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Renewal of Aging and Deteriorated Reinforced Concrete Bridges with Titanium Alloy Bars (TiABs)

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Punch Magazine, 1891

Overview

- Introduction, Background, and Motivation
- Gravity Loading
- Seismic Loading
- Laboratory Test Results from Full-Scale Specimens
    - Shear Strengthening
    - Flexural Strengthening
    - Reversed Cyclic Performance for columns
- Field Implementation on Mosier Bridge over I84
- Conclusions and Future Directions

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Introduction-Gravity Loads

During the 1950 and 60’s:

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

Now:

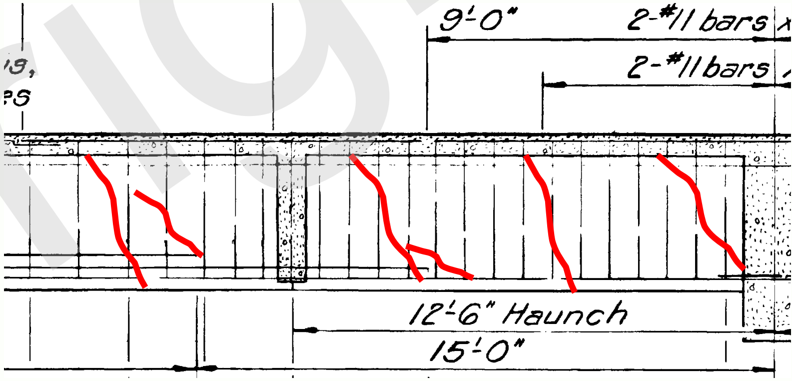
- Visual distress, changes in use, extend life
- Using updated ***design*** codes to assess

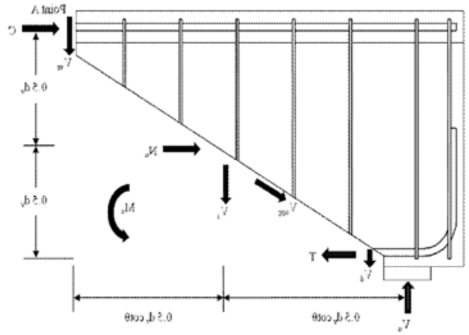
Results:

- Replace, limit loads, retrofit

Retrofit*:*

- *Want **environmentally insensitive material with high strength, well defined properties, and efficient mechanical anchorages***





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

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

-> Titanium

Flexural girder strengthening with CFRP laminate

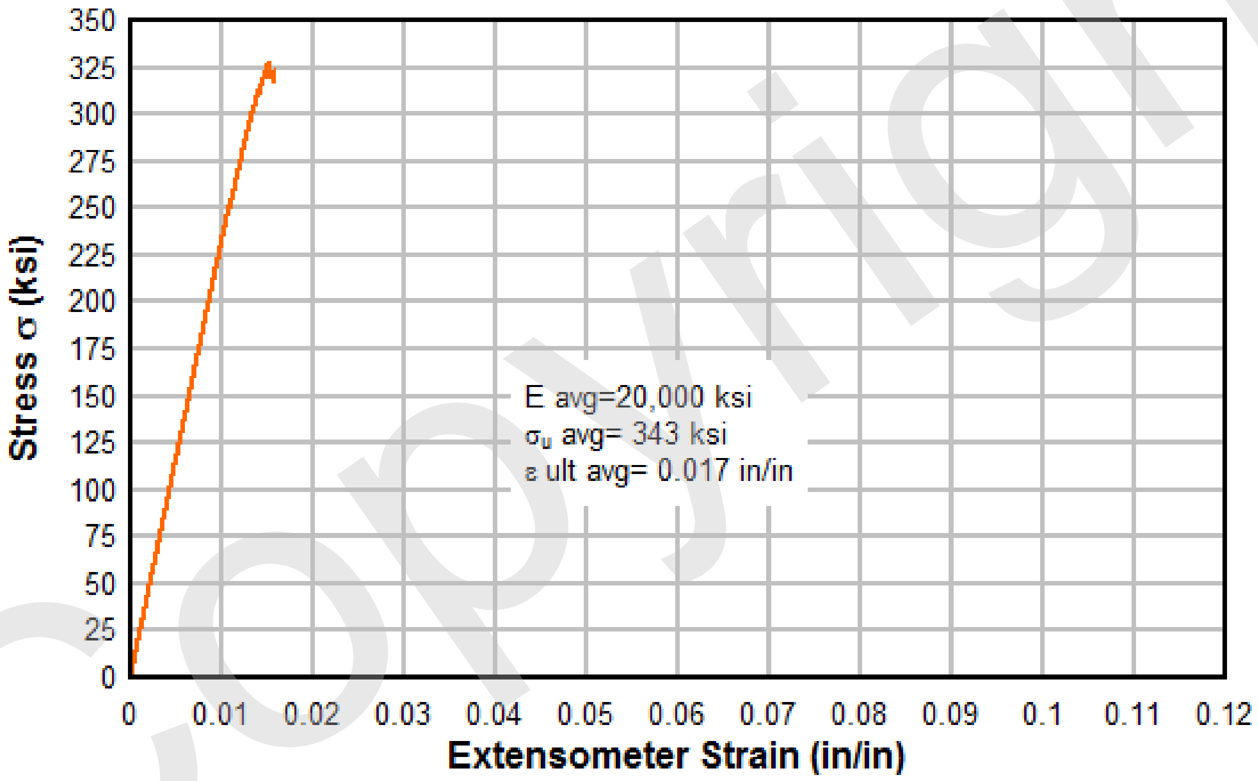
http://aslanfrp.com/Aslan400/Resources/Aslan400.pdf

Strengthening with NSM CFRP strips

http://aslanfrp.com/Aslan500/aslan500-pg2.html

Background: NSM Strengthening Materials

Carbon Fiber Reinforced Polymer (CFRP)



CFRP Bond Failure – Limits material strength

CFRP-NSM

Outer shell peeling

Inner core cracked diagonally

Wide CFRP-NSM

Tightly spaced CFRP-NSM

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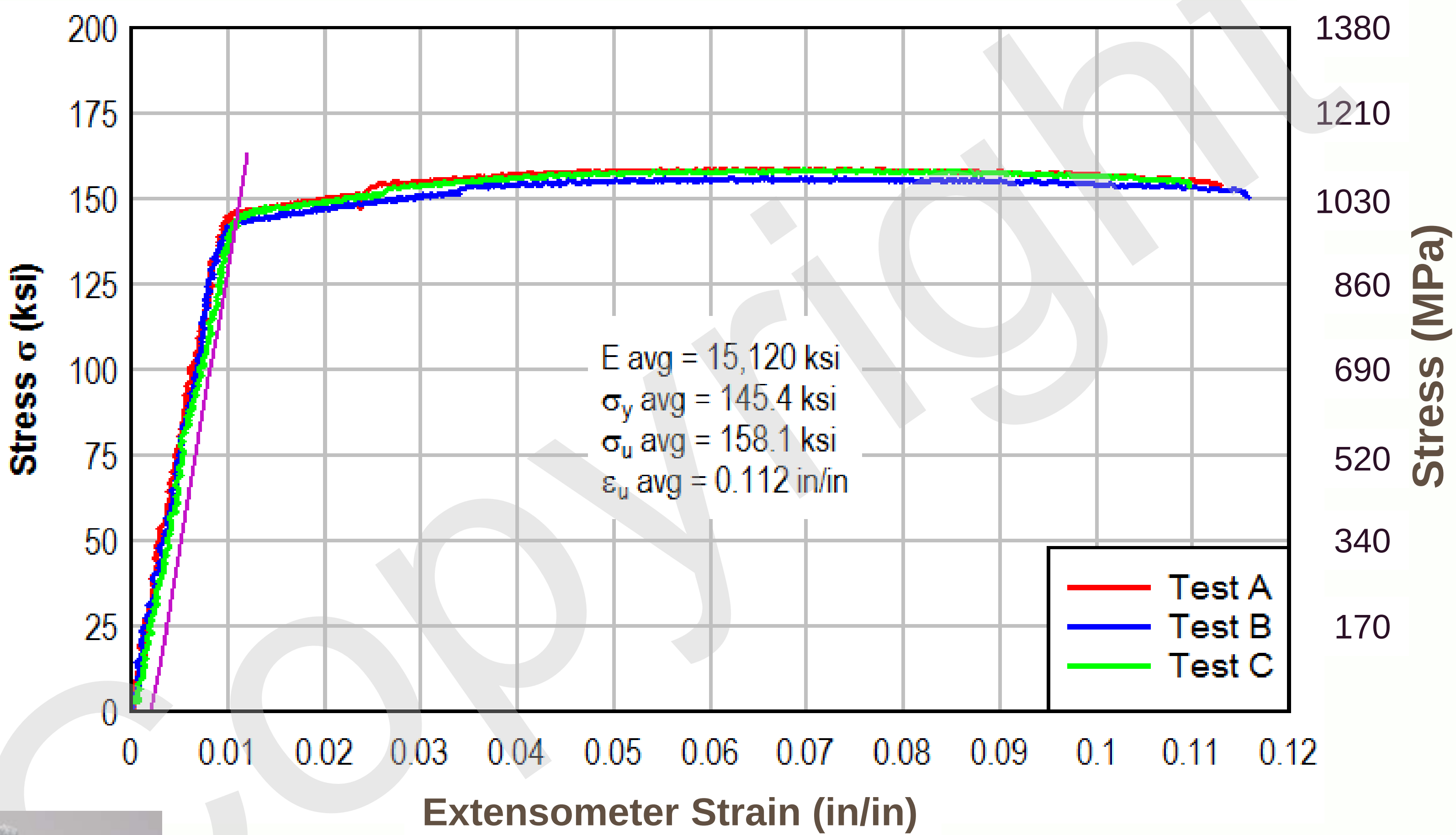
Titanium?

