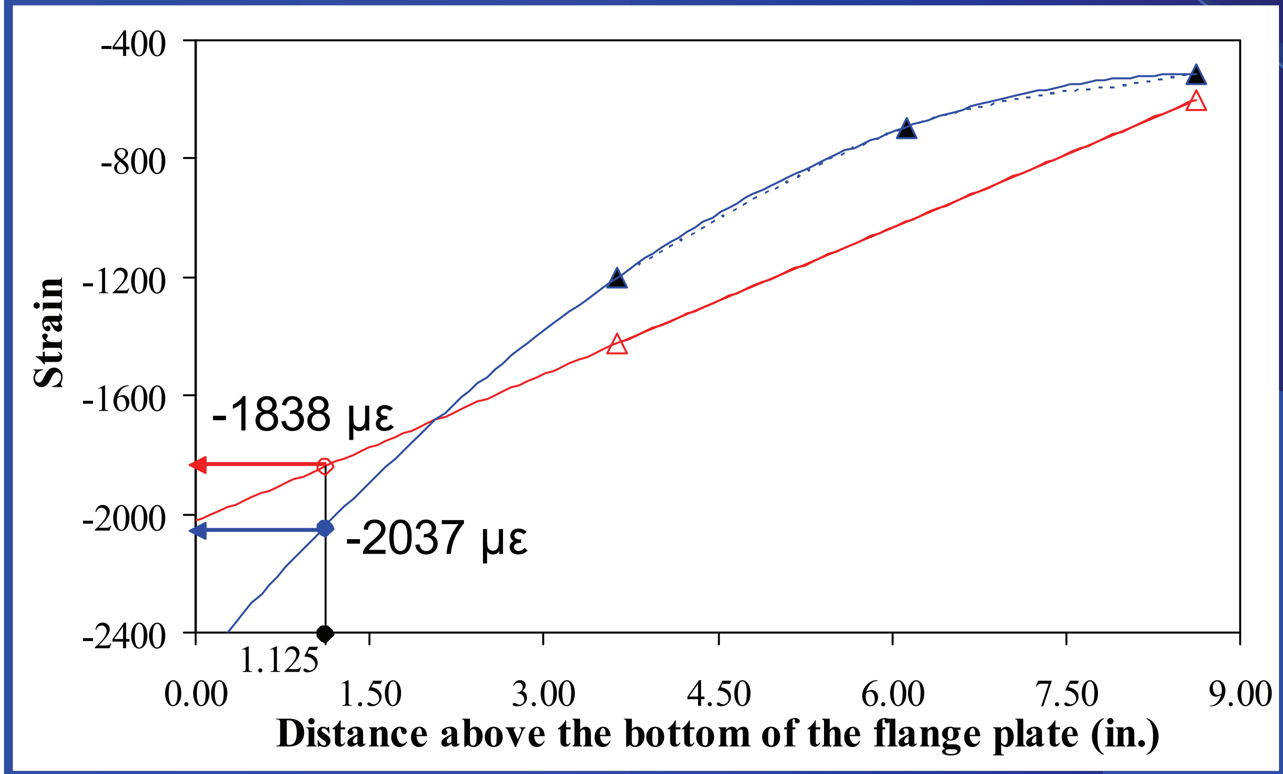
- Longitudinal flange strain measured > F_y

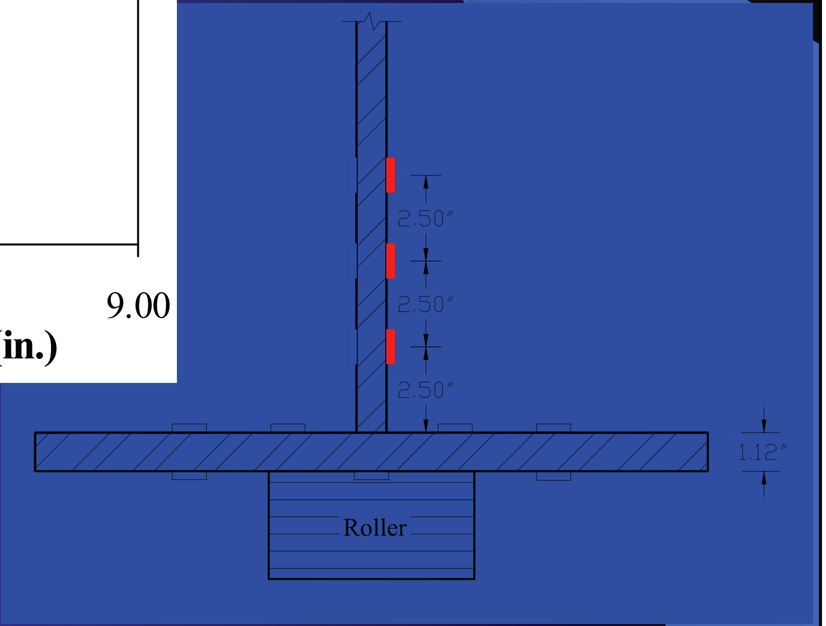




Superstructure Monitoring - Results

- Significant vertical strain measured





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Superstructure Monitoring - Results

- Cross-frame behavior is complex and sensitive
- (includes axial forces, biaxial bending and torsion)
- Measured values exceeded AASHTO design values

Diaphragm Member Type	Design Force (kips)	Calculated Force (WB1) (kips)	Calculated Force (WB5) (kips)
Upper Chord	20.2 (C)	42.6 (T)	86.2 (T)
Diagonals	38.3 (T or C)	56.2 (T)	172.1 (T)
Bottom Chord	20.2 (T or C)	31.1 (T)	39.7 (C)

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Action Related to Contact Stress Issue

- Post-construction inspection
  - Visual and magnetic particle
  - No signs of cracking or other damage

High stresses can result in “cold work” region
  - Fracture characteristics not impacted

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Launch Project Recommendations

- Use large contact surface area for launch rollers
- Design crossframe members/connections to support the weight of one girder supported only by crossframe
- Provide comprehensive monitoring program
  - Identify potential problematic issues
  - Alert contractor during launch

Iowa Department of Transportation

Launch Project Recommendations

- Develop a launching system that is reversible
- Use a set of mirrors or other system to monitor the "plumbness" of piers
- Use constant width bottom flanges for I-girders

Iowa Department of Transportation

Monitoring and Video Documentary Project

- FHWA
- Iowa Department of Transportation
- Iowa State University CTRE
- Jensen Construction
- HNTB

- Final Report & DVD sent to all DOTs and FHWA Division office

- Project Website: www.iowariverbridge.org

Iowa Department of Transportation

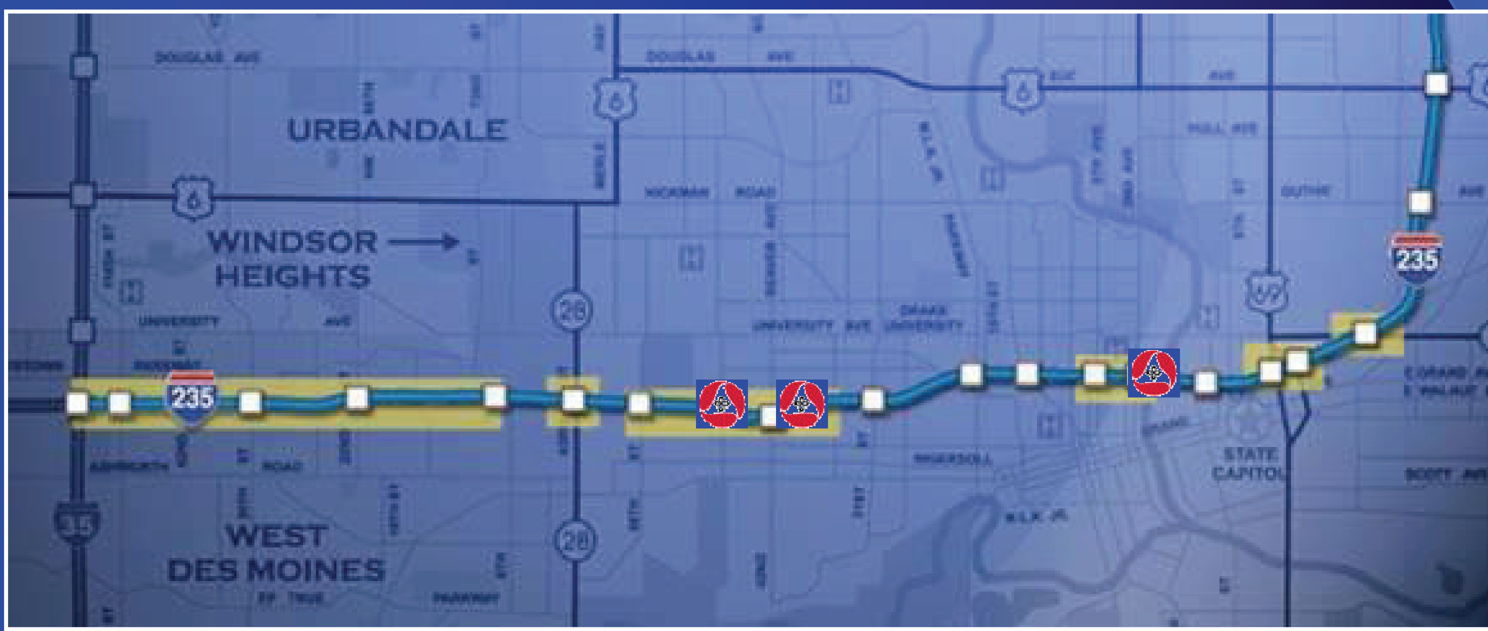
Chapter 12

Monitoring of I-235 Pedestrian Bridges

Iowa Department of Transportation

Bridge Location & I-235 Corridor

- **I-235 Reconstruction**
  - **70 Bridges reconstructed or replaced**
  - **$426 million total construction cost**
- **Pedestrian Bridges**
  - **1st bridge completed January 2004**
  - **Two similar bridges constructed 2005**



Quick Facts

– Gateway to the City

– Arch spans ranging from 70 m to 80 m

- 80 m @ Botanical (88.5 m total bridge)
- 80 m @ 40th Street (83.2 m total bridge)
- 70 m @ 44th Street (78.5 m total bridge)

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Quick Facts

– Drilled shafts and pile foundations
  - 4 - 1680 mm drilled shafts @ Botanical
  - 67 - HP 310x79 piles @ 40th Street
  - 78 - HP 310x79 piles @ 44th Street

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Quick Facts

– Steel box arch ribs
  - 500 mm x 700 mm at crown
  - 750 mm x 1250 mm at base

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Quick Facts

– Precast/post-tensioned deck segments

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Quick Facts

– Dywidag hangers

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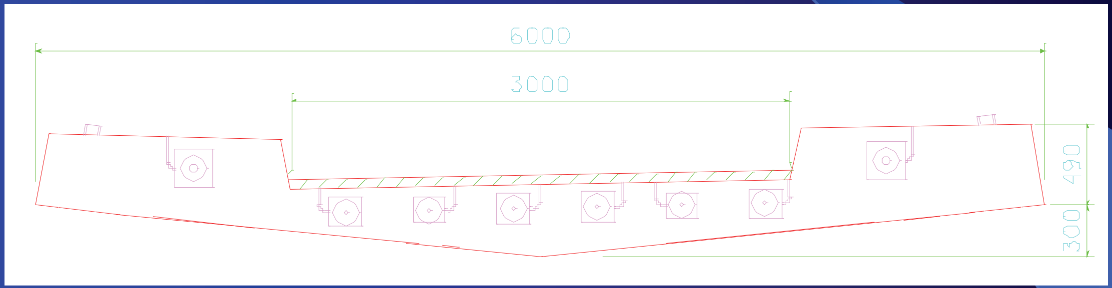
Quick Facts - precast deck panels

– 6.0 m width x 4.2 m length

– 3.0 m wide walking surface



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Steel Erection

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Steel Erection

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Self-Consolidating Concrete

- Admixtures provide temporary flowability
- Measure "spread" rather than "slump"

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SCC – Formwork is Critical

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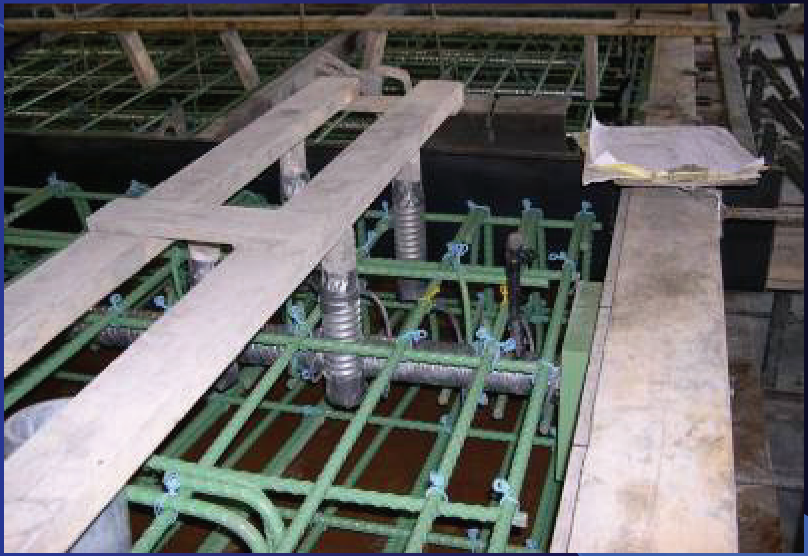
Precast Deck Panels



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Precast Deck Panels – Match casting

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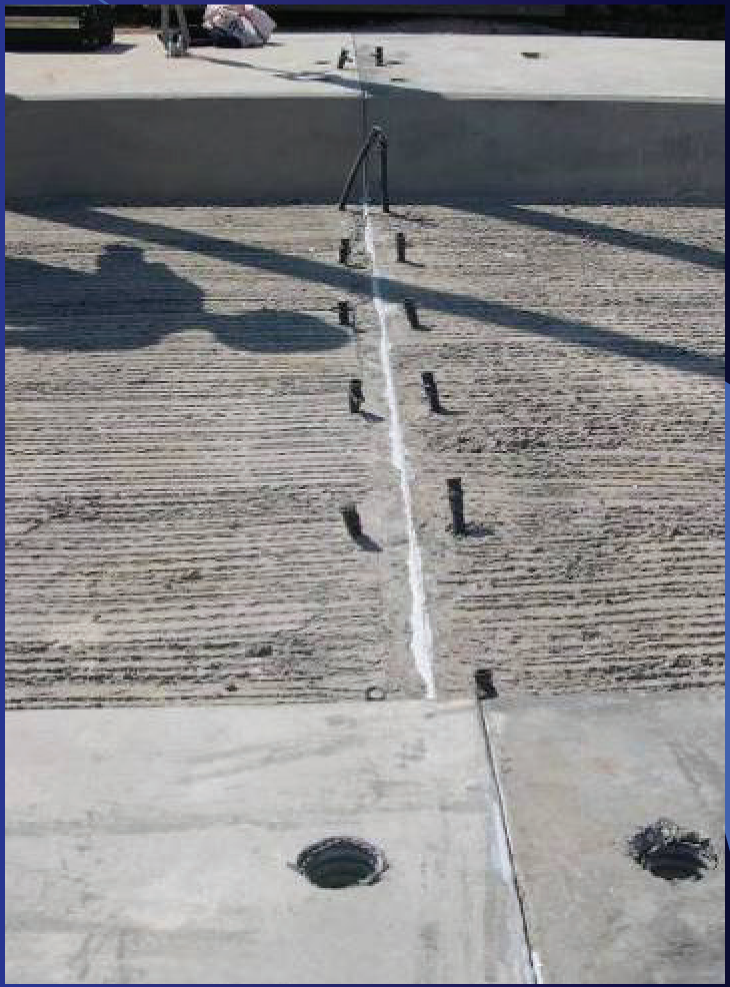
Center Panels Stressed on the Ground



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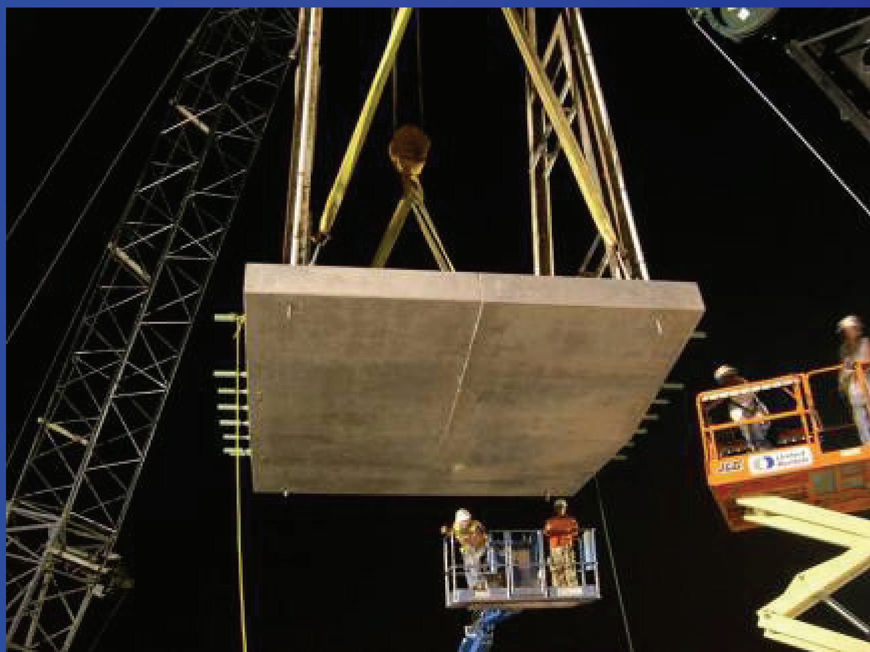
Hanger and Precast Panel Installation



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Post-tensioning of Deck Panels

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Measure Elongation During PT stressing

Aesthetic Lighting

Iowa Department of Transportation

Gateway to the City of Des Moines

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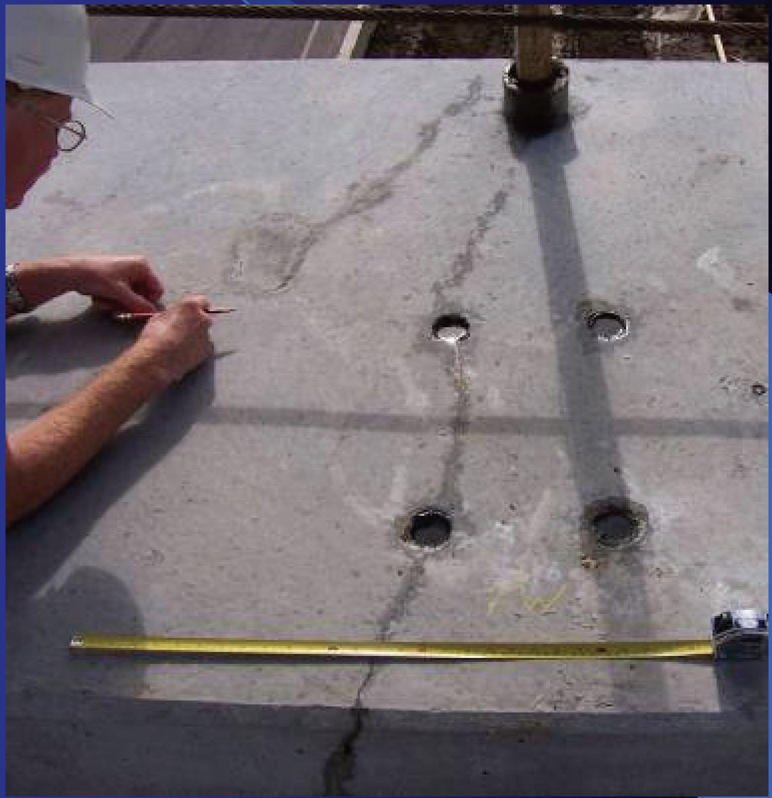
Concrete Panel Cracking

- Minor cracking of panels occurred during 2003 construction



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Construction Monitoring – 2005

- Unequal loading of hanger rods considered most likely cause of panel cracking
- ISU Bridge Engineering Center hired to perform monitoring during construction of 2005 bridges
- Goals of monitoring:
  - Short term – eliminate panel overstresses during construction
  - Long term – monitor redistribution of loads in hangers (concrete creep)

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Instrumentation and Monitoring

- Fiber optic sensors (FOS) can be used to monitor:
  - Temperature
  - Moisture/humidity
  - Pressure
  - Strain
- ISU Bridge Engineering Center has used FOS for a number of projects over past few years

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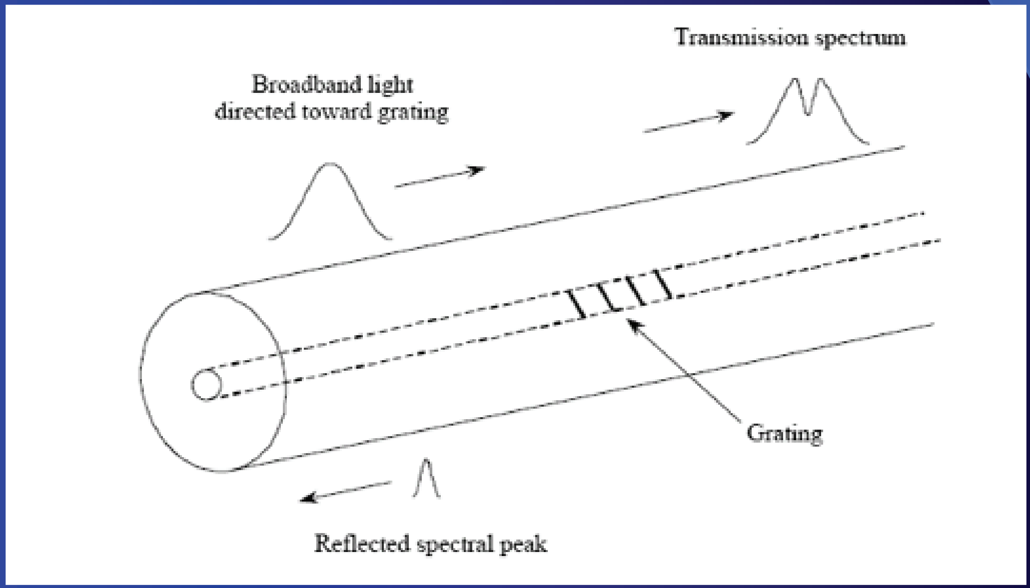
Fiber Optic Strain Sensors

- Fiber Bragg Gratings (FBG)
  - Introduced 1995
  - FBG reflects very narrow band of wavelengths – all others pass through
  - Any change in strain/temperature causes proportional shift in reflected spectrum



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Fiber Optic Sensors

- Advantages:
  - No drift during long term monitoring
  - Very durable when embedded or installed on completed structure
  - Low signal loss with long lead lengths.
  - Can be serially multiplexed

Disadvantages:
  - Expensive compared to convention strain sensors
  - Delicate and easily damaged during construction

