Instrumenting Anchorage Zones of Post-tensioned Box Girder Bridges

University of Nevada, Reno

Caltrans

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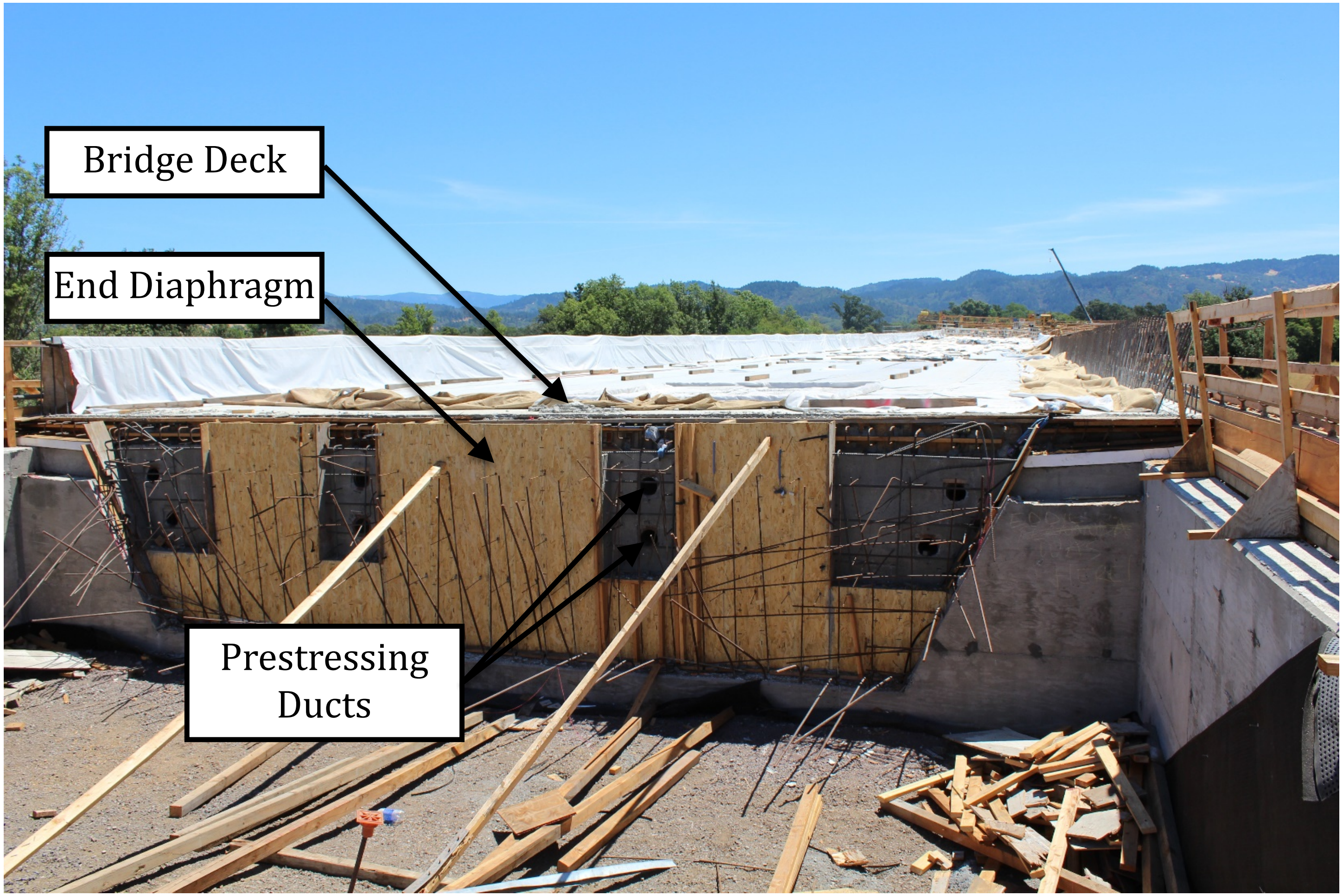
Western Bridge Engineers' Seminar, September 9 – 11, 2015, Reno, NV
"PRACTICAL SOLUTIONS TO BRIDGE ENGINEERING CHALLENGES"

Outline

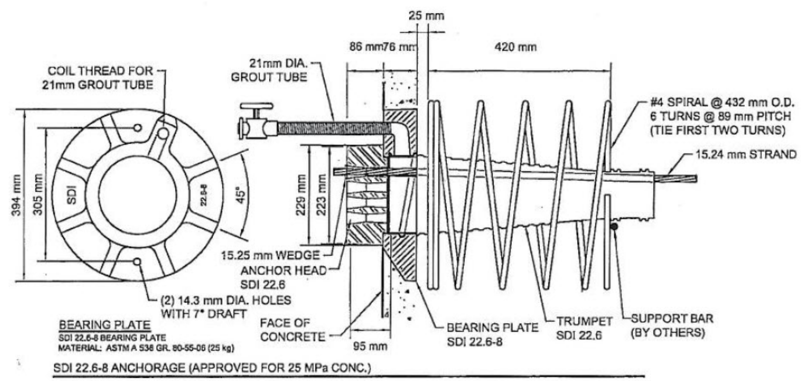
- **History of Anchorage Zone Design (Caltran's efforts)**
- **Research Problem Statement**
  - Case Studies
  - Effectiveness of existing design
- **Project Objectives**
- **Preliminary Analysis**
  - Finite Element Modeling
  - Box Girder Bridges Database
- **Field Instrumentation**
  - Instrumentations Preparation
  - Instrumentation Plans
  - Instrumentations Installation
- **Field Investigation Results**
  - Adequacy of Instrumentation
  - Corrections performed
  - Sample of results
- **Expected Anchorage Performance**
- **Conclusions**
- **Future Plans**

End Diaphragm of Box Girder

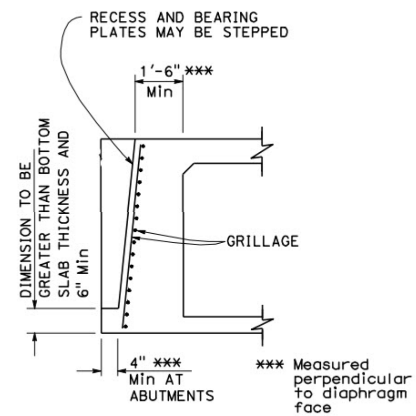


History of Anchorage Zone Design

- **Disturbed Regions: Abrupt changes in cross section, such as End Diaphragms for post tensioned box girders**
- **General zone versus local zone**
  - **Local zone by contractor**



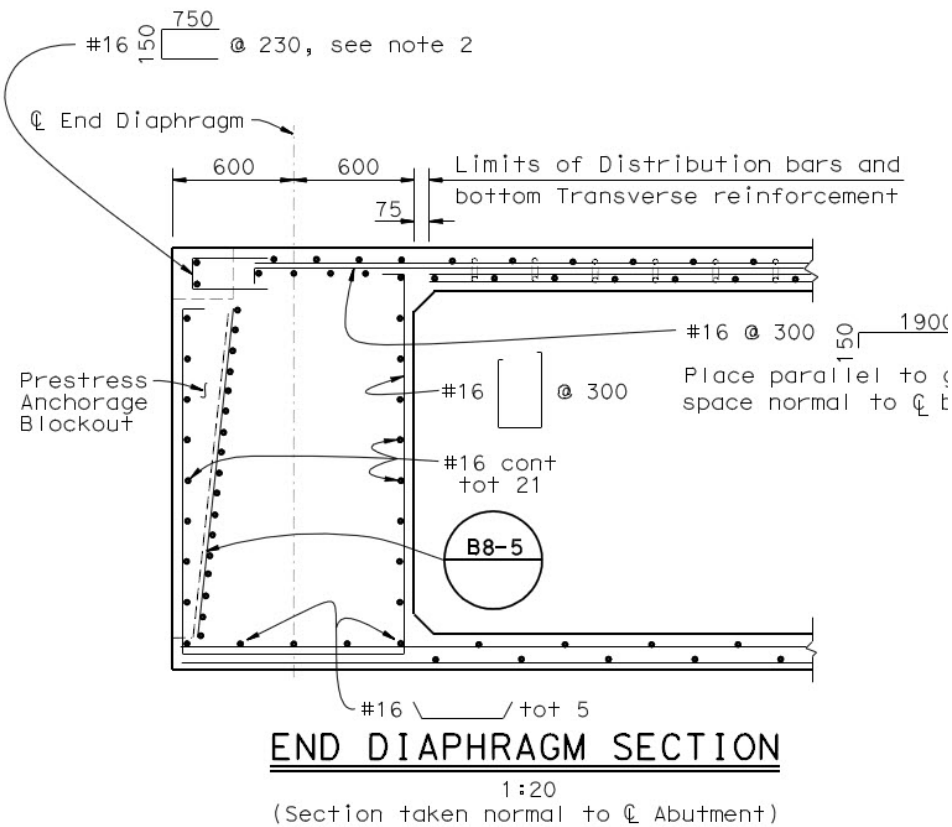
  - **General zone: Standard plans B8-5**



SECTION B-B

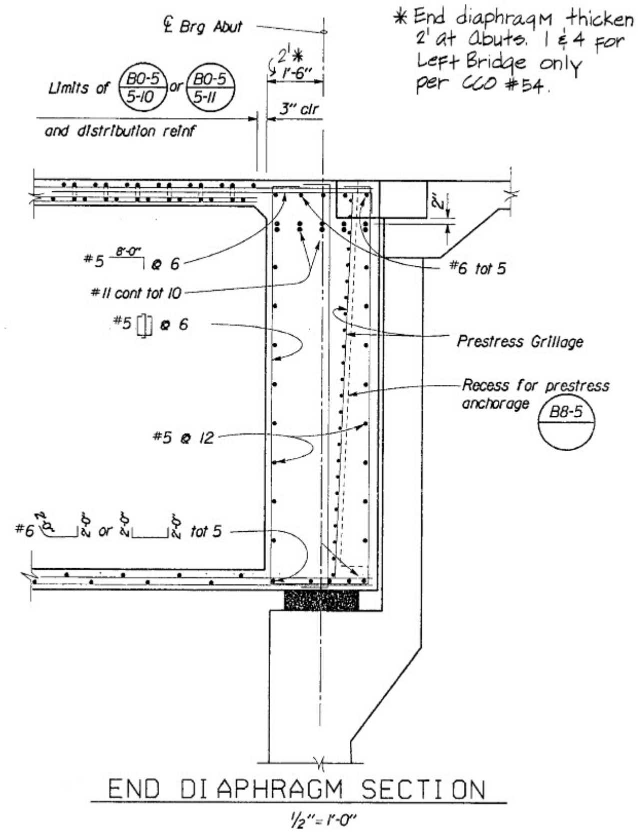
History of Anchorage Zone Design

- **Typical end diaphragm details**



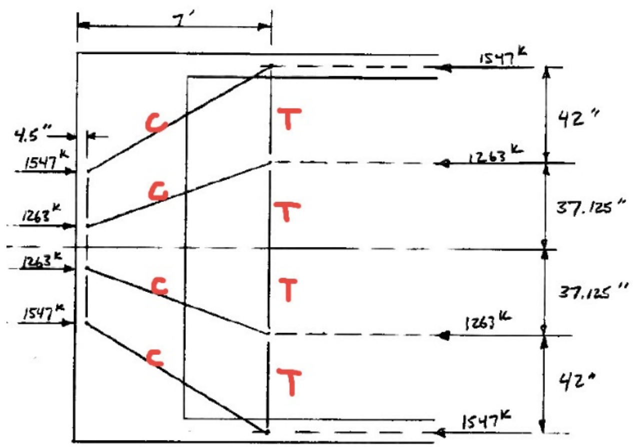
History of Anchorage Zone Design

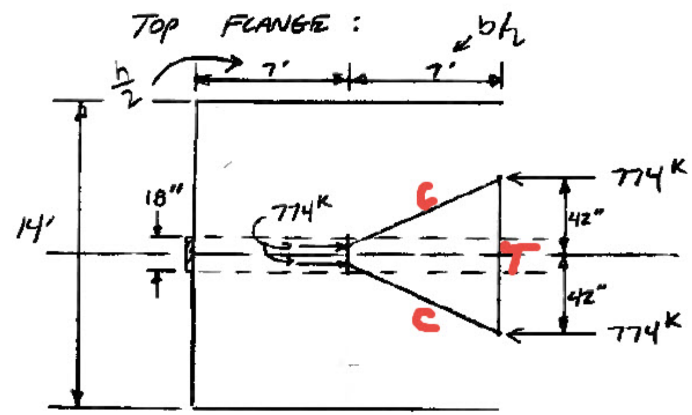
- **Monument Blvd end diaphragm details**



History of Anchorage Zone Design

- **Strut and tie methods**
  - Example from Collins and Mitchell, "Prestressed Concrete Structures"