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)



E avg = 15,120 ksi
σ_y avg = 145.4 ksi
σ_u avg = 158.1 ksi
ε_u avg = 0.112 in/in

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)

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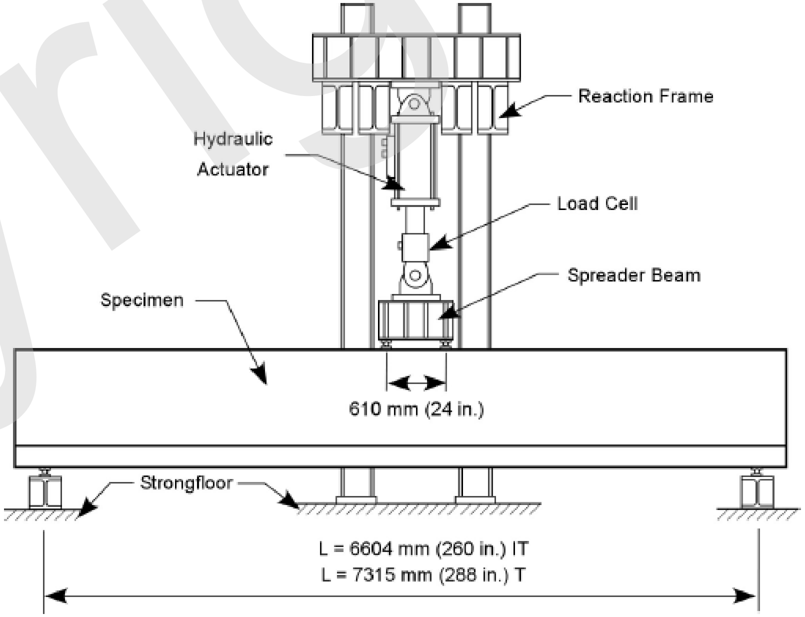
Experimental Work

- **Full-scale tests** with typical proportions and materials from legacy designs
- **Shear specimens: 10** (3 control)

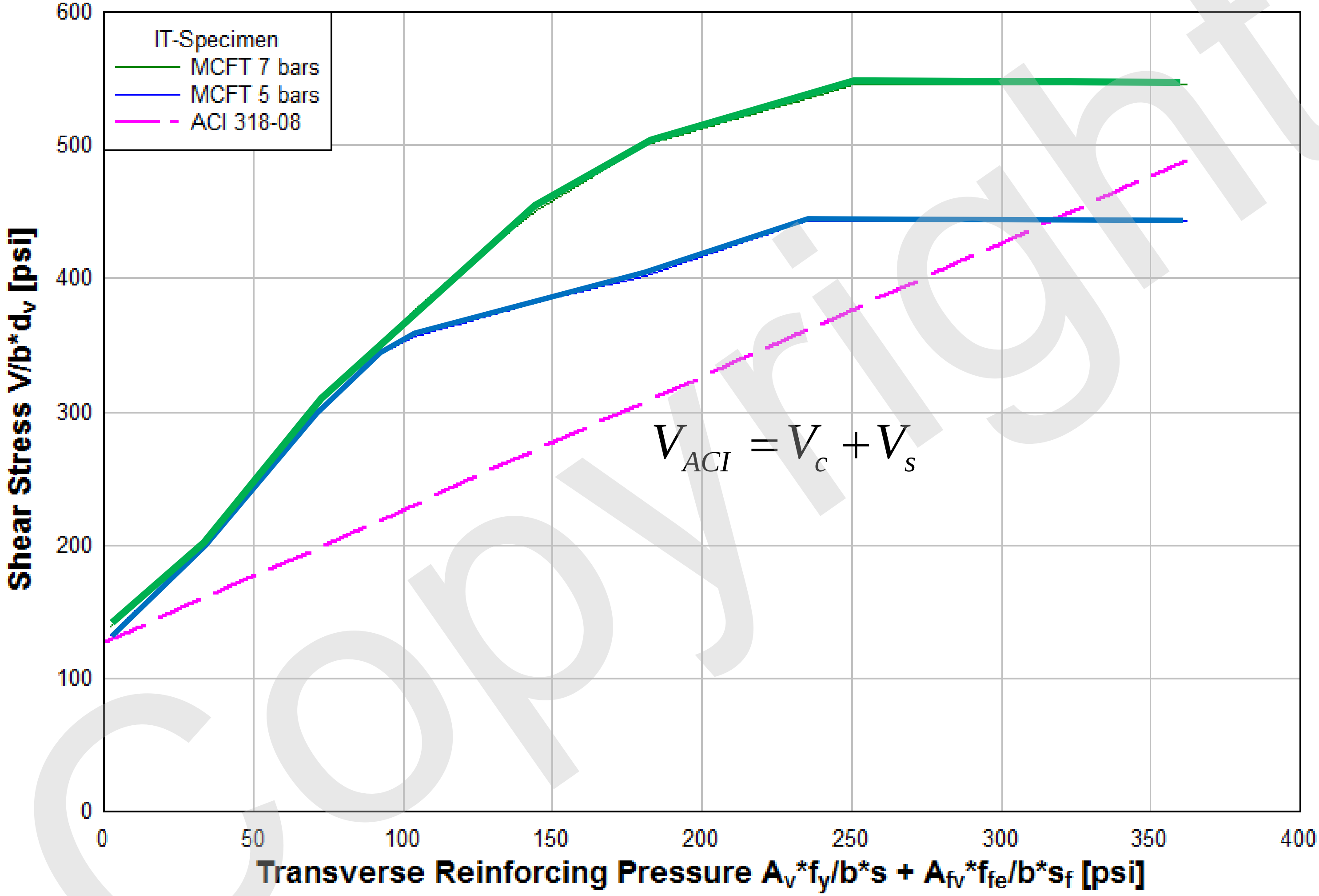
  1/4 in. diameter TiABs
- **Flexure specimens: 10** (3 control)

  5/8 in. diameter TiABs
- **Fatigue and freeze-thaw exposure**: 3 (2 shear, 1 flexure)



