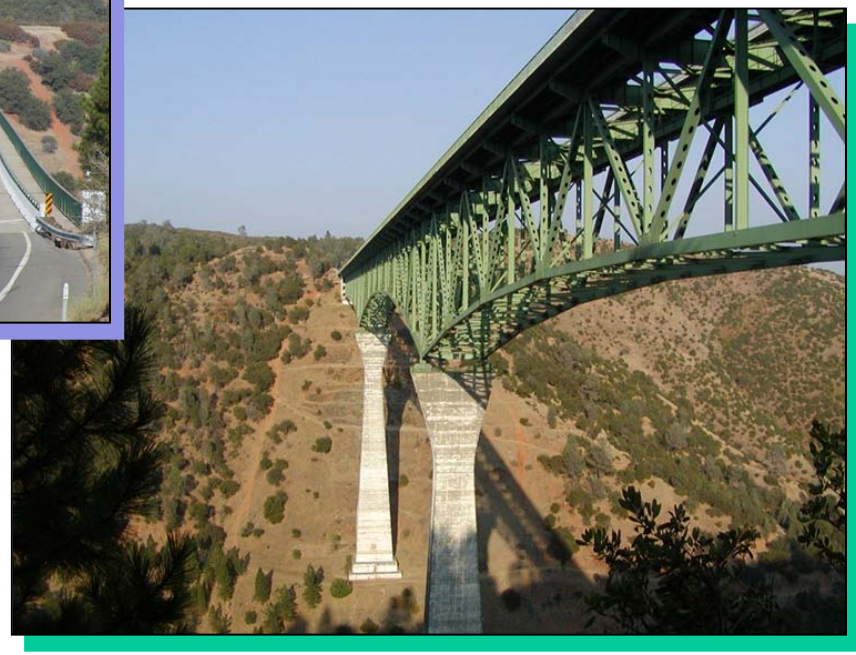
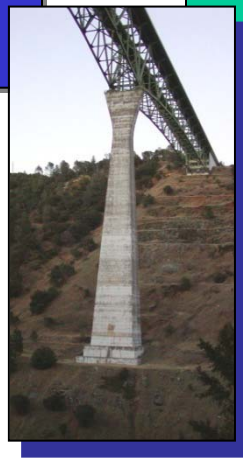
Western Bridge Engineers' Seminar

Seismic Retrofit of the Foresthill Bridge





Presented by:

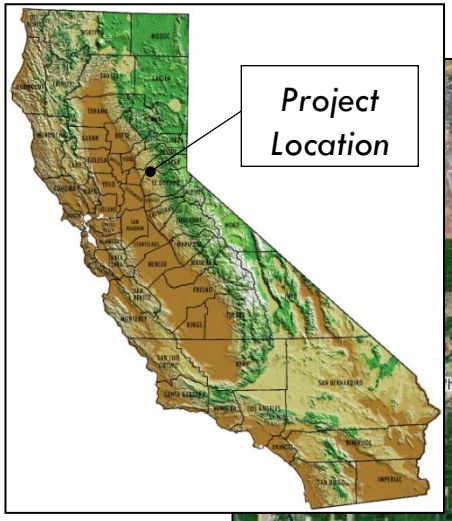
Sherri Berexa, P.E. & Mark Reno, P.E.

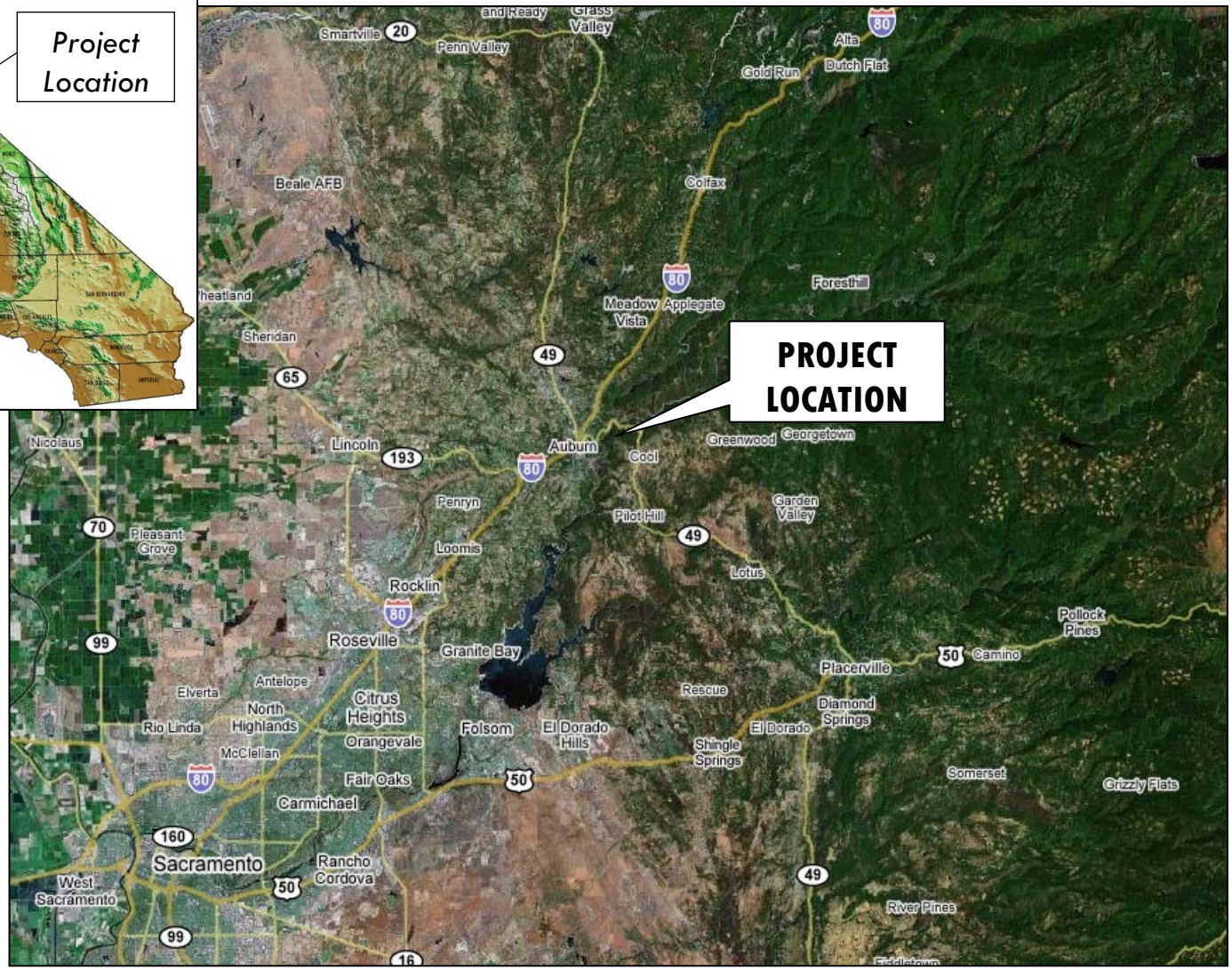
Placer County

Quincy Engineering, Inc.

September 21, 2009

Introduction





Placer County

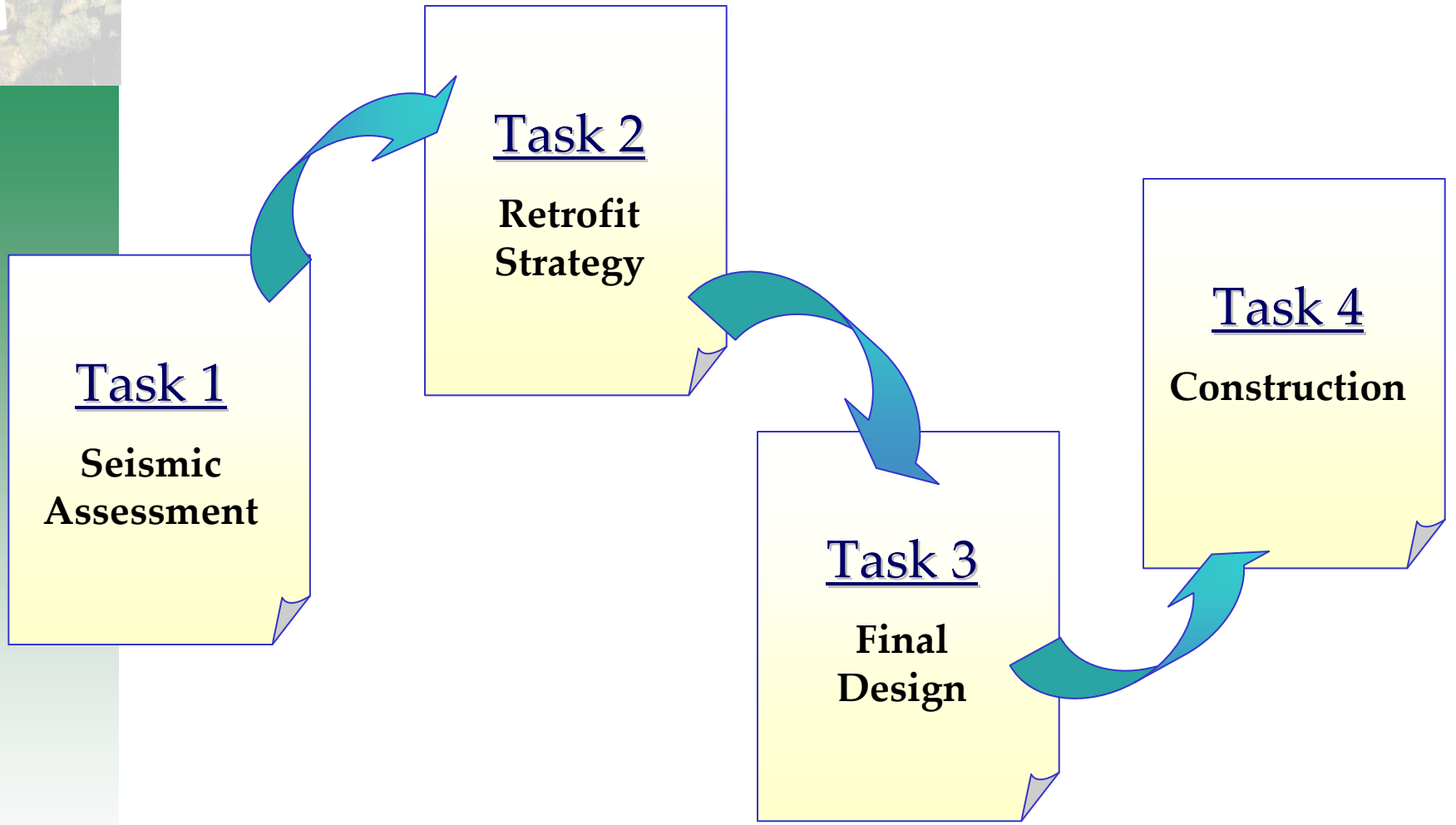
Quincy Engineering, Inc.

Introduction

Description of Foresthill Bridge

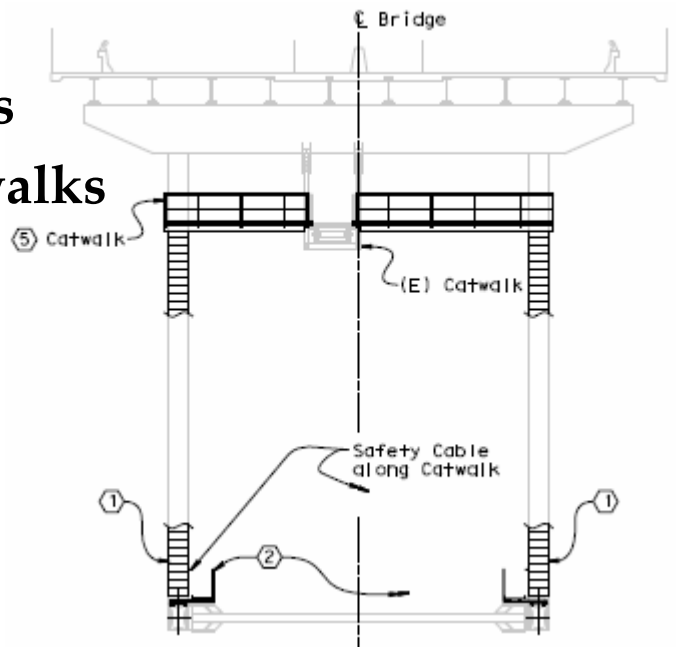
- Designed in 1970 by Bureau of Reclamation
- Built in 1973 by Kawasaki Heavy Industries
- Overall length is 2,428-ft
- Bridge deck approximately 730-ft above canyon
- Bridge deck intended to be 140-ft above reservoir

Work Plan Process



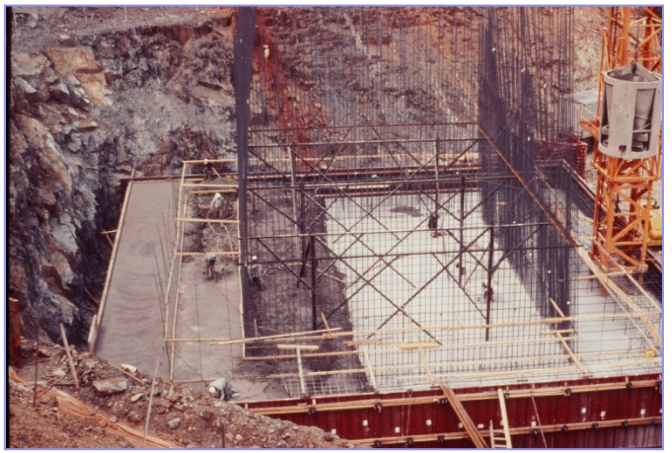
History of Project

- The Foresthill Bridge is on the Mandatory Seismic Retrofit Program List by Caltrans
- This project has had an aggressive schedule
- Additional tasks ended up bundled with this project including:
  - **Repainting of the entire bridge**
  - **Pedestrian railing modifications**
  - **Fracture-critical inspection catwalks**



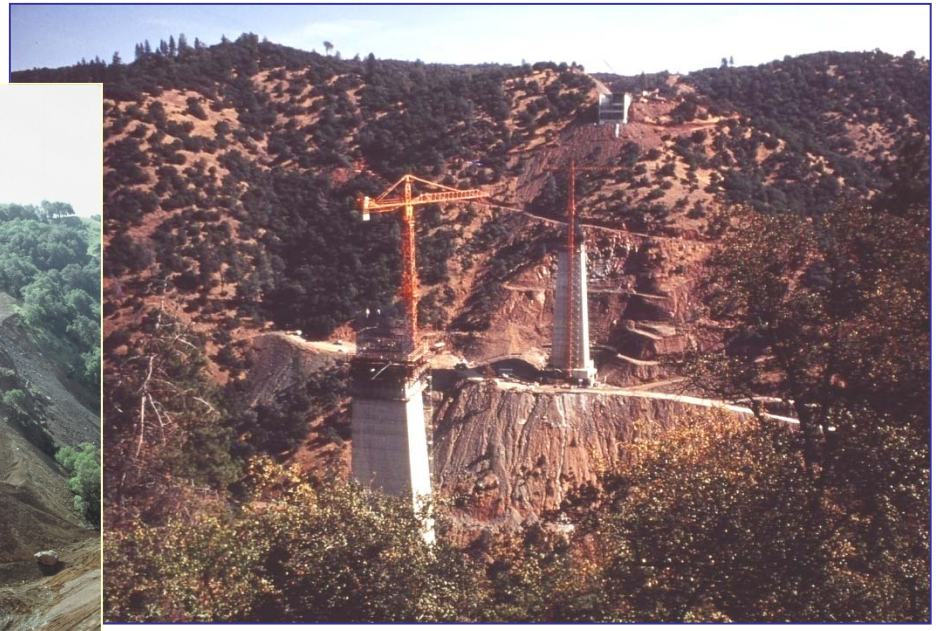
Description of Foresthill Bridge

- Bridge located 3,000-ft upstream of North and Middle Fork confluence of American River
- Foundations excavated to rock
- Footings 85-ft by 85-ft



Description of Foresthill Bridge

- Piers approximately 403-ft tall
- Base of pier 45-ft by 60-ft
- Pier is cellular and tapers
- Piers walls up to 14-ft thick
- Top of Pier 60-ft wide

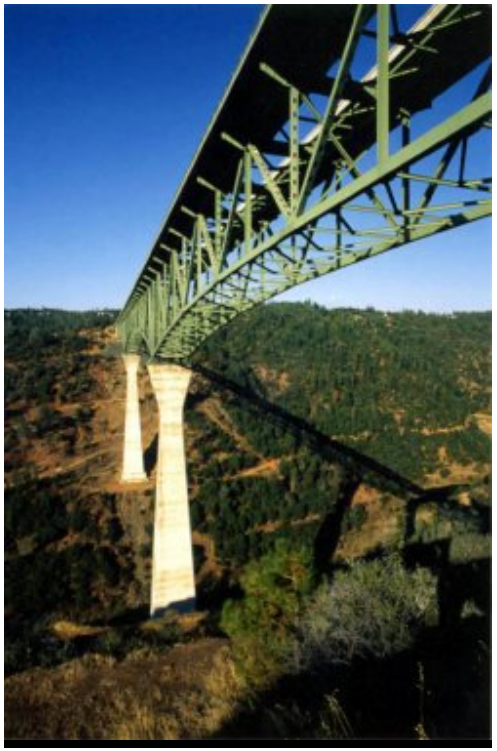


Description of Foresthill Bridge

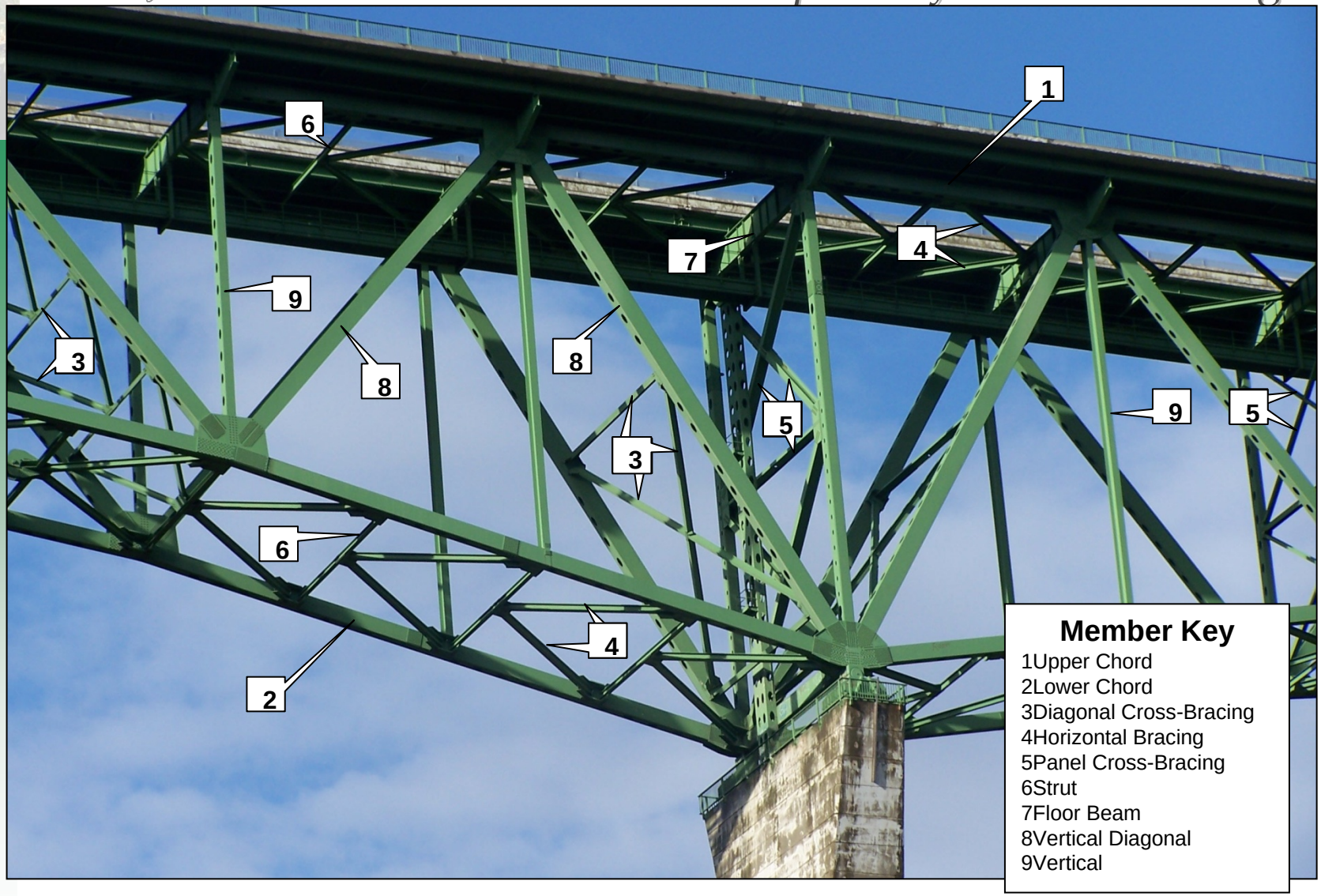
- Three-Span Deck -Type Warren Truss
- Truss supports two roadway decks
- Cantilever construction