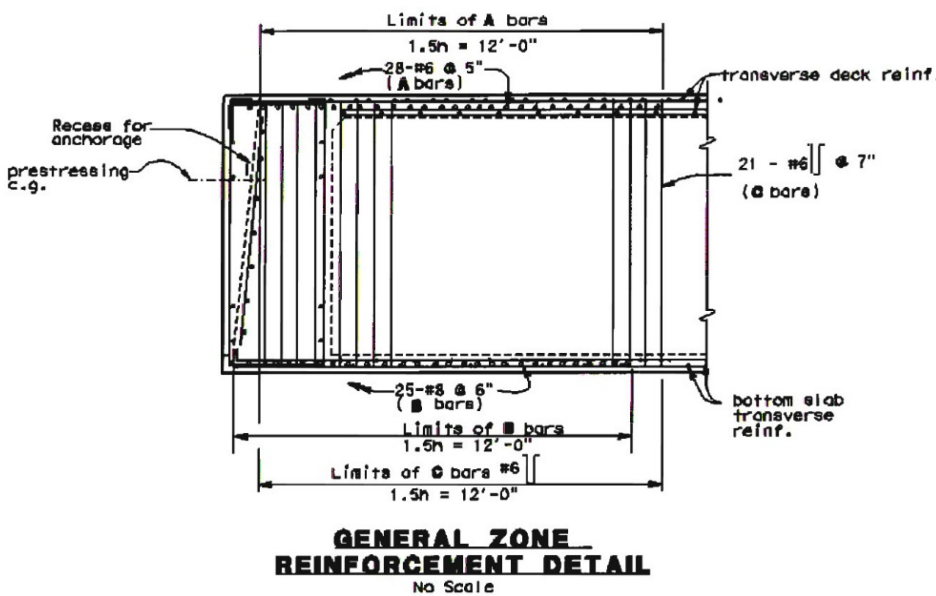


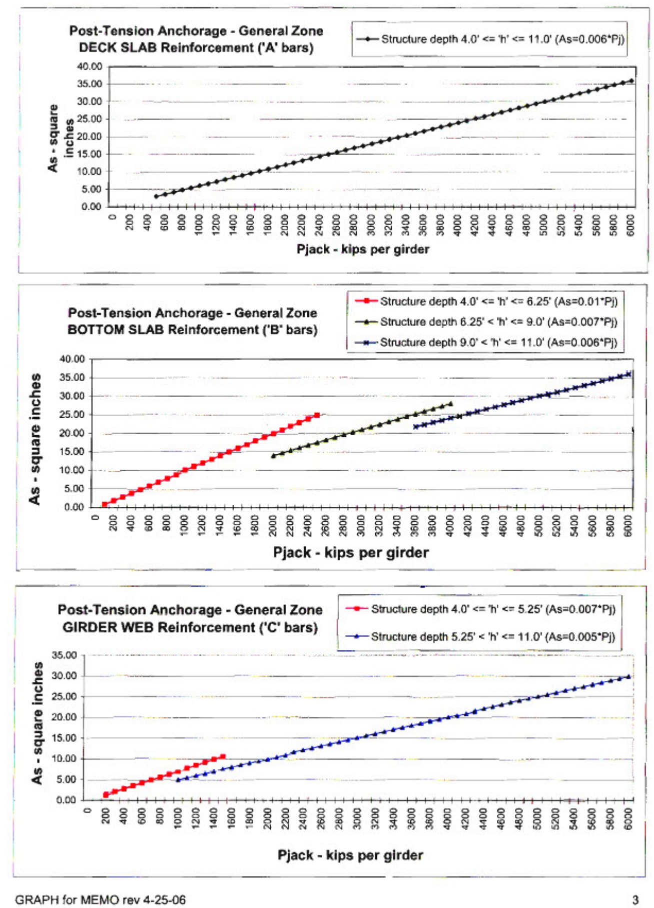


  - PS forces spread to web, top flange, bottom flange via tributary area

History of Anchorage Zone Design

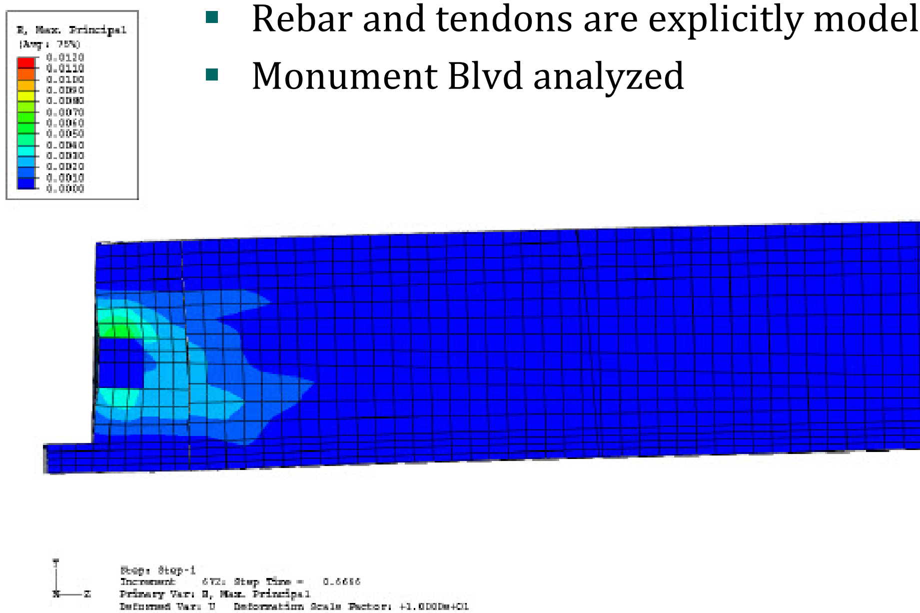
- **Strut and tie methods**
  - Conservative method resulting in:
    - Added stirrups
    - Added transverse bars in deck
    - Added transverse bars in soffit slab



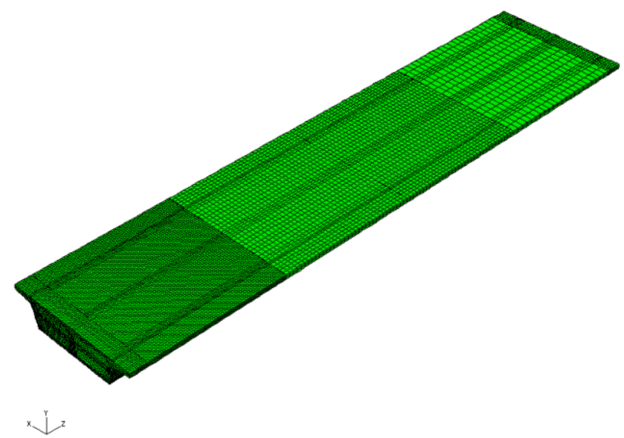


History of Anchorage Zone Design

- **Finite Element Analysis Methods**
  - DEA Task Orders (Detailed non-linear Analysis approach)
    - Use of ABAQUS and inelastic concrete properties in 3D FE models
    - Solid elements
    - Rebar and tendons are explicitly modeled
    - Monument Blvd analyzed

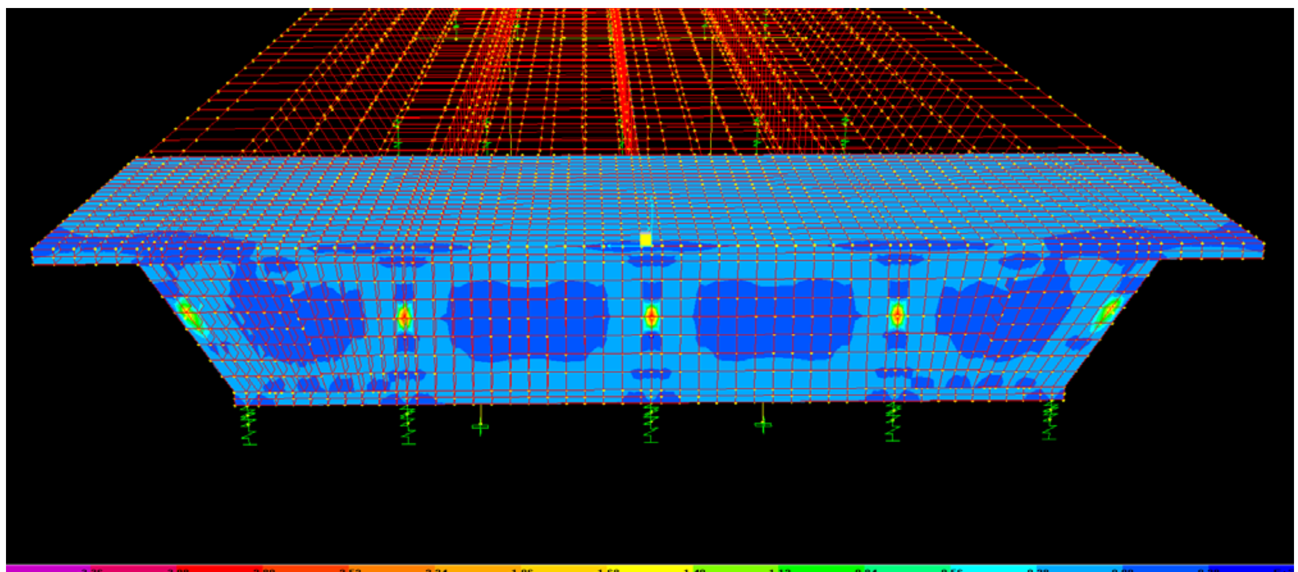


Max Principal Strains, CL Girder 3, 100% of Pre-Stress and Dead Load



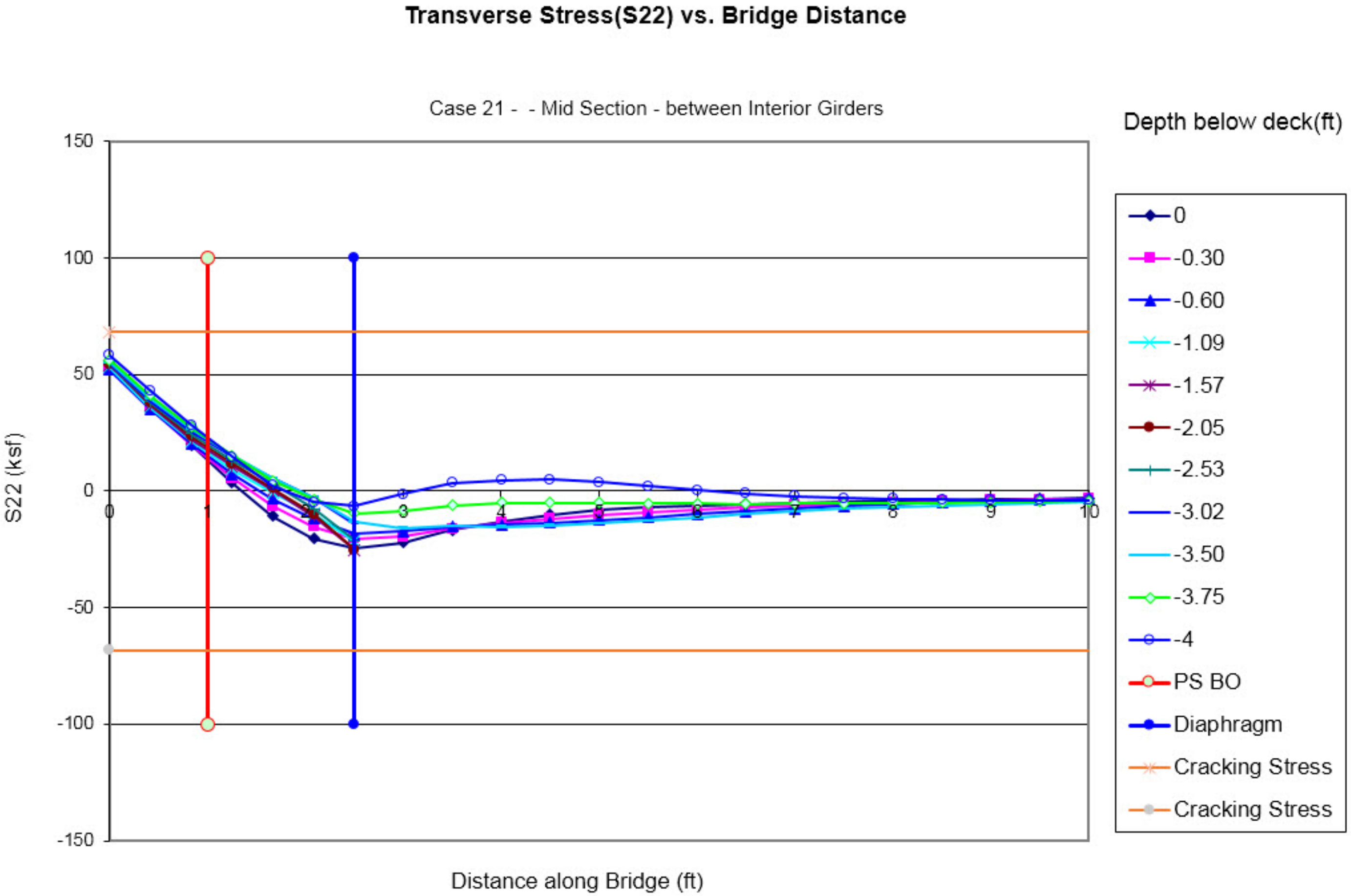
History of Anchorage Zone Design

- **Finite Element Analysis Methods**
  - Caltrans linear analysis parametric studies using SAP2000
    - 38 parametric cases analyzed
    - Single span and 3 span bridges
    - Depth of span from 4ft to 9.5ft
    - Web spacing/Depth from 1.5 to 2.0
    - Span range from 89ft to 238ft
    - Number of ducts per girder: 1 to 3



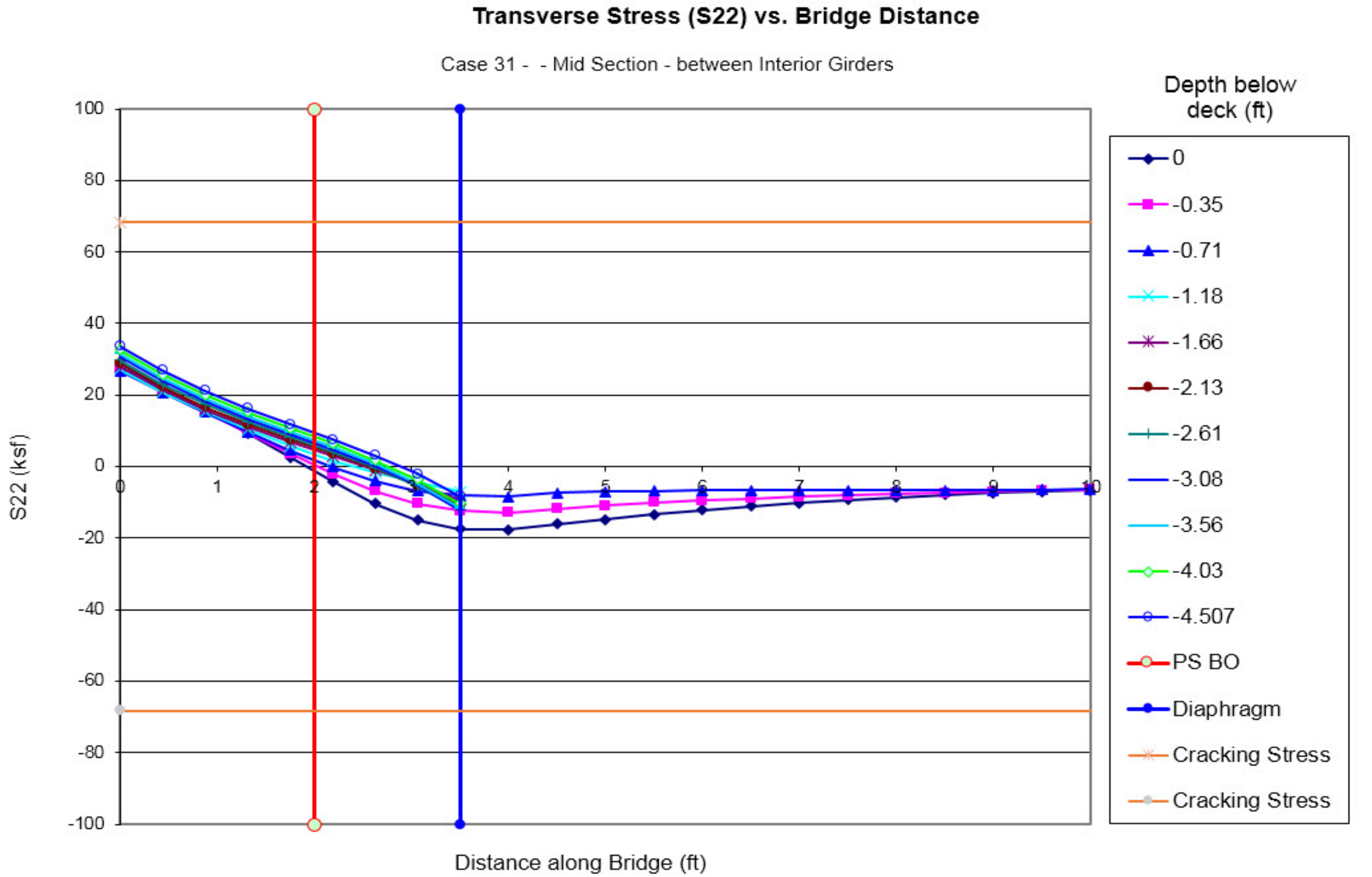
History of Anchorage Zone Design

Horizontal stresses (short/shallow bridges)