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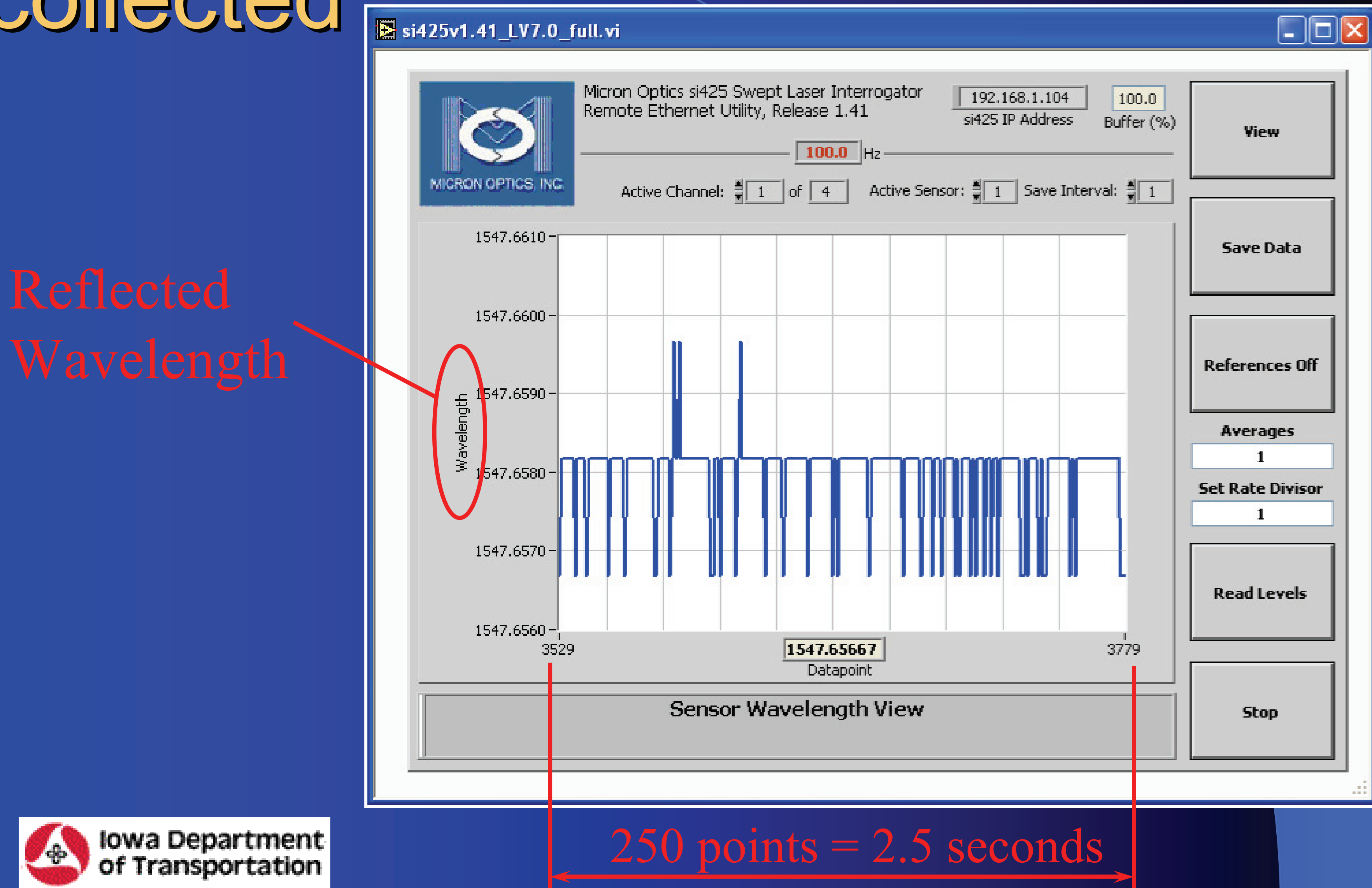
Fiber Optic Strain Sensor – data collected



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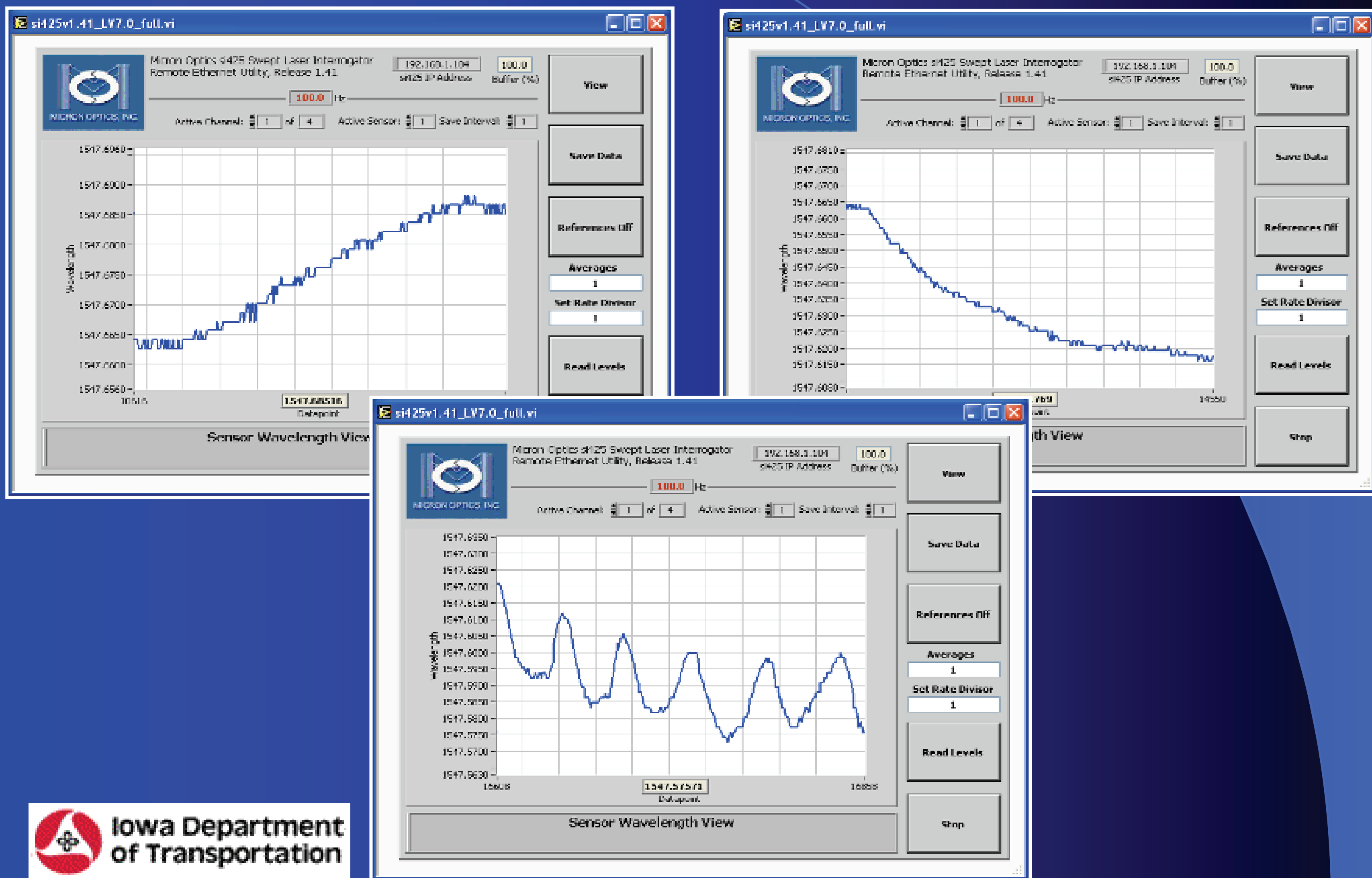
Fiber Optic Sensors – sample data collected



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Fiber Optic Sensors - Installation

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Fiber Optic Sensors – Handling in Field

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Problems with FOS survivability

- Original intent of monitoring:
  - Connect sensors in series to simultaneously read multiple l
  - Each quadrant of bridge separated
  - Monitor load in each hanger as each subsequent panel installed
- Damage during construction prevented series connections and required individual readings at each stage

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Fiber Optic Sensors - Protection

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Survivability of Fiber Optic Sensors

- First bridge – 44th Street:
  - Total of 28 hangers installed
  - Only 13 were usable after construction
- Second bridge – 44th Street:
  - Total of 36 hangers installed
  - Total of 31 hangers working after construction

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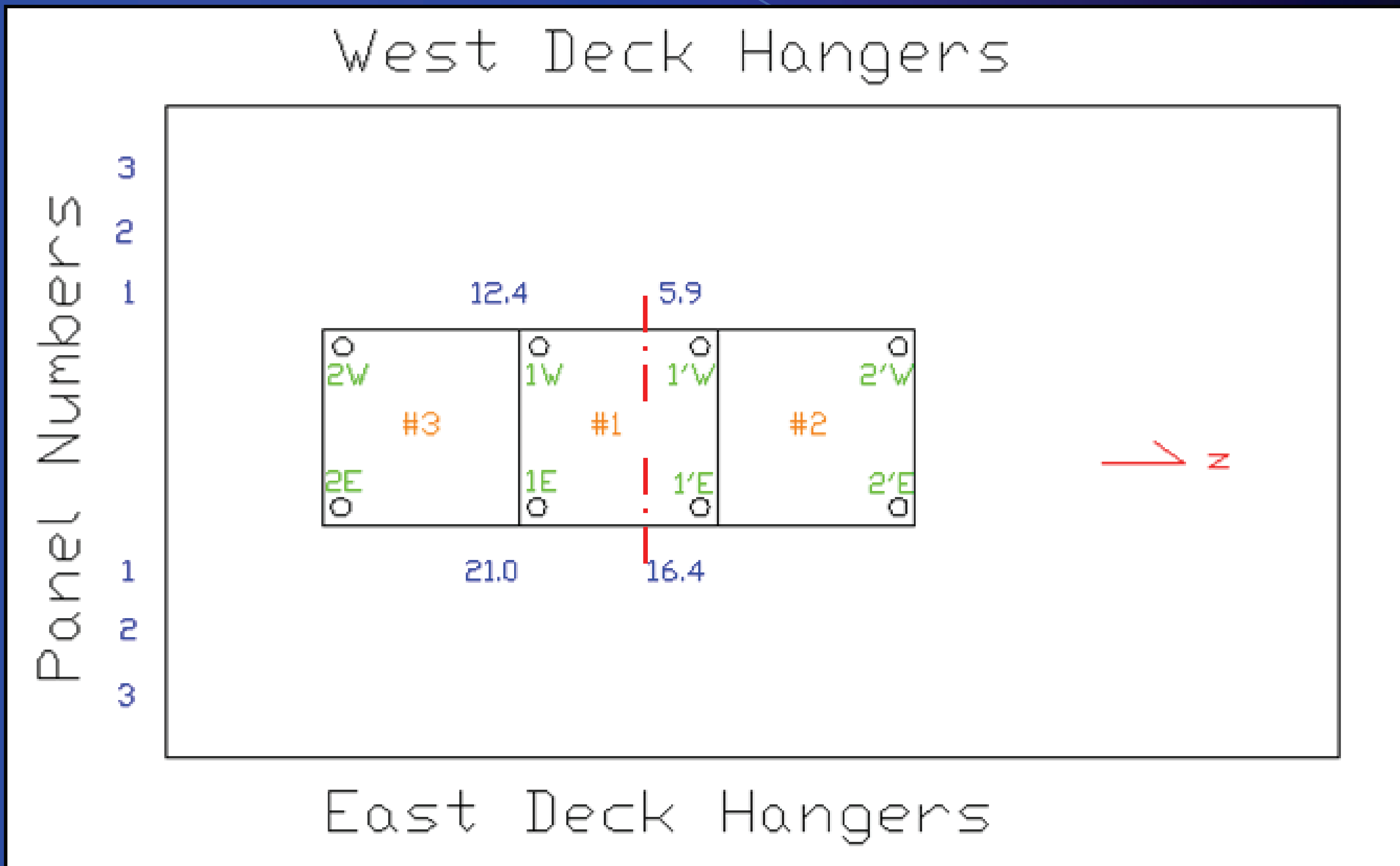
Fiber Optic Strain Sensor Results



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Long term monitoring of hanger loads

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Natural frequency monitoring - hanger loads

Hanger assumed to be uniform beam subjected to axial load with:

- Distributed mass and elasticity properties
- Length, L
- Area, A
- Flexural rigidity, EI
- Mass density, r

$$T = \rho A \left(\frac{L}{n\pi} \left[\omega_n - (\beta_n L)^2 \sqrt{\frac{EI}{\rho A L^4}} \right] \right)^2$$

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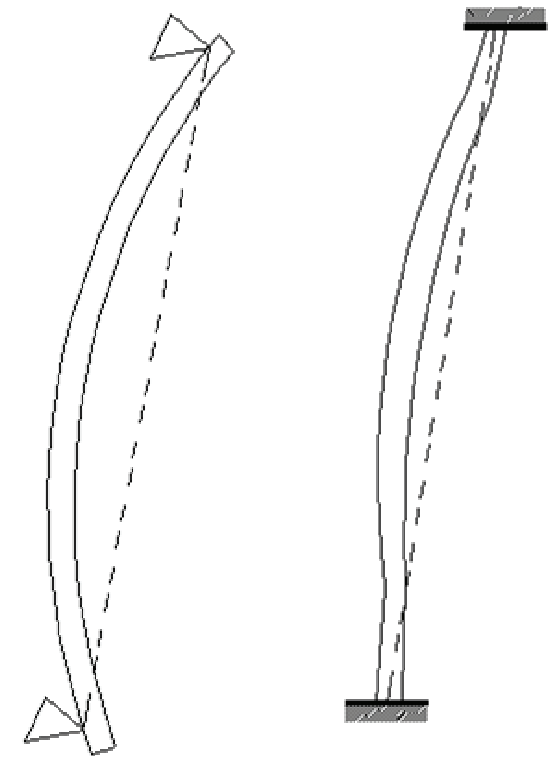
Other Modeling Considerations

Which section properties are "correct" :

- Steel rod alone?
- Steel rod with grout?
- Grout composite w/ rod?

Natural frequencies for simple span beams, b_1L:

- Pinned-pinned = 3.141
- Fixed-fixed = 4.730



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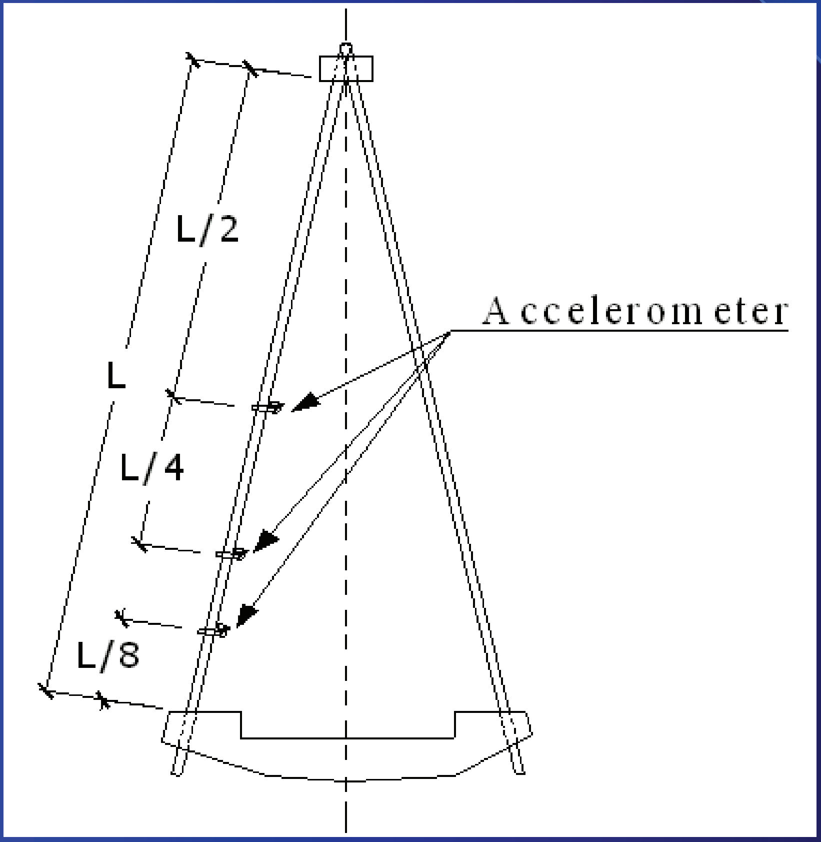
Vibration Testing of Hanger Rods

Initial testing included varying the position of the accelerometer to ensure identical ω_n measured



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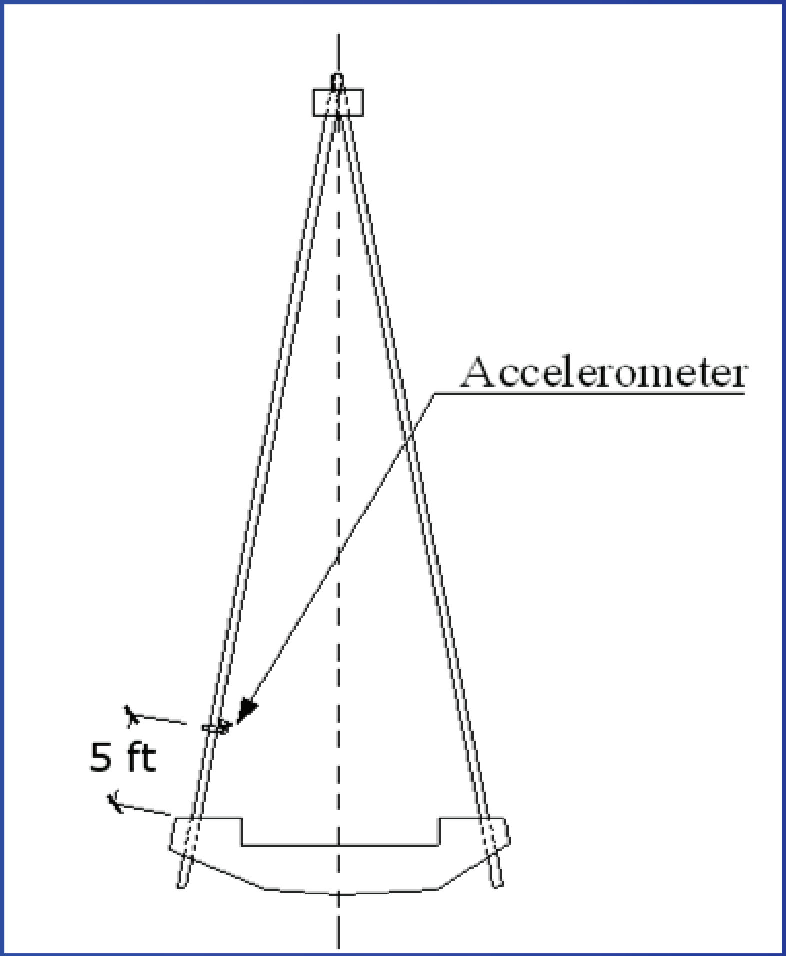
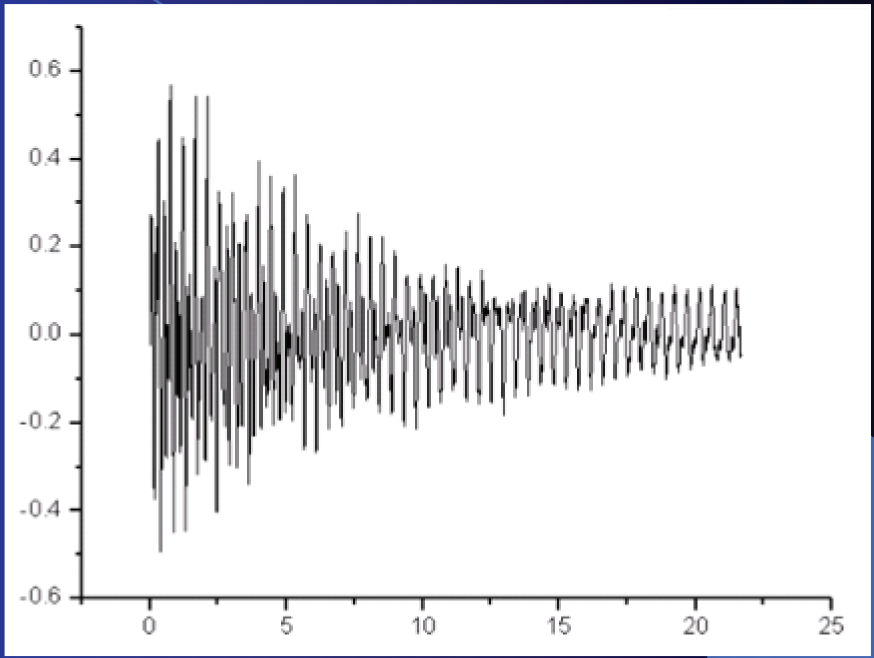
Free vibration of hanger rods





Each hanger excited and allowed to vibrate for 10-15 seconds

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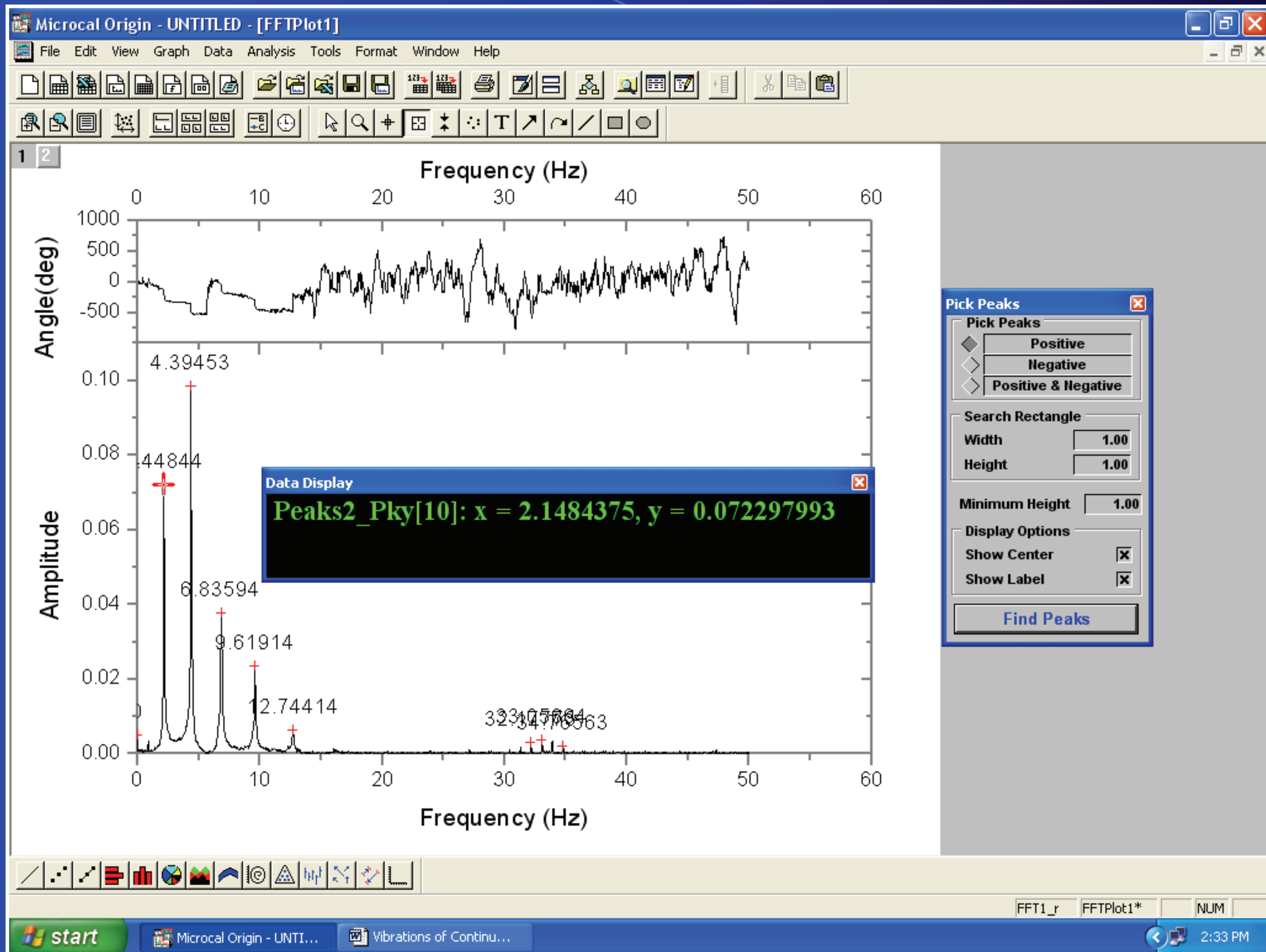
Calculation of Natural Frequencies