- Truss has T-1 steel
- Main span is 862-ft

Description of Foresthill Bridge



Description of Foresthill Bridge



Member Key

1Upper Chord
2Lower Chord
3Diagonal Cross-Bracing
4Horizontal Bracing
5Panel Cross-Bracing
6Strut
7Floor Beam
8Vertical Diagonal
9Vertical

Seismology

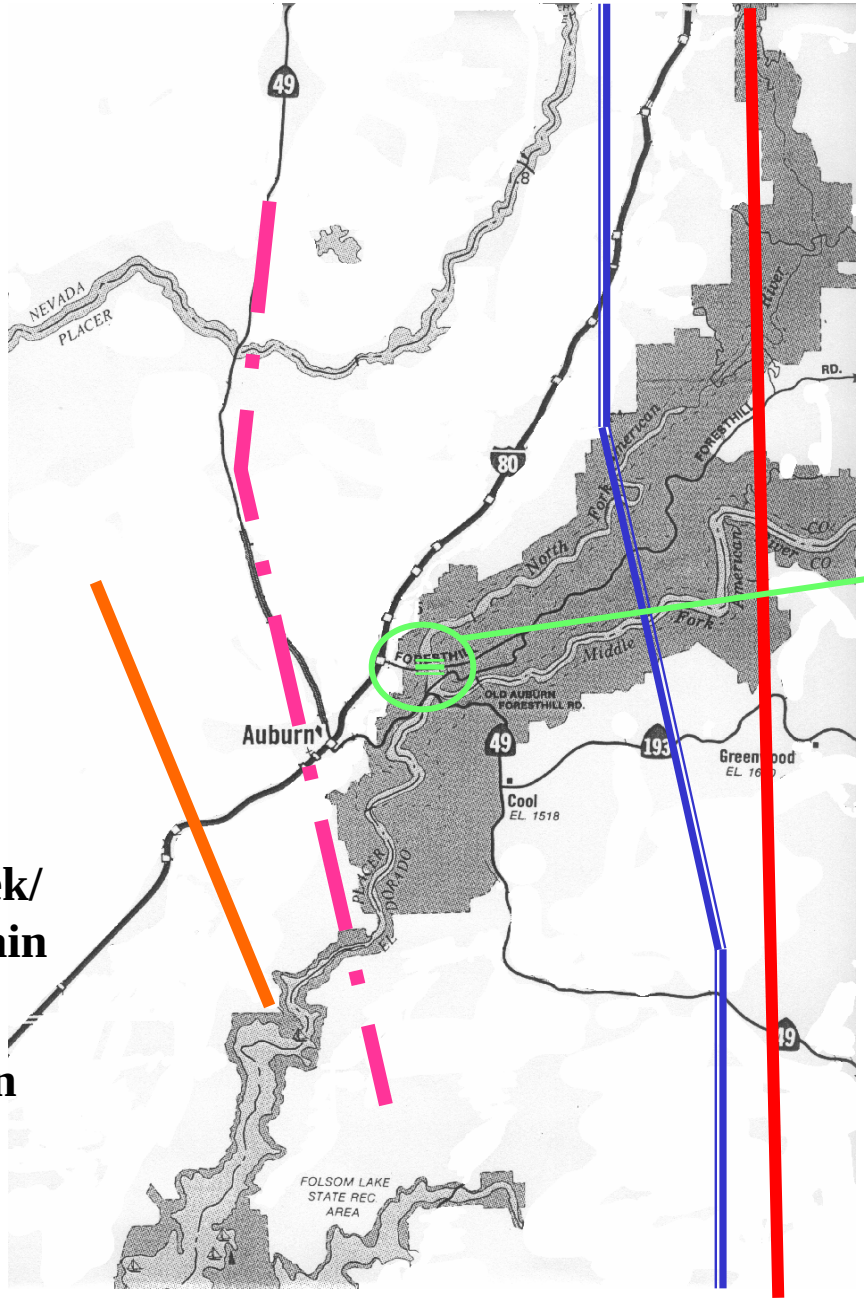
Faults

BMW = Bear Mountain

GMT = Gillis Mountain

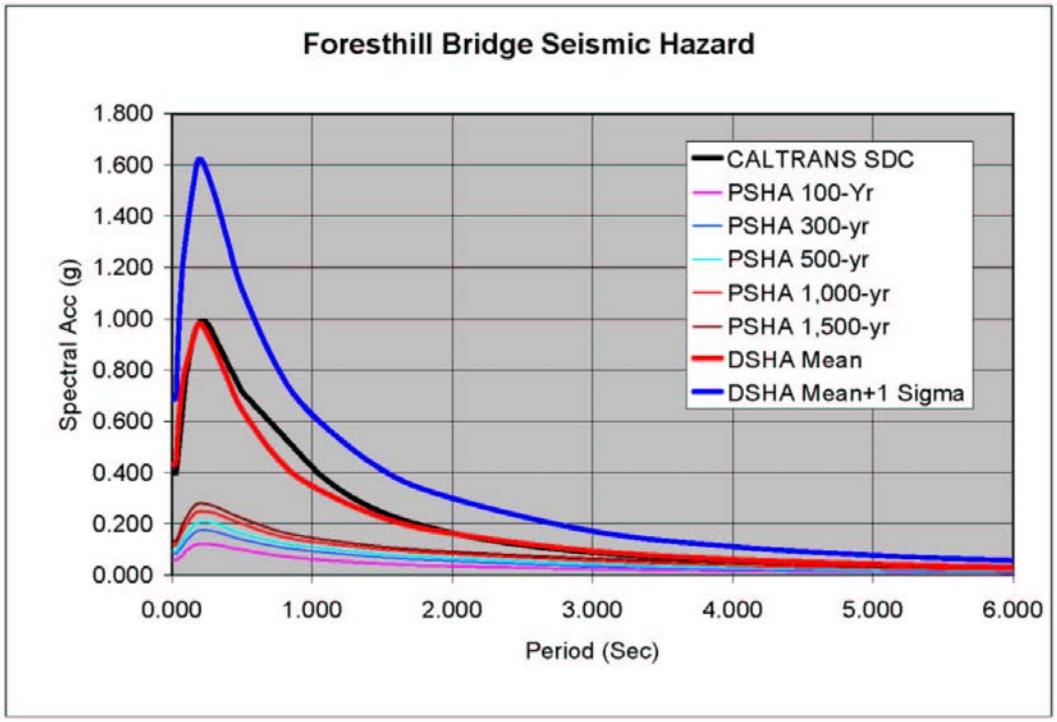
BWM = Big Bend/Wolf Creek/ Maidu/Bear Mountain

PSD = Prairie Creek/ Spenceville/Dentman



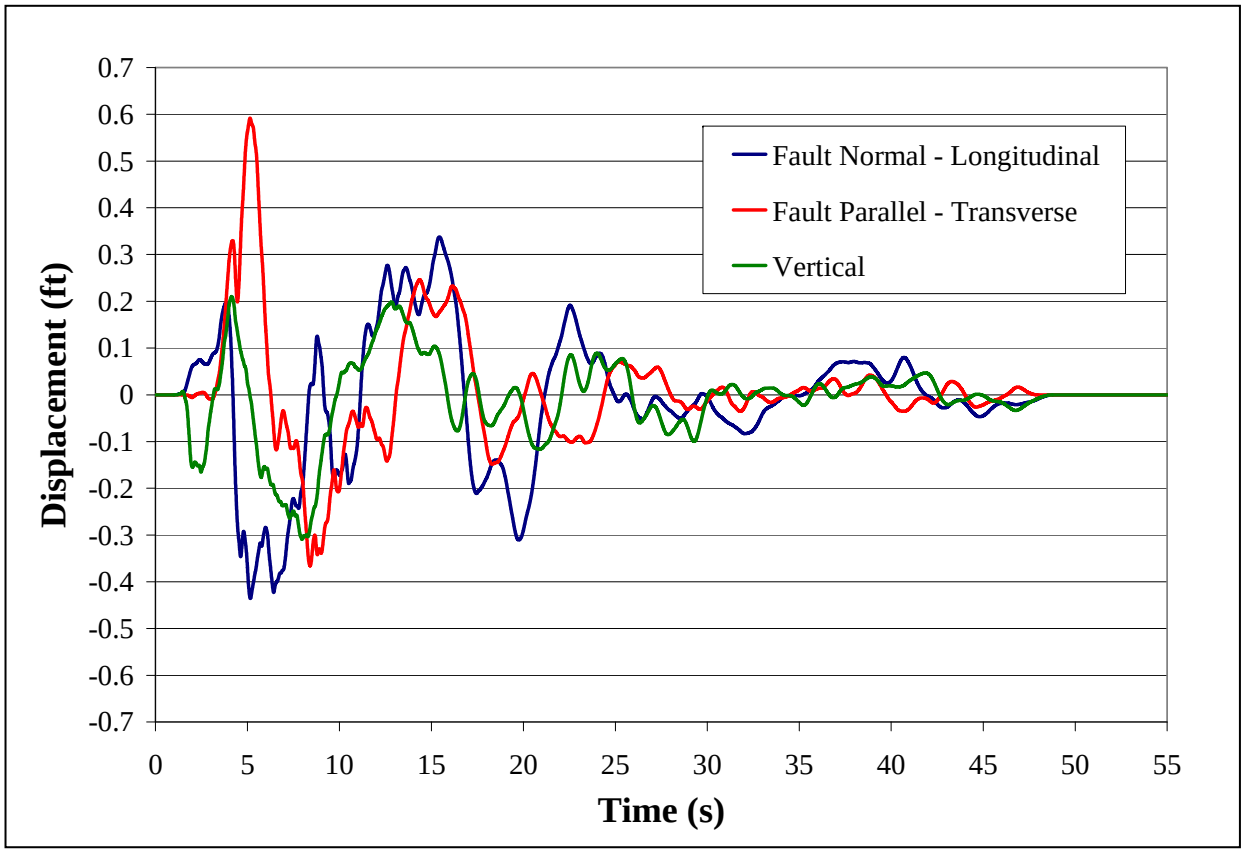
Foresthill Bridge

Design Spectrum



- **For response spectrum analysis, Caltrans SDC used**
- **Caltrans SDC peak ground acceleration: 0.99g**

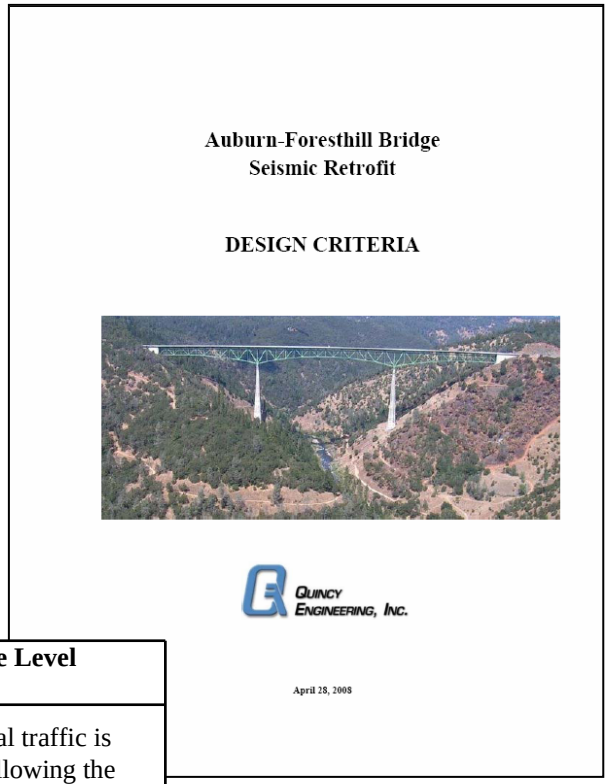
- **Defines Input Ground Motions**
  - **Longitudinal, transverse, and vertical motions**
  - **Final analysis with 3 separate ground motions**



Ground Motion 1

Design Criteria

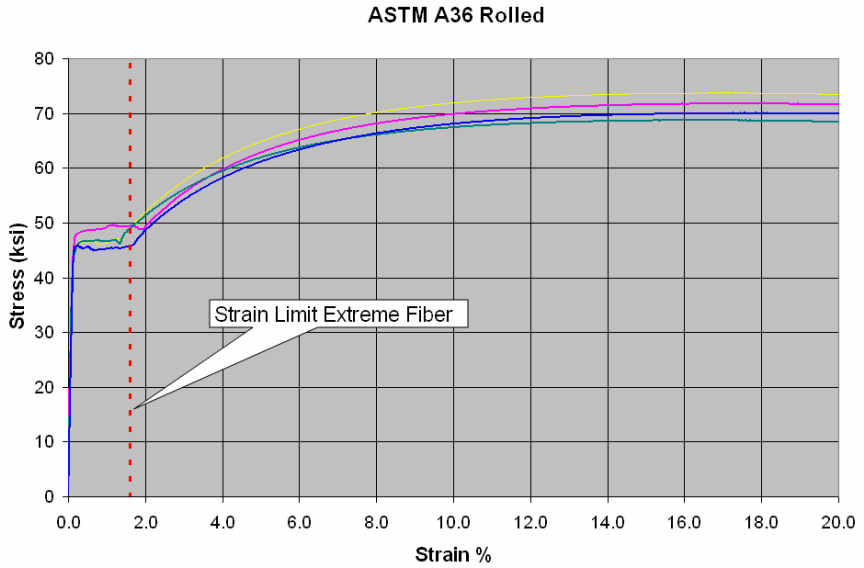
- Performance definitions
- Linked to anticipated damage
- Member material strain
- Slenderness limits
- Local buckling criteria from force demand to strain
- Has been reviewed and approved by Project Peer Review Panel



Ground Motion	Damage Level	Post Earthquake Service Level
Functional Evaluation Earthquake (FEE)**	Minimal – essentially elastic performance	Immediate – full access to normal traffic is available almost immediately following the earthquake
Safety Evaluation Earthquake (SEE)	Significant – the structure may be closed temporarily or partially, but can be repaired.	Limited – limited access with reduced lanes or permitting only light emergency traffic is possible within days of the earthquake. Full service is restorable within months.

***For a return period of 300 years the Functional Evaluation Earthquake (FEE) for structural periods greater than 1.5 seconds, the maximum ground acceleration is approximately equal to the original seismic design ~10% dead load. See Figure 5 in Appendix B. No other evaluation will be done.*

- **Limit strains in primary and secondary members**
  - **Extreme fiber strain**
  - **Axial strain**

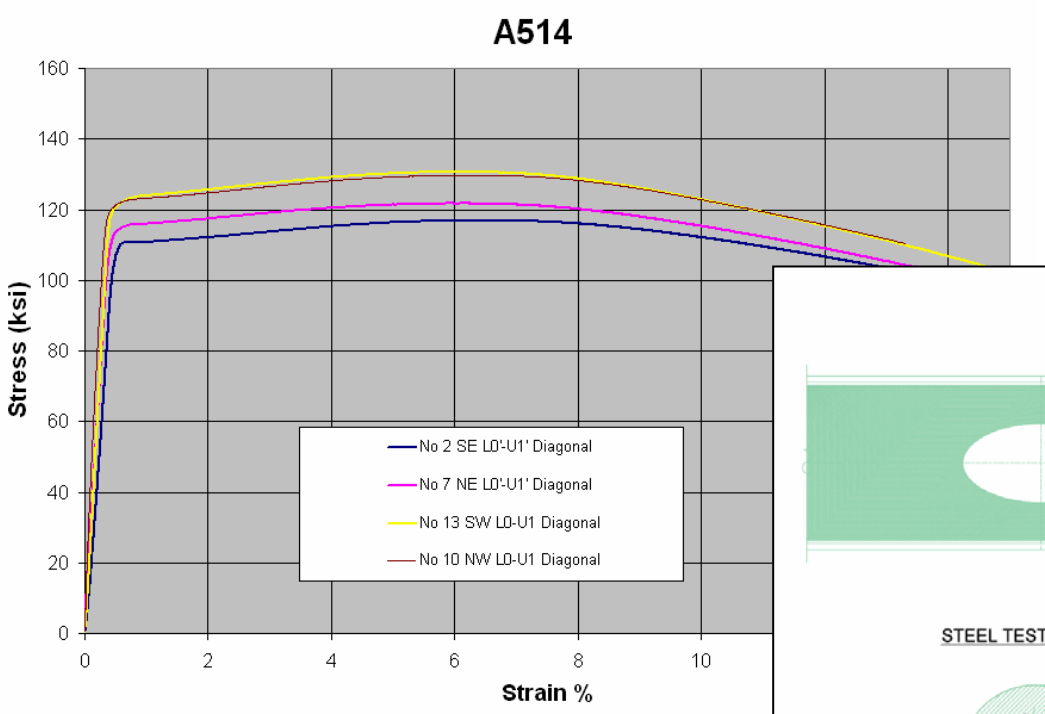


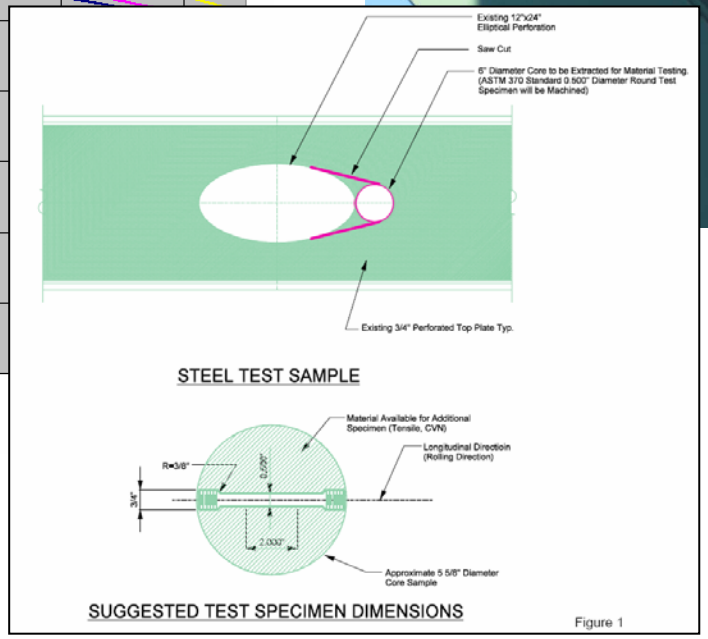
Acceptable Strain Levels (SEE)				
Category	Group	Damage Level	Maximum Strain	
			At Section Centroid	At Extreme Fiber
Primary	Main Truss	Minimal	$0.80\varepsilon_y$	Larger of 0.003 or $1.5\varepsilon_y$
Primary	Stringer & Floorbeam	Significant	Larger of 0.008 or $(2/3)\varepsilon_{sh}$	ε_{sh}
Secondary	Truss Bracing	Significant	Larger of 0.008 or $(2/3)\varepsilon_{sh}$	ε_{sh}

