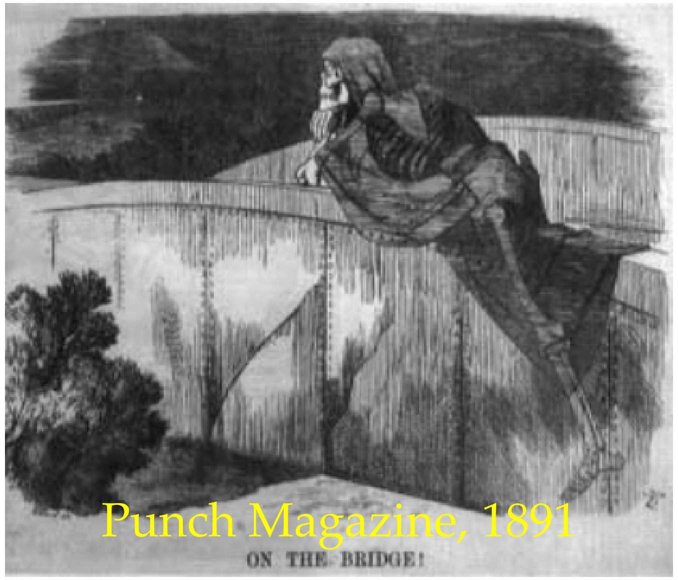
Designing with Titanium Alloy Bars (TiABs) for Strengthening Concrete Bridges

Christopher Higgins, Ph.D., P.E.
Laura Baughman, M.S.
Jonathan Knutdsen, M.S.
Deanna Kuhlman, M.S.
Mackenzie Lostra, M.S.
Sharoo Shresta, Ph.D.
Eric Vavra, M.S.
Amanda Slawinski, M.S.



Punch Magazine, 1891

STRUCTURAL ENGINEERING
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Overview

- Introduction and Background
- Laboratory Test Results from Full-Scale Specimens
    - Shear Strengthening
    - Flexural Strengthening
- Field Implementation on Mosier Bridge over I84
- AASHTO Design and Construction Guide
- ASTM Material Specification
- Conclusions

Introduction

During the 1950 and 60's:

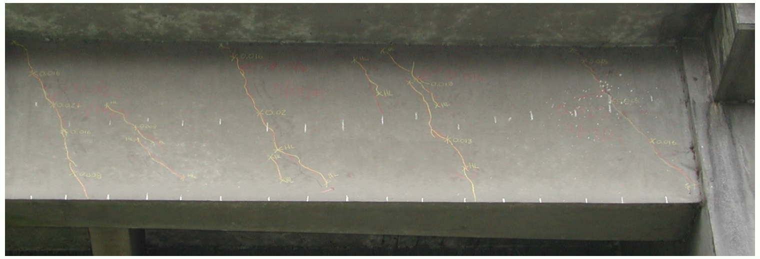
- Post-war construction boom
- Reinforced concrete widely used
- Newly standardized deformed reinforcing steel bars produced poor details
- Design codes were not conservative

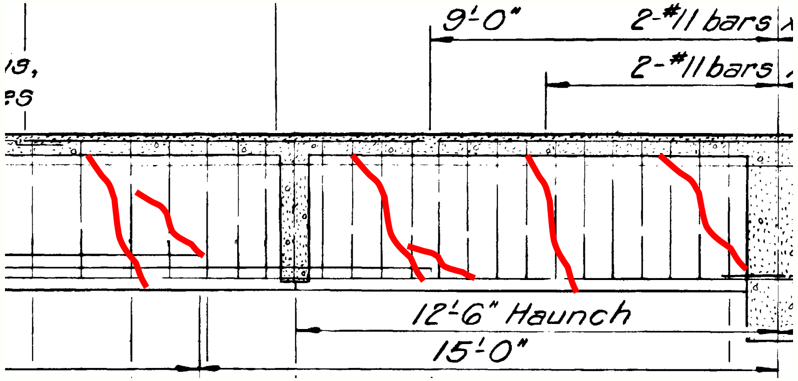
Now:

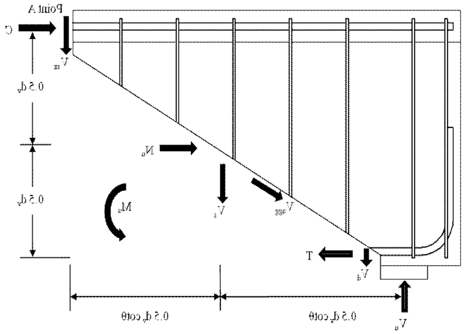
- Visual distress, changes in use, extend life
- Using modern ***design*** codes to assess

Results:

- Replace, limit loads, retrofit







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Strengthening Approaches

- Post-tensioning
- Wrapping/confining
  - Carbon fiber reinforced polymer (CFRP) laminate
- Near-surface mounted (NSM)
  - Carbon fiber reinforced polymer rod/strip
  - Glass fiber reinforced polymer (GFRP) rod
  - Stainless steel bars

FRP rods and laminates fail due to bond and anchorage and materials are nonductile

Concerns with corrosion at surface for most metals

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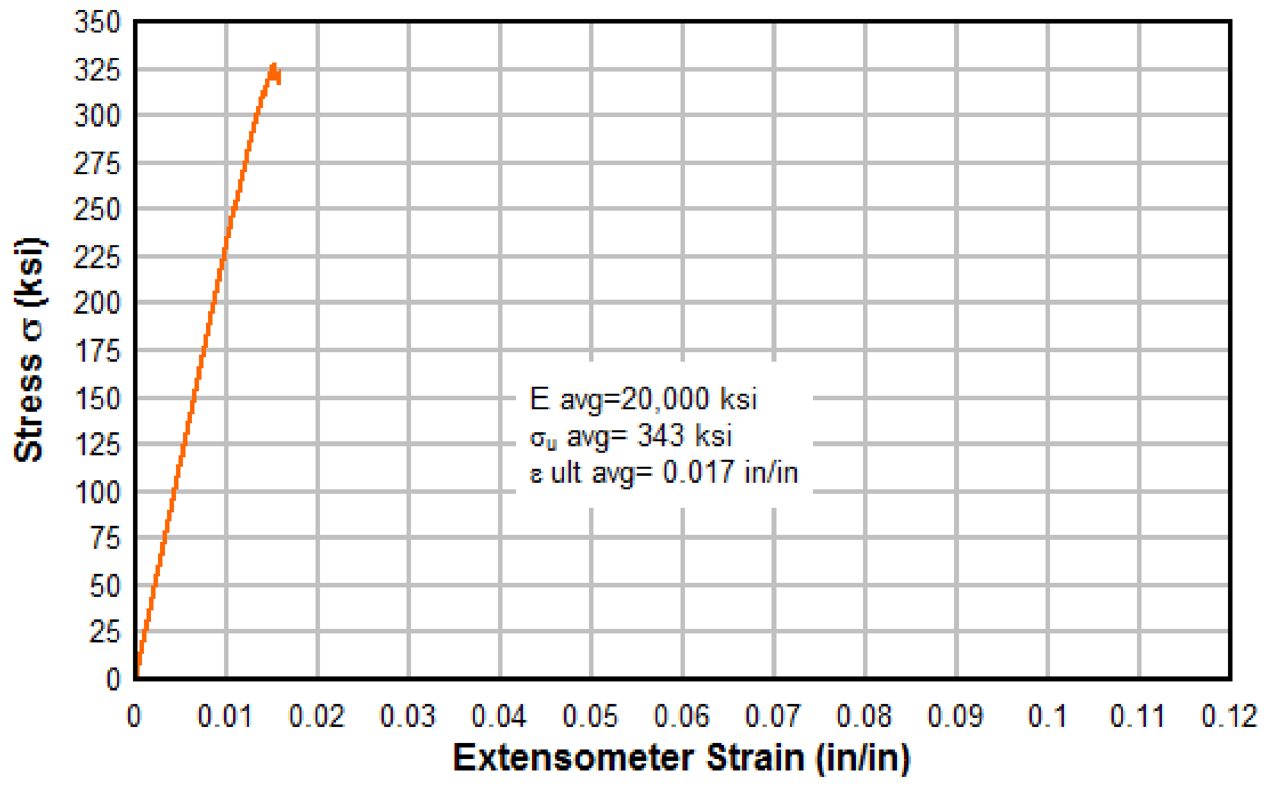
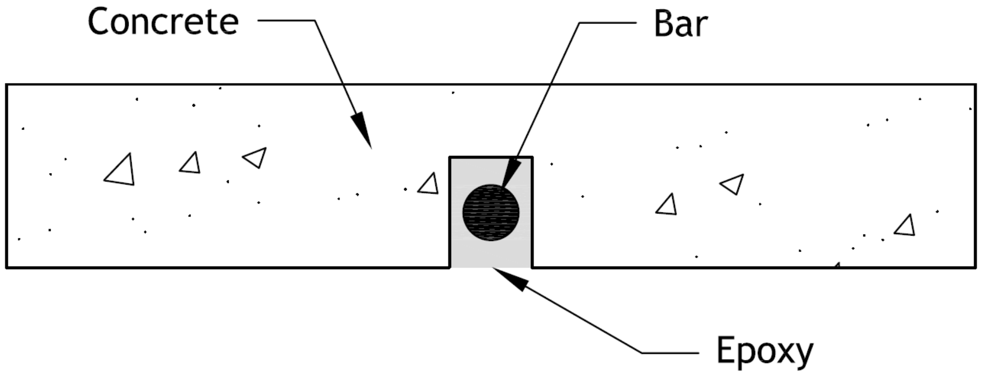
Background: NSM Strengthening Materials

Carbon Fiber Reinforced Polymer (CFRP)



CFRP Bond Failure – Limits material strength

Near-Surface Mounting



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CFRP-NSM

Outer shell peeling

Inner core cracked diagonally

Wide CFRP-NSM

Tightly spaced CFRP-NSM

Alternatives?

Want environmentally insensitive material with high strength, well defined properties, and efficient mechanical anchorages to engage core

-> Titanium

Ductile FRP

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Titanium?

No one uses titanium in structural engineering!

It is too expensive…

It's only for aircraft or medical devices….

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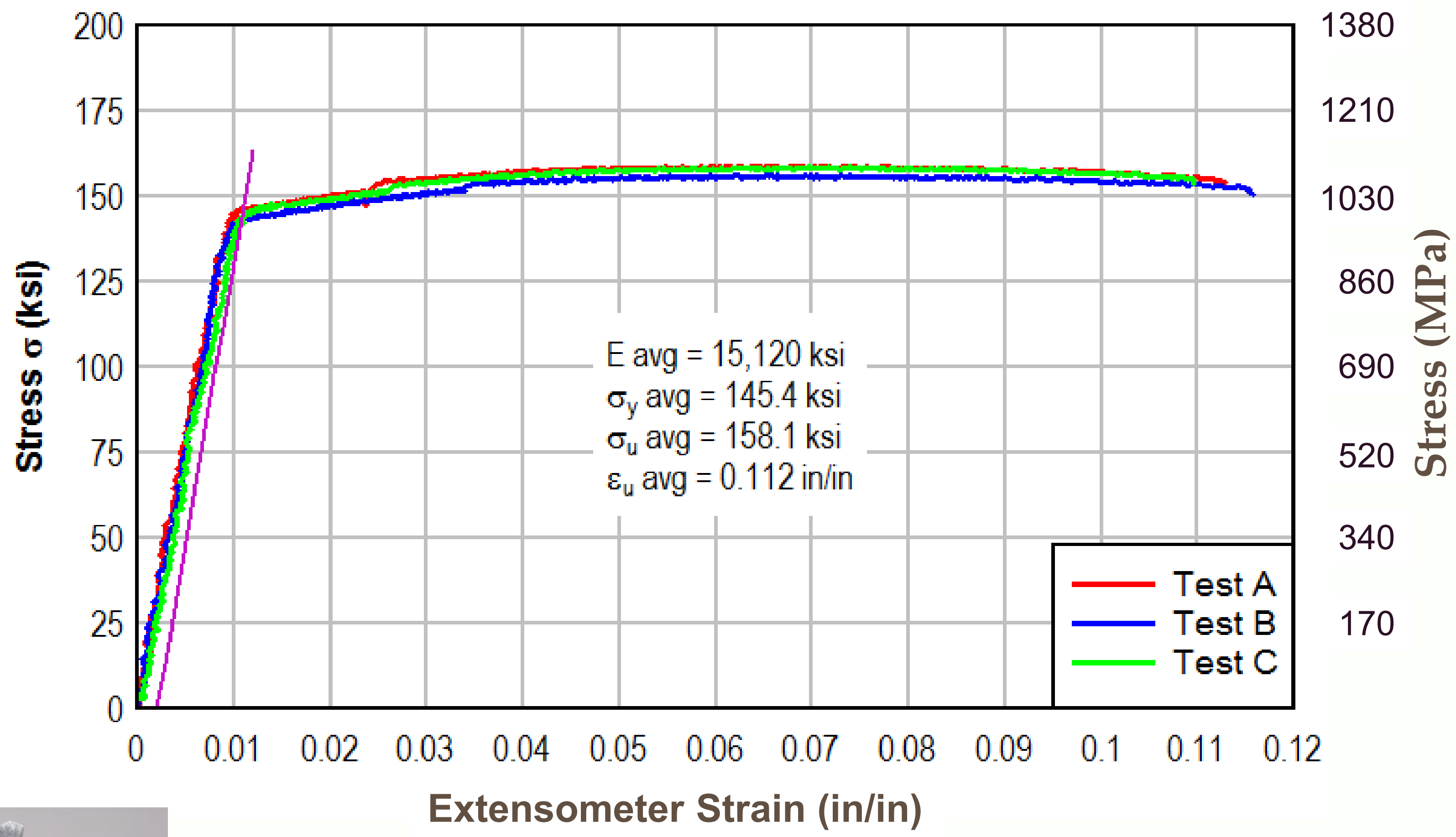
Titanium Alloy Material Properties (Ti-6Al-4V)