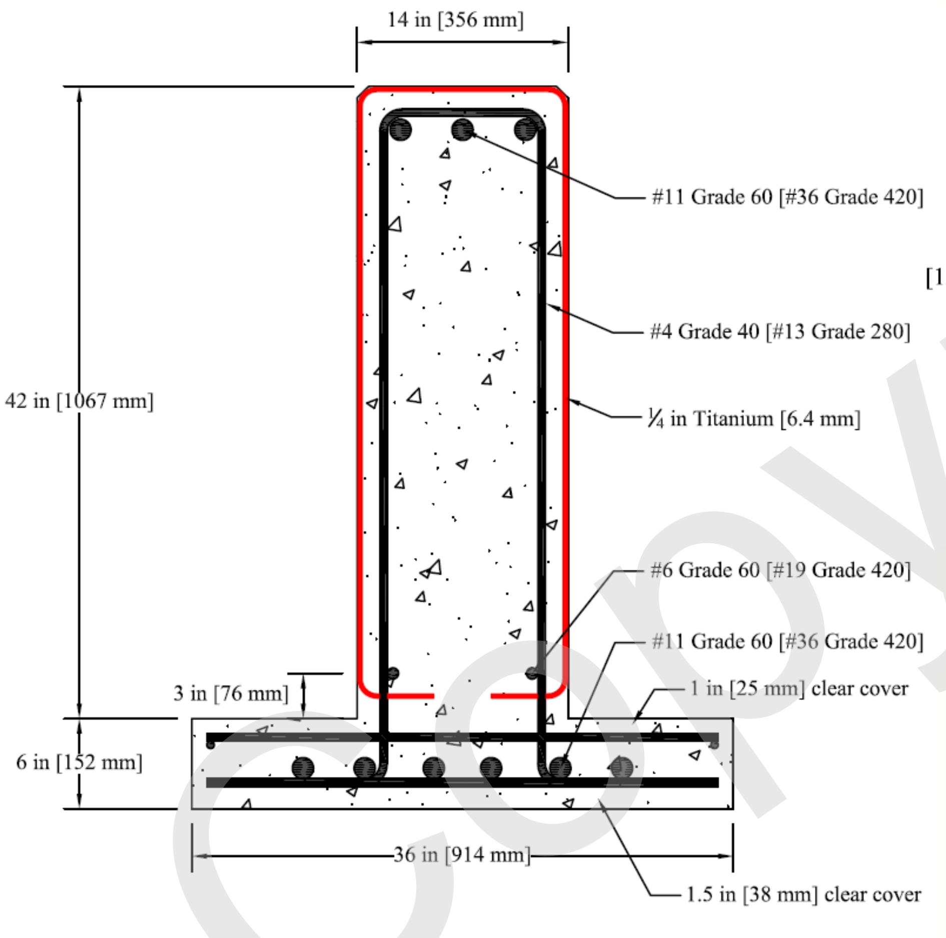
4 ft height, 24 ft long, 20,000 lb

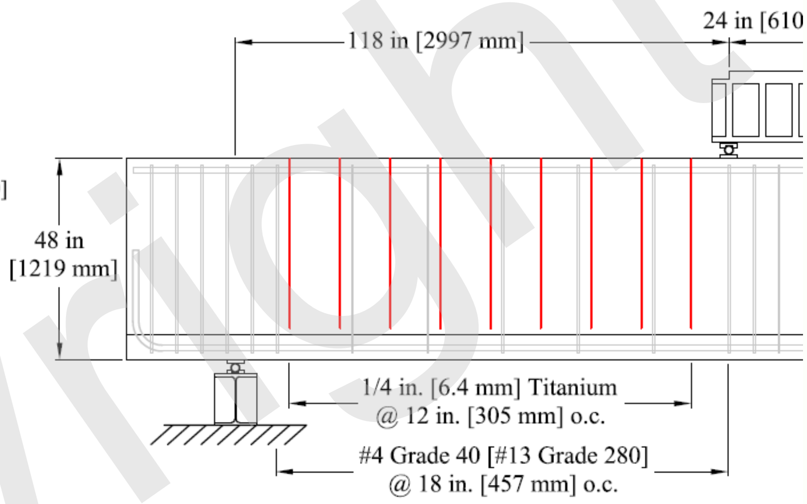
Shear Strengthening Considering MCFT

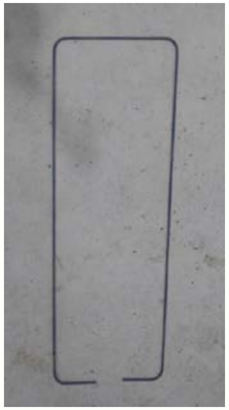


$$V_{ACI} = V_c + V_s$$

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







Shear : Installation

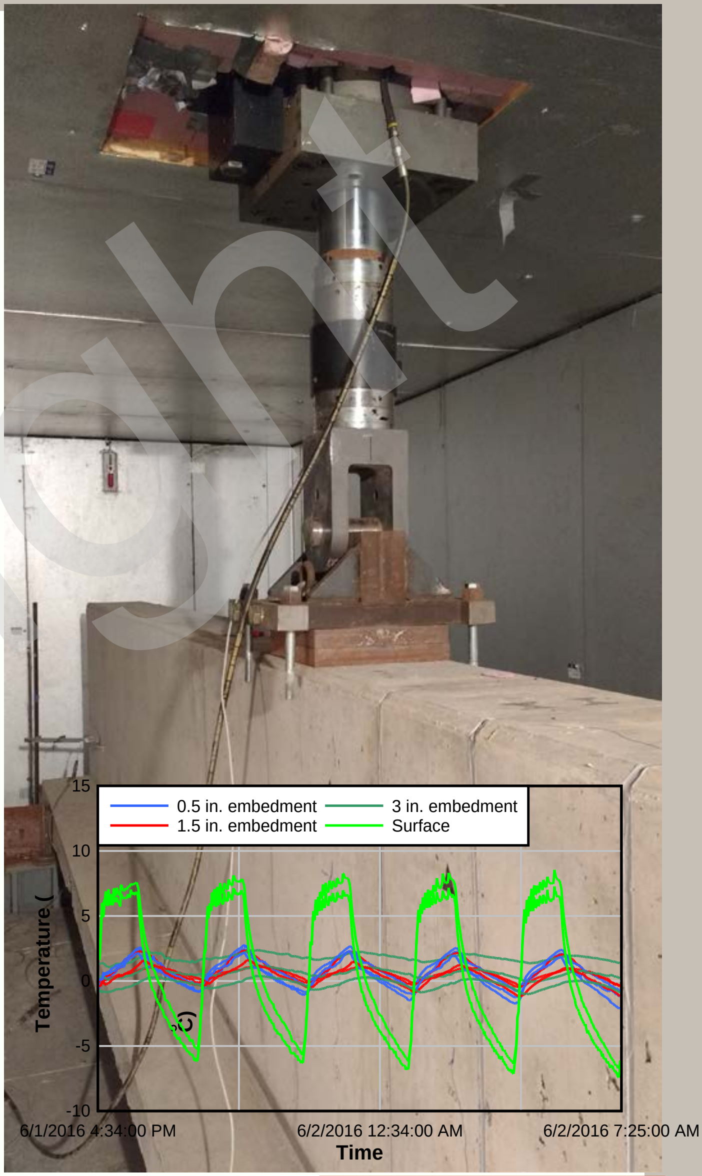
Shear : Fatigue with Freeze-Thaw

- 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



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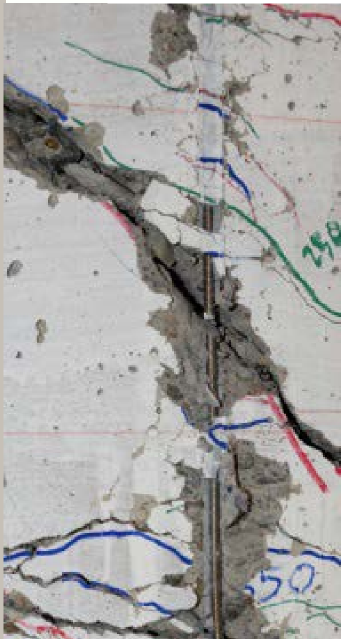
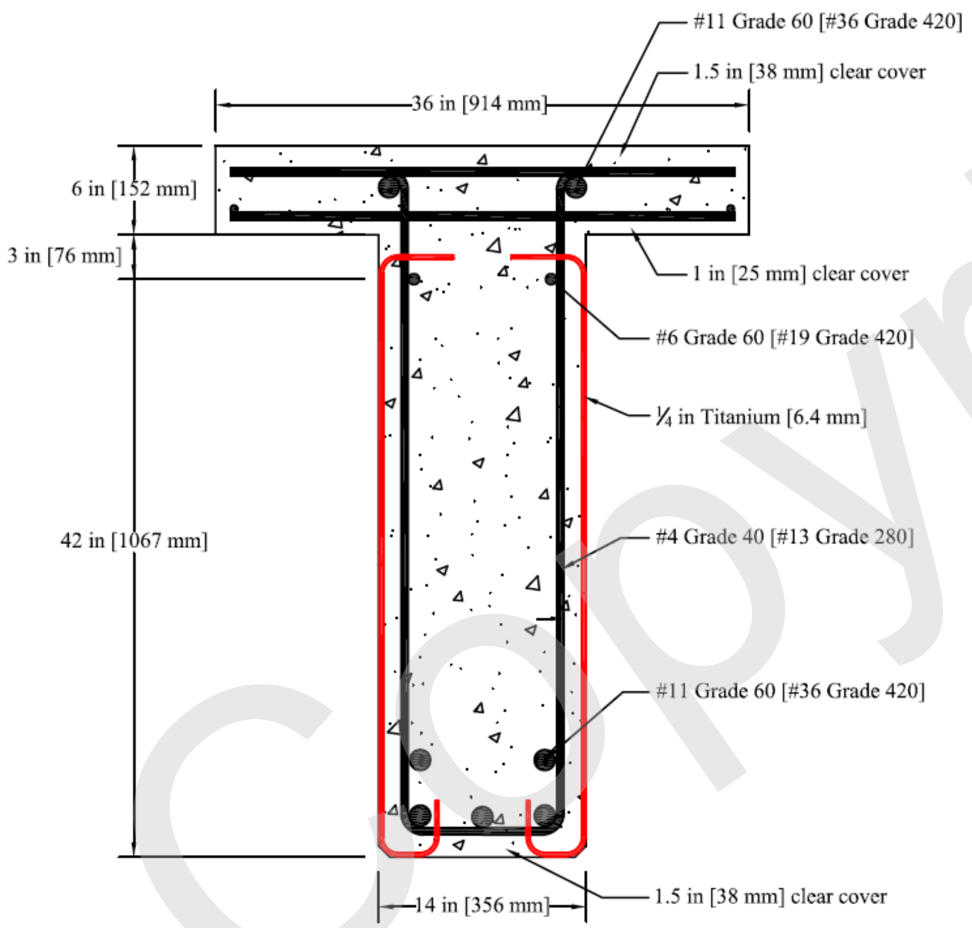
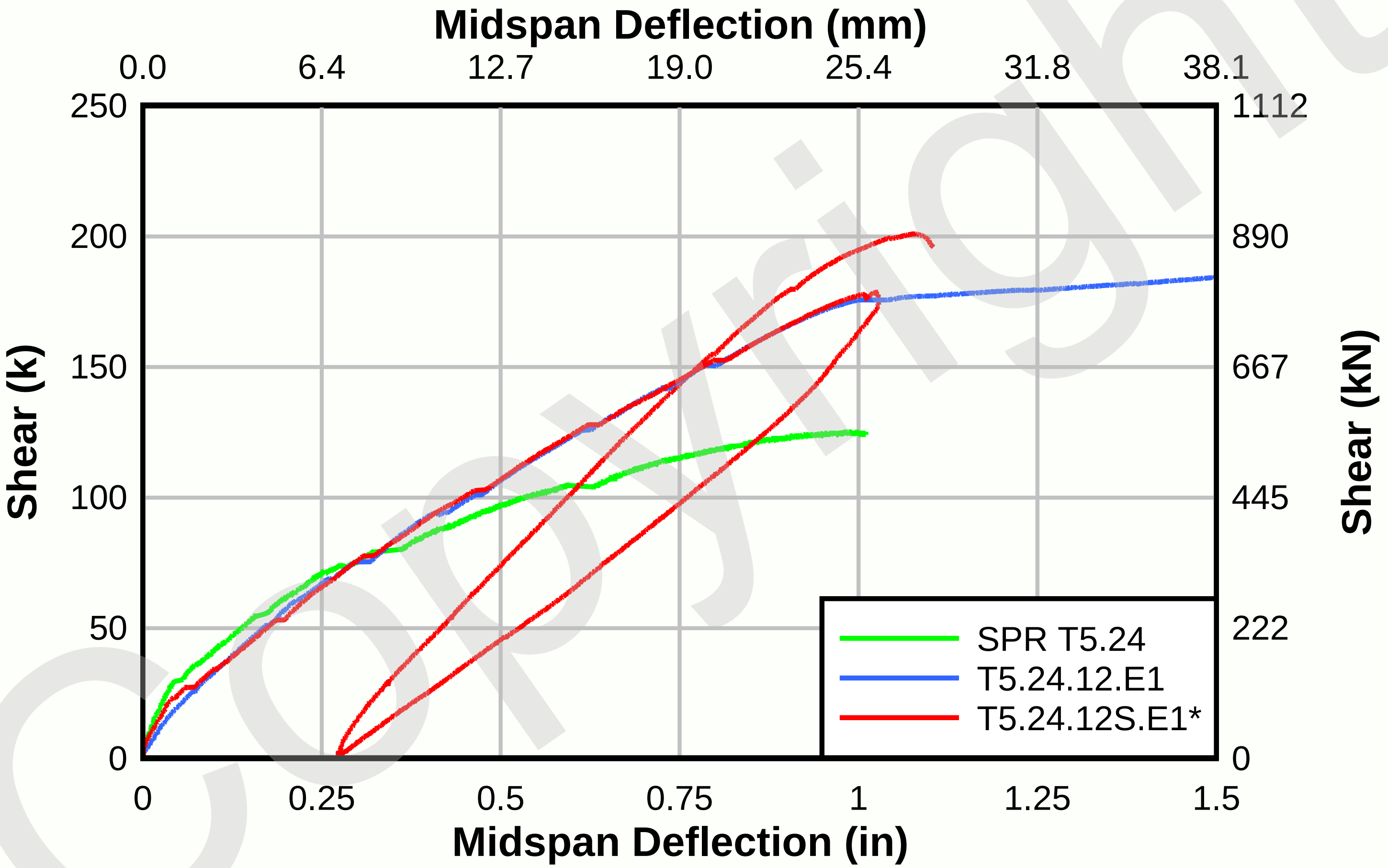