Strategy Criteria

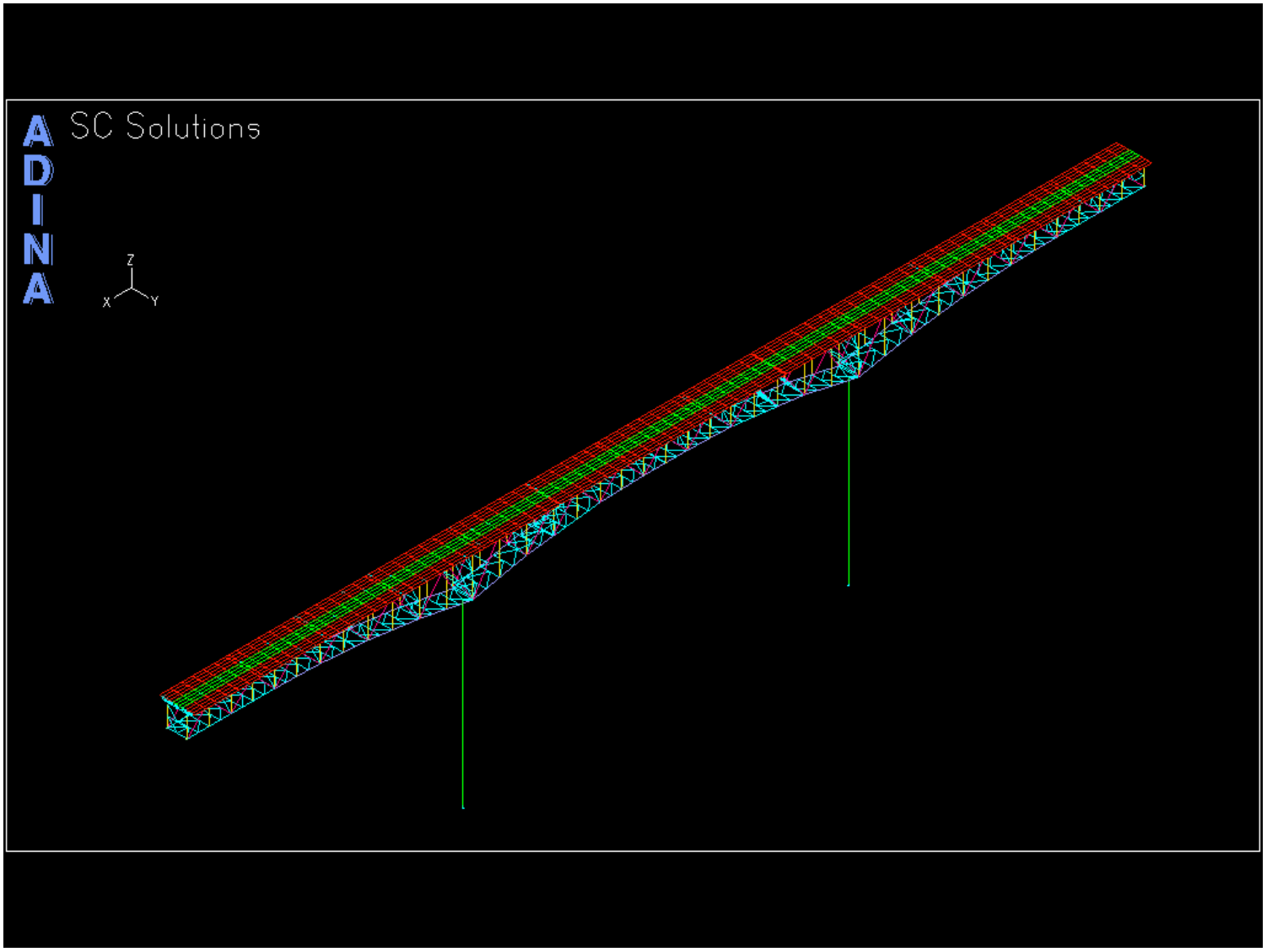
Design Criteria

- Properties based on construction records and FEMA 356
- Verified Steel Properties by actual coupon testing