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Estimated hanger loads – end conditions

	West Arch	
Hanger	Pinned – Pinned (kips)	Fixed – Fixed (kips)
9	-----	-----
8	30.8	17.7
7	31.3	21.9
6	35.6	27.5
5	32.5	25.8
4	33.4	27.4
3	27.7	22.5
2	25.6	20.9
1	36.2	30.7

Not computed

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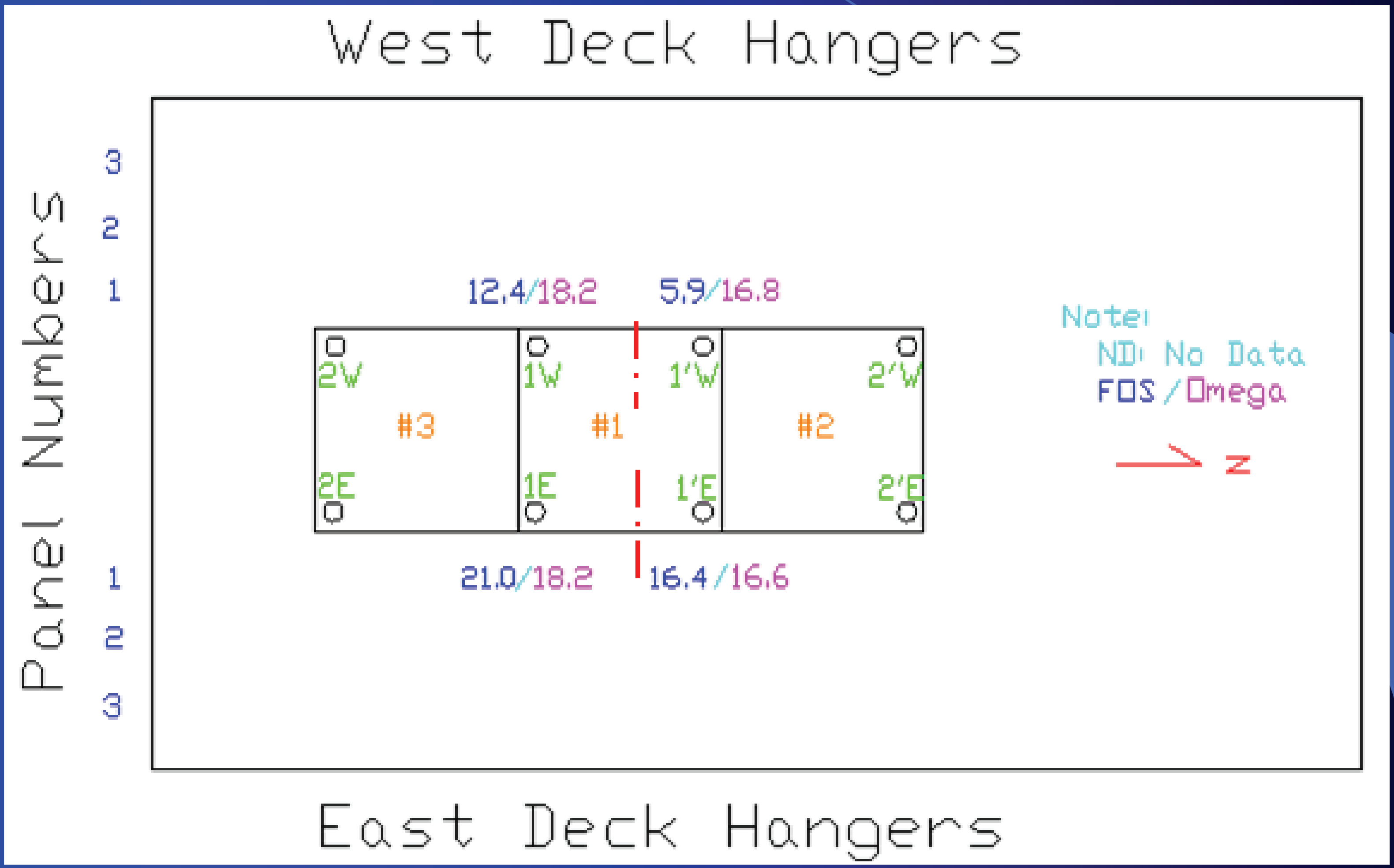
Comparison of FOS and dynamics results



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Adjustment of Hanger Loads

- Recall that deck must be constructed to match the profile grade as precast
- On the shortest hanger rods, a change in length of 1/8” changes force by approx. 40 kips

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Adjusted Hanger Loads

Hanger	West Arch	
	Before Adjustment (Pinned-Pinned) (kips)	After Adjustment (Pinned-Pinned) (kips)
8	6.0	30.8
7	27.8	31.3
6	49.6	35.6
5	52.3	32.5
4	33.1	33.4
3	5.6	27.7
2	23.2	25.6
1	83.9	36.2

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Conclusions

- Hanger loads are much more uniform than in 2003 bridge construction
- Visual inspection indicates fewer cracks in precast concrete panels
- BEC will return to 2005 bridges in six months to a year to monitor changes in hanger loads due to creep, etc.
- Use of fiber optic strain sensors during construction is difficult due to survivability concerns
- It is possible to use vibration records to monitor loads of axial members which also provide flexural stiffness

Iowa Department of Transportation

Chapter 13

Deck Overhang Sufficiency for Barrier Rails

Iowa Department of Transportation

Outline

- Objectives
- Protocol
- Modeling
- FEM Result Validation of KSDOT Study
- Model Results
- Observations

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Introduction

- Problem Statement
  - AASHTO LRFD requires deck overhang strength equal or greater to barrier rail
- Approach
  - Finite Element Analysis performed to evaluate required deck overhang slab reinforcement

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Introduction

- Bridge damage near Alton, Iowa resulting from a suspected vehicle impact: minor scratches and gouges < 1 /4" deep

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Outline

- Evaluation of Deck Overhang Sufficiency
  - Use commercial Finite Element Modeling (FEM) program
  - Compare the FEM results with AASHTO LFRD Bridge Design Specifications

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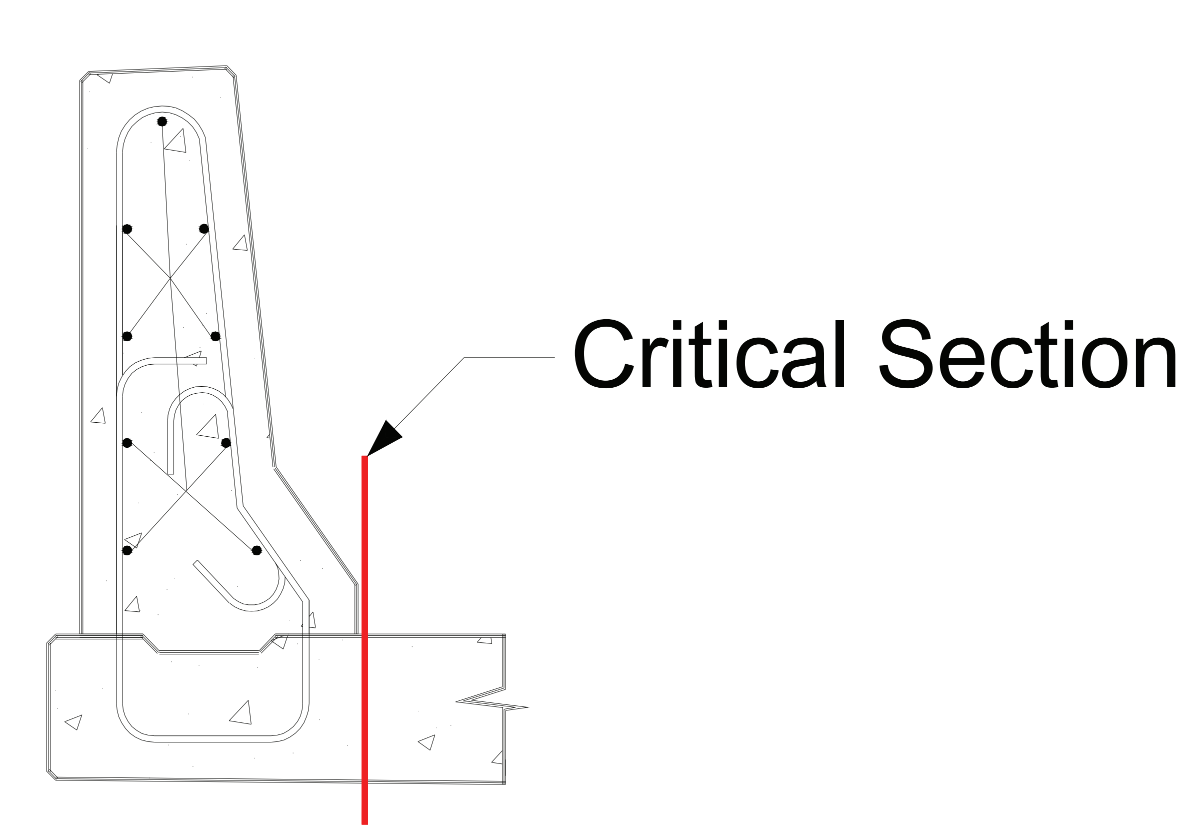
Protocol

Iowa F-Section Barrier



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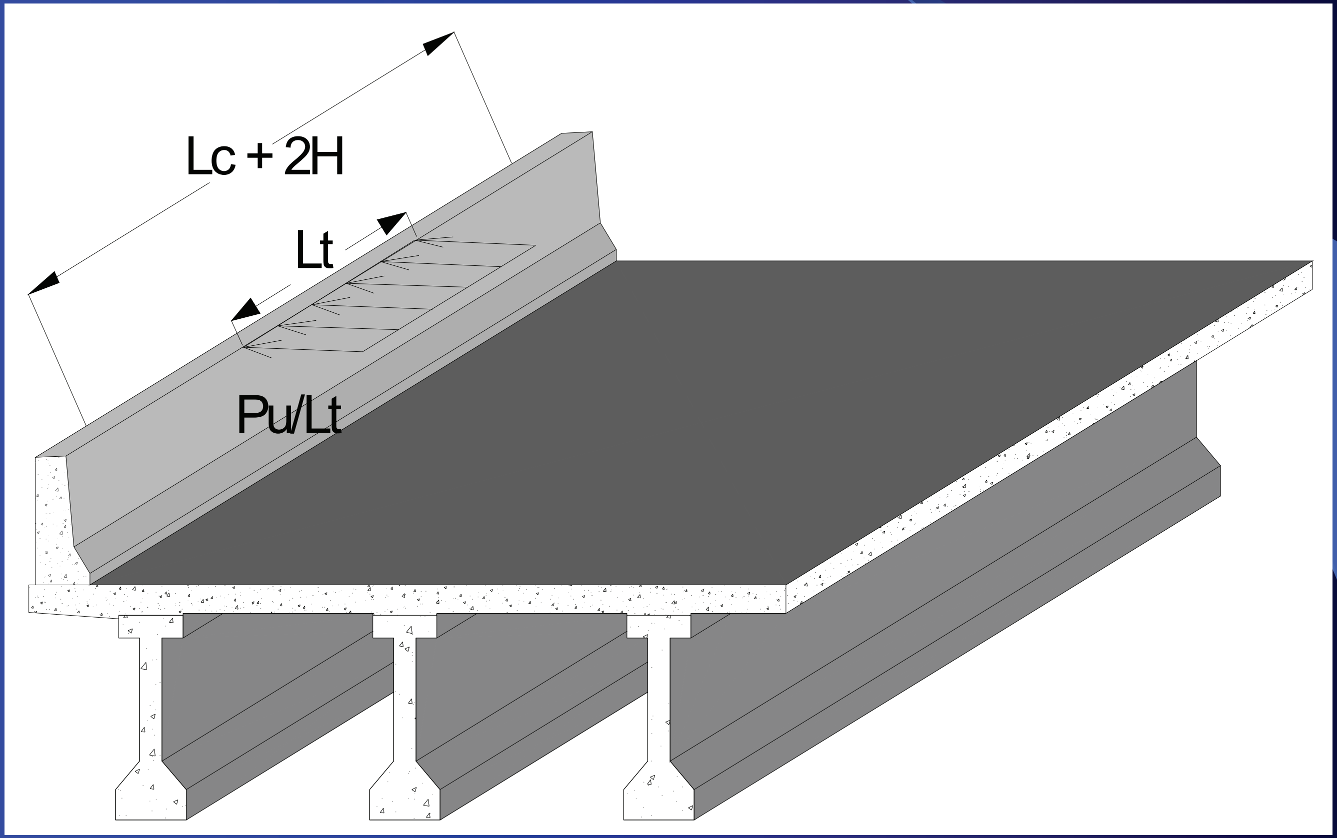
Protocol

Loading the bridge model under extreme event P_U : Total Codified Transverse Force (R_w)



Protocol

Total Applied Moment (per unit length):

$$M_U = M_{U-FEM} + M_{U-DL}$$

- ***M_U*** **Ultimate moment**
- ***$M_{U\text{-}FEM}$*** **Ultimate moment from the FEM results**
- ***$M_{U\text{-}DL}$*** **Ultimate moment due to the dead load of the barrier and deck overhang under the barrier**

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Protocol

Corrected Deck Nominal Moment Capacity (per unit length):

$$M_{N-IC} = \phi M_N \left(1 - \frac{P_U}{\phi P_N}\right)$$

- $M_{N\text{-}IC}$ Nominal moment capacity using the interaction curve
- ϕ Reduction factor (1, for service conditions)
- M_N Nominal Moment Capacity
- P_U Ultimate load equal to *RW*
- P_N Nominal Axial Load

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Protocol

Comparison of:

$$M_{N-IC} \geq \phi M_U$$

If any reserve capacity, a possible reduction in the transverse reinforcement could be considered.

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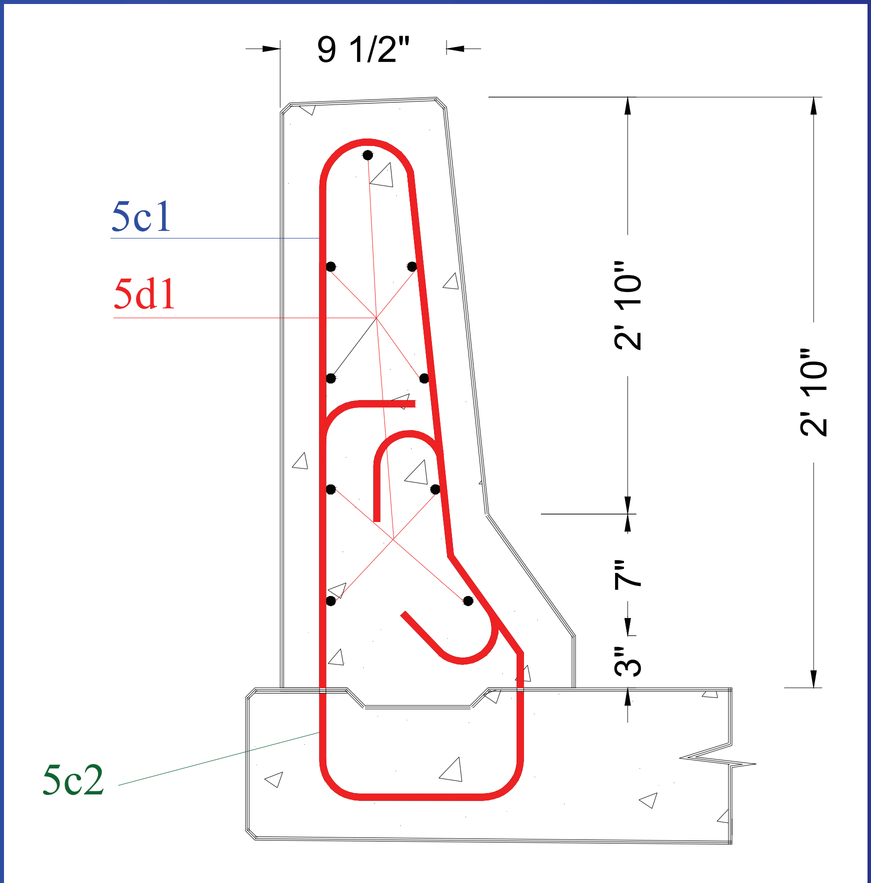
Modeling

Three models were analytically evaluated.



Iowa F-Section Barrier provided by the IADOT Office of Bridge and Structures.

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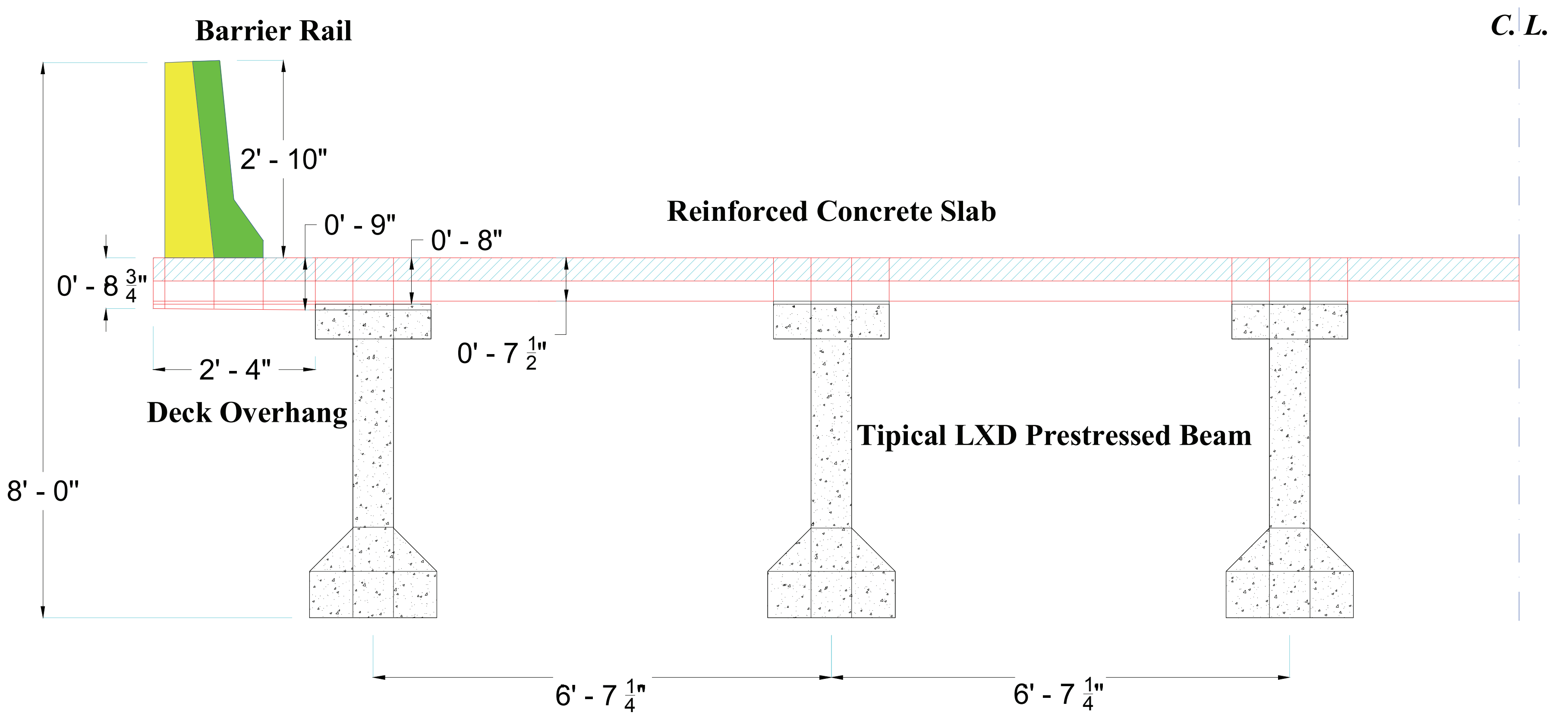
Modeling