250
350


300

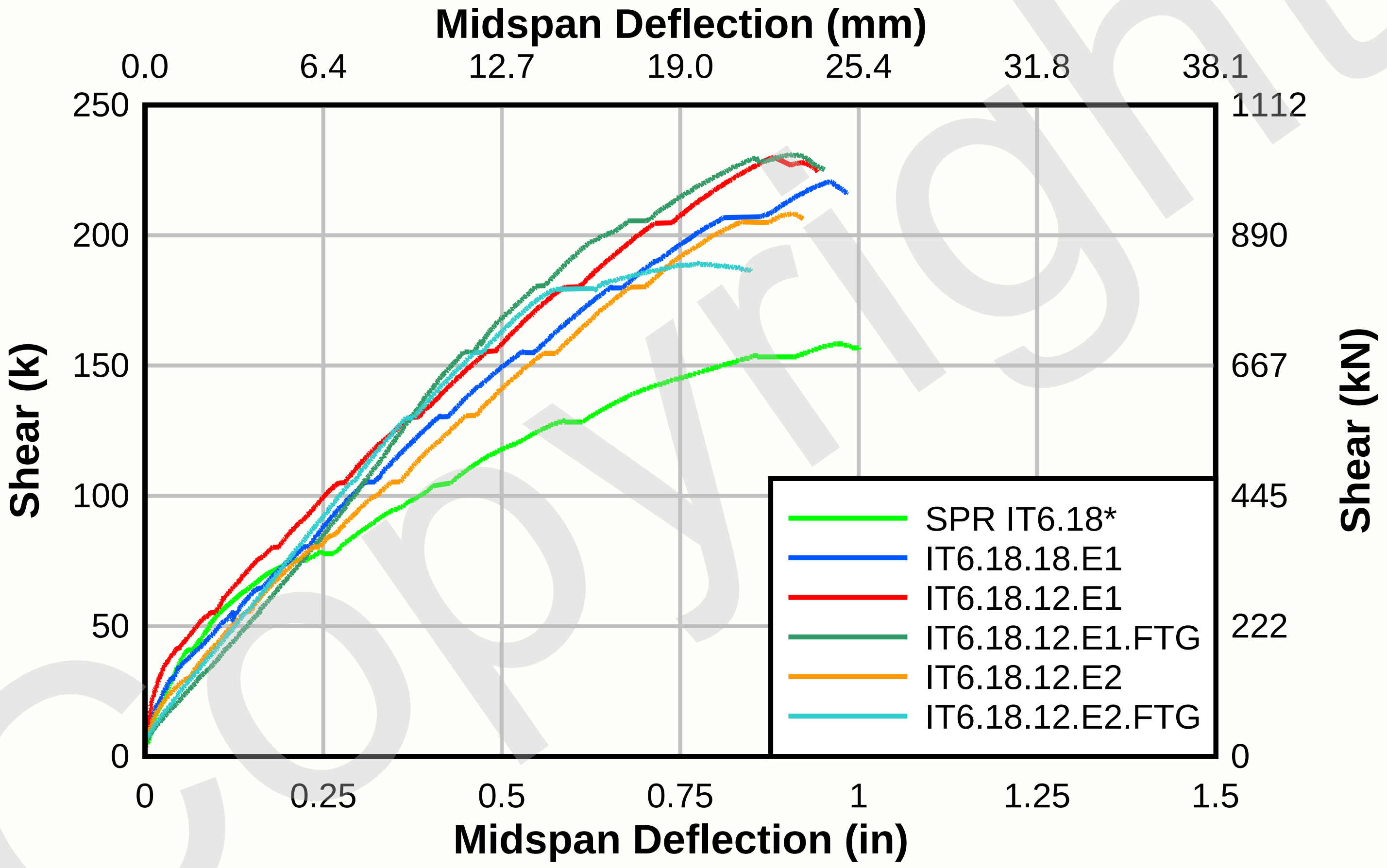
Single Leg Stirrups



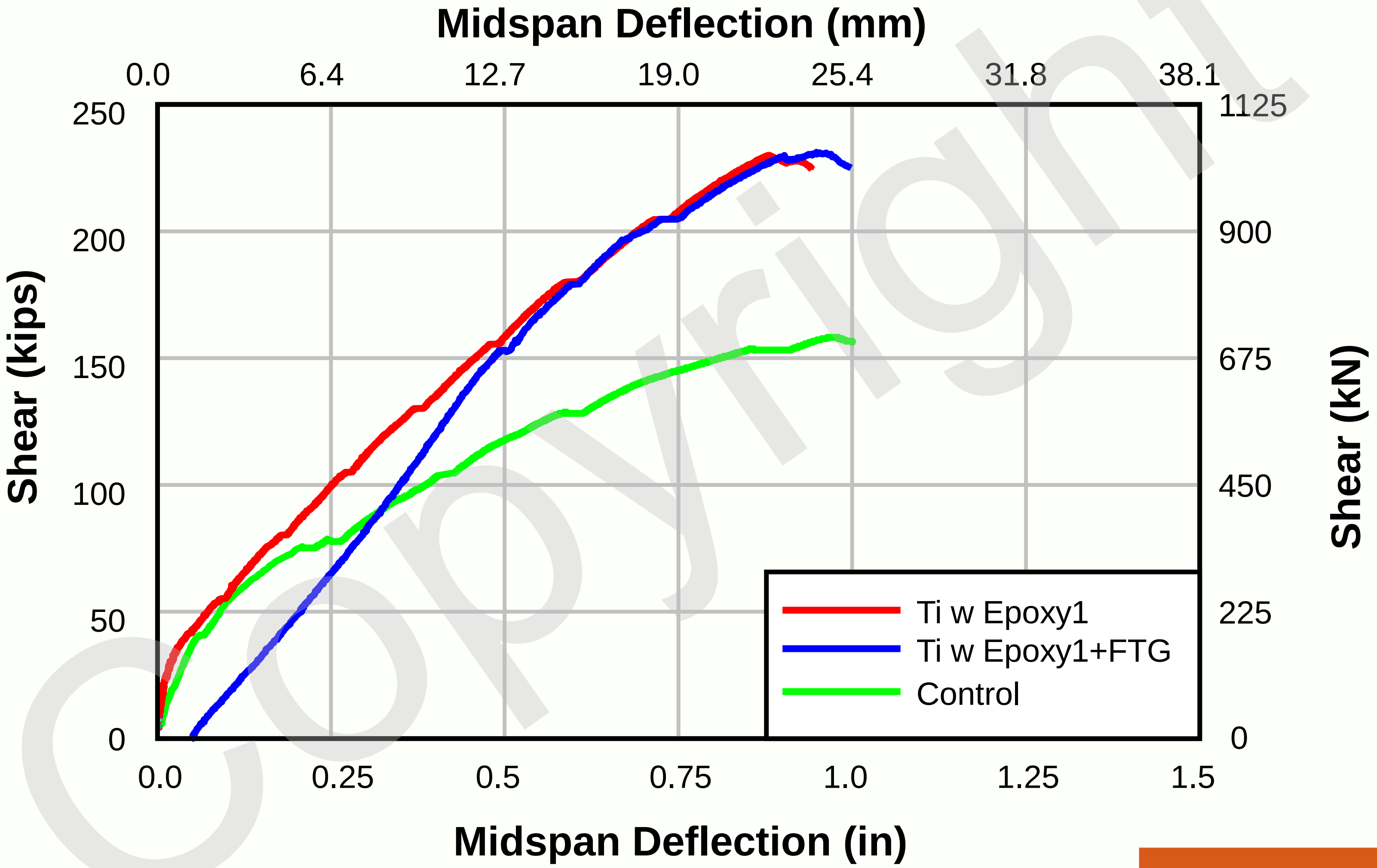
T Specimens Load-Deflection



IT Specimens Load-Deflection



Shear Results Epoxy E1 Ti@ 12 in.



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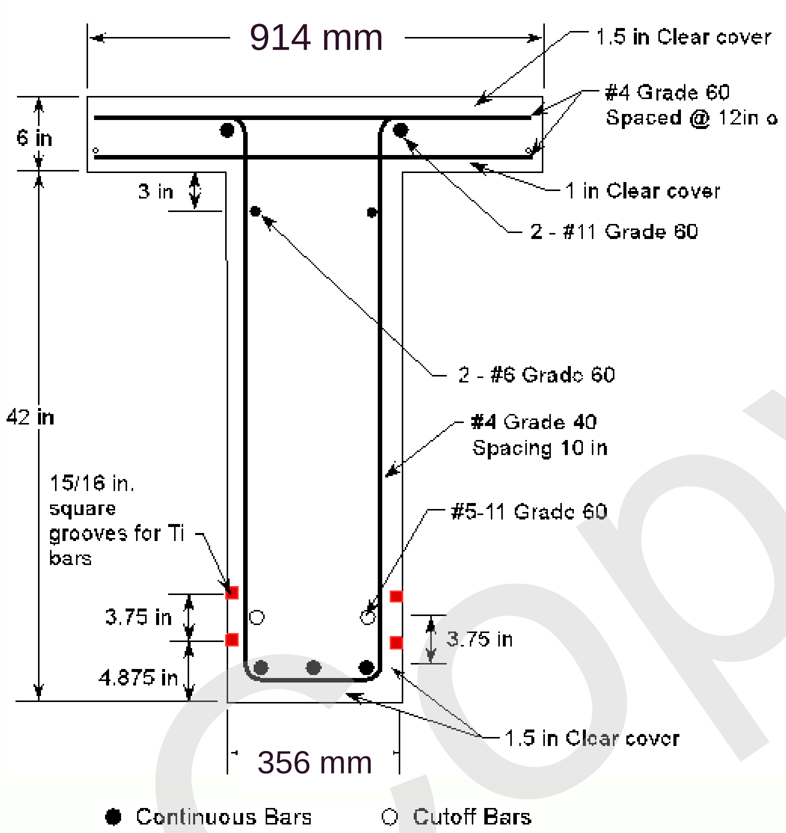
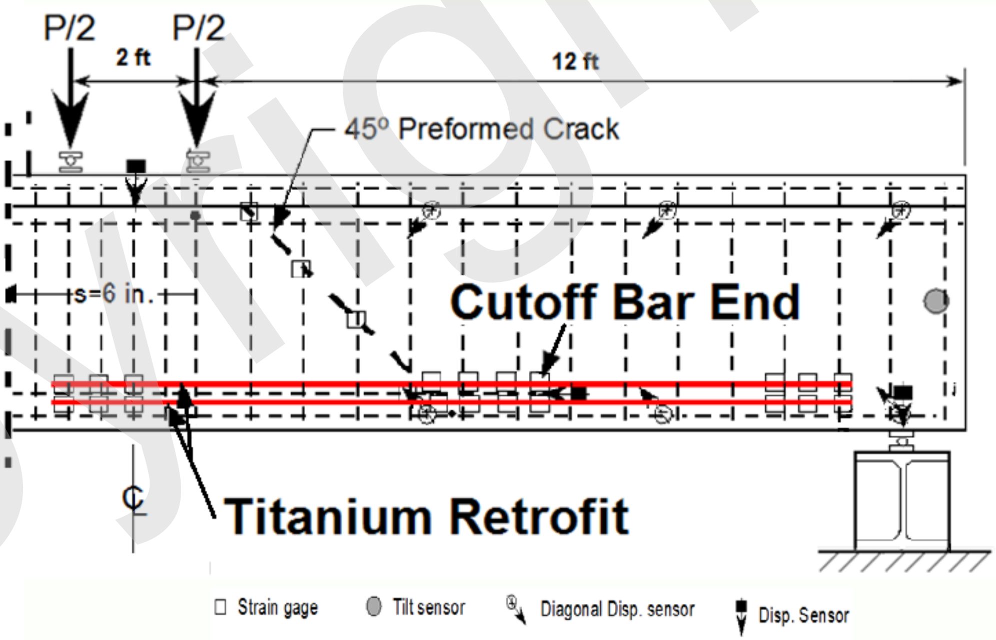
Flexure T Beam Details