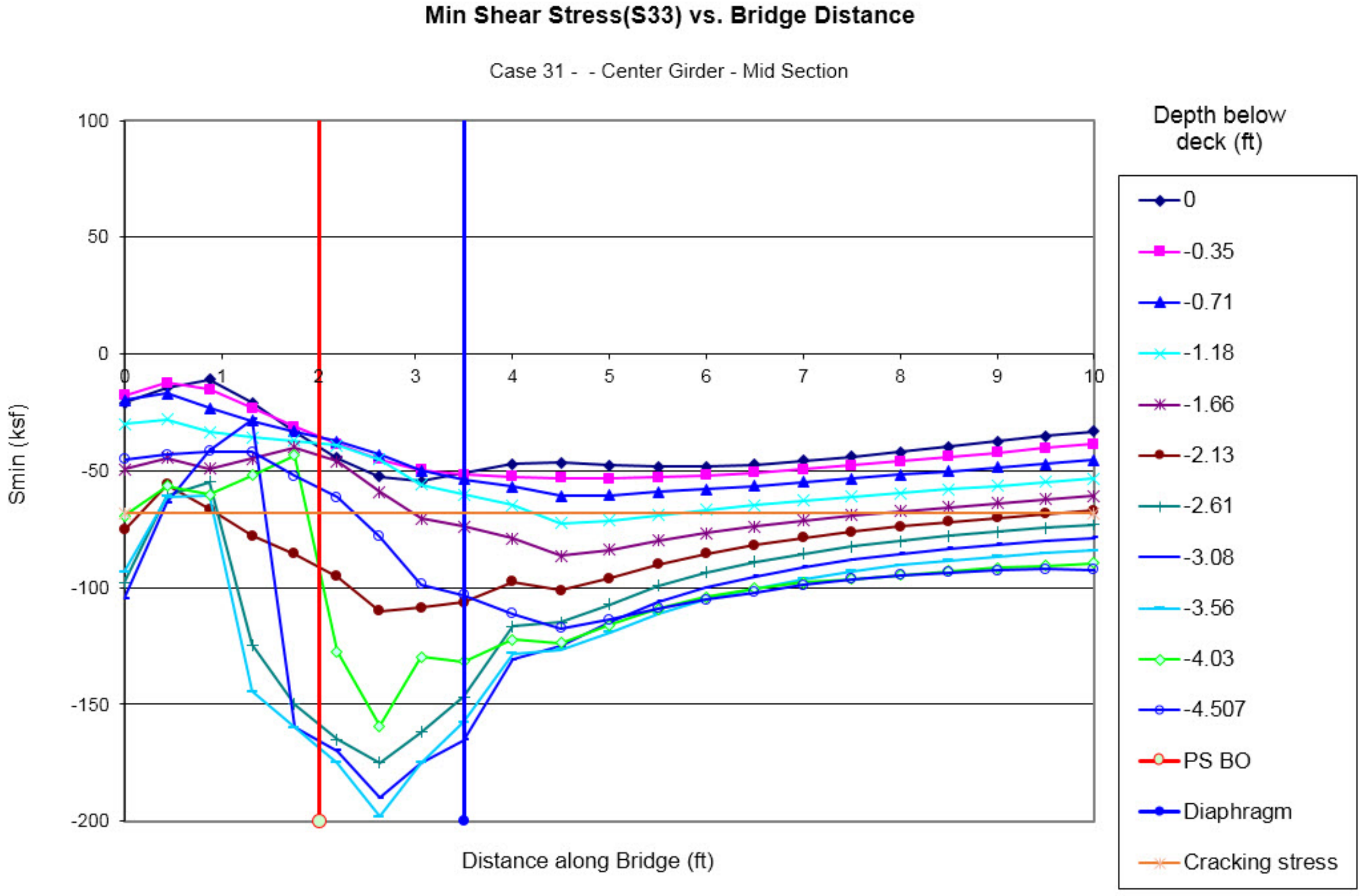
History of Anchorage Zone Design

Horizontal stresses (long/deeper bridges)



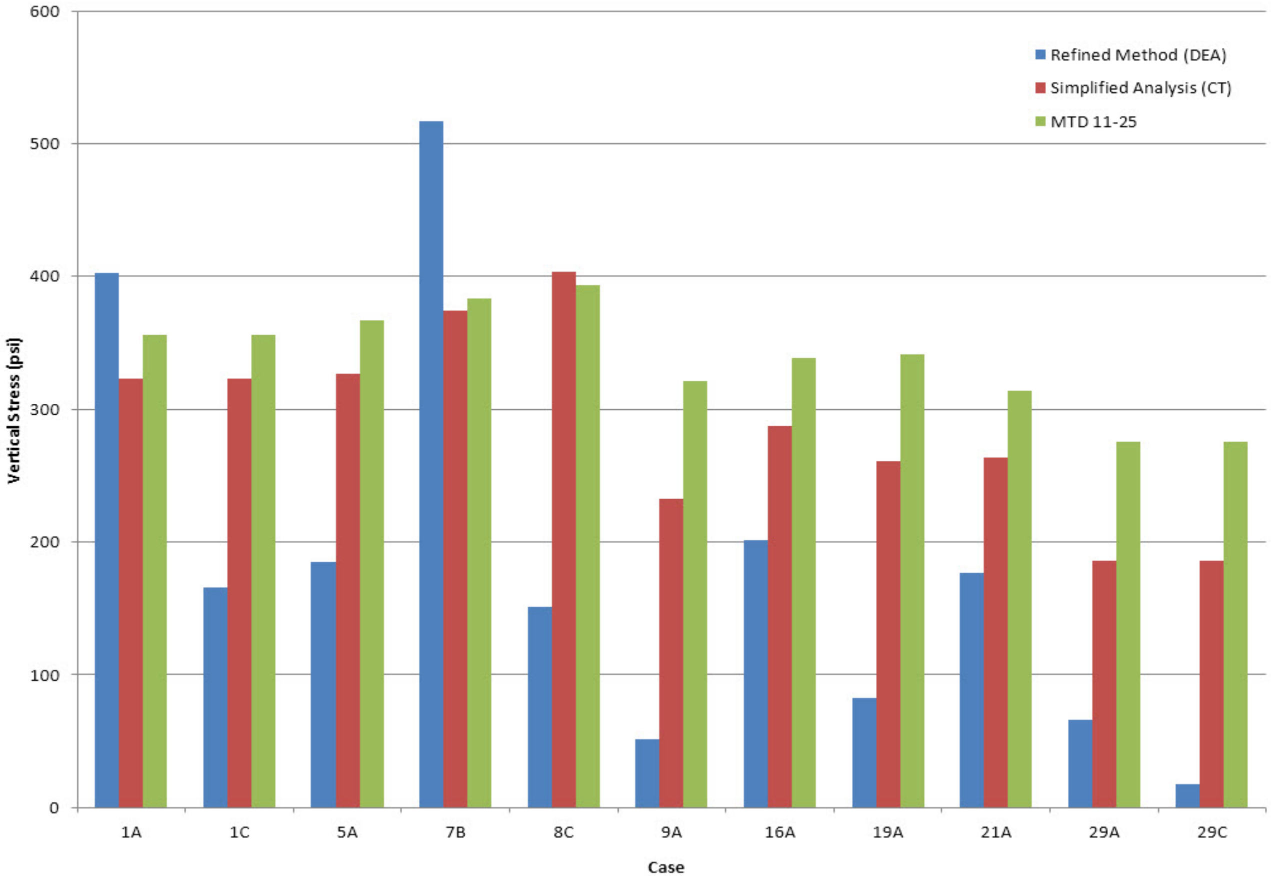
History of Anchorage Zone Design

Vertical stresses (long/deeper bridges)



History of Anchorage Zone Design

Comparison between design methods for Vertical Stress



History of Anchorage Zone Design

- CT simplified method uses single girder approach and linear elastic material properties
- AASHTO 5.10.9.3 Strut and Tie methods or refined methods.
- Empirical formulas generated (MTD 11-25)

History of Anchorage Zone Design

11-25 Anchorage Zone Design

General

The anchorage zone of a post-tensioned concrete box girder member is that area in front of the prestress blockout where stress concentrations occur. The design engineer is responsible for the design of both the local zone and the general zone. AASHTO LRFD 5.10.9 covers the requirements for these regions. In Figure 1, the limits of the anchorage zone are defined for the purposes of this memo. The equations presented herein are the result of empirically enveloping three dimensional model results and can be applied to bridges with P_{jack} per girder up to 6000 kips.

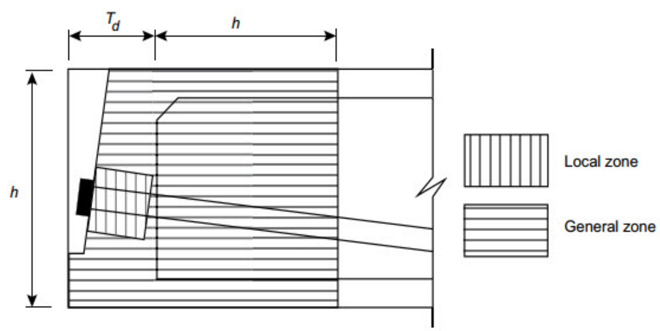


Figure 1 - Anchorage Zone limits

Background

General zone design can be accomplished with 3D finite element modeling. Such models show that most of the post-tensioning stresses within this region that are of concern to designers are the vertical tensile stresses and the longitudinal compressive stresses in the girder webs. Tensile stresses in the top and bottom slabs are relatively small and can be resisted with typical section transverse reinforcement. Because it is impractical to develop 3D models for every bridge, this memo provides a conservative approach to the design of the general zone.

Designed Elements

- Diaphragm thickness
- Girder stem widths
- Girder stirrup reinforcement design

History of Anchorage Zone Design

- End Diaphragm thickness:

$$T_d \geq 0.3 \times h$$

- Girder stirrup design:

$$A_{s1} = \frac{1.33P * \left(h - \frac{P}{1200}\right)}{300 * h^2}$$ Place within the first h/2

$$A_{s2} = \frac{0.67 * P \left(h - \frac{P}{1200}\right)}{300 * h^2}$$ Place within the last h/2

- Girder stem width:

$$(t_w)_{REQUIRED} \geq \frac{P * 1000}{\left[\left(\frac{P}{1200} - 1\right) * 18 + 3(T_d - 12)\right] * 0.7\phi f'_{ci}}$$

History of Anchorage Zone Design

- Example comparison: Strut and tie method versus MTD 11-25 method
- Willits Bypass Floodway viaduct Frame 1: h=7.2ft; P_j/girder=2248k
- SNT: A_s web req'd: 11.24 in^2
- MTD 11-25 A_s web req'd: 1.53 in^2

History of Anchorage Zone Design

- General zone design method based on analysis
- Validation req'd by experimentation
- UNR research contract currently underway to validate MTD 11-25 by field measurements and lab specimens.

Research Problem Statement

Anchorage Zone Problems

- Invalidated design
- Inconsistent reinforcement detailing
- Congested diaphragms (overdesigned)
- Improper concrete placement

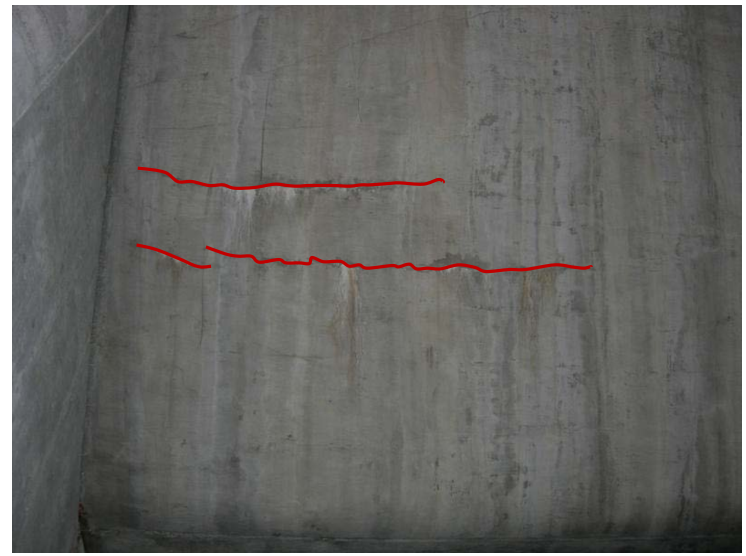
- **Construction Issues**
- **Cracking Problems**

- **Monument Boulevard UC**
- **Crack propagation out of pre-stressing block-outs**

Monument Boulevard UC Bridge

- **Right bridge of Monument Boulevard UC experienced significant cracking in the deck and girders during construction.**

- **The main reason for these cracks was excessive stresses in post-tensioning anchorage zone.**

