Skyway Pile-to-Pilecap Weld Inspection Investigation
"FHWA-Phase I"

version 6_BHM

1.0 GENERAL BACKGROUND AND PURPOSE

During the construction of the SFOBB Skyway, a welding and/or welding inspection investigation has arisen. Allegations of less than perfect welding-welding repairs have been made and are currently being investigated by the FBI. In order to assist the FBI, FHWA, and others, the California Department of Transportation is assisting those groups with understanding the approaches employed in the design of the bridge and the associated design codes in order to better understand the level of safety present in the pile-to-pilecap connection design. These slides and accompanying text, in part, are to contribute to that effort.

The slides within this package were developed to visually present and explain in a relatively simple and clear way the level of safety incorporated into the design of the Skyway pile-to-pilecap connection and how levels of safety would tend to be affected by changes in dimension and/or material strengths of the connecting welds. The fundamental approach followed to accomplish this is to extract and present from the design procedure the basic structural bridge design code equations. These equations establish conservative estimates of capacities defined first by material strengths and dimensions of the structural components, and then by reducing those numbers by multiplying them by numbers less than unity. Thus, the bridge design codes offer appropriately conservative design capacities. The purpose of this attached summary in text form is to offer a self-contained explanation of the slides, which refer to sources and/or topics, which may not be readily understood by engineers unfamiliar with the subject.

2.0 SLIDE PRESENTATION

2.1 Introduction

Slides 1 through 3 are introductory slides that offer topic and basic background information. Slides 4 through 7 offer perspective of the Skyway pilecap. Slides 4 and 5 focus the attention of the viewers to the pilecap and the pile-to-pilecap connection. Slide 6 presents a plan view and a cross-sectional view of the pilecap with the shear plates identified. Slide 7 is a photograph of a Skyway pilecap from above the pilecap prior to placement of the column reinforcement.

2.2 Pile-to-Pilecap Connection

Slides 8 and 9 are Skyway structural plan sheets showing the pile-to-pilecap details. In slide 8 a top view of the connection shows the eight different shear plates equally distributed in a circular pattern with the pile being the inner ring and the pilecap sleeve being the outer ring. This configuration offers a well-distributed stress and an indeterminate load transfer subsystem. The shear plates are slipped through cut vertical slots in the piles and the sleeves and then welds are made between the shear plates and the piles and sleeves, respectively. Slide 9 specifically offers a plan sheet that shows a cross-sectional view of the pile-to-pilecap connection including the concrete bearing system designed to transfer bending, the shear plates designed to transfer shear, and in detail the "grout-weld bead" system designed to brace the shear plates and carry a small percentage of shear during a large seismic event.

Slide 10 presents a photograph of an actual shear plate, pilecap sleeve, and the weld between the two structural elements taken inside of an actual Skyway pilecap. Within slide 10 a cross-section A-A is defined and idealized in slides 11 and 12. The weld cross-section and profile shown in slide 11, is as-assumed during the design stage. Slide 11 also documents the weld type and size established at the time of design. Further, the strength of the weld material was established to be a minimum of 70 ksi during the design phase. During the construction stage of the Skyway, the contract was changed with CCO-50 (i.e., Contract Change Order #50) to increase the beveled weld dimension from 31 to 35 mm, as shown in slide 12, to simplify the construction and inspection process. That is, the contractor offered a larger weld to streamline inspection. Slide 13 presents a photograph of a polished cross-section of an actual shear plate-to-pilecap sleeve weld extracted from the structure by FHWA. It is of value to note that Mayes Testing Engineers, who were hired to evaluate the extracted connections, evaluated these connections as possessing "excellent workmanship." In this slide the basic geometry of the partial-joint-penetration (PJP) weld can be more easily understood, as well as the effective throat dimension. With this slide, it may be valuable to some viewers/readers to understand that in a PJP weld, the weld does not extend all of the way through the base metal interface by definition.

2.3 Pilecap Mechanics During a Large Earthquake

The Skyway is designed to withstand 1500-year return period earthquake motions. The pilecap is part of that system. The seismic response is complex, but for purposes of communicating fundamental approaches within the design, a pier can be considered to have two basic behaviors: one in which the pilecap and the superstructure sway back and forth in the same direction, and another in which the pilecap and the superstructure sway back and forth in opposite directions. These fundamental behaviors where identified during the design phase of the project and are illustrated in slides 14 and 15. Depending on the dominant type of behavior excited during a particular earthquake, the loading from the column to the pile will vary in direction and magnitude. This information, combined with principles of limit state structural mechanics, allow engineers to picture conditions that are likely to develop if such a rare earthquake occurs.

Slide 16 offers an idealized free-body-diagram (FBD) of the anticipated deformed shape and loading on the pilecap. The pilecap is anticipated to have loads applied from the column (shown in orange), from the piles (shown in green), and from the inertia of the pilecap itself (shown in yellow). Further, slide 17 is a simplified illustration that offers insight into the basic working mechanics of the pile-to-pilecap connection. The illustration demonstrates that movement of the pilecap relative to the piles creates a set of moments, shears, and axial loads through the connection. The transfer mechanism between a column, its pilecap, and piles is 3-dimensional and complex, but if simplified to its very basics, the following statements can be made. The axial load in the piles is predominately carried through the connection by the shear plates. The moment in the piles is carried through the connection by the eccentric and opposing lateral loads (i.e., force couple) at the top and bottom of the pile-to-pilecap connection and incremental differentials in shear on the sides of the pile. And finally, the shear in the pile is carried through the pile-to-pilecap connection through the lateral system.

2.4 Weld Shear Strength

As is illustrated in slide 17, load through the shear plates is complex, but is predominantly shear, hence the label “shear plate.” The American Association of Highway and Transportation Officials (AASHTO) bridge design code offers a formula to designers that defines an appropriately safe and conservative design. The design formula for this type and geometry of weld is offered and explained in slide 18. The formula includes numbers less than 1.0 to reduce the minimum strength required by the contract to a conservative strength that has a very high probability associated with it. Also in the formula are the minimum weld material strength that the contractor must supply by contract and the minimum weld throat thickness the contractor must supply by contract. It is valuable to recognize that confidence in the capacity of the weld is in part developed by knowing the contractor is held to minimum contract requirements AND the designers are required to assume a reduced weld capacity well below the capacity required of the contractor. These reduction factors are in part to account for less than perfect craftsmanship and material strengths in construction.

2.5 Measurements of Welds Taken During Skyway Construction Phase

In order to develop new and additional physical test data FHWA extracted samples from the actual Skyway bridge structure. This work allowed for normally unattainable measurements of the pile-to-pilecap sleeve welds to be obtained for review. Those measurements offer clear documentation that the extracted welds from the Skyway were even better than that required by the contract. Slide 19 is a simple statement addressing this work.

Slides 20 and 21 highlight that data from actual extracted welds show that all of the measured welds were actually larger than what is required by the contract, offering extra safety. Slide 20 presents the design specified weld throat thickness, 40 mm, and the range of weld throat thickness measurements, 45 to 57 mm. Slide 21 is a selected image from the Mayes Testing Engineers' report, which reports that the average throat thickness measured was 25% greater than that required.

Slides 22 through 24 highlight that test data from the weld procedure qualification trials, documented in the procedure qualification records (PQRs) show the weld material used in those welds is stronger than that required by the contract. Slide 22 presents the design specified weld tensile strength is 70 ksi and the PQR documents received from METS, report tensile strengths ranging from 89 to 93 ksi, offering greater safety. Slide 23 is a selected image from the Fisher-FHWA report documenting the over-strength. It is worth noting that the Fisher report reference calls out yield strength. Regardless if a reference to yield strength, or ultimate strength is used, the points is the same, the actual weld samples showed higher strengths than required by the contract. Slide 24 offers a sample of a PQR and its documentation of over-strength.

3.0 SUMMARY

Slides 25 through 27 are summarizing slides. Slide 26 offers the opportunity to summarize the level of safety in a more qualitative sense, while slide 27 offers a similar opportunity in a more quantitative sense. Both slides project from the basic weld shear strength equation presented previously in slide 18. From these summarizing slides it is clear the appropriate application of the code shear strength equation, the over-sized welds, and the weld material over-strength offer considerable reserve strength, adding to the level of safety of the bridge.

REFERENCES

Skyway Plans and Specifications, various dates.

Skyway Procedure Qualification Records (PQRs), various dates.

Fisher, J., FHWA Bay Bridge Pile Connection Plate Welding Report, FHWA, 2005.