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*





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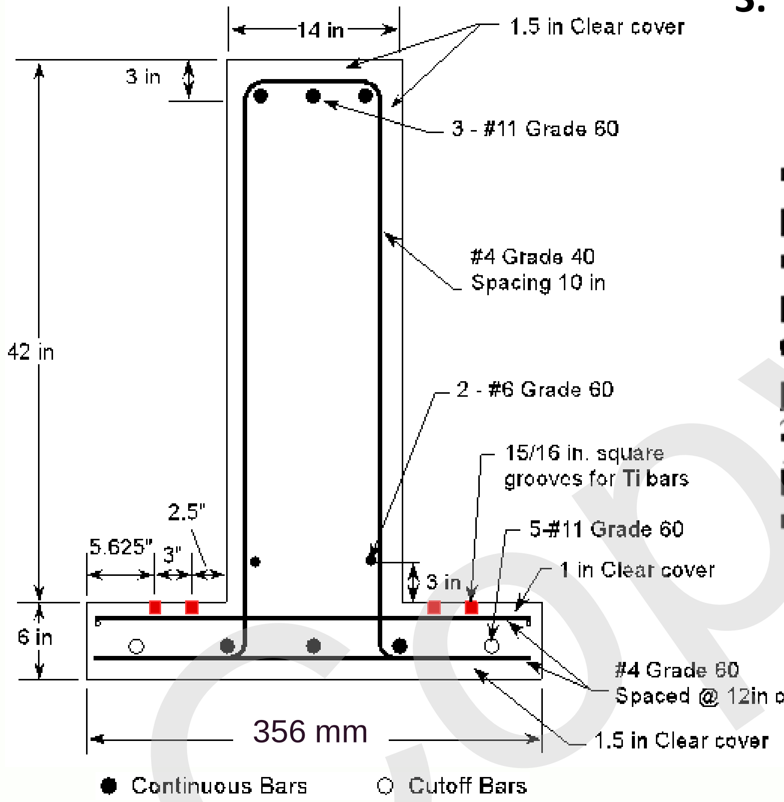
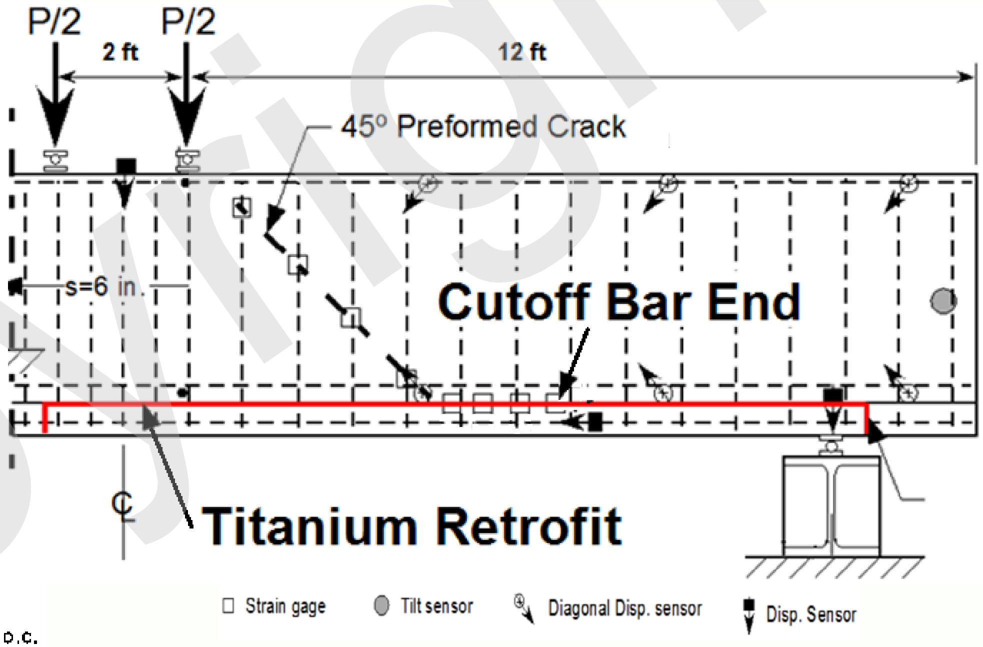
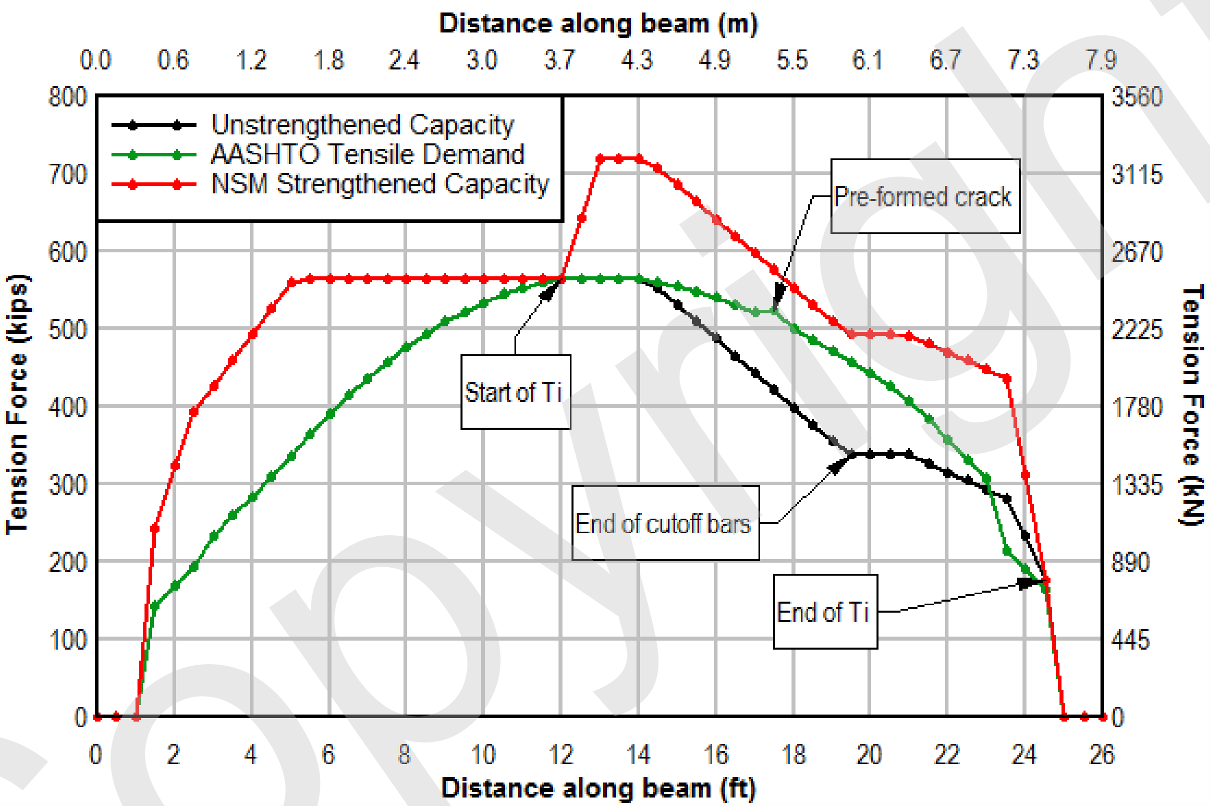
IT Beam Details

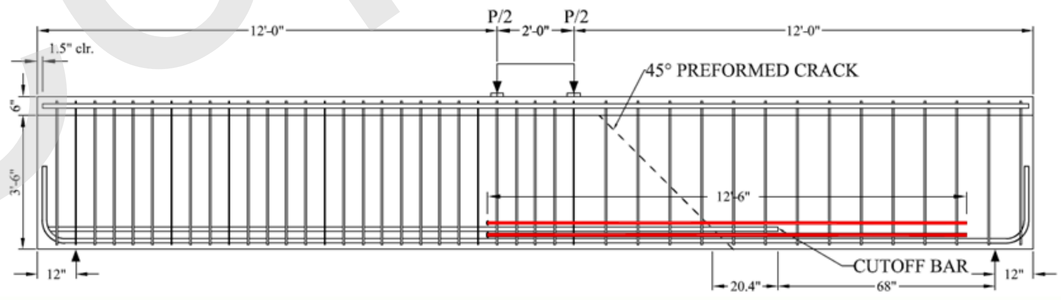
1. **IT.45.Ld2:** *Baseline IT Beam*
2. **IT.45.Ld3.NSM-Ti:** *Titanium with 10 in. stirrups*
3. **IT.45.Ld3.NSM-Ti.2:** *Titanium with 6 in. stirrups*





