

# Designing with Titanium for Strengthening Reinforced Concrete Bridges

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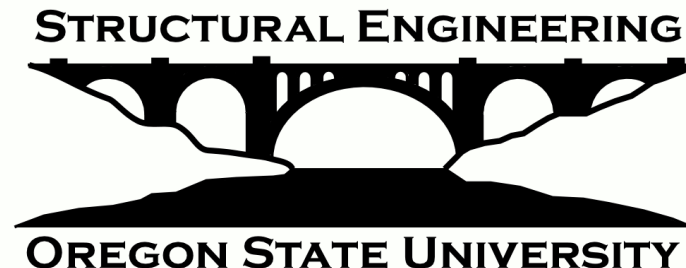
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# Overview

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

# Introduction

## During the 1950 and 60's:

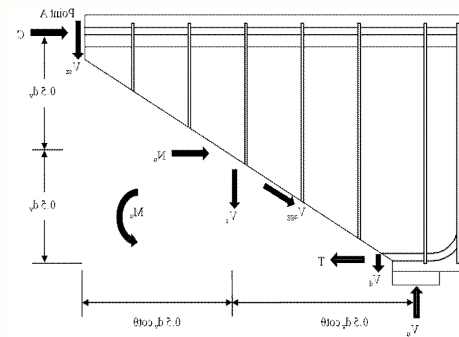
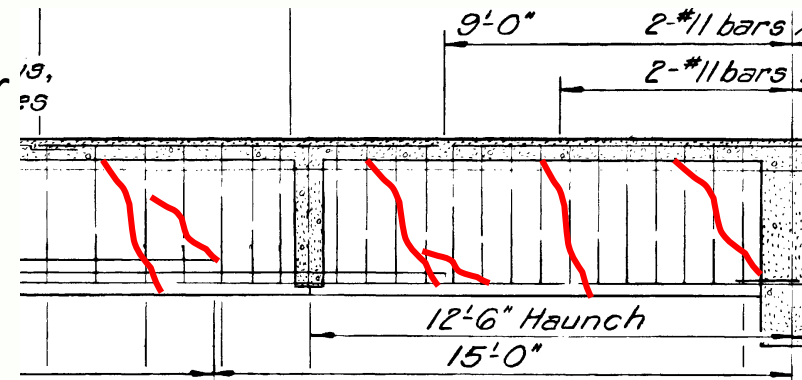
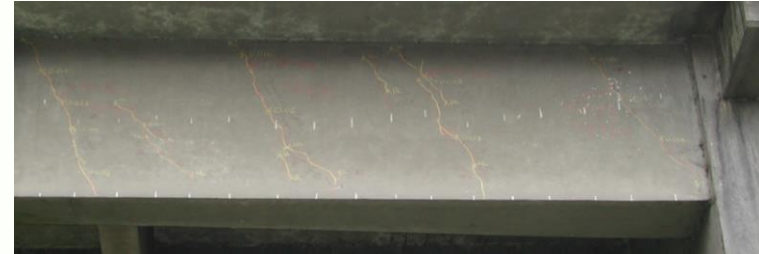
- Post-war construction boom
- Reinforced concrete widely used
- Newly standardized deformed reinforcing steel bars produced poor details
- Design codes were not conservative

## Now:

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

## Results:

- Replace, limit loads, retrofit



# 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

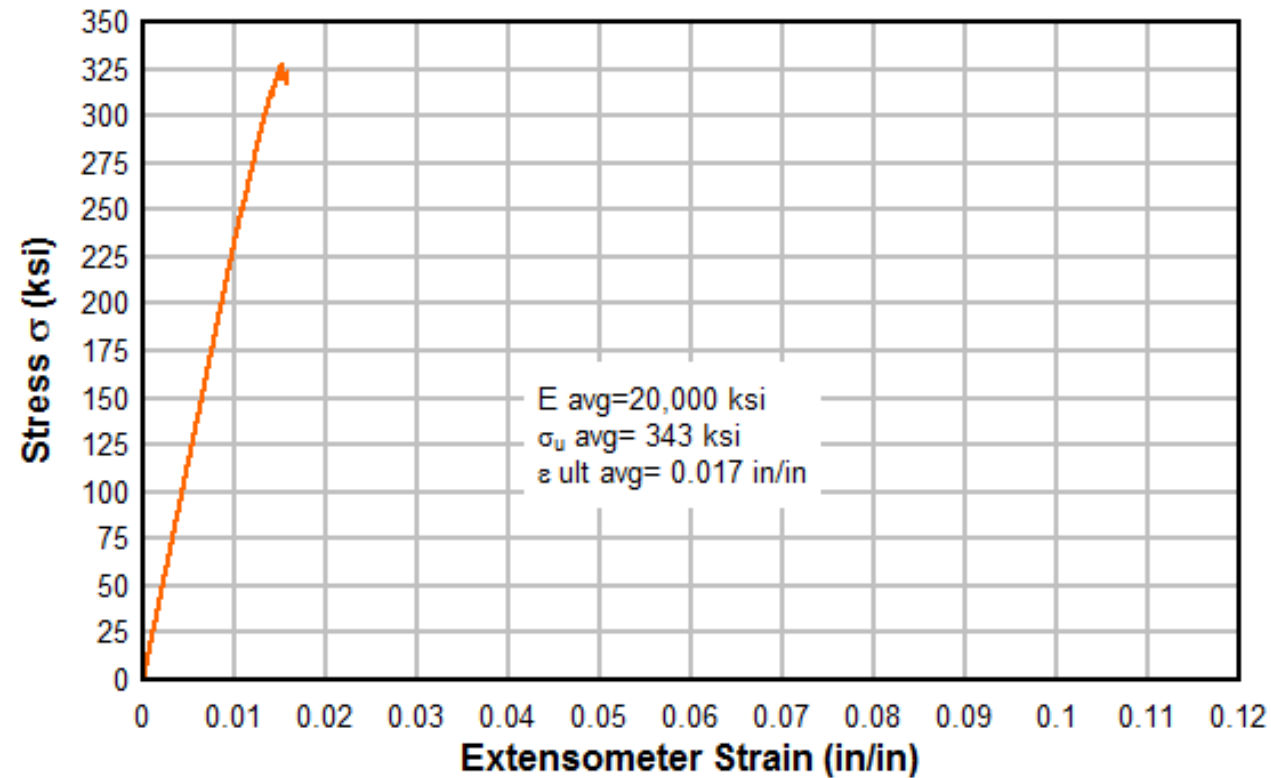
***FRP rods and laminates fail due to bond and anchorage and materials are nonductile***

***Concerns with corrosion at surface for most metals***



# Background: NSM Strengthening Materials

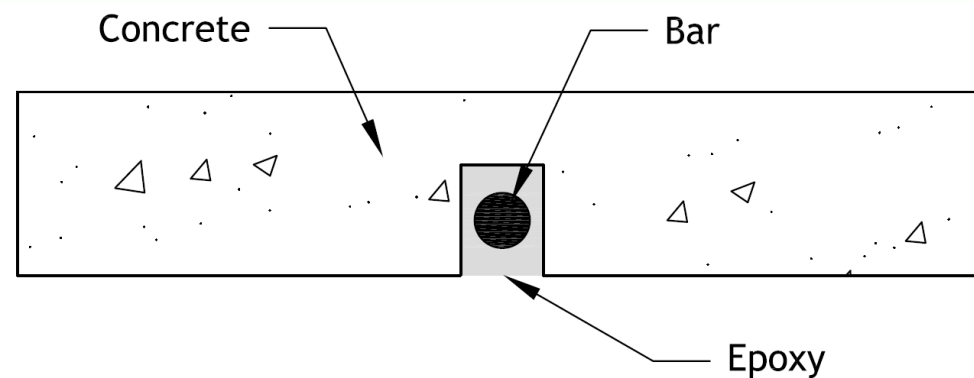
## Carbon Fiber Reinforced Polymer (CFRP)



## CFRP Bond Failure – Limits material strength



# Near-Surface Mounting





# 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 Alloy**  
**Ductile FRP**

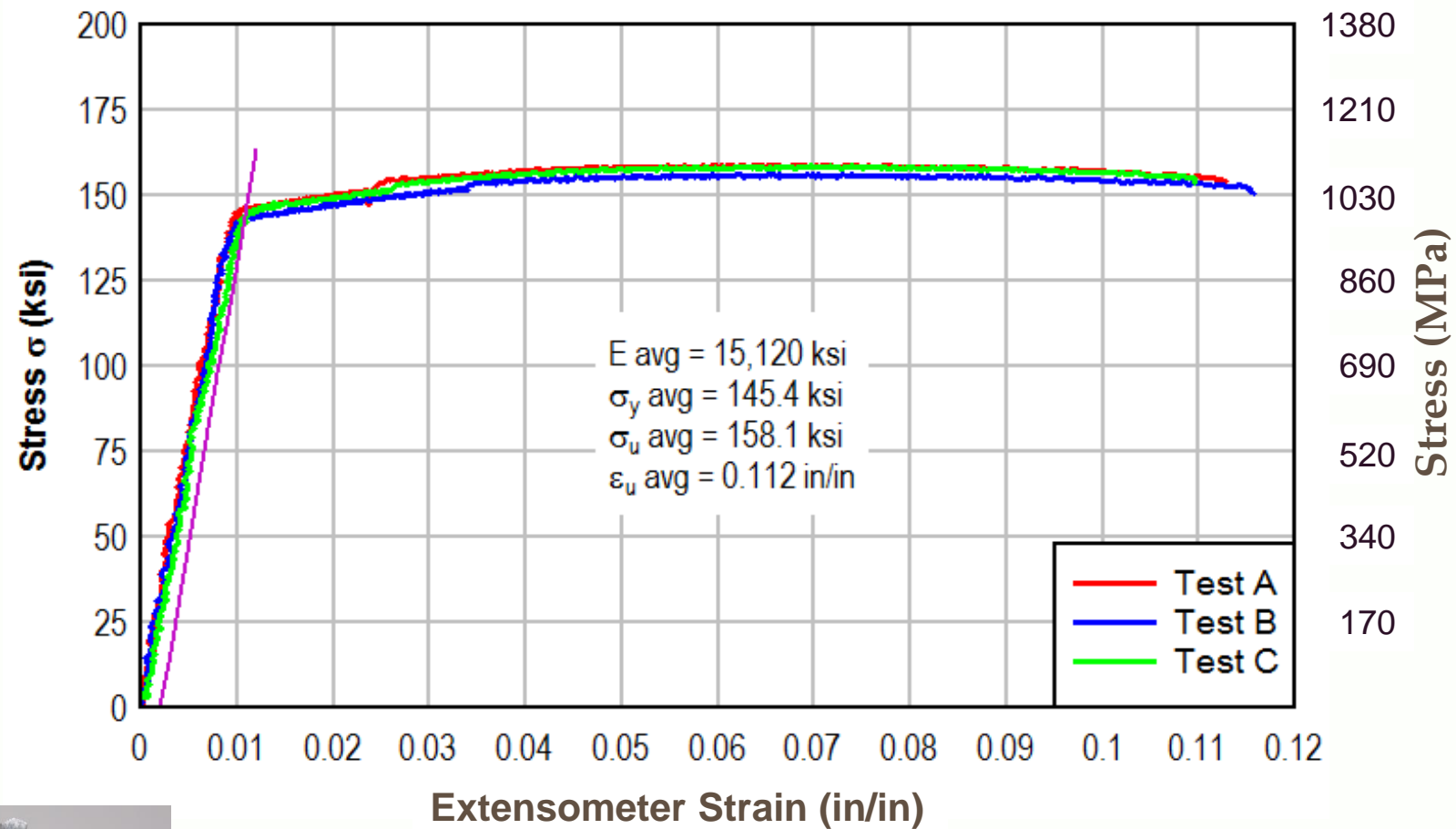
**Titanium?**

**No one uses titanium in  
structural engineering!**

**It is too expensive...**

**It's only for aircraft or  
medical devices....**

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

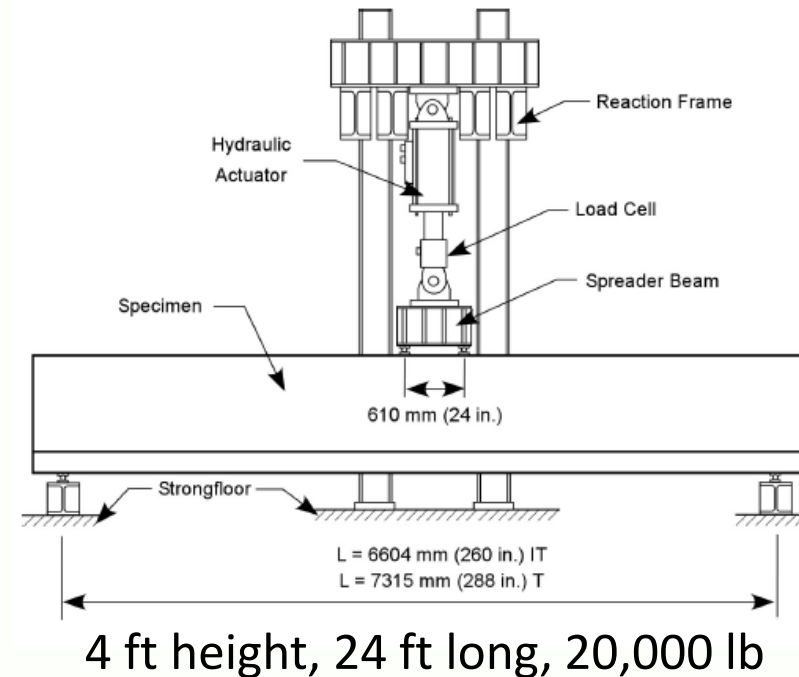


# Titanium Alloy Material Properties (Ti-6Al-4V)

- **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** ( $8.6\mu\epsilon/^{\circ}\text{C}$ ) (8-12 Con. and 12 St.)
- **Conventional fabrication** (shear, cut, and bend)
- **Relatively lightweight** of 281 lb/ft<sup>3</sup> (steel 1.7x)
- **Bends facilitate anchorage**