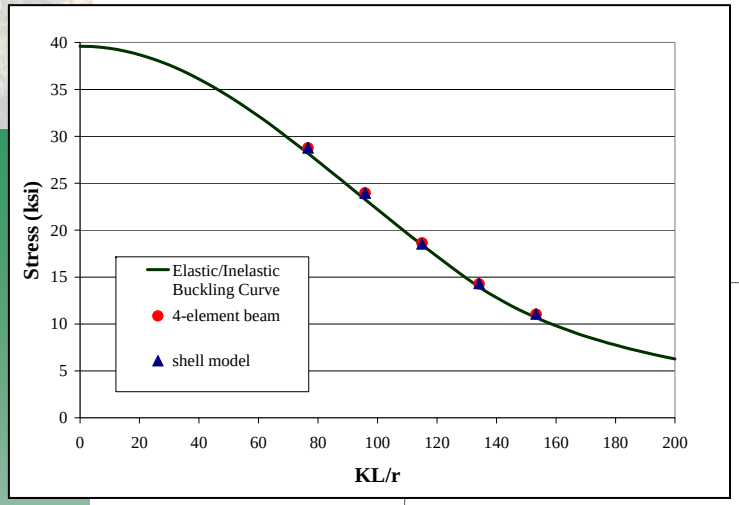
Nonlinear Global Model



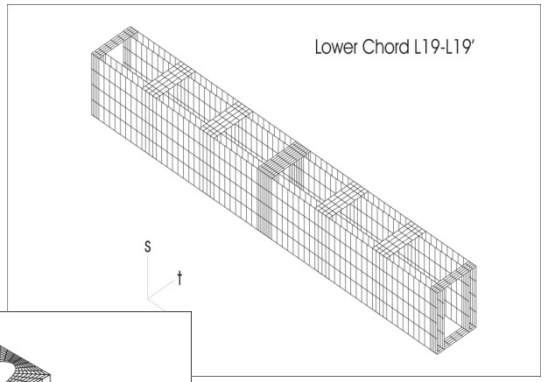
Foresthill Bridge

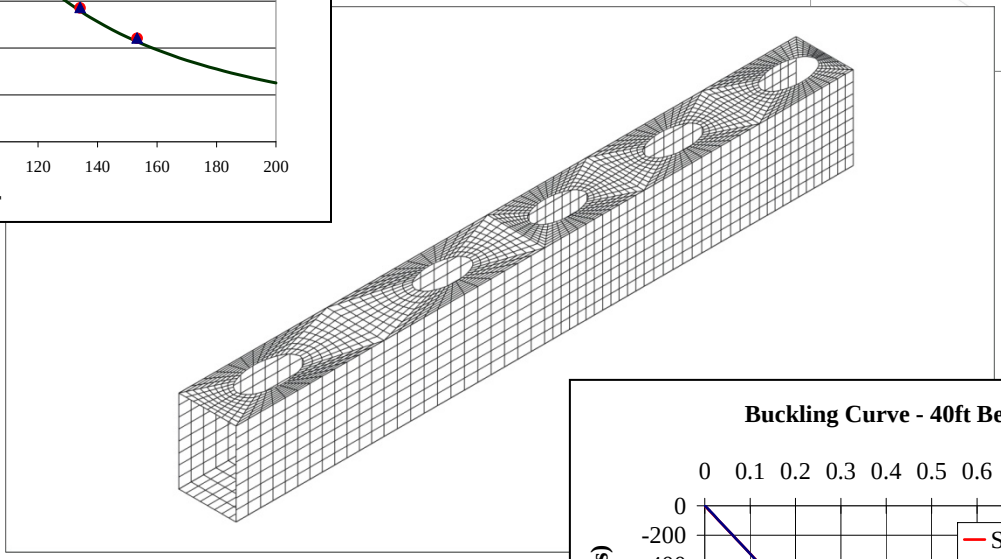
Nonlinear Global Model - Validation

Test Models

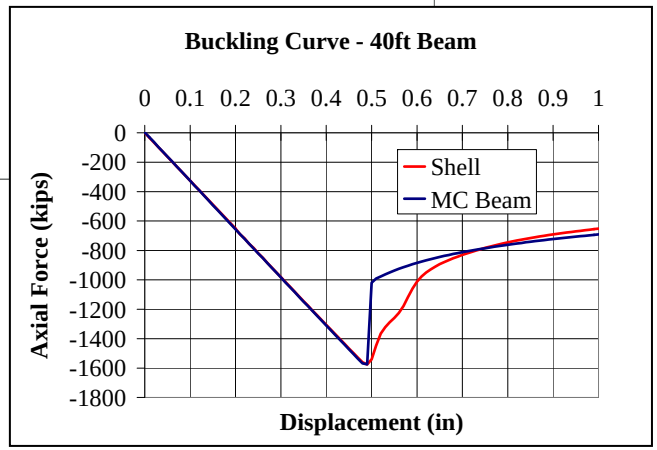


FE Model

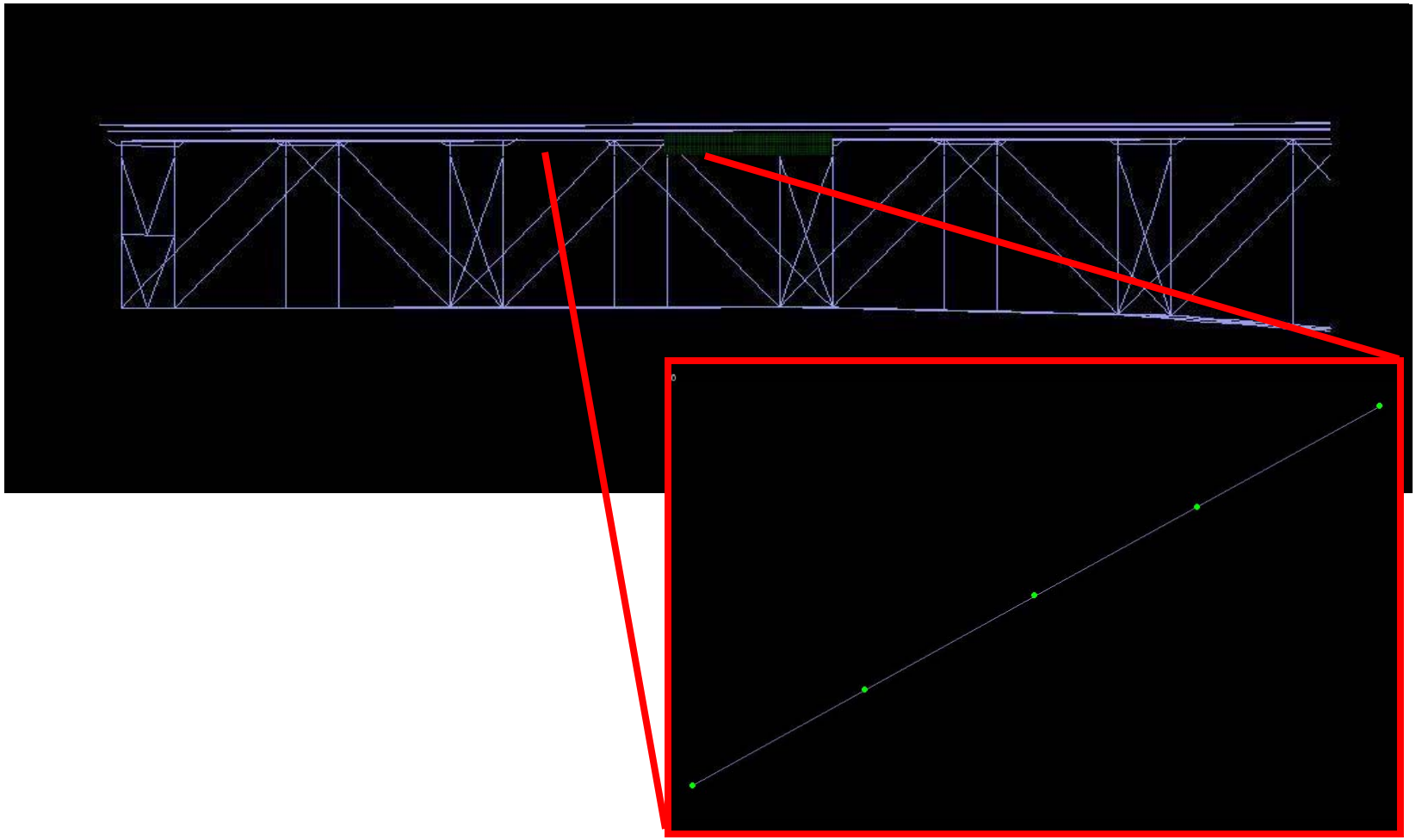




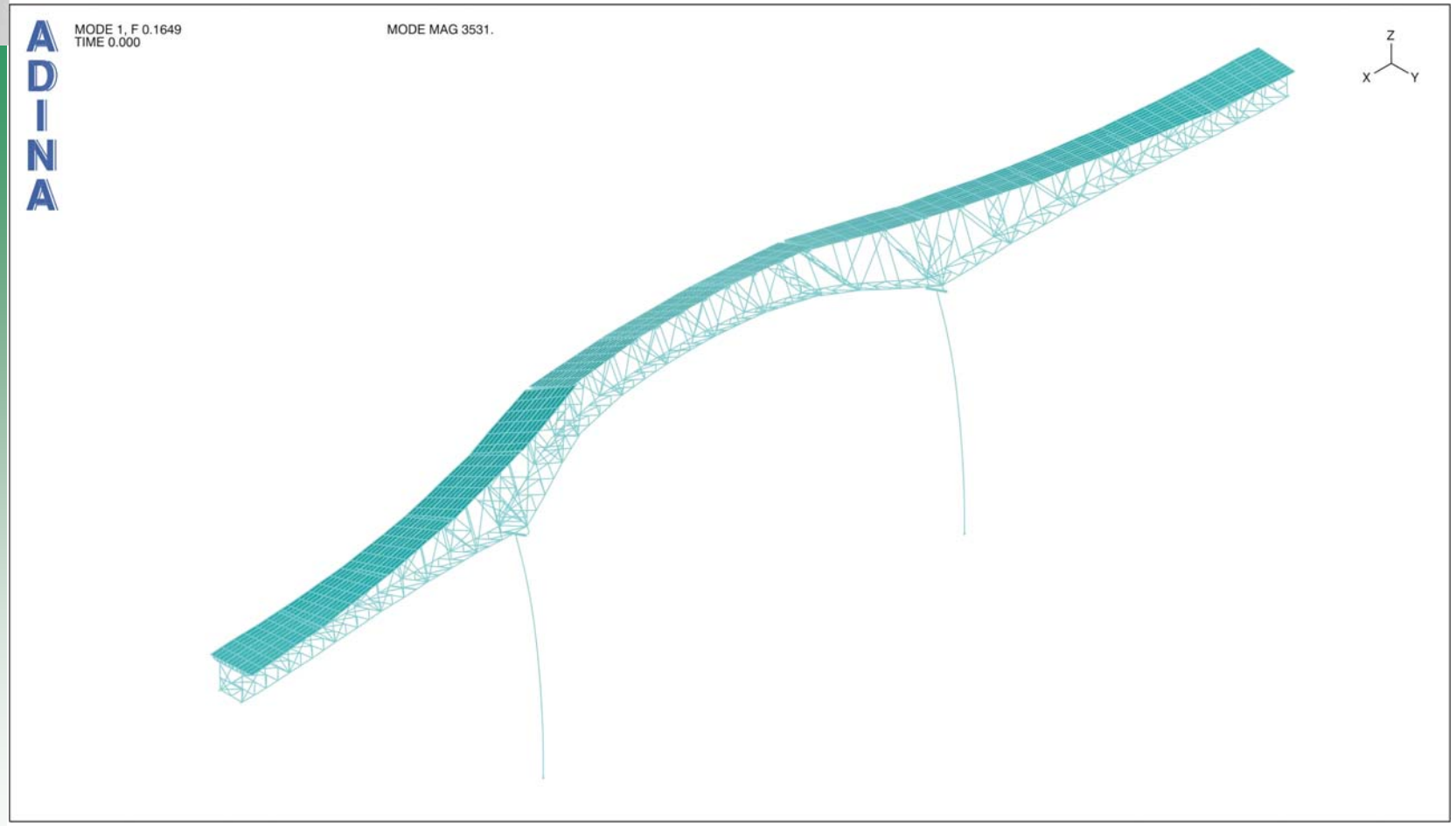
FE Model vs. MC Beam Model



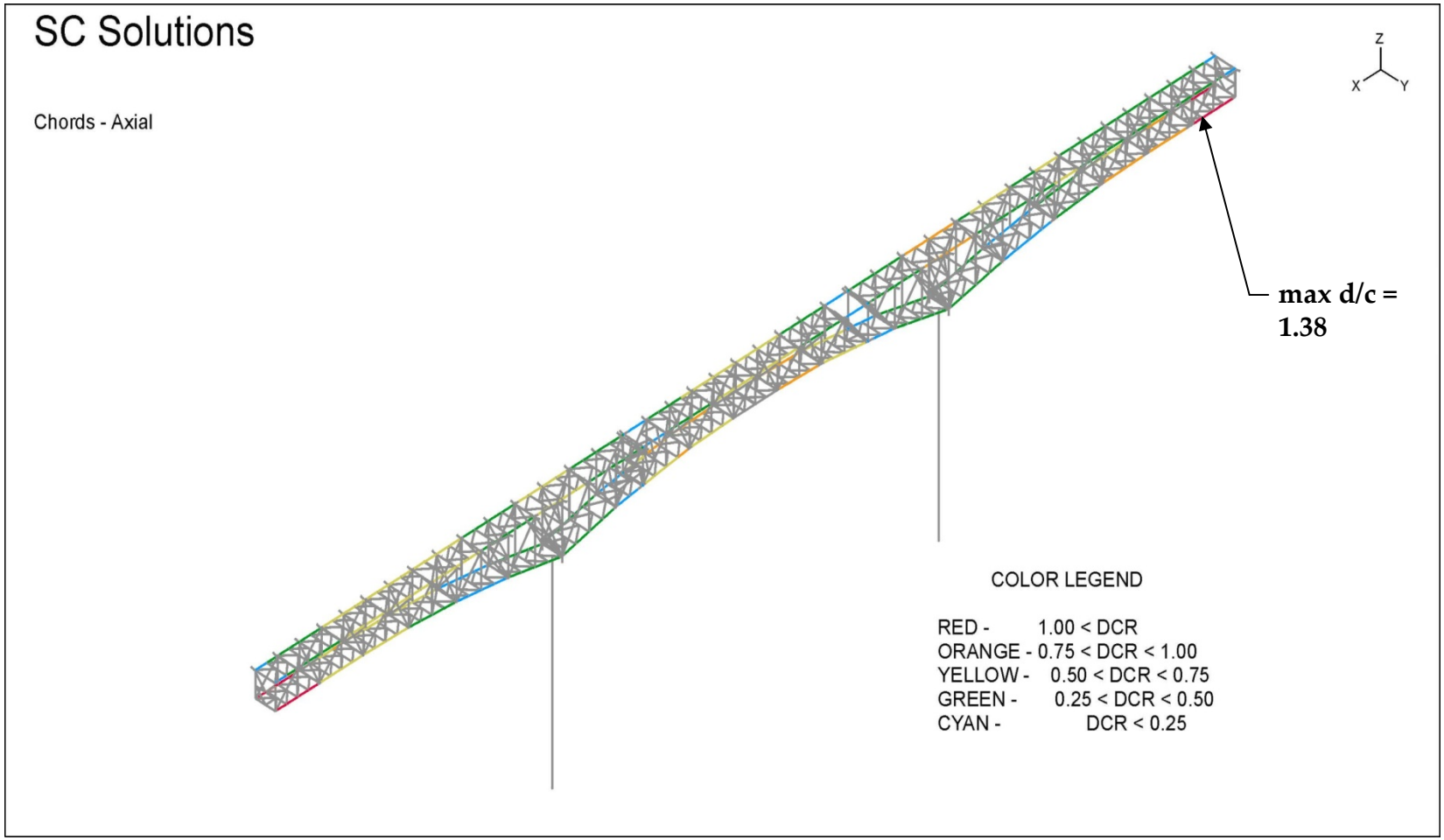
Nonlinear Global Model - Validation



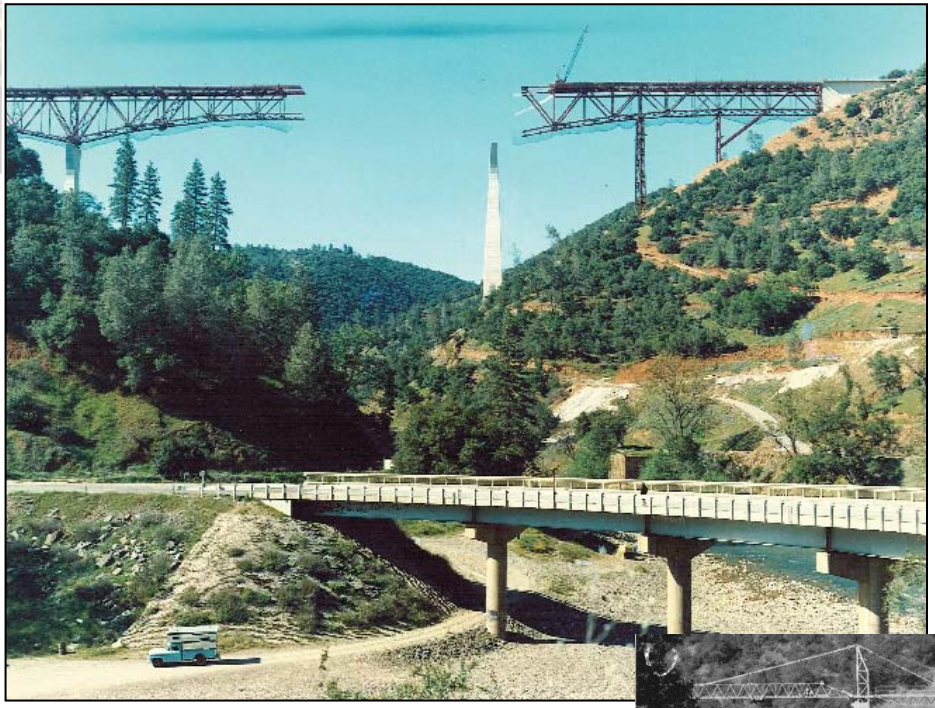
Nonlinear Global Model

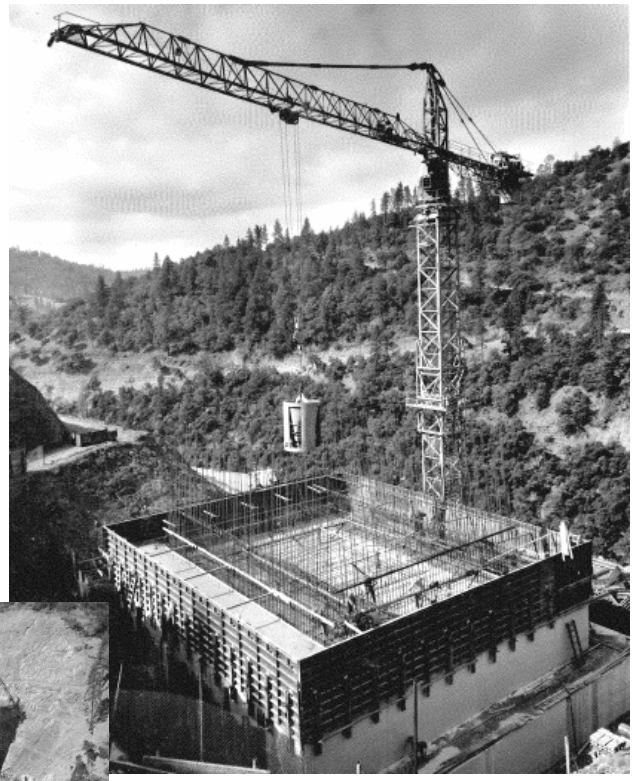


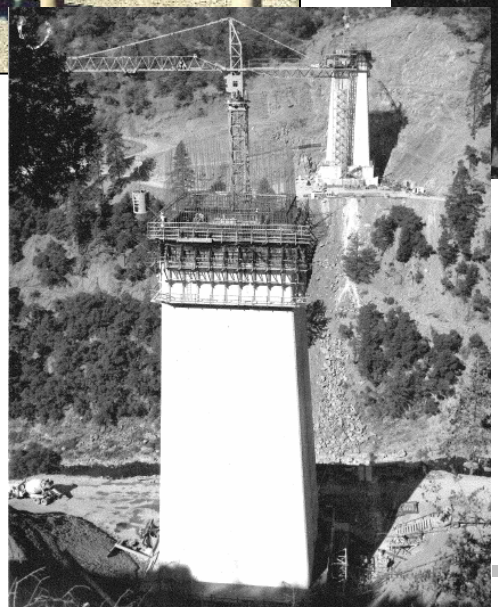
Nonlinear Global Model – Results



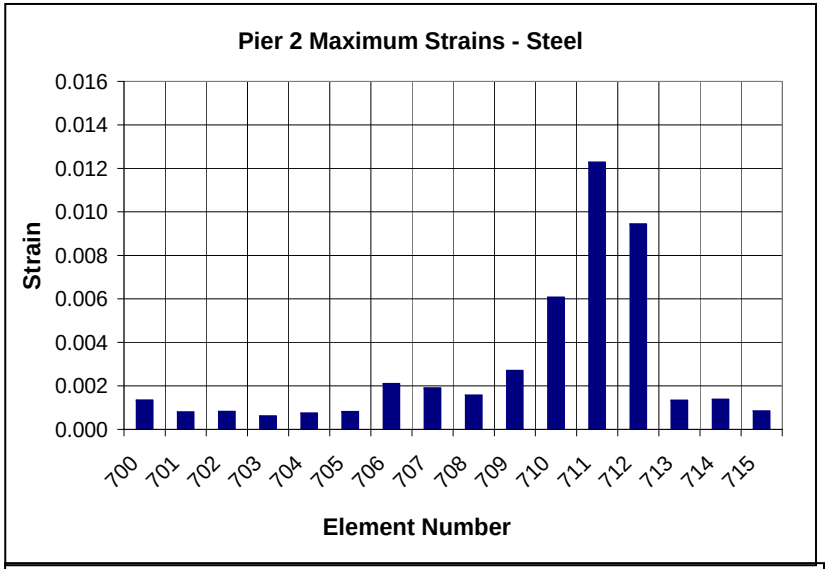
Pier Analysis

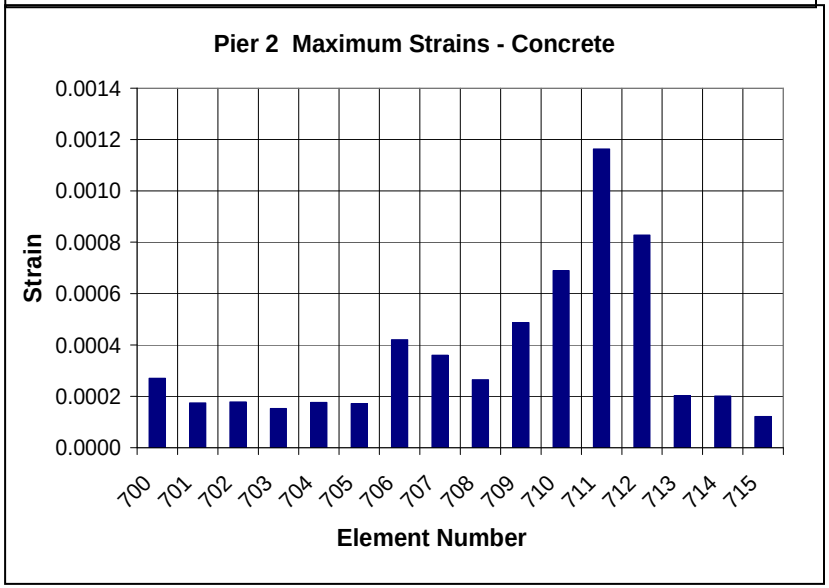


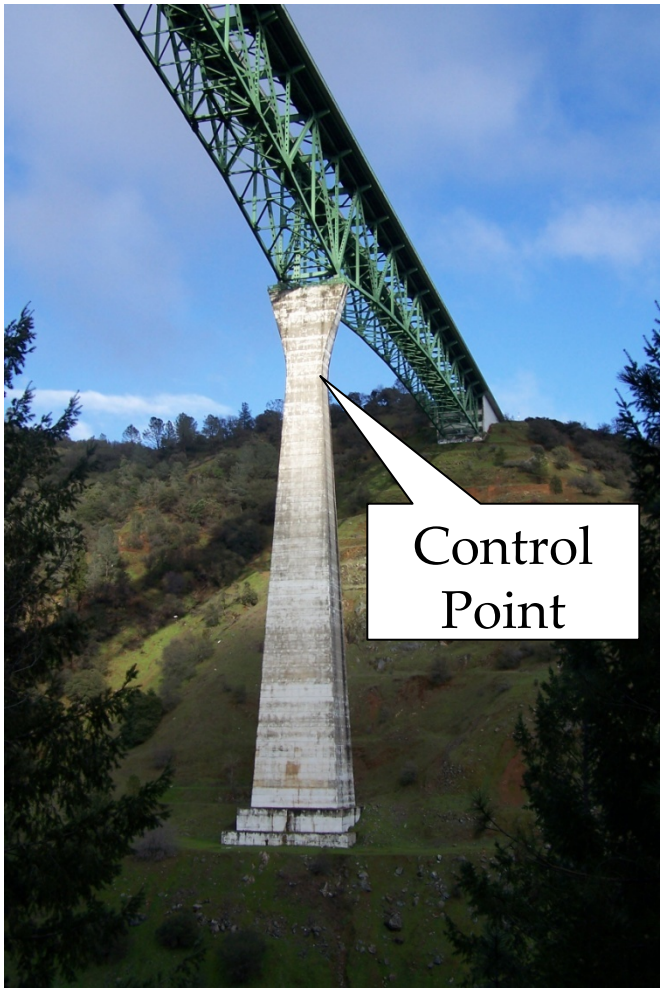




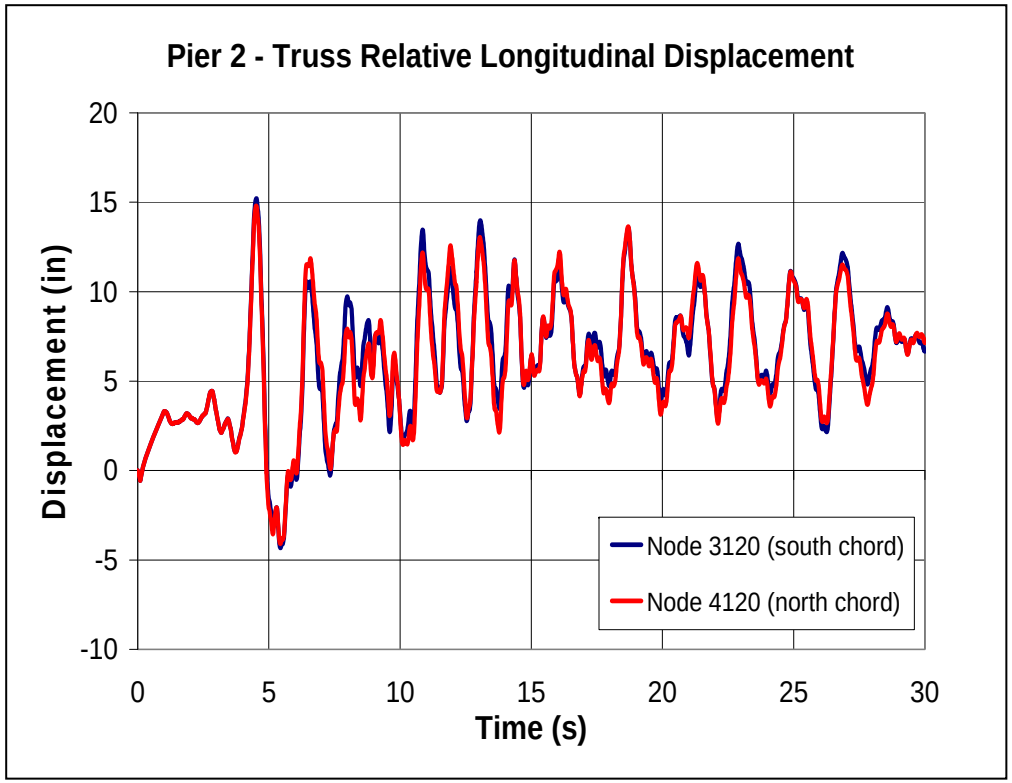
Pier Analysis





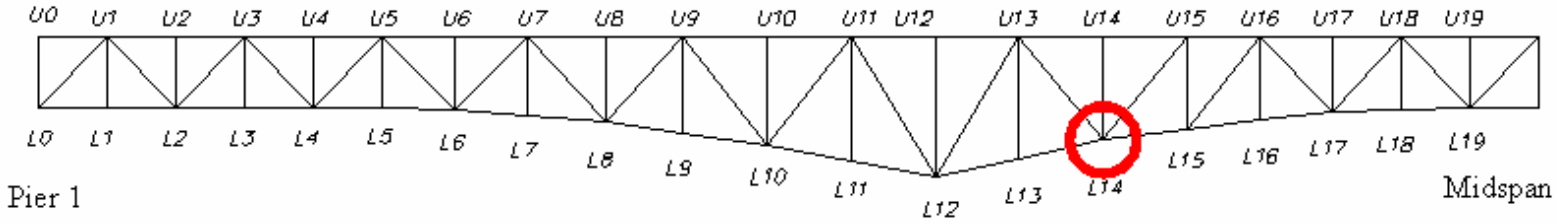


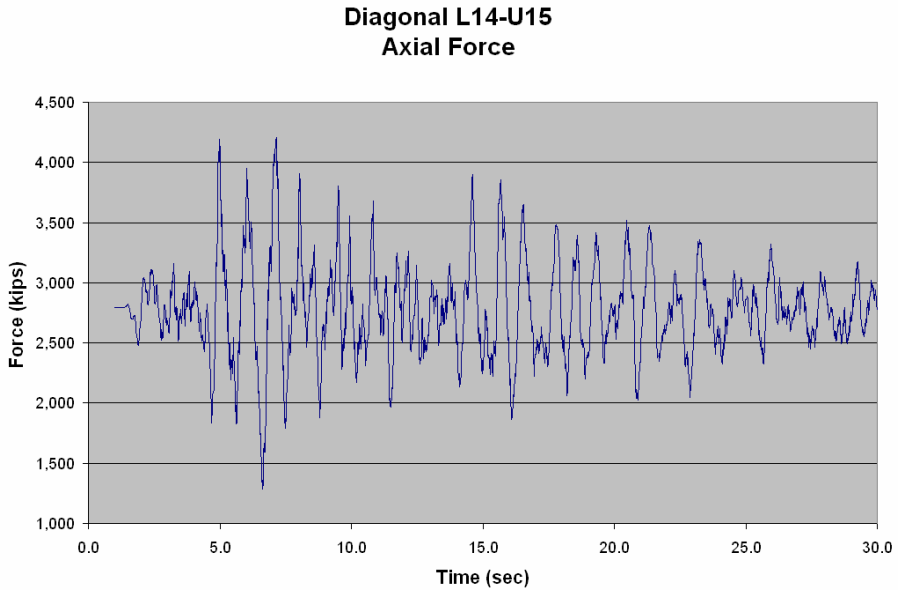
Pier Analysis



Detailed Gusset Analysis

- Member forces from the non-linear time-history analysis
- Each 0.01 second time step over 30.0 second time-history





Acceptance Criteria

- Elastic members - Capacity ϕR_r to resist at least 1.25 x seismic demand forces in the members.