Model 1



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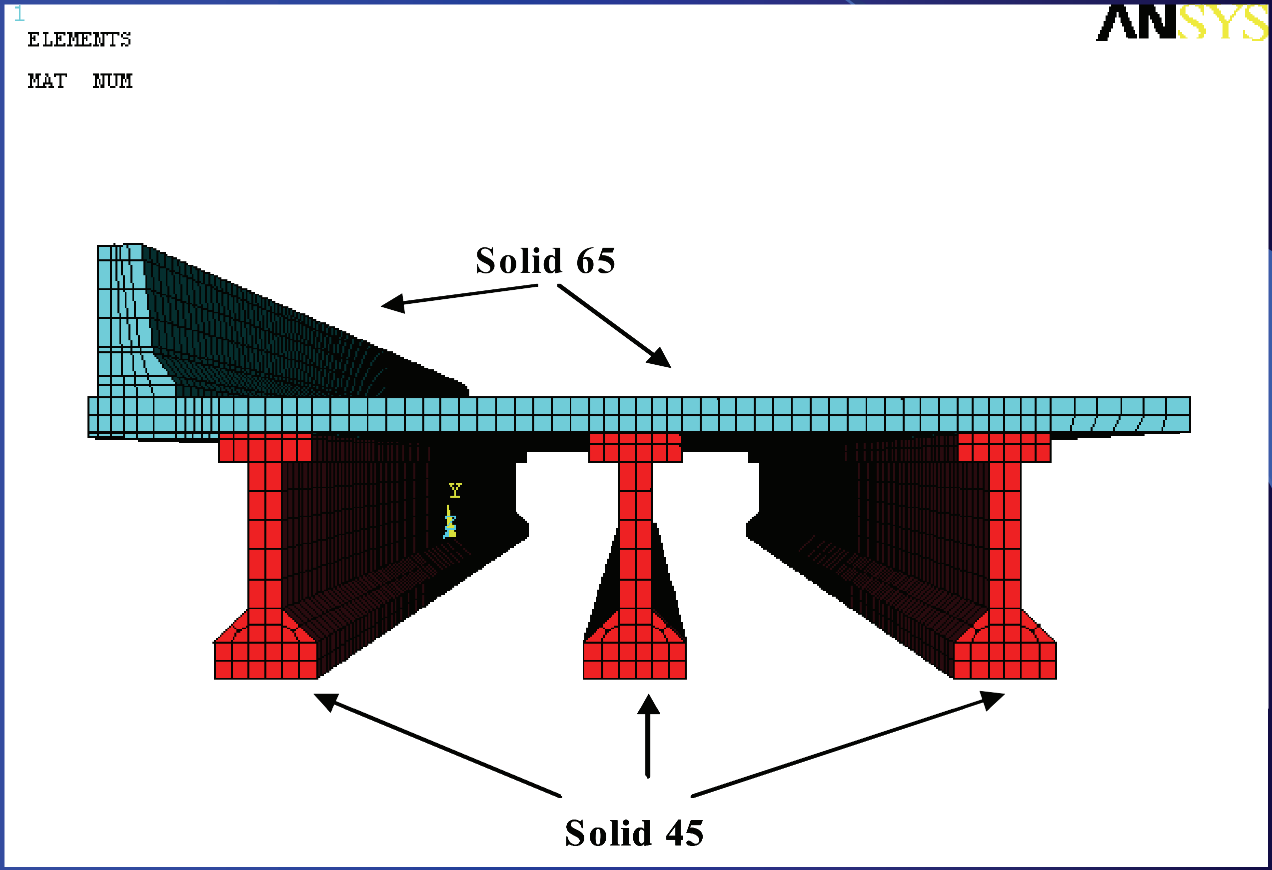
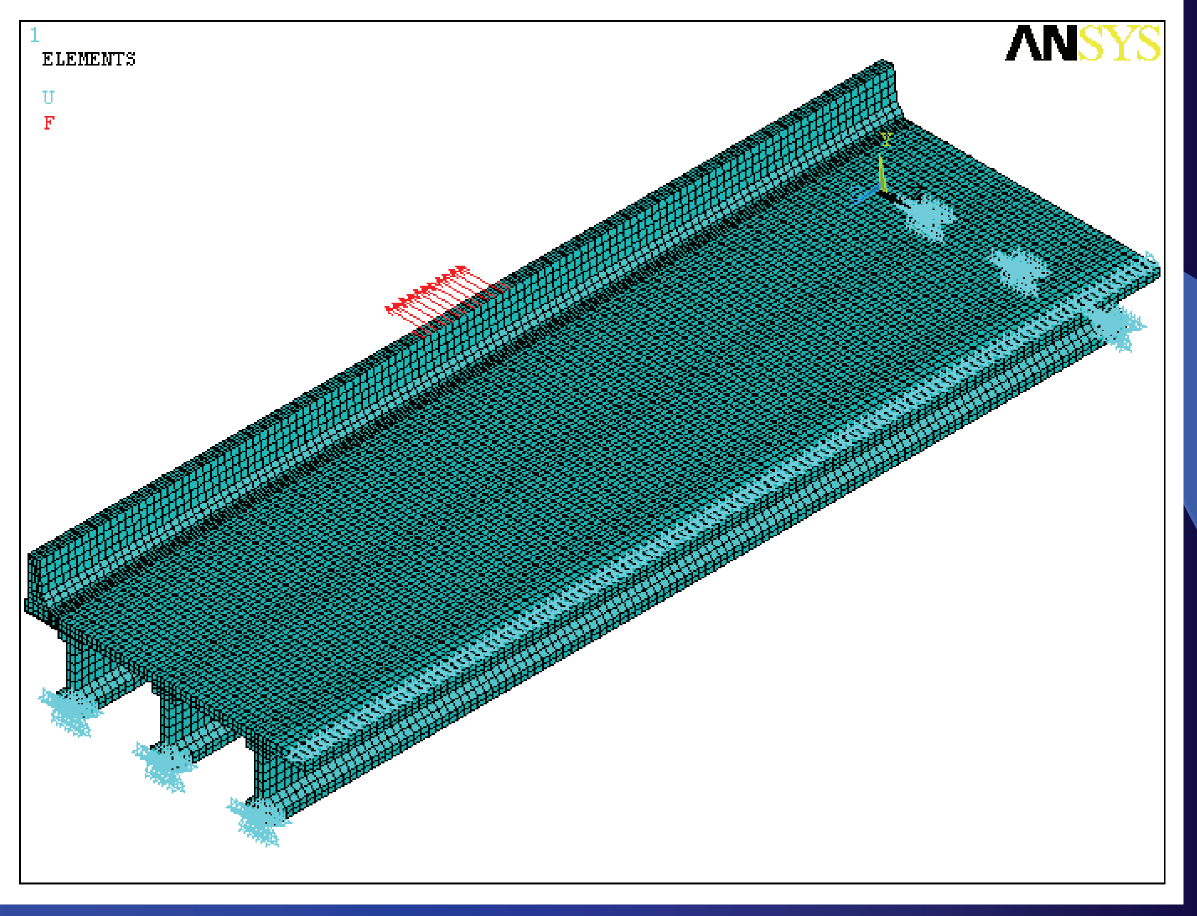
Modeling

Model 1



Modeling

Model 1



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Modeling

Iowa Railing System: Material Properties

Structural Member	***f'c [psi]***	***E [ksi]***	***μ [Poisson Ratio]***
Deck Overhang, Slab and Barrier	3,500	3,400	0.18
Steel Reinforcement	60,000	29,000	0.30
Prestressed Girders	5,000	3,500	0.18

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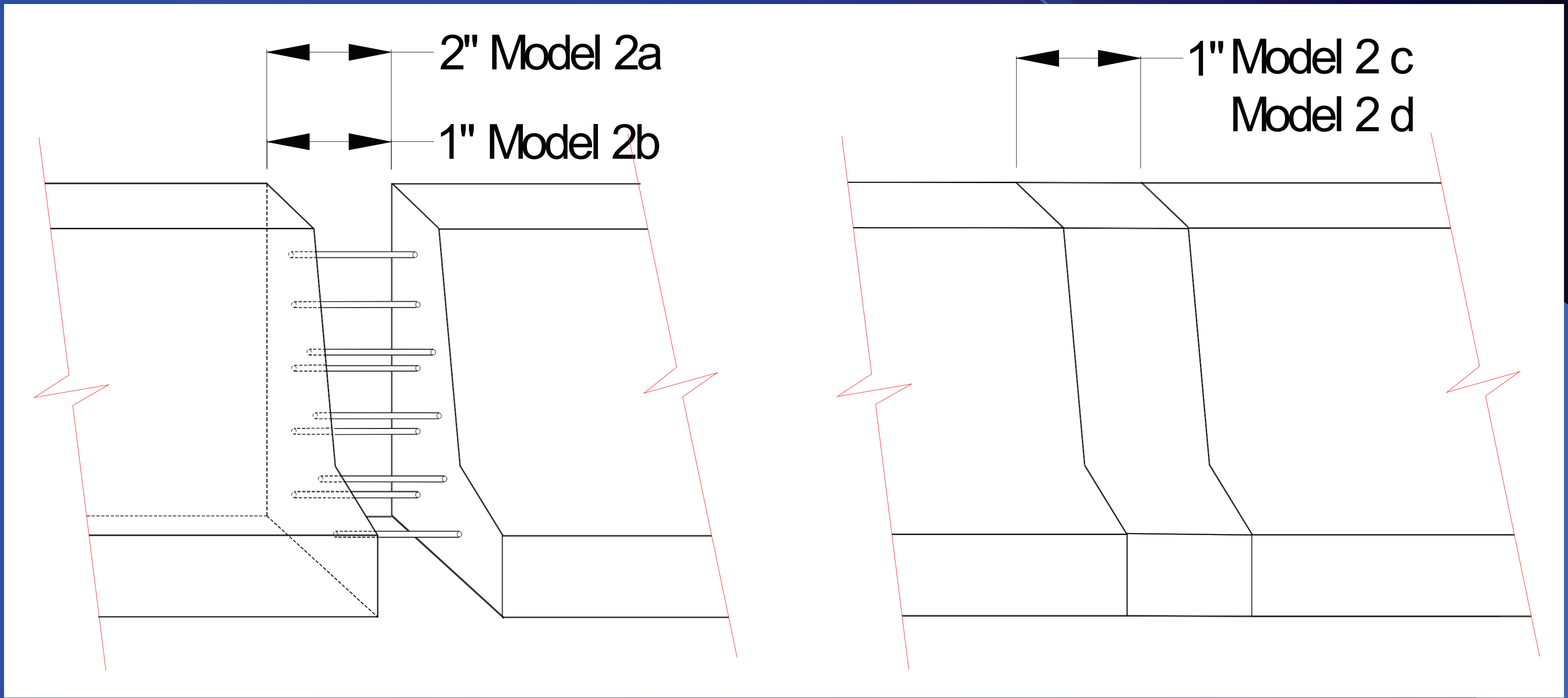
Modeling

Model 2



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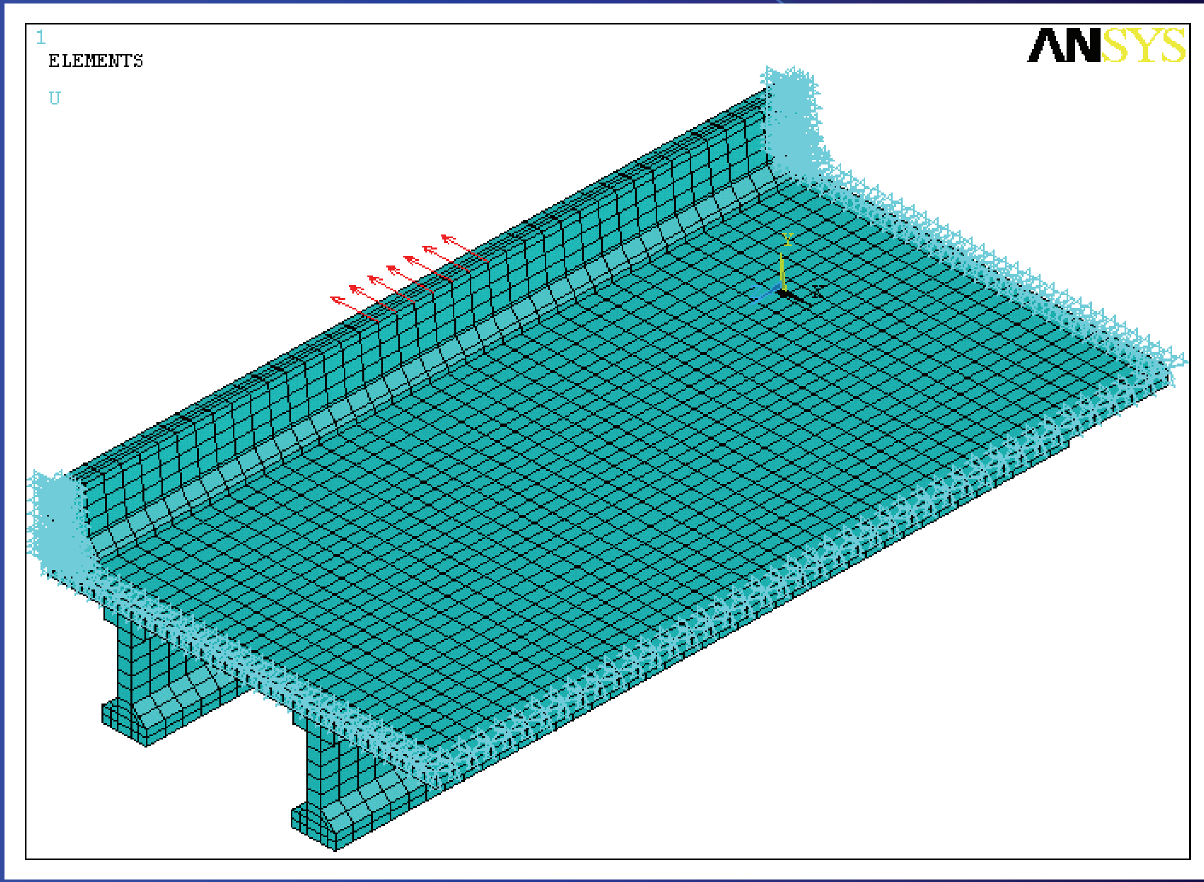
FEM Result Validation of KSDOT Study

Model 3



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FEM Result Validation of KSDOT Study

Model 3

Kansas DOT - Concrete Barrier

Deck Material Properties

Structural Member	***f'c [psi]***	***E [ksi]***	***μ [Poisson Ratio]***
Concrete	4,351	3,796	0.18
Steel Reinforcement	60,000	29,000	0.30

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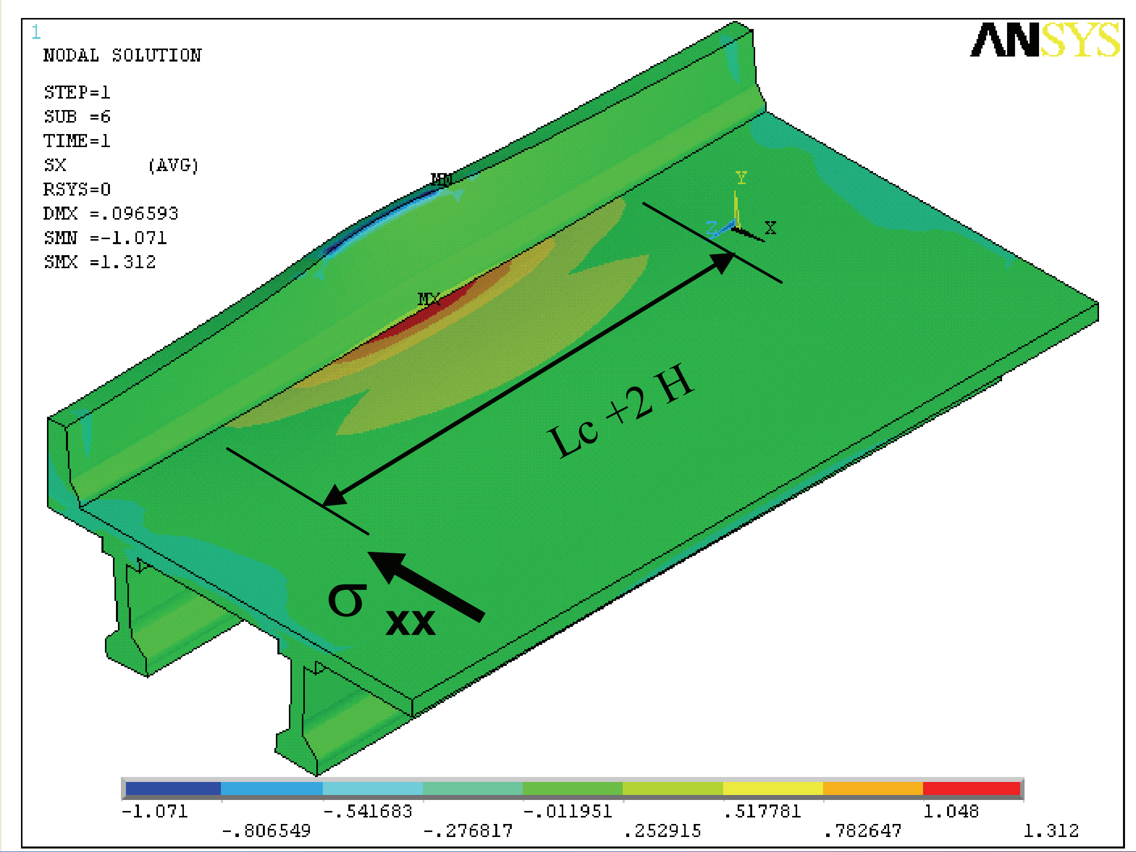
FEM Result Validation of KSDOT Study

Model 3



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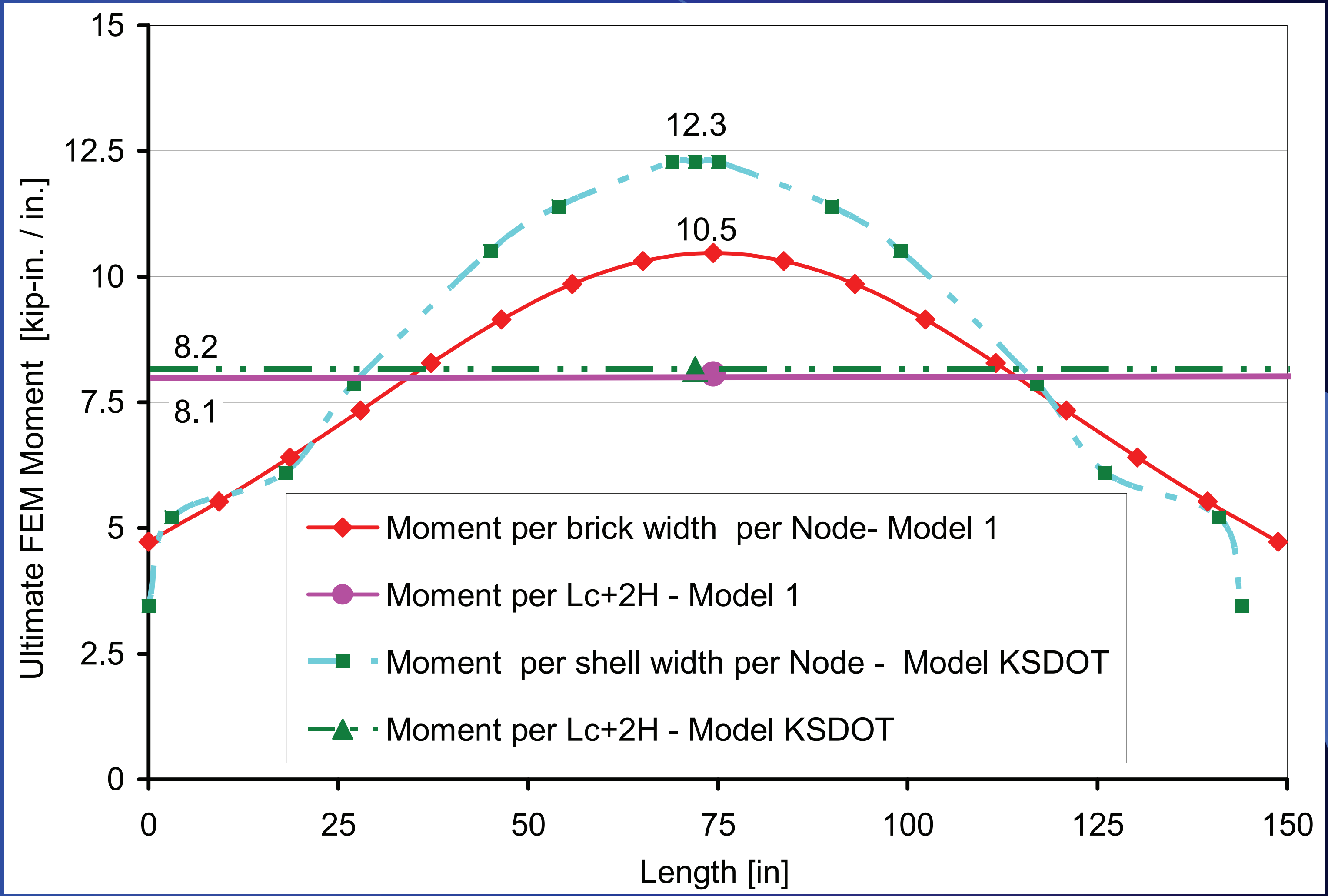
FEM Result KSDOT Study



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Model Results

FEM: Applied Ultimate Response

Model	*$M_{U\text{-}FEM}$* *[kip-in. / in.]*	*$M_{U\text{-}DL}$* *[kip-in. / in.]*	*M_U* *Ultimate Moment* *[kip-in. / in.]*
1	13.6	0.6	14.2
2a – 2-in. B-St	14.9	0.6	15.4
2b – 1-in. B-St	14.8	0.6	15.3
2c – 1-in. Sl-G	13.8	0.6	14.4
2d – 1-in. Sl-St	13.8	0.6	14.4

B: Bar connector   Sl: Solid connector St: Steel   G: Grout

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Model Results

Structural Sufficiency Analysis

Model	*ϕM_{N-IC} - M_U [tension reinforcement] ϕM_{N-IC} =19.7 [kip-in. / in.]*	*%Reserve %Capacity*	*ϕM_{N-IC} - M_U [tension and compression reinforcement] ϕM_{N-IC} =21.0 [kip-in. / in.]*	*% Reserve Capacity*
1	5.5	28%	6.8	32%
2a – 2-in. B-St	4.3	22%	5.5	26%
2b – 1-in. B-St	4.4	22%	5.6	27%
2c – 1-in. Sl-G	5.3	27%	6.5	31%
2d – 1-in. Sl-St	5.3	27%	6.6	31%

B: Bar connector   Sl: Solid connector St: Steel   G: Grout

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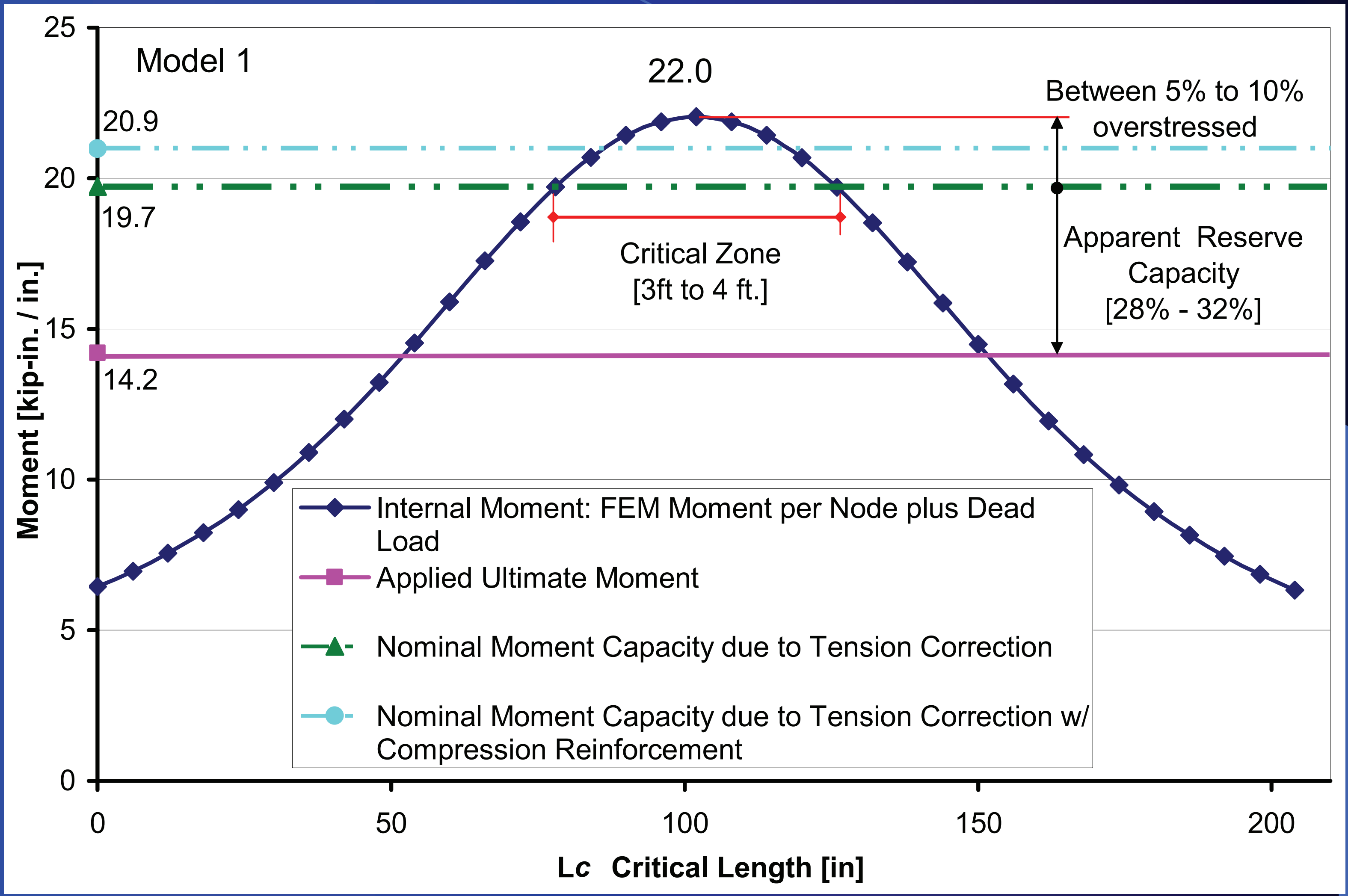
Model Results