NSM: DESIGN DEMAND & CAPACITY





T and IT Beam Construction

45° preformed crack

1.5 in. spacer

Cutoff bar

Blockout for slip sensor

Strain gage

Specimen Construction

Blockout for slip sensor

45˚ preformed crack

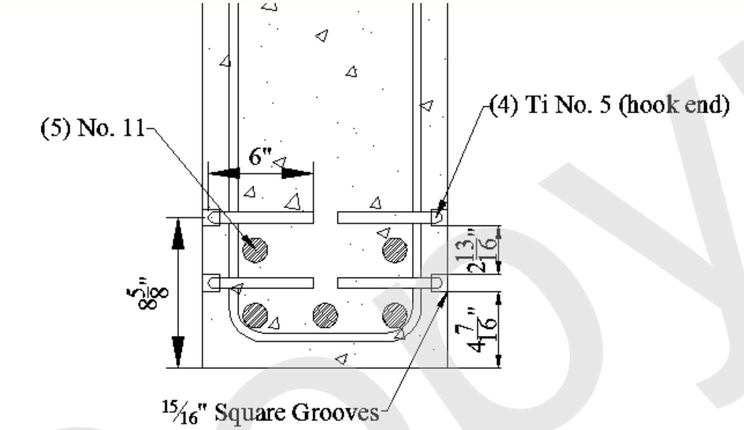
1 in. spacer

Cutoff bar

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

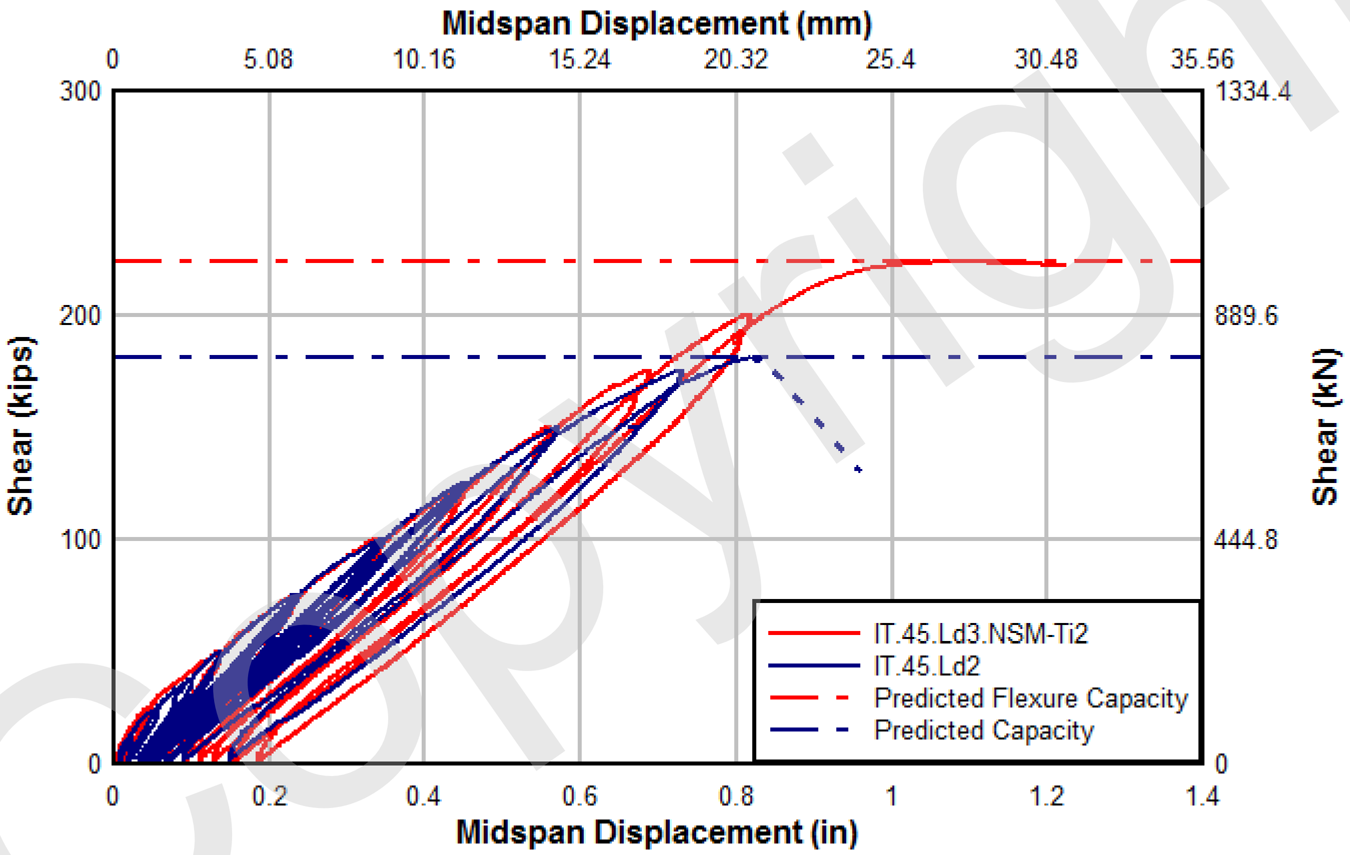
Hook Fabrication

- 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

IT.45.Ld2 Failure

IT.45.Ld3.NSM-Ti2 Failure

IT Beam Experimental Results

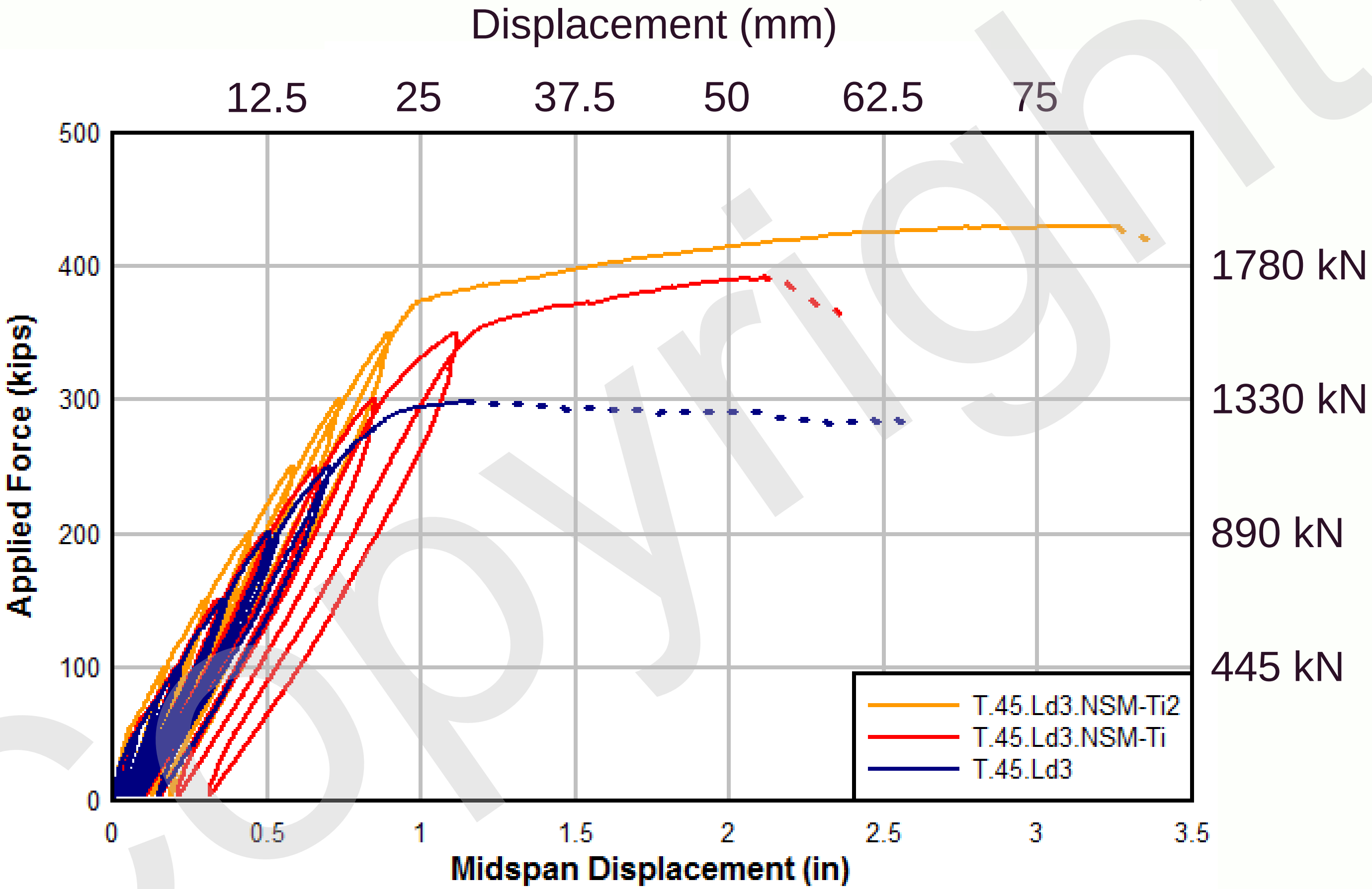


T.45.Ld3 Failure

T.45.Ld3.NSM-Ti Failure

T.45.Ld3.NSM-Ti2 Failure

T 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.

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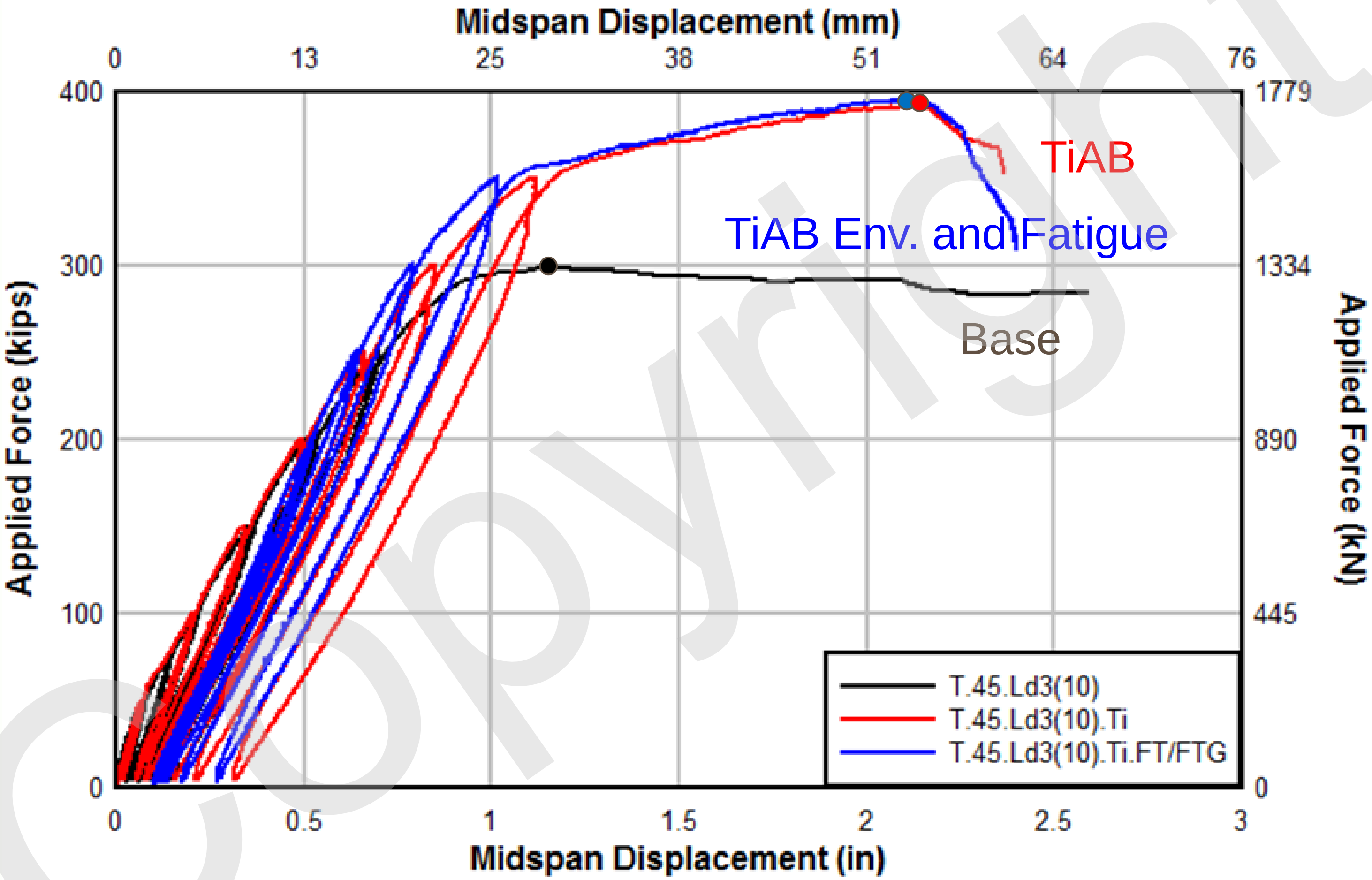
T Beam Experimental Results – Durability (s=10 in.)



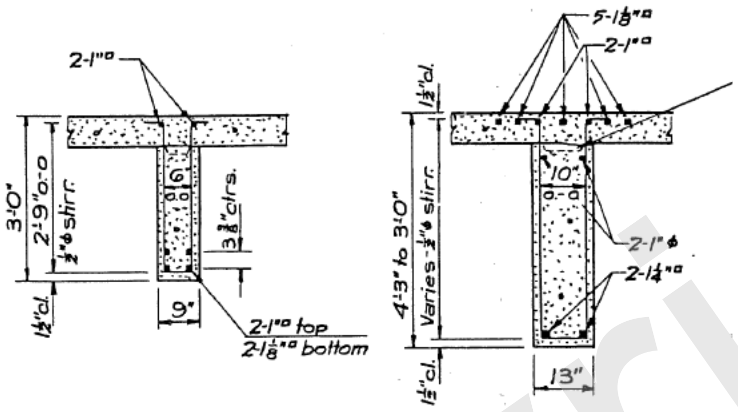
Mosier Overcrossing of Interstate 84

- Built in 1952
- Serves a nearby quarry

Vertical offset on crack face


Elevation View
(2) No. 8 @130" o-o
(2) No. 8 @ 160" o-o
(2) No. 7 @ 212" o-o
(1) No. 8 @202" o-o
(2) No. 6 Gr 60 @136" o-o
(2) No. 8 @132" o-o
(2) No. 7 @97" o-o
2'-8"
8'
(2) No. 9 @112" o-o
8'
11 3/4