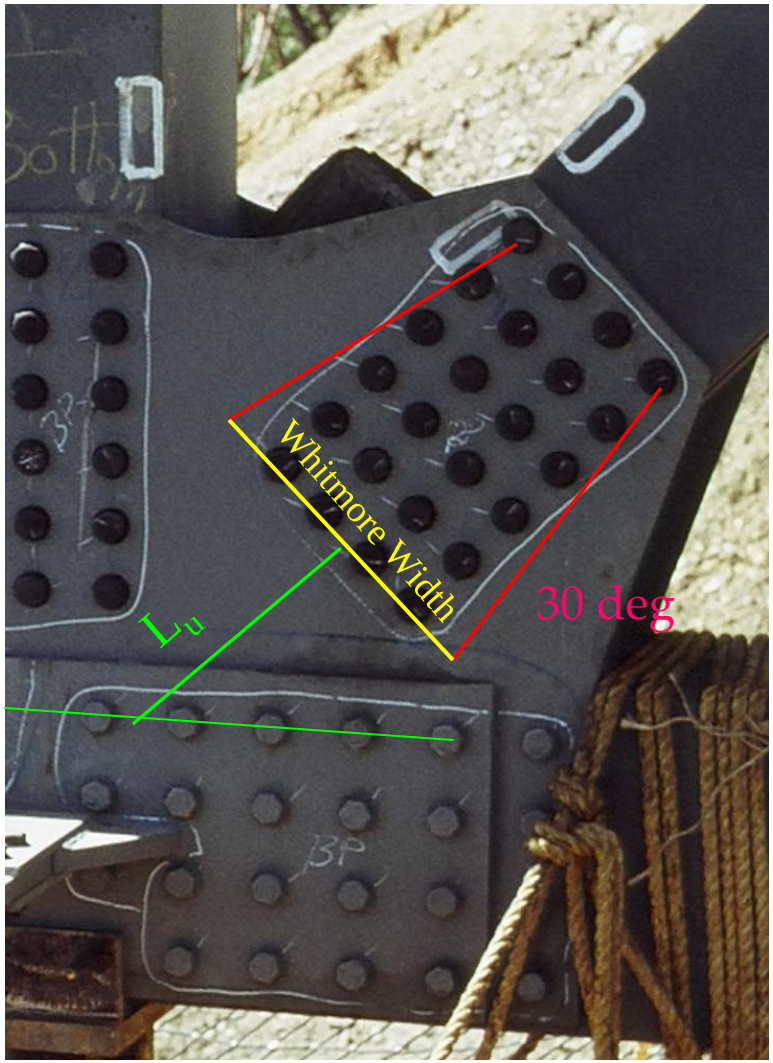
- Yielding members - Capacity ϕR_r to resist the expected yield strength of the member

- Design Force = $Lesser\ of \begin{Bmatrix} 1.25xDemand \\ (Area)F_{YE} \end{Bmatrix}$

Detailed Gusset Analysis

- Bolts at each member checked for effects of Forces F_r-F_s-F_t and Moments M_r-M_s-M_t
- Moments M_r and M_s Resolved into Force Couple on Near and Far Gusset

Detailed Gusset Analysis



Gusset at each member checked for tension and compression using Whitmore Width and assumed buckling length L_u

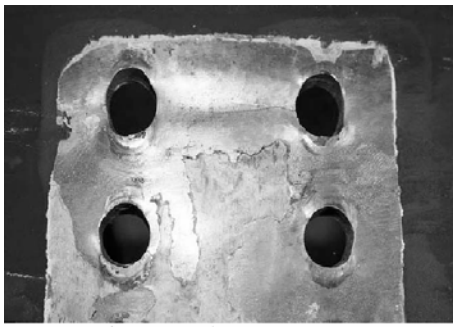


Figure 2-2. *Bolt Bearing Limit State*

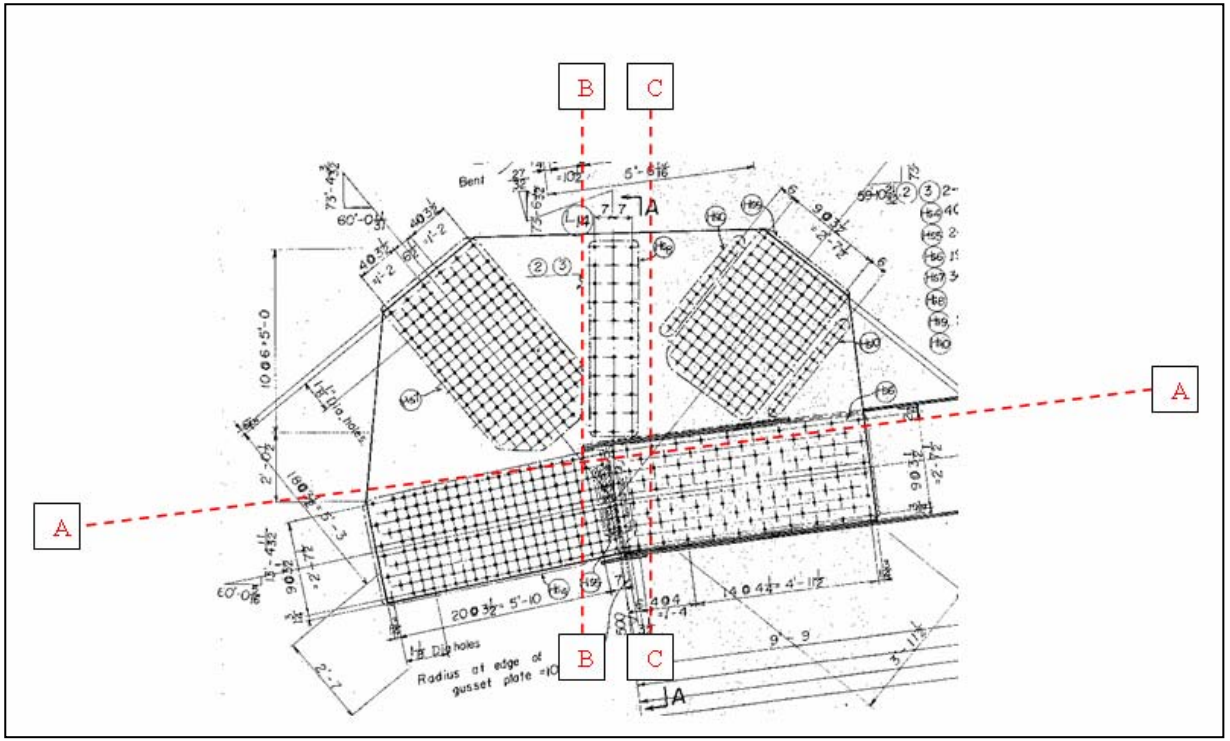
Check bolt shear and bolt bearing

Check Block Shear

L_{14S} - Bolt Shear and Bearing Results

Member	Maximum Bolt Force	Time at Max Force	Allow Shear	Allow Bearing Gusset	Allow Bearing Member	D/C
	kips	sec	kips	kips	kips	
L12L14 - Chord	3.91	6.05	29.0	211.2	343.2	0.135
L14L15 - Chord	12.27	11.21	29.0	211.2	369.6	0.424
U13L14 - Diag	19.79	5.20	29.0	211.2	211.2	0.684
U14L14 - Vert	25.99	5.24	29.0	211.2	83.5	0.898
L14U15 - Diag	27.65	5.20	36.2	211.2	343.2	0.764
L14L14C - BC Strut	24.94	5.19	36.2	158.4	97.4	0.689
L14L14AC - BC Brace	15.30	5.59	36.2	158.4	100.9	0.423

Detailed Gusset Analysis



- 1" Thick A514 Gusset plate at Joint L_{14} was evaluated at:
  - Upper bolt line of $L_{14}L_{15}$ – Chord = Section A
  - Vertical plane through the gusset along the left and right bolt line of $L_{14}U_{14}$ – Vertical = Section B and Section C
  - Find Axial, Shear and Moment at each section at each timestep

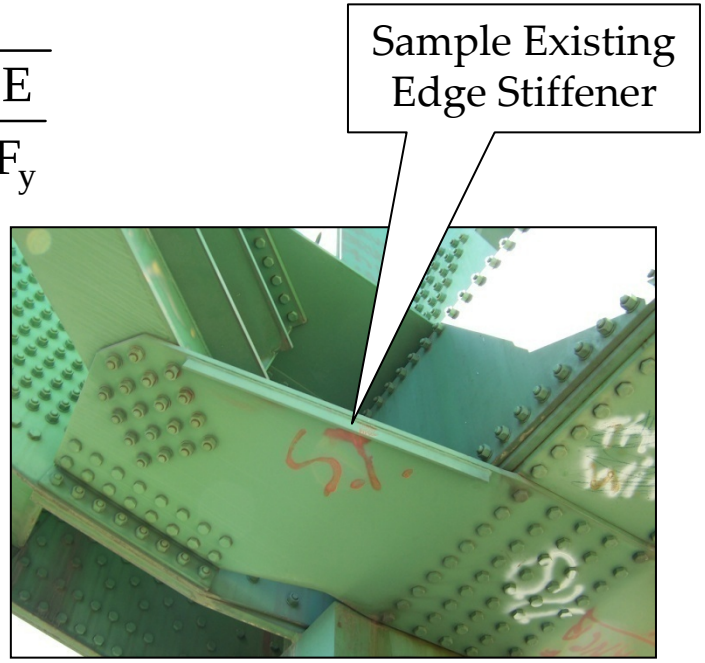
Detailed Gusset Analysis

- Limit states evaluated for the gusset plate at each section:
  - In-Plane Shear through the gross and net section
  - Out-of-Plane Shear
  - Combined In-Plane Shear and Axial Force
  - Out-of-Plane Bending
  - In-Plane Bending combined with In-Plane Axial Loads

Detailed Gusset Analysis

Gusset Edge Buckling Criteria

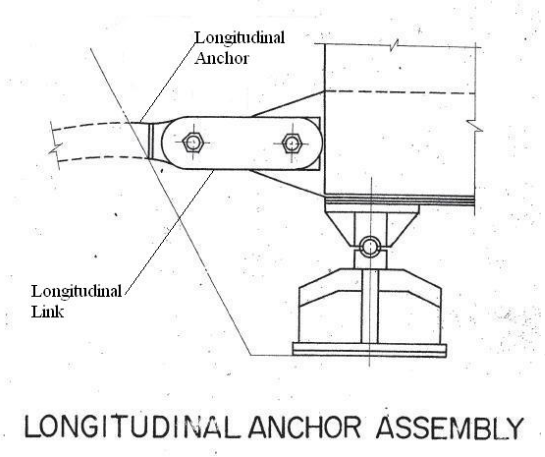
- Unstiffened Edge with $f_c < 0.8F_y$ $\quad \frac{L}{t} < 2.06\sqrt{\frac{E}{F_y}}$
- Unstiffened Edge with $f_c > 0.8F_y$ $\quad \frac{L}{t} < 1.60\sqrt{\frac{E}{F_y}}$
- Otherwise edge shall be stiffened



Vulnerabilities & Retrofits

Vulnerability

Longitudinal anchor plates at Piers 1 and 4 will experience forces and strains that significantly exceeds their capacity which leads to longitudinal instability



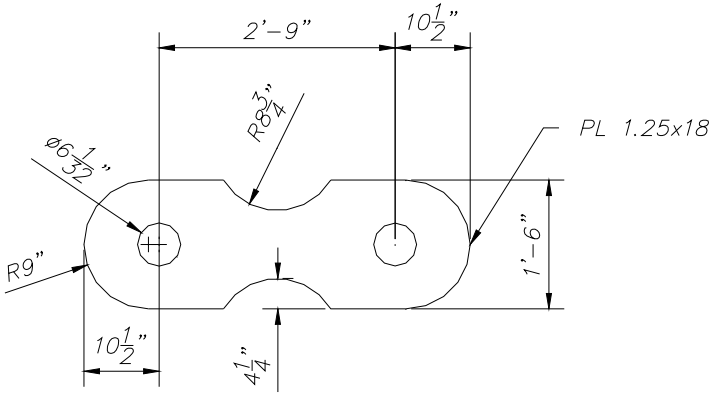
LONGITUDINAL ANCHOR ASSEMBLY

Link plates are stronger and remain elastic

Retrofit Measure

Change geometry of link plates at Piers 1 and 4 to reduce their capacity so that yielding occurs in link plates instead of anchor plates so that system can be inspected and repaired after a significant seismic event.

Add Buckling Restrained Braces (BRB) at Piers 1 and 4 to provide longitudinal stability

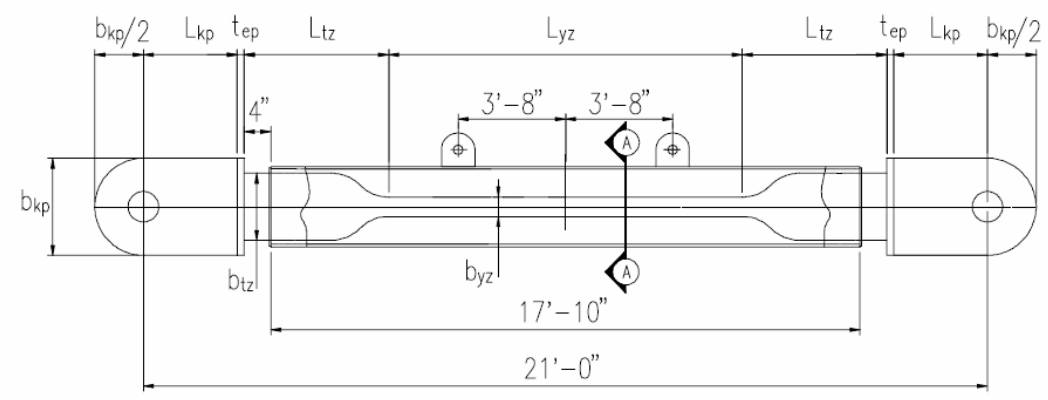


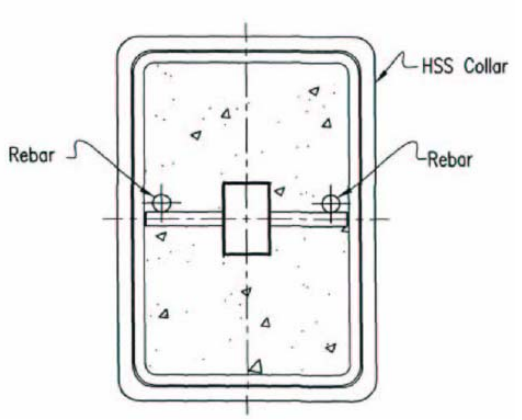
Link Plate

Vulnerabilities & Retrofits

- Buckling Restrained Braces (BRB's) - constructed of a cruciform or rectangular steel core surrounded by a debonding material and encased in a steel hollow tube filled with grout.

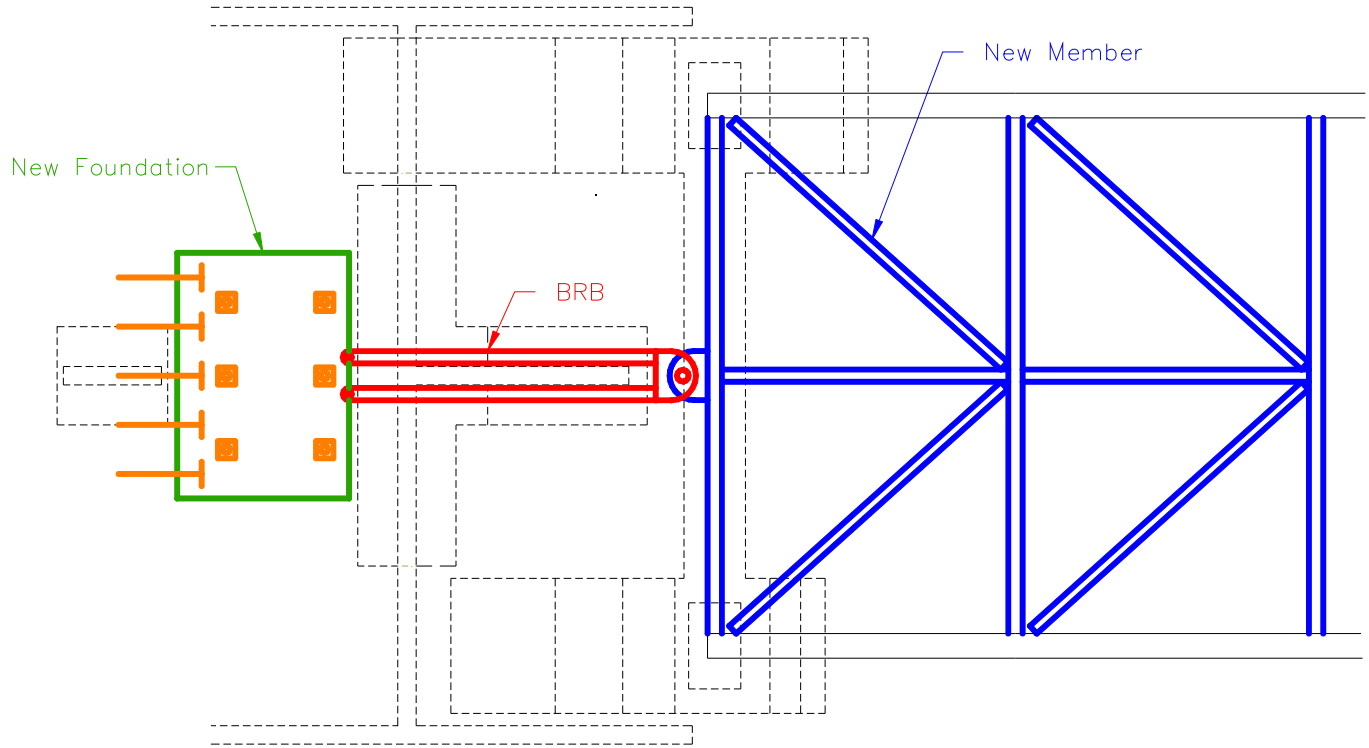
- The steel core carries the axial load while the outer tube, via the concrete, provides lateral support to the core and prevents global buckling. The core is free to yield in tension and compression.