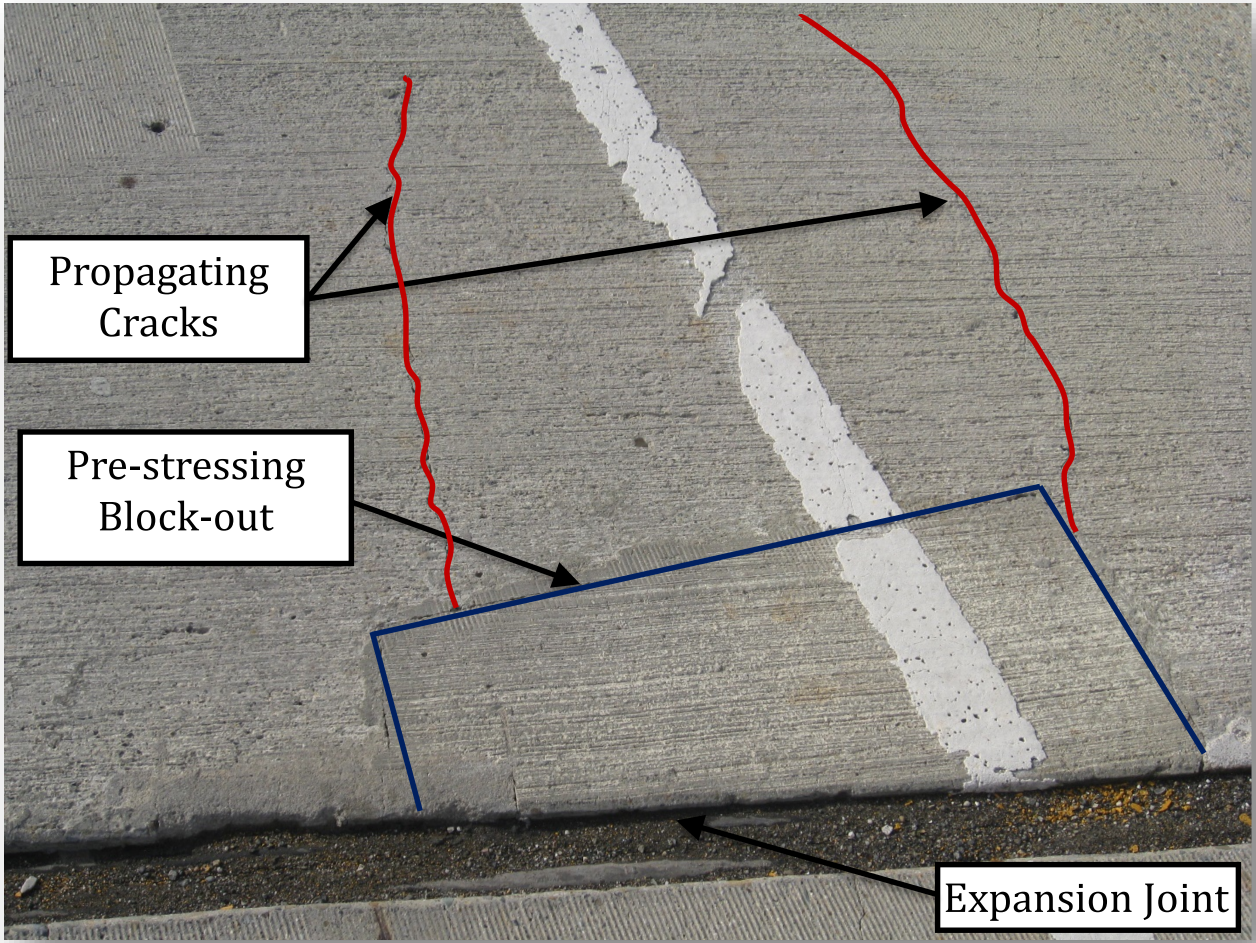


Longitudinal cracks in the external girder

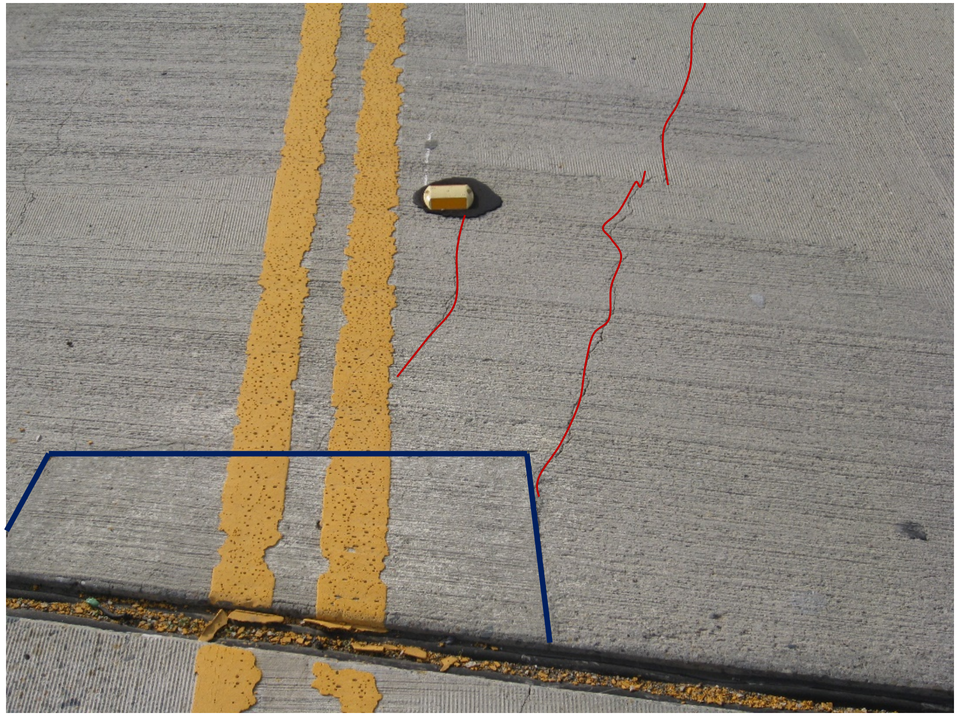
Detailed Finite Element Analysis →

- **Thickening the End Diaphragm**
- **Adding Girder Web Flares**

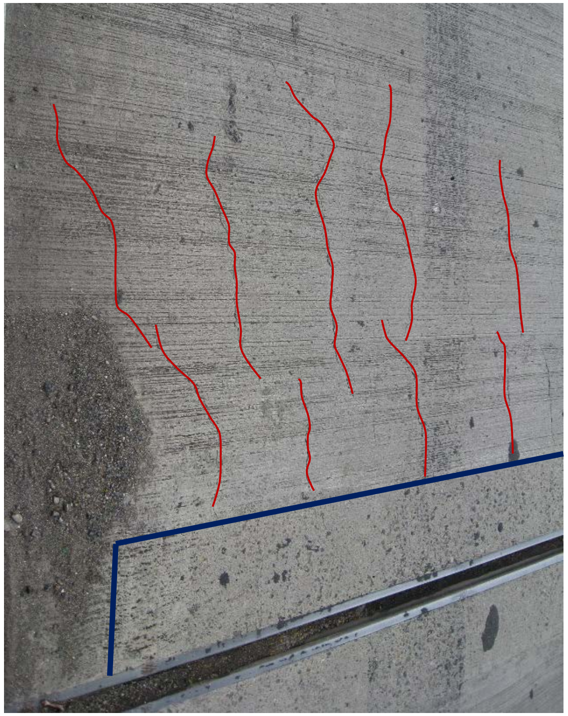
Crack Propagation out of Block-Outs



Crack Propagation out of Block-Outs



Cracks developed out of the block-out corner



Distributed cracks over the block-out

Effectiveness of Existing Design

Available Design Codes

- AASHTO, 2012
- CALTRANS MEMO 11-25
- ACI-318, 2011
- British Standard BS-8110, 2002
- Eurocode 2: Design of concrete structures, 2004
- CEB-FIP Model Code, 1990

Effectiveness of Existing Design

Available Design Codes Approximate Equations

Parameter	Design Codes	BS 8110	AASHTO 2012	CALTRANS MEMO 11-25	ACI-318	CEB-FIP Model Code	EURO Code 2
Applicability		Rec. Section ONLY	Rec. Section ONLY	Box Section	Rec. Section ONLY	Rec. Section ONLY	All Section
Input Data	Section Dimensions	√	√	√	√	√	√
	Bearing Plate Dimensions	√	√	√	√	×	√
	Eccentricity	√	√	√	√	√	√
	Tendon Inclination	×	√	√	×	×	√
Bursting	T_{burst}	Variable	Variable	Same as AASHTO	Approximate Equations Refer to AASHTO	Variable	Variable
	d_{burst}	Constant = 0.55h	Variable			Variable	Variable
Spalling		×	Constant = 2% P_u			Variable	×
Bearing Stresses		$0.8F_{cu}$	Variable			×	×
Limits	As_{min} Web	×	×	√	×	×	×
	T_d (Diaphragm)	×	×	√	×	×	×
	$t_{w\ min}$ Girder	×	×	√	×	×	×

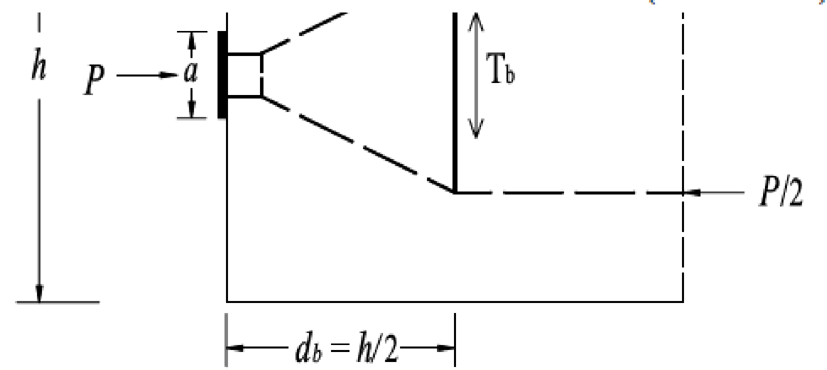
Effectiveness of Existing Design

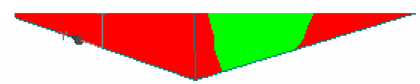
Different Design Methods

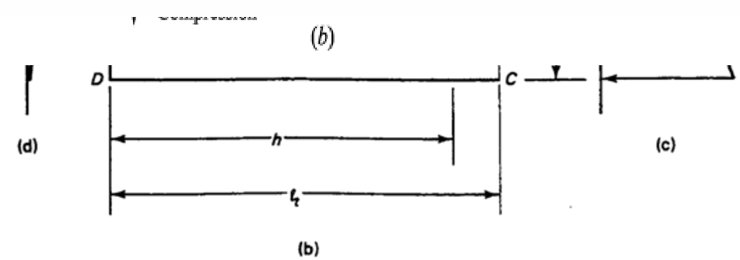
- Approximate Design Equations
- Elastic Finite Element Analysis
- Elastic Analysis Method
- Strut and Tie Models
- Iso-Static Lines to Obtain Actual Transverse Stresses

AASHTO, 2012

$$T_{burst} = 0.25 \sum P_u \left(1 - \frac{a}{h}\right) + 0.5 \left|\Sigma \left(P_u \sin\alpha\right)\right| \qquad (5.10.9.6.3\text{-}1)$$







Project Objectives

Performing Several Tasks:

- Literature and Bridge Review,
- Preliminary Analysis,
- Specimen Development,
- Field Investigations,
- Experimental Study,
- Analytical Study,
- Implementation,
- Conclusions and Findings.

Recommendations for design procedures and details for anchorage zones of Box Girders

Preliminary Analysis

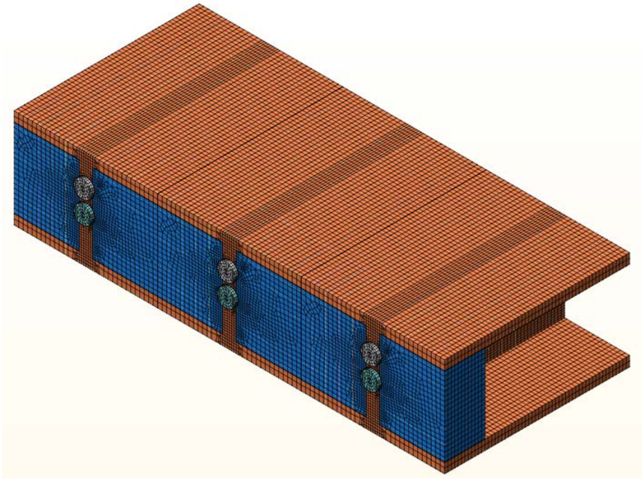
1	Finite Element Modeling	→	Critical Zones of Stress Concentration	→	Location of Instrumentation
2	Box Girder Bridges Database	→	Box Section Properties Prestressing Data & Cable Profile	→	Average Dimensions Existing Reinforcement Ratios

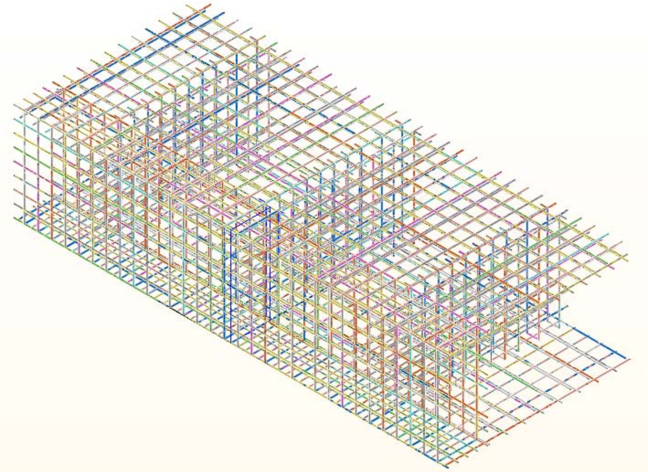
Preliminary Finite Element Modeling

TNO DIANA
A TNO Company

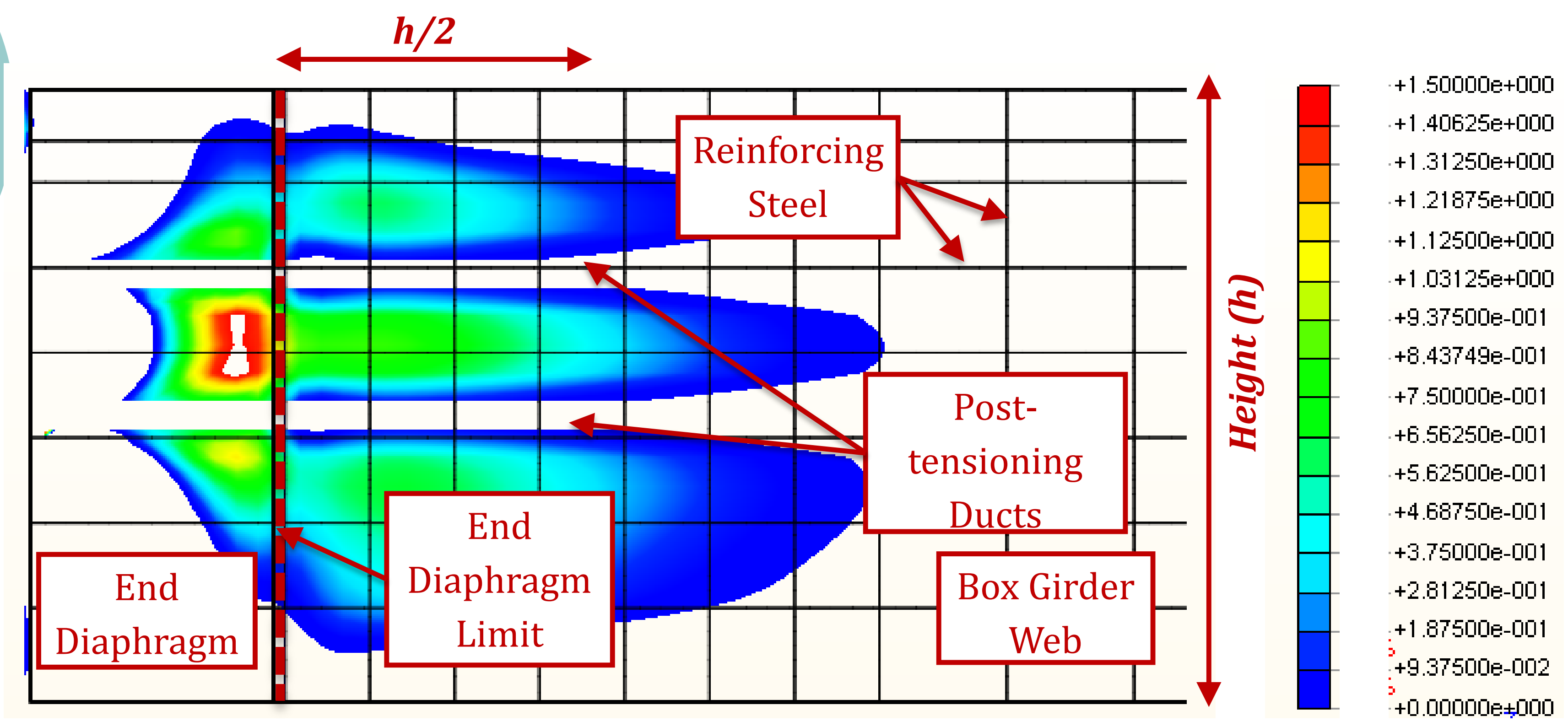
<u>Typical Repetitive Girder</u>

- Height (h) = 220 cm
- Spacing between girders (S) = 320 cm ,
- Girder width = 40 cm
- End diaphragm thickness = 90 cm
- Two eccentric pre-stressing straight ducts were modeled as voids.
- The applied prestressing load was 7800 kN, which represents 15% of the concrete section axial capacity.
- Loads were applied on circular loading plates.