Mayes, M., Oakland Bay Bridge Pile Connection Plate Weld Investigation Report, FHWA, 2005.

AASHTO Bridge Design Specifications, 1994.

ANSI/AASHTO/AWS D1.5-95, Bridge Welding Code, 1995.

Popov, E., Mechanics of Materials – 2nd Edition, Prentice Hall, 1976.

Vanderbilt, M.D., Matrix Structural Analysis, Quantum, 1974.

Galambos, T., Lin, F.J., & Johnston, B., Basic Steel Design with LRFD, Prentice Hall, 1996.

AUTHORS

Major contributions to this package were made by the following personnel: Sajid Abbas, Ade Akinsanya, and Brian Maroney of Design; Jim Merrill of METS; Mark Woods of Construction; and Nancy Bobb of FHWA.

Pile-to-PileCap Connection

FHWA Phase I

SFOBB Skyway

California Department of Transportation
Federal Highway Administration

Background

During the construction of the SFOBB Skyway, a welding and/or welding inspection investigation has arisen. Allegations of less than perfect welding-welding repairs have been made and are currently being investigated by the FBI. In order to assist the FBI, FHWA, and others, the California Department of Transportation is assisting those groups with approaches in the design and the associated design codes. These slides and accompanying text, in part, are to contribute to that effort.

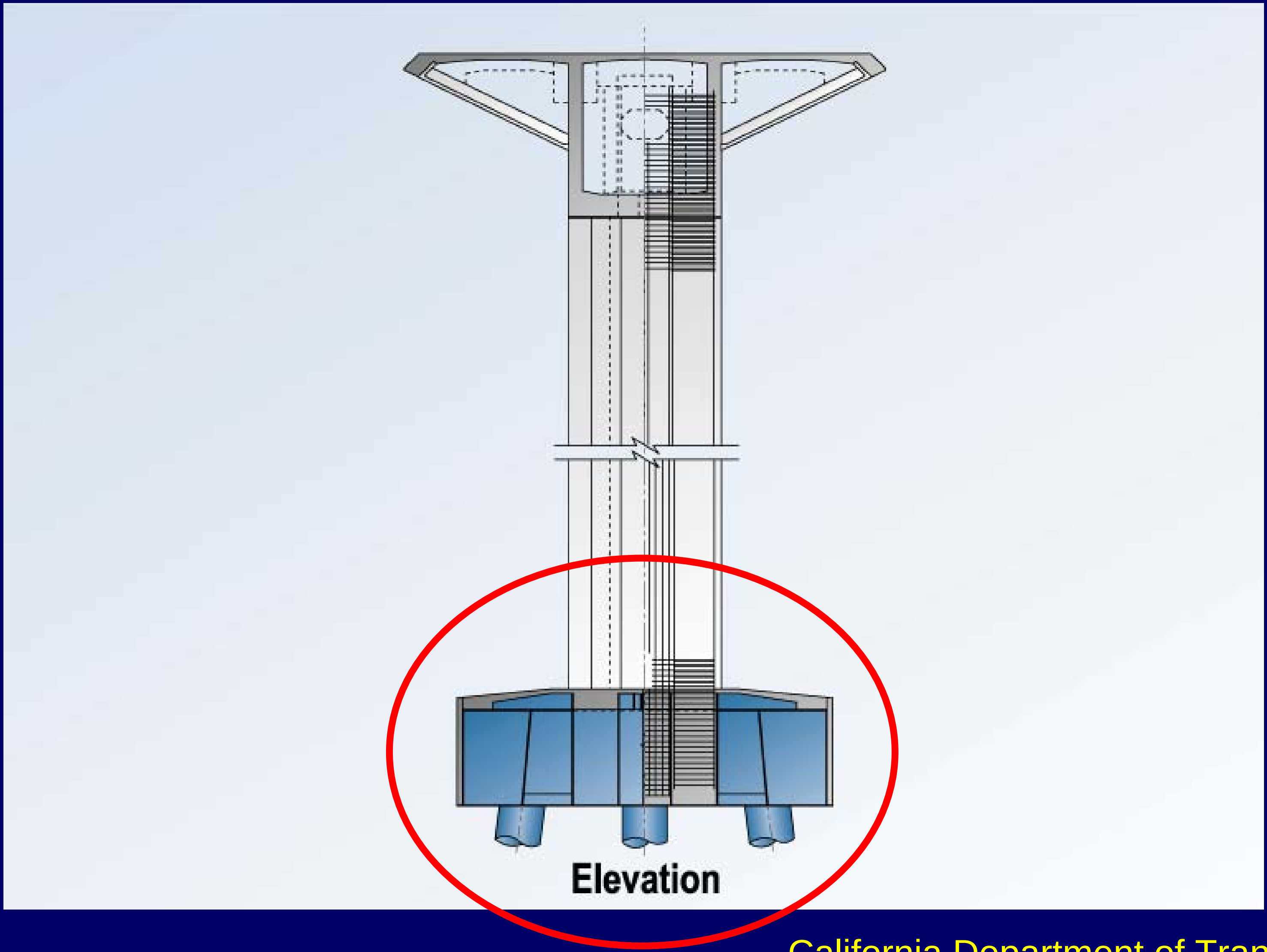
Smart analysis is well-planned analysis

Though there are commonly a multitude of perspectives and solutions to a problem, the best models and/or solutions are always the simplest that offer the necessary accuracy and no more. With this strategy in mind, the California Department of Transportation and the Federal Highway Administration have advanced an effort to communicate the level of safety offered in the design by its adherence to the AASHTO bridge design code and the AWS D1.5 bridge welding code. The design and the codes do not assume or require “perfect” welds, which are improbable. This effort has been formally labeled “FHWA-PHASE I.”

Skyway pilecap

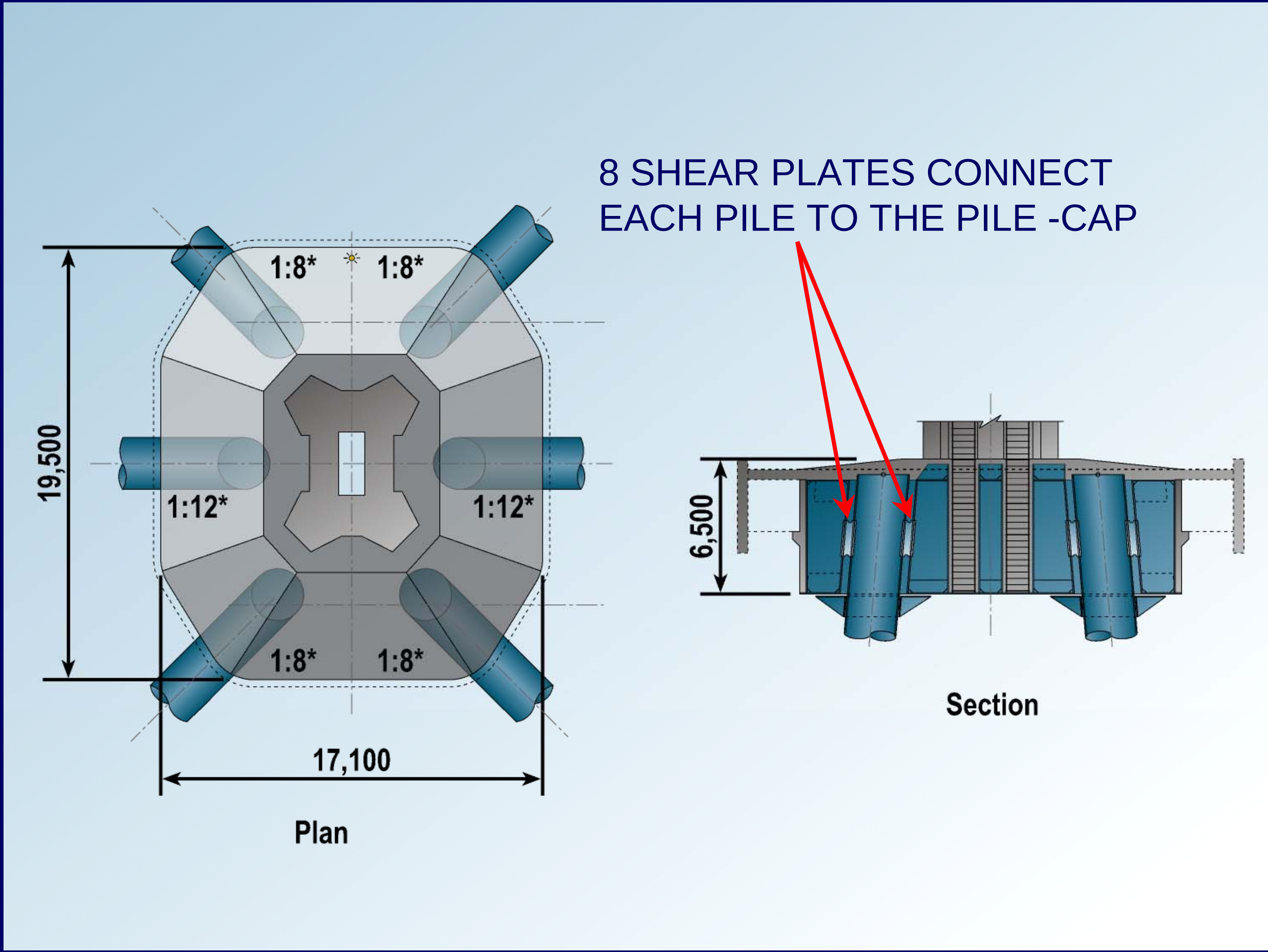
California Department of Transportation
Federal Highway Administration