# 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)





## Epoxy Properties

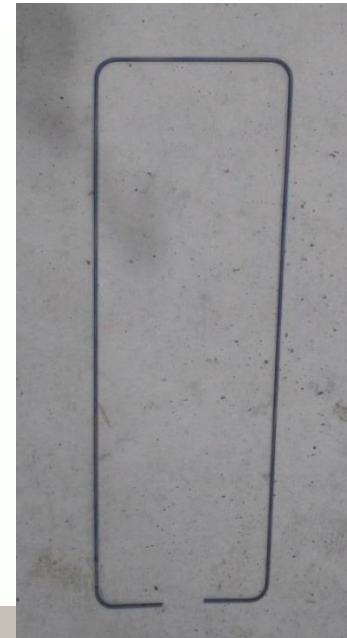
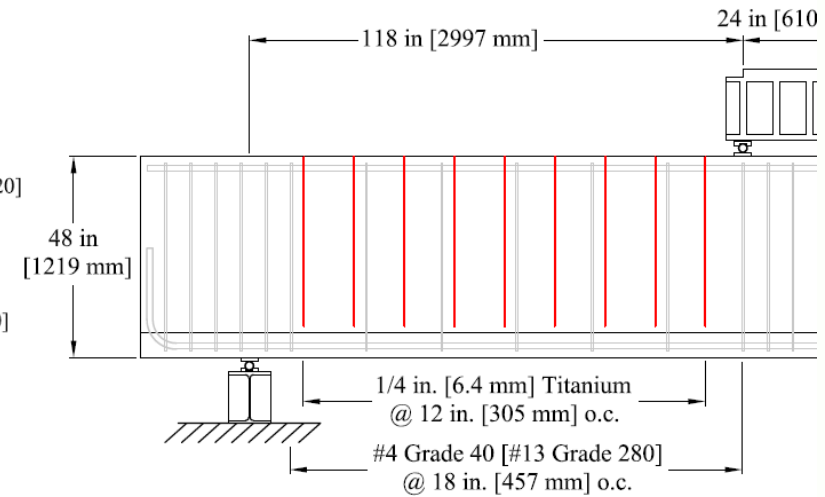
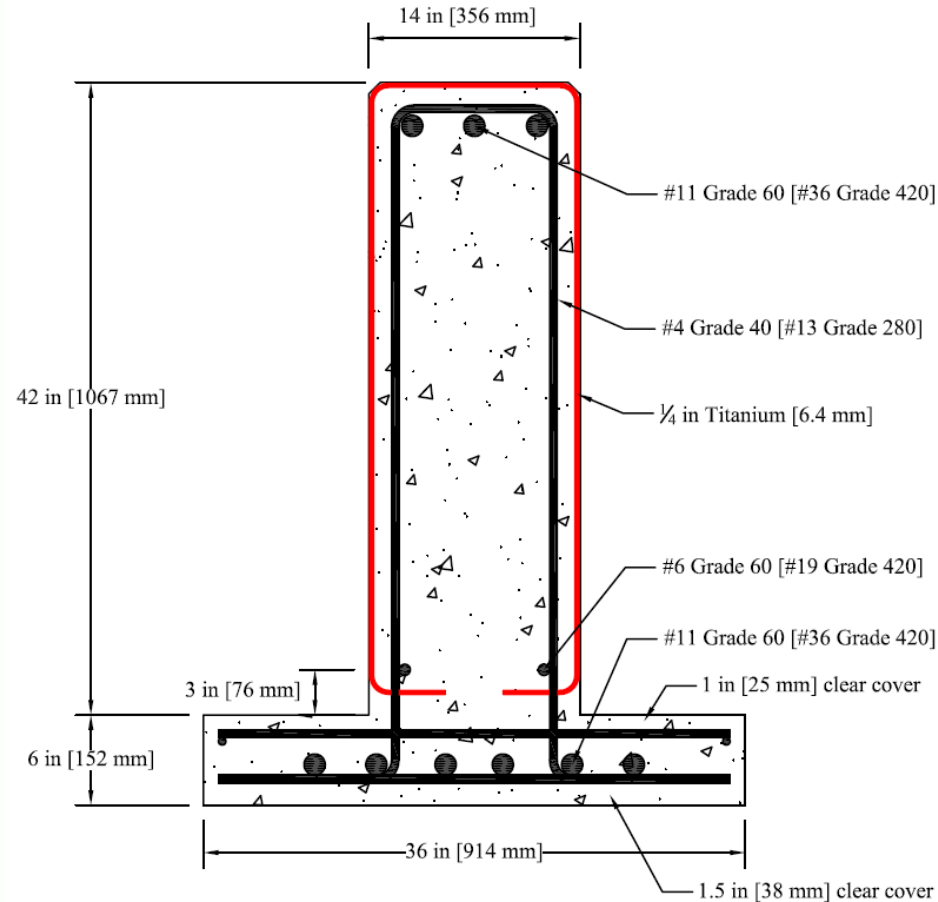
BASF MasterEmaco ADH 1420: Bond = 2000 psi

Unitex Pro-Poxy 400: Bond = 2800 psi

Hilti HIT-RE 500 V3: Bond = 1700 psi



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



## Shear : Installation



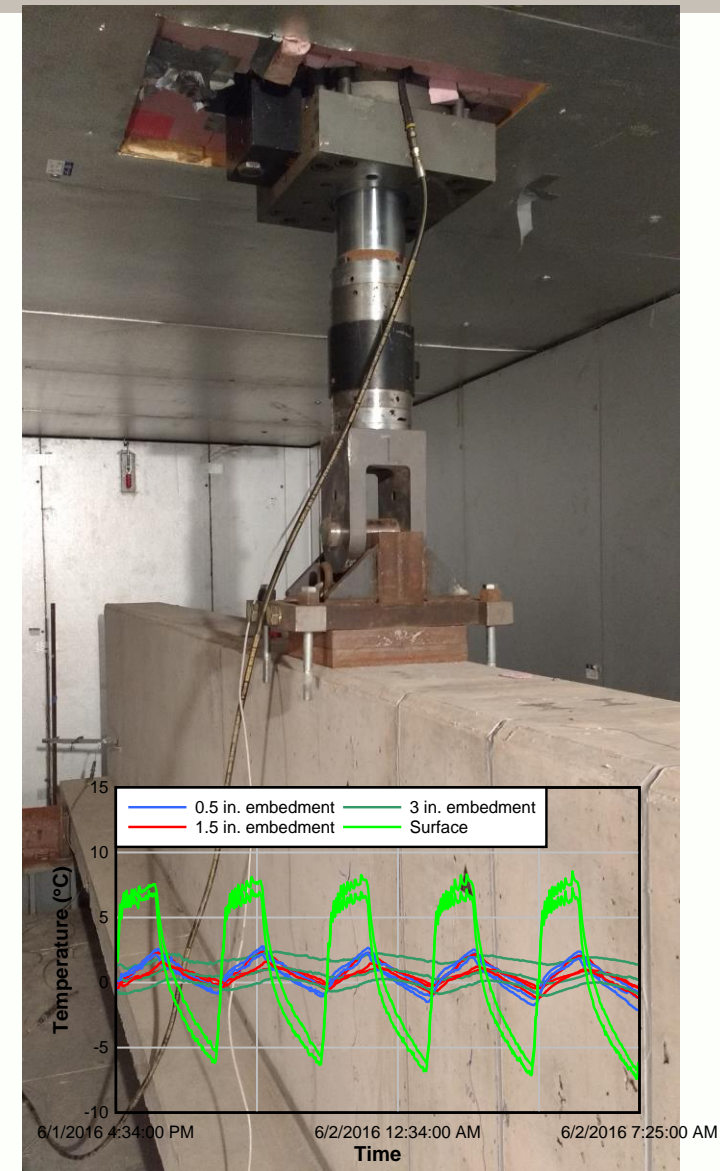
## Shear : Fatigue with Freeze-Thaw

- 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

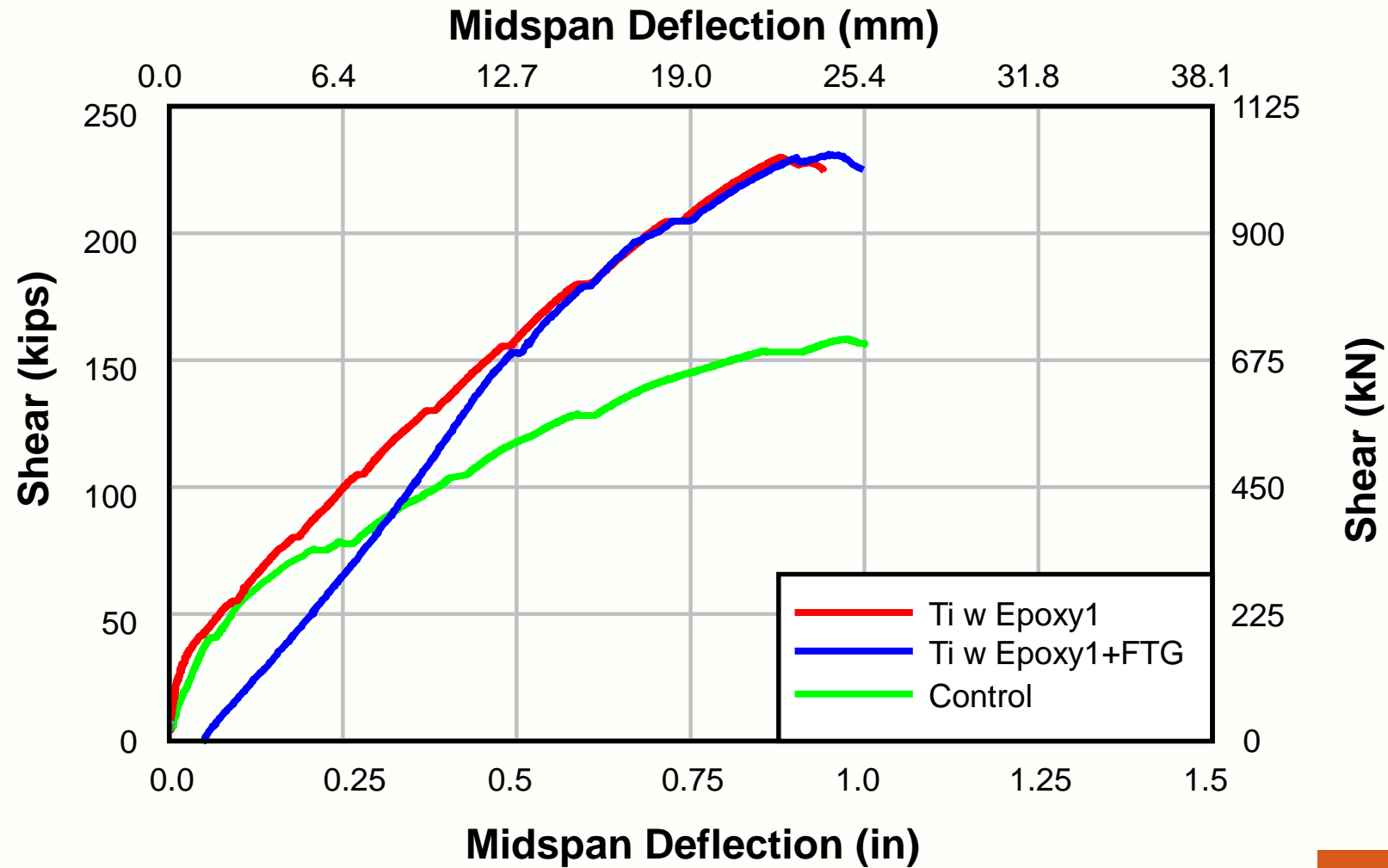




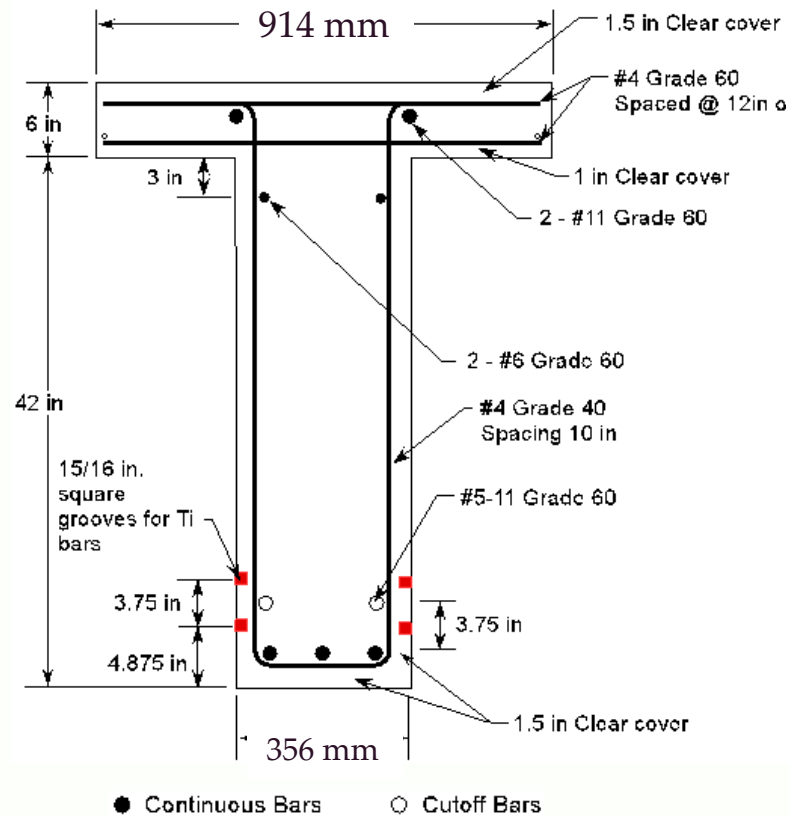




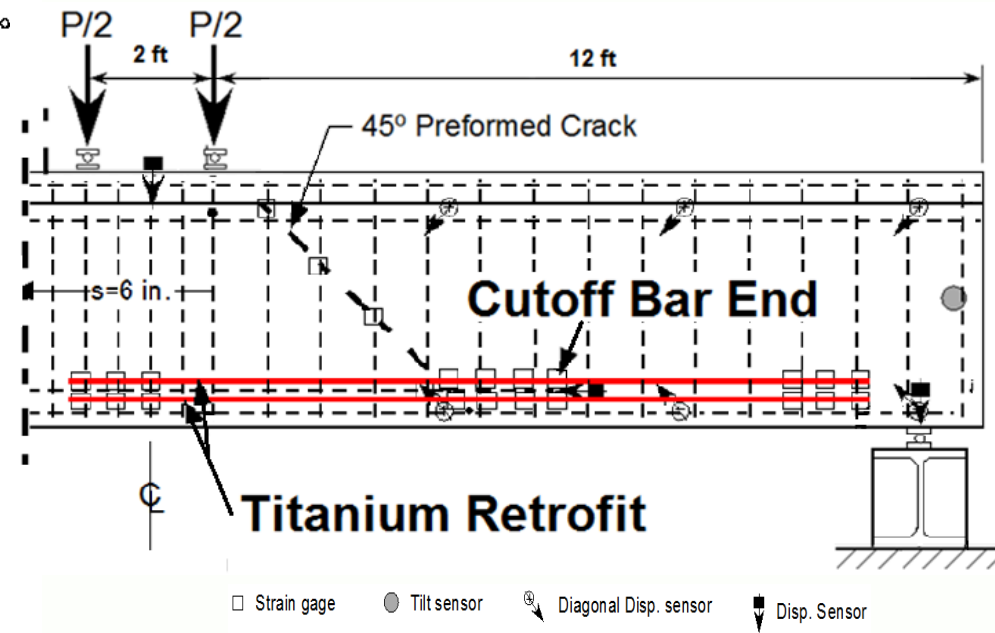
## Shear Results Epoxy E1 Ti@ 12 in.