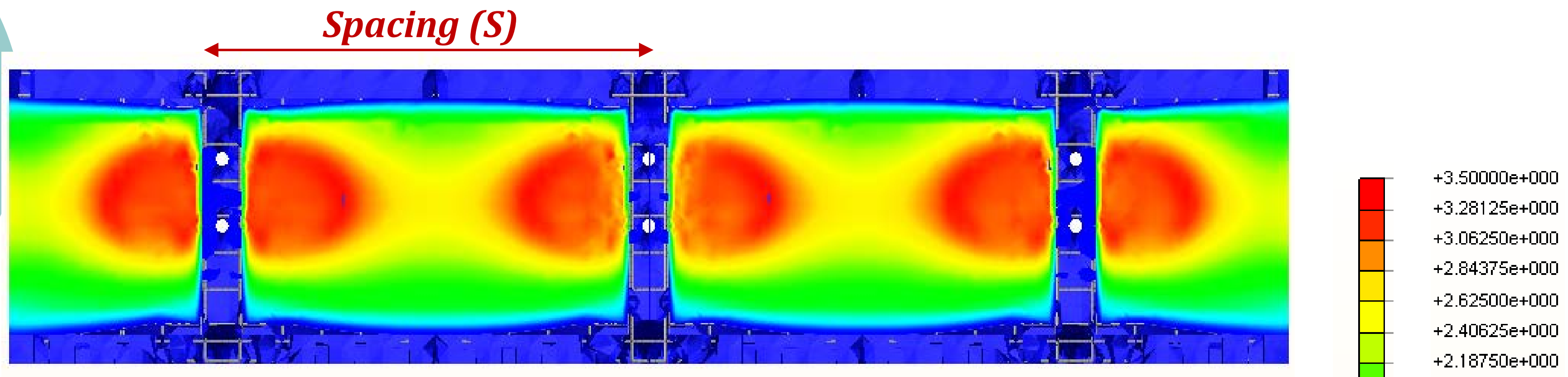


Preliminary Finite Element Modeling

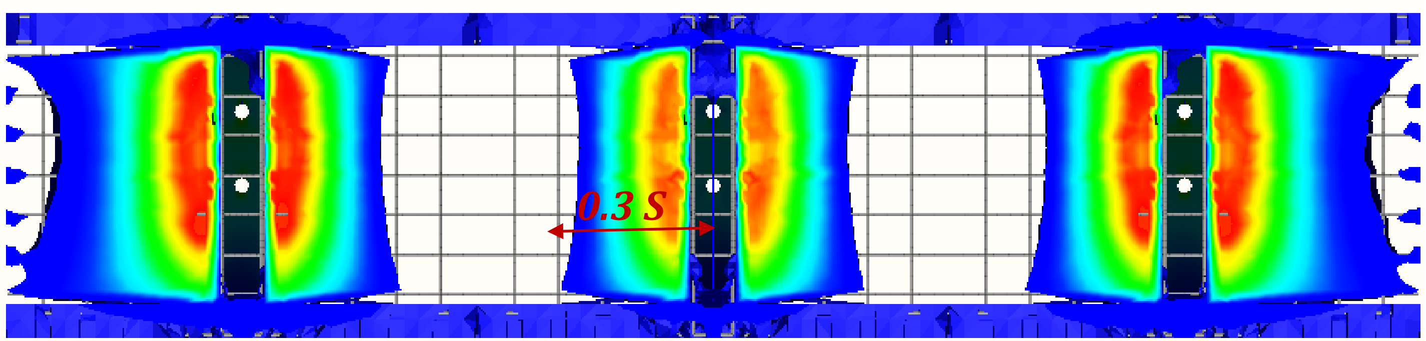


Longitudinal section of the web girder

Preliminary Finite Element Modeling



Vertical Tensile Stresses (MPa)



Horizontal Tensile Stresses (MPa)

Box Girder Bridges Database

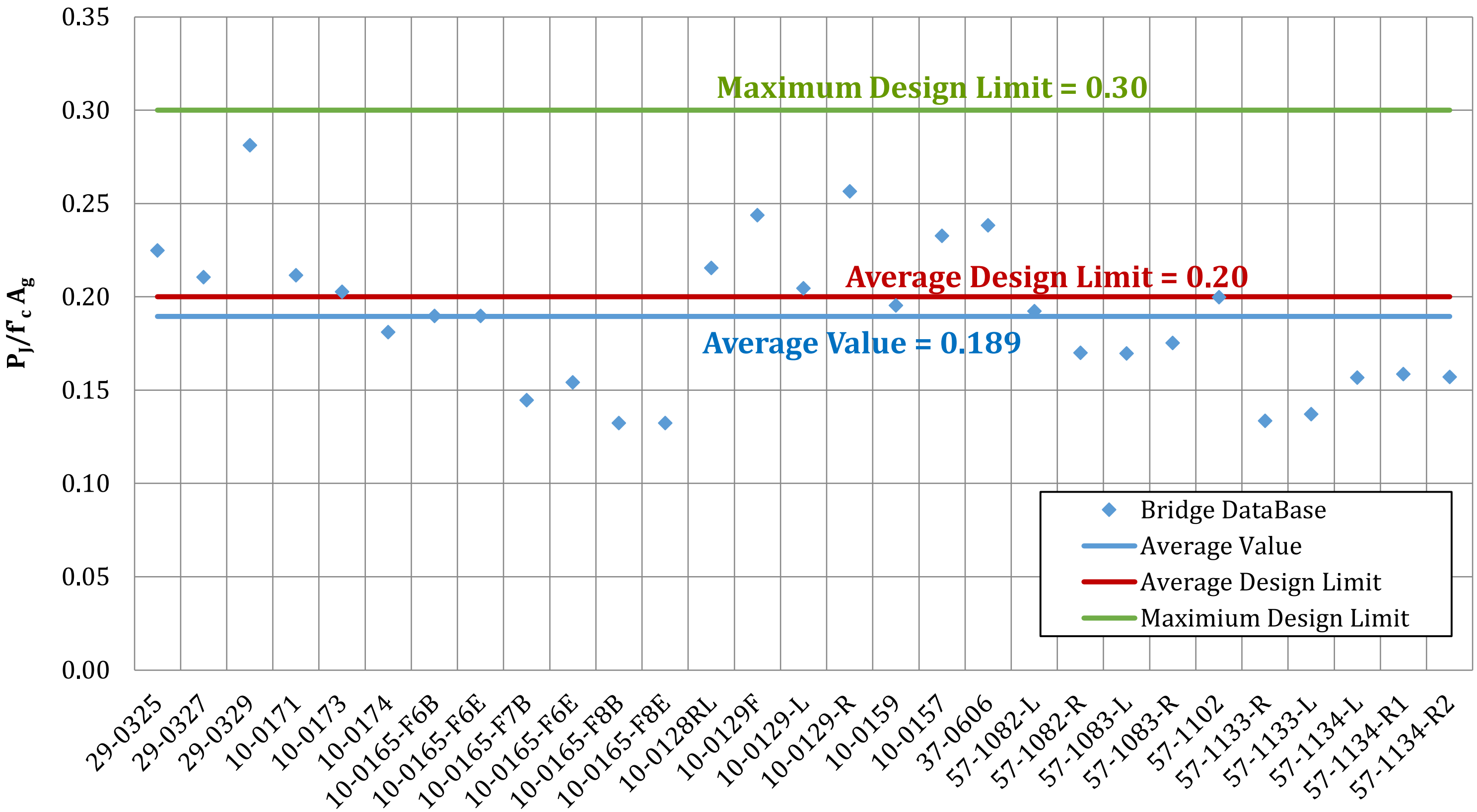
Bridge Database for Provided Drawings by CALTRANS

#	Bridge Name	Bridge No.
1	Mariposa Road OC	29-0325
2	Main Street OC	29-0327
3	Dr. MLK Jr. Blvd. OC	29-0329
4	Quail Meadows OH	10-0171
5	Quail Meadows UC	10-0173
6	Upp Creek Bridge	10-0174
7	FV-Frame 6 Start	10-0165-F6B
8	FV-Frame 6 End	10-0165-F6E
9	FV-Frame 7 Start	10-0165-F7B
10	FV-Frame 7 End	10-0165-F6E
11	FV-Frame 8 Start	10-0165-F8B
12	FV-Frame 8 End	10-0165-F8E
13	Route 101/20 Separation	10-0128RL
14	S101-W20 Connector	10-0129F
15	Haehl Creek (Left Bridge)	10-0129-L
16	Haehl Creek (Right Bridge)	10-0129-R
17	Haehl Creek	10-0159
18	East Hill Road UC	10-0157
19	Smith Creek	37-0606
20	McGonigle Creek (Left)	57-1082-L
21	McGonigle Creek (Right)	57-1082-R
22	Camino Ruiz UnderCr. (Left)	57-1083-L
23	Camino Ruiz UnderCr. (Right)	57-1083-R
24	Duenda Road OC	57-1102
25	Green Valley Creek (Left)	57-1133-R
26	Green Valley Creek (Right)	57-1133-L
27	Lake Hodges (Left)	57-1134-L
28	Lake Hodges (Right 1)	57-1134-R1
29	Lake Hodges (Right 2)	57-1134-R2

- Box Section Properties
- Prestressing Data
- Diaphragm Reinf. Ratios
- Longitudinal Profile
- $P_J/f'_c A_g$
- Diaphragm Width to Girder Height