Titanium Alloy Material Properties (Ti-6Al-4V)

- **Aircraft fastener quality** (6% Aluminum 4% Vanadium)
- **Well-defined, high strength, and ductile** (limited hardening->protects bond, structural fuse)
- **High fatigue resistance** (CAFL~ 75 ksi), low notch sensitivity
- **Impervious to chlorides** due to stable oxide layer
- **Coeff. of thermal expansion** (8.6$\mu\varepsilon/^{o}C$) (8-12 Con. and 12 St.)
- **Conventional fabrication** (shear, cut, and bend)
- **Relatively lightweight** of 281 lb/ft^3 (steel 1.7x)
- **Bends** facilitate anchorage

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Experimental Work

- **Full-scale tests** with typical proportions and materials from legacy designs

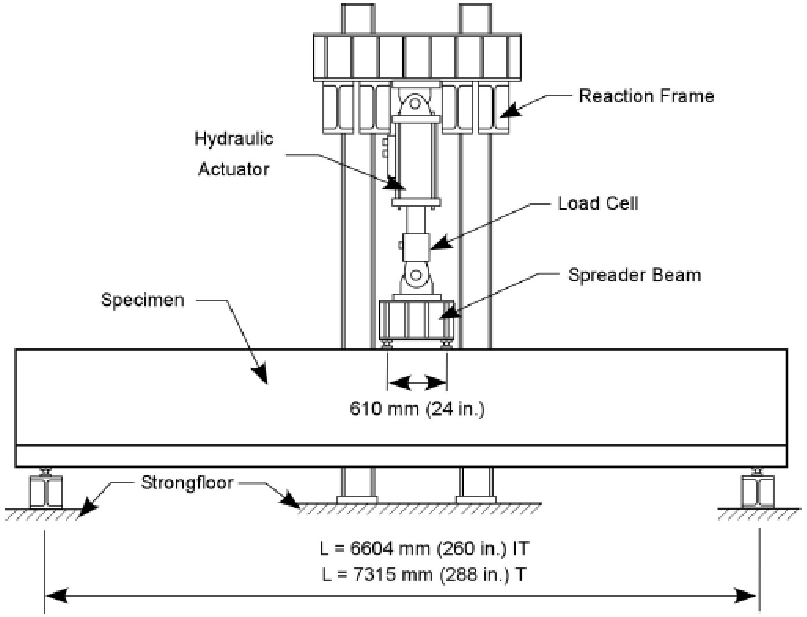
- **Shear specimens: 10** (3 control)

  1/4 in. diameter TiABs

- **Flexure specimens: 10** (3 control)

  5/8 in. diameter TiABs

- **Fatigue and freeze-thaw exposure**: 3 (2 shear, 1 flexure)

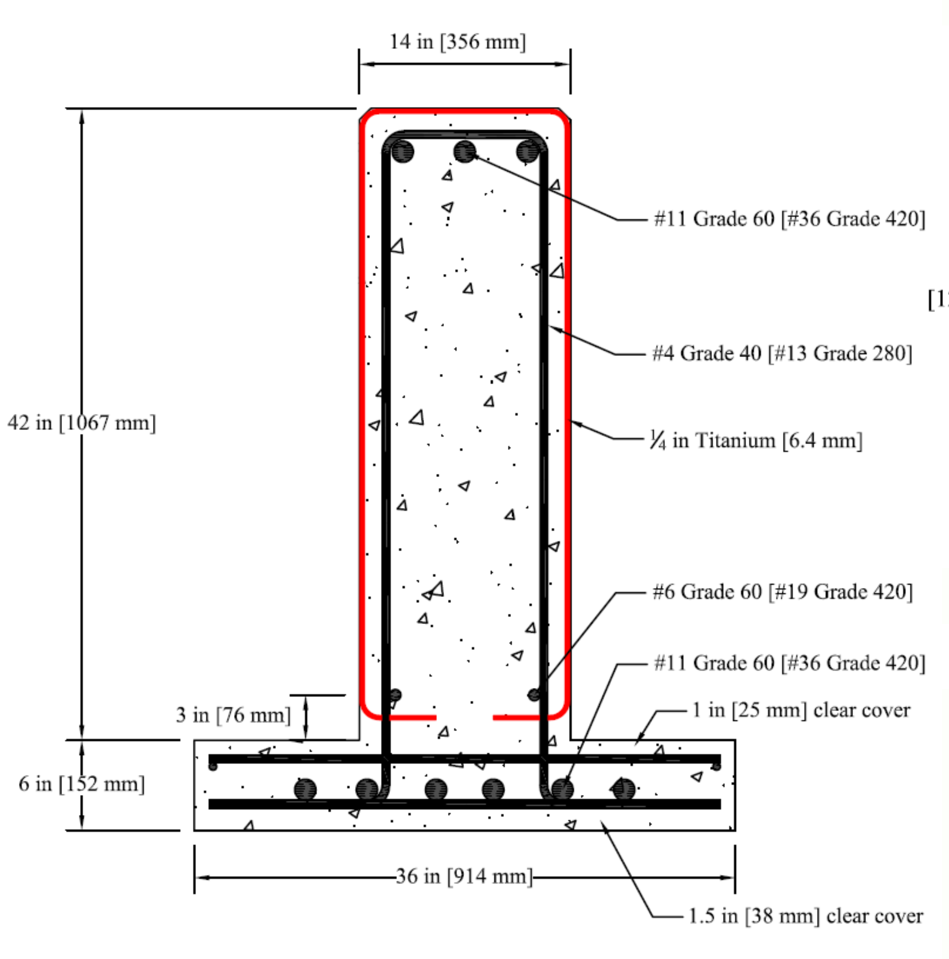


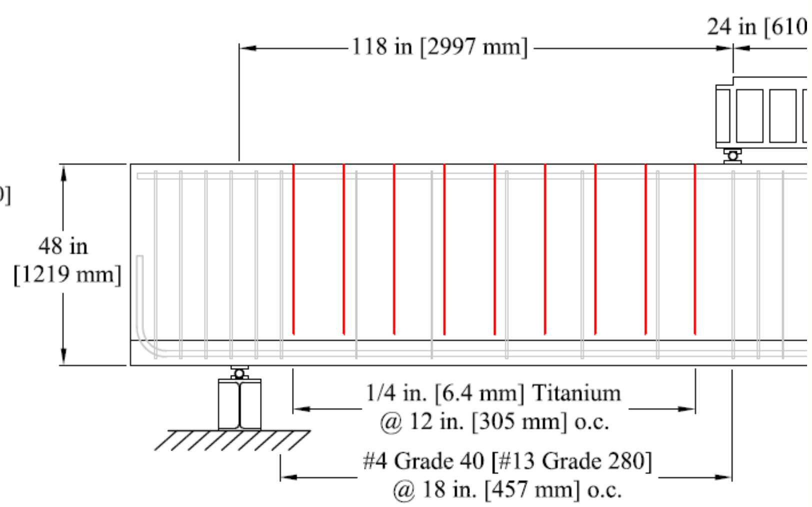
4 ft height, 24 ft long, 20,000 lb

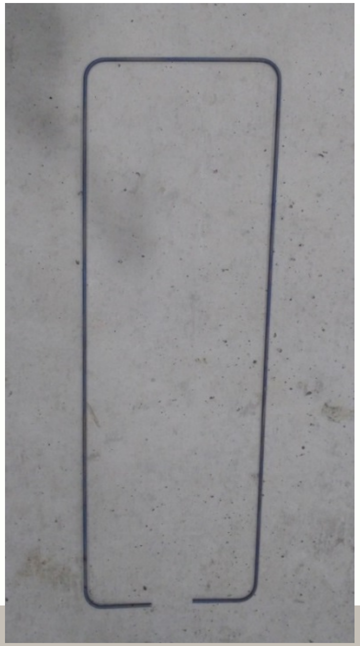
Epoxy Properties

BASF MasterEmaco ADH 1420:	Bond = 2000 psi
Unitex Pro-Poxy 400:	Bond = 2800 psi
Hilti HIT-RE 500 V3:	Bond = 1700 psi

Shear Strengthening – Cross sections (High V and M-)







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Shear Strengthening: Installation

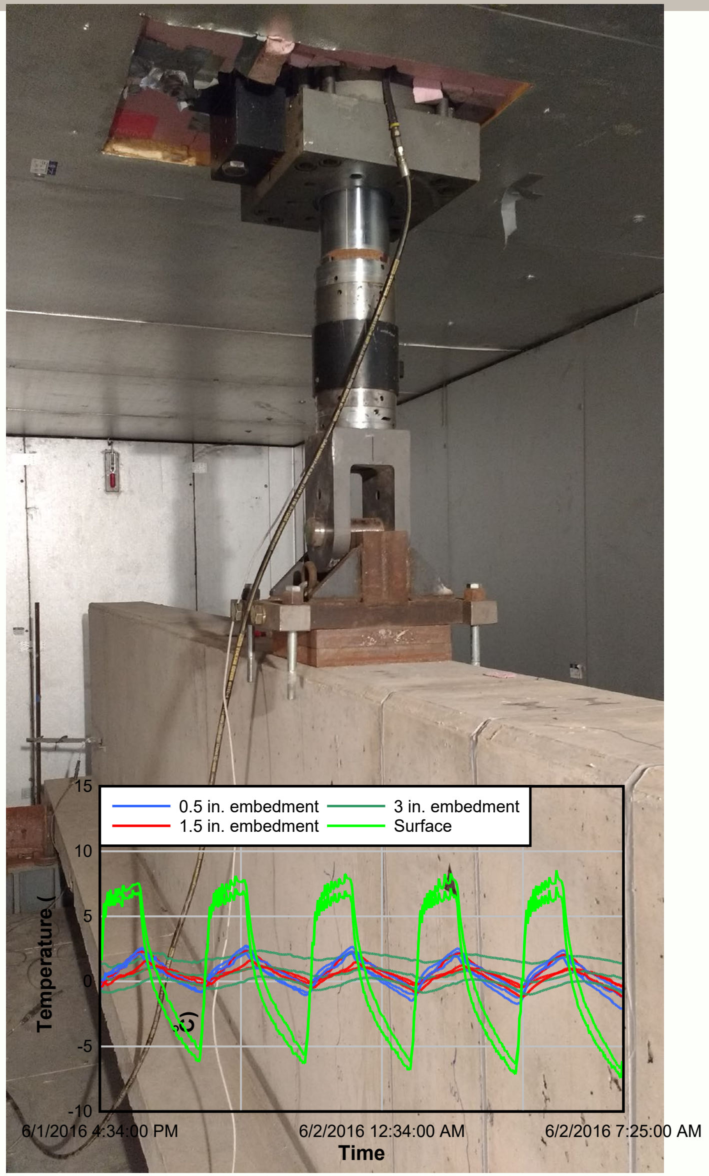
Shear : Fatigue with Freeze-Thaw

- Designed to simulate 50 years of damage based field testing
- 2,400,000 cycles
- Internal stirrup stress range of 13 ksi

$$SR_{eqv} = \sqrt[3]{\sum \frac{n_i}{N_{tot}} SR_i^{3}}$$

Freeze-Thaw

- 120 cycles
- Represents 25-100 years of damage in Oregon, depending on location



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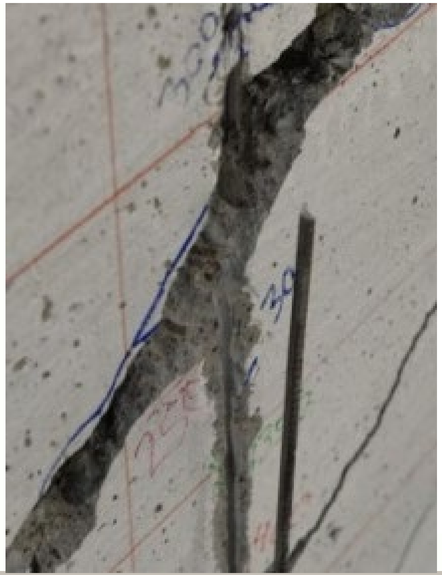

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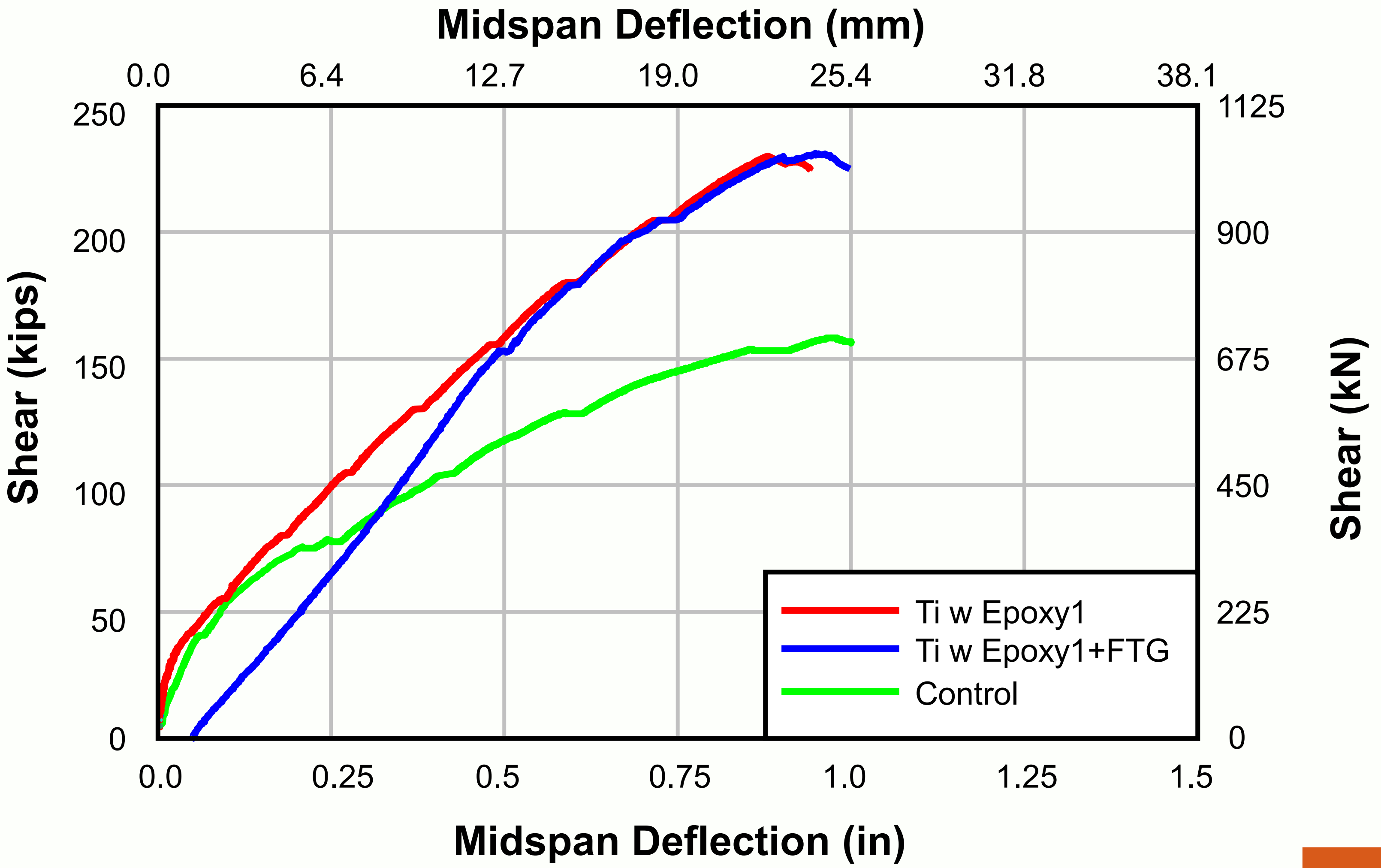
Shear Results Epoxy E1 Ti@ 12 in.