# Flexure T Beam Details

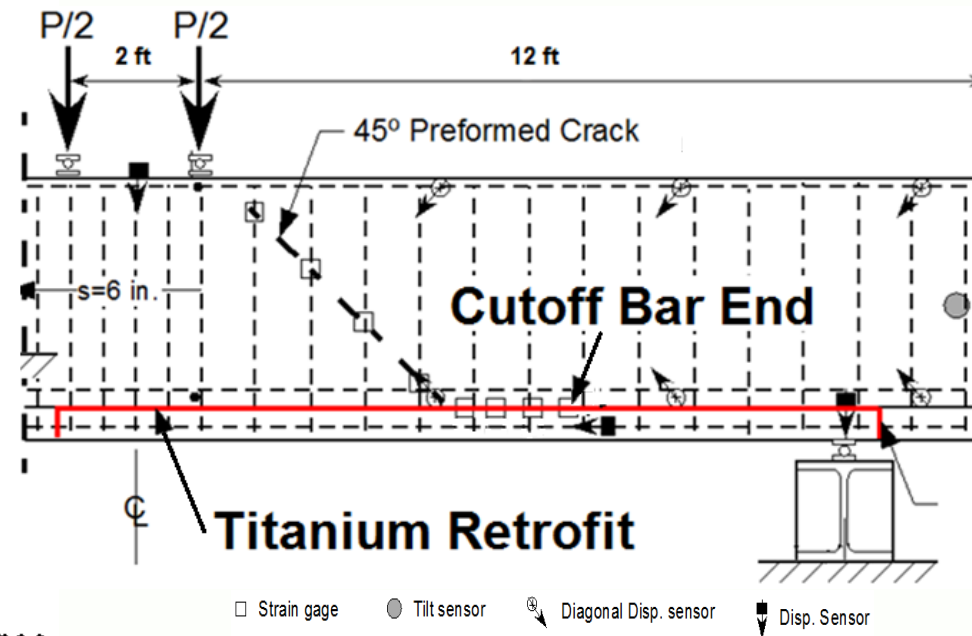
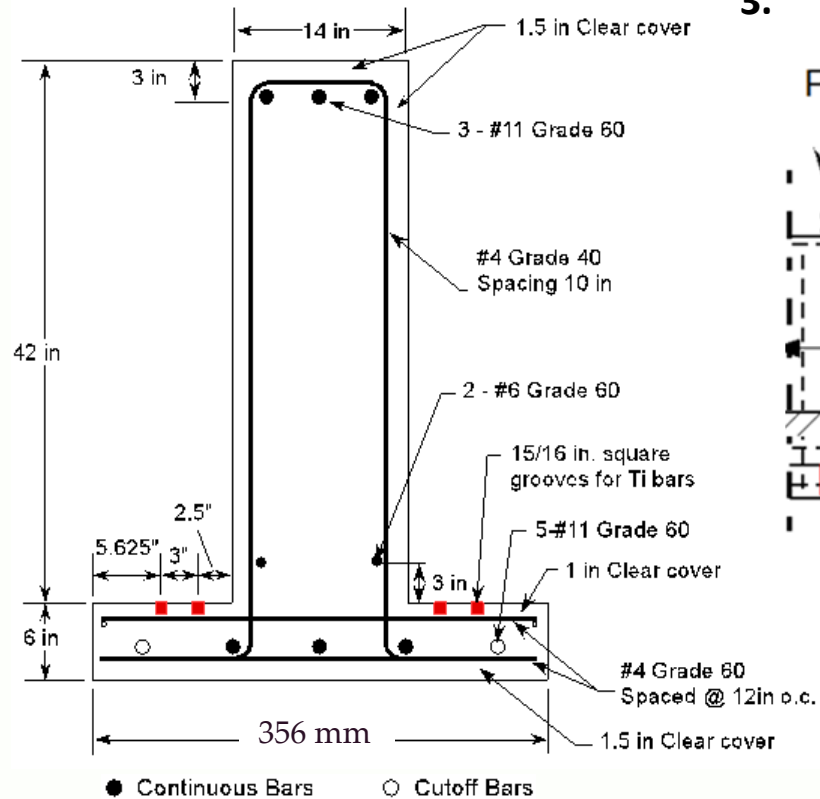


1. **T.45.Ld3:** *Baseline T Beam*
2. **T.45.Ld3.NSM-Ti:** *with 10 in stirrups*
3. **T.45.Ld3.NSM-Ti.2:** *Titanium with 6 in stirrups*

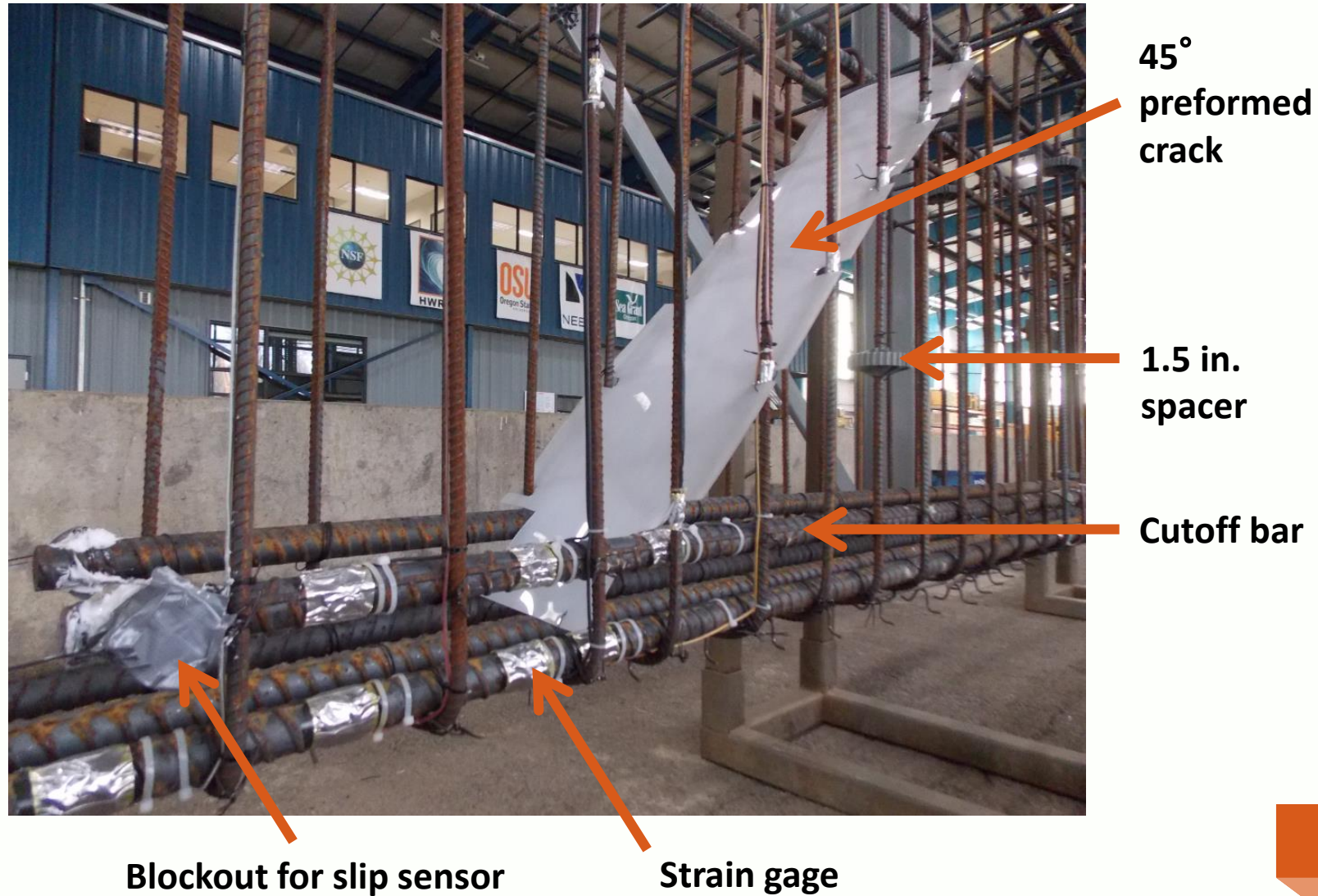


## IT Beam Details

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*



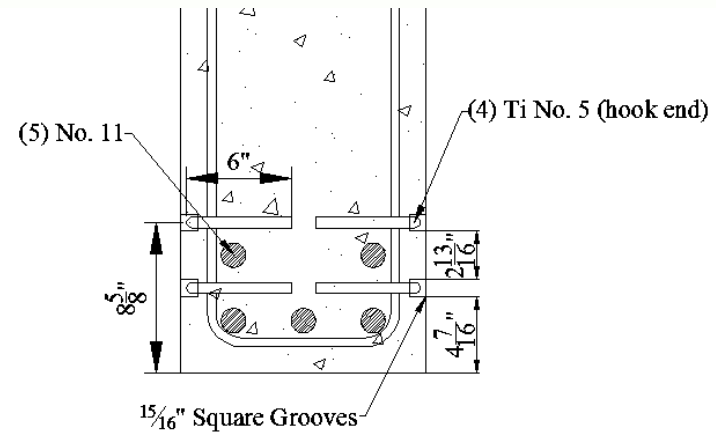
# T and IT Beam Construction



# Experimental Setup: 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



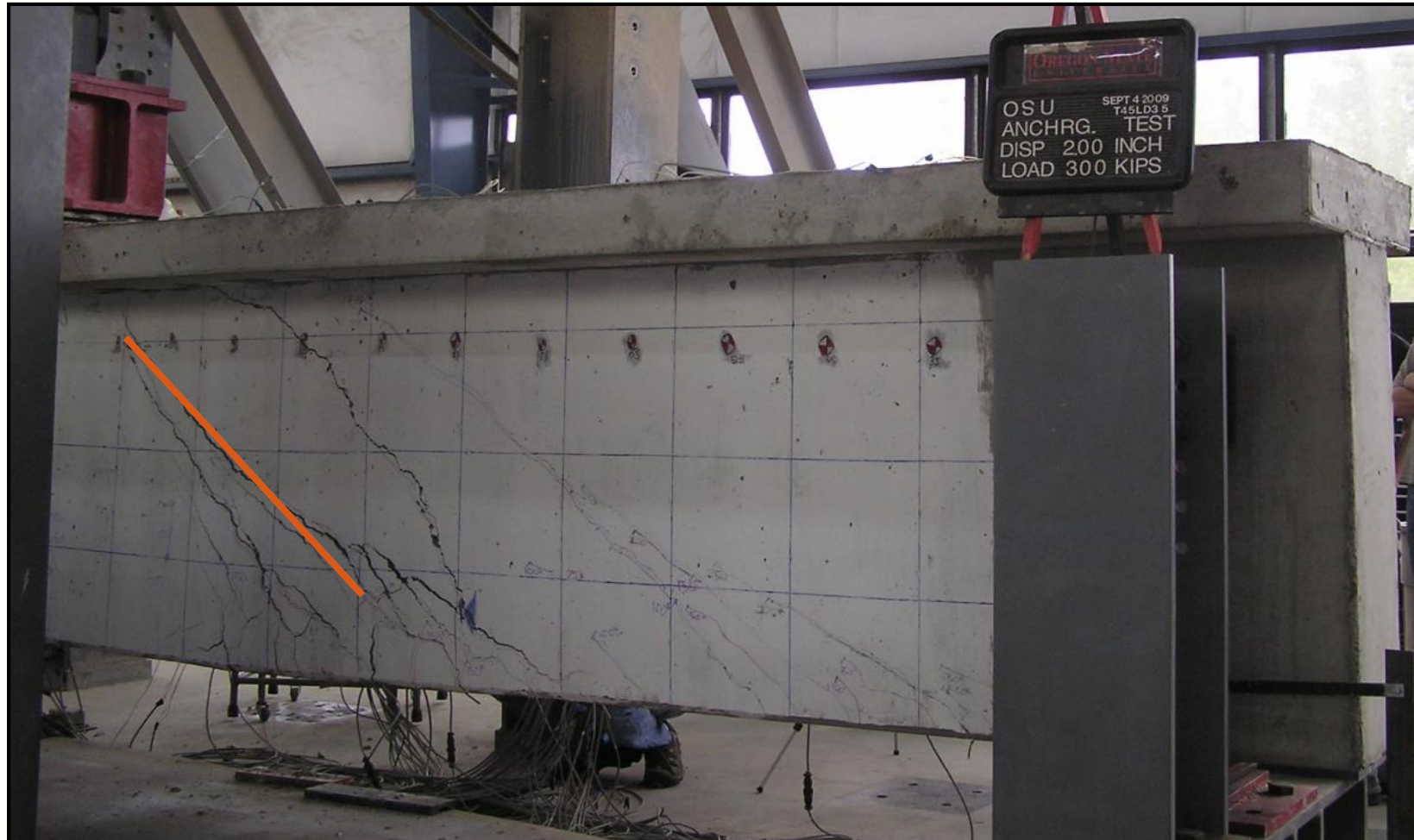
# Experimental Setup: NSM Strengthening Methodology