Vulnerabilities & Retrofits

- Install BRB at the centerline of the bridge
- Anchor BRB to new foundation
- Anchor plates fail at prescribed strain = 0.4, then BRB takes over

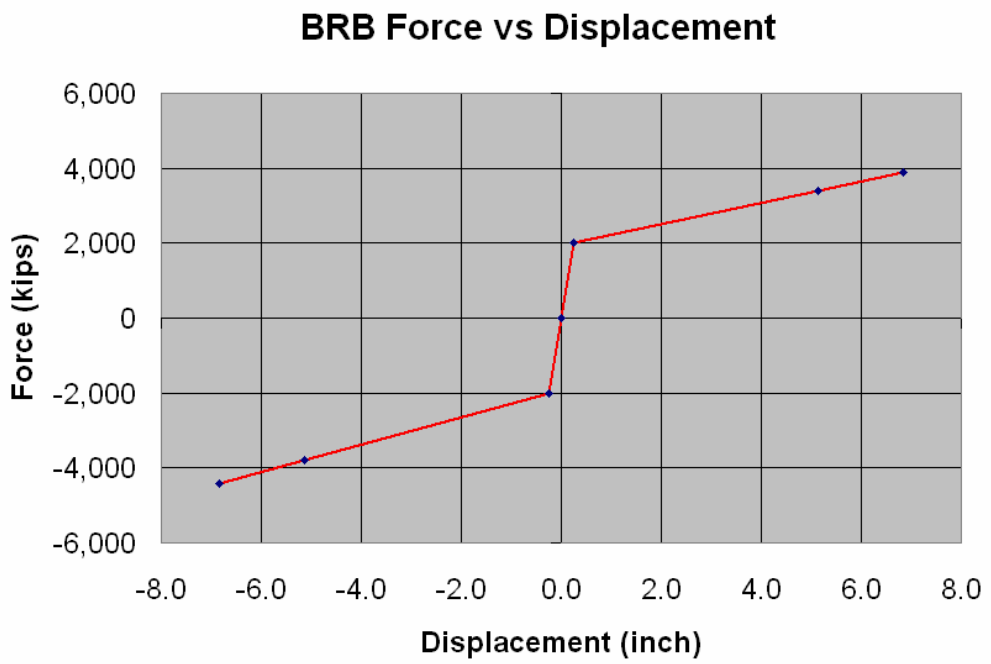


Plan

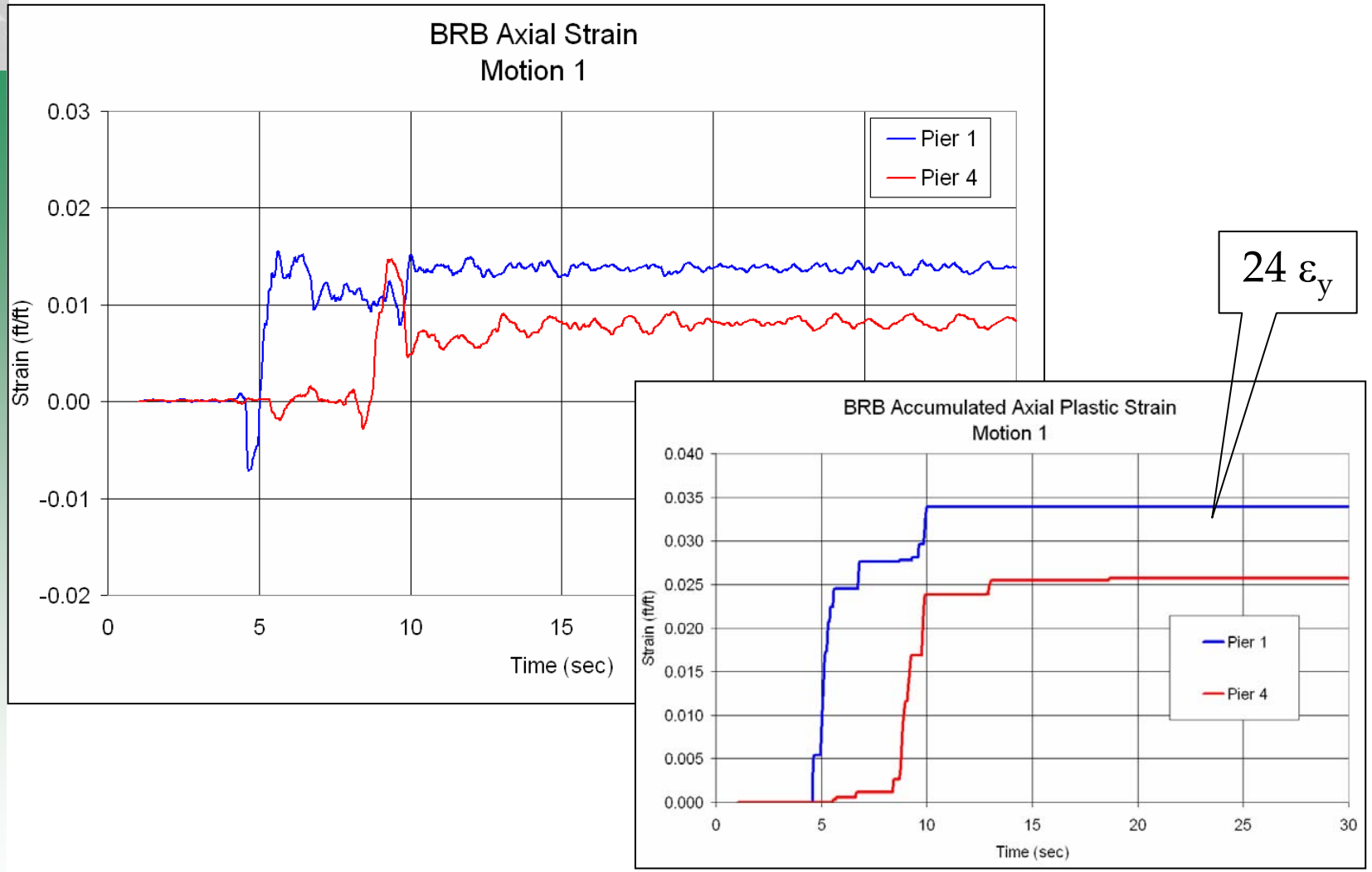
Vulnerabilities & Retrofits

- BRB Manufacturers
  - Core Brace West Jordan, UT
  - Star Seismic Park City, UT
  - Nippon Steel Reno, NV
- BRB Properties
  - Yield force = 1,000 kip
  - Weight = 7,000 lbs
  - Width Square = 16 inch
  - Length = 22 feet
  - 22 – 1.125" A490 Bolts each end
- Low Maintenance
  - Painting
  - Inspection after seismic events
  - Replacement after major seismic event

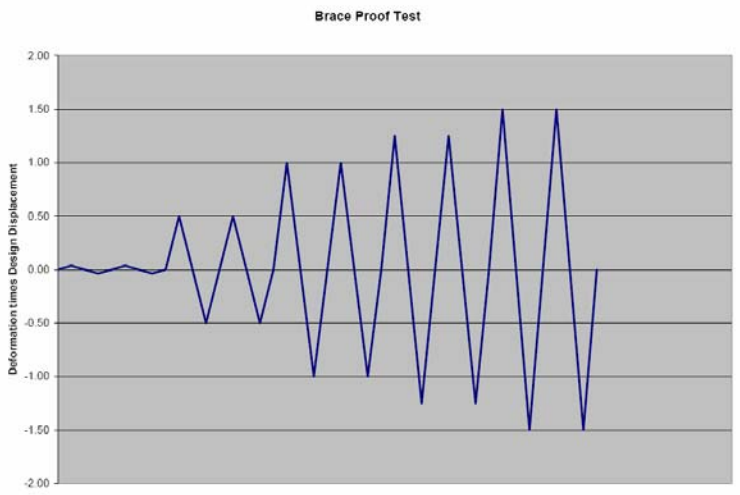
- BRB's - modeled in the non-linear time-history model using a non-linear plastic link element with kinematic hardening
  - Yield Force = 2,000 kips
  - Yield Length = 171 inch
  - Plastic Stiffness = 3% Elastic Stiffness



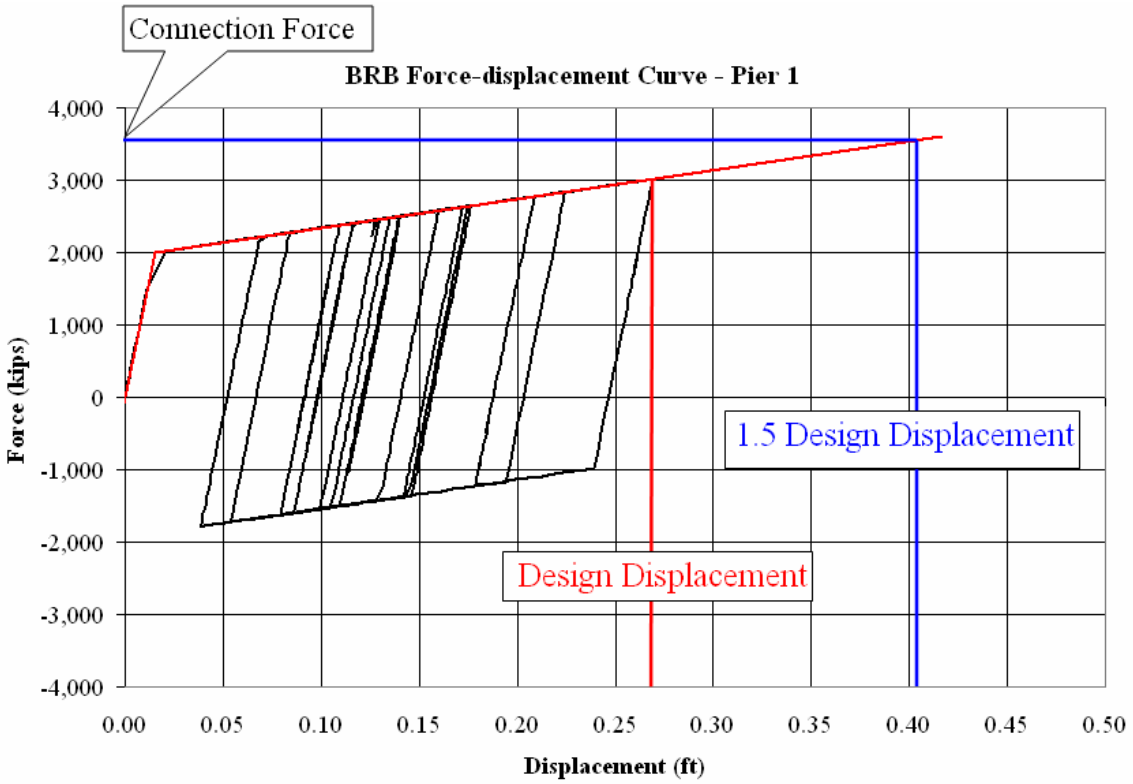
Strain Results



- Proof Test
  - Propose to test to AISC 341 Protocol at 1.5 x Design Displacement
  - Test Limits for 1000 kip yield force within limits of test apparatus
  - Strain limits at (2% design)(1.5 overstrength) = 3% strain are within limits of previous test results
  - Test protocol needs to duplicate design cumulative strain demands



- BRB Connections
  - Connect for force at 1.5 design displacement



Vulnerabilities & Retrofits

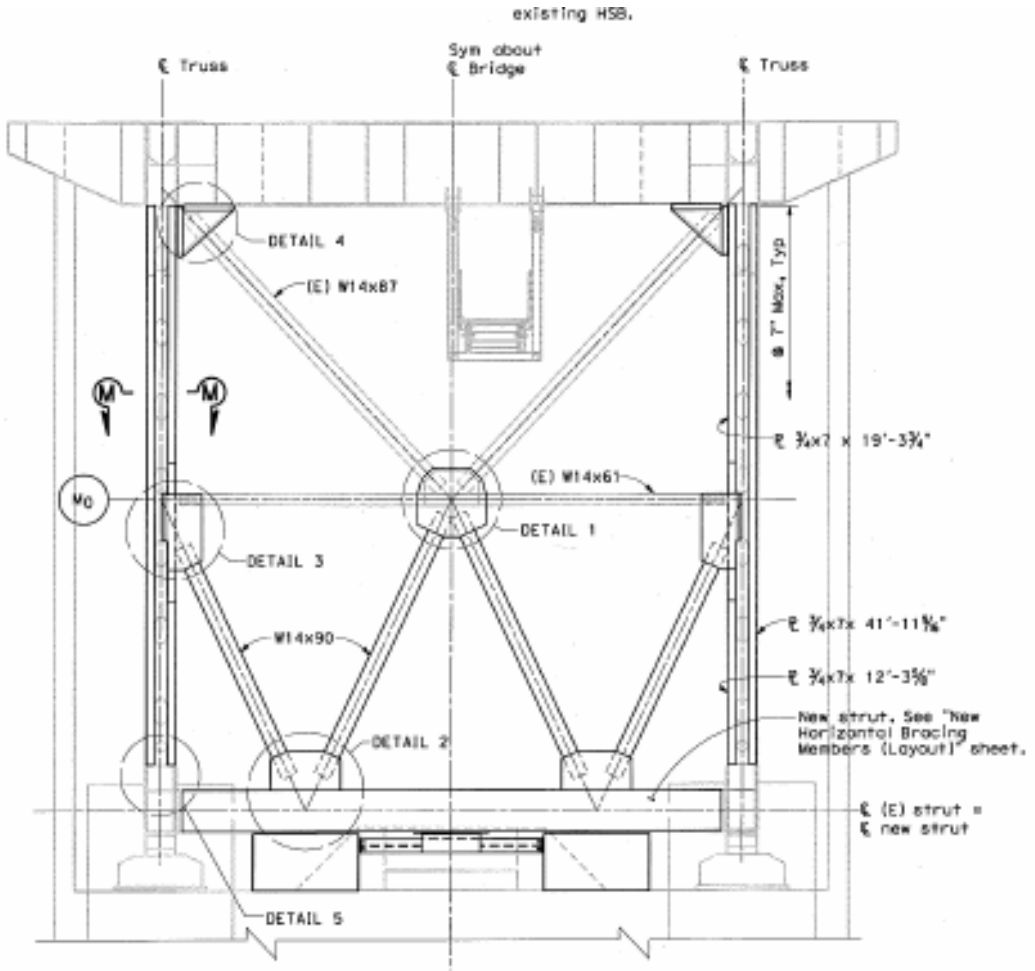
Vulnerabilities

Transverse anchor system as well as the end panel bracing had demands exceeding capacities

Retrofit Measure

Revised load path based on re-configuration of the end panels. Loads addressed with new configuration

Vulnerabilities & Retrofits



Retrofitted End Panel

Revised configuration that helps transmit transverse load

Stage Construction – Explicitly defined

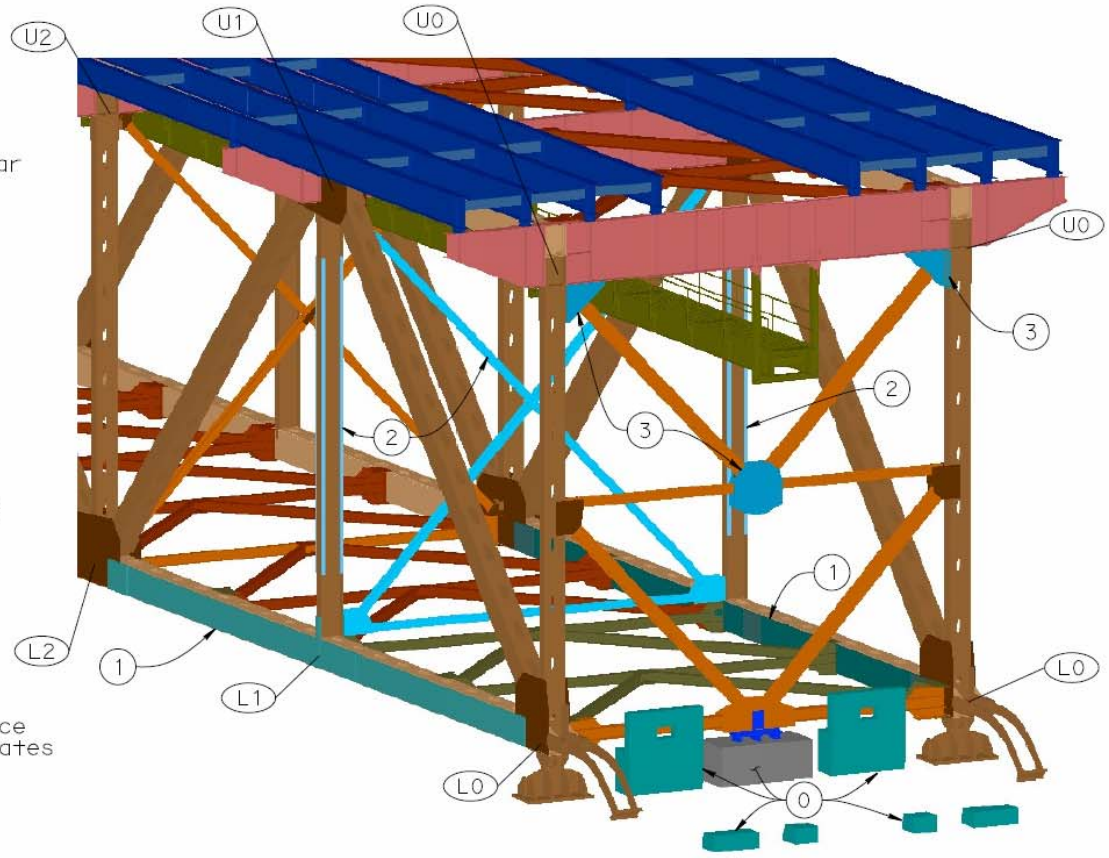
Legend (Stages 0 - 3)

0. Partially remove exist shear key, see "Shear Key Pier 1 & 4 (Layout)" sheet for removal location. Install shear keys (½) and end blocks for temporary bracing, see "Shear Key Pier 1 & 4 (Details No. 2)" sheet for Const Joint location.

1. Install lower chord modifications. See "Chord Modifications (Stage Construction)" sheets.

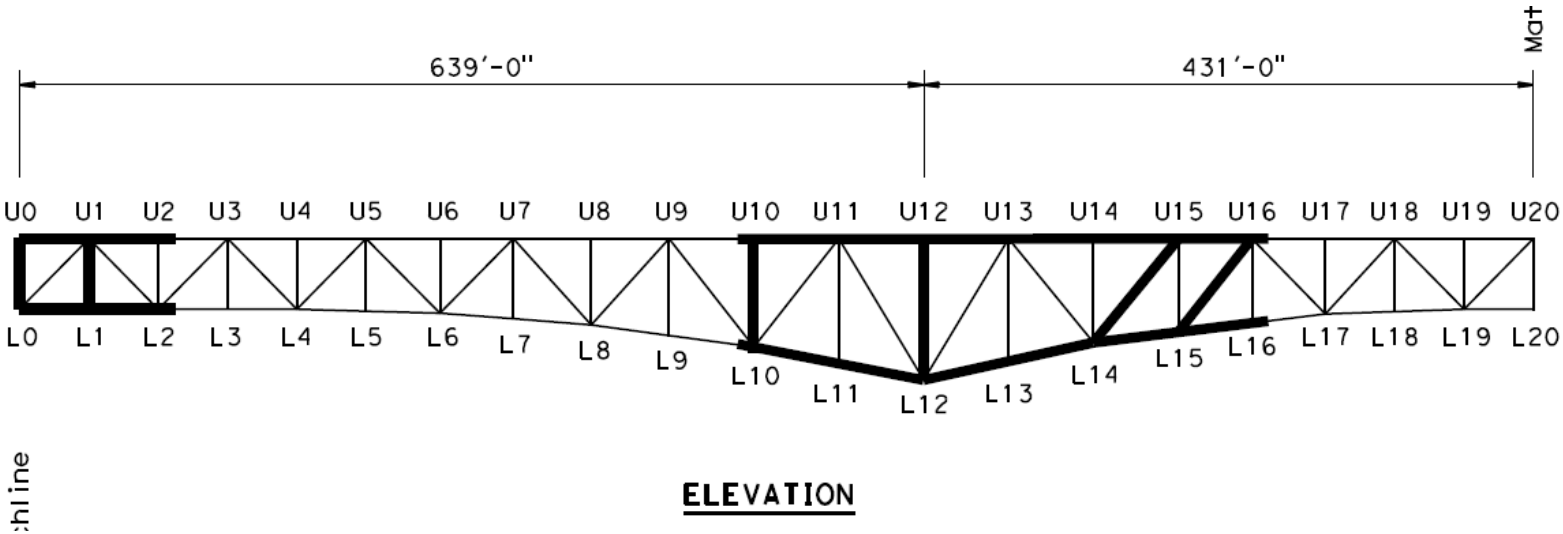
2. Panel 1 - Install temporary bracing. See "Temporary Bracing U1-L1 (Stage Construction)" sheets. Install Global Stiffening vertical member retrofits. See "Global Stiffening Vertical Members (Details No. 1)" sheet.