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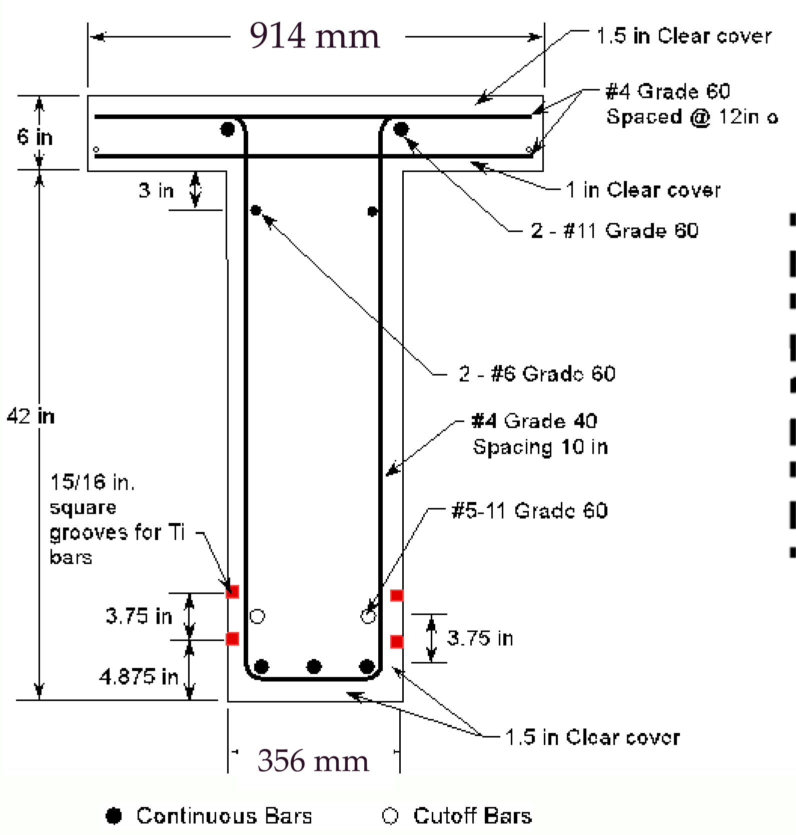
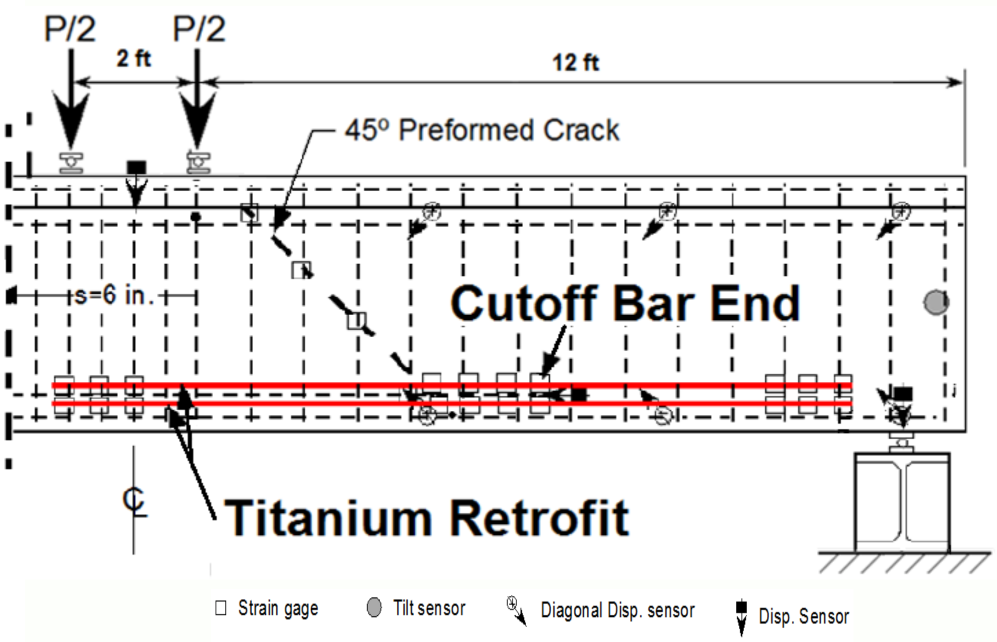
Flexure T Beam Details

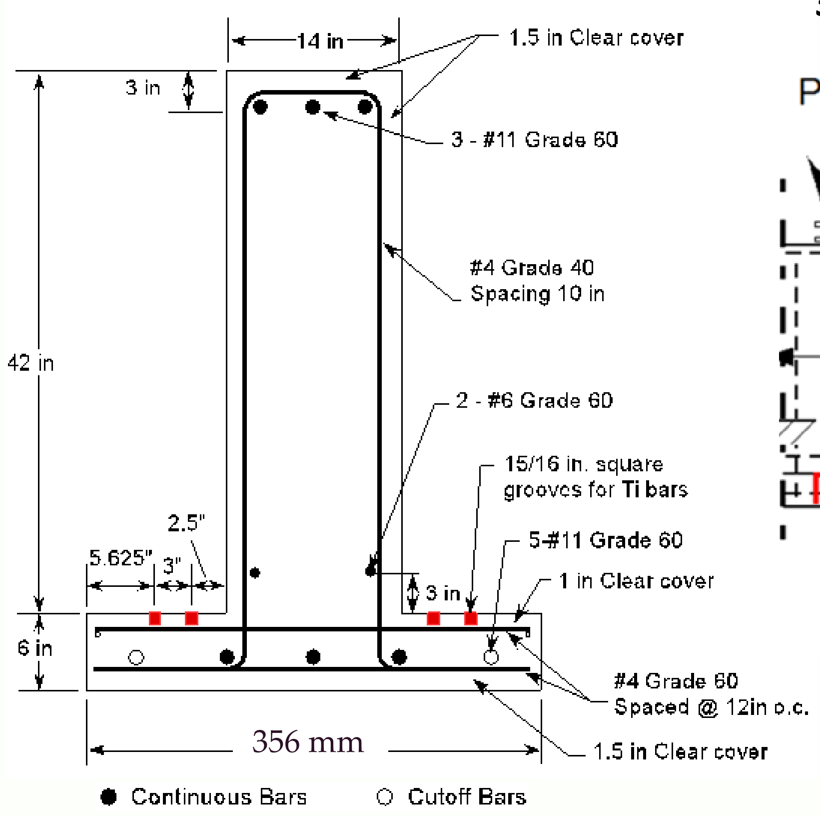
1. **T.45.Ld3:** *Baseline T Beam*
2. **T.45.Ld3.NSM-Ti:** *with 10 in stirrups*
3. **T.45.Ld3.NSM-Ti.2:** *Titanium with 6 in stirrups*

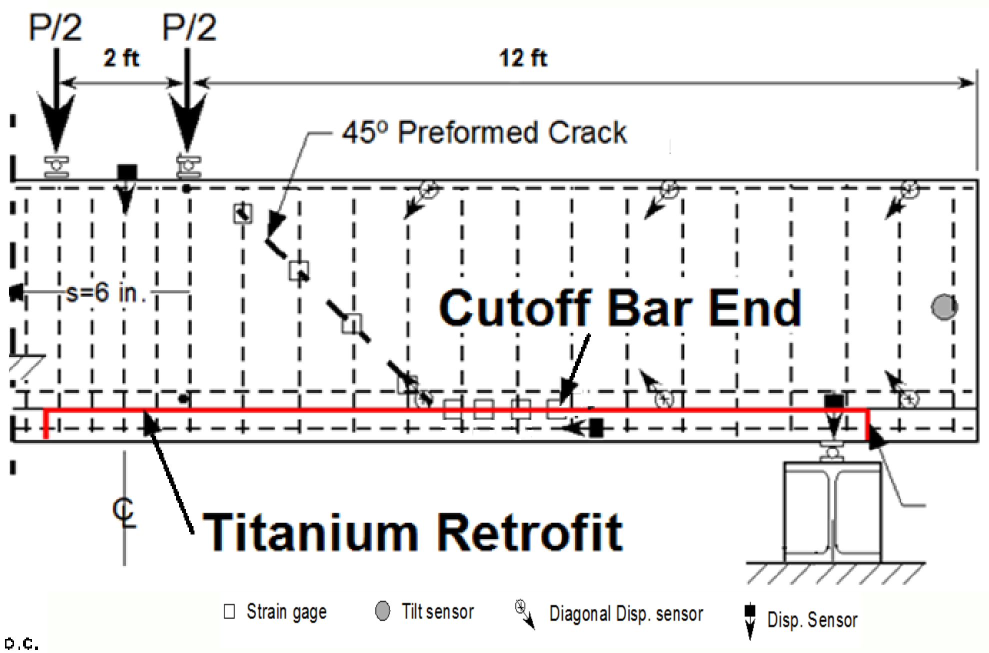




Flexure IT Beam Details

1. **IT.45.Ld2:** *Baseline IT Beam*
2. **IT.45.Ld3.NSM-Ti:** *Titanium with 10 in. stirrups*
3. **IT.45.Ld3.NSM-Ti.2:** *Titanium with 6 in. stirrups*





Specimen Construction

45˚ preformed crack

1.5 in. spacer

Cutoff bar

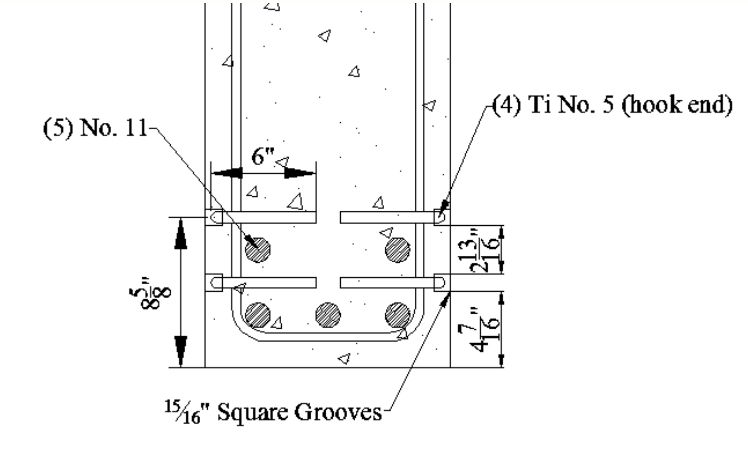
Blockout for slip sensor

Strain gage

NSM Strengthening Methodology

ACI 440.2R

- Groove Spacing
- Groove dimensions



Epoxy Manufacturer Data

Tensile Strength (ksi)	Elongation at Break (%)	Compressive Yield Strength (ksi)	Bond Strength (2 day cure) (ksi)
4	1	12.5	>2

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NSM Strengthening Methodology

Hook Fabrication

- 2 Ti bars on each side
  - 12.5 ft length
  - 6 in. hooks
- 2 in. bend diameter
- Ti: Heat to 900 ˚F or 1250 ˚F

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T.45.Ld3 Failure (without TiABS)

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T.45.Ld3.NSM-Ti2 Failure (with TiABs)