## 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



## T.45.Ld3 Failure

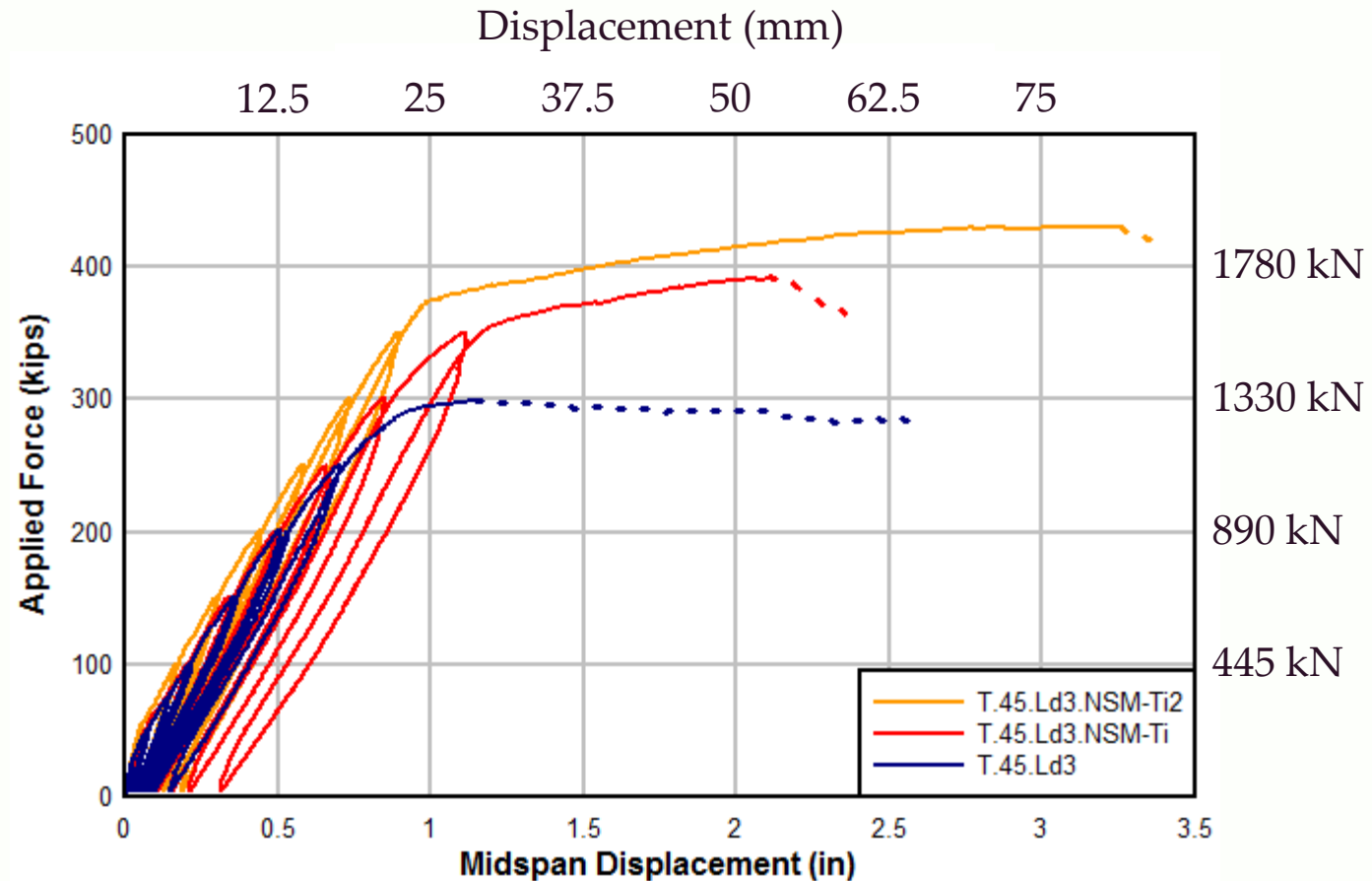


## T.45.Ld3.NSM-Ti2 Failure

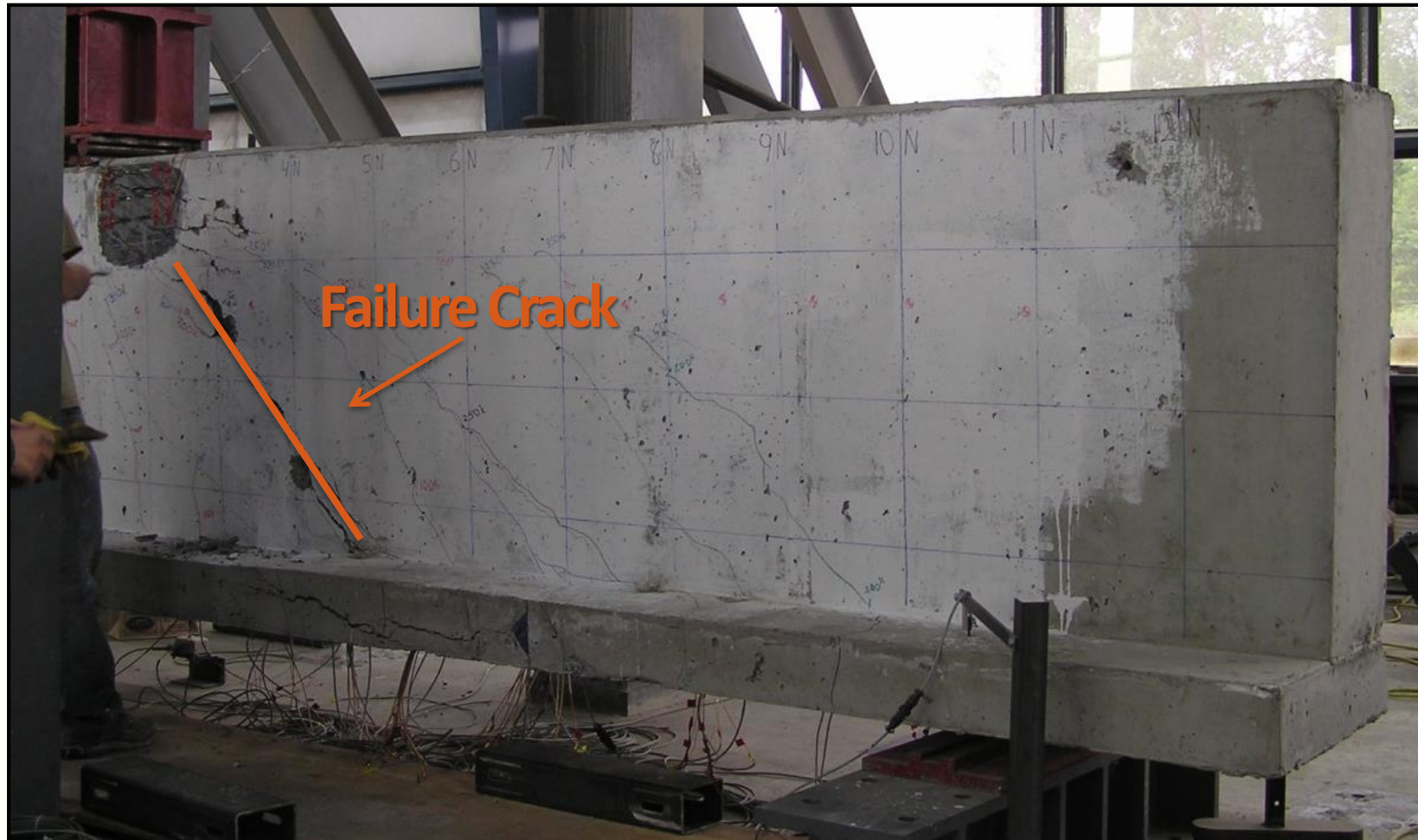




# T Beam Experimental Results



## IT.45.Ld2 Failure

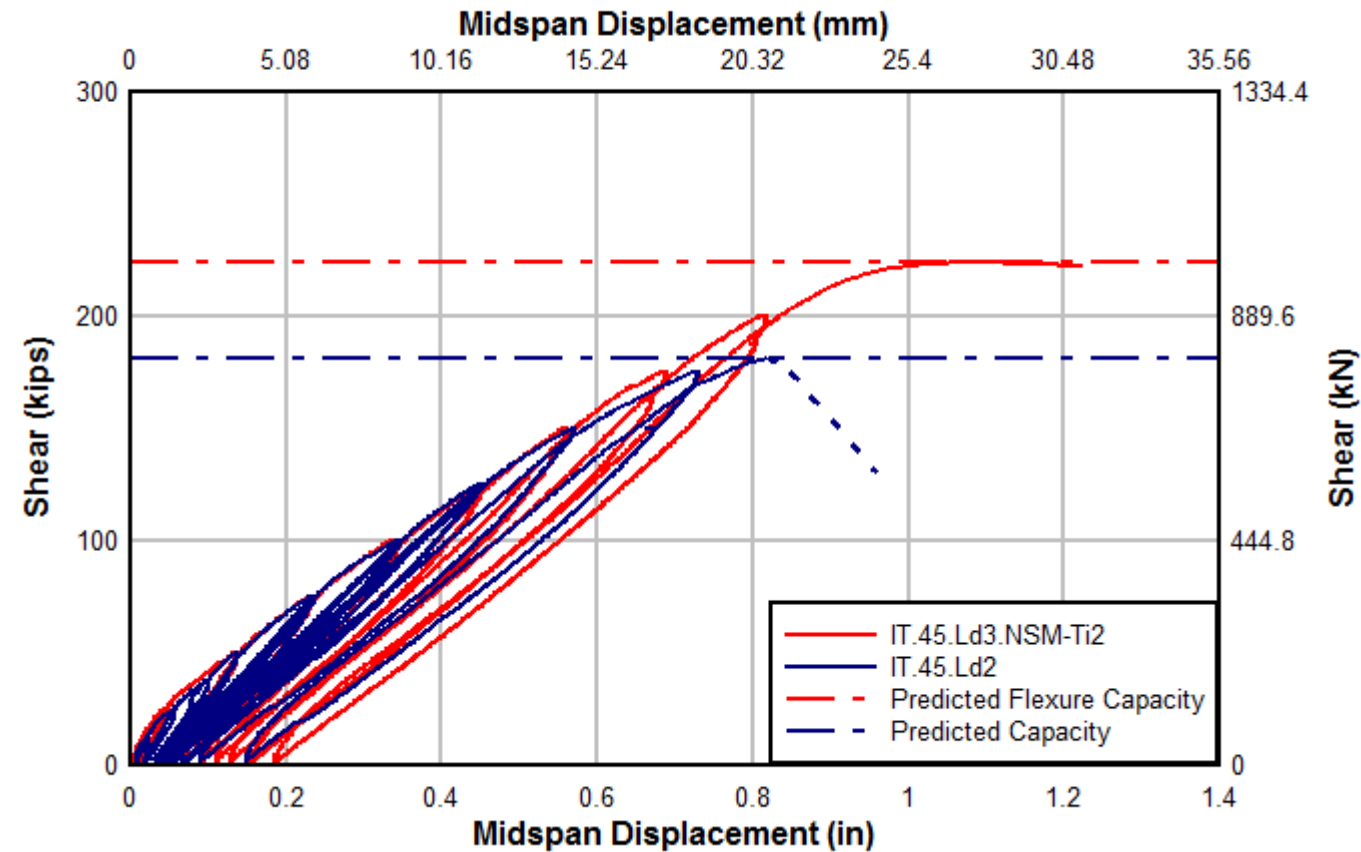




## IT.45.Ld3.NSM-Ti2 Failure

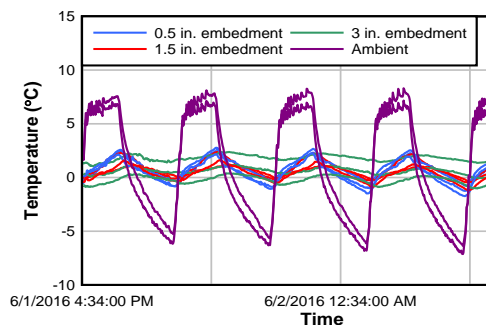


# IT Beam Experimental Results

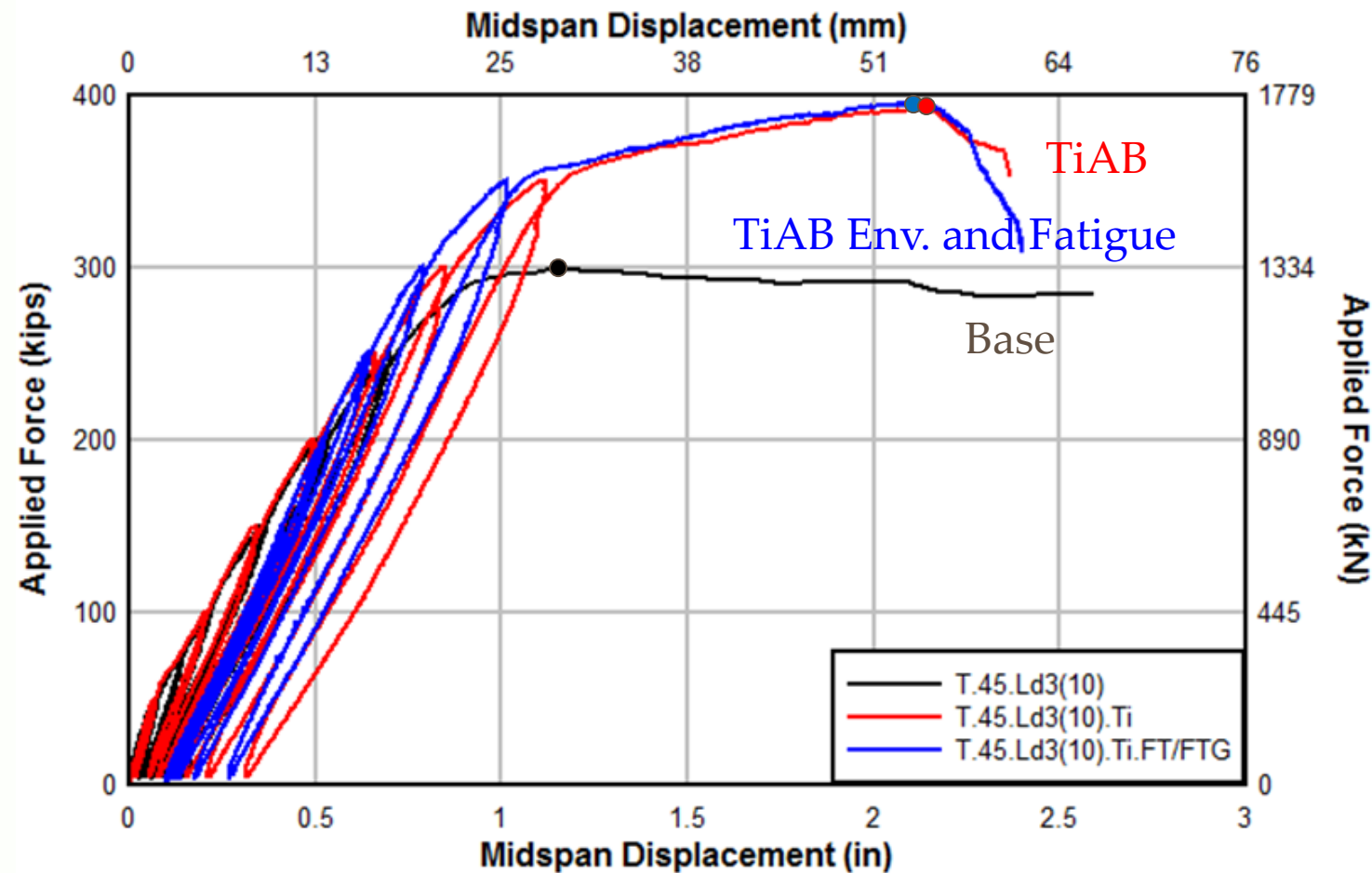


# Durability High Cycle Fatigue and Freeze-Thaw Combined

- Largest combined structural-environmental chamber
- 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.)