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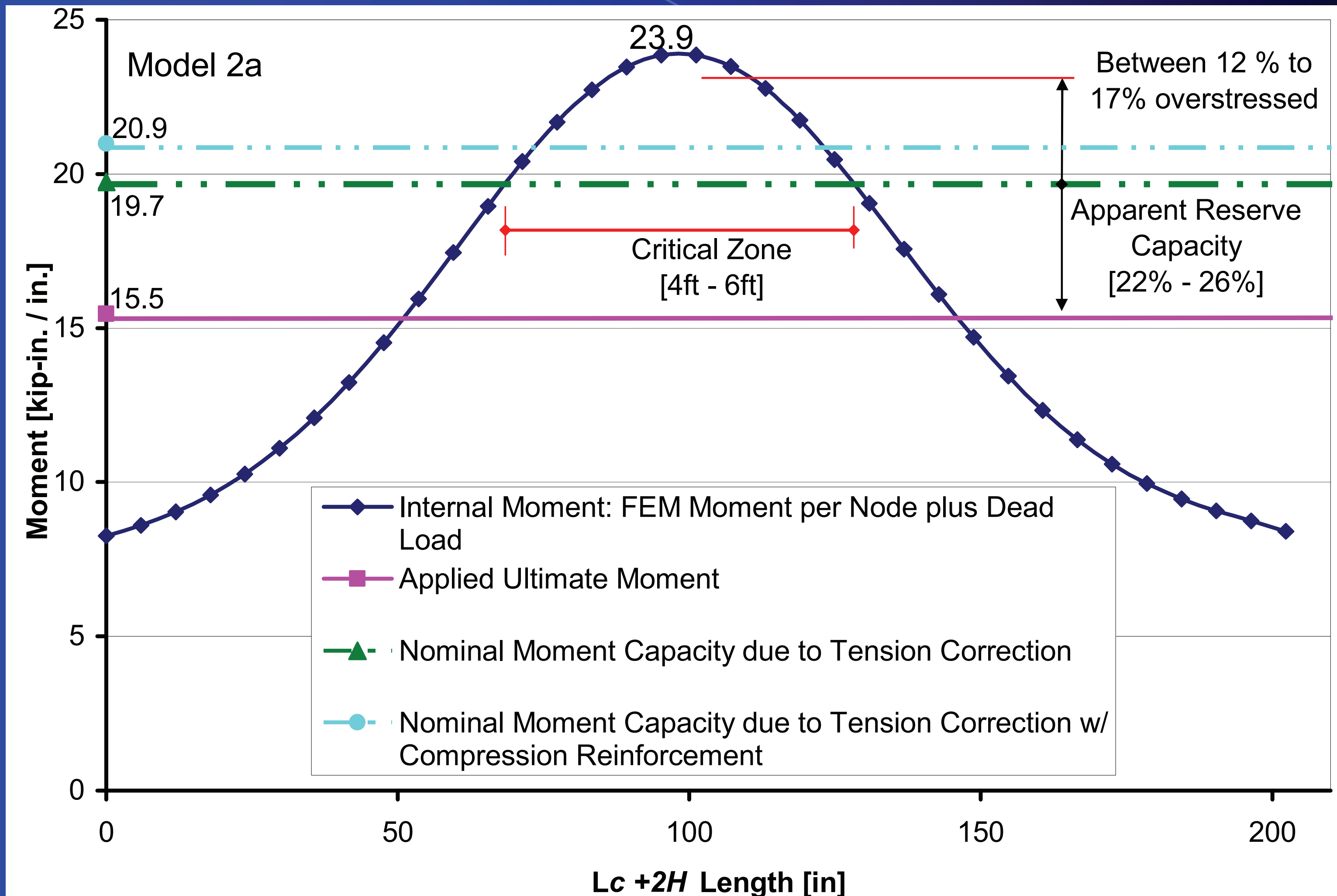
Model Results



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Observations

- 3-D Modeling Techniques used in this work adequately describe the deck overhang behavior
- Observed reserve capacity (LFRD specs.) seems to indicate a possible reduction in the steel reinforcement
- Internal Moments along the critical section (node-by-node) exceeded the corrected nominal moment capacity: zone of overstress.

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LOAD TESTING PROGRAM

- Implementation of Physical Testing for Typical Bridge Load and Superload Rating
- Field Test of the Red Rock Reservoir Bridge

Iowa Department of Transportation

Chapter 14

Implementation of Physical Testing for Typical Bridge Load and Superload Rating

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Bridge Rating

- Evaluation based on:
  - Visual inspection
  - Code based
- Iowa has 25,000 bridges
  - 4,000 on primary highway system
- Invest in innovative solutions to supplement existing rating procedure

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Iowa Load Testing Needs

- More accurate ratings for:
  - Older bridges with unknown or insufficient design data
  - Assessing need for temporary load restriction on damaged bridges
  - Possibly reducing the number of bridges that restrict a reasonable flow of overweight trucks

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Iowa Load Testing Needs

- More accurate ratings for:
  - Verifying the need for and the effectiveness of new strengthening techniques
  - Removing load restrictions imposed on additional bridges due to the implementation of new weight laws
  - To determine the behavior of structures under heavy load (superload) that have calculated load ratings below anticipated capacity needs

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The Problem

- Unknown bridge conditions
  - Live load distribution
  - End restraint
  - Edge stiffening
  - Composite action
  - Effectiveness of specific bridge details
  - Other details contributing to bridge capacity

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Other Methods

- Proof load testing
- Destructive testing (laboratory)
  - Use to complement diagnostic testing for better understanding

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The Diagnostic Testing Solution

- Physical testing to understand the specific characteristics of each bridge
- Field collected data to calibrate a bridge computer model
- Accurate, calibrated computer model to determine bridge response to rating vehicles and other loads

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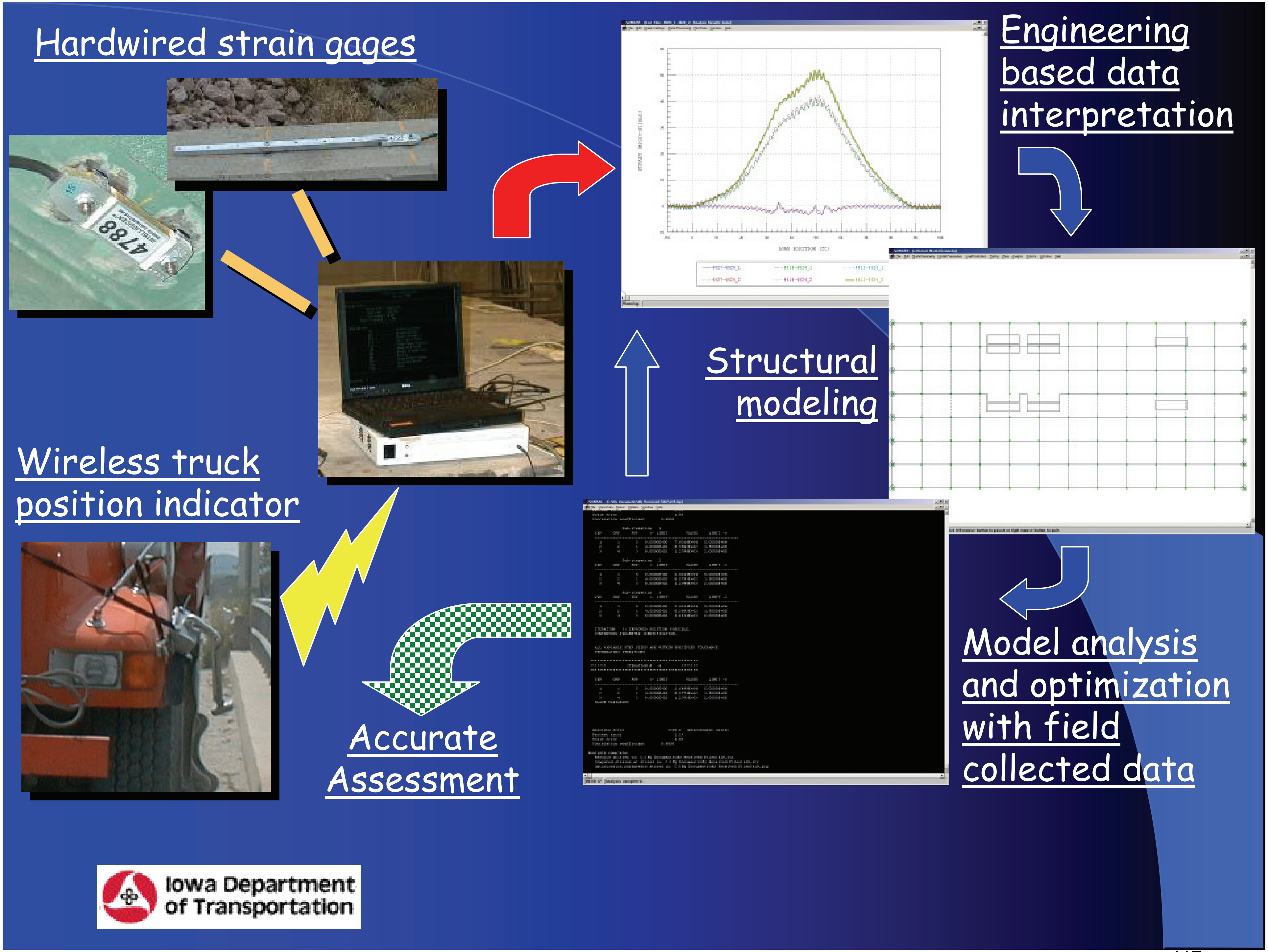

Hardwired strain gages
4788
Engineering based data interpretation
Structural modeling
Wireless truck position indicator
Accurate Assessment
Model analysis and optimization with field collected data
Iowa Department of Transportation

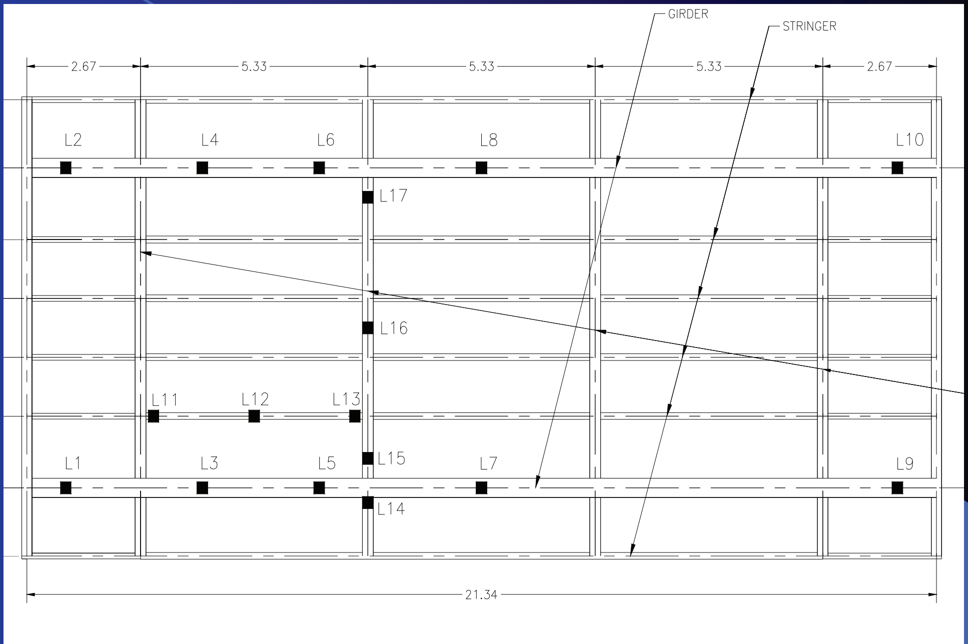
Diagnostic Testing of a Bridge-Brief Case Study

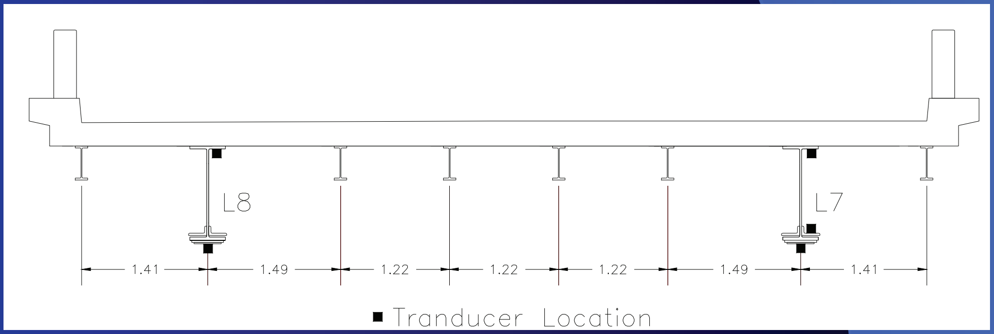
- Carries US 6 over a small stream
- 21.34 m single span
- Two main girders w/ floor beams & stringers
- Welded plates & strengthening angle on girders

Iowa Department of Transportation

Instrumentation

- 36 Intelliducers at 17 locations used
- Focused on:
  - Effectiveness of angles
  - End restraint
  - Load distribution
- Instrumented:
  - Both girders
  - Typical floor beam and stringers





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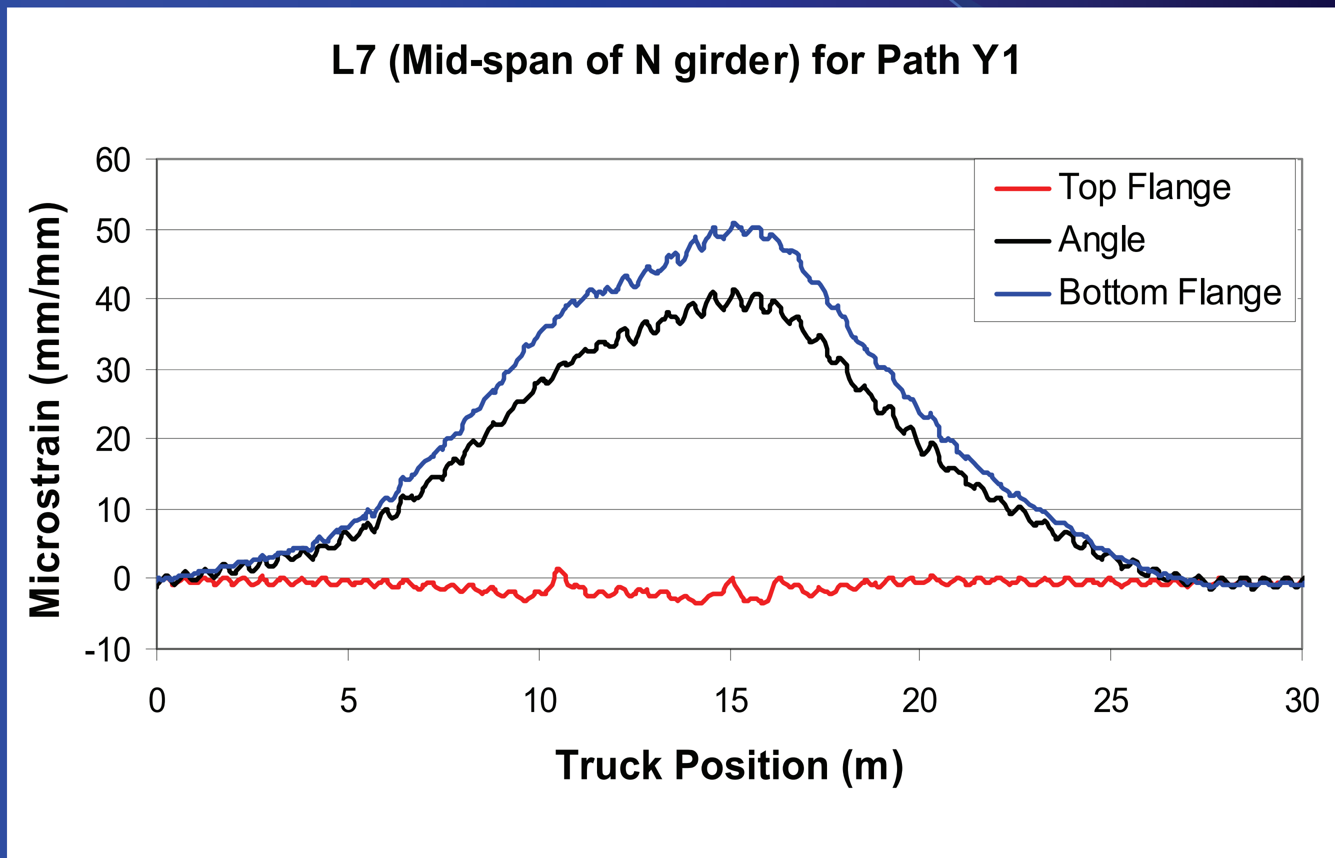
Test Results

- Strengthening angles are effective



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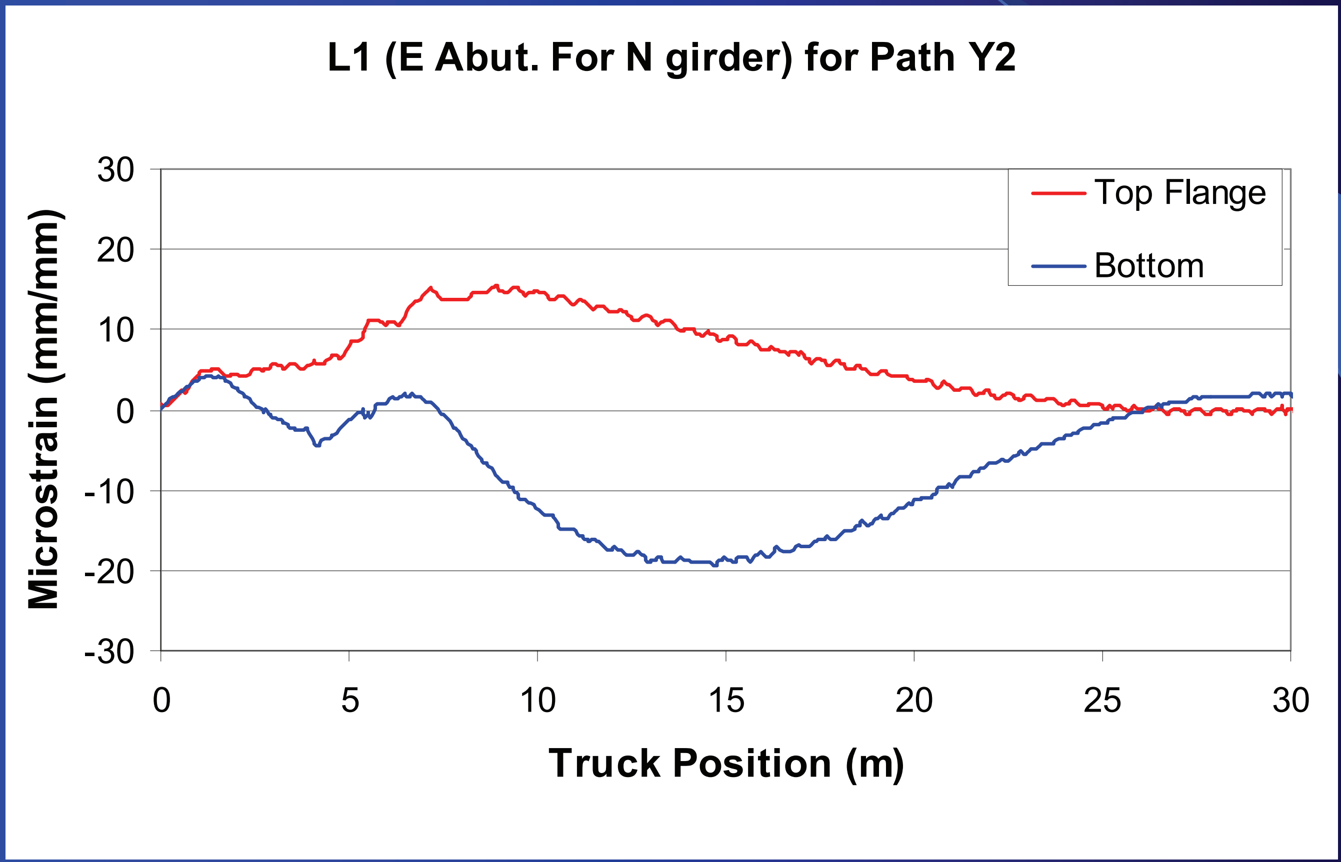
Test Results

- Significant end restraint identified



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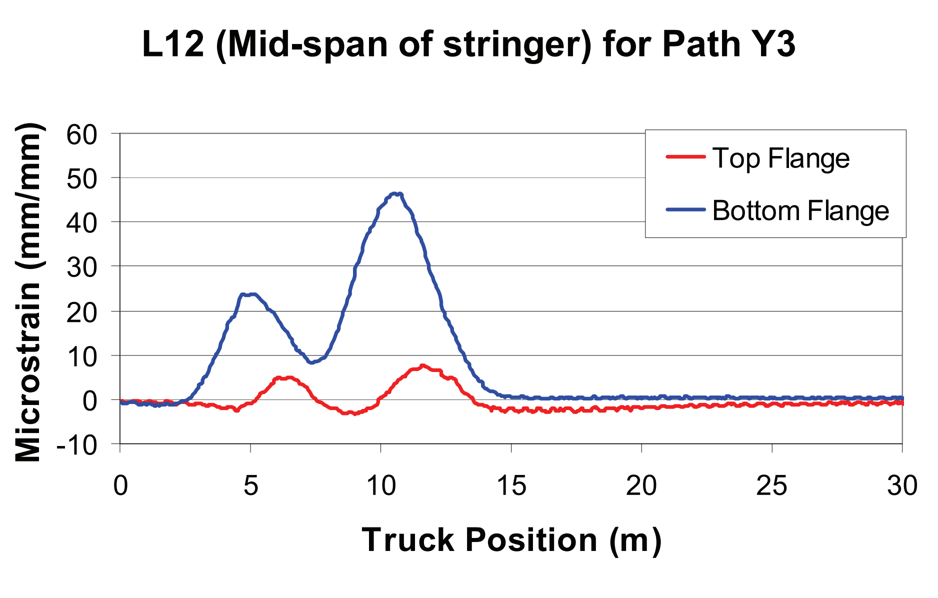
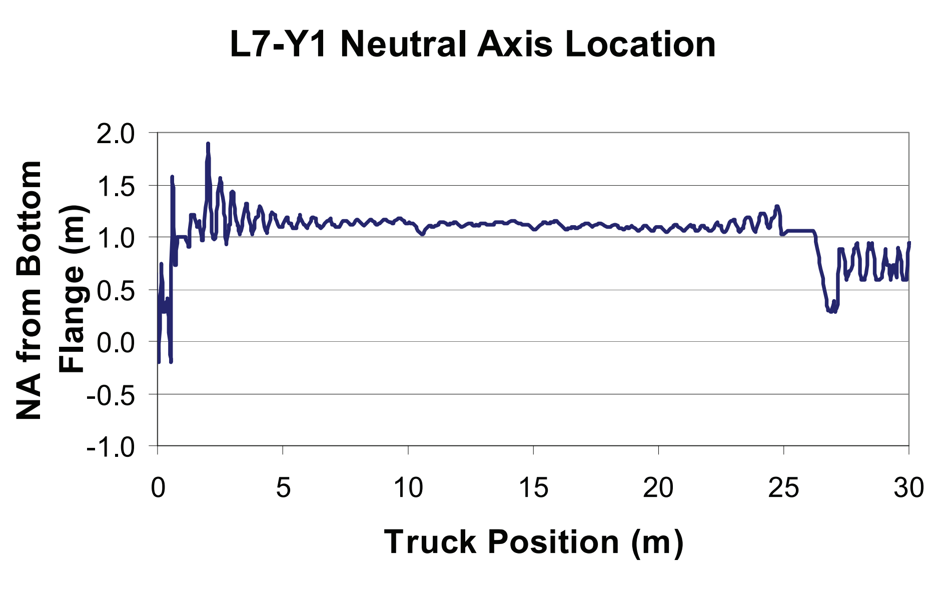
Test Results