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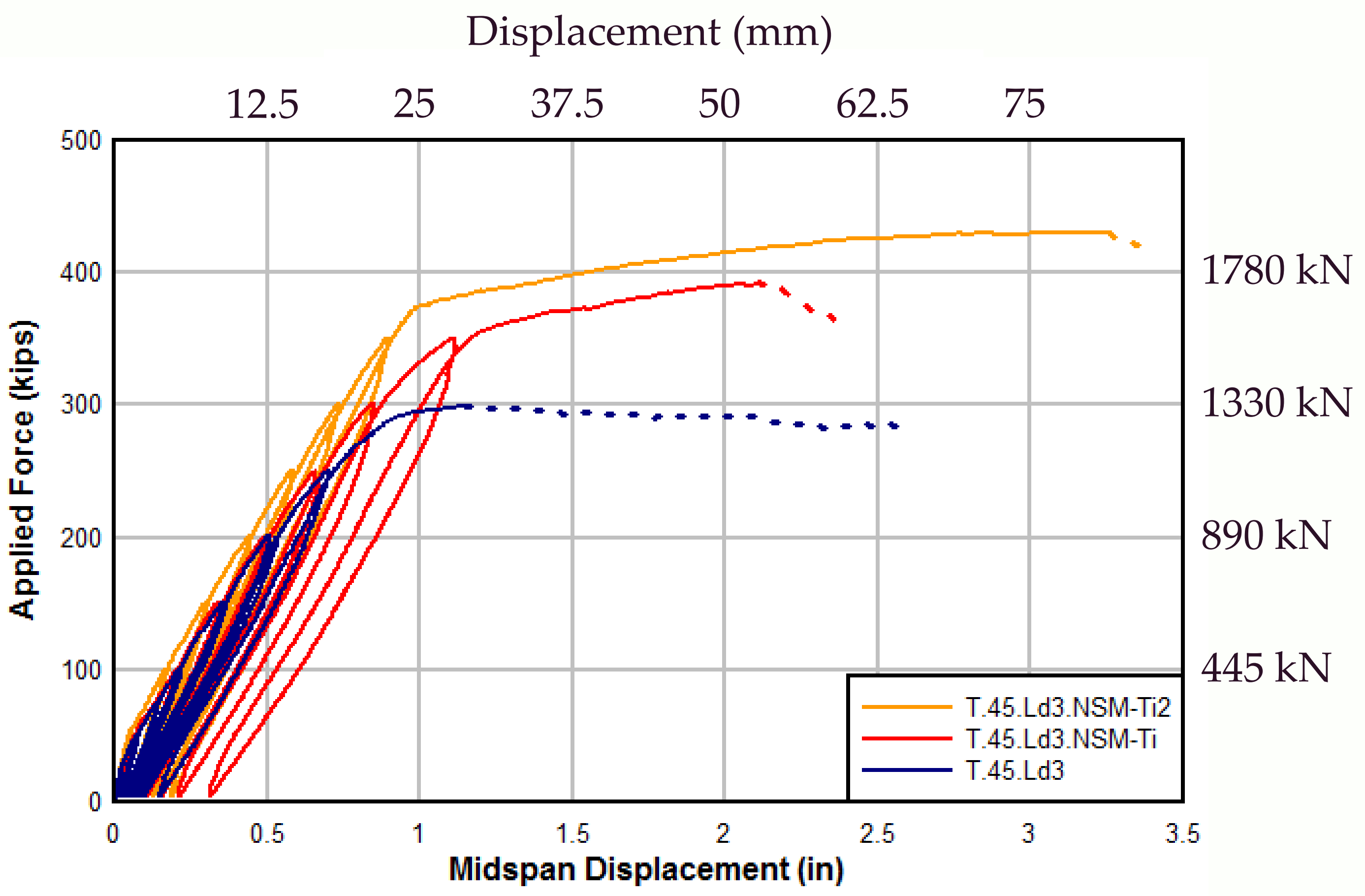
T Beam Experimental Results



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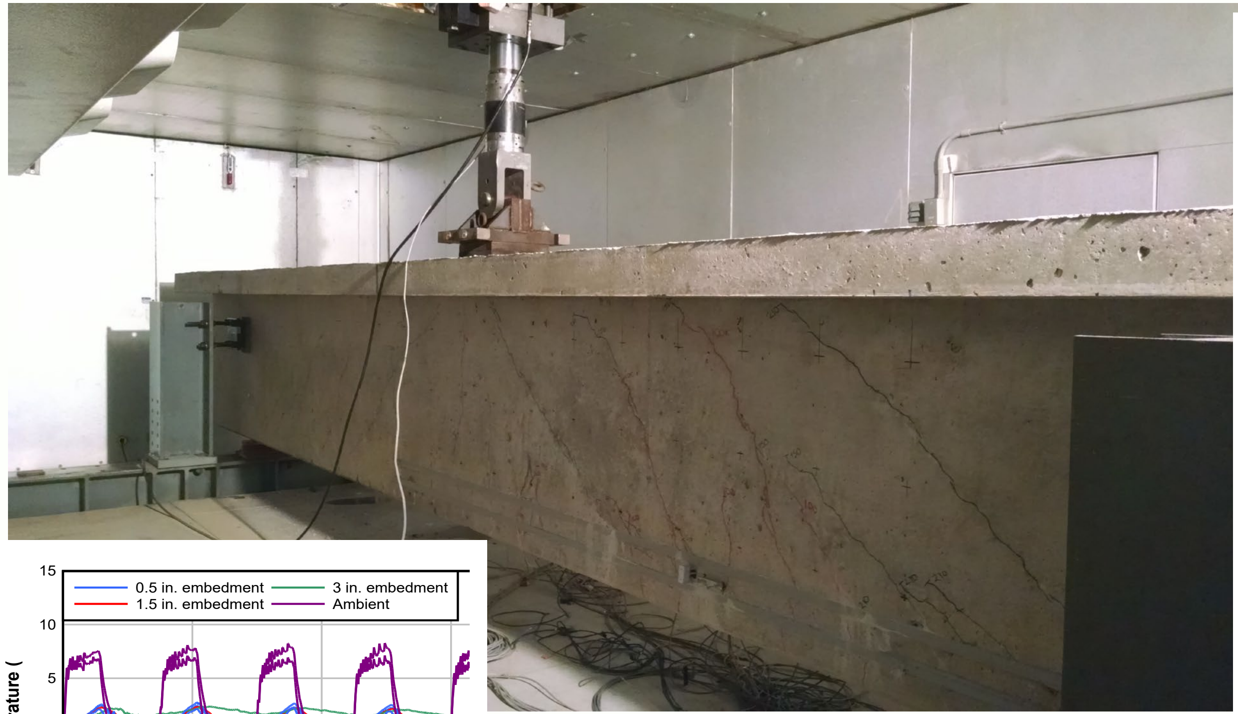
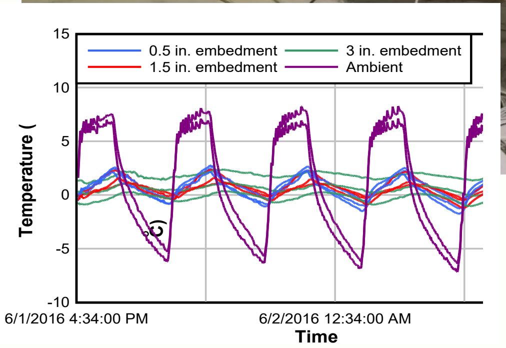
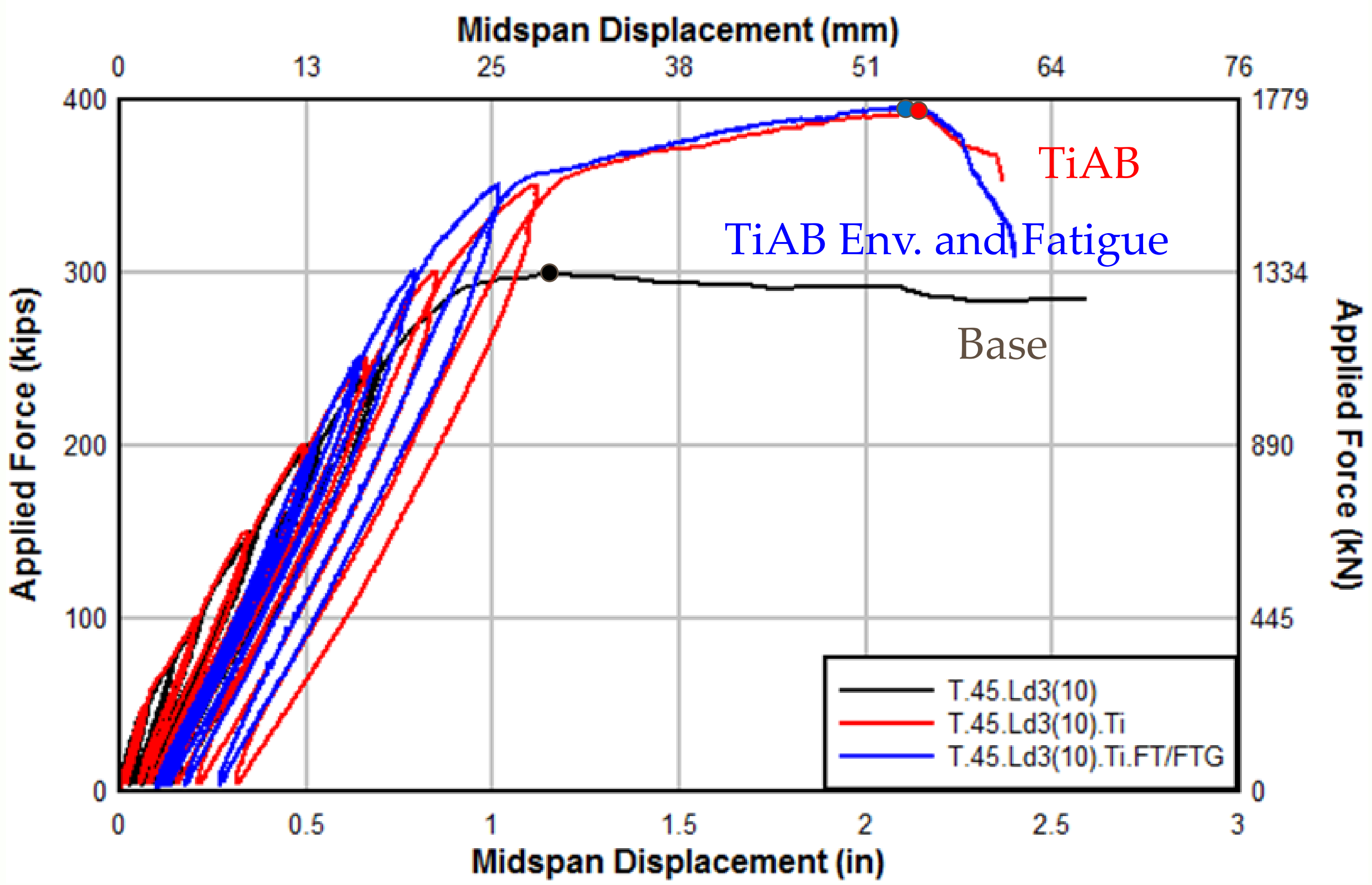
Durability High Cycle Fatigue and Freeze-Thaw Combined

- Largest combined structural-environmental chamber in US
- Thermocouples at 0.5, 1.5, and 3 in. ensure temperature targets
- 1.6 million cycles @ steel stress range >50 years of life.





T Beam Experimental Results – Durability (s=10 in.)



Mosier Overcrossing of Interstate 84

- Built in 1952
- Serves a nearby quarry


Vertical offset
on crack face

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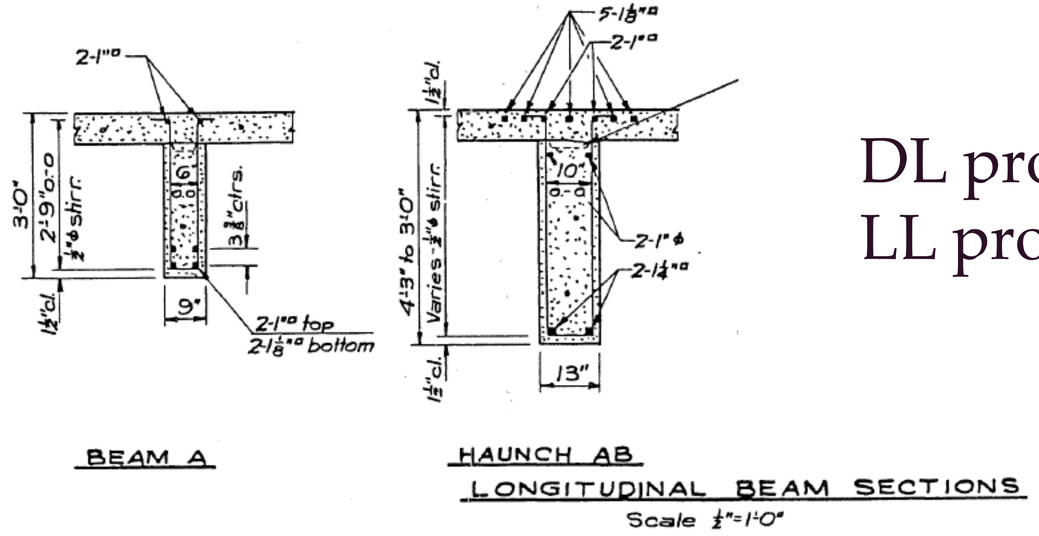
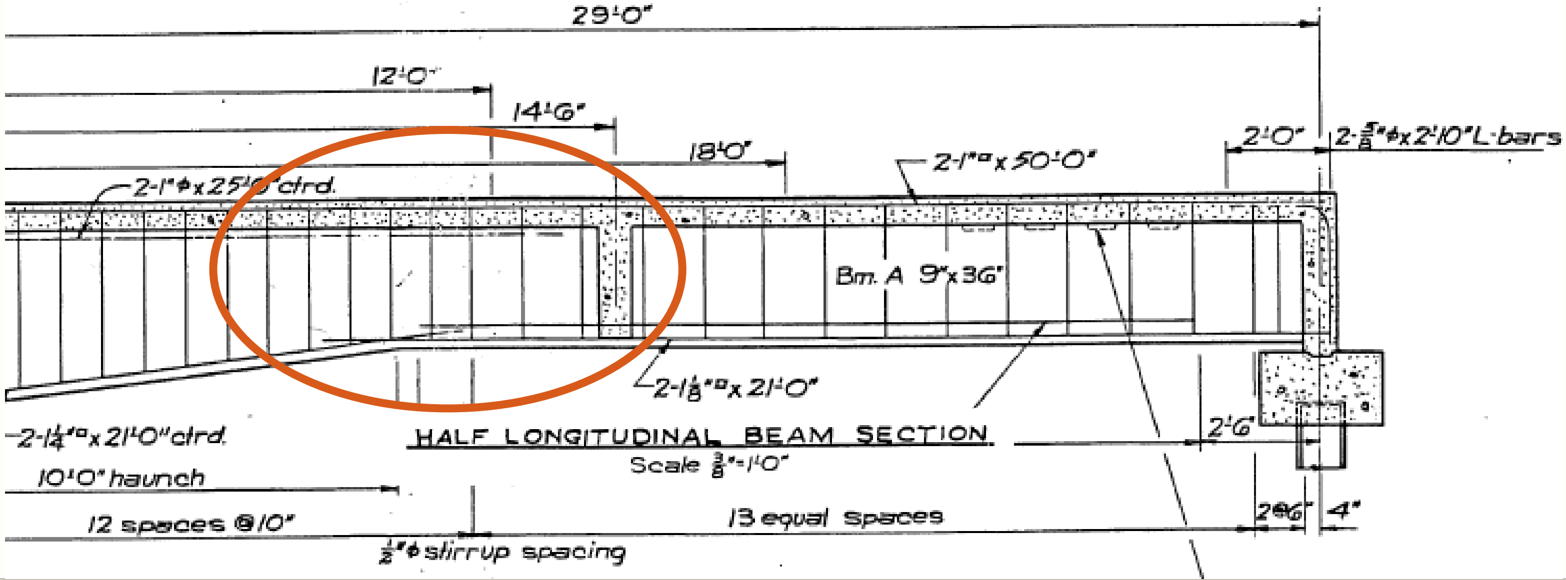
Mosier As-Built Details