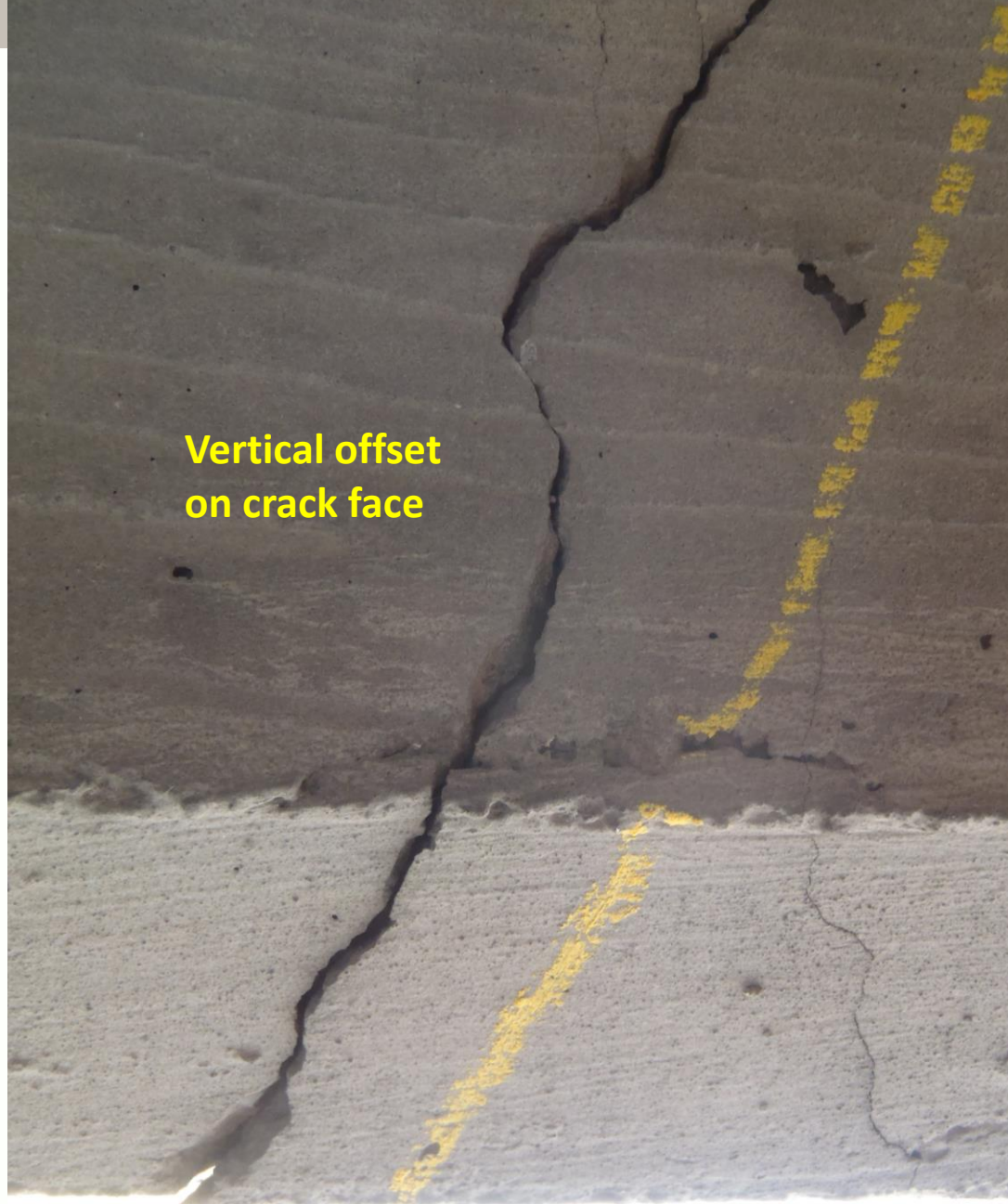


# Mosier Overcrossing of Interstate 84

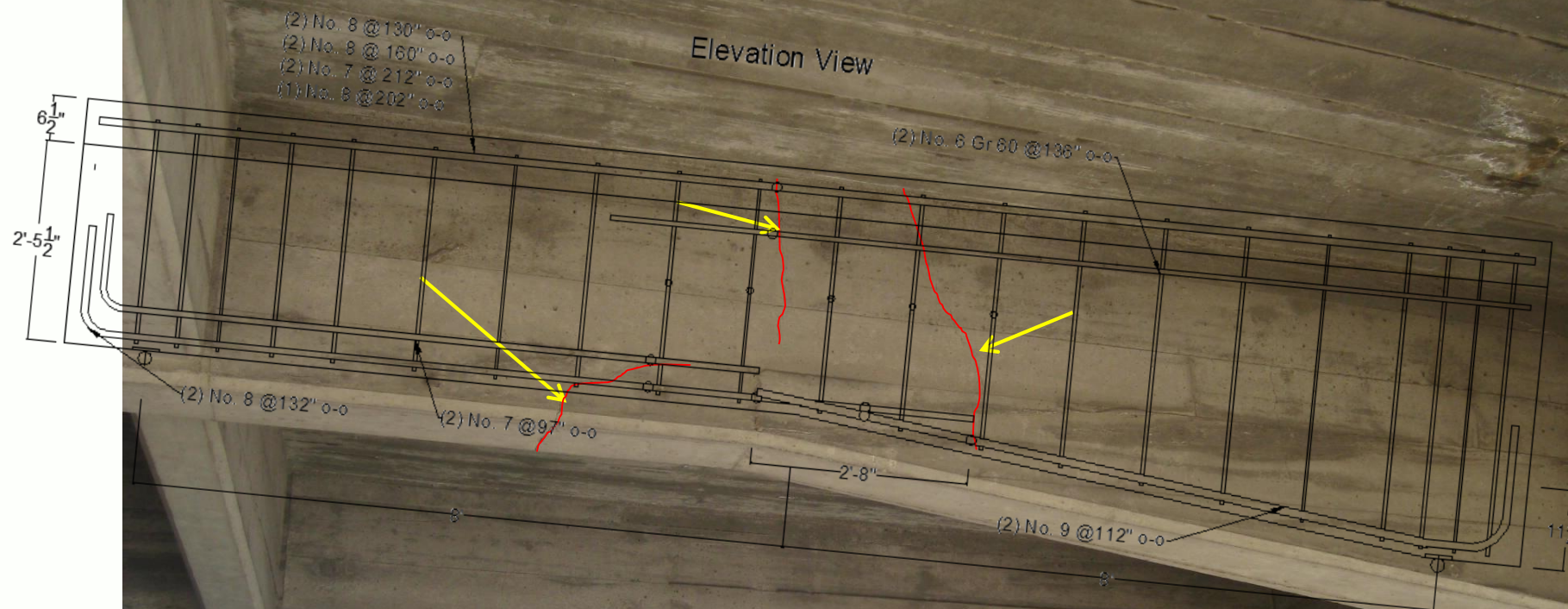
- Built in 1952
- Serves a nearby quarry



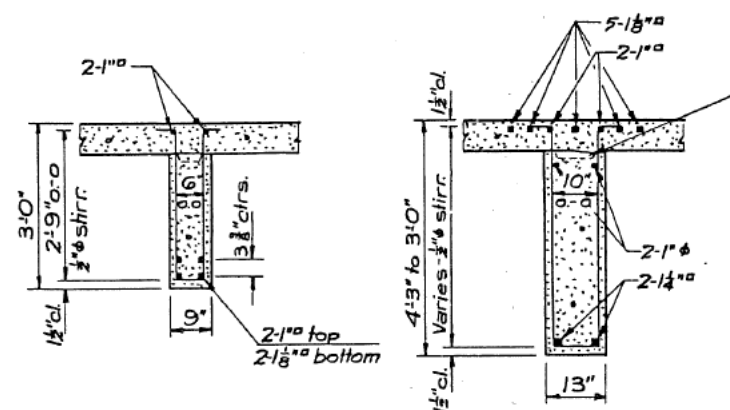
**Vertical offset  
on crack face**







# Mosier As-Built Details



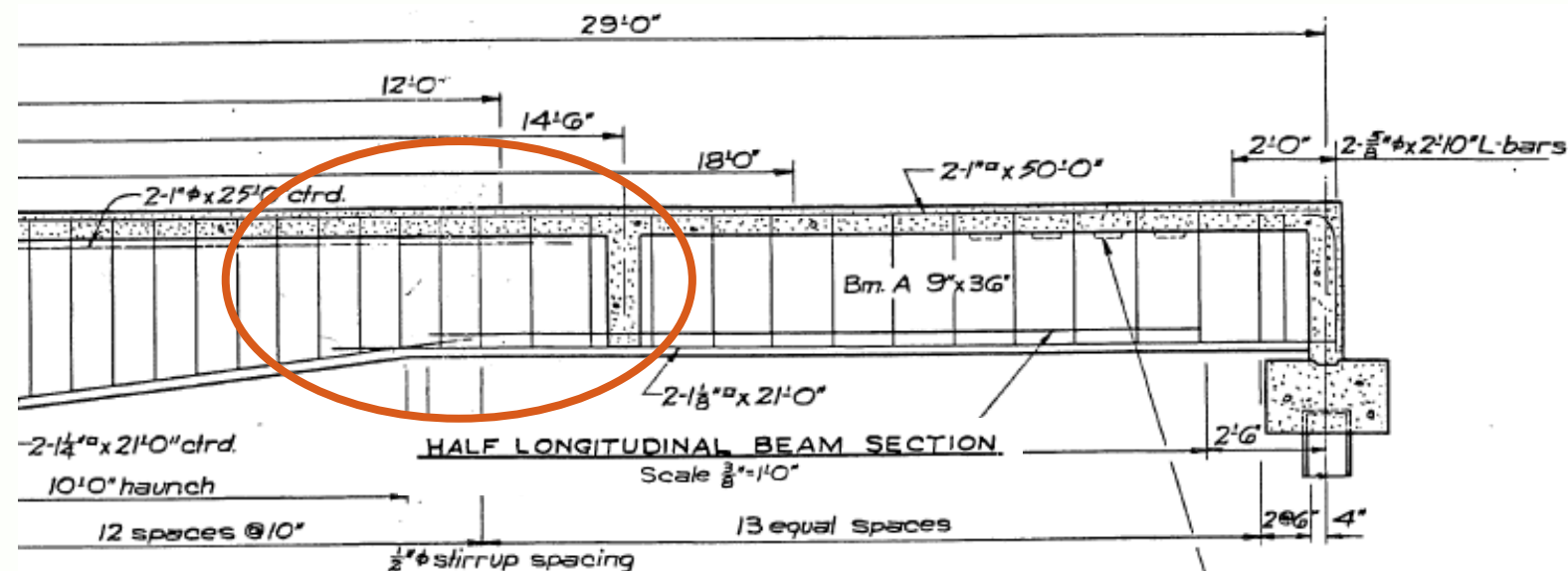
BEAM A

HAUNCH AB

LONGITUDINAL BEAM SECTIONS

Scale 1/2"=1'-0"