3. Panel 0 - Remove and replace upper and middle gusset plates one plate at a time.



TOP ISOMETRIC VIEW

Stage Construction - Wind Speed Constraints



When the fastest mile wind speed exceeds 60 mph, all portions of existing and new members and connections shall be fully installed and remain intact. When the fastest mile wind speed exceeds 50 mph, the same constraints apply for those members shown in bold.

The locations shown in bold represent all connections within the width of the bridge.

Vulnerabilities & Retrofits

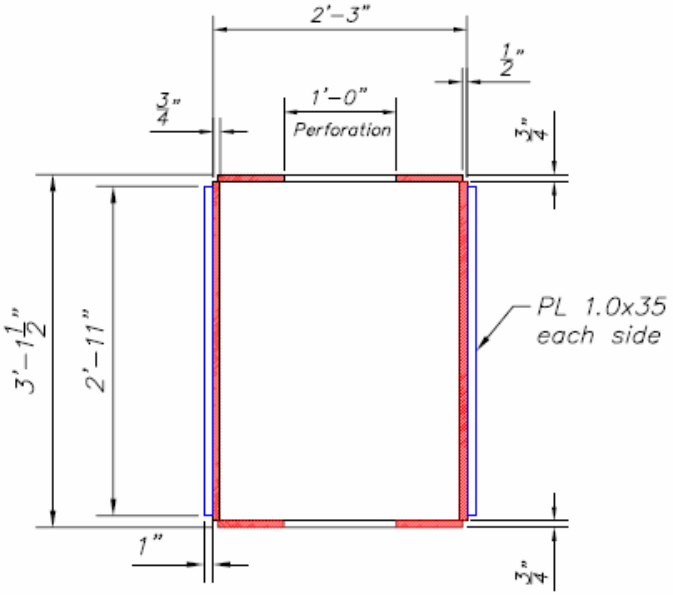
Vulnerability

Lower chord members L0-L2 near Piers 1 and 4 and lower chord between L15-L17 have strain demands exceeding criteria.

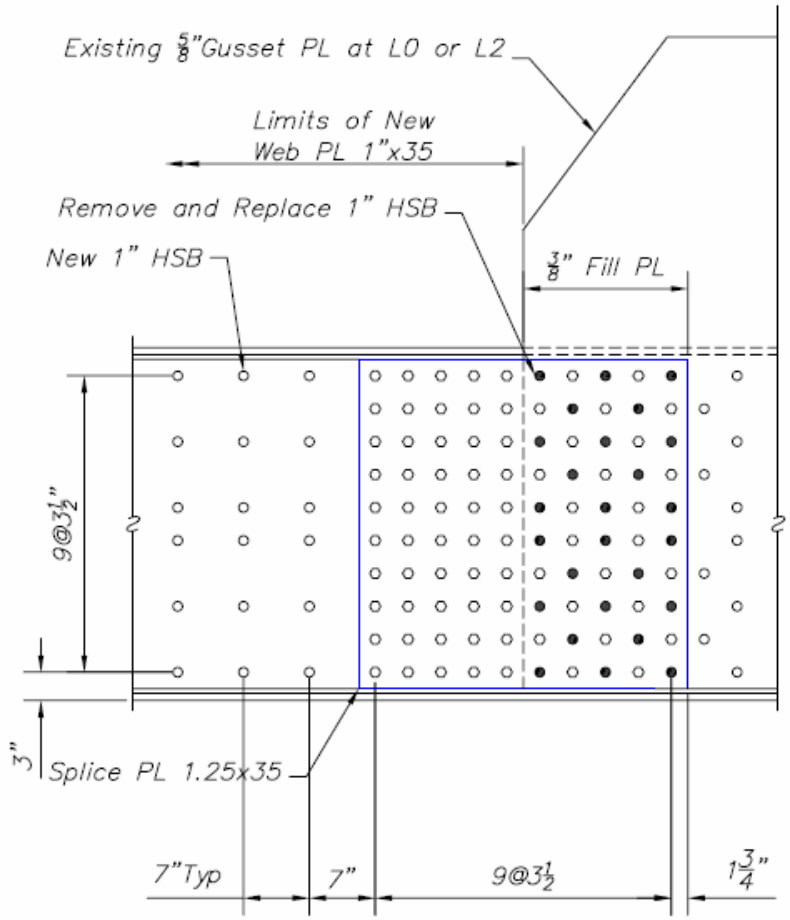
Retrofit Measure

Strengthen chords to insure strains are within design criteria limits

Chord Retrofit Measure



Chord Section



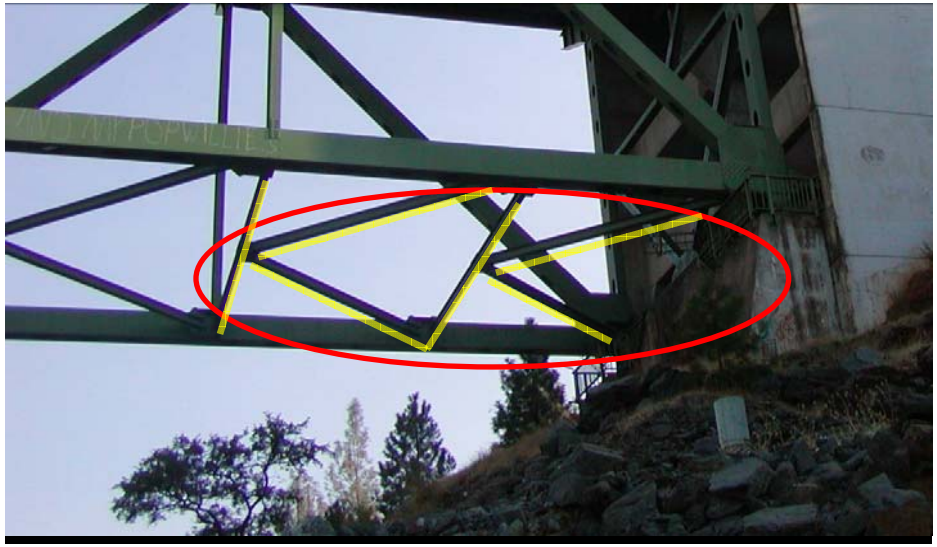
Chord Elevation at L0 and L2

Vulnerability

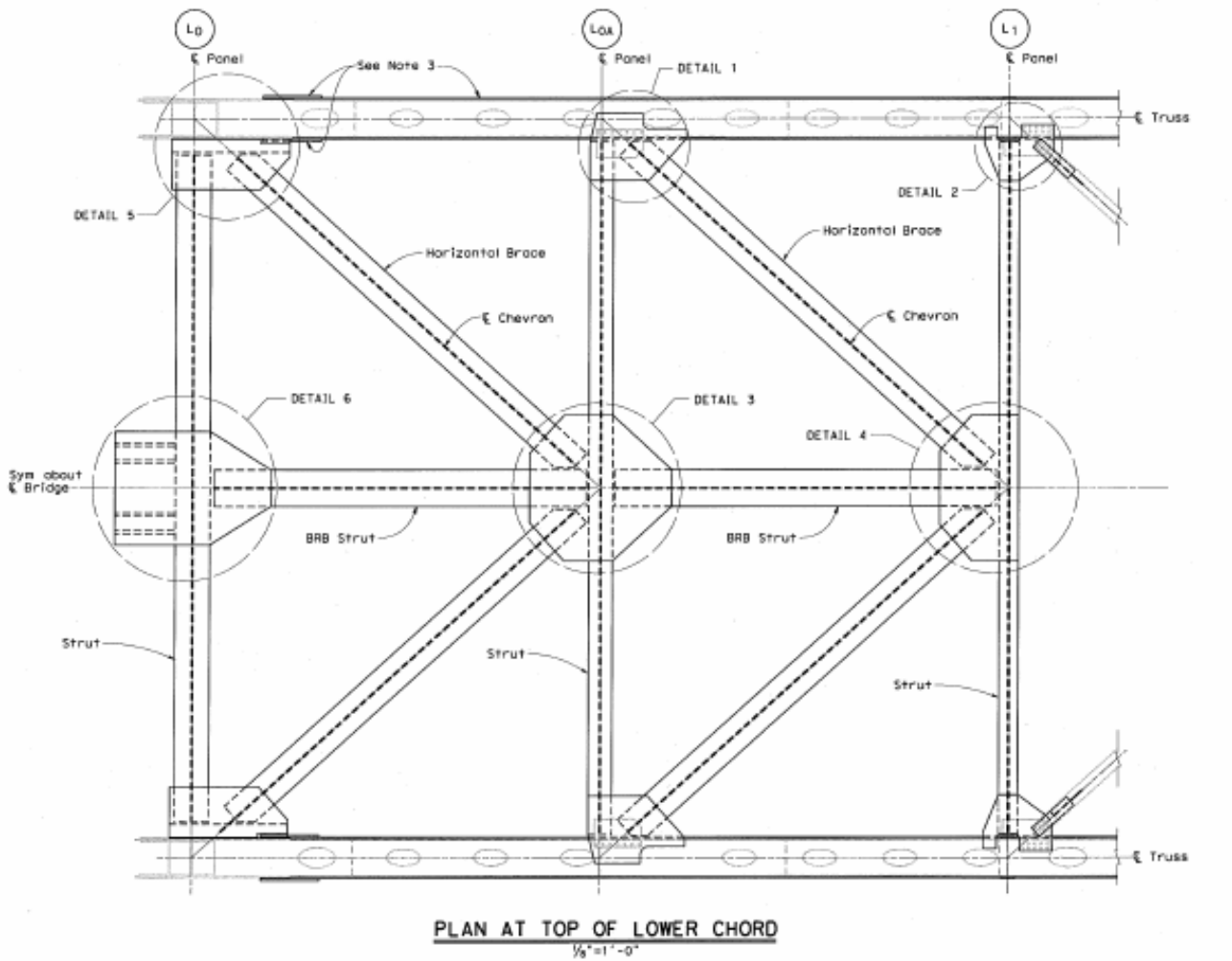
Horizontal (chevron) bracing members near Piers 1 and 4 have strain demands exceeding criteria

Retrofit Measure

Replace members for BRB, add new longitudinal member and revised load path



Vulnerabilities & Retrofits



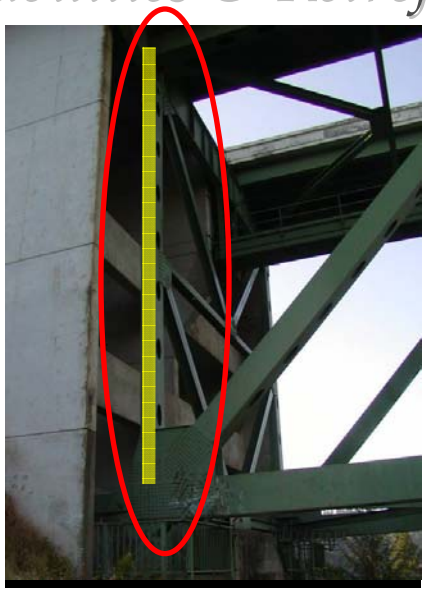
Replace Lower Horizontal Chevron Braces

Take conservative loads into critical load path system

Vulnerabilities & Retrofits

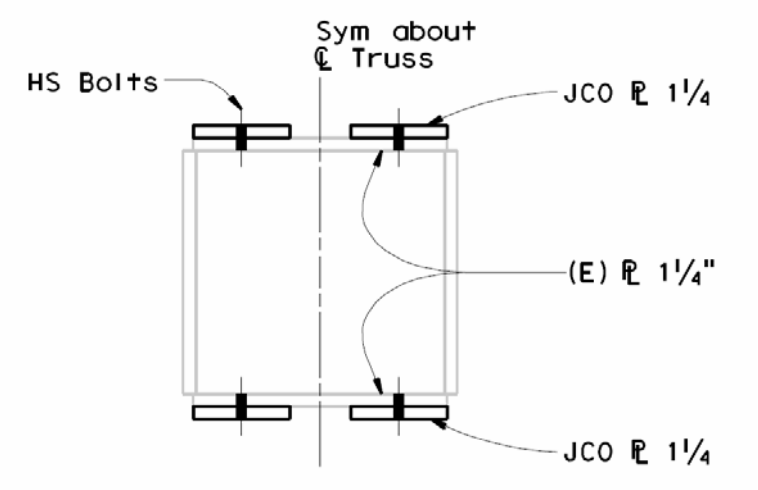
Vulnerability

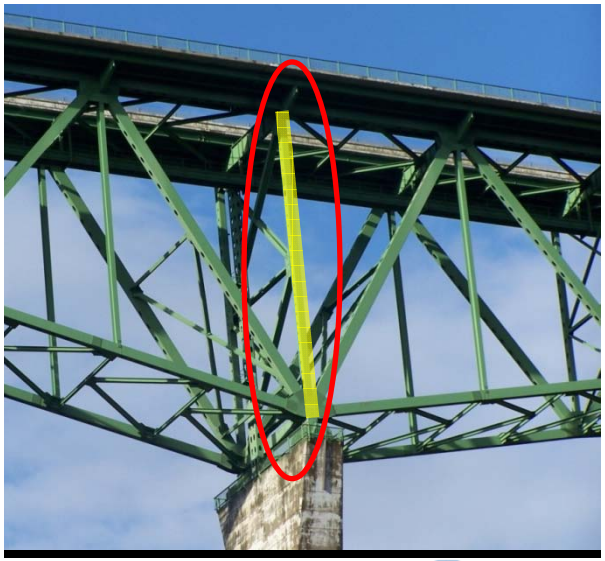
Vertical members at Pies 1, 2, 3 & 4 have strain demands exceeding criteria



Retrofit Measure

Strengthen verticals to insure strains are within design criteria limits





Vulnerability

A number of truss members do not meet the global buckling slenderness limits of the design criteria

Design criteria specifies the following maximum slenderness parameters for compression members:

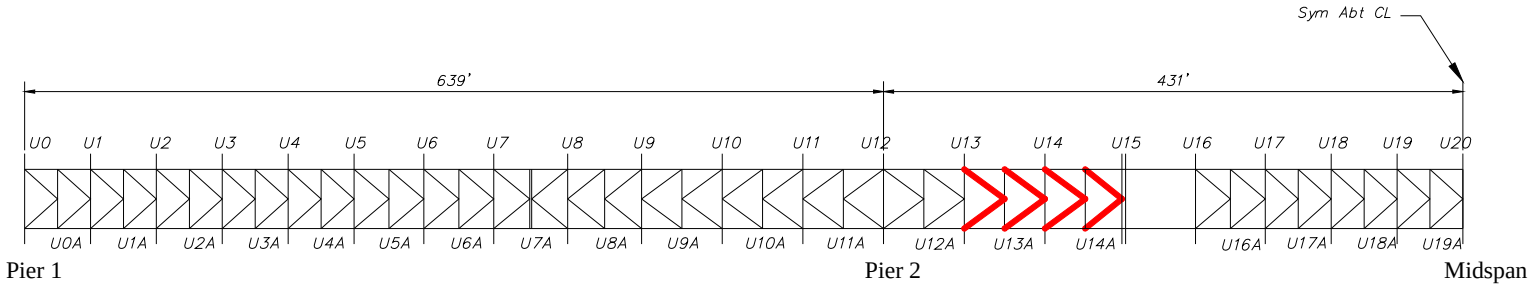
Main members	$Kl/r \leq 120$
Bracing members	$Kl/r \leq 140$

Compression members with Force D/C > 1.0

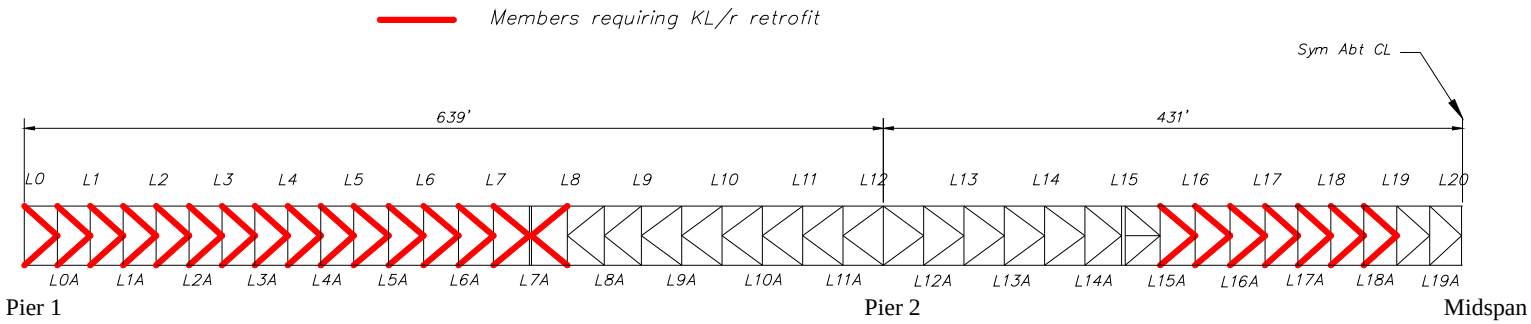
$$\frac{KL}{r} \leq 4.71\sqrt{\frac{E}{F_y}}$$