DL produces M-

LL produces M+



Test Plan

Three specimens:

1. **Mosier 1**: *As-Built*
2. **Mosier 2**: *Strengthen after failing reinforcing steel anchorage (designer's assumption)*
3. **Mosier 3**: *Strengthen with reinforcing steel anchorage intact*

Searched mill certifications to locate bars that best matched strength curves of original design. Used smaller sized Grade 420 (60) rebar to match development length of intermediate grade steel (280 MPa (40 ksi))

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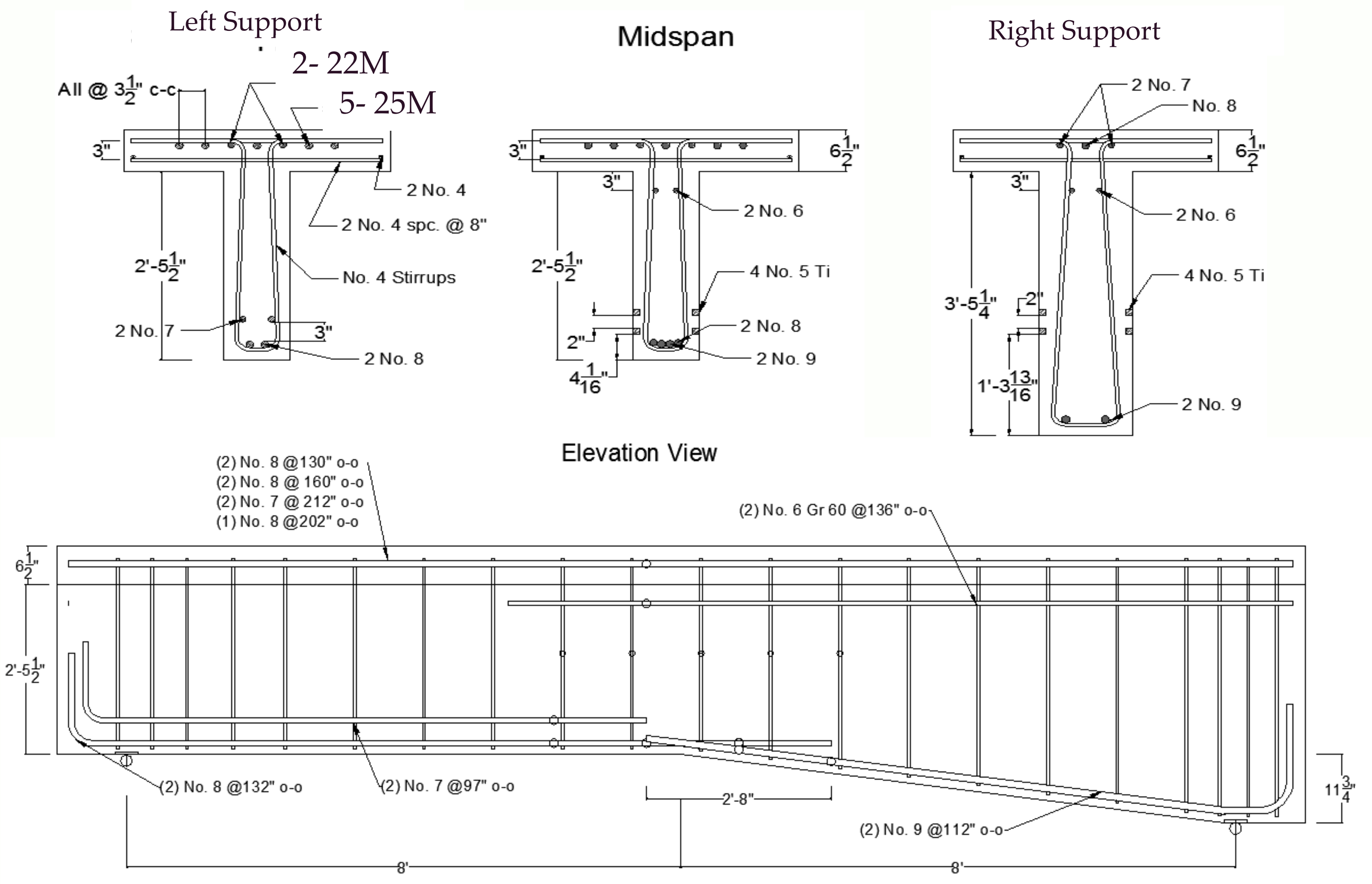
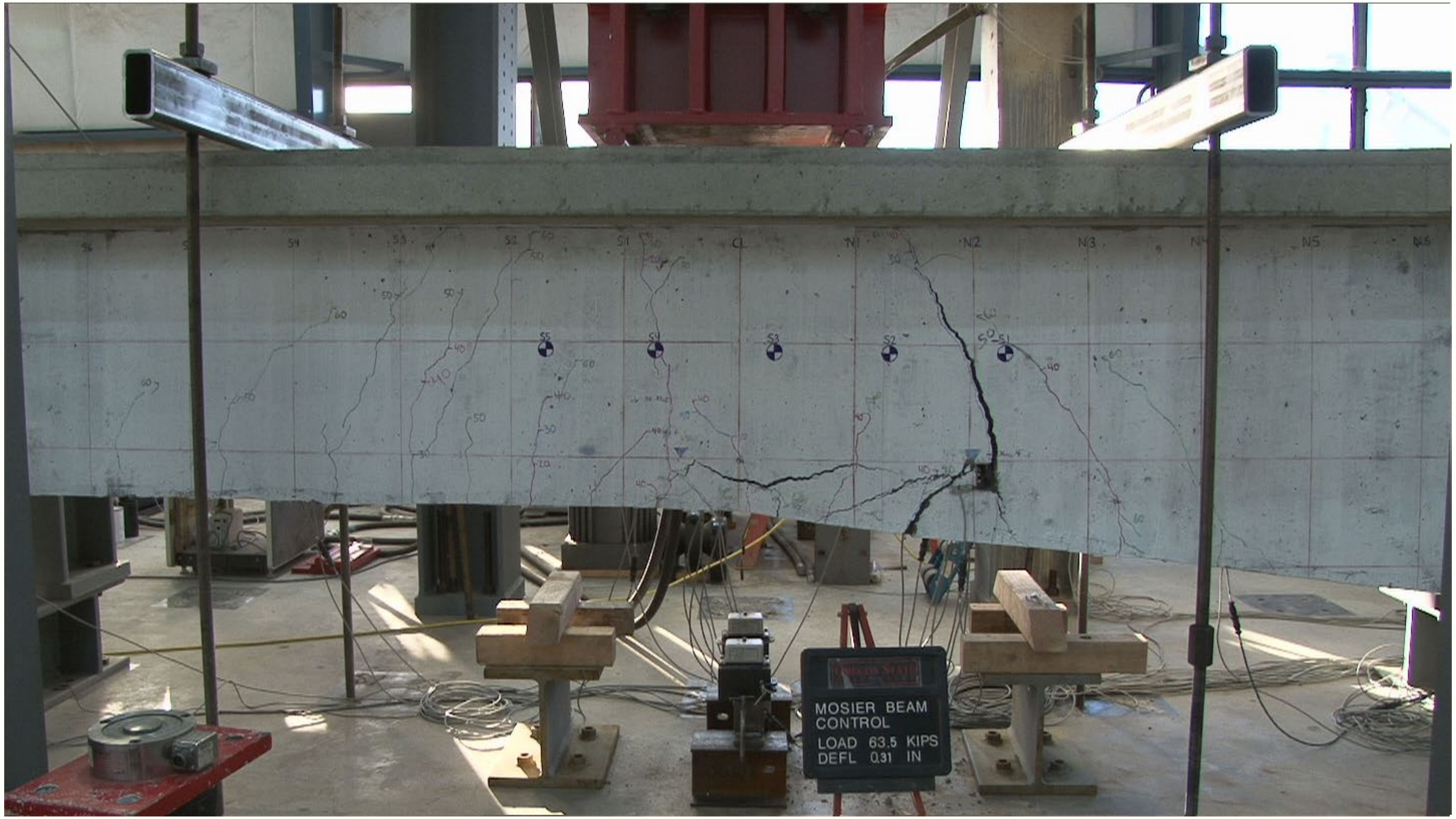
Mosier Beam Details



Experimental Results: Mosier 1



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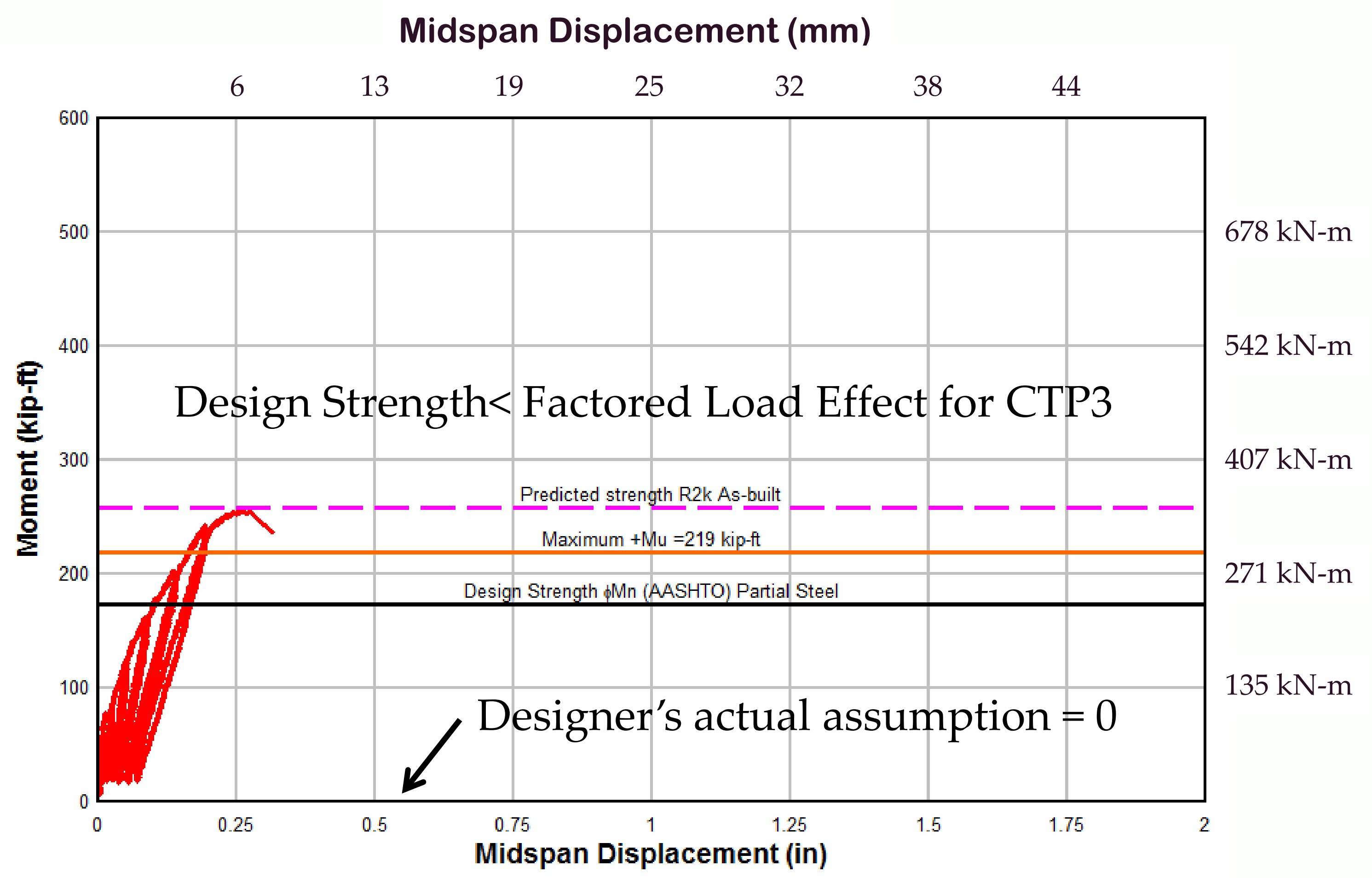
Experimental Results: Mosier 1