DL produces M-  
LL produces M+



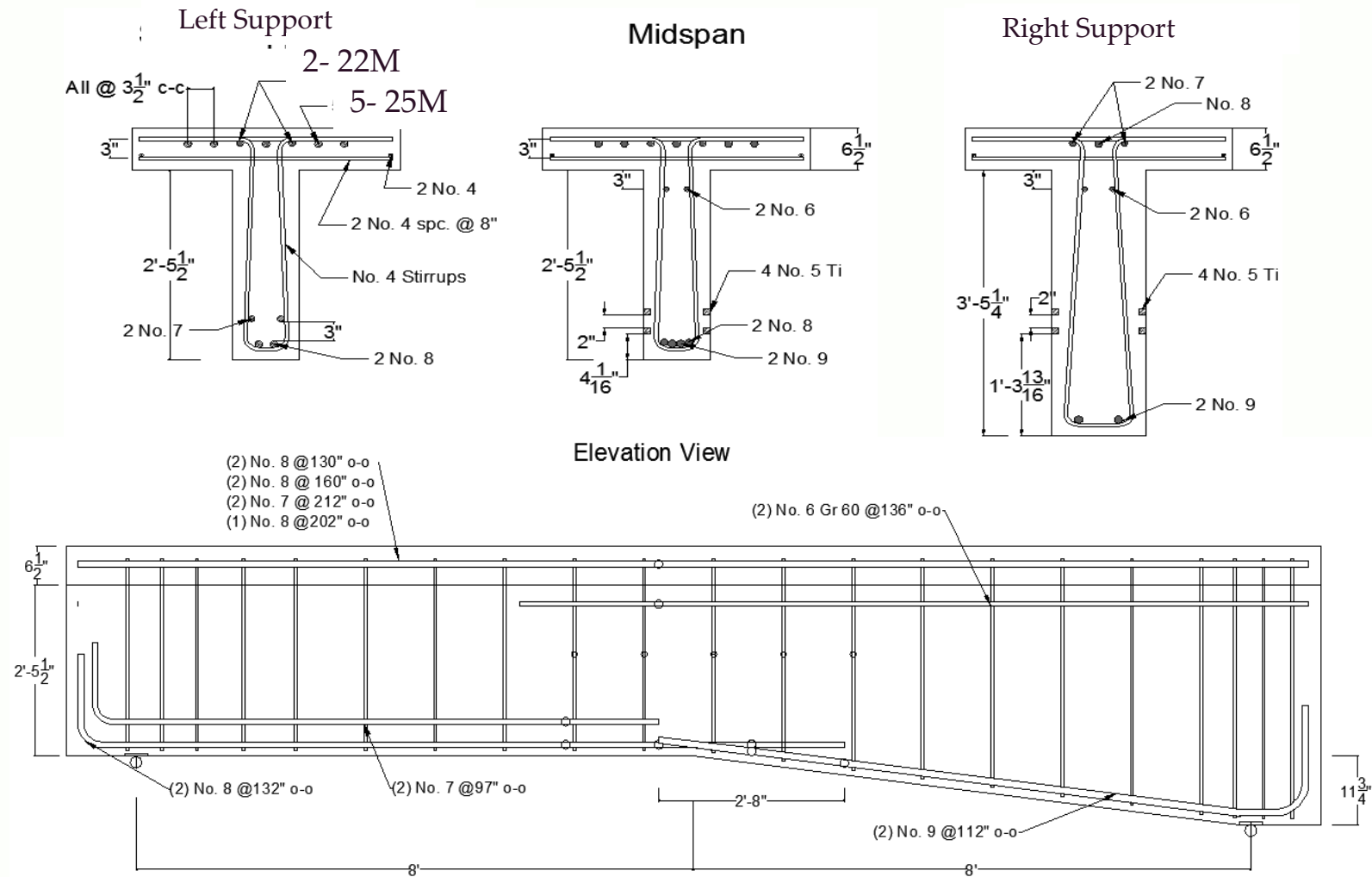
# Test Plan

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*

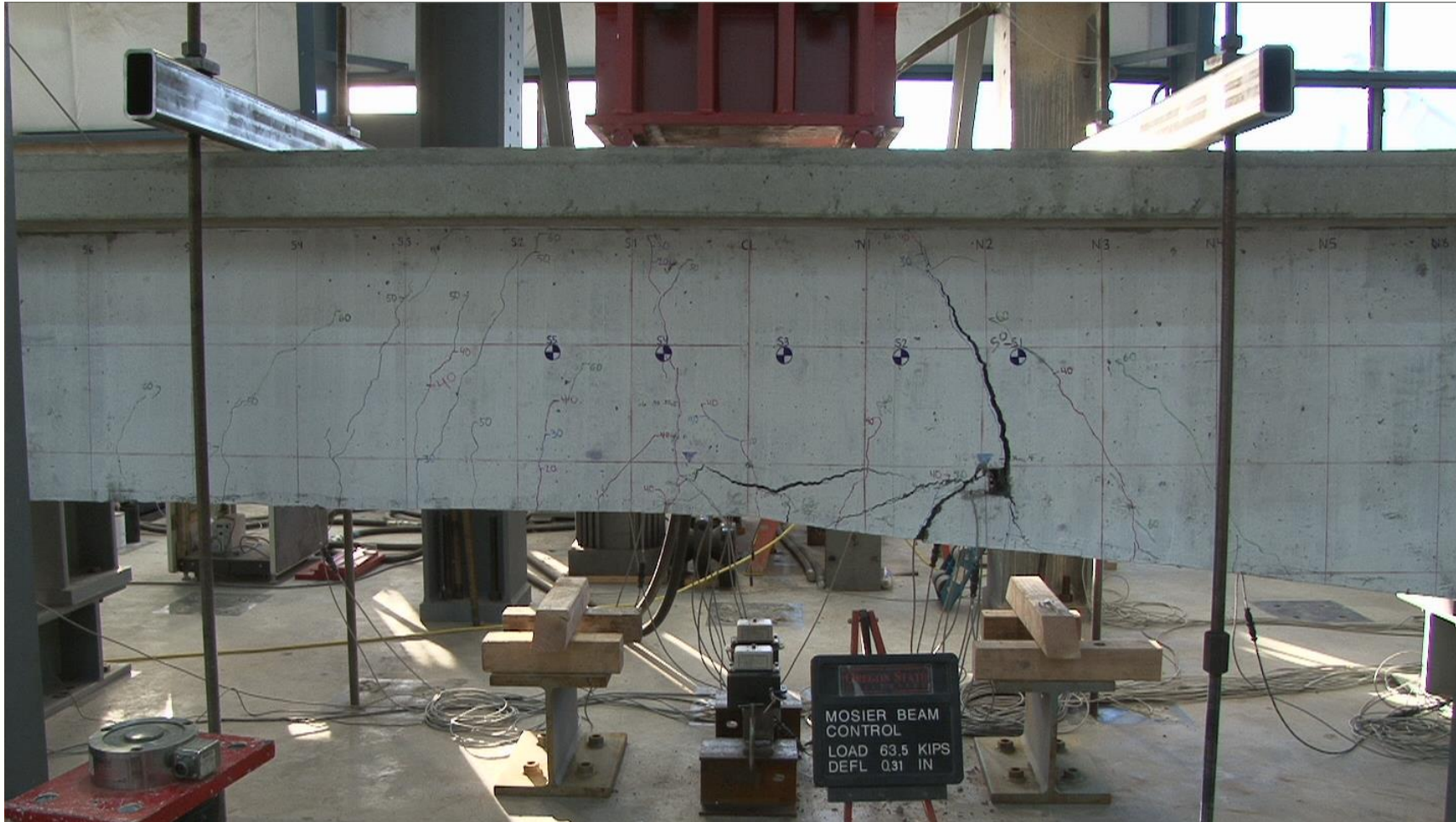
Searched mill certifications to locate bars that best matched strength curves of original design. Used smaller sized Grade 420 (60) rebar to match development length of intermediate grade steel (280 MPa (40 ksi))

# Mosier Beam Details

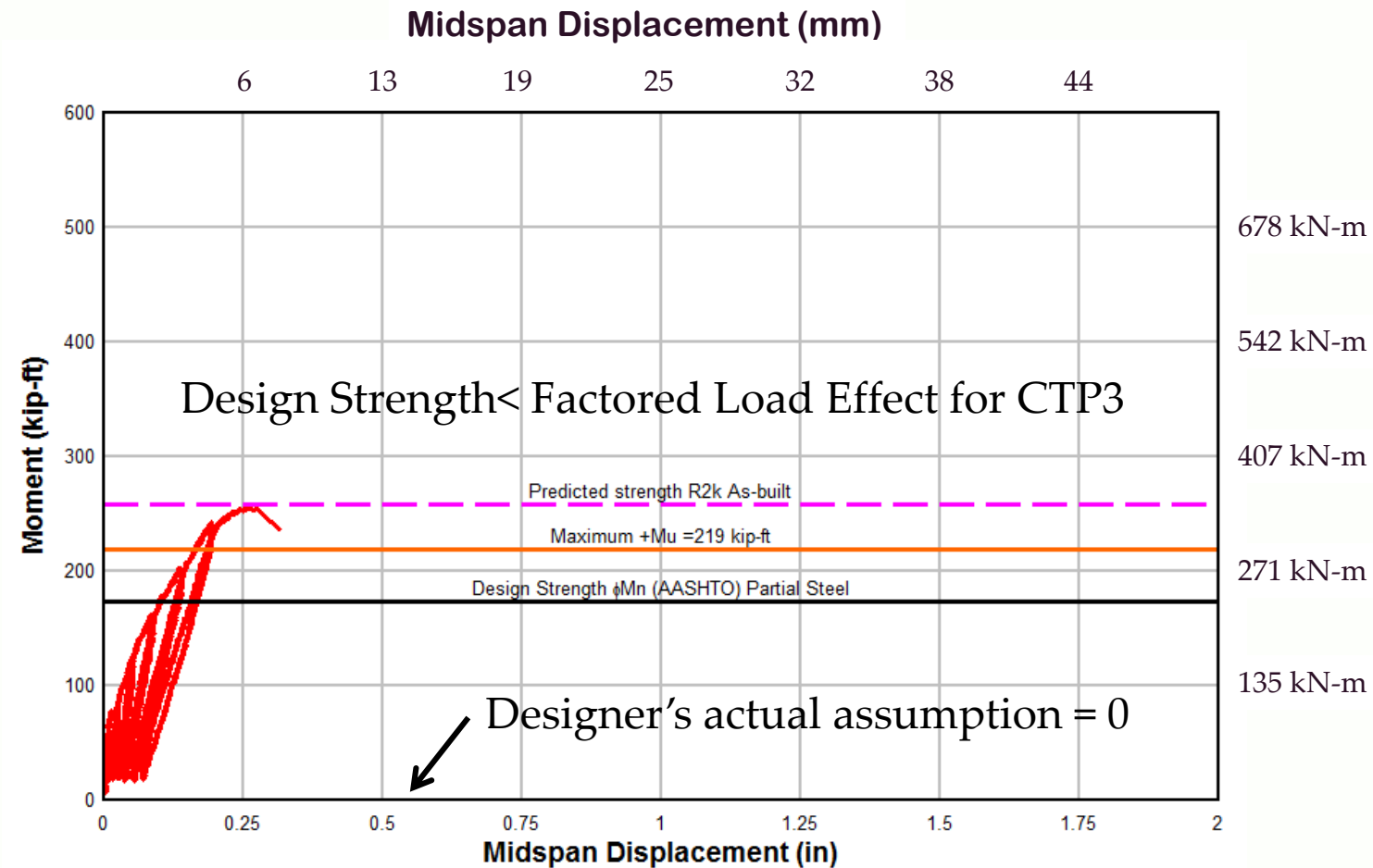




# Experimental Results: Mosier 1



# Experimental Results: Mosier 1

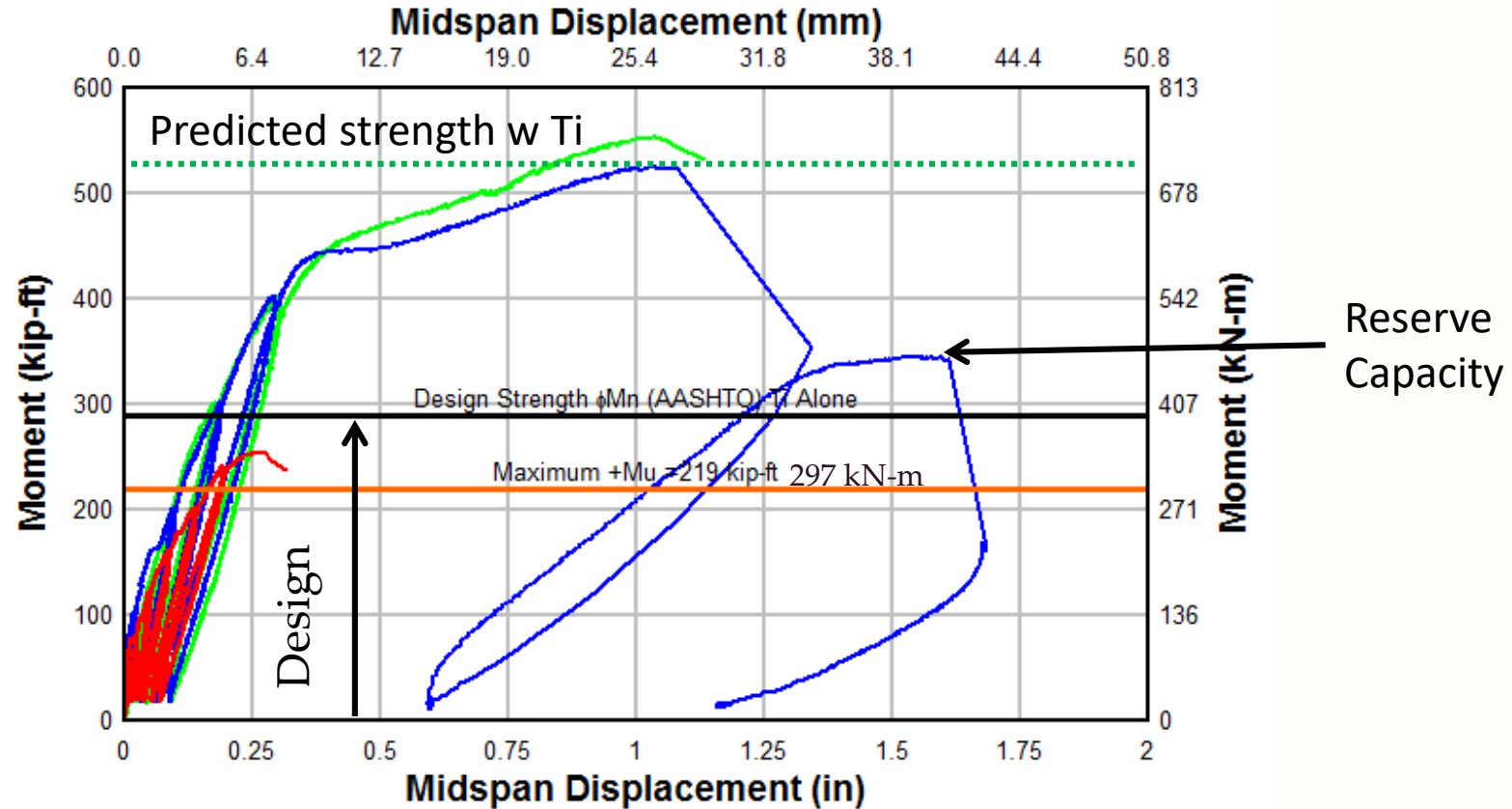




# Experimental Results: Mosier 3

# 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**

# **ASTM Specification for NSM Titanium**

Main Committee: Committee B10 –  
Reactive and Refractory Metals and Alloys

Sub-Committee: Committee B10.01 on Titanium



# Approved Nov. 2018



Designation: B1009 – 18

## Standard Specification for Titanium Alloy Bars for Near Surface Mounts in Civil Structures<sup>1</sup>

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 ( $\epsilon$ ) 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 Nitrogen in Titanium and Titanium Alloys by Gas Analysis



# ASTM B1009-18 Requirements:

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



# **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!!)
- Nine Bridge in OR...

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

# Acknowledgements

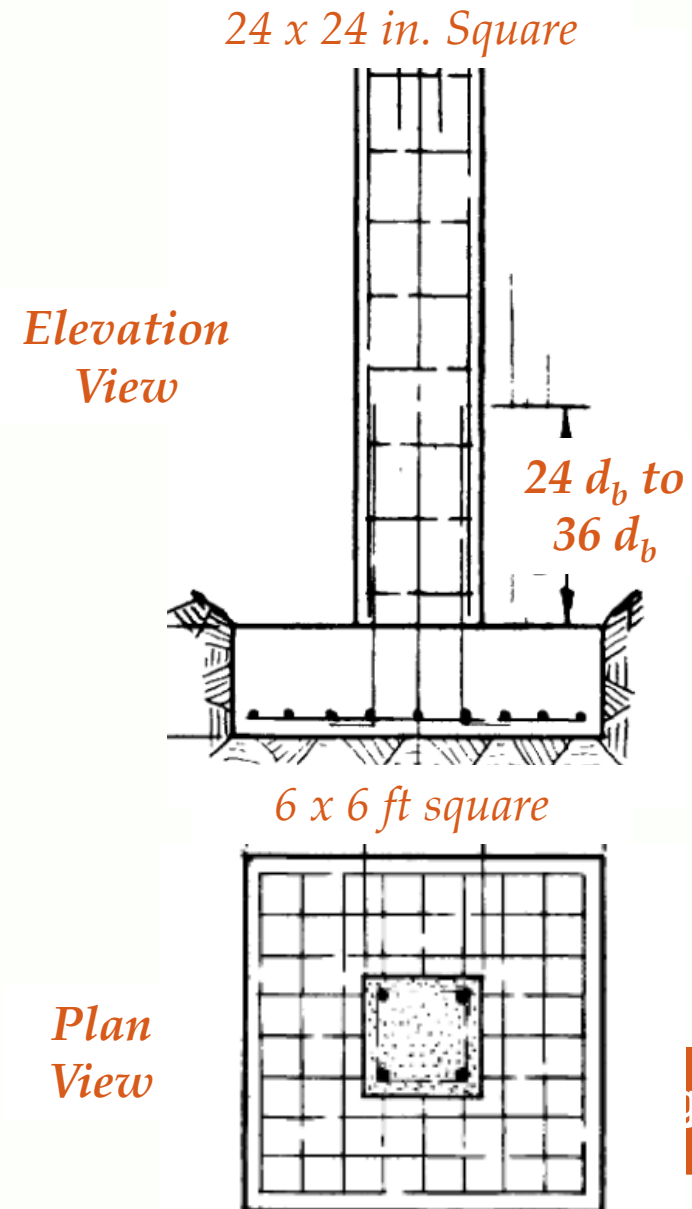
- Oregon Department of Transportation
  - Bruce Johnson, TACs, and Research group
- Perryman Company, Houston, PA
- Undergraduate Research Assistants: Kyle Logan, Jonathon Roy, Aléxia Ribeiro, Lance Parson, Hunter Anderson, Kyle Sonnevile, John Huntoon, Glen Galant, Corey Groshong, James Kemp, and Spencer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



# Seismic Deficiencies of pre-1970's columns

- Insufficient transverse reinforcement
  - #3 @ 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)