Retrofit Measure

Truss Horizontal Bracing Members



Plan - Top Horizontal Bracing

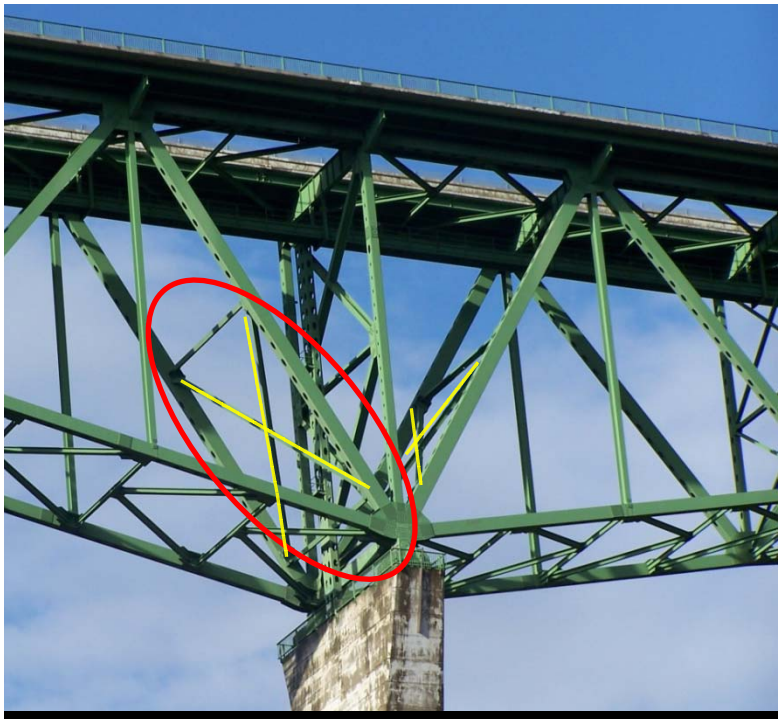


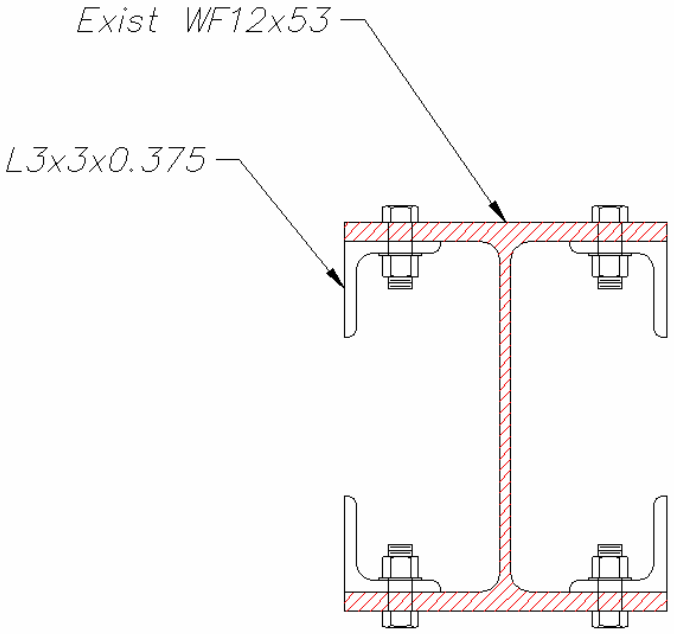
Plan - Bottom Horizontal Bracing

Truss Horizontal Bracing Members that Require Retrofit

Retrofit Measure

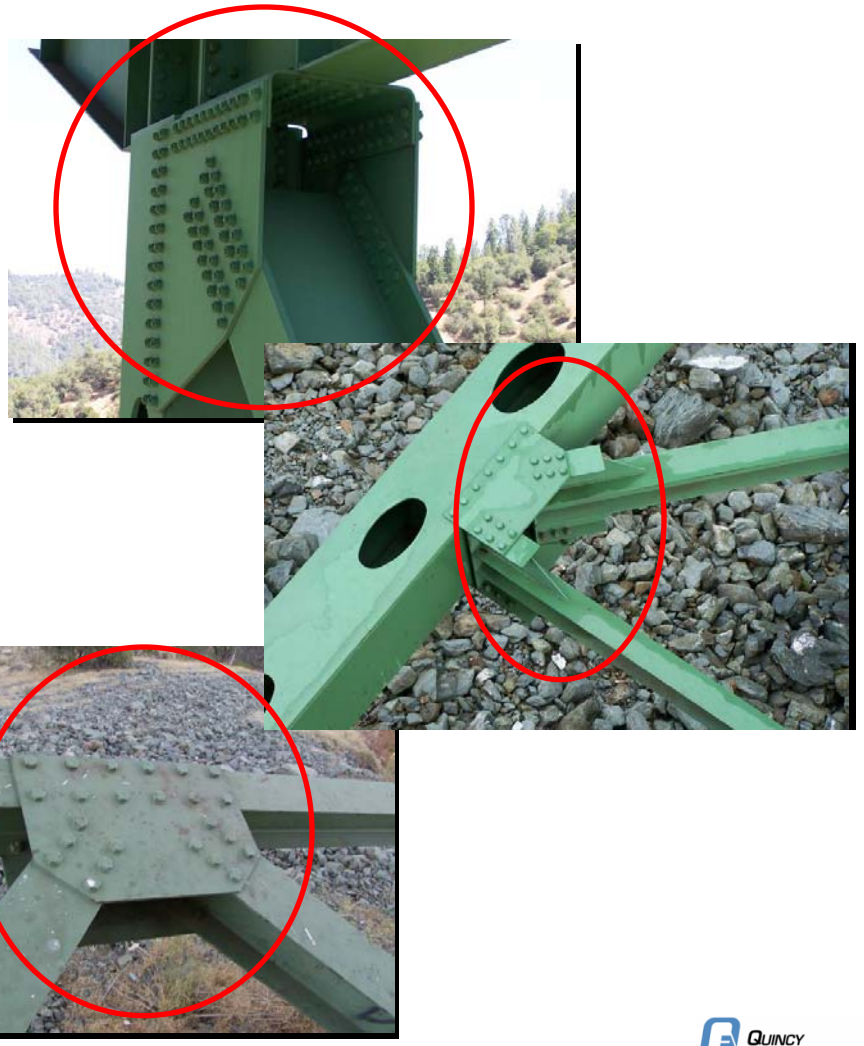
Panel Cross-Bracing Members





Vulnerability

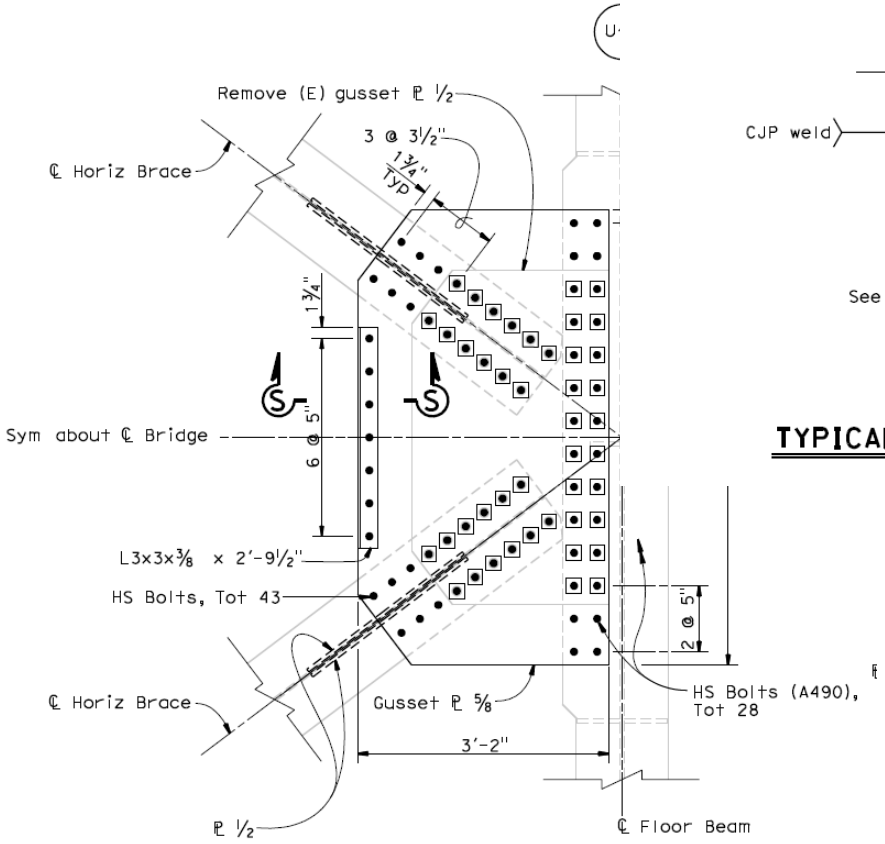
Some member connections for the main truss and many bracing members have insufficient capacity to resist member yielding or meet the seismic force demands



Retrofit Measure

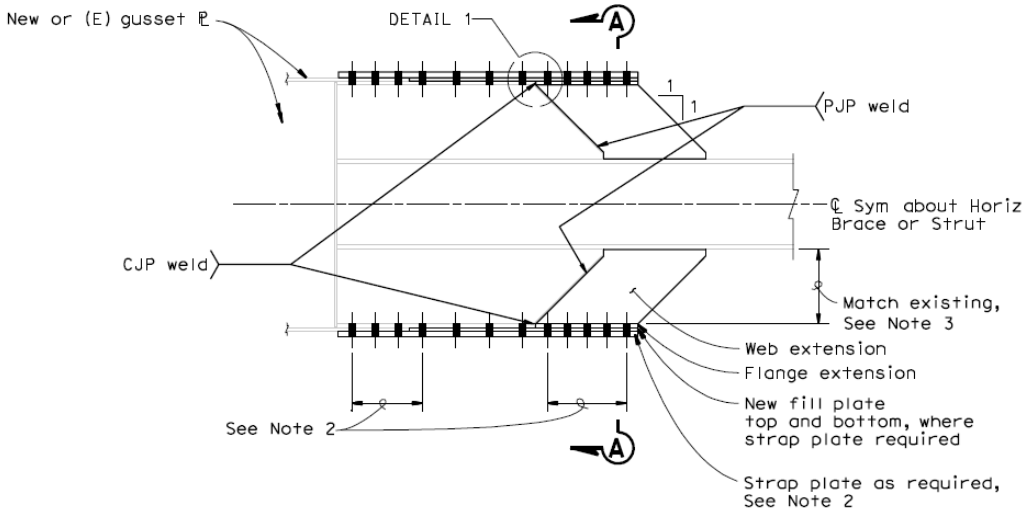
Strengthen connections

Strengthen - Cross-Bracing Members



PLAN AT TOP OF FLOOR BEAM

1"=1'-0"



TYPICAL ELEVATION AT STRUT OR HORIZONTAL BRACE

1"=1'-0"

Vulnerabilities & Retrofits

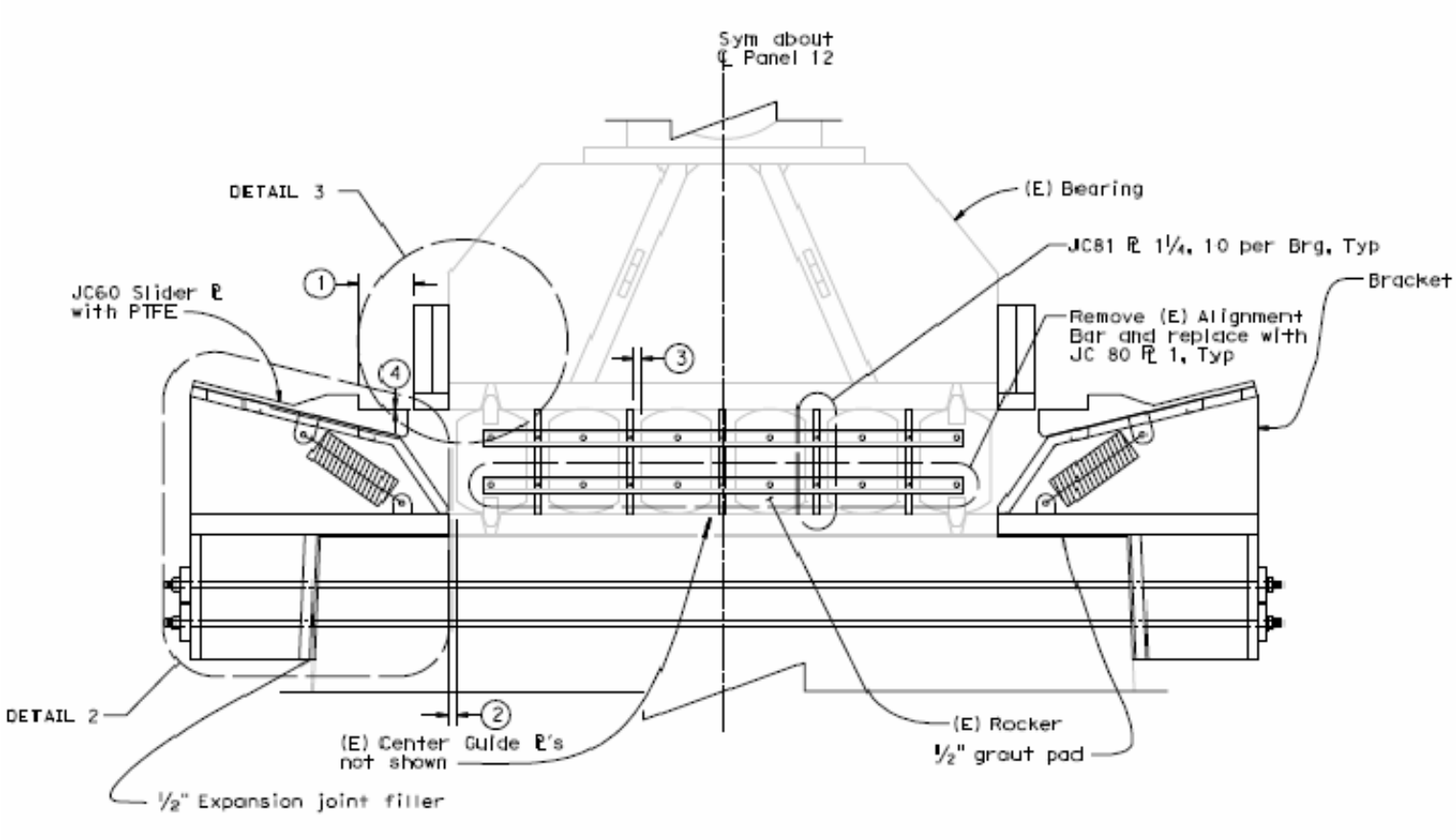
Vulnerability

The maximum relative longitudinal displacement between the bottom of truss (at L12/L12') and the top of pier exceeds the displacement capacity of the main bearing rockers

Retrofit Measure

Prevent rocker bearings from rolling over and install bumper

Vulnerabilities & Retrofits



Pier 2 & 3 Bearing Retrofit

Vulnerabilities & Retrofits

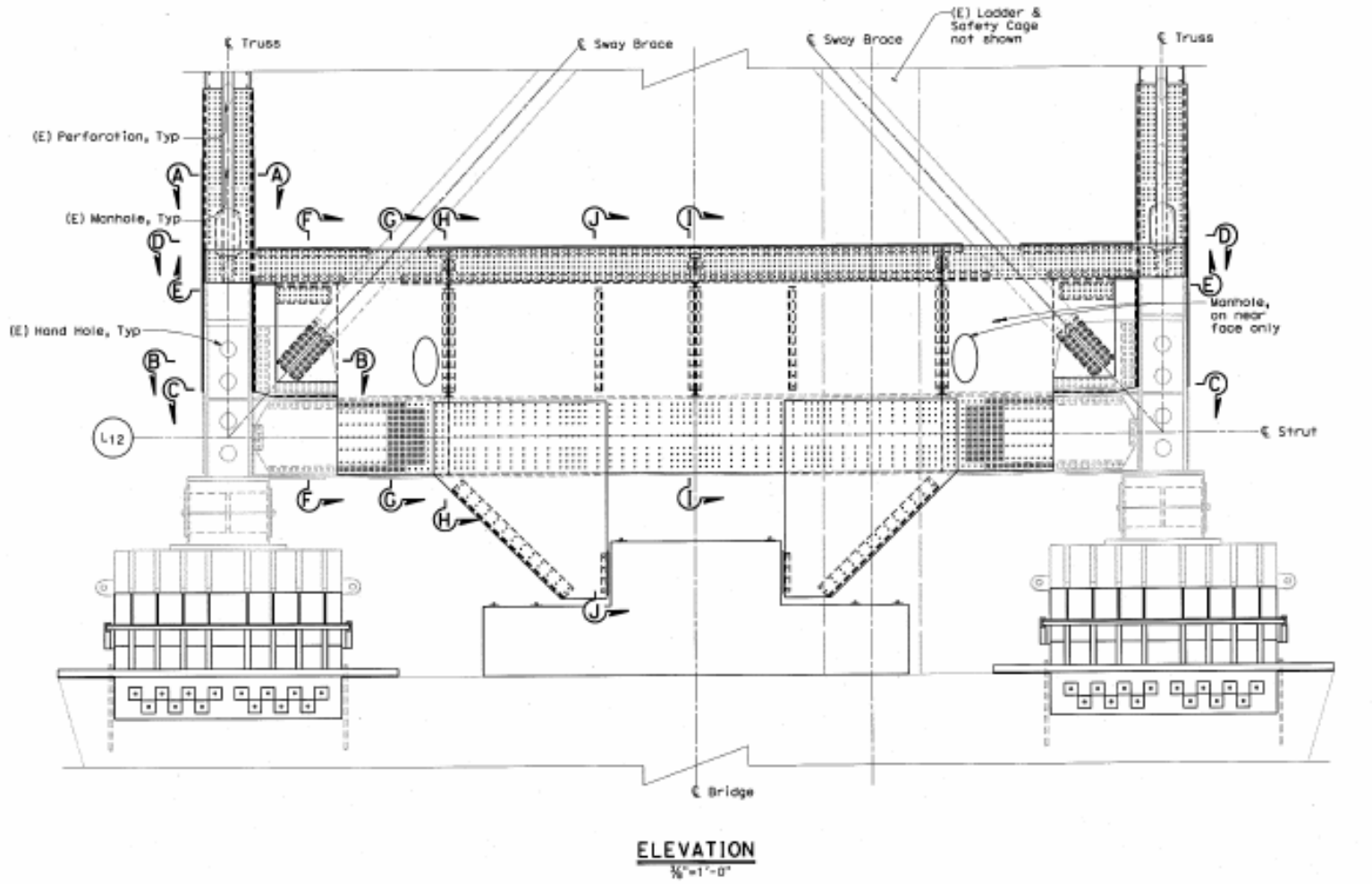
Vulnerability

Main bearings at Piers 2 & 3 do not have sufficient capacity to resist anticipated transverse seismic force demands

Retrofit Measure

Add new transverse shear key system and strengthen existing struts

Vulnerabilities & Retrofits

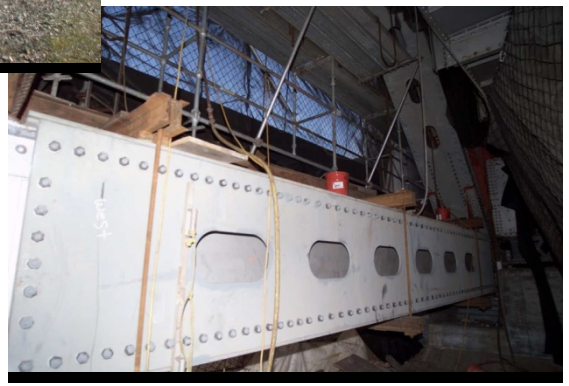


Transverse Key for Piers 2 & 3

Accessibility

Foresthill Bridge

Accessibility & Containment



Placer County

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Western Bridge Engineers' Seminar

Acknowledgements

Placer County

CH2MHILL

SC SOLUTIONS

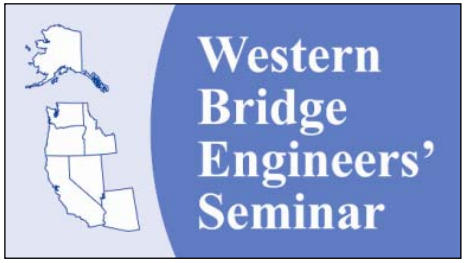
Cadre DESIGN GROUP, INC.

FUGRO

Earth Mechanics, Inc.
Geotechnical & Earthquake Engineering

Peer Review Panel

Caltrans



Questions & Answers