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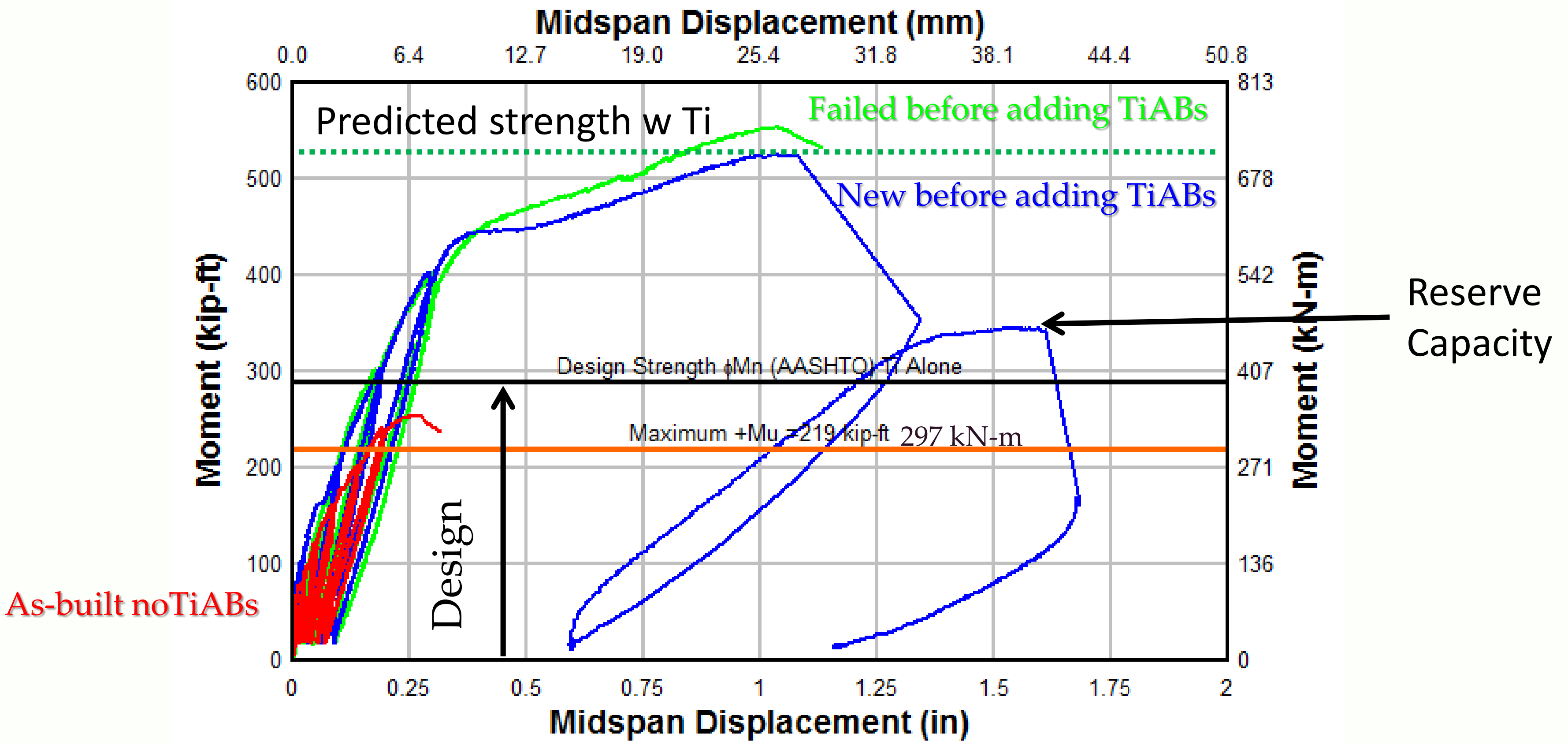
Experimental Results: Mosier 3

Analysis

- Reserve strength of Ti girder substantially exceeds factored demands
- Failed anchorage provided similar response as intact



- Design strength of Ti girder exceeds factored demands even with conservative assumptions

30% less expensive than CFRP

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ASTM Specification - Approved Nov. 2018

Main Committee: Committee B10 – Reactive and Refractory Metals and Alloys
Sub-Committee B10.01 on Titanium

INTERNATIONAL

Designation: B1009 – 18

Standard Specification for Titanium Alloy Bars for Near Surface Mounts in Civil Structures[1]

This standard is issued under the fixed designation B1009; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers titanium alloy bars with surface deformations and 90-degree anchorage hooks for use as near surface mounts for flexural and shear strengthening of concrete beams. The product can be furnished with or without anchorage hooks as specified by the purchaser. If supplied without hooks, the hooks shall be bent on-site prior to installation, as this method requires two 90-degree anchorage hooks.

1.2 The values stated in inch-pound units are to be regarded

D7913/D7913M Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing

E8/E8M Test Methods for Tension Testing of Metallic Materials

E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications

E539 Test Method for Analysis of Titanium Alloys by X-Ray Fluorescence Spectrometry

E1409 Test Method for Determination of Oxygen and Nitro-

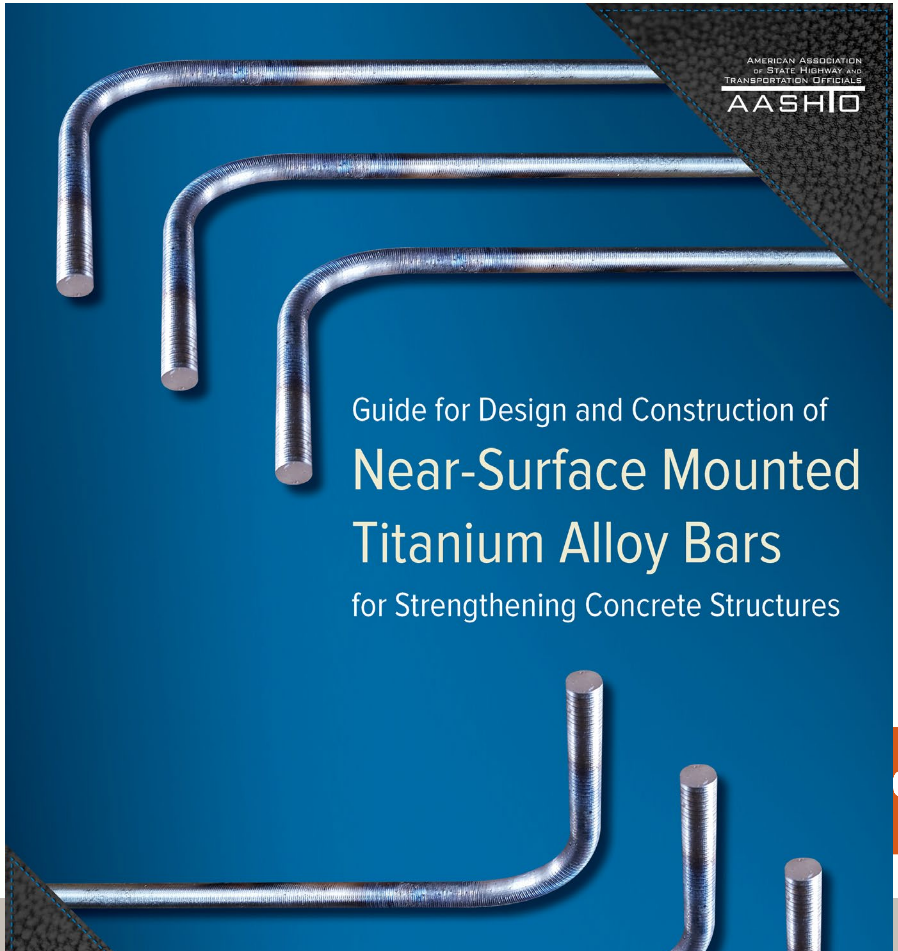
ASTM B1009-18 Requirements:

- Tensile properties
- Chemical requirements
- Bond strength
- Cross-Sectional area calculation
- Bending requirements

ASTM INTERNATIONAL
Standards Worldwide

AASHTO Design Guide Approved COBS 2019

- **“Guide for Design and Construction of Near-Surface Mounted Titanium Alloy Bars for Strengthening Concrete Structures”**
- AASHTO-LRFD Format
- General Conditions
- Materials
- Construction
- Installation
- Design
  - Flexure and Shear (MCFT)



Design Guide

- Conventional analysis methods
- Design TiABs at yield if conditions are met
- Includes environmental durability factor (epoxy)
- 3 Limit states for flexure and 1 for shear
  - Strength
  - Service (check bond stress at cutoffs and where retrofitted strength above base capacity)
  - Fatigue (not of TiAB but of reinforcing steel)
- Comprehensive design example (shear and flexure)

Conclusions

Titanium Alloy Bars (TiABs)

- Well-defined material properties
- High strength
- Ductility
- Environmental durability
- Ability to fabricate mechanical anchorages
- Cost effective ($200k project, $17k Ti, $19k Epoxy!!)
- Ten Bridge in OR…

These attributes make the Ti-6Al-4V alloy reinforcement a promising material for economically strengthening bridges and other structures.

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Acknowledgements

- Oregon Department of Transportation
  - Bruce Johnson, TACs, and Research group
- Perryman Company, Houston, PA
- Undergraduate Research Assistants: Kyle Logan, Jonathon Roy, Aléxia Ribeiro, Lance Parson, Hunter Anderson, Kyle Sonnevile, John Huntoon, Glen Galant, Corey Groshong, James Kemp, and Spencer Maunu

The findings and conclusions are those of the author and do not necessarily reflect those of the project sponsors or the individuals or companies acknowledged.

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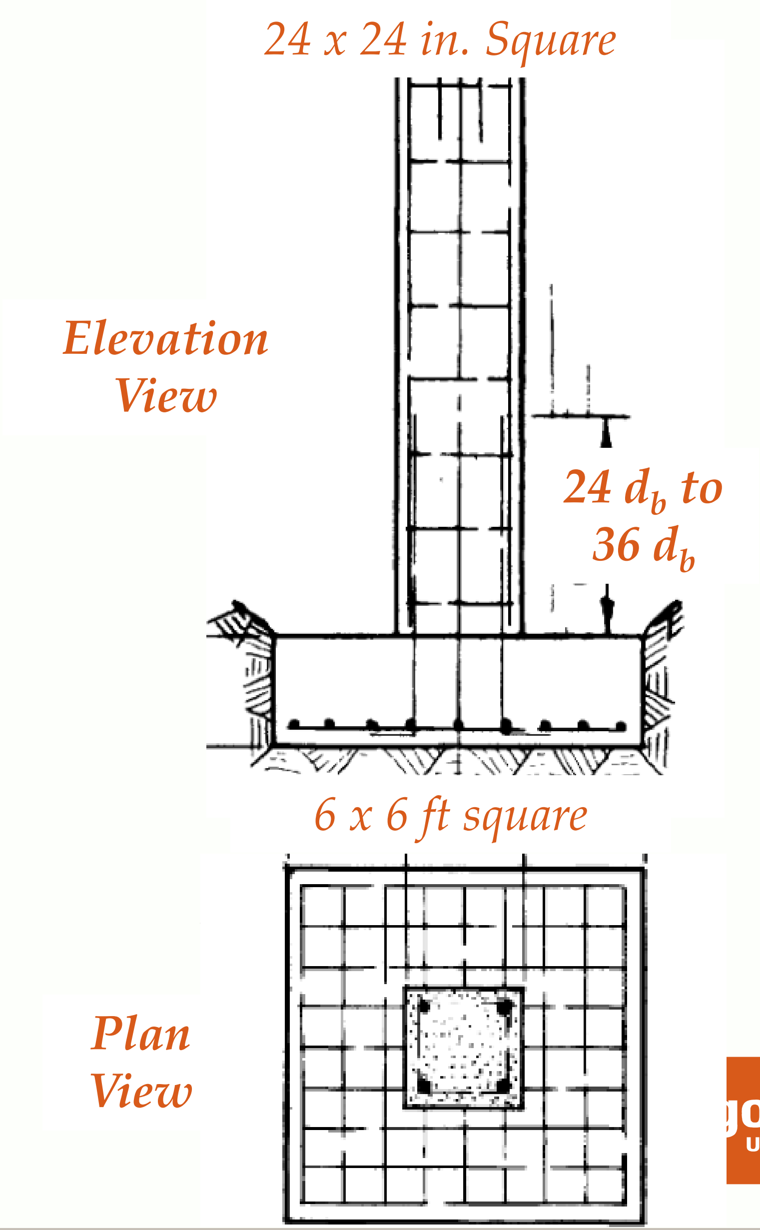
Seismic Deficiencies of pre-1970's columns

- Insufficient transverse reinforcement
  - #3 a@ 12 in spacing
- Common design details:
  - Lap-splice lengths of 24 d_b to 36 d_b
  - Large bar sizes (> #11; square and round)
  - Longitudinal rebar placed at column corners
  - Grade 40 steel (275 MPa)
  - f'_c = 3300 psi (22.7 MPa)