SFOBB East Span Pier Transverse Section



California Department of Transportation
Federal Highway Administration

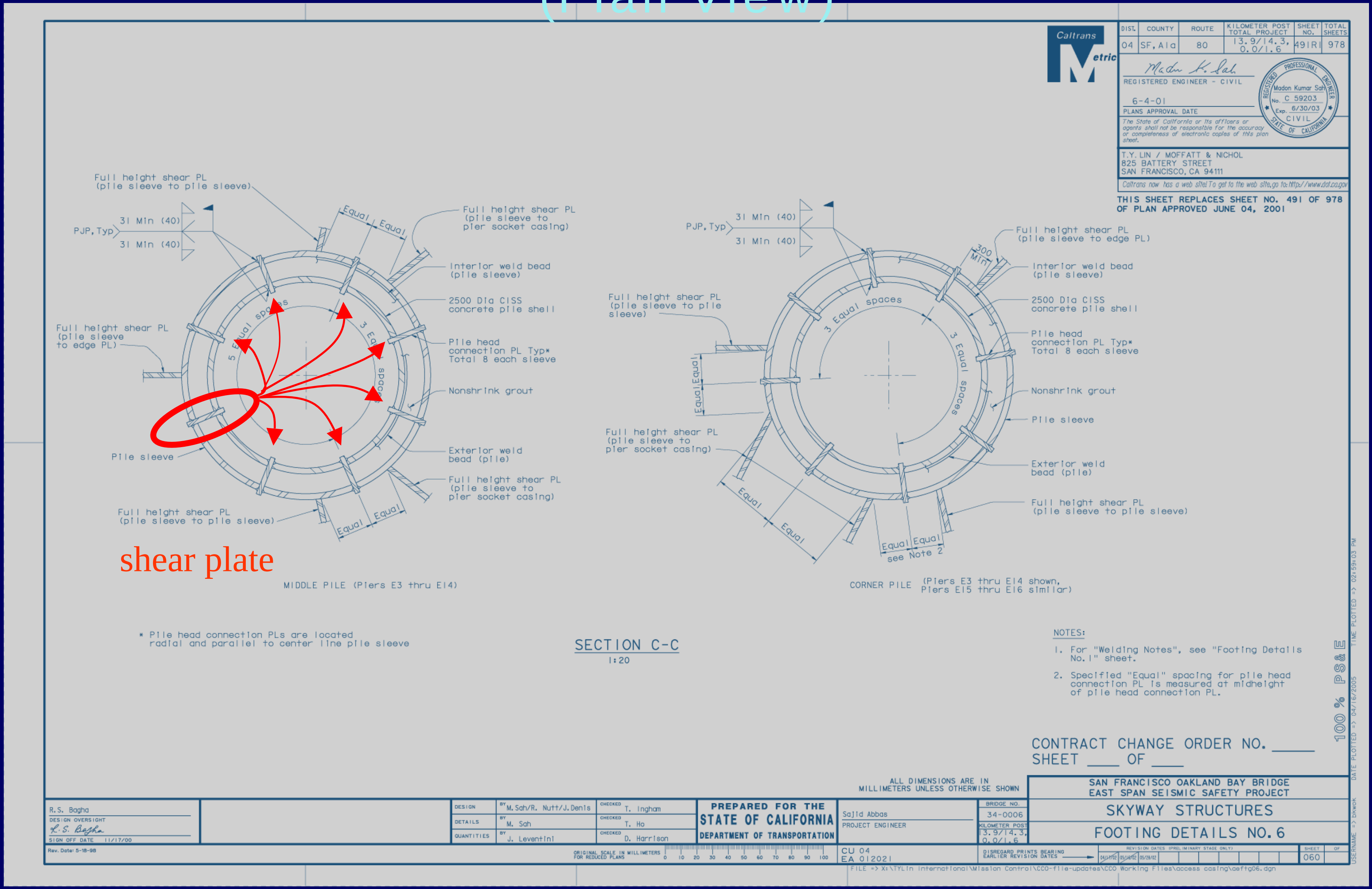
SFOBB East Span Pilecap



SFOBB East Span Pilecap in the Field

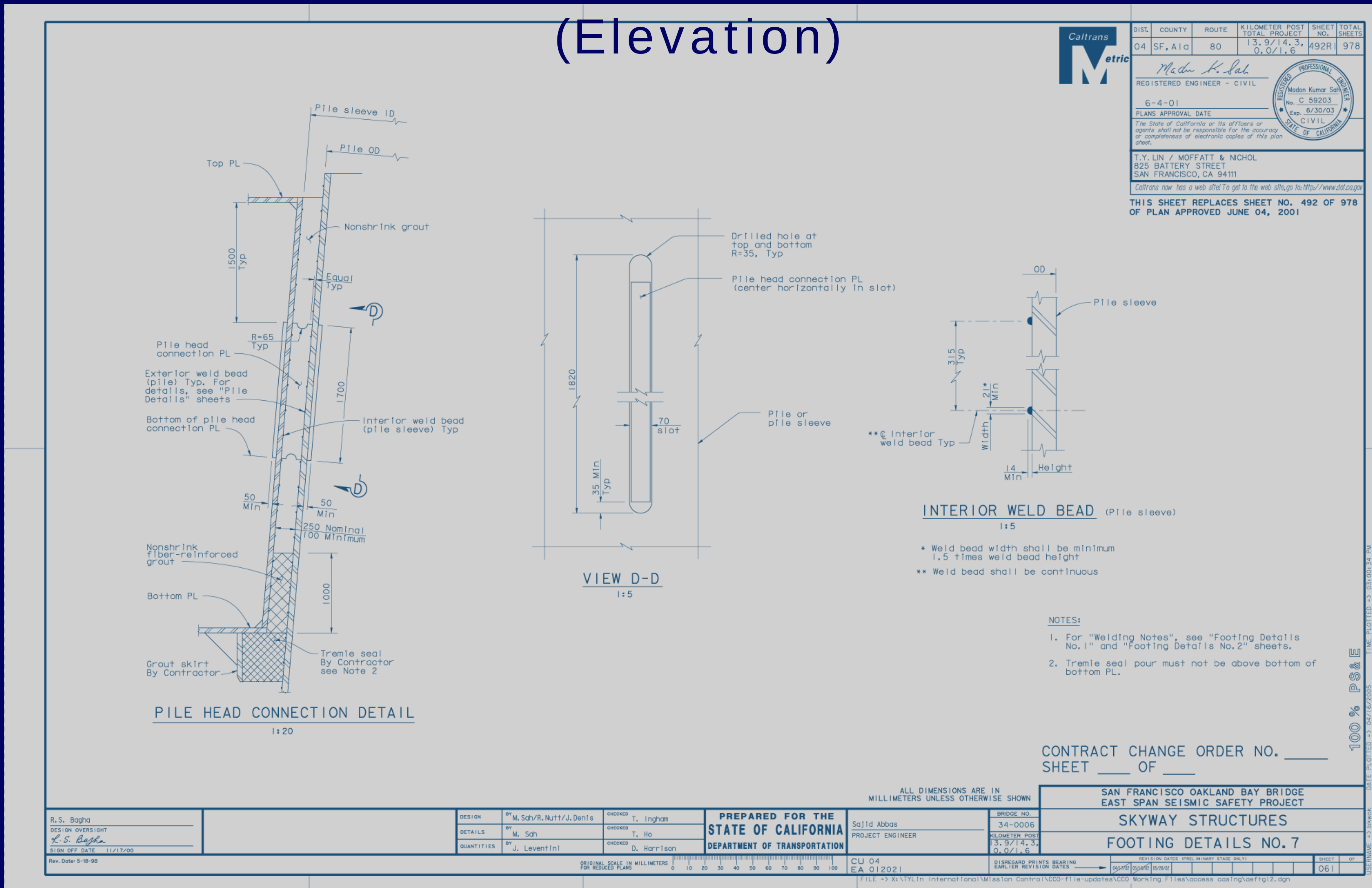
California Department of Transportation
Federal Highway Administration