- Composite action determined





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LFD Rating for HS-20 Vehicle

Conventional AASHTO LFD

- Shear (stringer)
  – 2.44
- Flexure (girder)
  – 2.39

WinSAC LFD

- Shear (stringer)
  – 1.79
- Flexure (floor bm)
  – 3.67

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Results of Diagnostic Testing

- General increase in flexural rating of all members
- Shear rating decreased and controlled for this bridge
- Effectiveness of unknown structural elements identified

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Superload Evaluation

- Summer 2003 – Passage of 6 superloads ranging from 600,000 lb. to 900,000 lb.
- Most bridges along route acceptable by traditional calculations
- Hand calculations for one bridge – rating factor of approximately 0.5
- Physical test needed

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Bridge Characteristics

- Six pre-stressed concrete girder lines
- Critical span
  ~ 122 ft (37 m)
- 40 ft (12 m)
  roadway
  carrying two
  lanes of traffic

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Initial Testing

- Tested with combinations of one and two loaded tandem axle dump trucks
- Much learned about behavior
  - Composite action
  - End restraint
  - Live load distribution
    - Improved load distribution characteristics used in hand calculations changed RF to 0.9

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Analytical Modeling

- Bridge modeled using WinGEN
  - 7 elements groups created and optimized
- Less than 10% error

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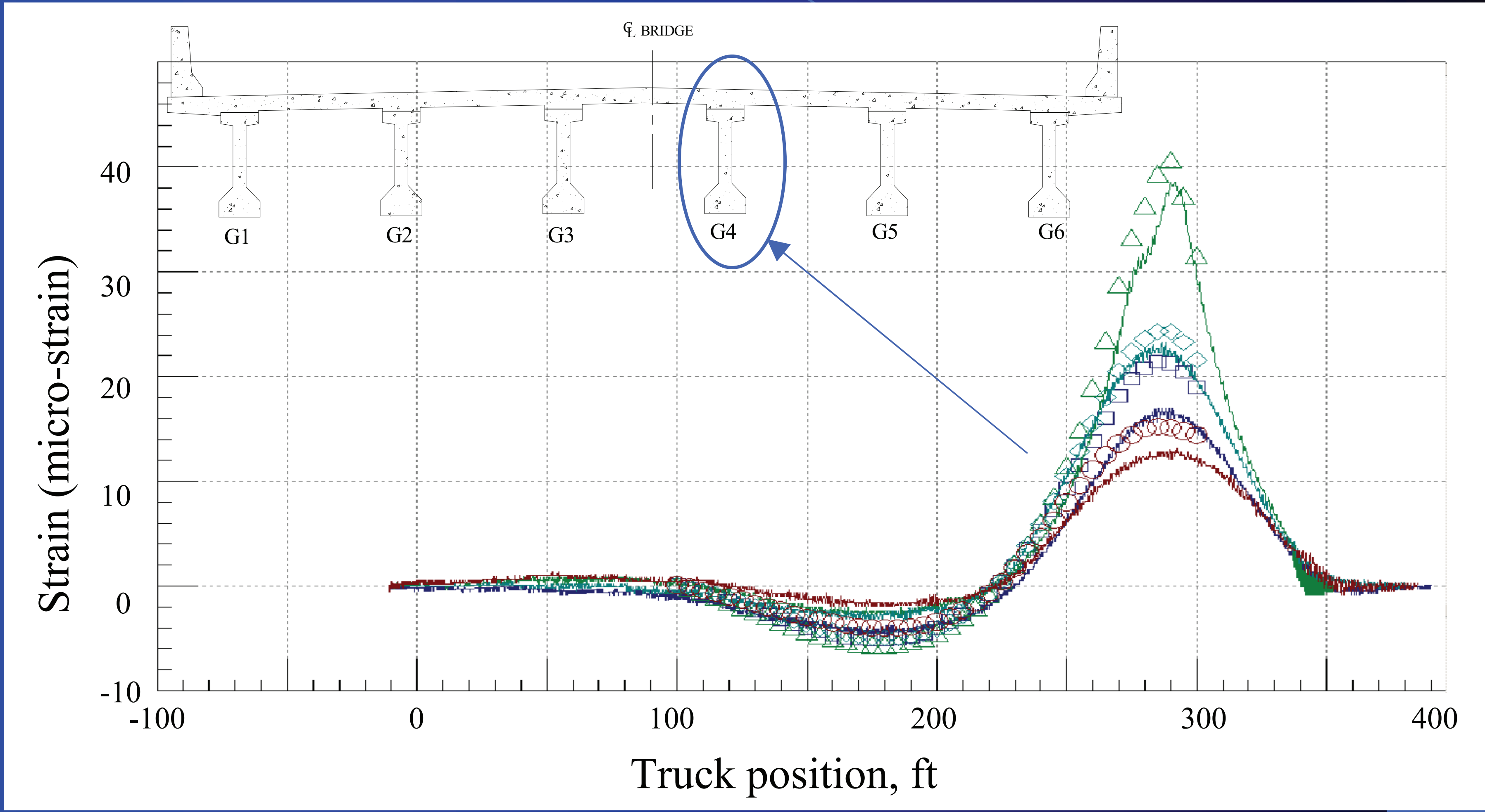
Preliminary testing (one load truck)



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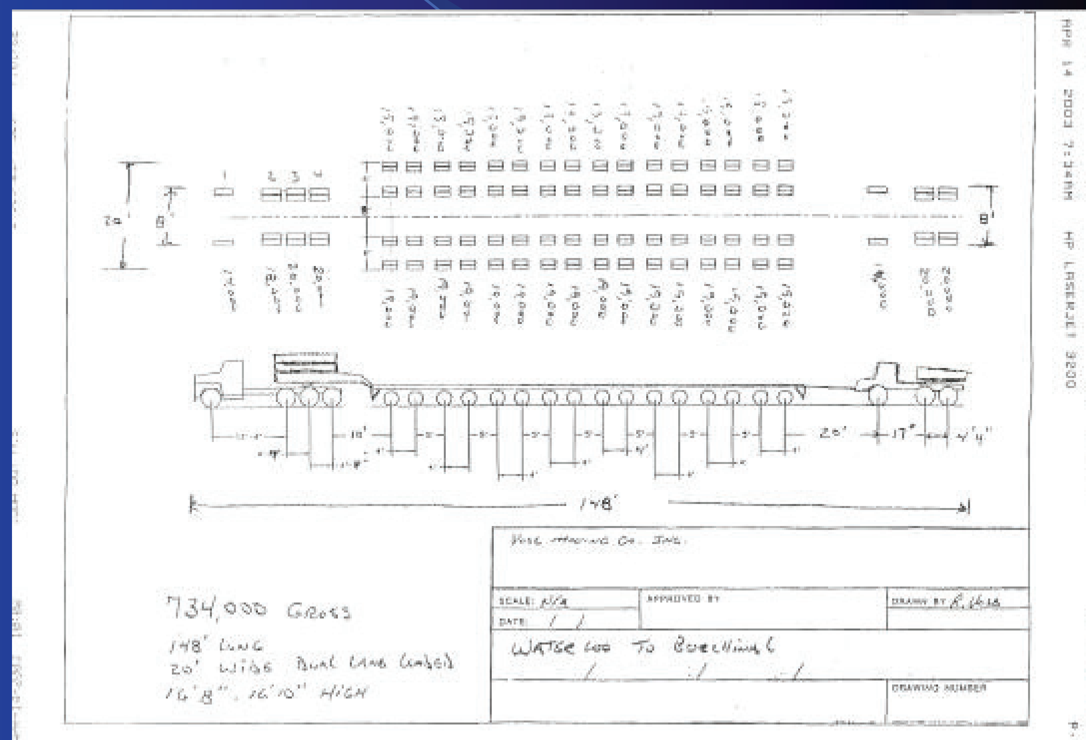
Analysis with Superload

- Optimized model used to predict bridge behavior to anticipated load
- Determined to be acceptable



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Monitoring During Passage

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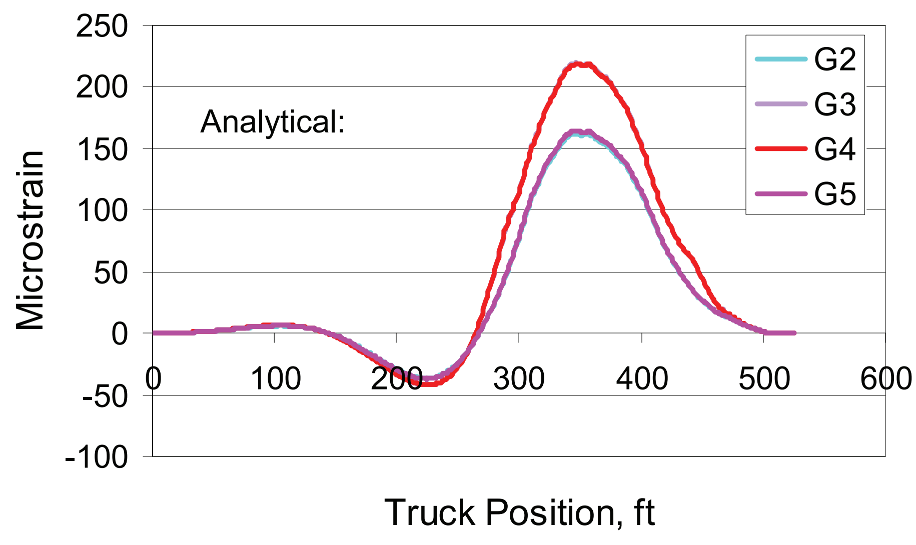
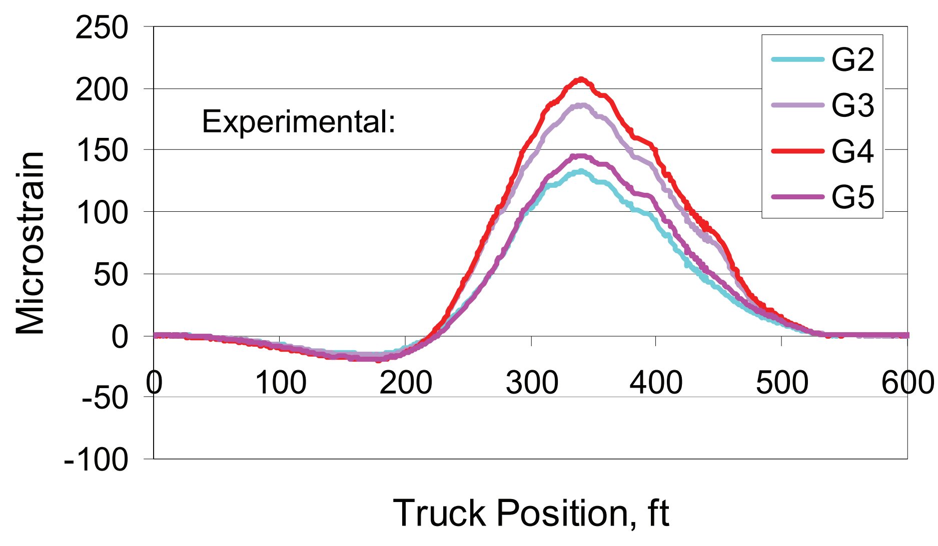
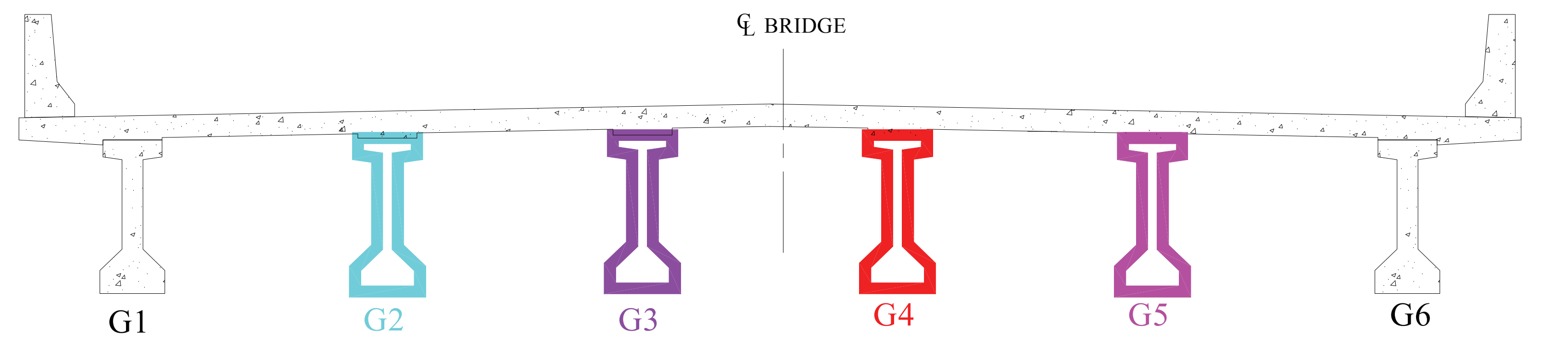
Accuracy of Prediction







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Conclusions

- System is well suited to rating "typical" highway bridges
  - Materials
    - Steel
    - Concrete
    - Timber
  - Type
    - Simple span
    - Continuous span
    - Truss

Iowa Department of Transportation

Conclusions

- Expect more opportunities to obtain superload data
- Other “bridge fleet” research underway

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Chapter 15

Field Test of the Red Rock Reservoir Bridge

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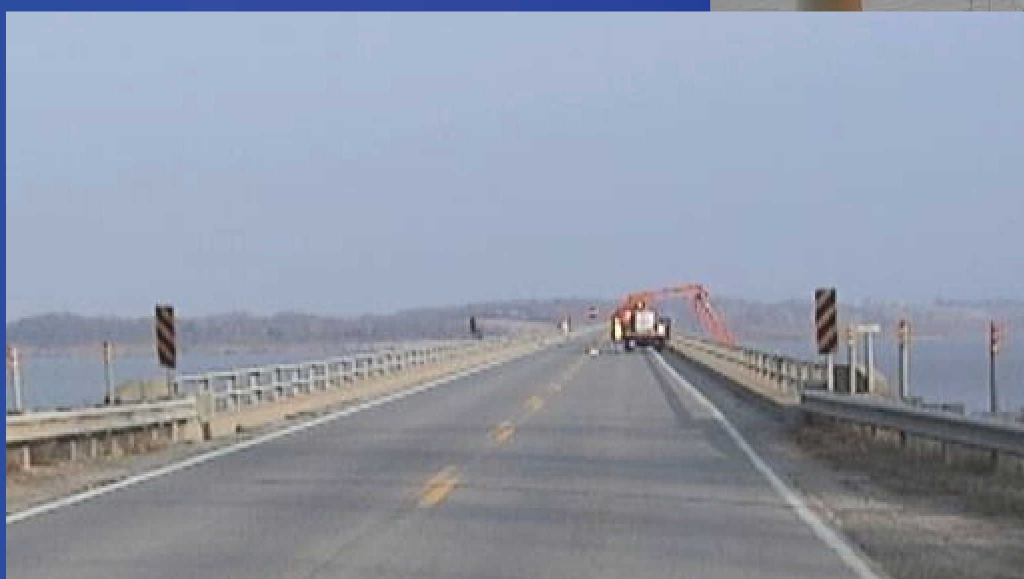

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Background

- Many floor beams were retrofitted with plug welds placed in improperly drilled holes on the tension flange
- No observed fatigue cracking during the life of the structure

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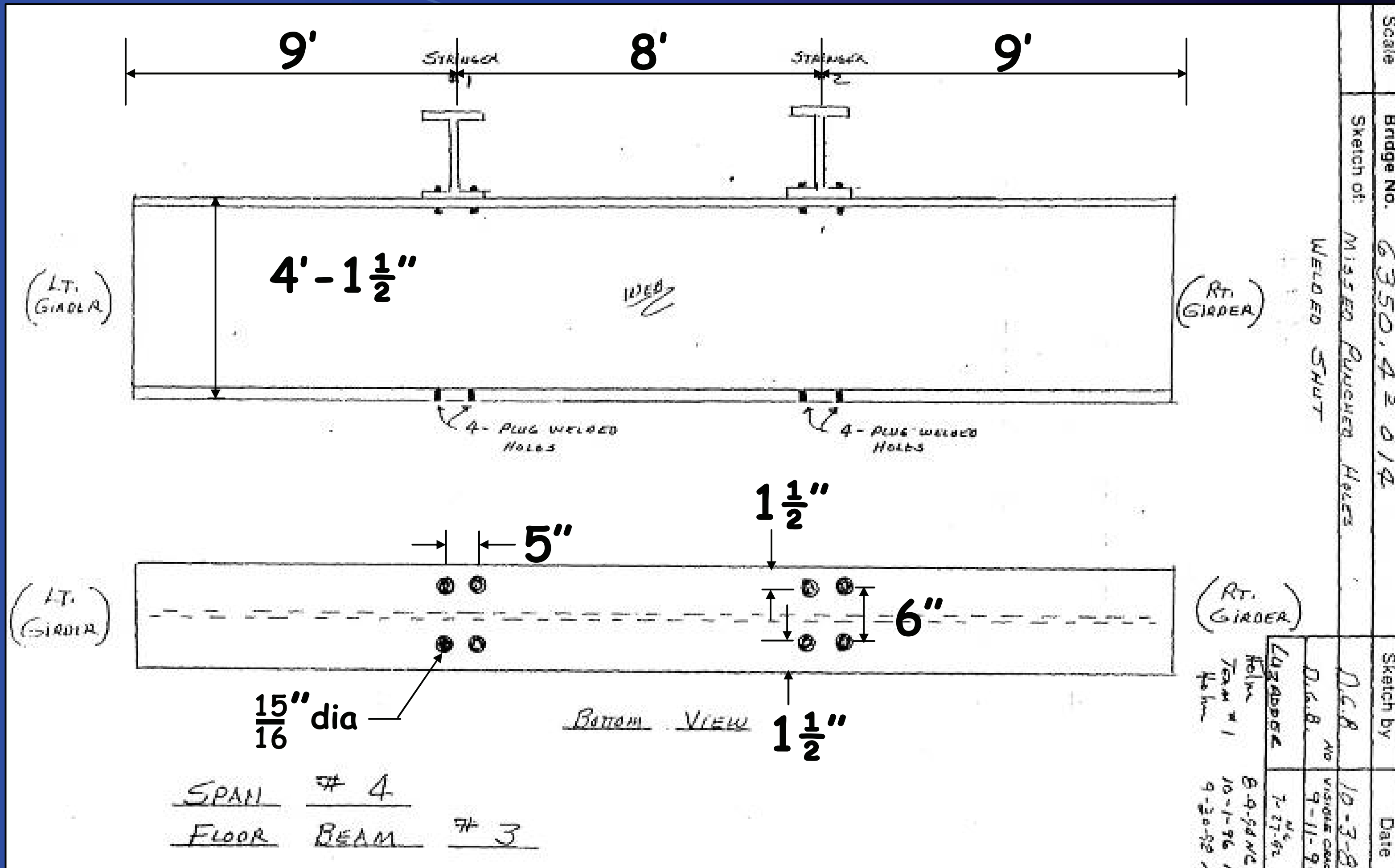

NOTE: Centerline of roadway corresponds with centerline of floor beam and strain gage location.

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Problem Statement

- Are the plug welded locations prone to fatigue cracking

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Objective

- Field load test with loaded trucks of known weight
  - measure local bending strain around a plug welded hole on typical floor beam to determine potential for large localized stresses
  - measure global bending strain at mid-span of typical floor beam both with and without plug welded holes to compare with magnitude of localized hole stresses

Iowa Department of Transportation

Test Instrumentation

- Span 4 Floor Beams instrumented on bottom flanges
  - Floor Beam 2 (no plug welds)
    - strain gage under east stringer (global)
    - strain gage under mid-span (global)
  - Floor Beam 3 (plug welds)
    - Strain gage under east stringer (global)
    - Strain gage under mid-span (global)
    - Six gradient strain gages around typical plug welded hole (local)

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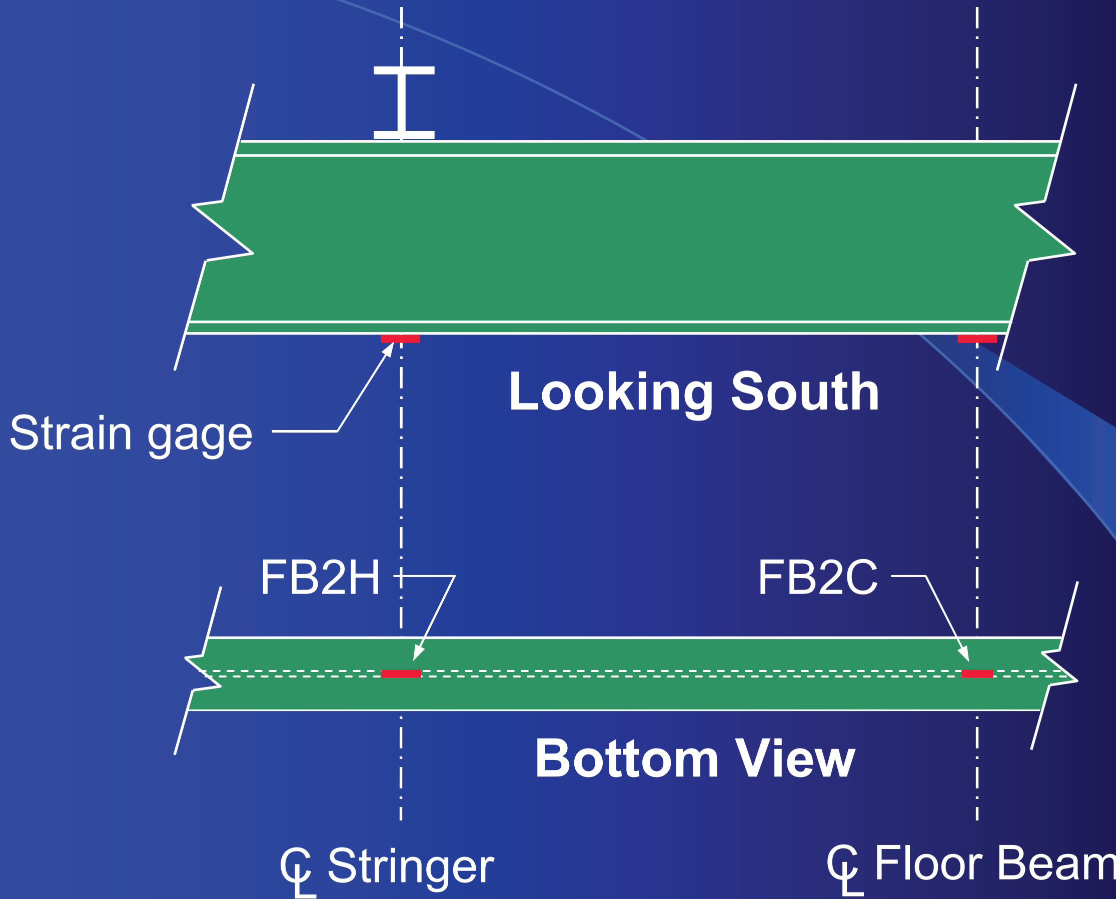