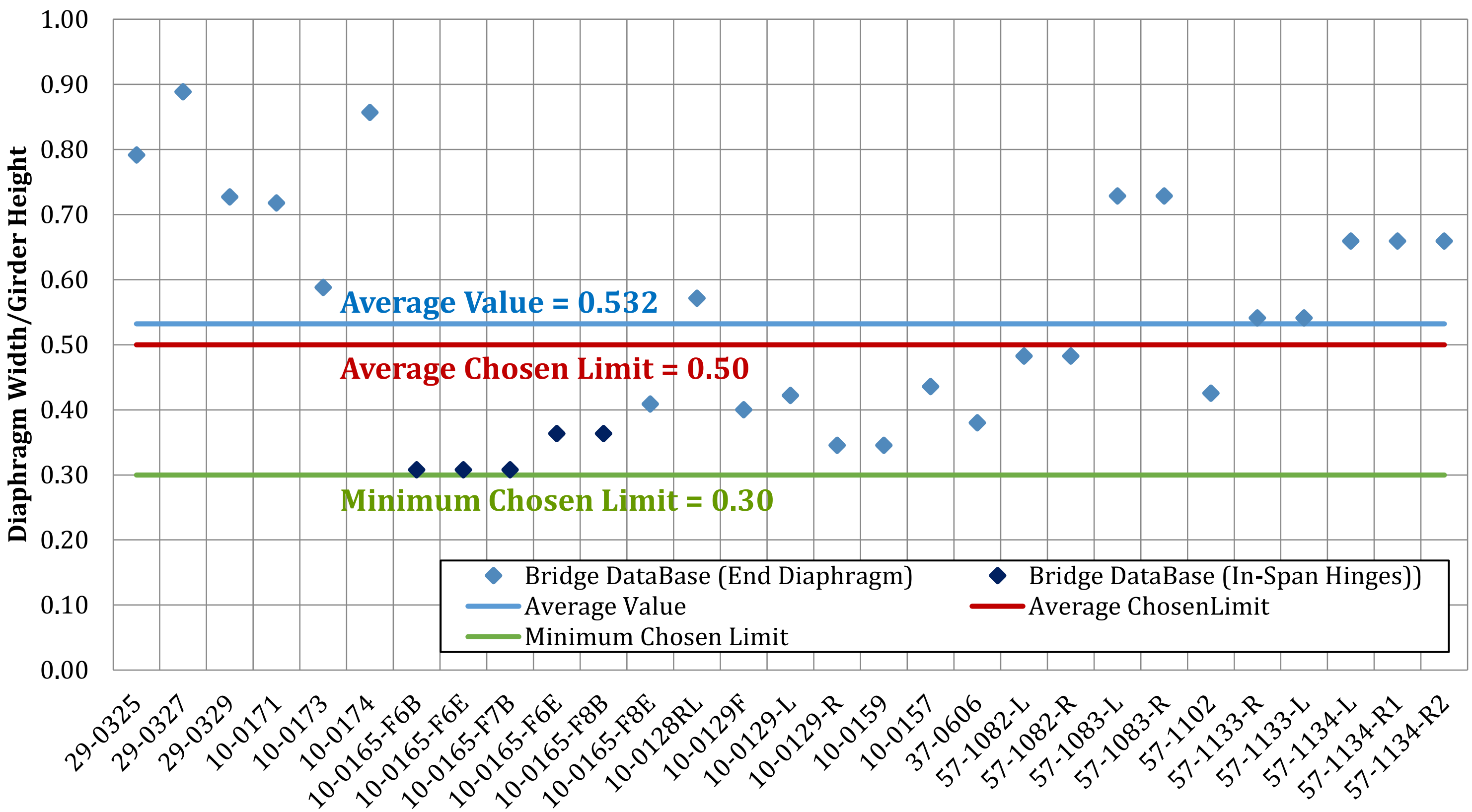
Box Girder Bridges Database

Ratio of Prestressing Force to Box Girder Section Capacity



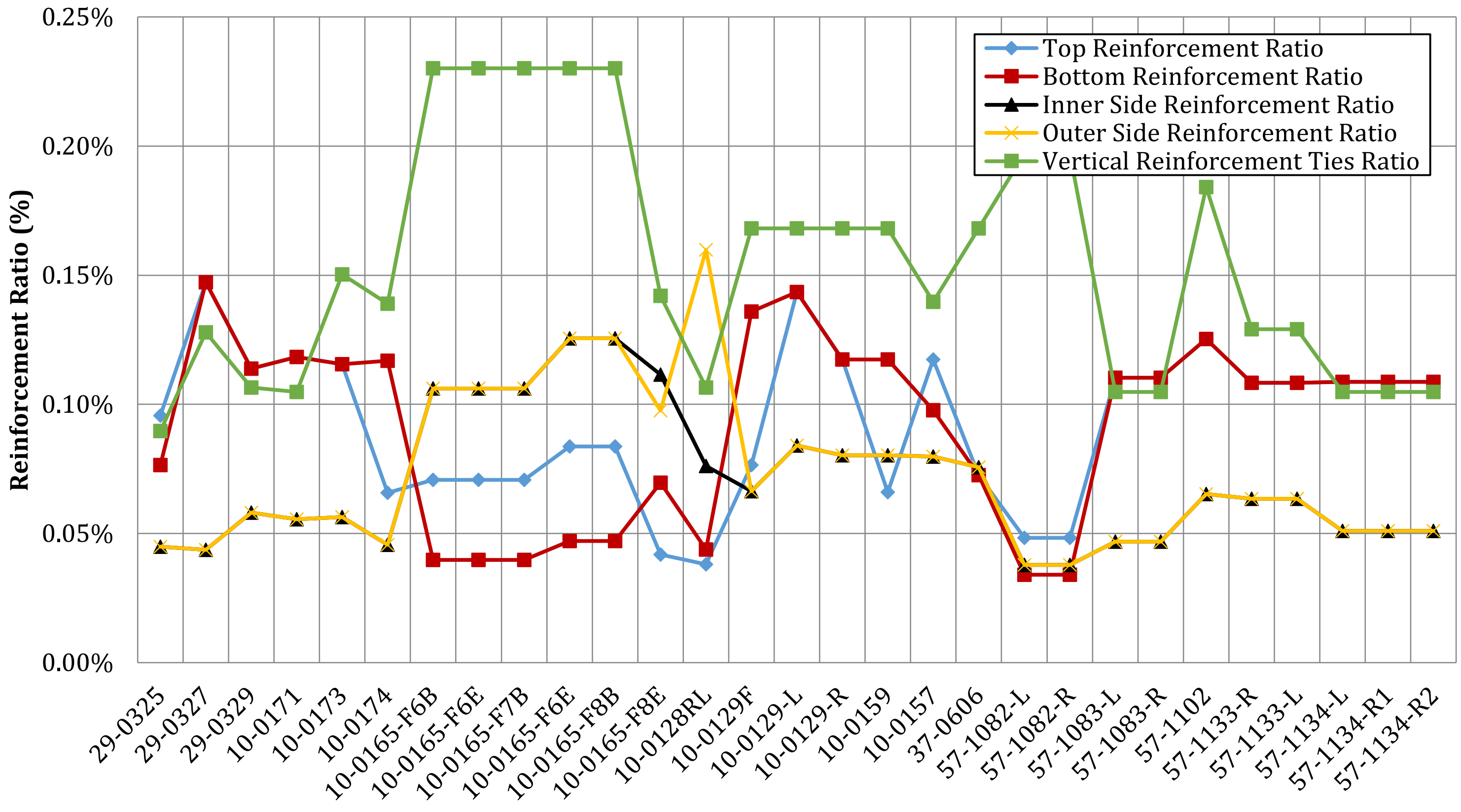
Box Girder Bridges Database

Ratio of Diaphragm Width to Box Girder Height



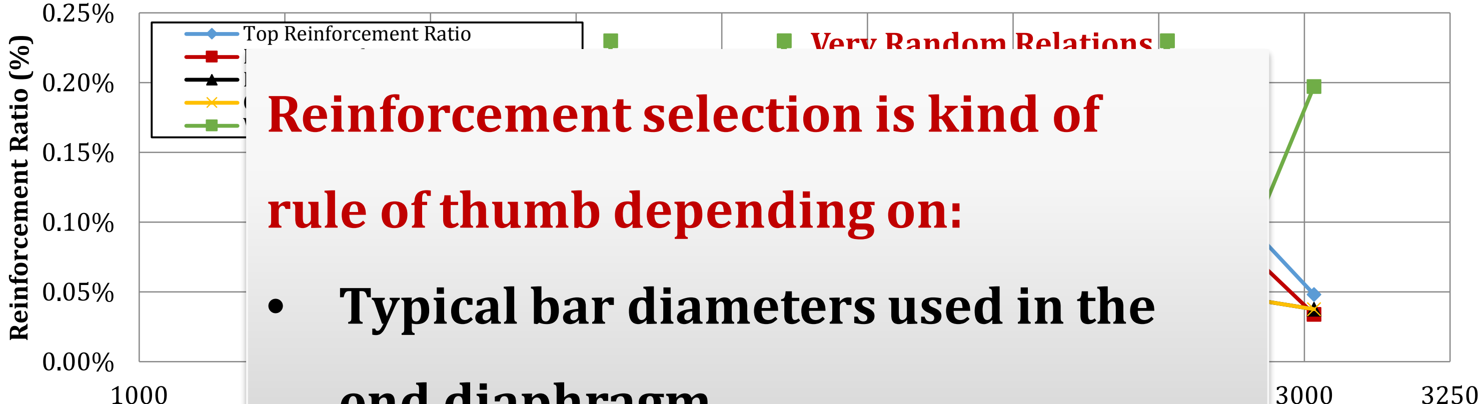
Box Girder Bridges Database

Diaphragm Reinforcement Ratios



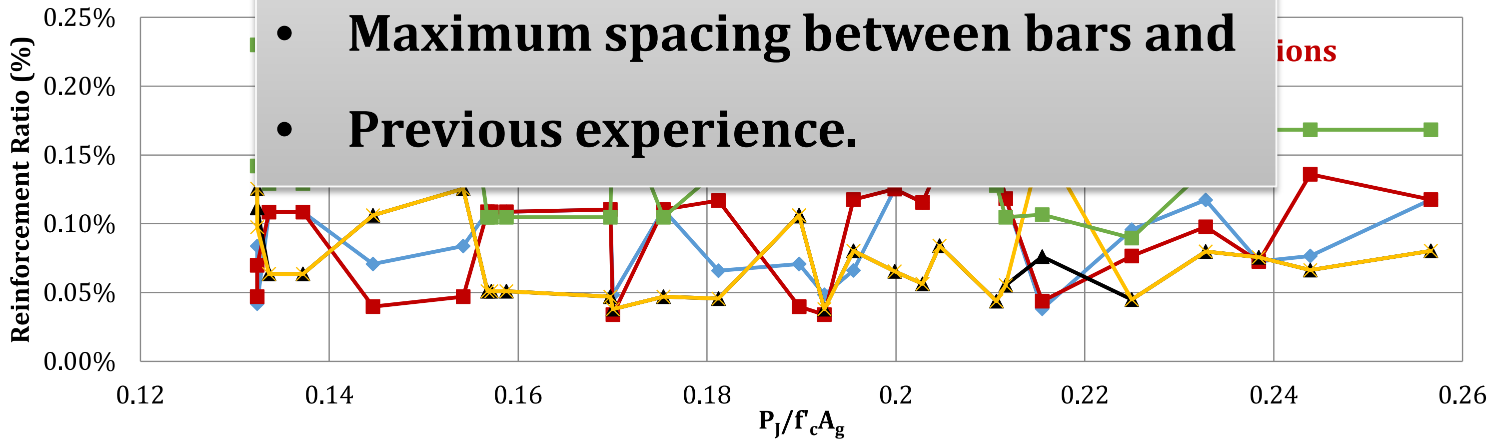
Box Girder Bridges Database

Diaphragm Reinforcement Ratios



Reinforcement selection is kind of rule of thumb depending on:

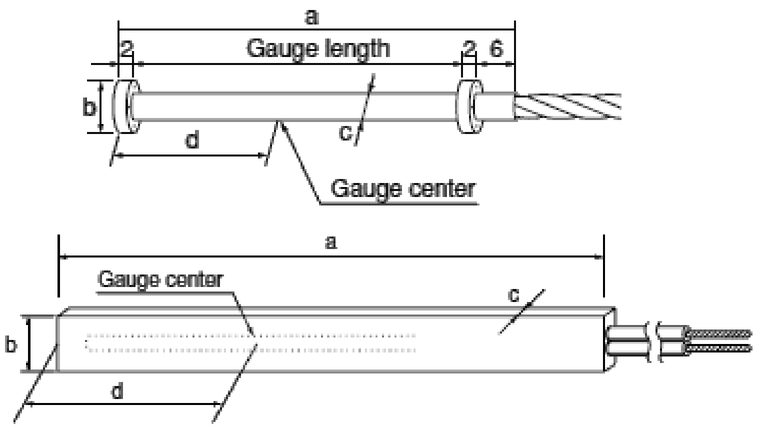
- **Typical bar diameters used in the end diaphragm,**
- **Maximum spacing between bars and**
- **Previous experience.**



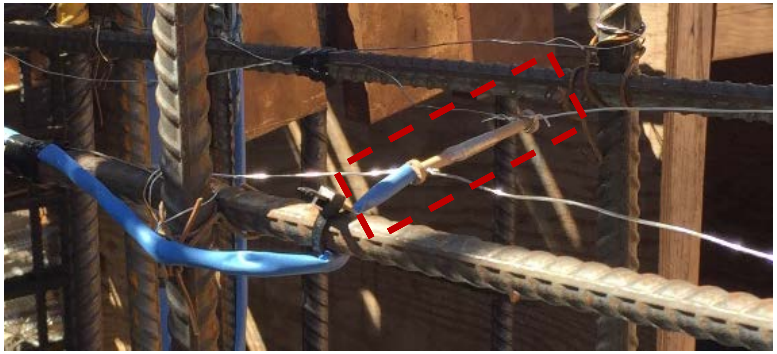
Choice of Instrumentation

Different Types of Instrumentation :

- Reinforcing Bars Strain Gauges
  - YF series Post-yield strain gauge (YFLA-5) Max. Strain 15-20%
  - YEF series Post-yield strain gauge (YEFLA-5) Max. Strain 10-15%
  - F series Foil strain gauge (FLA-6) Max. Strain 5%



- Embedded in Concrete Strain Gauges
  - PM series Mold strain gauge
  - PMFL series Mold strain gauge



- Surface of Concrete Strain Gauges
  - FLM/WFLM series Metal backing
  - Refused as it needs 24 hours for surface preparation
  - Refused as it affects the final surface finish

- Pressure Gauges

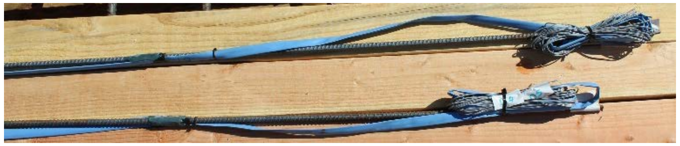
Field Instrumentation

Construction time schedule

Convenient type of instrumentation

Sister Bars

Instrumented reinforcing bars prepared in the lab



- *#3 bars (10 mm diameter)*
- *Maximum increase in reinforcement ratio was 10%, which can be considered as negligible*

Instrumentation Preparation

Thick layer of wax
Water Seal

Flexible (SB) tape
Soft layer above strain gauge

Thick epoxy layer
Coating to prevent damage during concrete casting

Mastic water sealant tape
Prevent damage during construction

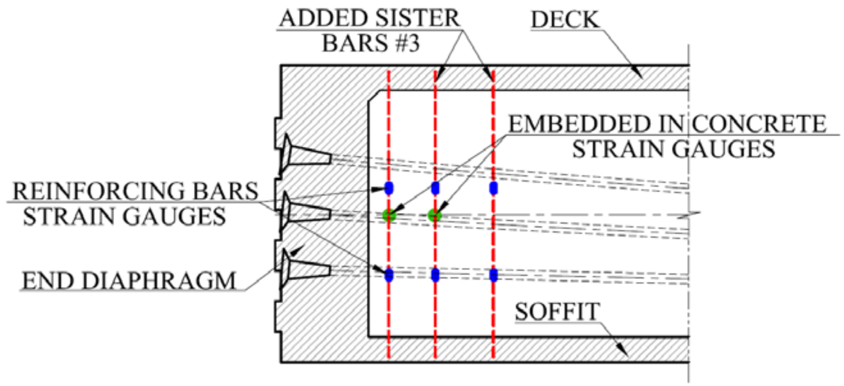
All strain gauges' wires were placed in heat shrink tubes as coating for wires

Instrumentation Plans

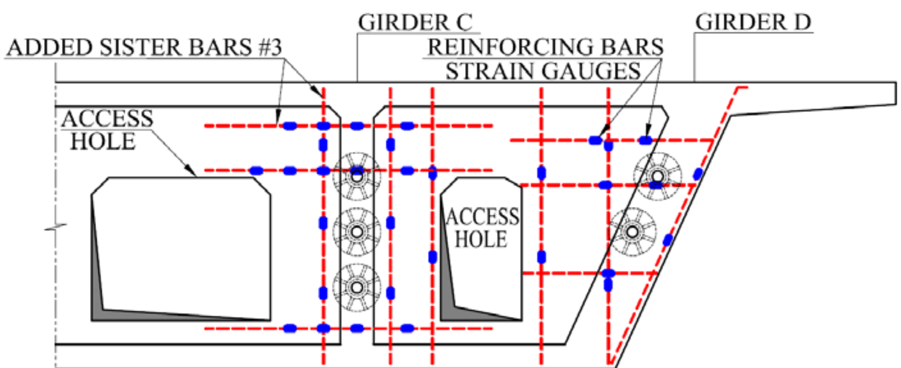
	Bridge I	Bridge II	Bridge III
Bridge Type	Straight	Curved	Curved
No. of cells	3	3	5
Jacking force per girder (kN)	12300	8050	12418
Box girder height (mm)	2600	2200	1650
Girder Spacing	3200	3200	3300
Width of end diaphragm (mm)	800	900	1200
Web thickness Internal / External (mm)	300/500	300/500	300/450
Deck thickness (mm)	220	220	215
Soffit thickness (mm)	190	190	190
Max. span length (m)	67.0	50.8	41.9
No. of pre-stressing ends	Two ends	Two ends	One end
Notes	Access holes for all bridge girders	Solid end diaphragm	Utility hole in end diaphragm

Instrumentation Plans

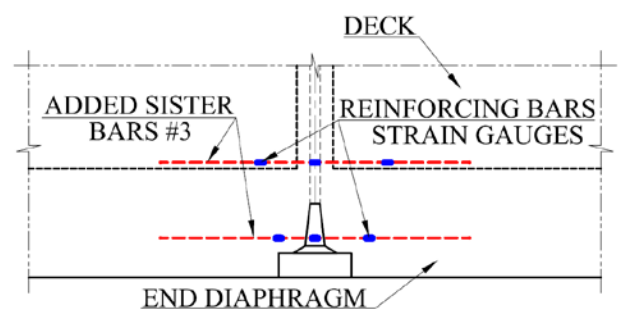
Type	Diaphragm	Girder	Deck	End Anchorage
Reinforcing Bars Strain Gauges	33	12	6	0
Embedded in Concrete Strain Gauges	0	4	0	0
Pressure Gauges	0	0	0	1
Total	56			