Details of the Eight Shear Plates (Plan View)

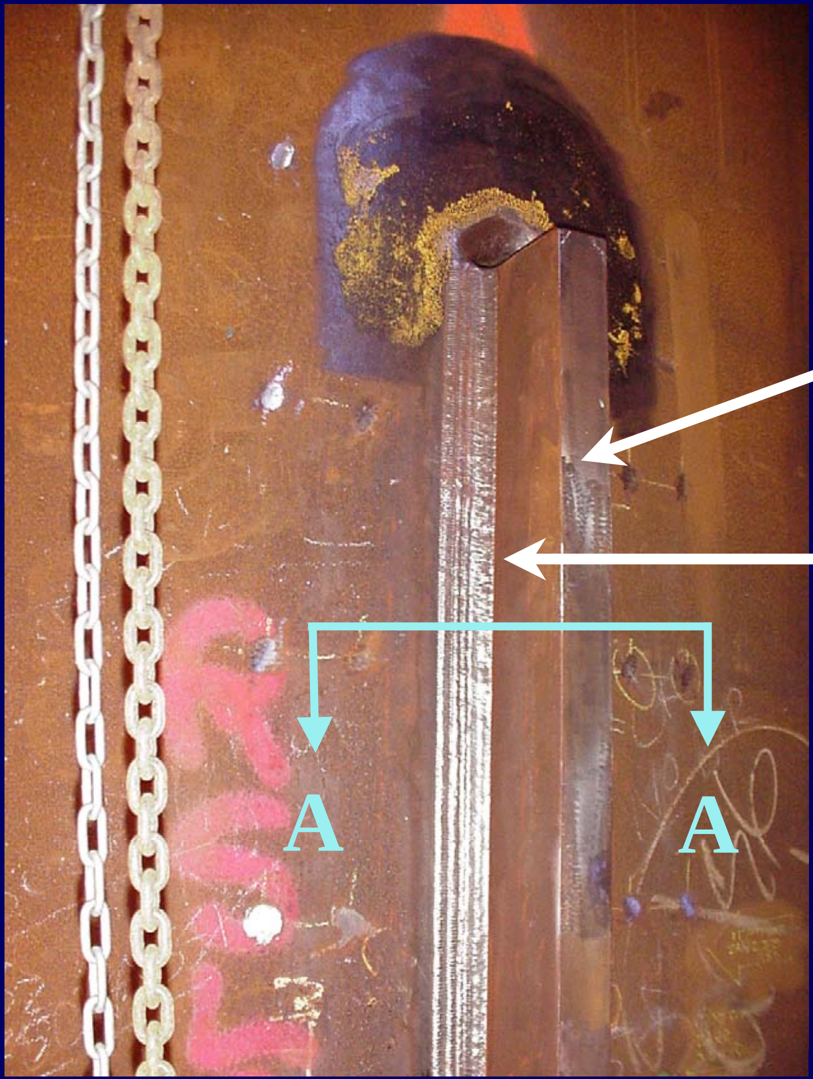


California Department of Transportation
Federal Highway Administration

Details of the Shear Plates Connecting the Piles to the Pile Sleeves (Elevation)



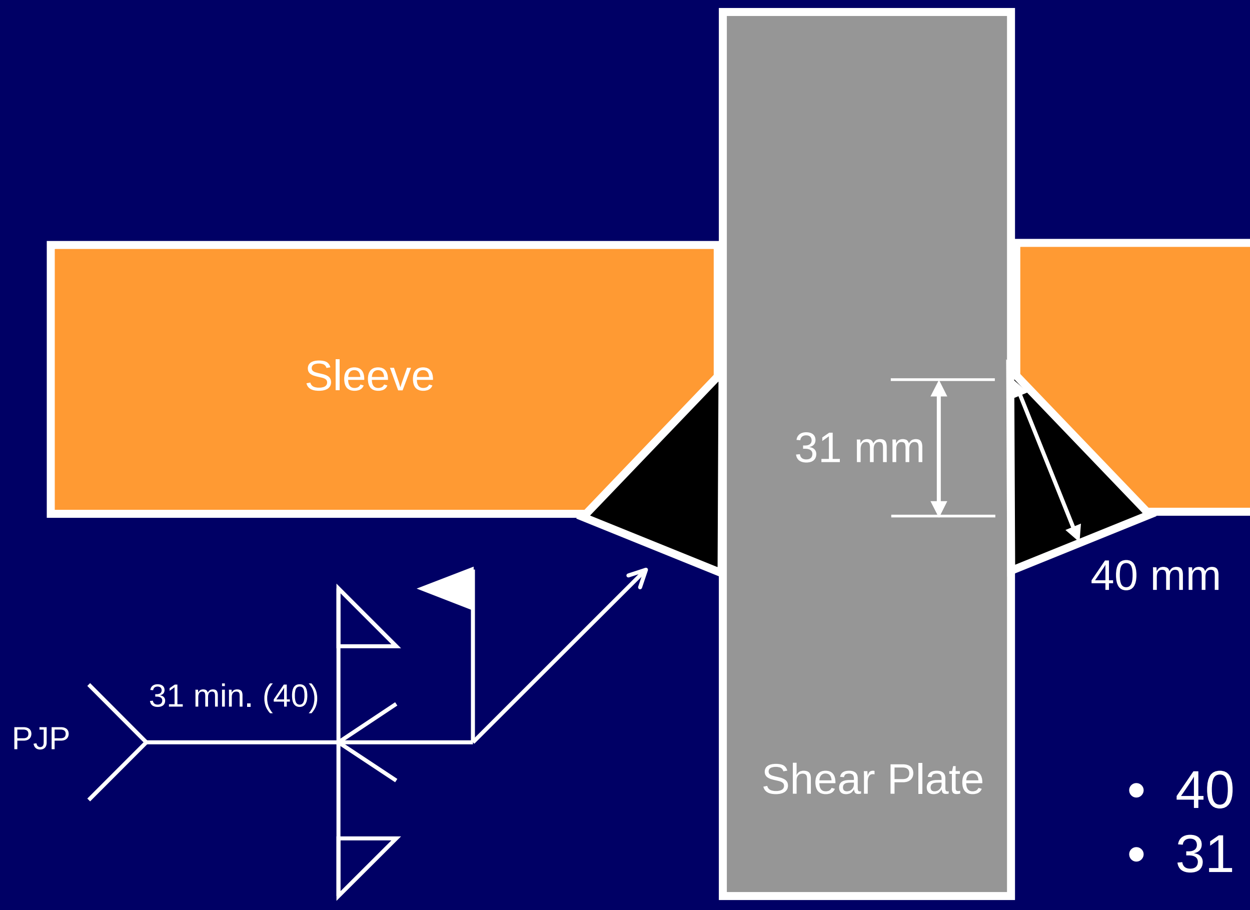
Zooming in on one of the Welded Shear Plates