Floor Beam 2

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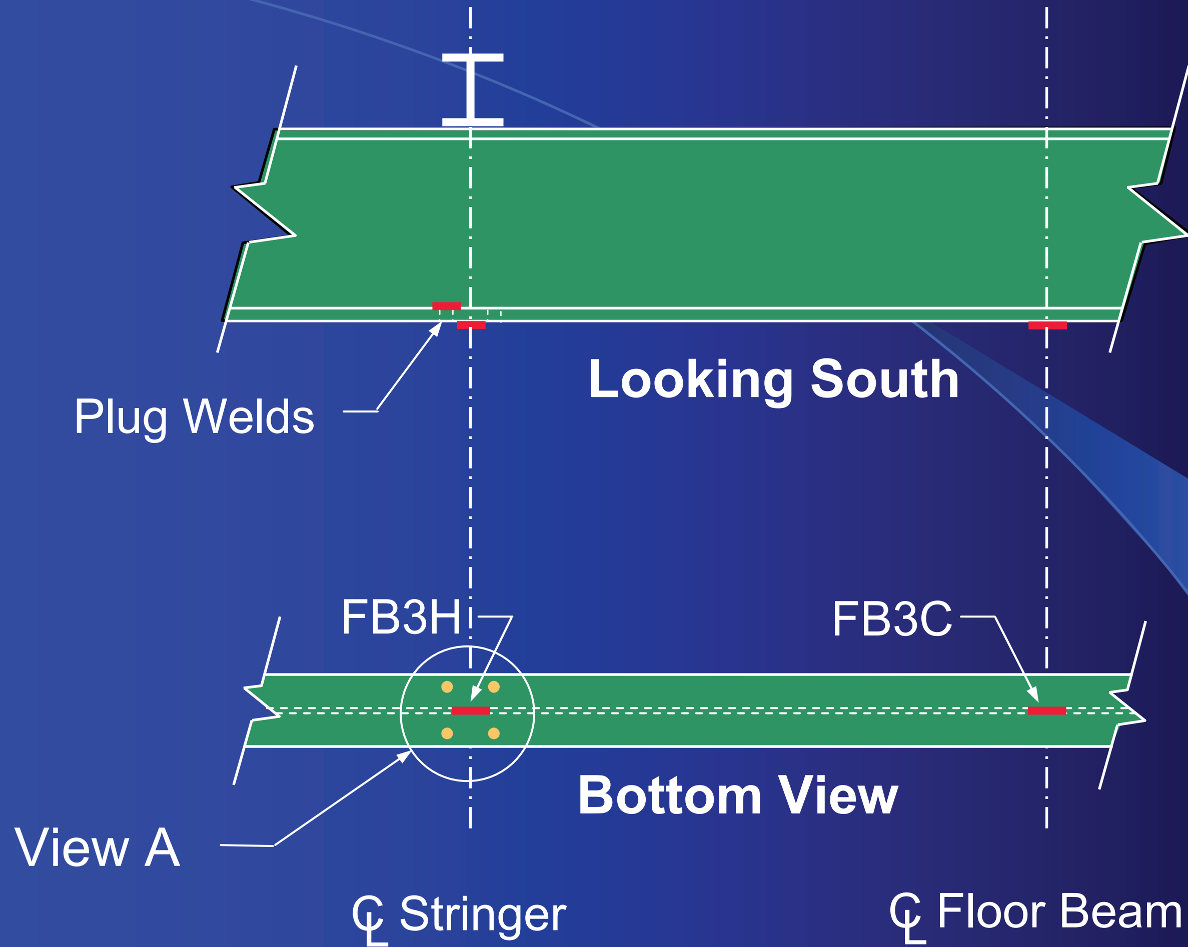
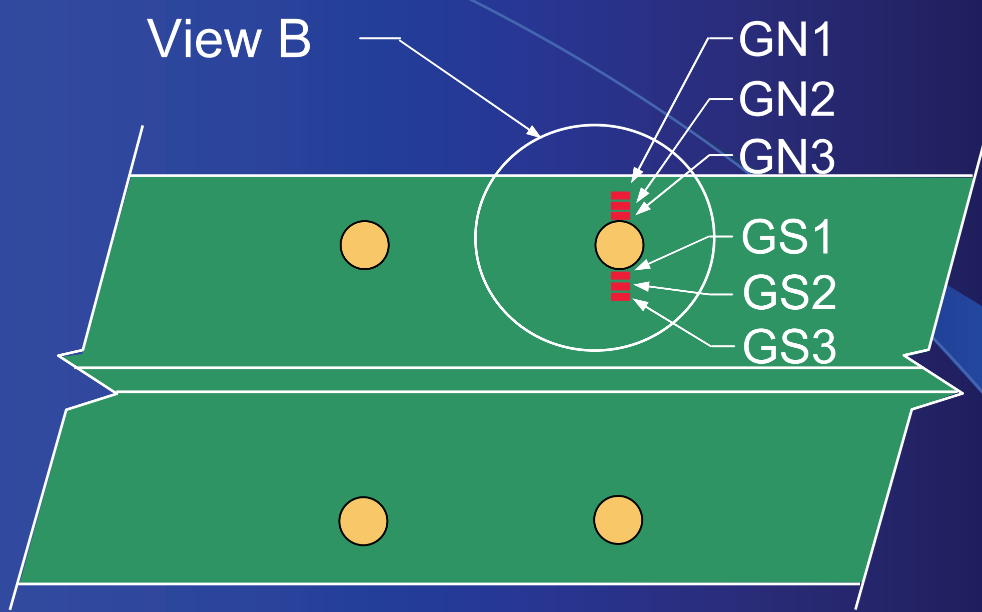
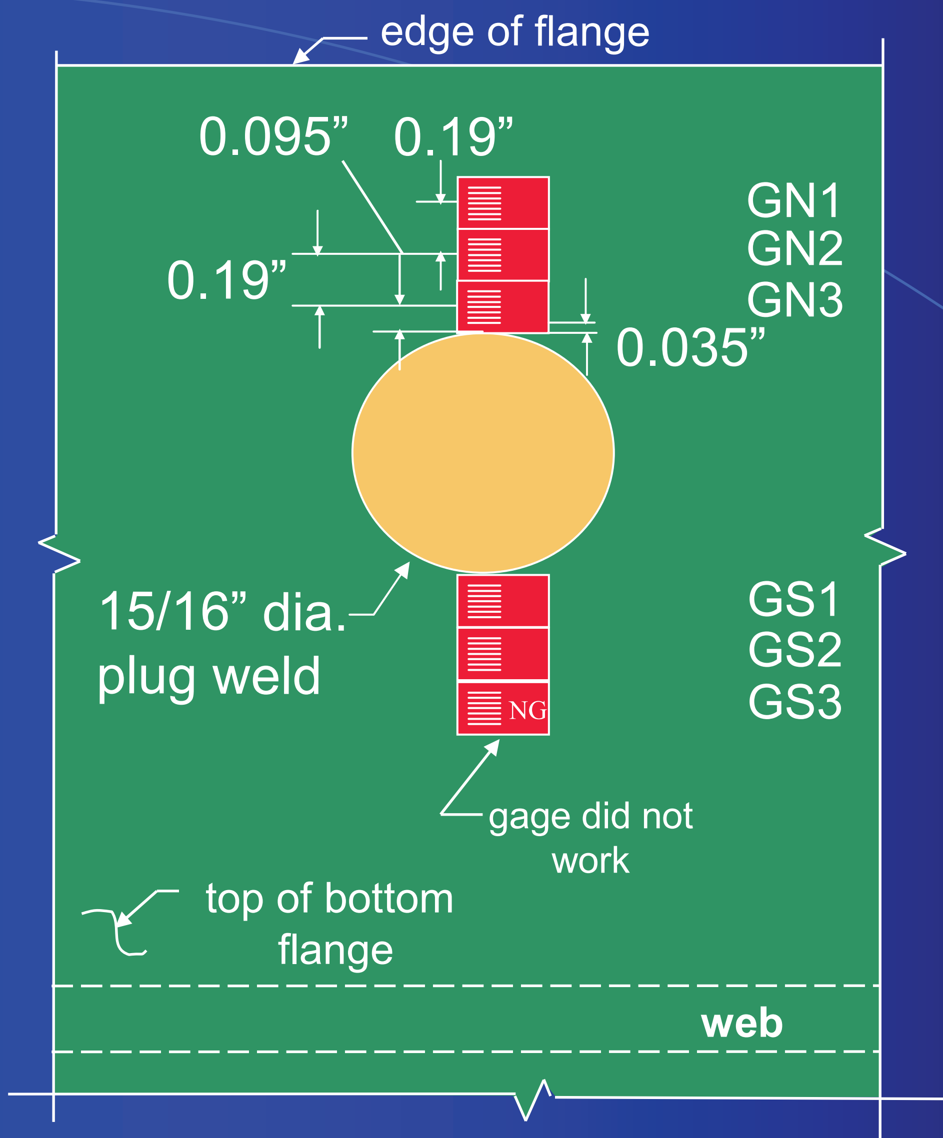

Looking South
Plug Welds
FB3H
FB3C
Bottom View
View A
℄ Stringer
℄ Floor Beam

Floor Beam 3



View A Top of Bottom Flange



View B Top of bottom flange

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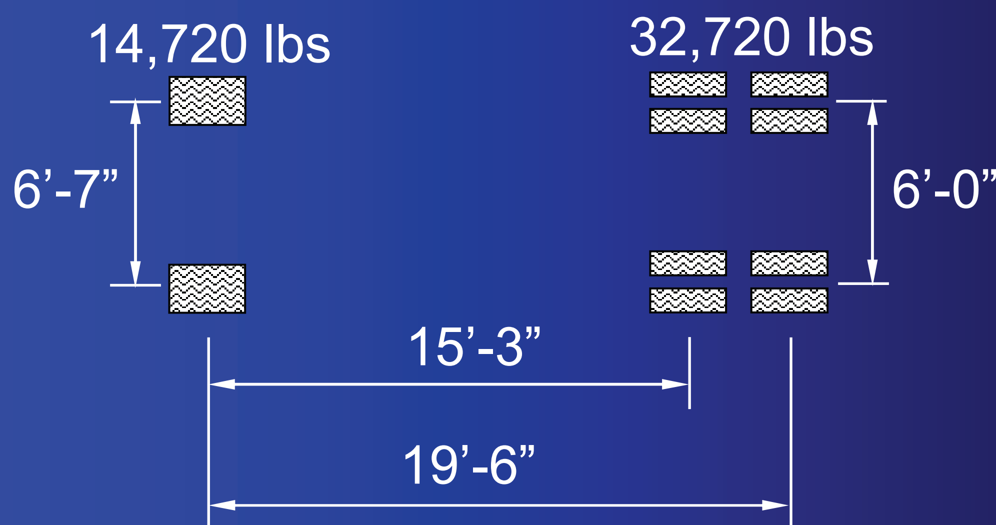
Truck 1



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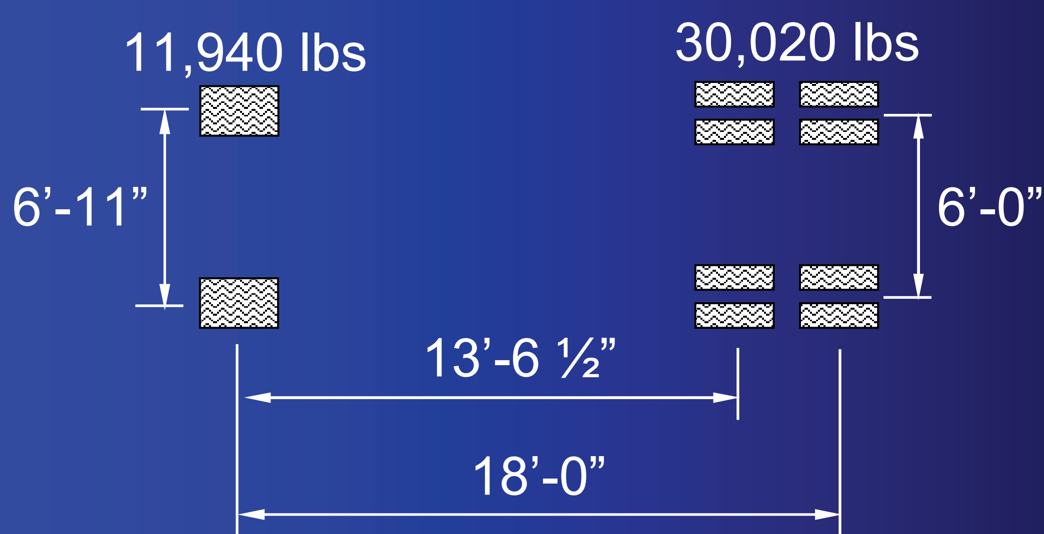
Truck 2



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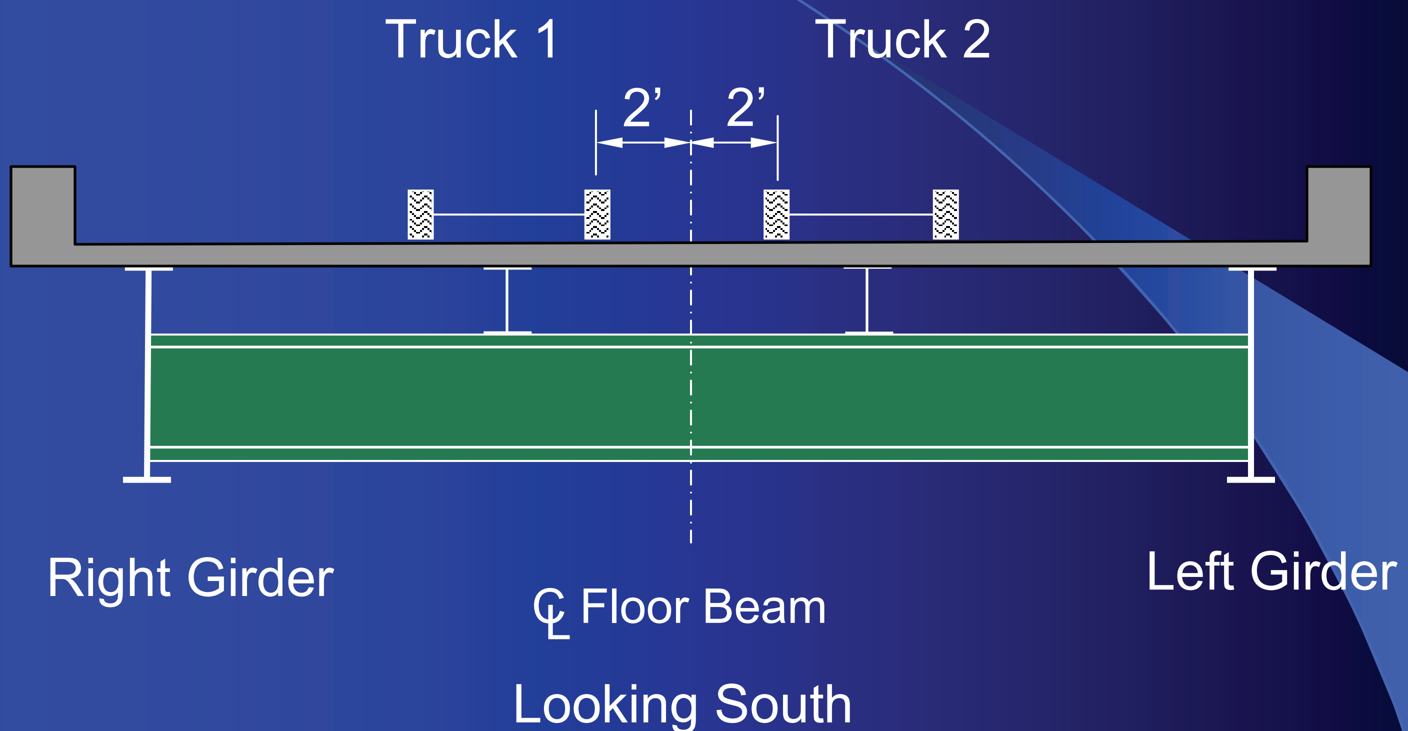
Test Truck Positions



Cross Section

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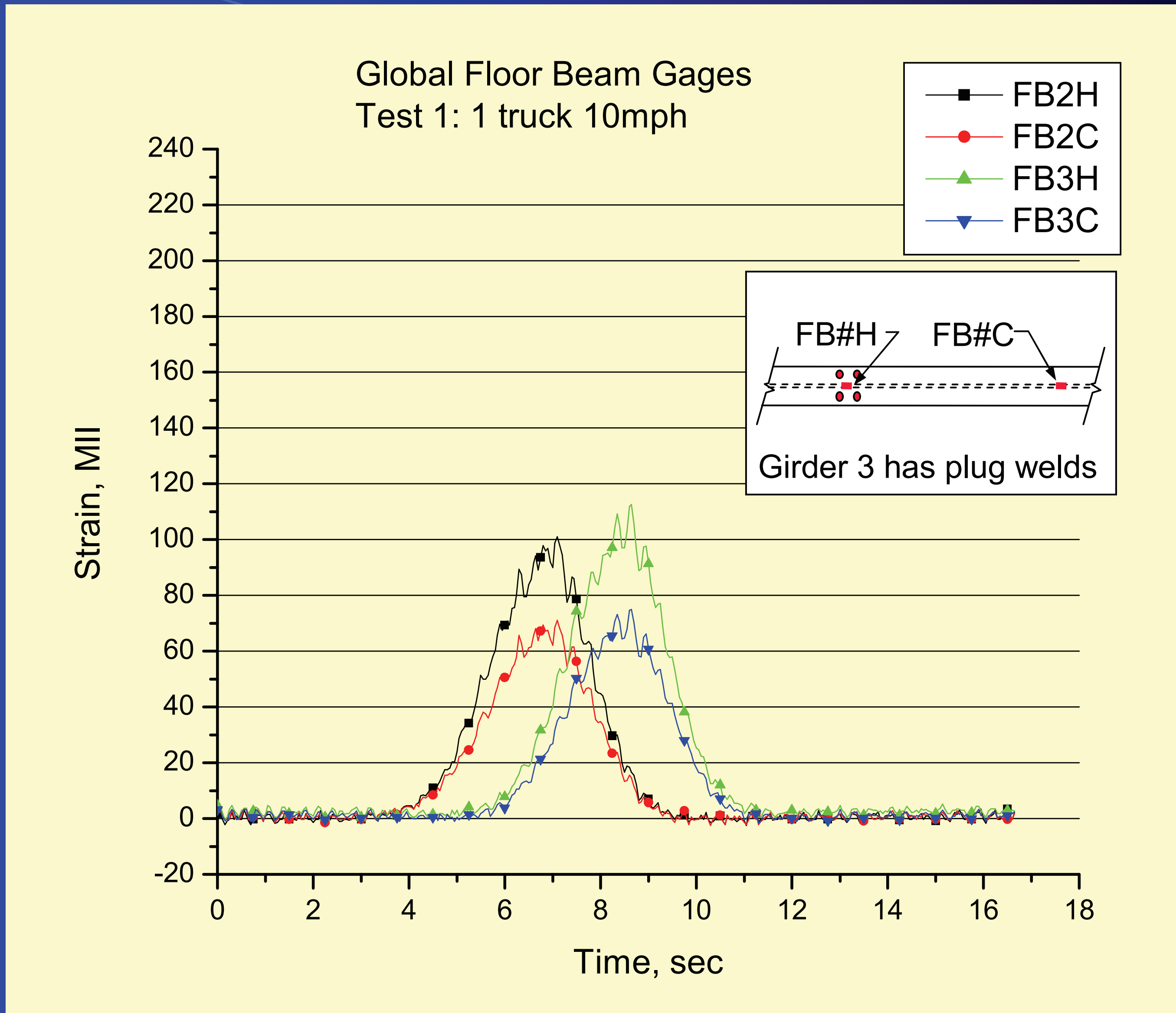
Field Test Results



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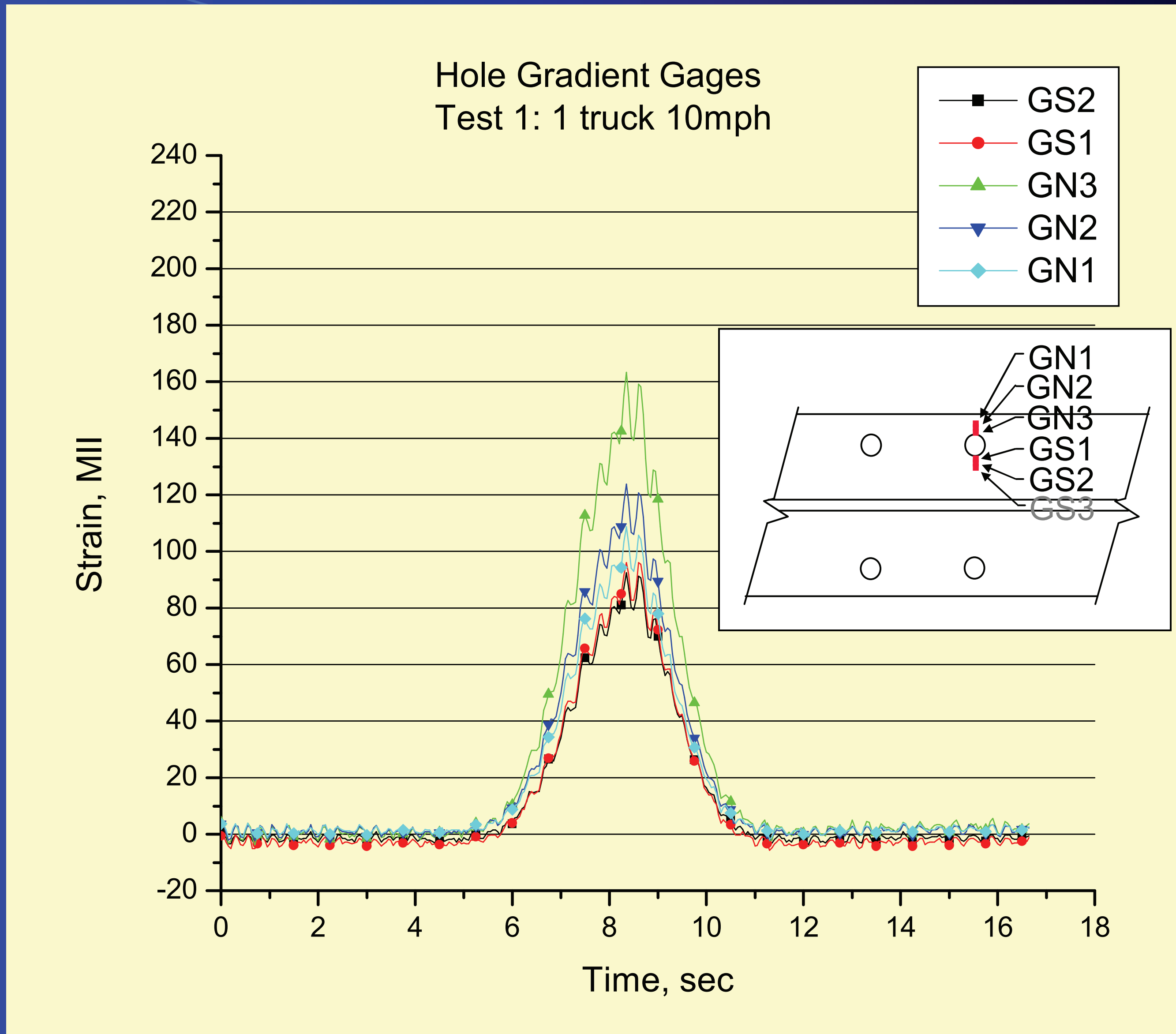