Mosier As-Built Details



BEAM A

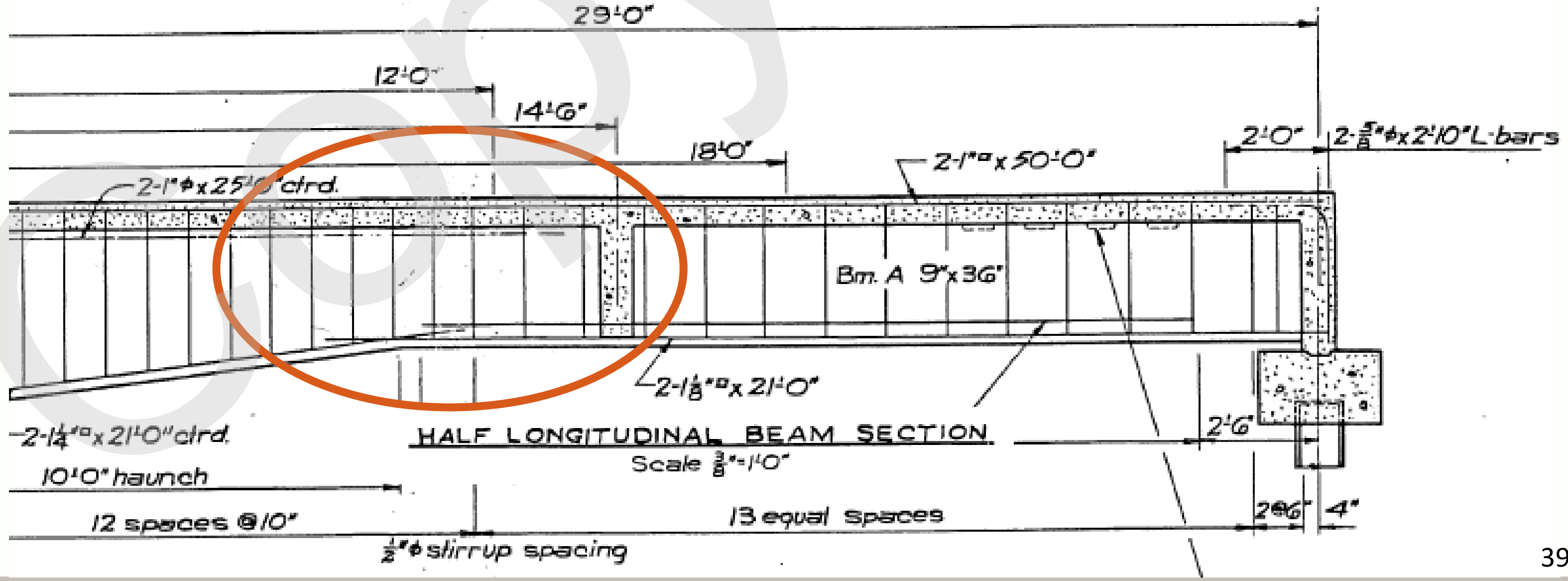
HAUNCH AB

LONGITUDINAL BEAM SECTIONS

Scale 1/2"=1'-0"

DL produces M-

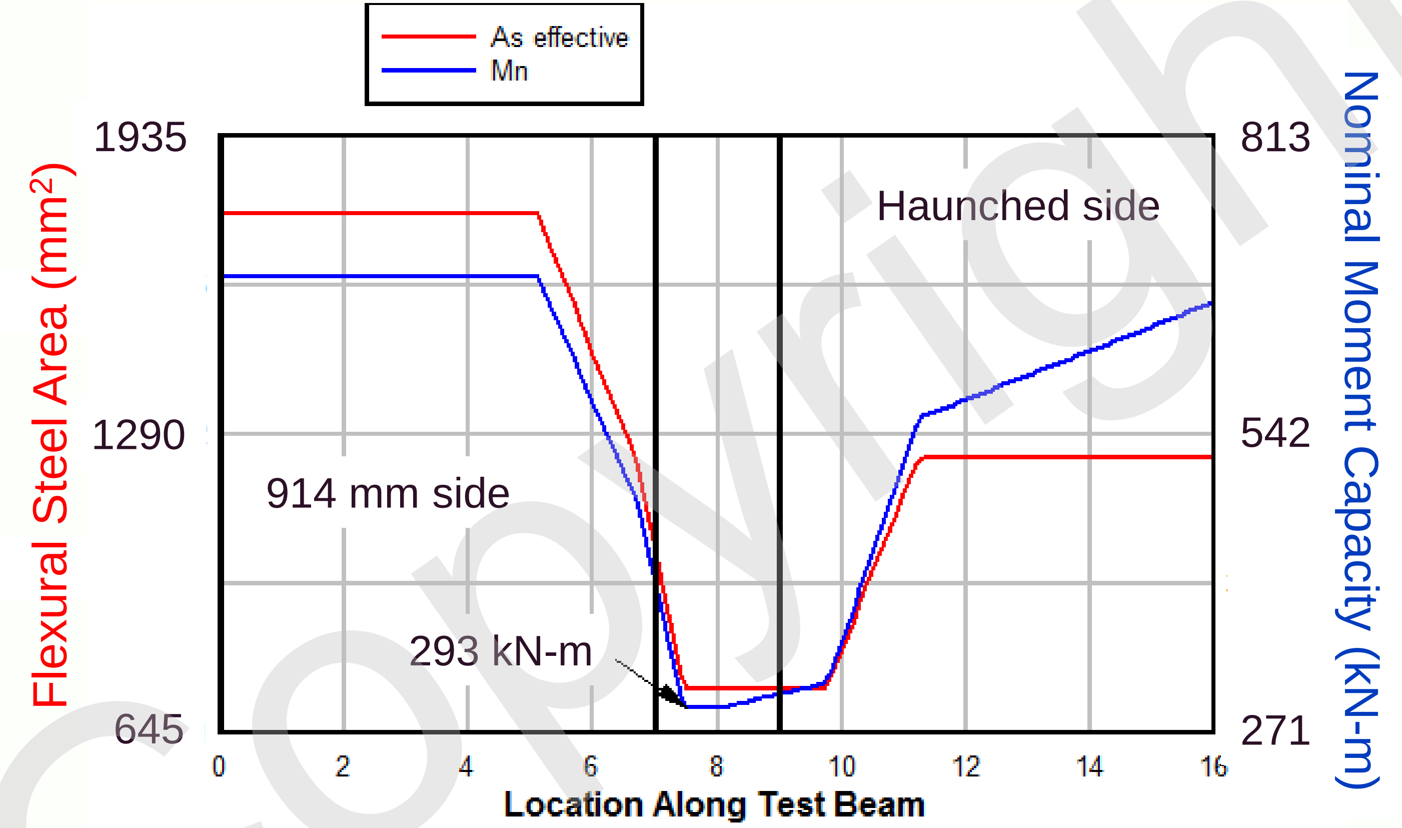
LL produces M+



HALF LONGITUDINAL BEAM SECTION

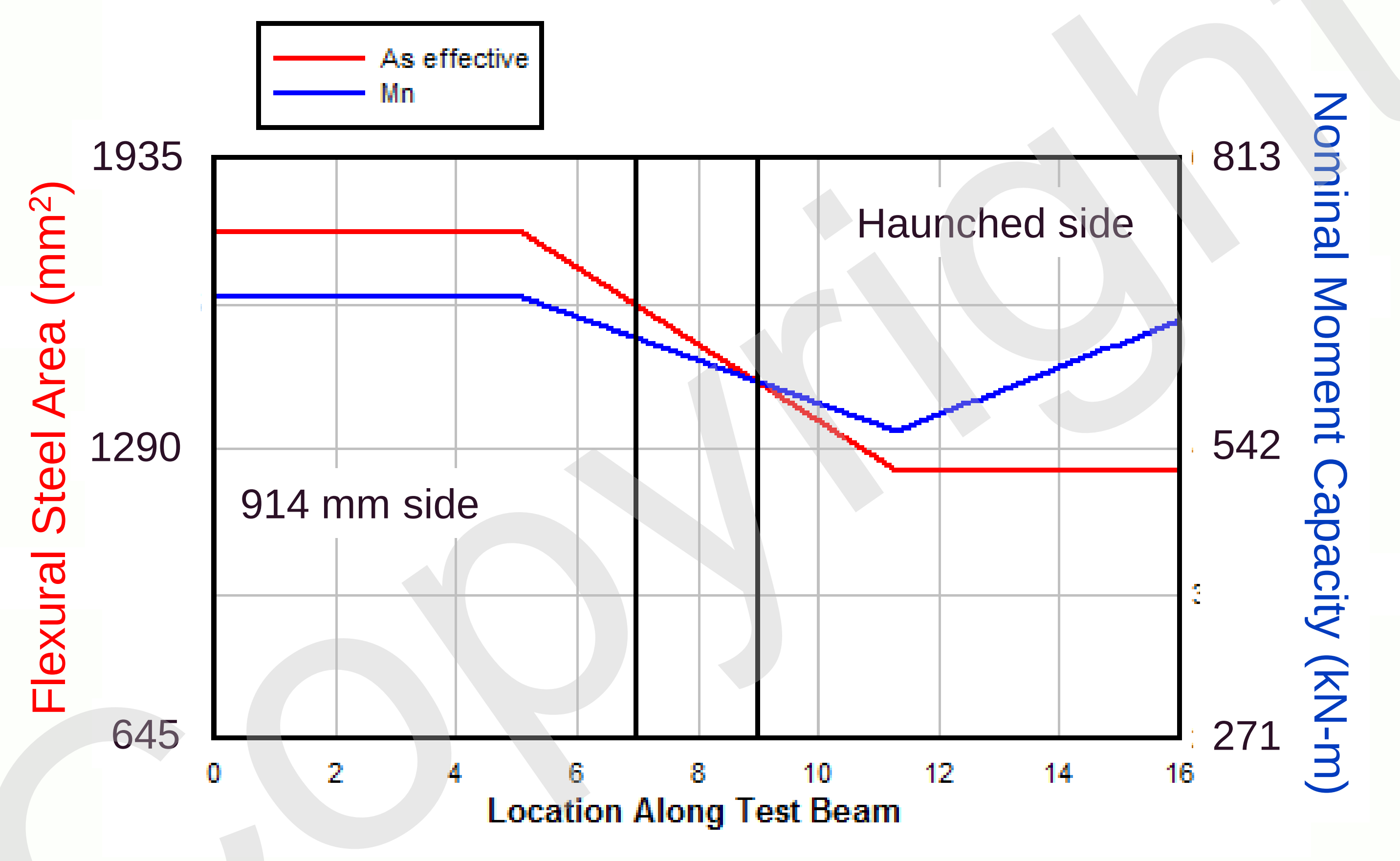
Scale 3/8"=1'-0"