SHEAR PLATE
IN THE FIELD

SHEAR PLATE TO PILECAP
SLEEVE WELD IN THE FIELD

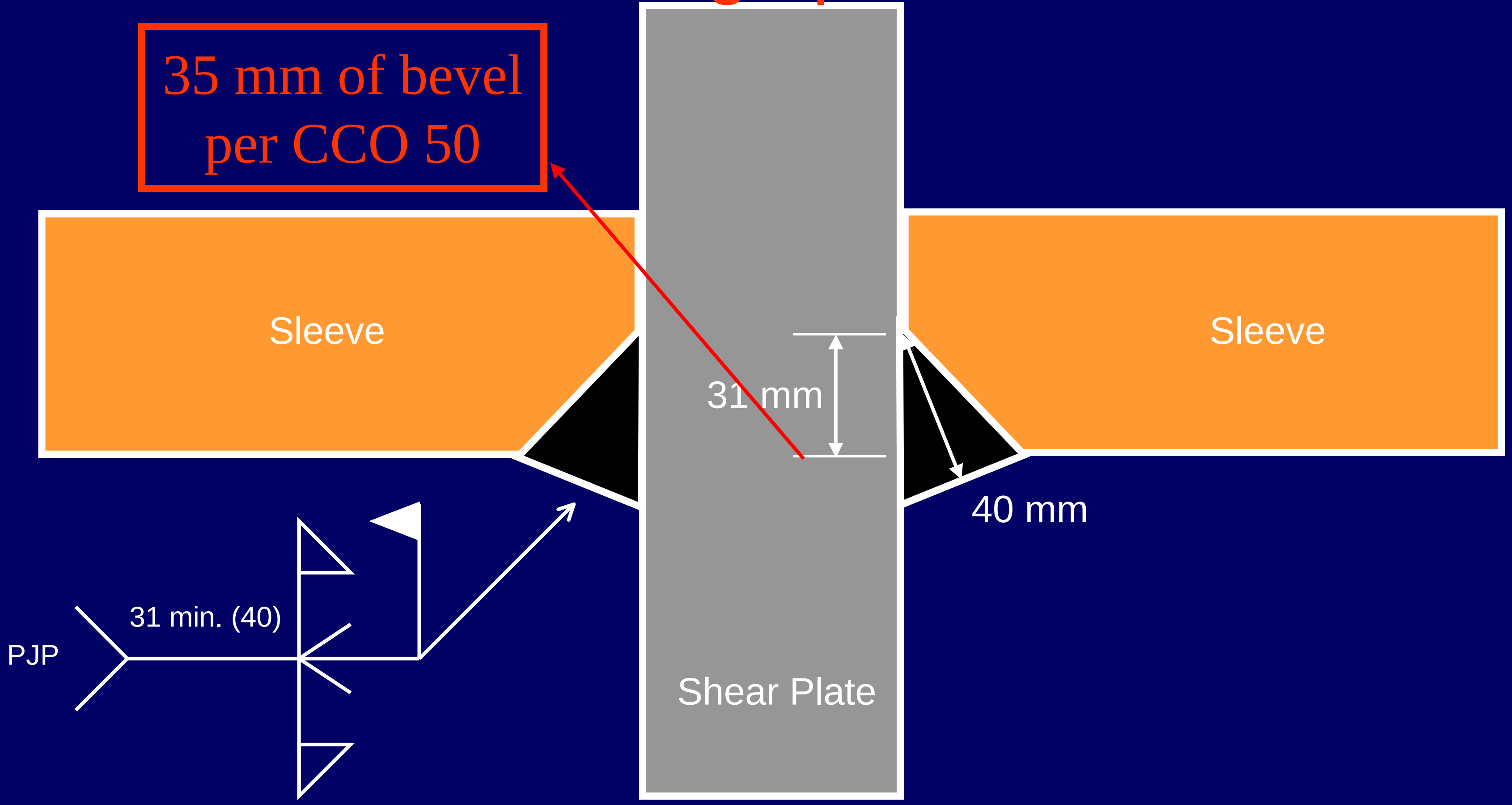
Weld Profile (as-designed)