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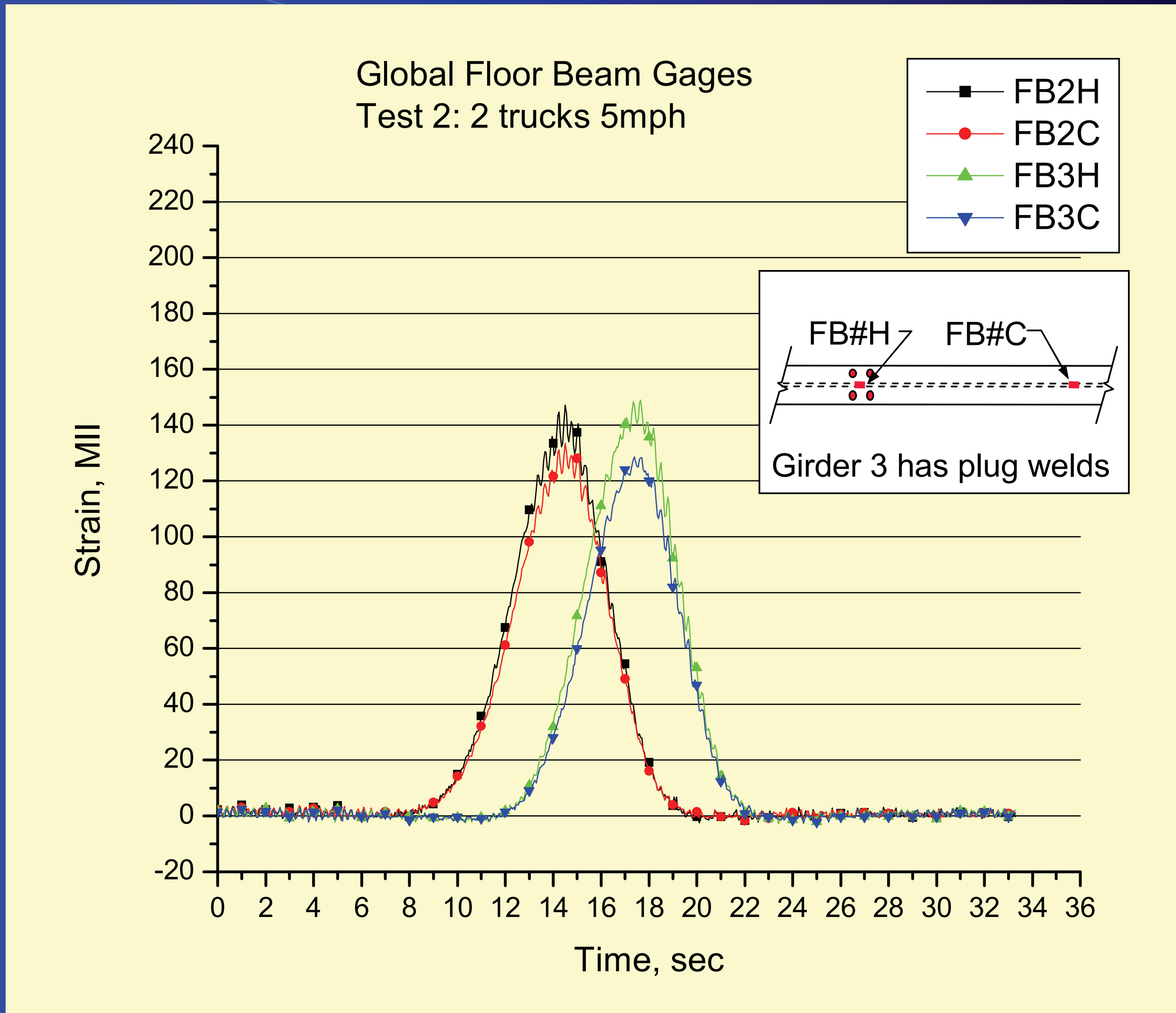

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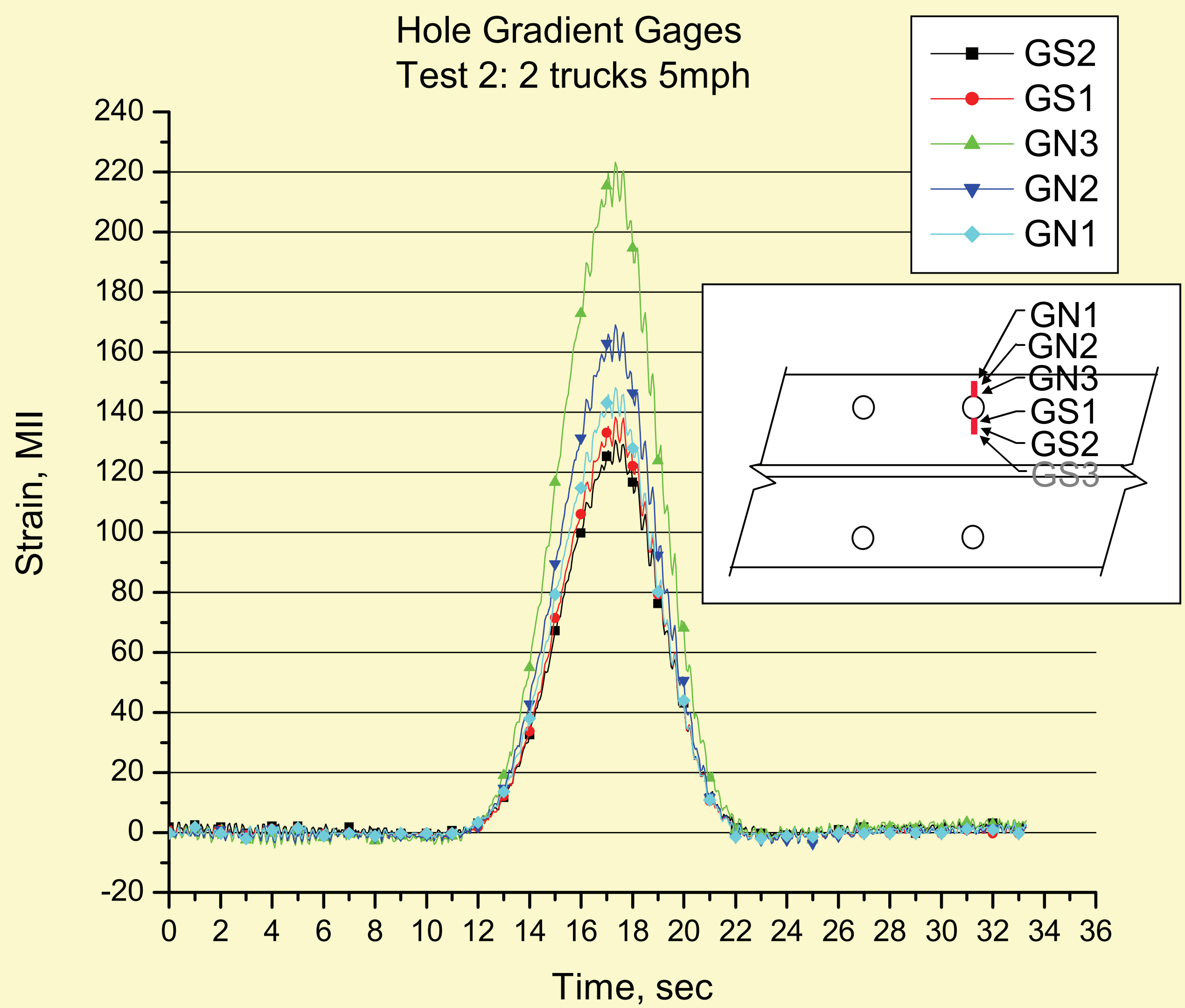

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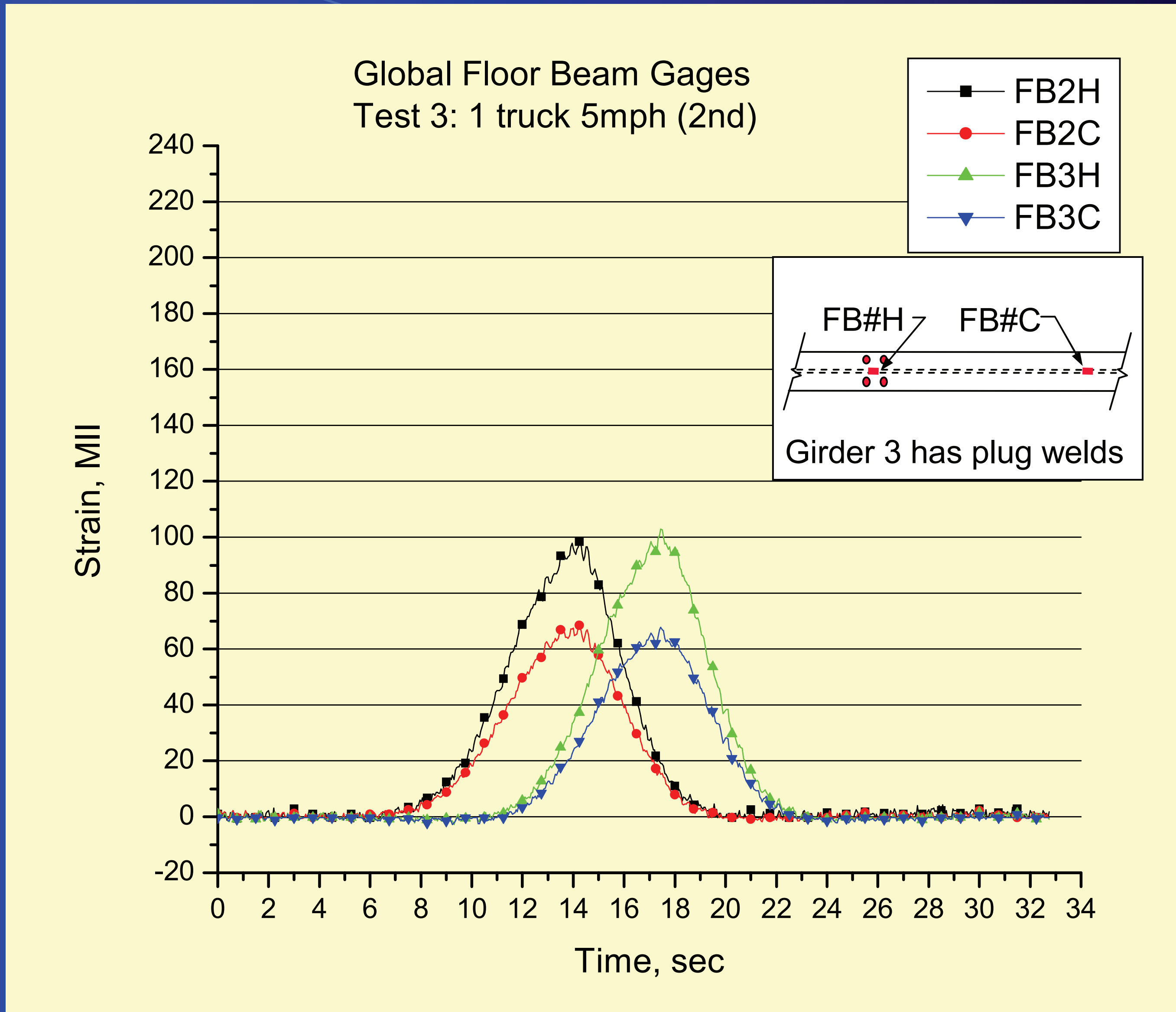
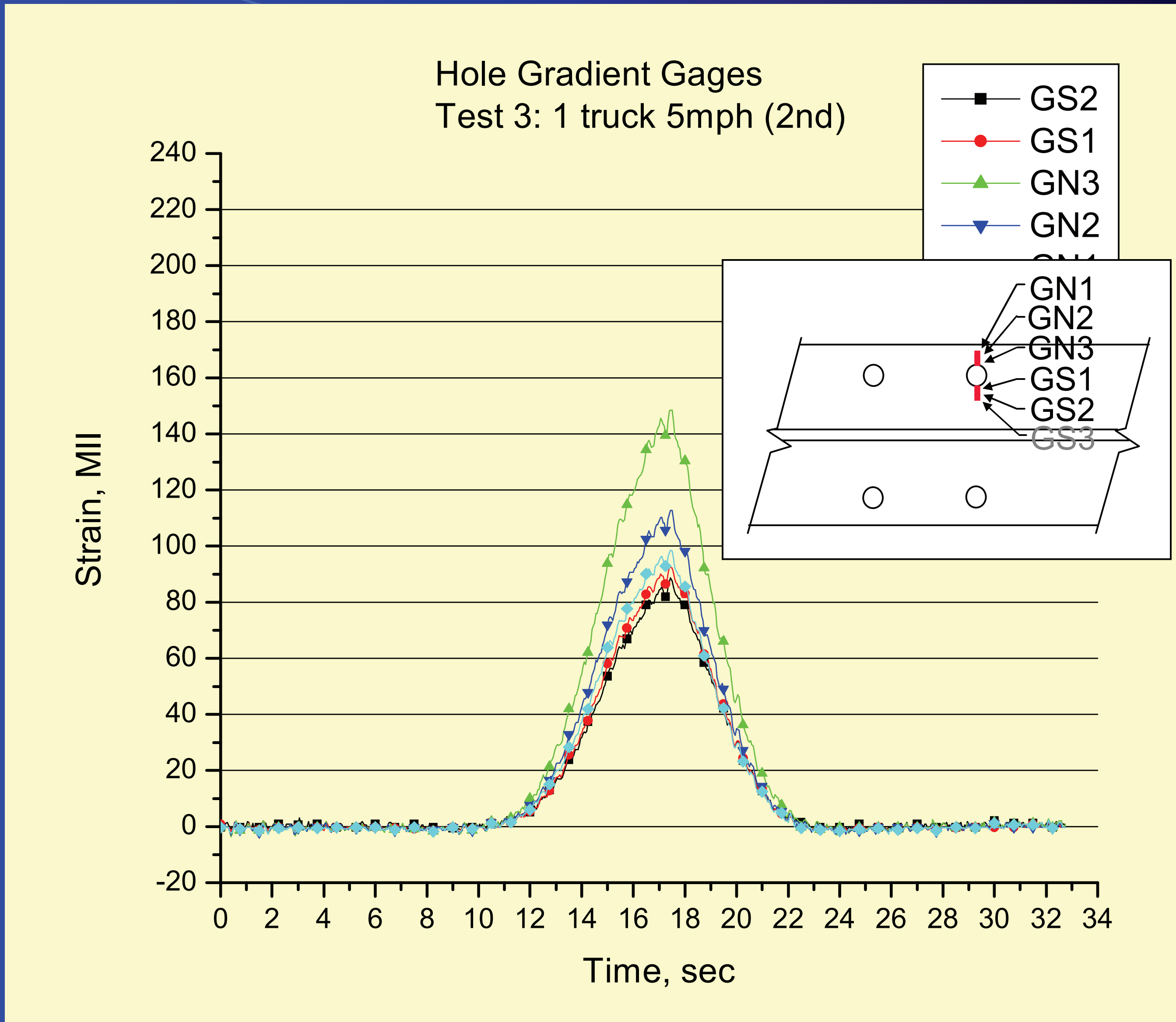


Global Floor Beam Gages
Test 3: 1 truck 5mph (2nd)
FB2H
FB2C
FB3H
FB3C
FB#H
FB#C
Girder 3 has plug welds
Strain, MII
Time, sec
240
220
200
180
160
140
120
100
80
60
40
20
0
-20
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34



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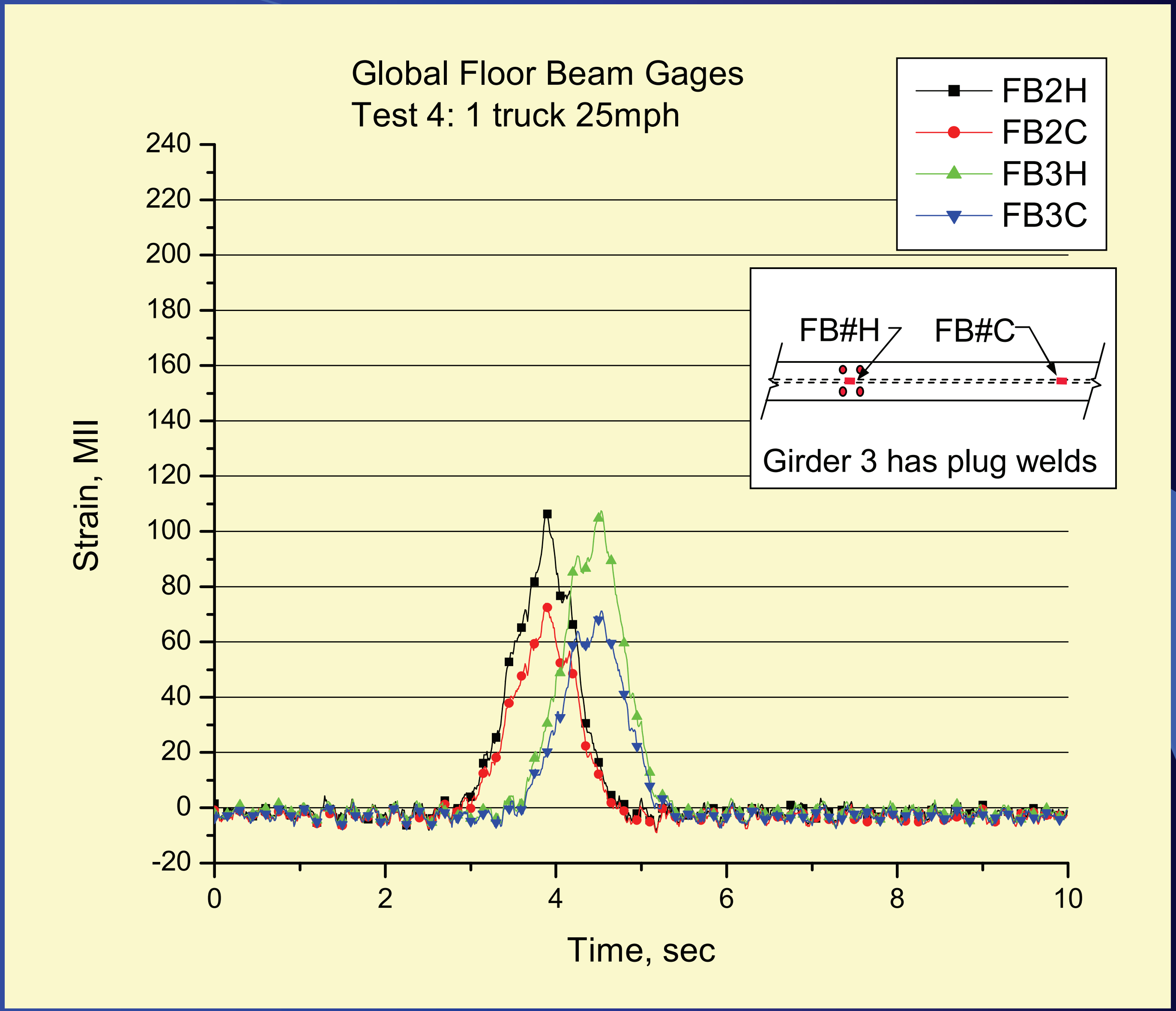

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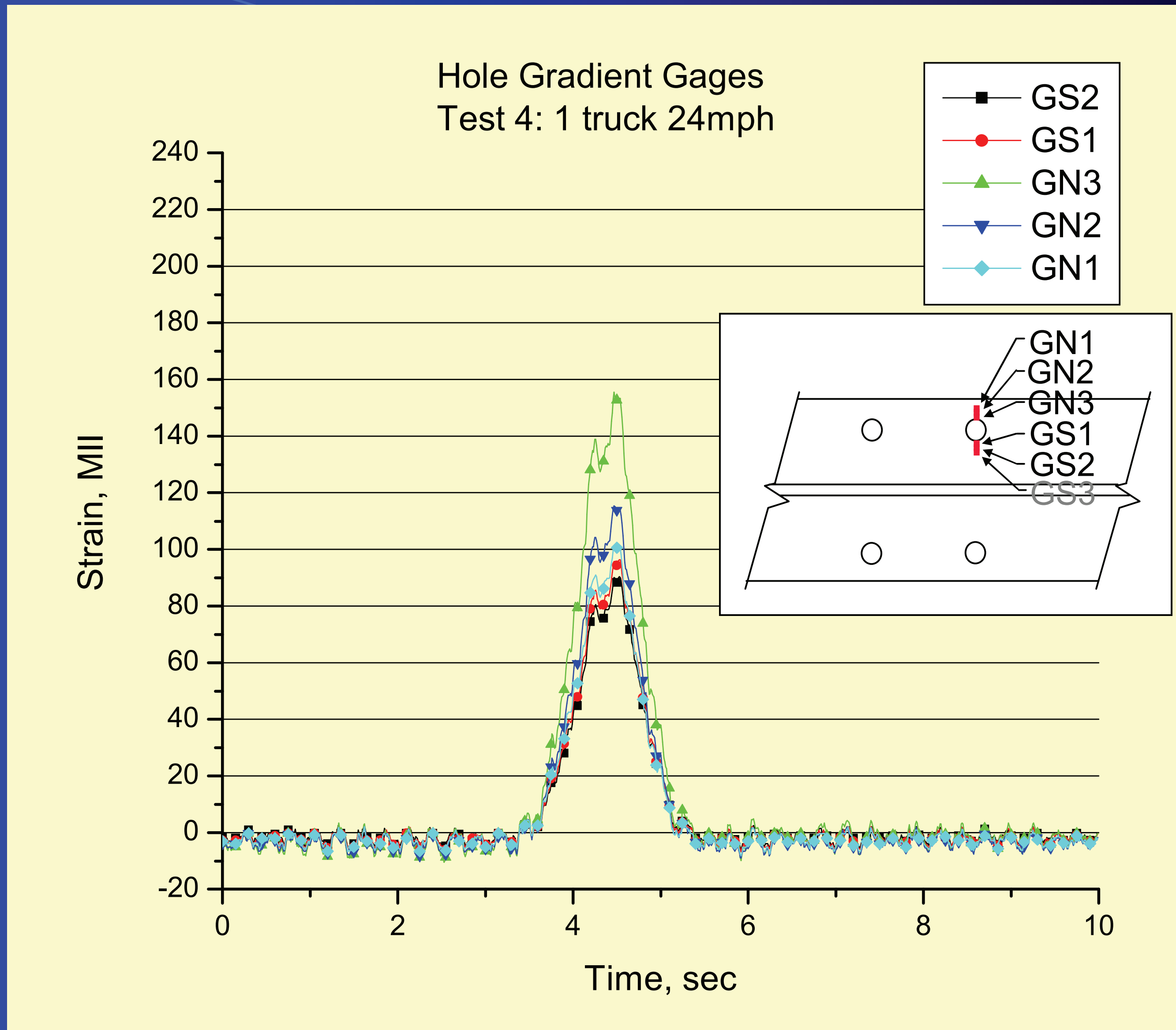

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Conclusions

- Two trucks side by side:
  - Maximum localized stress approximately 57% greater than maximum global stress

- Single truck:
  - Maximum localized stress approximately 56% greater than maximum global stress