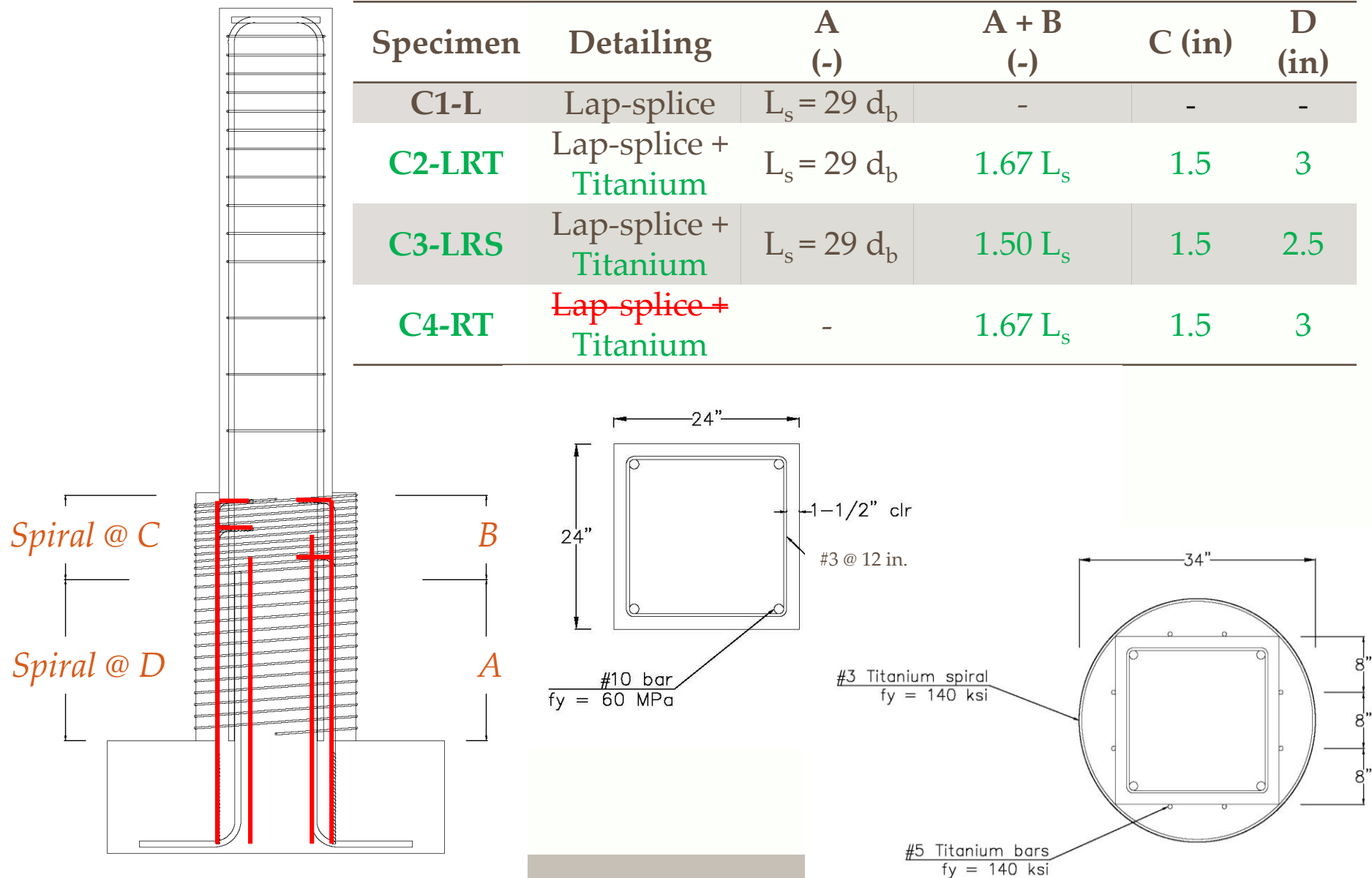
# Common Approach for Retrofitting

## Fiber reinforced (FRP) laminates (Confinement)

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

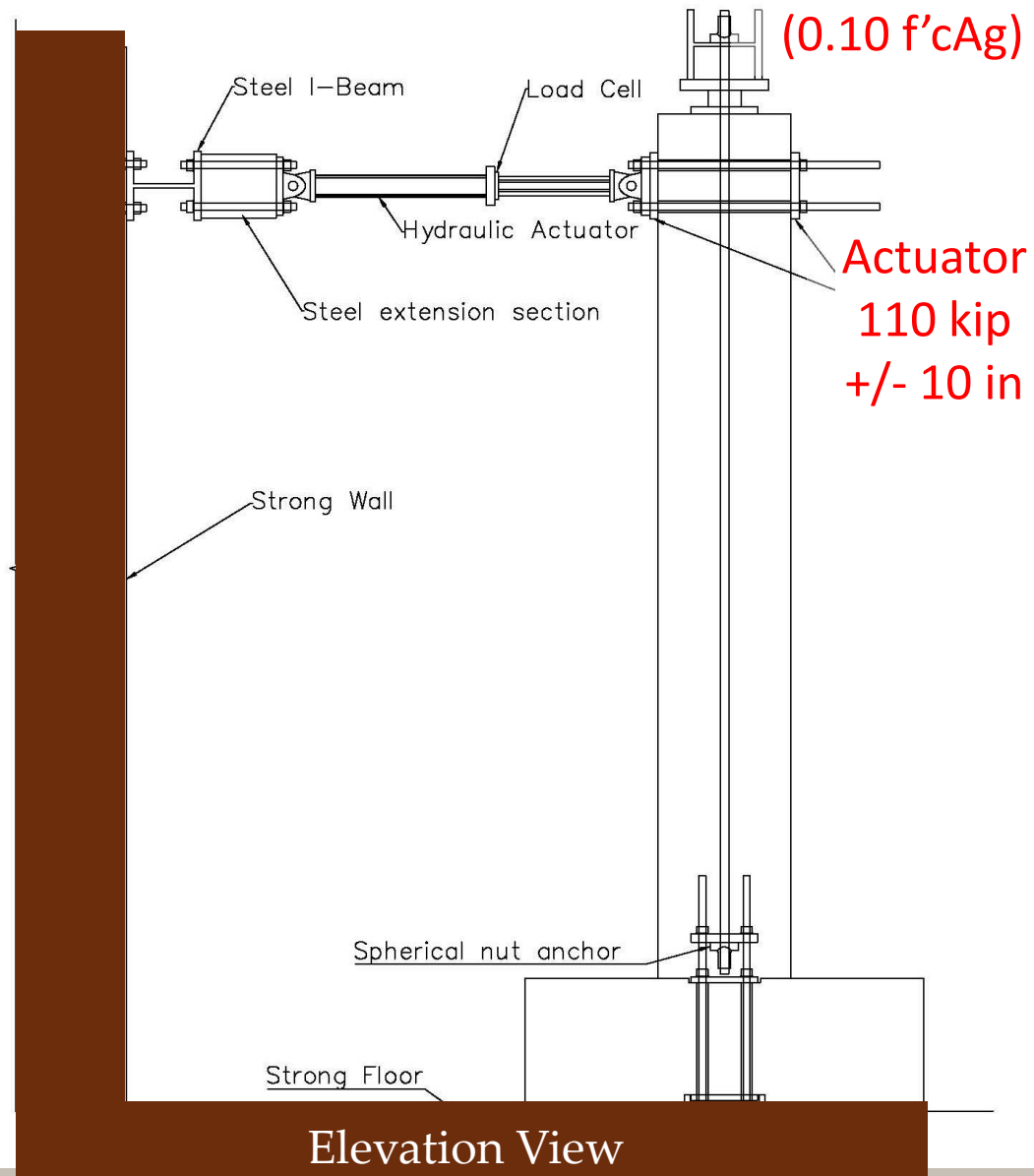


# Seismic Performance



# Experimental Set-Up

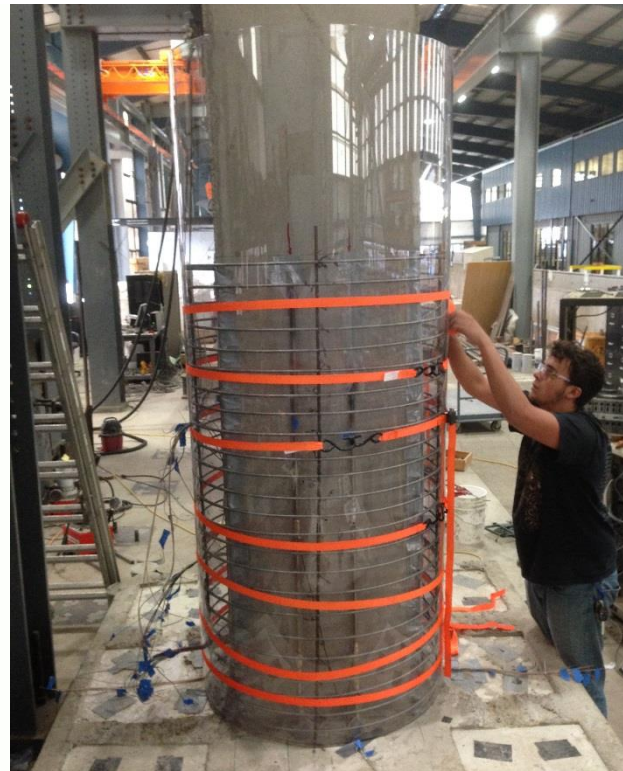
Axial load  
200 kip  
( $0.10 f'_c A_g$ )





# 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

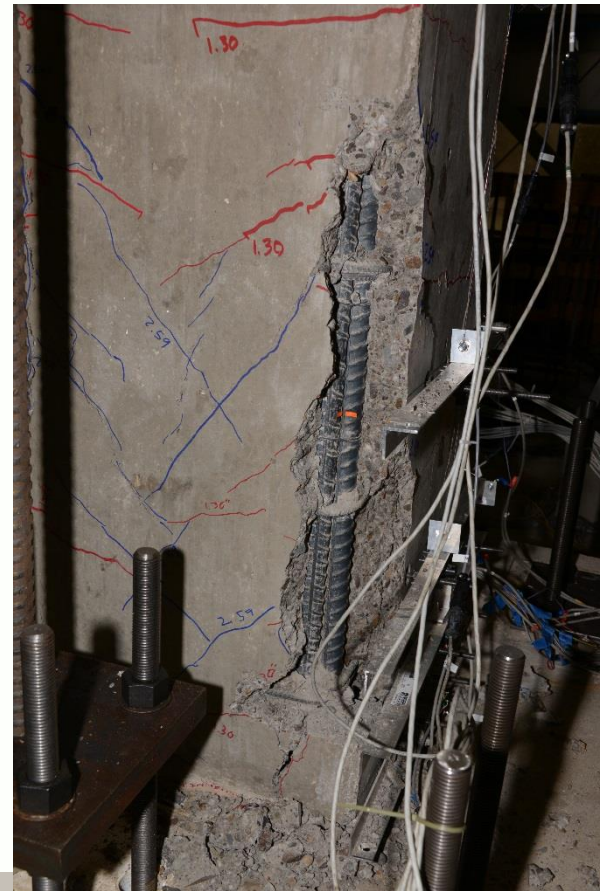
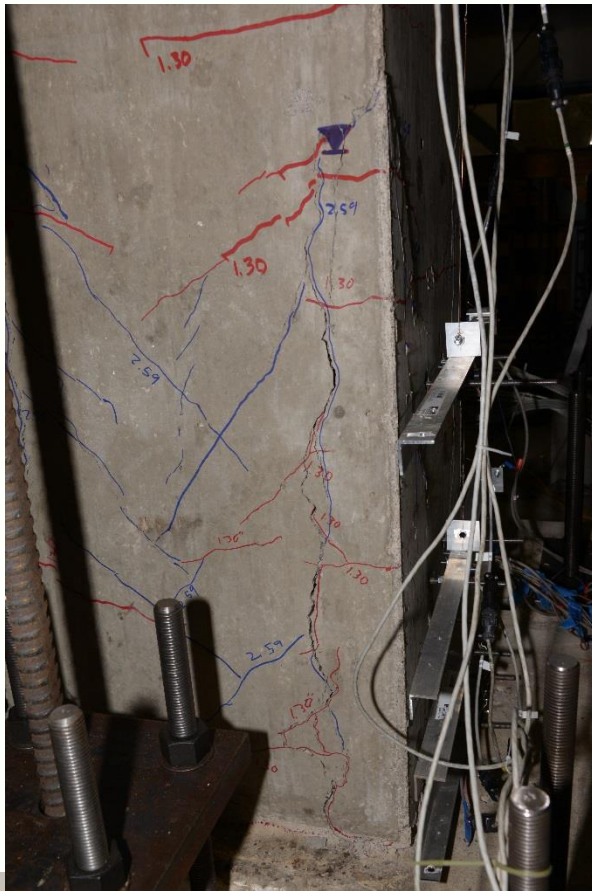