- 40 mm effective throat
- 31 mm weld prep

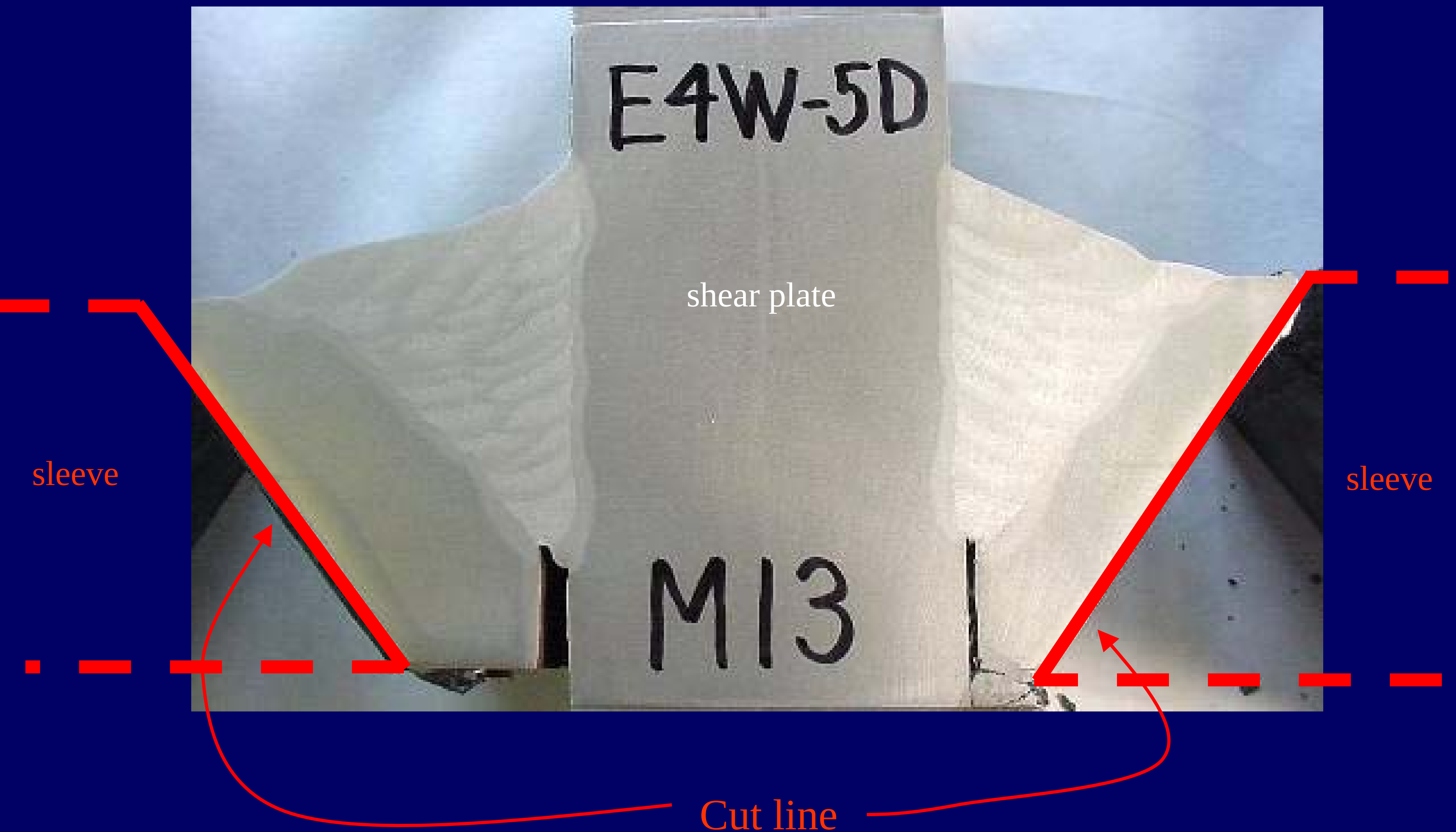
View from A-A

Weld Profile (per designed) and change per CCO 50



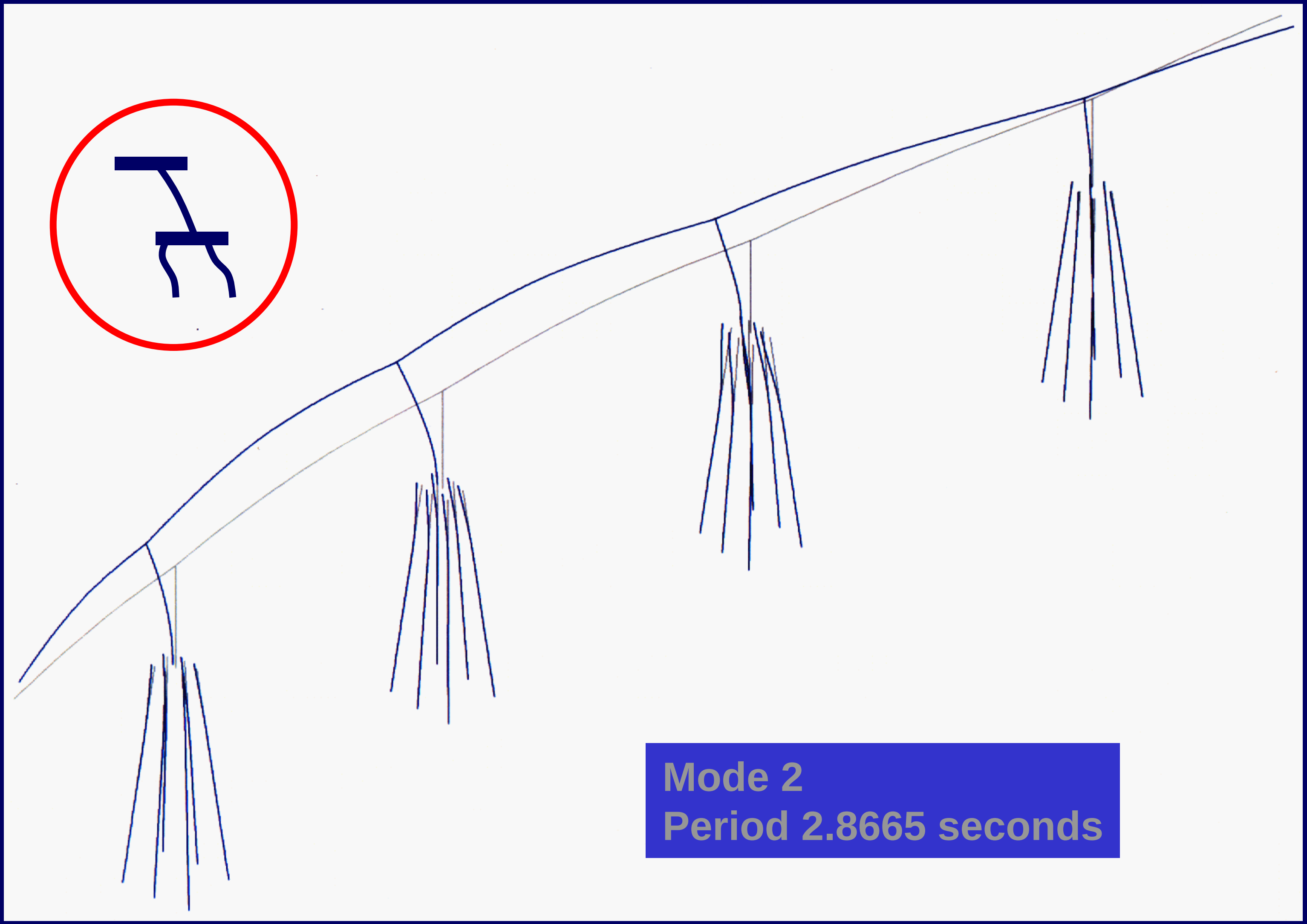
View from A-A

Extracted Welded Connection from Skyway Structure Showing Weld Profile and Detail of a PJP weld

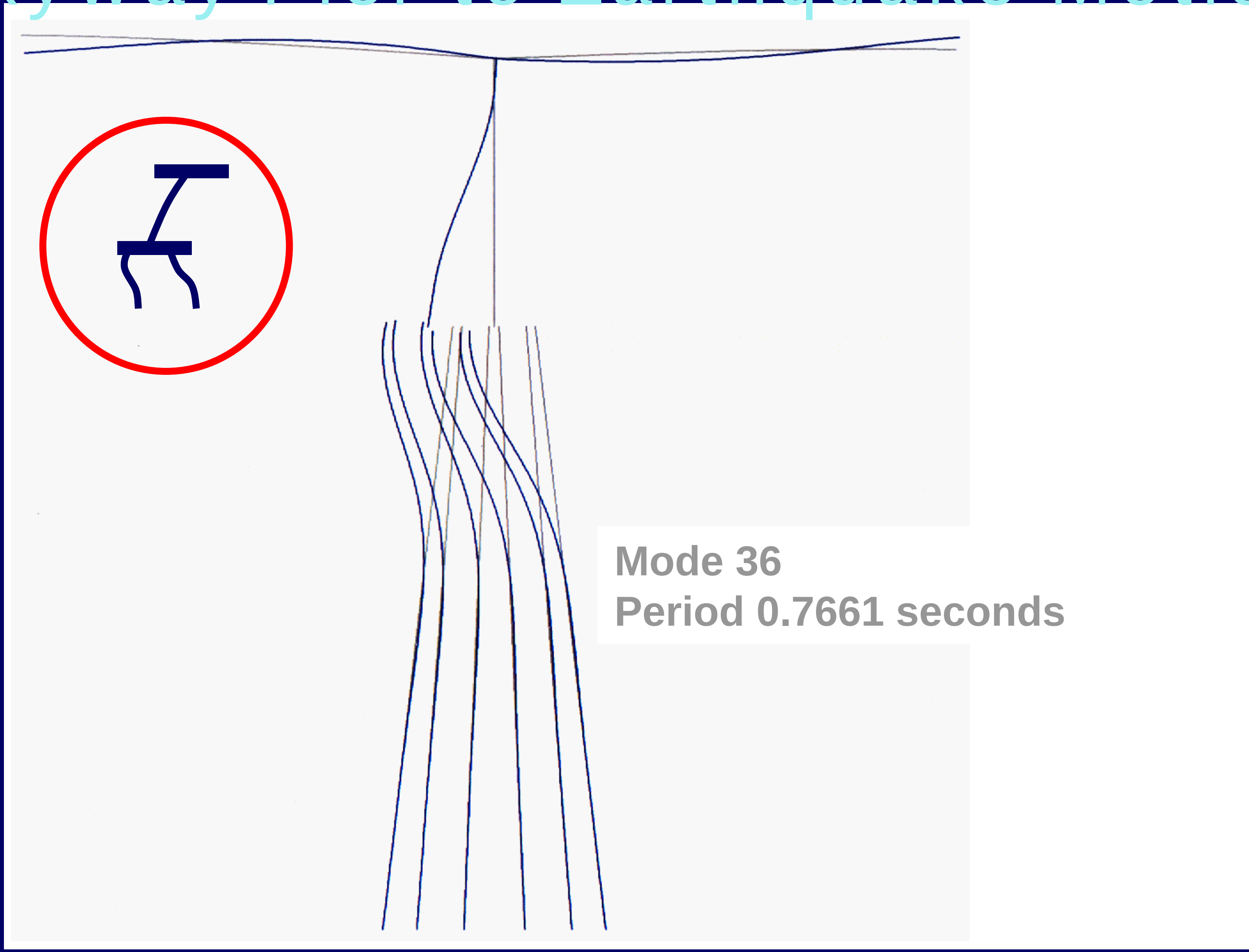


California Department of Transportation
Federal Highway Administration

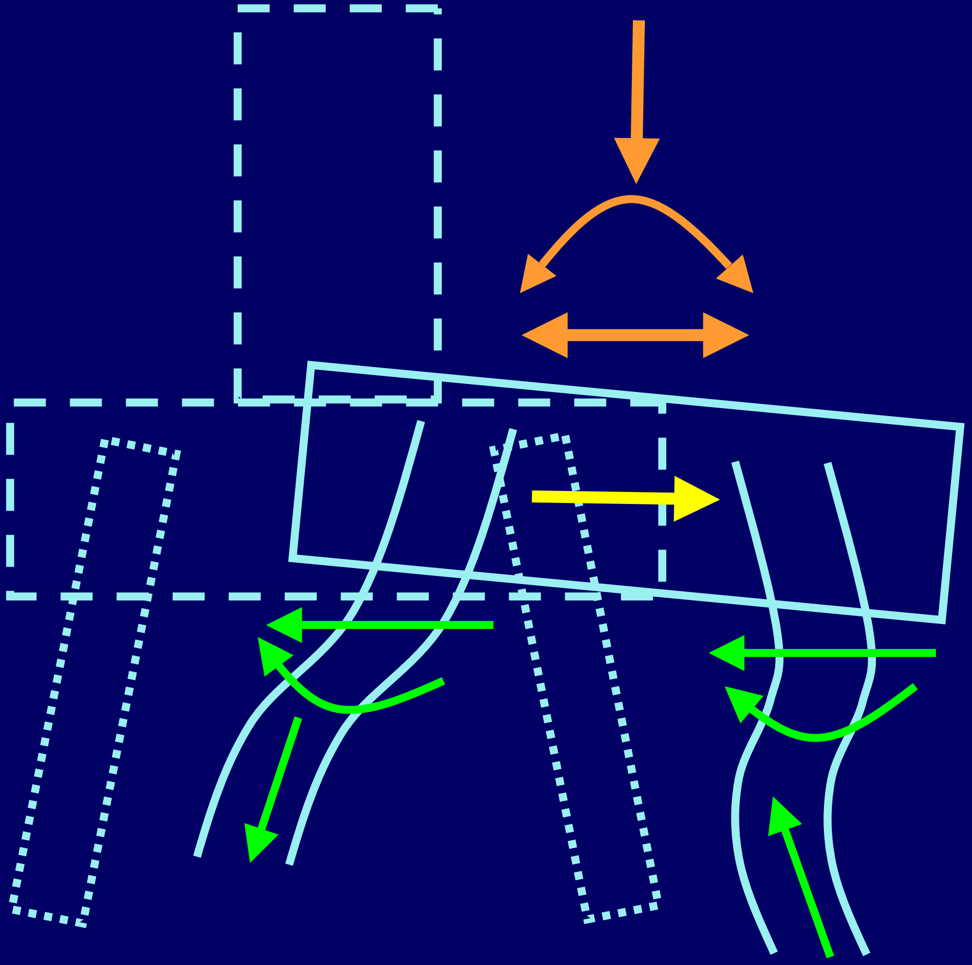
Note Fundamental Behavior of Skyway Pier to Earthquake Motions