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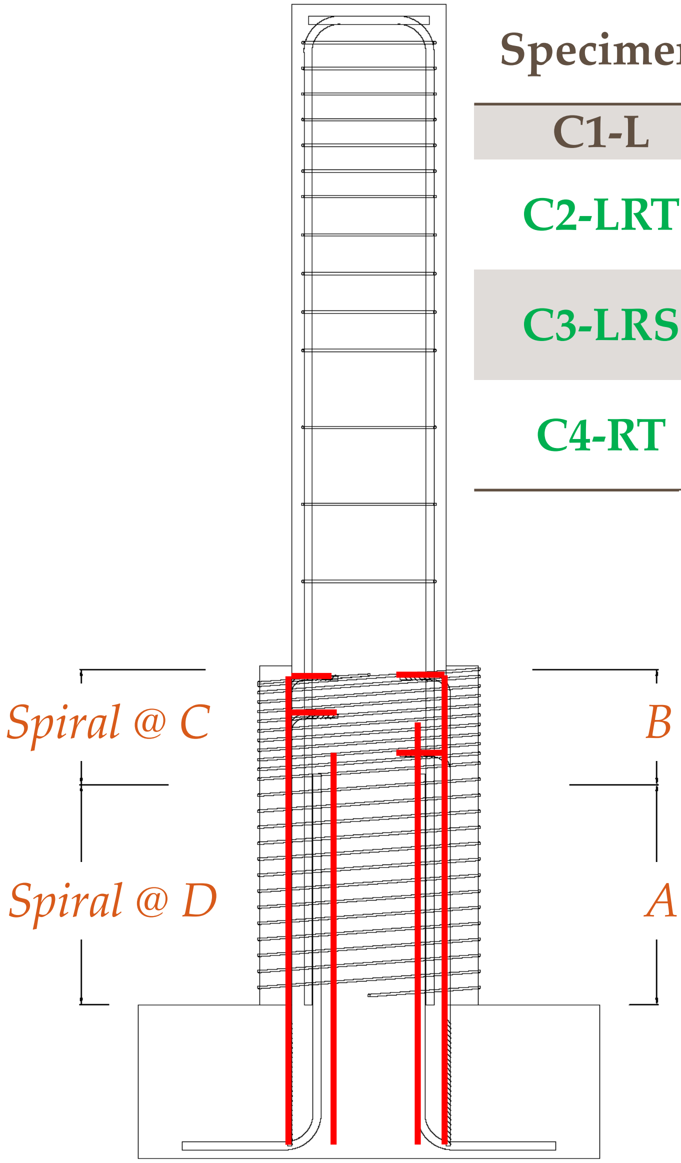
Common Approach for Retrofitting

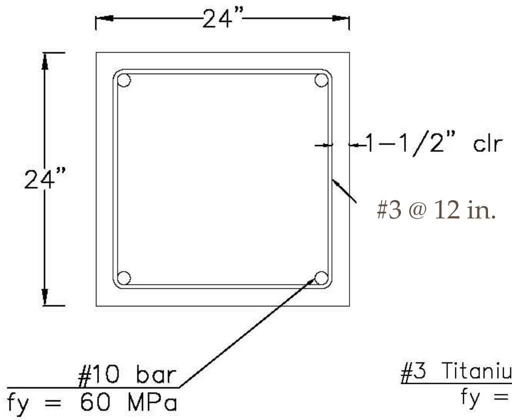
Fiber reinforced (FRP) laminates (Confinement)

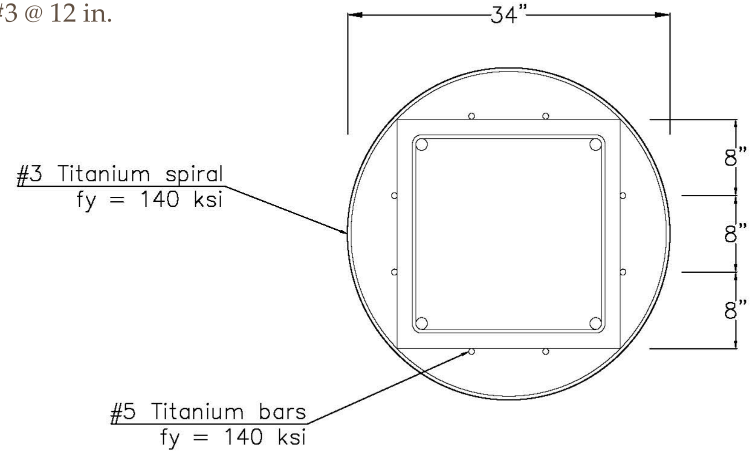
- High-strength
- Surface preparation
- Non-ductile
- Degradation concerns
- Not inspectable

Seismic Performance



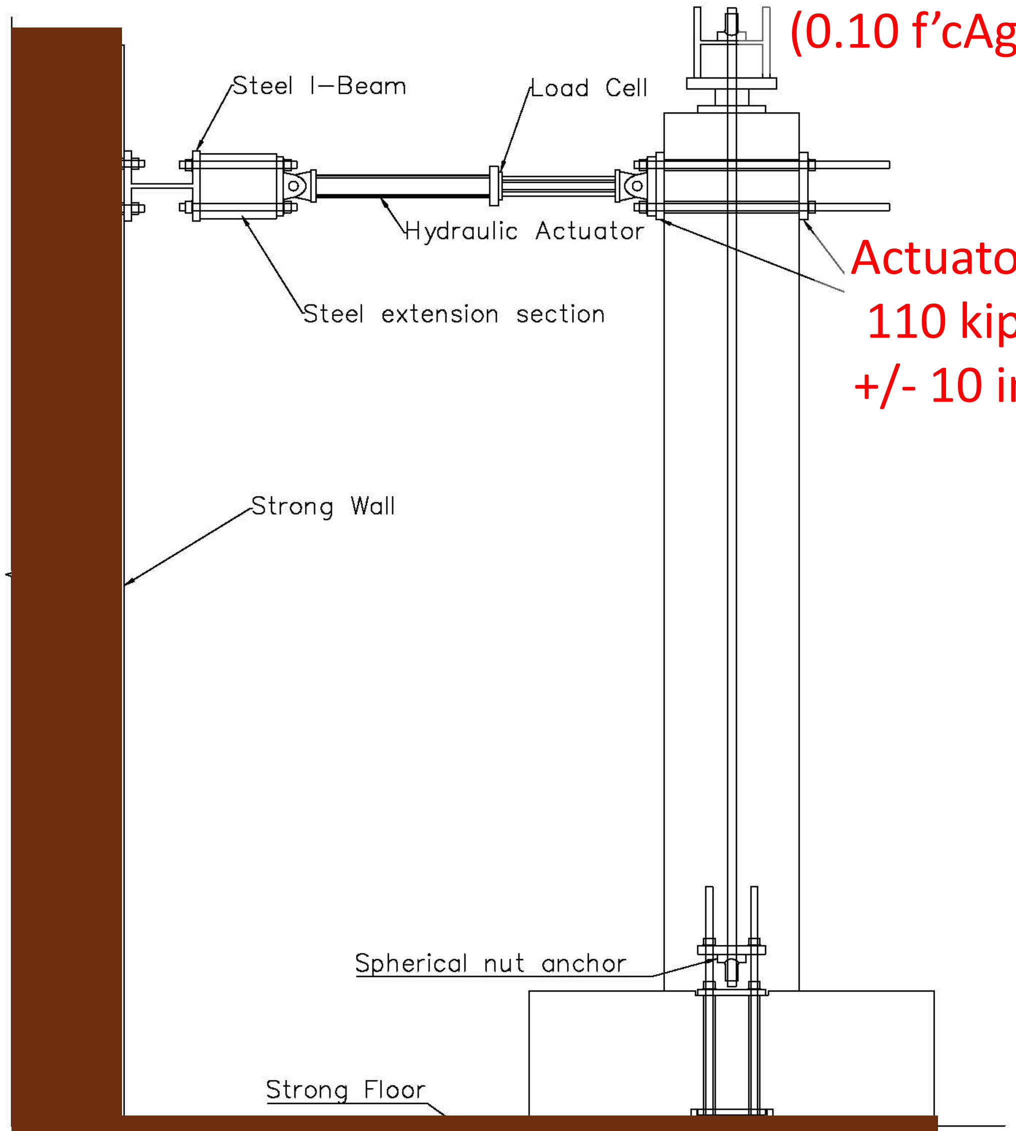
Specimen	Detailing	A (-)	A + B (-)	C (in)	D (in)
C1-L	Lap-splice	$L_s = 29\ d_b$	-	-	-
C2-LRT	Lap-splice + Titanium	$L_s = 29\ d_b$	$1.67\ L_s$	1.5	3
C3-LRS	Lap-splice + Titanium	$L_s = 29\ d_b$	$1.50\ L_s$	1.5	2.5
C4-RT	~~Lap-splice +~~ Titanium	-	$1.67\ L_s$	1.5	3





Experimental Set-Up

Axial load
200 kip
(0.10 f’cAg)



Elevation View

Actuator
110 kip
+/- 10 in

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TiAB Spiral Reinforced Concrete Shell

- Continuous spiral
- Debonded shell from column with plastic sheet
- Flexible polycarbonate sheet formwork
- Ratchet strap drawn tight to TiAB spiral (no cover) and holds form
- See-through, so know completely filled

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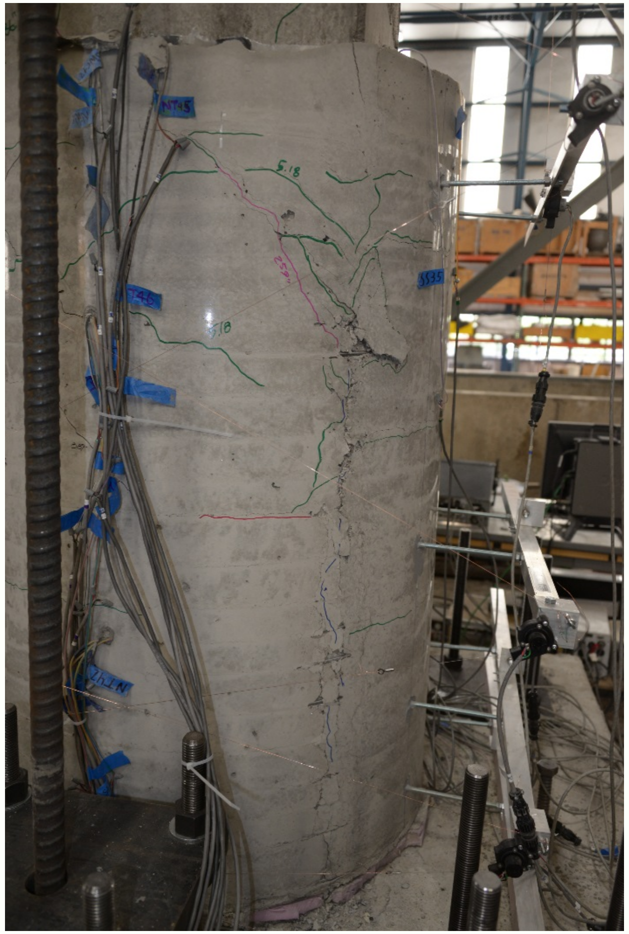
Control Specimen: Observed Performance

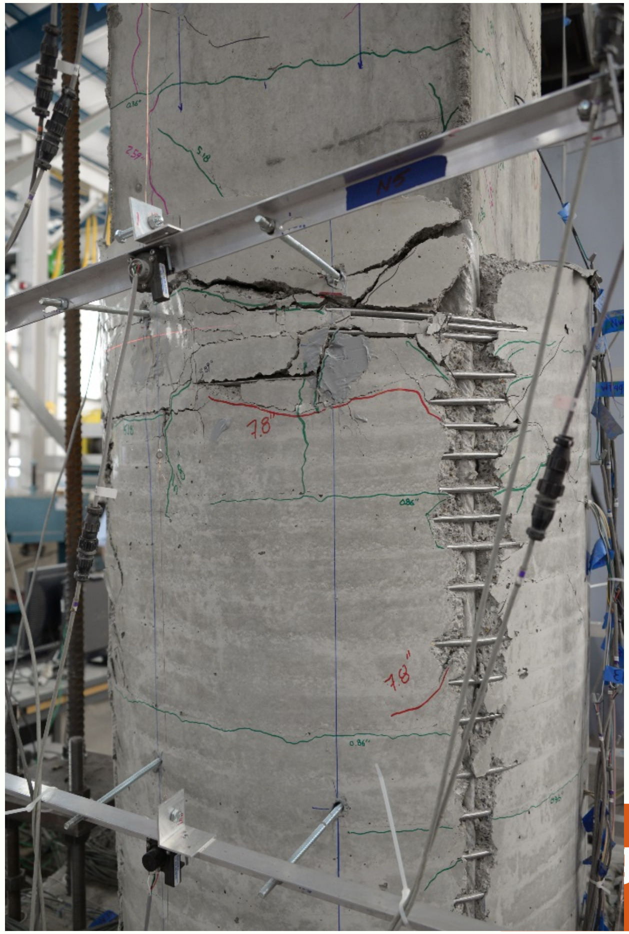
Progression of lap-splice exposure and bond-slip

- Lap-splice failure -> rapid flexural strength degradation
- Severe spalling
- Non-ductile

Titinium Observed Performance

Retrofitted specimens: corner spalling progression





Observed Performance

Retrofitted specimens with lap splices (similar performance):

- Ductile withdrawal of hooked anchorages
- Footing concrete spall cones
- Rocking column behavior