Web girder section

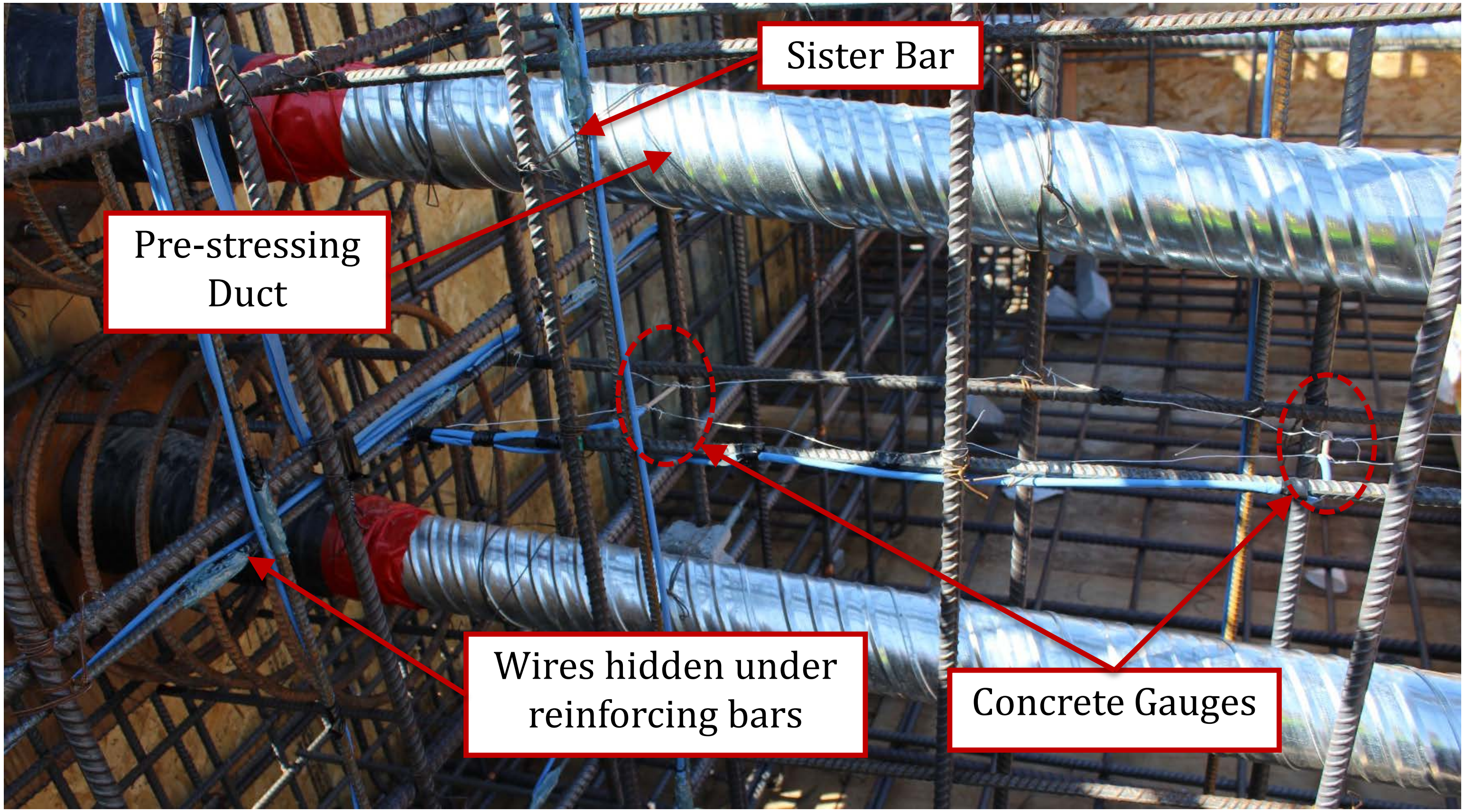


Inner face of diaphragm

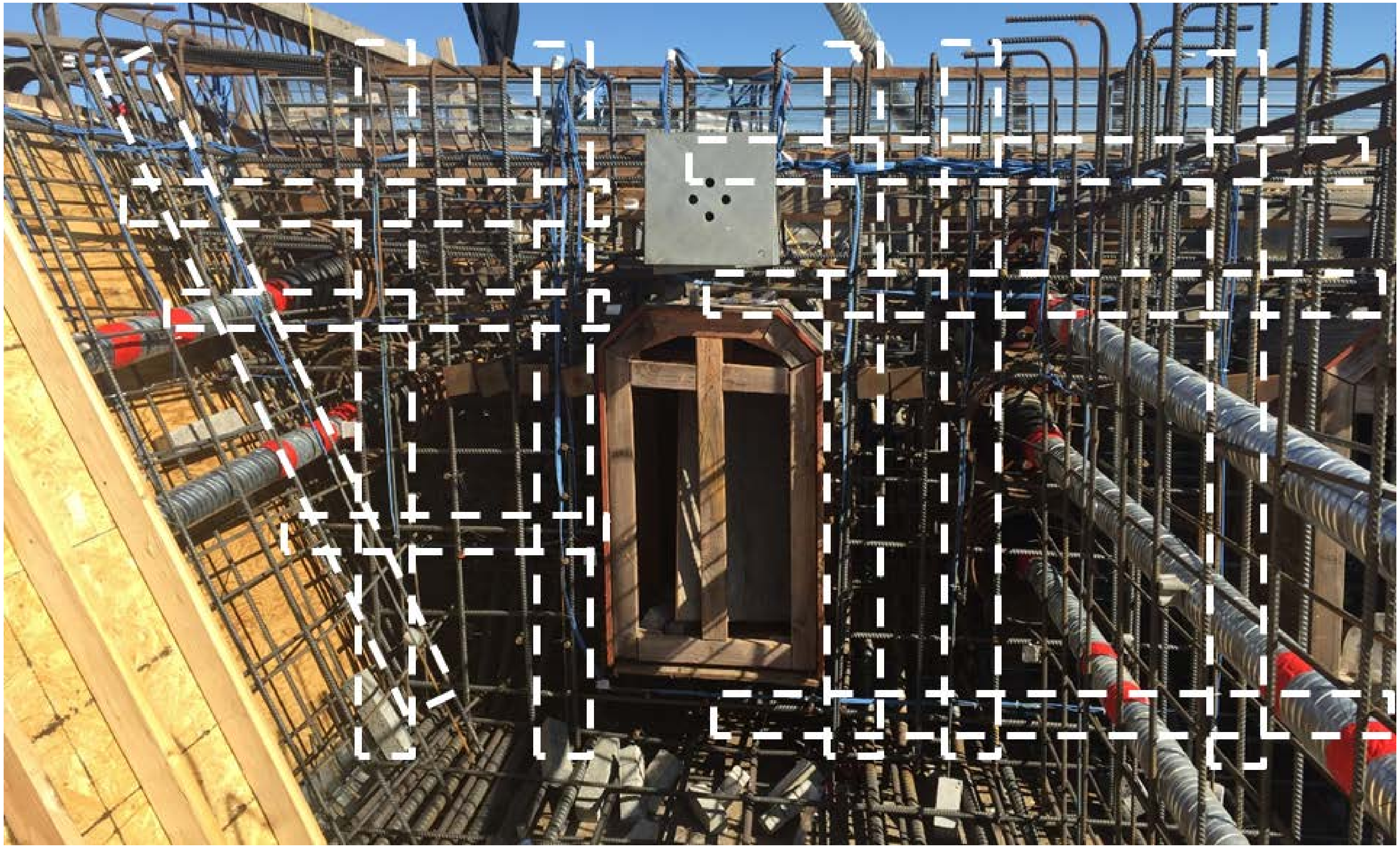


Top view of the deck

Instrumentation Installation



Instrumentation Installation



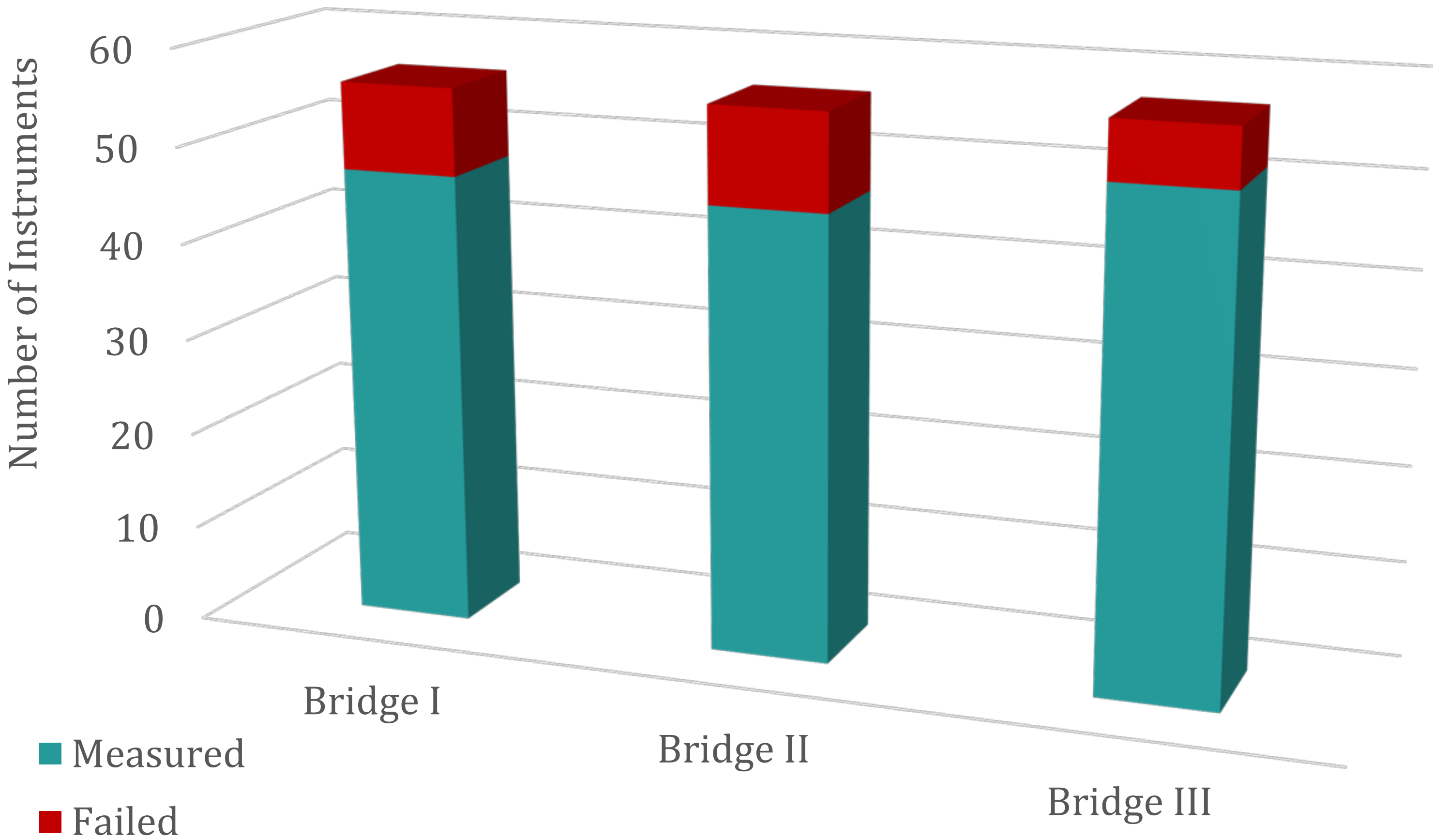
Installed sister bars in the inner face of the diaphragm

Instrumentation Installation

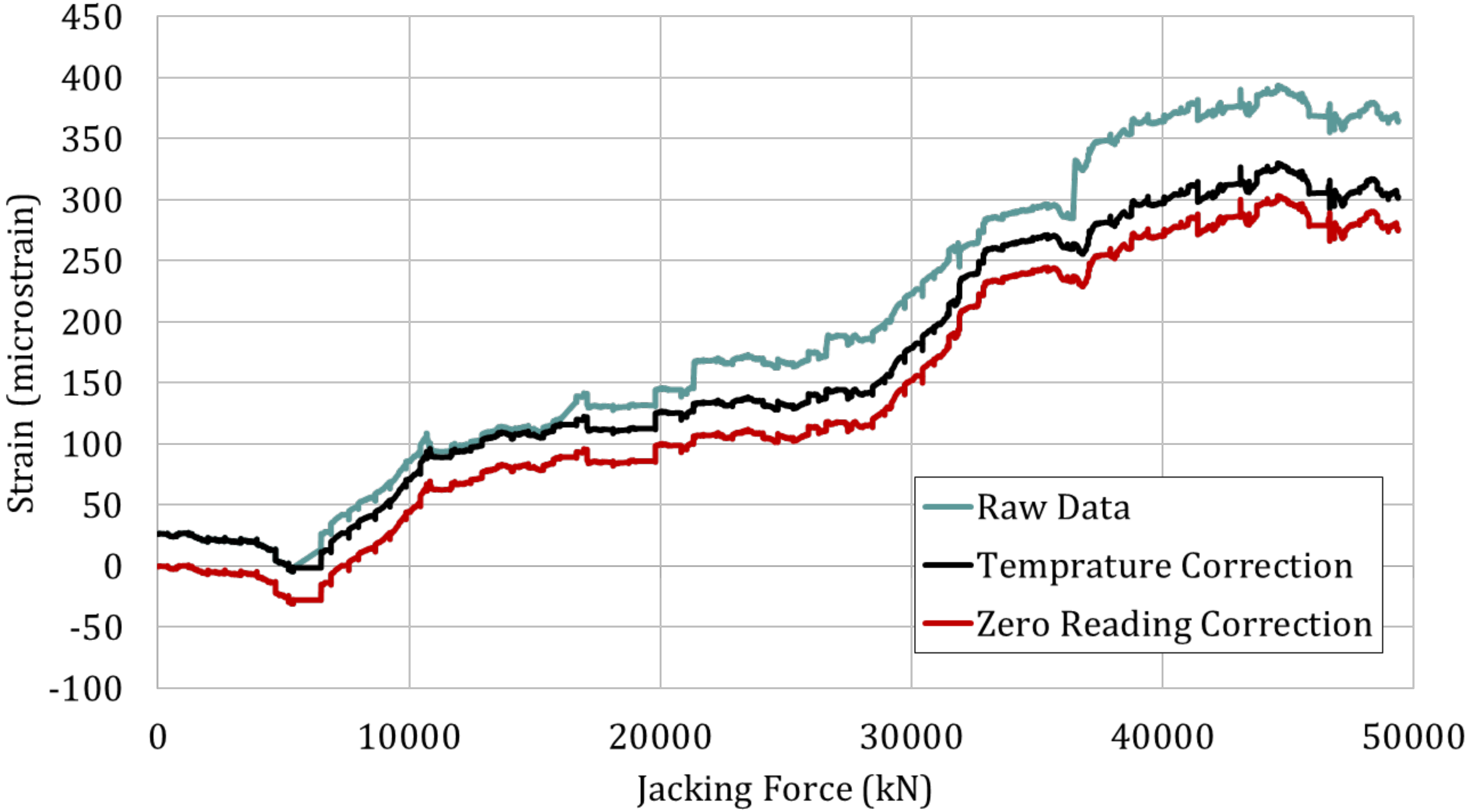
Installed sister bars in the external web