Note Secondary Behavior of Skyway Pier to Earthquake Motions



Anticipated Deformed Shape and Free-Body-Diagram of Pilecap Region During a Future Earthquake



Earthquake related loads from column in orange

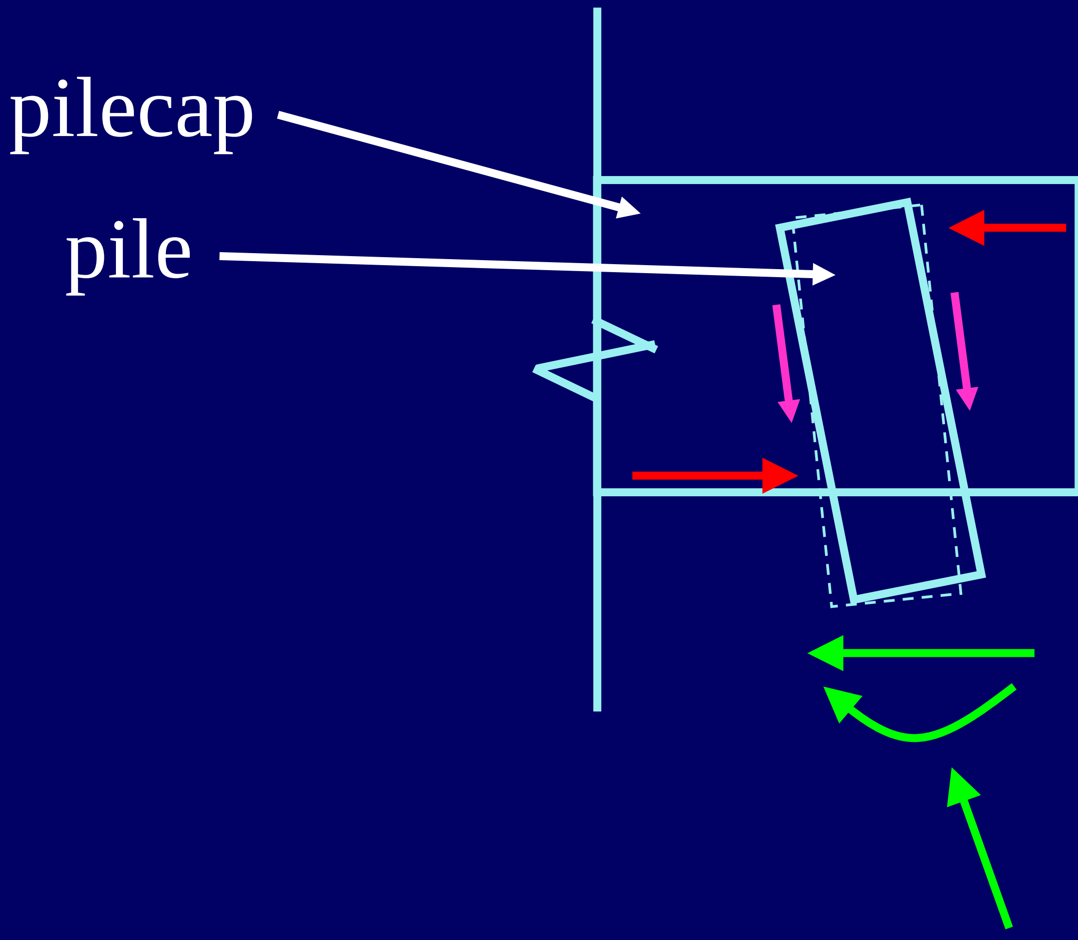
Earthquake related loads from pilecap inertia in yellow

Earthquake related loads from piles in green

California Department of Transportation
Federal Highway Administration

Anticipated Free-Body-Diagram of Pile-to-Pilecap Region During a Future Earthquake

"basic load transfer through connection"



Predominately "shear"

(at 1500 yr EQ, 90% through shear plates 10% through grout)

California Department of Transportation
Federal Highway Administration

Skyway pile-to-pilecap weld design

$$\text{Shear Capacity} = 0.8 * (0.6 * F_{EXX}) * t * L$$

Capacity reduction factors
to account for “real world”
strength of weld imperfections
(craftsmanship, dimensions,
weld material strength) and to
keep allowable in the elastic range

Minimum specified strength
of weld material

Throat thickness of weld

Length of weld

Reference: AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS 6.13.3

FHWA has carried out selected sampling in the field and conducted measurements on those samples. That work offered documentation that the work sampled is even better than that assumed during the design phase and is even better that that specified by the contract, which is also better than that assumed during the design phase (as appropriate per code).

Actual Weld Oversize (FHWA)

- Effective weld throat at Pier E4W is greater than design requirements
- Design required: 40 mm
- Field measured: 45 mm to 57 mm
  (average = 51.5 mm)

➔ This offers data to support that the actual size of the weld is larger than required. This leads to extra safety.

Actual Weld Oversize (**Based on Report by Mayes)**

Oakland Bay Bridge
Pile Connection Plate
Welding Investigation Report

Federal Aid Project ACIM-080-1 (085) 8N
MTE File No. S5021

May 3, 2005

Figure 1: Pier footing at E4W

Summary of Results

The field and laboratory work performed by the Mayes Testing Engineers evaluation team shows excellent workmanship in the pile connection plate welds in pier footing structure E4W. There was no evidence of gross flaws. In fact, there was no evidence of any unacceptable flaws in any of the samples tested. The weld cross-section significantly exceeds the minimum design requirements. The weld average cross-section depth (weld effective throat) is 25 percent greater than design requirements and the weld cross-section also shows a very regular pattern of weld bead deposition indicating a consistent and controlled welding process.

Respectfully Submitted,
MAYES TESTING ENGINEERS, INC.

REGISTERED PROFESSIONAL ENGINEER
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No. C043415
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STATE OF CALIFORNIA

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Welding Engineer/NDE Level III

Summary of Results

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Actual Weld Over-Strength

Weld strength greater than design requirements

Design required: 70 ksi

PQR measured yield strength: 76 to 83 ksi

PQR measured F_{EXX} strength: 89 to 93 ksi

➔ This offers data to support that the actual strength of the weld is larger than required. This leads to extra safety.

Actual Weld Over-Strength (Documented in Report by Fisher)

U.S. Department of Transportation
Federal Highway Administration

FHWA Home | Feedback

FHWA Bay Bridge Pile Connection Plate Welding Investigation

By John W. Fisher, PhD, PE

Introduction

Quality Control/Quality Assurance

Initial Fabrication Experience

Field Observ…

$P_a = {}^{50}/_{\sqrt{3}} \times 68 \times 2.36 = 4{,}632.7$ kips

c) PJP Welds

On the Weld Throats:

$P_V = 0.7E_{xx} \times L_w \times t_w \times 2$

Where: L_w = Length of the weld, in.

t_w = Weld throat size, in.

E_{xx} = Minimum strength of the electrode, ksi

$= 0.7 \times 70 \times 68 \times 1.575 \times 2 = 10{,}495.8$ kips

On the Weld leg:

$P_V = 0.7F_u \times L_w \times l_w \times 2$

Where: L_w = Length of weld, in.

l_w = Weld leg size, in.