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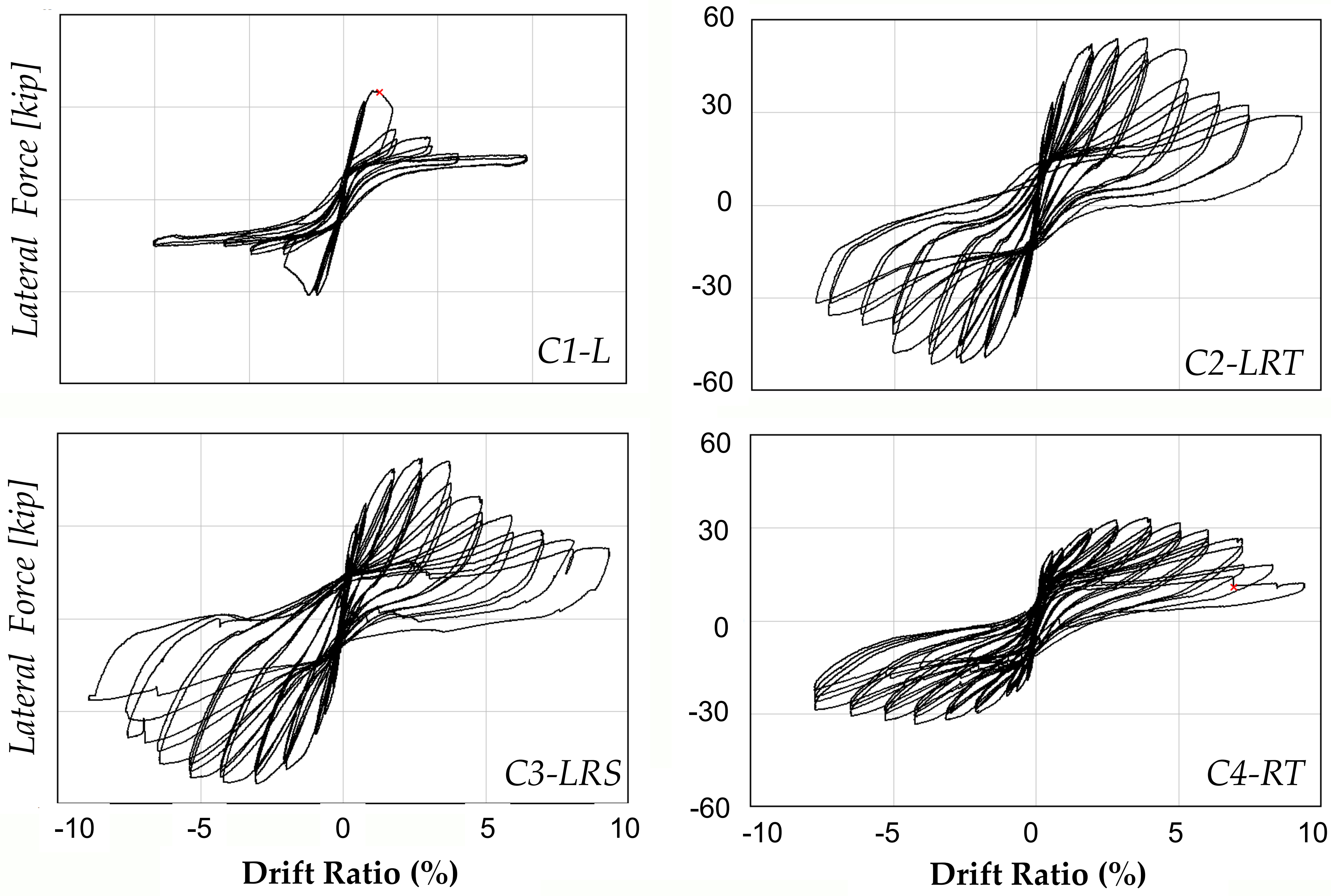
Load-Deformation Response



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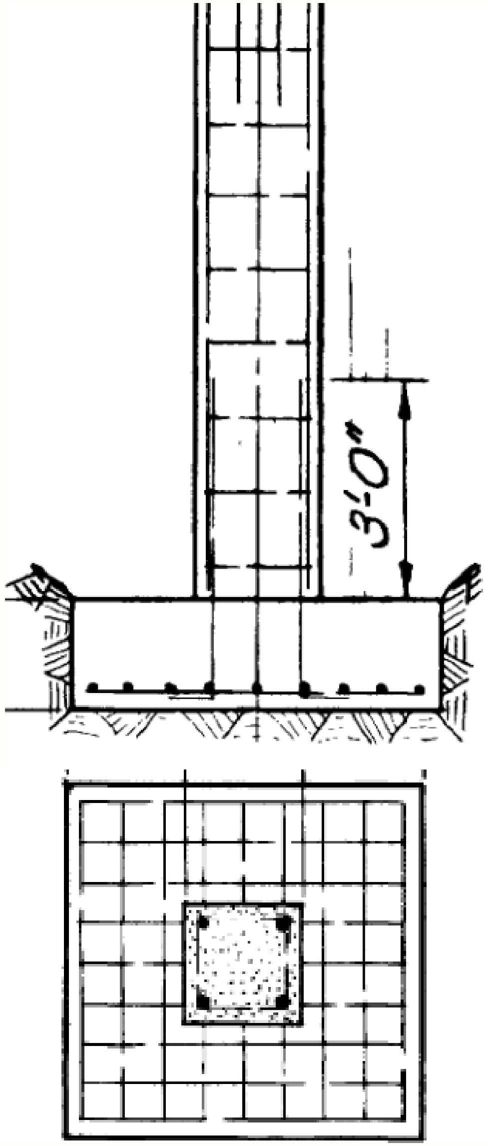
Fuse Seismic Forces Imparted on Footing

- Spread footing
- Timber pile



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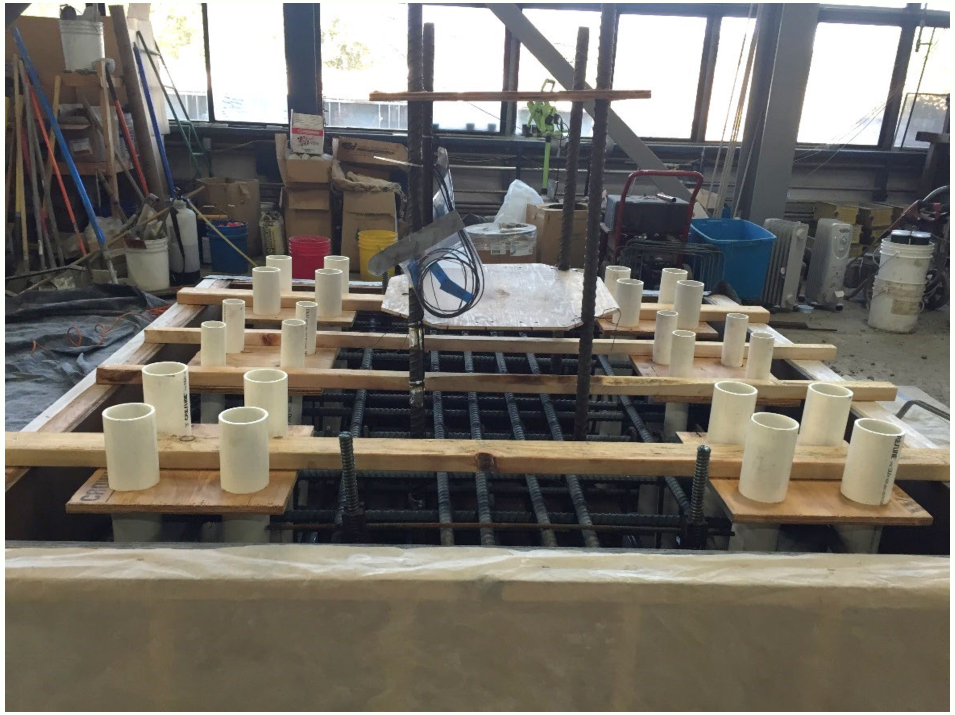
Experimental Tied Footing Details



Force column failure

But do not reflect in situ details or reactions

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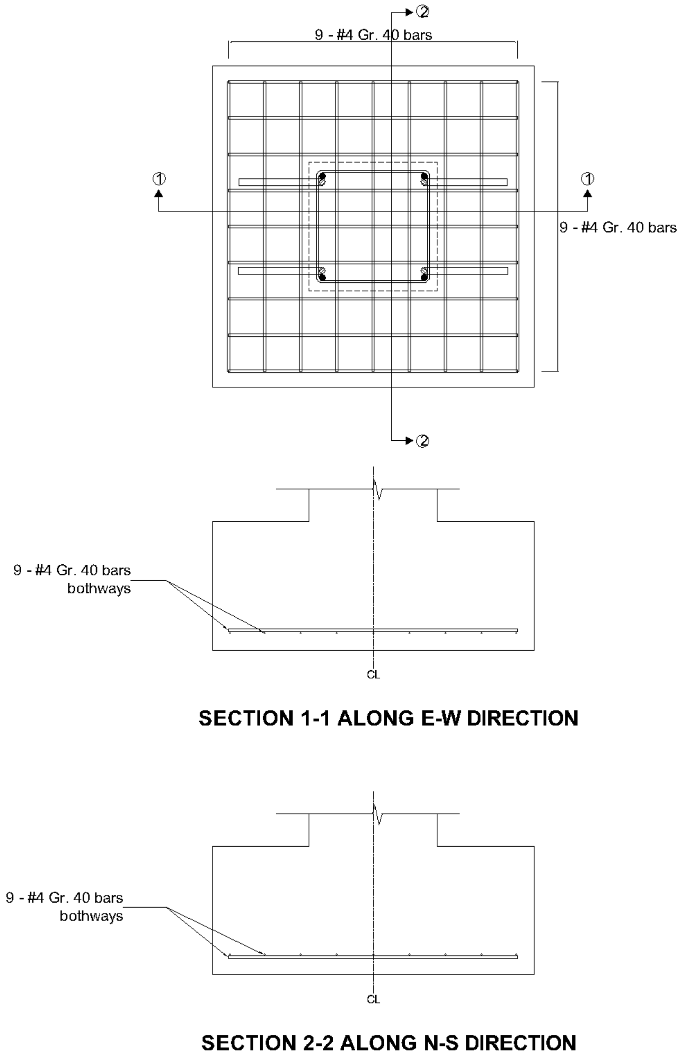
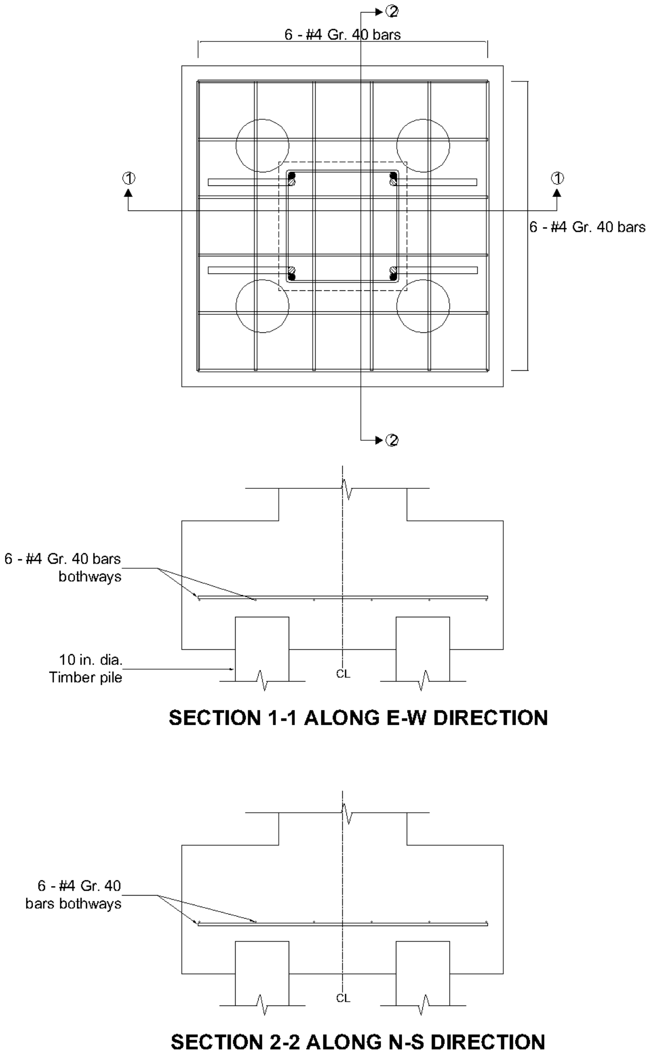
Typical Footing Details

Typical Spread Footing



Typical Timber Pile Footing



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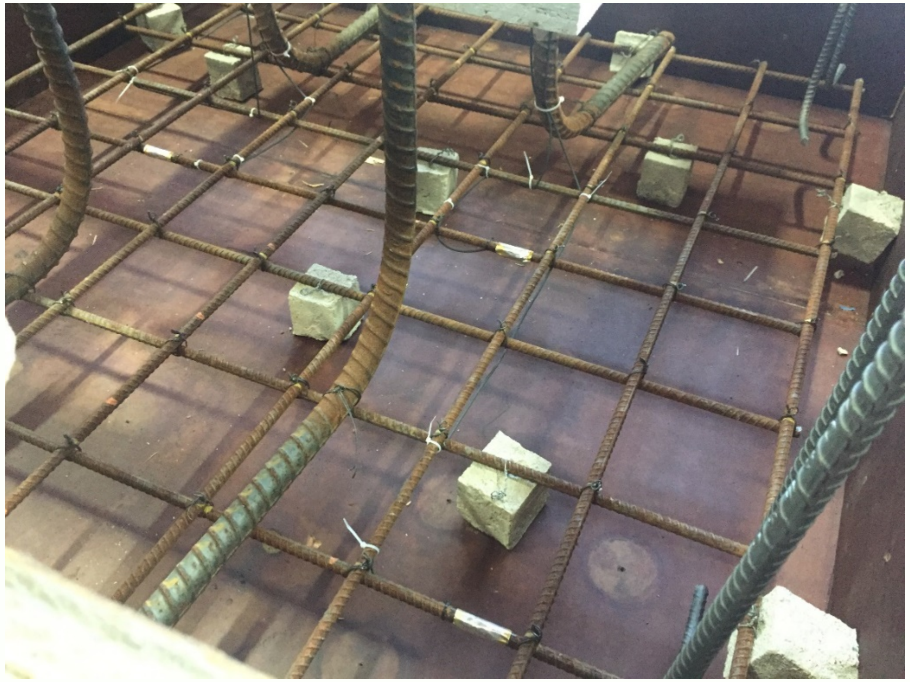
Typical Footing Details

Typical Spread Footing



Typical Timber Pile Footing

Final 2 specimens

Conclusions

Titanium's

- Well-defined material properties
- High strength
- Ductility
- Environmental durability and
- Ability to fabricate mechanical anchorages

make the Ti-6Al-4V alloy reinforcement a promising material for economically strengthening bridges for gravity loads and achieving high seismic performance of poorly detailed bridge columns.

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Acknowledgements

- Oregon Department of Transportation
- Perryman Company, Houston, PA
- Undergraduate Research Assistants: Kyle England, Brandon Zaikoski, Caleb Lennon, Liam Kucey, Tyler Redman, Anthony Quinn, and Jonathan Roy

The findings and conclusions are those of the authors and do not necessarily reflect those of the project sponsors or the individuals or companies acknowledged.

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