## Control Specimen: Observed Performance

## 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





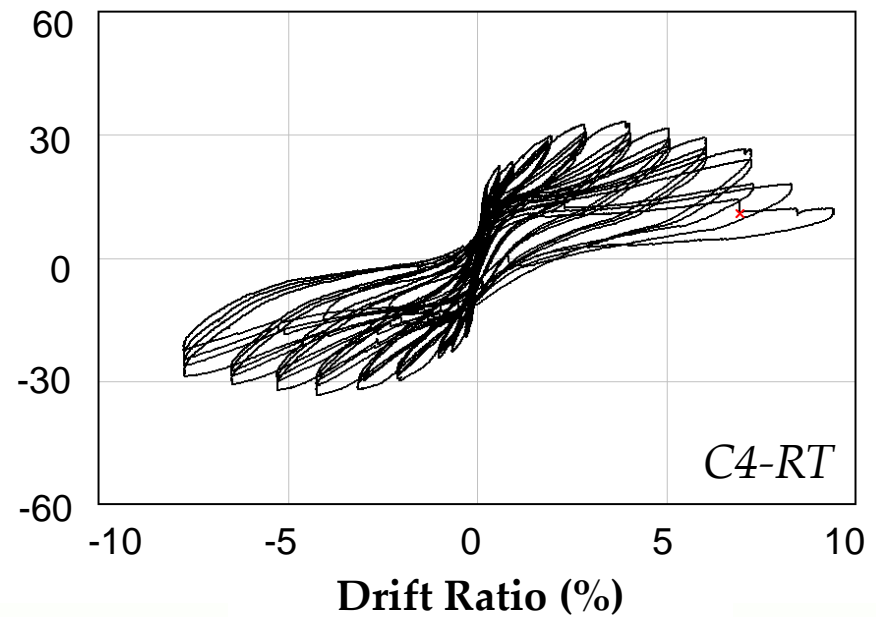
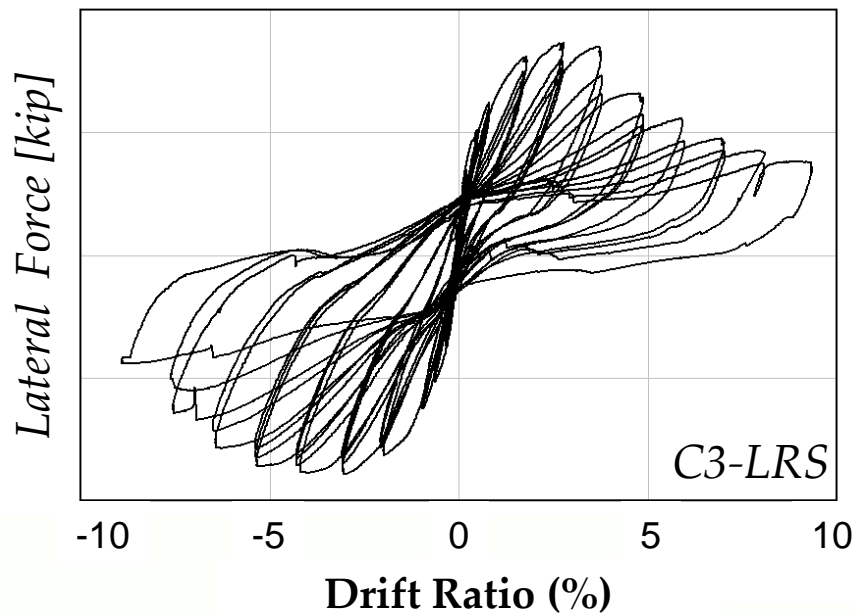
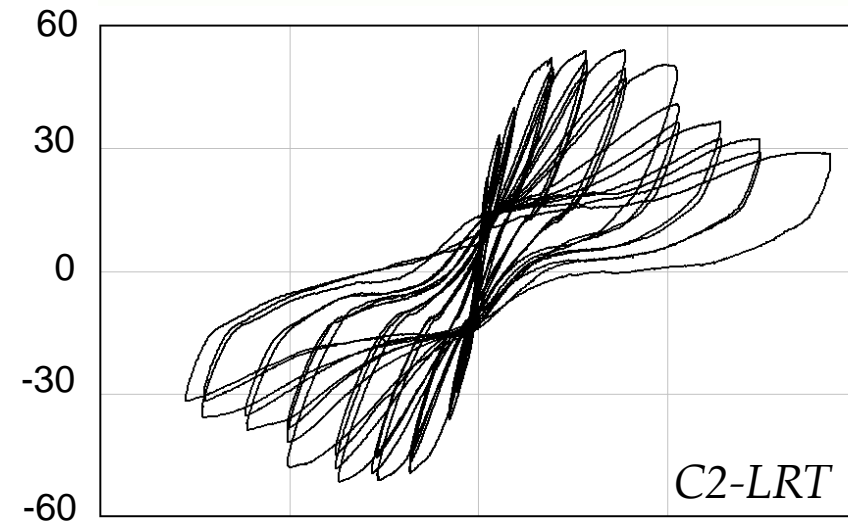
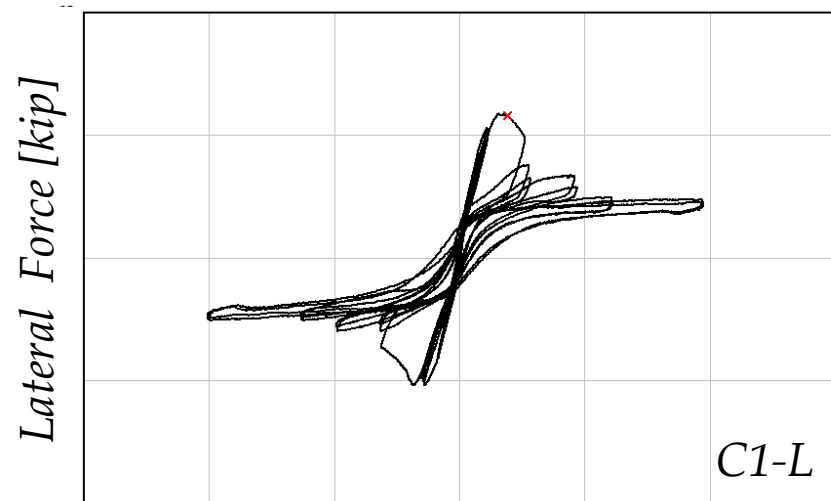
# Observed Performance

**Retrofitted** specimens with lap splices (similar performance):

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



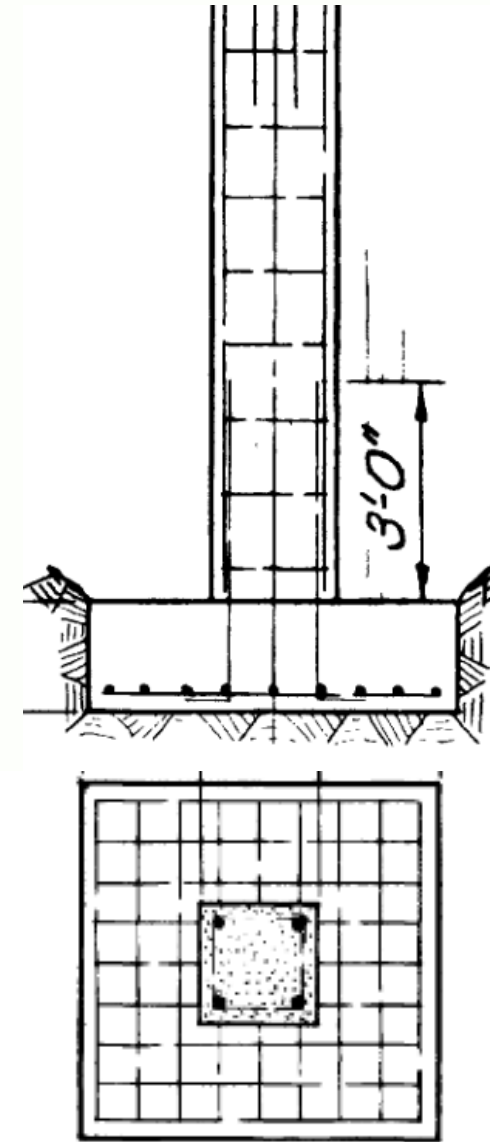
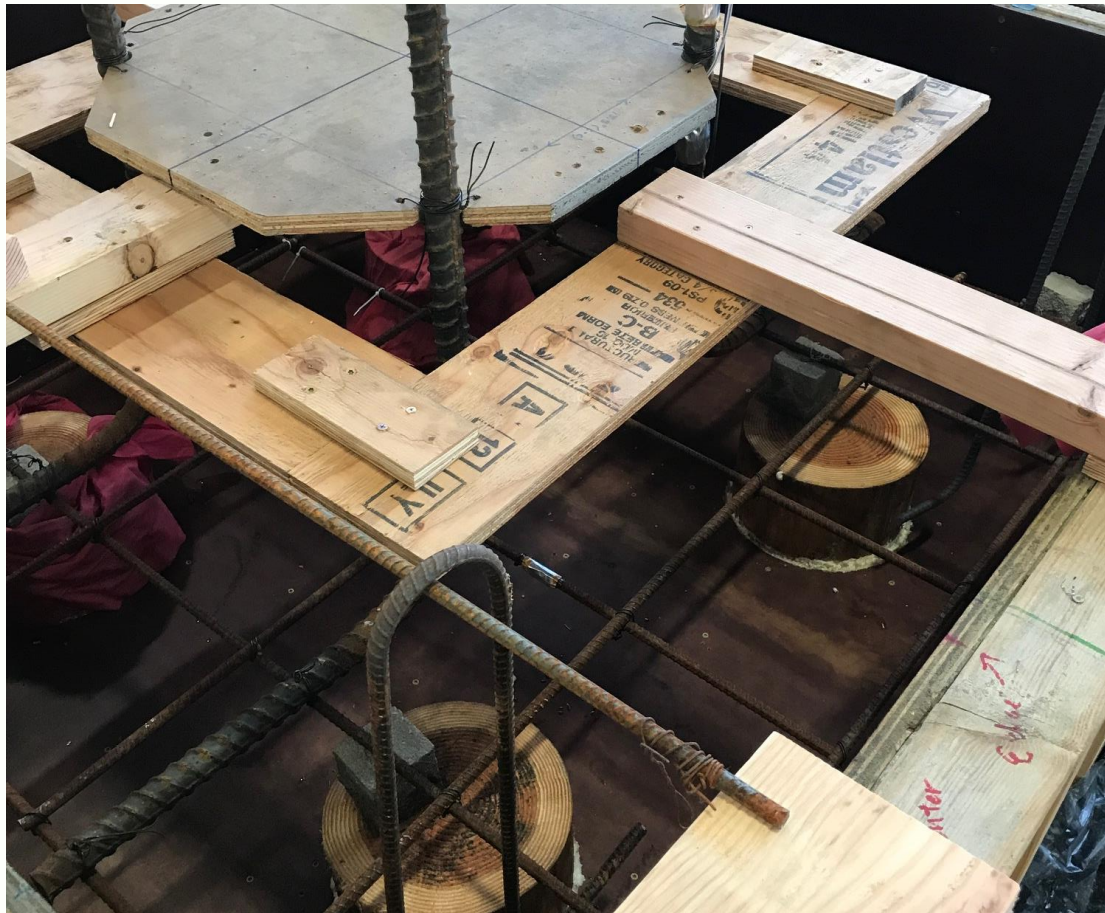
# Load-Deformation Response





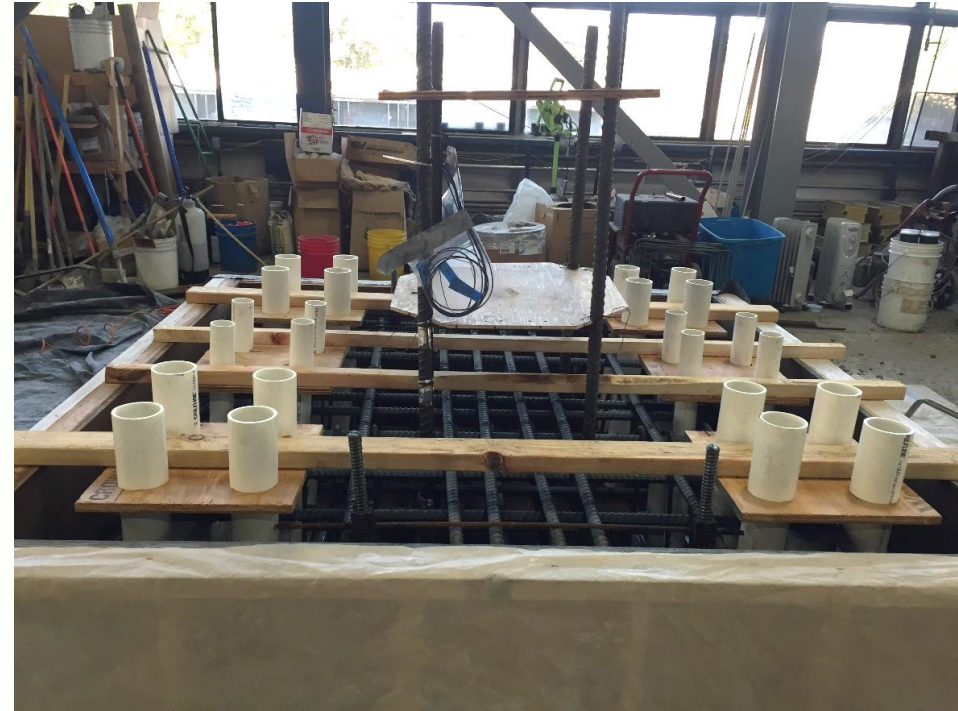
# Fuse Seismic Forces Imparted on Footing

- Spread footing
- Timber pile





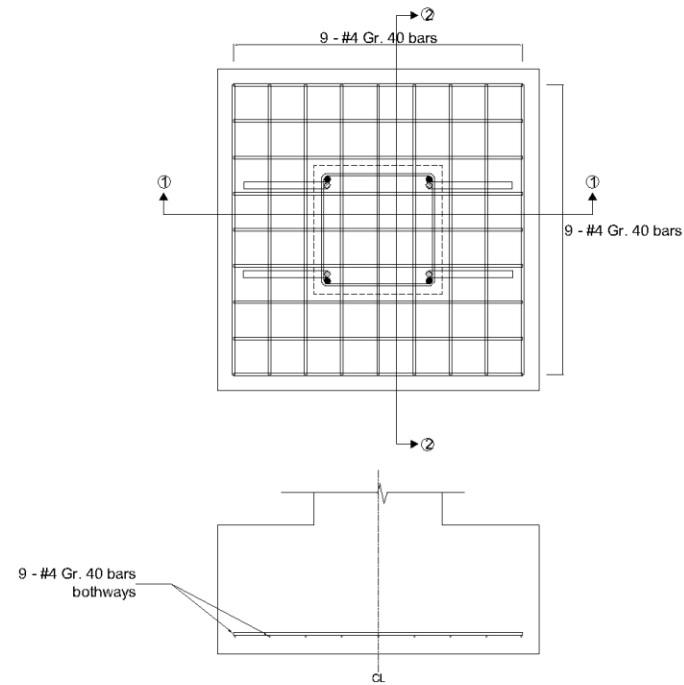
# Experimental Tied Footing Details



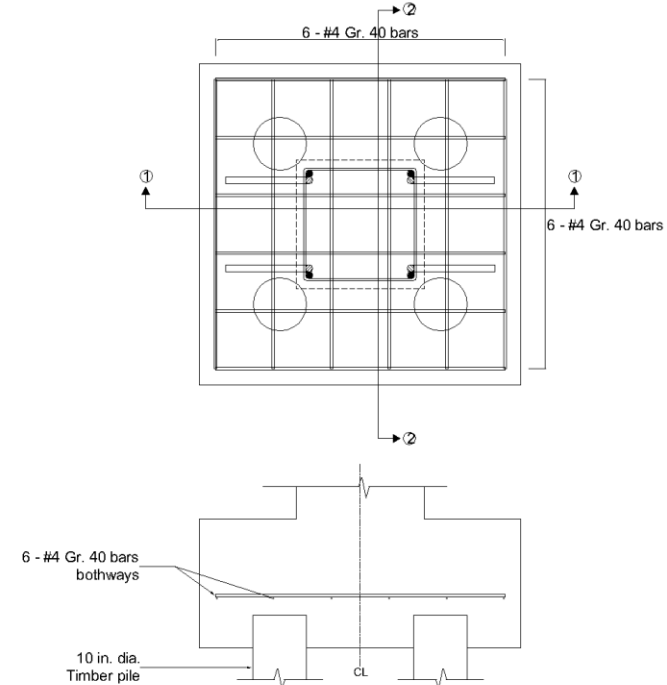
**Force column failure  
But do not reflect in situ details or reactions**

# Typical Footing Details

## Typical Spread Footing



## Typical Timber Pile Footing



# 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.



# Acknowledgements

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

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