From the weld qualification test data that was provided by Caltrans, the notch toughness test data of the E71T-1 weld metal was quite high. Values at 0°F were in the range of 57ft-lbs. to 91ft-lbs. for the weld metal. The weld yield point was between 76ksi and 83ksi. Hence, the fracture resistance to small cracks or other discontinuities in the weld will be very great and will not be susceptible to fracture. It was hydrogen cracking and high restraint that resulted in cracks extending into the base metal that resulted in the fractures in the early fabrication.

was eliminated by making changes to the weld process, using run off tabs to start and stop the weld passes and to provide more effective preheat.

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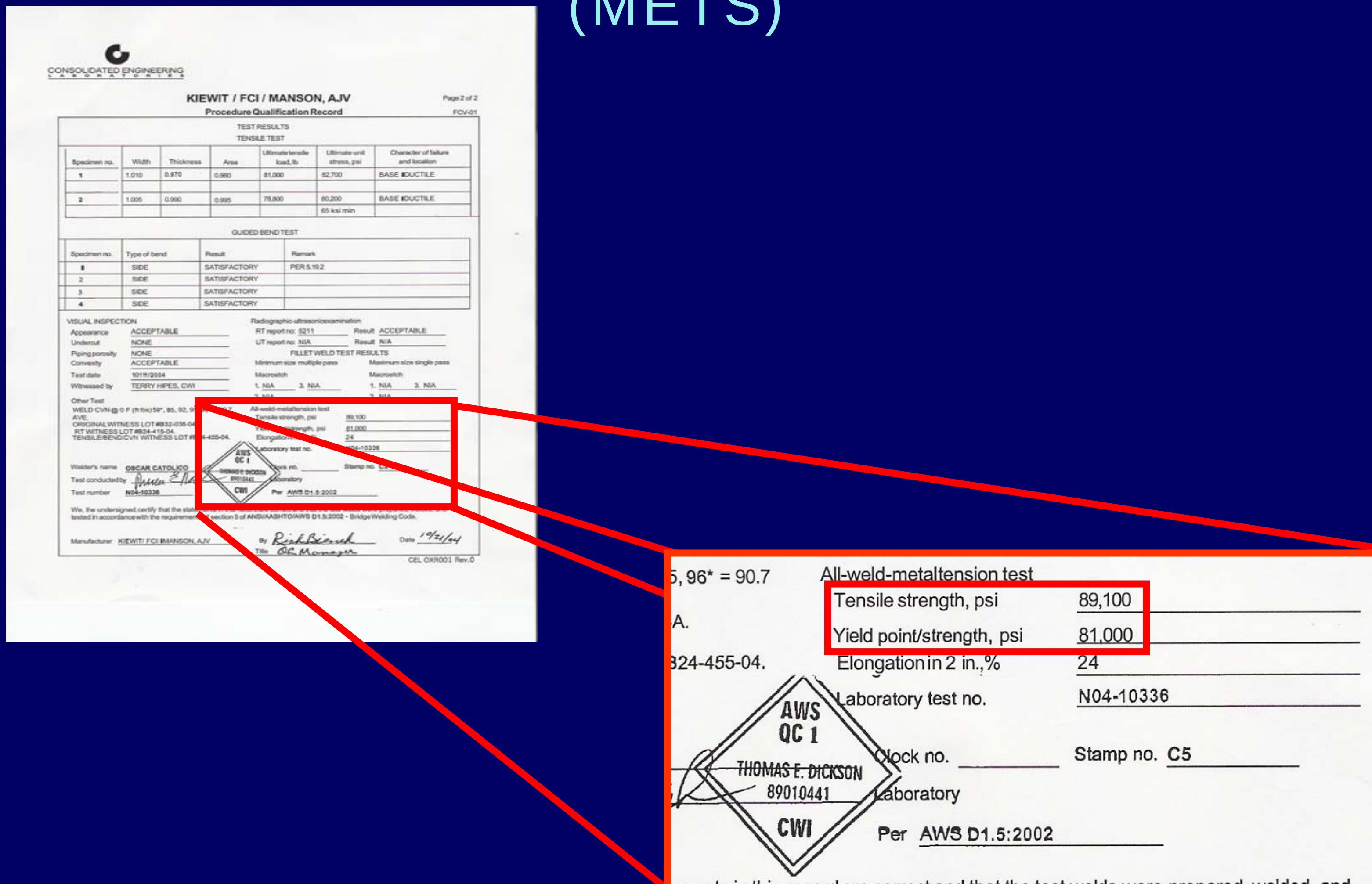
That is being prevented by the careful inspection of the base metal at the access holes after the welded joints are completed, the run off tabs removed, and the access hole cleaned and ground smooth.

This fact can be seen by examining the fracture resistance to a hypothetical but unlikely 0.25in. deep surface crack in the weld metal at the access hole.

The fracture toughness of the weld metal can be estimated from the Charpy V-Notch test data using the Barsom correlation

Actual Weld Over-Strength

Example from Procedure Qualifications Records (METS)



CONSOLIDATED ENGINEERING LABORATORIES

KIEWIT / FCI / MANSON, AJV

Procedure Qualification Record

Page 2 of 2

FCV-01

TEST RESULTS

TENSILE TEST

Specimen no.	Width	Thickness	Area	Ultimate tensile load, lb	Ultimate unit stress, psi	Character of failure and location
1	1.010	0.970	0.980	81,000	82,700	BASE DUCTILE
2	1.005	0.990	0.995	79,800	80,200	BASE DUCTILE
					65 ksi min	

GUIDED BEND TEST

Specimen no.	Type of bend	Result	Remark
1	SIDE	SATISFACTORY	PER 5.19.2
2	SIDE	SATISFACTORY	
3	SIDE	SATISFACTORY	
4	SIDE	SATISFACTORY	

VISUAL INSPECTION

Appearance ACCEPTABLE

Undercut NONE

Piping porosity NONE

Convexity ACCEPTABLE

Test date 10/19/2004

Witnessed by TERRY HIPES, CWI

Radiographic-ultrasonic examination

RT report no: 5211 Result ACCEPTABLE

UT report no: N/A Result N/A

FILLET WELD TEST RESULTS

Minimum size multiple pass Macroetch 1. N/A 3. N/A

Maximum size single pass Macroetch 1. N/A 3. N/A

Other Test

WELD CVN @ 0 F (ft lbs) 59*, 85, 92, 96* = 90.7 AVE.

ORIGINAL WITNESS LOT #B32-036-04A.

RT WITNESS LOT #B24-455-04.

TENSILE/BEND/CVN WITNESS LOT #B24-455-04.

All-weld-metal tension test

Tensile strength, psi 89,100

Yield point/strength, psi 81,000

Elongation in 2 in., % 24

Laboratory test no. N04-10336

Welder's name OSCAR CATOLICO

Clock no. Stamp no. C5

Test conducted by Laboratory

Test number N04-10336

Per AWS D1.5:2002

AWS QC 1 THOMAS E. DICKSON 89010441 CWI

We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of section 5 of ANSI/AASHTO/AWS D1.5:2002 - Bridge Welding Code.

Manufacturer KIEWIT/ FCI MANSON, AJV

By Rick Bianch Date 10/21/04

Title QC Manager

CEL OXR001 Rev.0

California Department of Transportation

Federal Highway Administration

In Summary…

Skyway pile-to-pilecap weld design

$$\text{Shear Capacity} = 0.8 * (0.6 * F_{EXX}) * t * L$$

The design has assumed the reduced values.
The contract holds the contractor to full F_{EXX}, t, and L values.
This generates a considerable margin of safety.

Fisher reports FHWA has measures of samples taken, that the contractor has provided <u>additional thickness, t</u>, and that Caltrans' PQRs document that the contractor has provided <u>additional weld material strength, F_{EXX}</u>.
This generates an even greater margin of safety.

Summary of multiple sources that lead to higher field capacities

$$\text{Shear Capacity} = \boxed{0.8 * (0.6} * F_{EXX}) * t * L$$

Capacity reduction factors
per AASHTO bridge code
to account for “real world”
strength of weld imperfections
(craftsmanship, dimensions,
weld material strength)

Length of weld

Throat thickness of weld
LARGER THAN SPECIFIED

not 40 mm as assumed in design, but

45 to 57 mm as measured in field conditions

Minimum specified strength
of weld material
GREATER THAN SPECIFIED

not 70 ksi as assumed in design, but
89 to 93 ksi as measured in tests

California Department of Transportation
Federal Highway Administration