Installed sister bars in the internal web

Reliability of Instrumentation

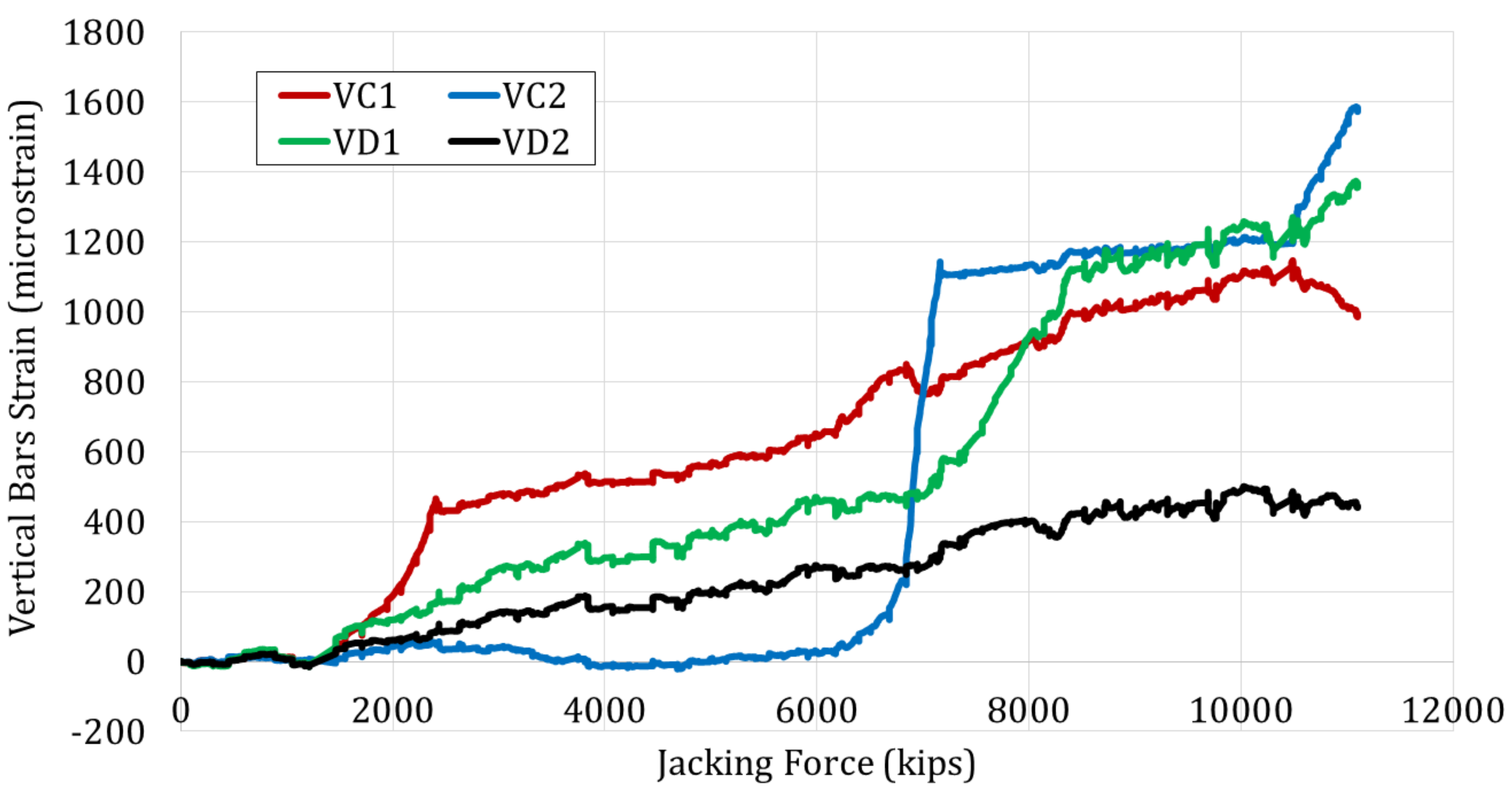


Corrections Performed



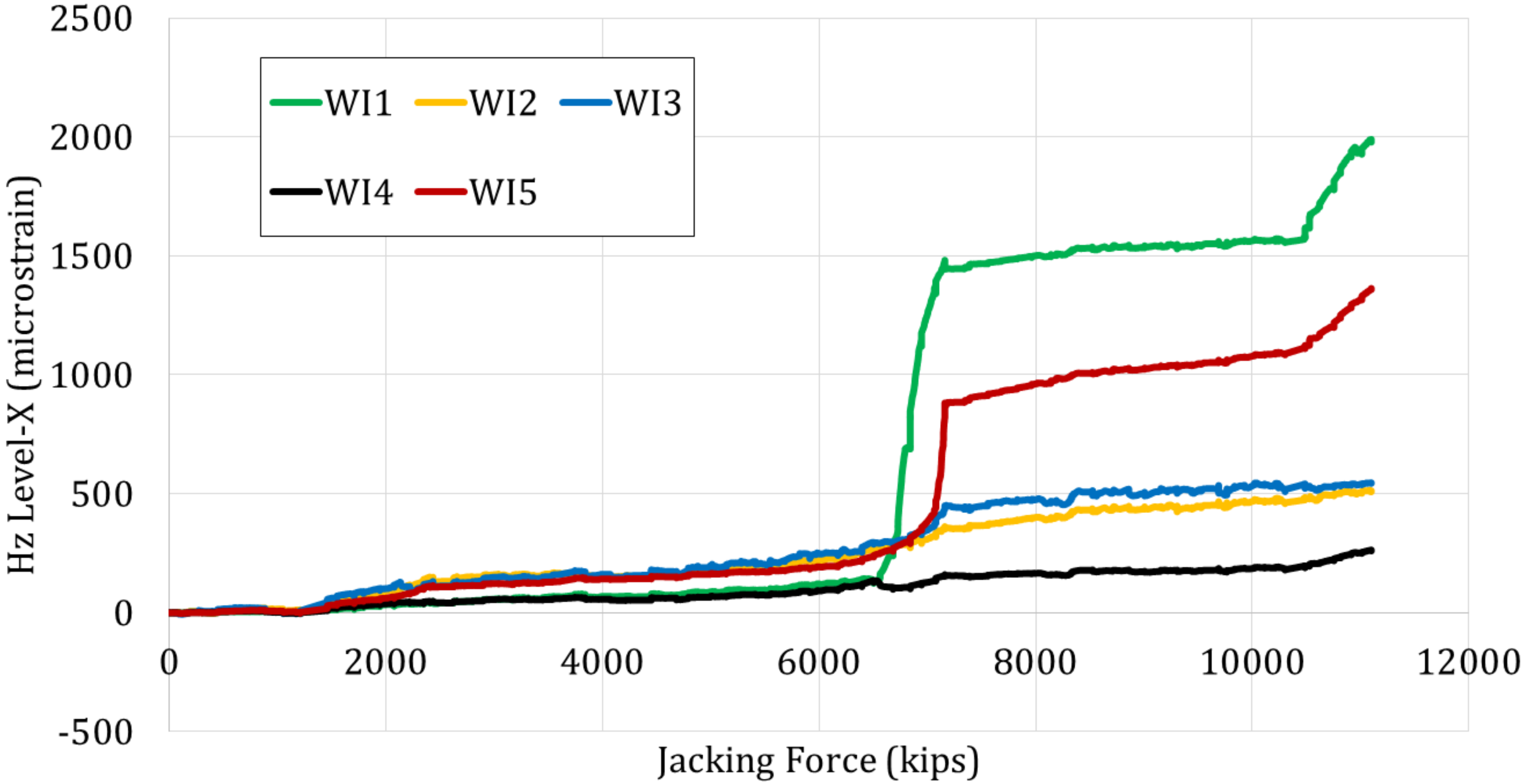
Sample of Results

Strain in vertical reinforcing bars (inner face of end diaphragm)

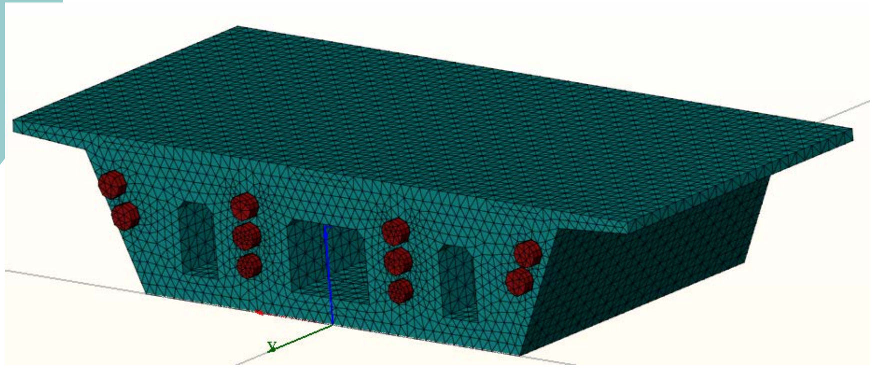


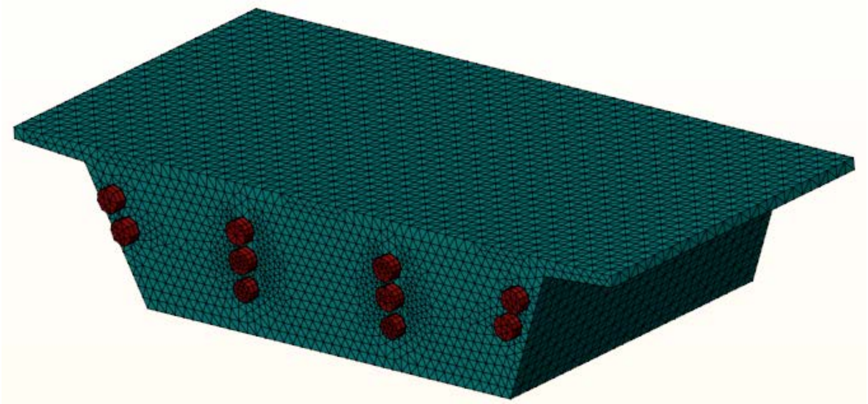
Sample of Results

Strain in vertical reinforcing bars (interior web)



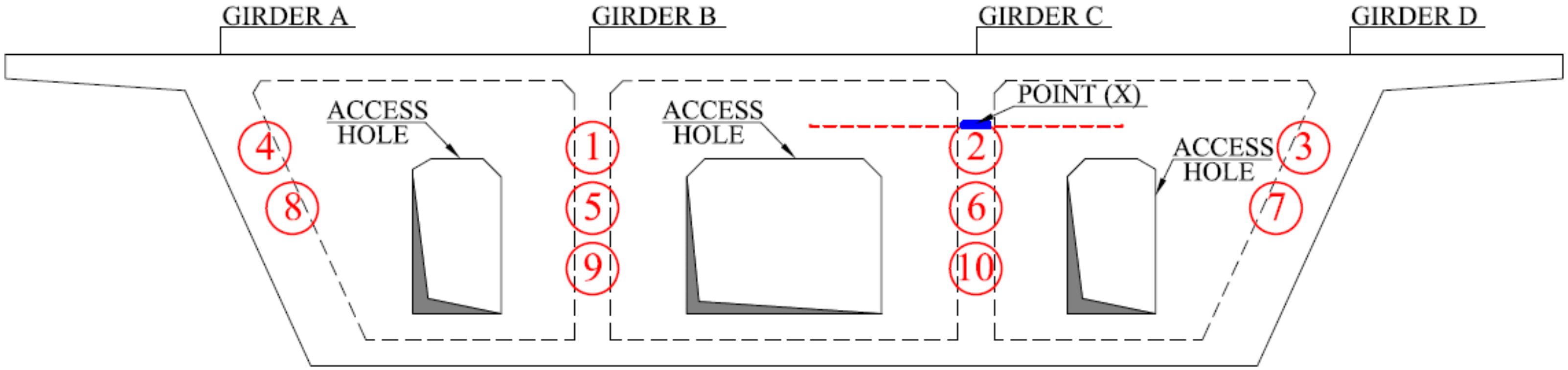
Expected Anchorage Performance



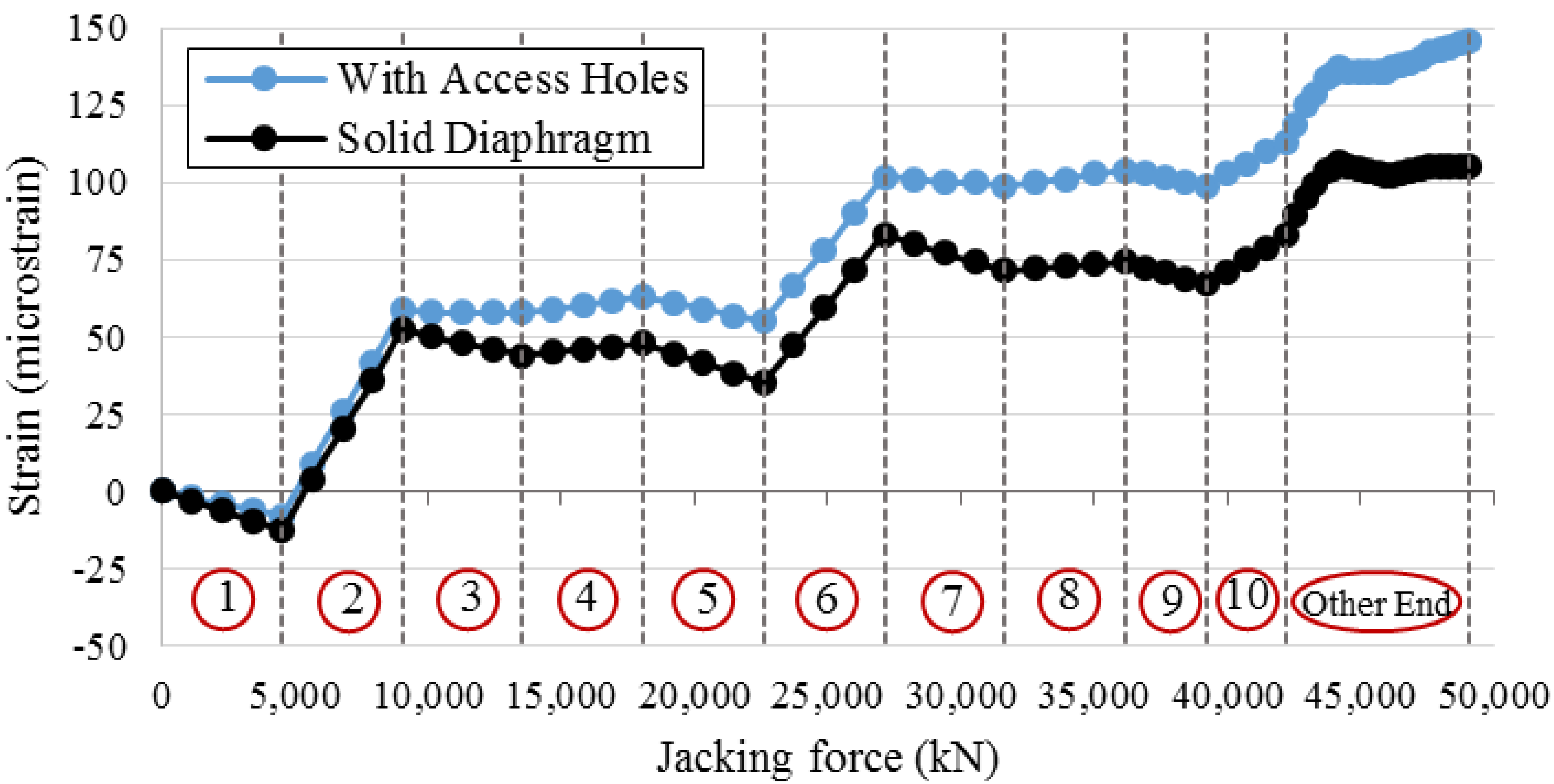


With access holes

Solid diaphragm



Expected Anchorage Performance



Preliminary Conclusions

- A realistic model is needed to prevent reinforcement congestion. The reduction of congestion will improve the chances of having high quality concrete in the anchorage zone and yield better performance.
- Preliminary finite element models determined the critical zones of stress concentration due to pre-stressing. The inner face of the end diaphragm and approximately 0.5 h of the web are affected by bursting tension forces.
- The developed database for anchorage zones of bridges illustrated wide variation in the values of reinforcement ratios in the end diaphragm. These variations show that reinforcement is selected by rules of thumb depending on typical bar diameters used in the end diaphragm, maximum spacing between bars and previous experience.

Preliminary Conclusions

- Care should be exercised in choosing a convenient type of strain gauge, suitable coating material, cover over the wires and installation method. The procedures used herein should be adequate for field instrumentation.
- Openings in the box girder diaphragm affect the performance of the end anchorage. These openings have a significant effect on the continuity of stresses in end diaphragm as well as the strains and stresses in reinforcing bars.

Future Plans

- Determine factors affecting performance of anchorage zones of box girder bridges.
- Extend the research using experimental specimens.
- Develop design guidelines for anchorage zones of box girders thereby expanding on the current MTD 11-25 guidance document.

THANK YOU

QUESTIONS ?