Reduced Positive Moment Capacity at Cutoffs



Designer assumes the steel is completely failed

Reduced Positive Moment Capacity at Cutoffs



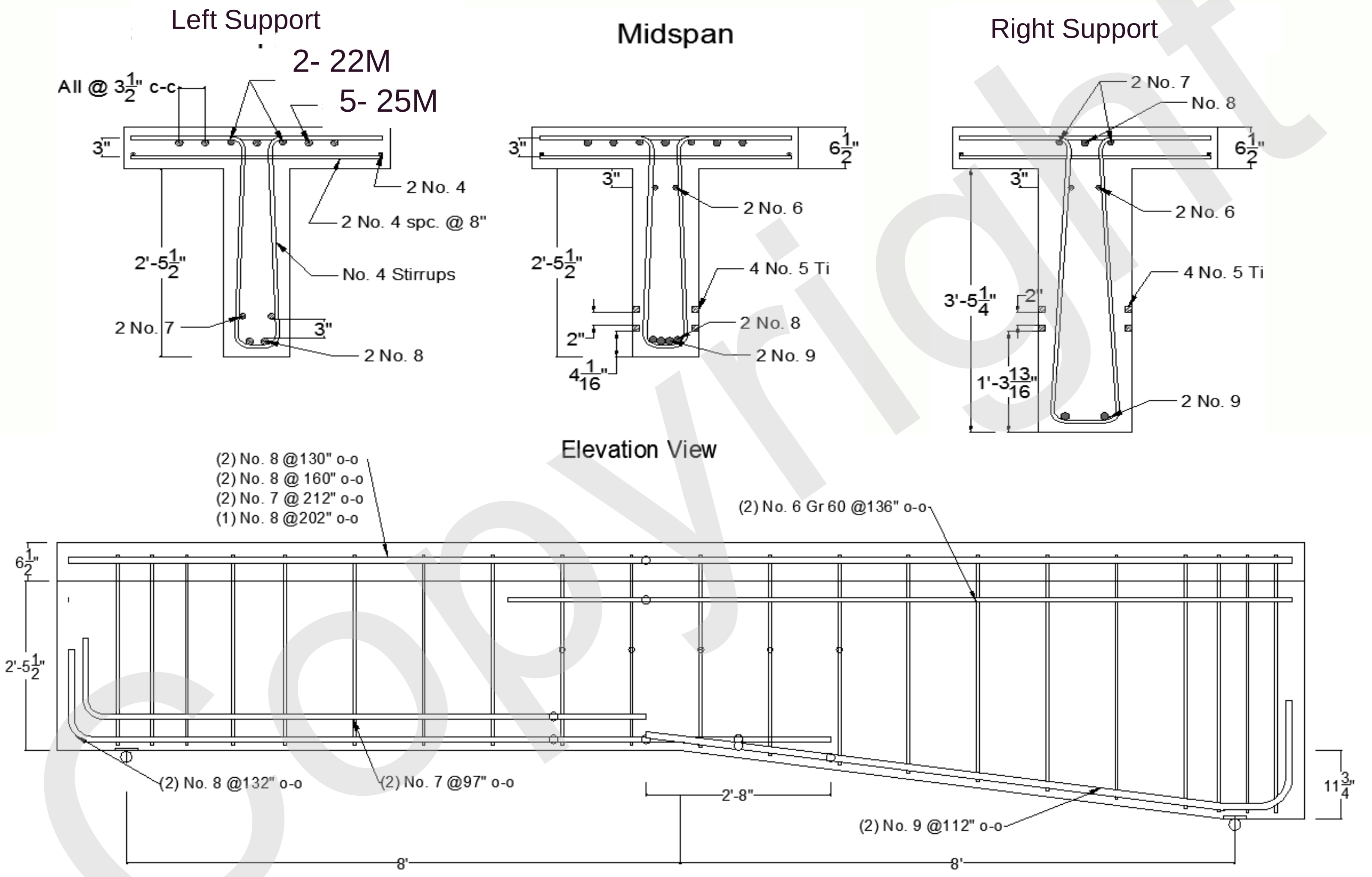
Test Plan

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))

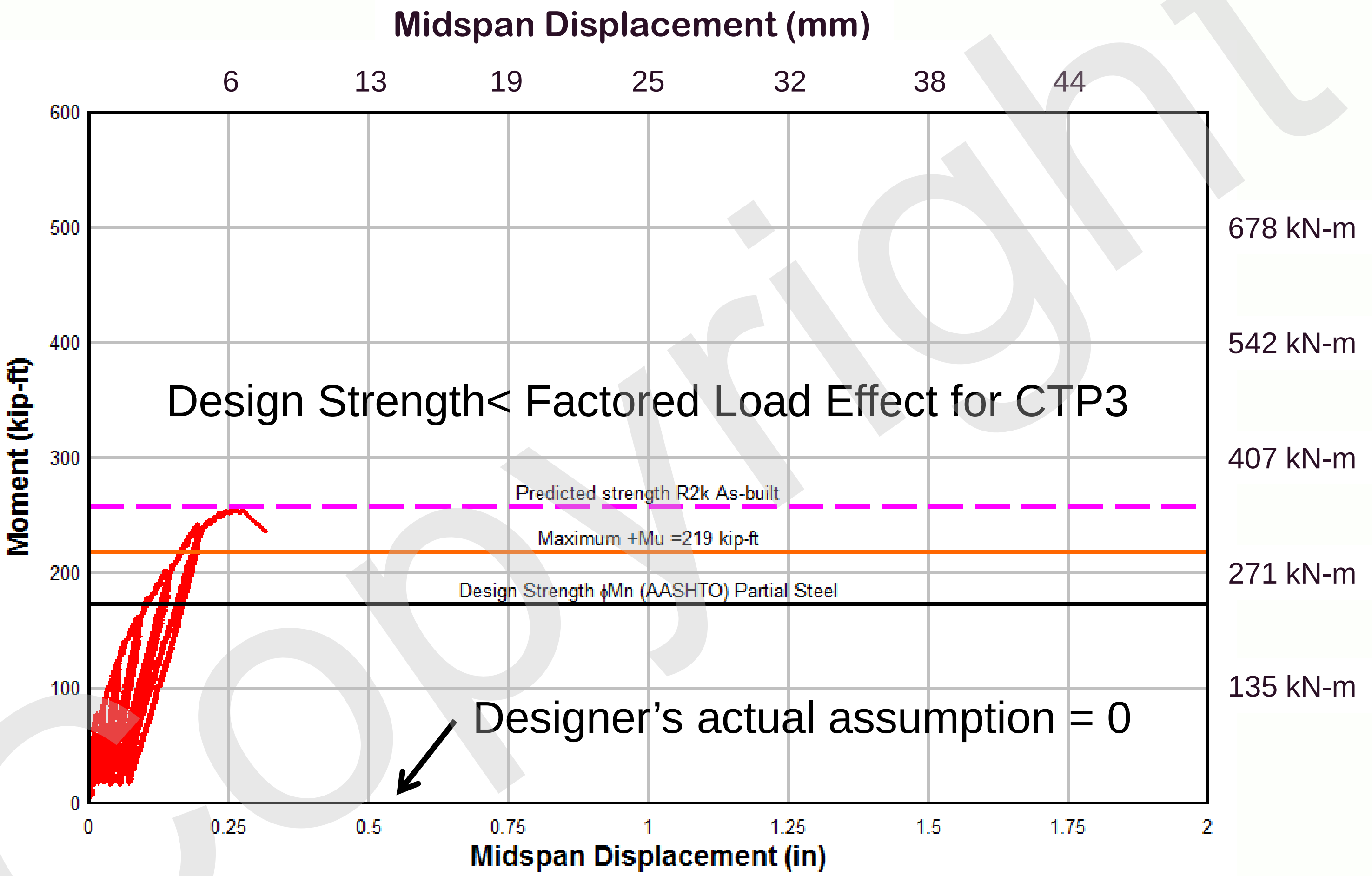
Mosier Beam Details



Mosier Construction

Experimental Results: Mosier 1

Experimental Results: Mosier 1

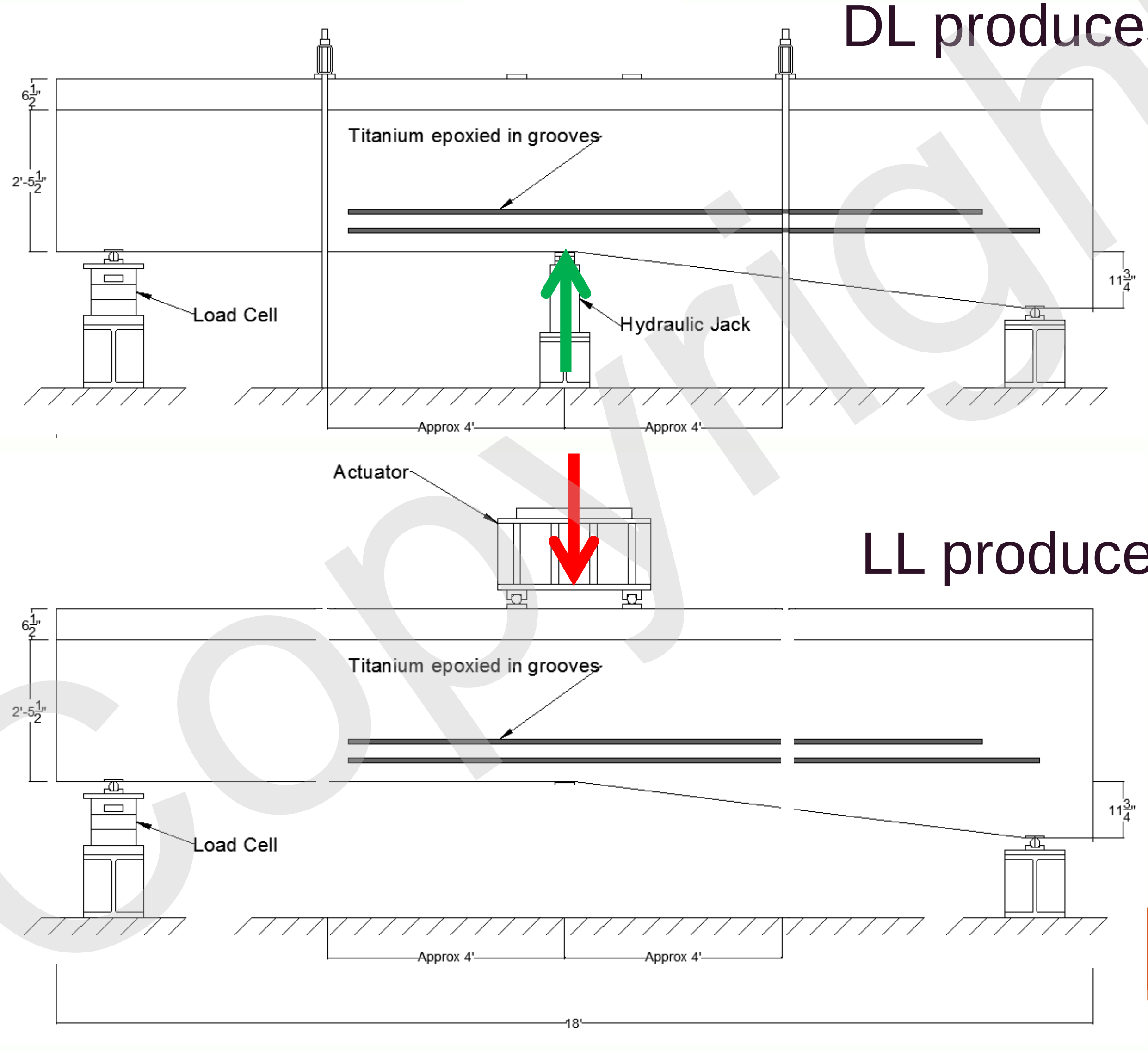


Design Strength< Factored Load Effect for CTP3

Designer's actual assumption = 0

Mosier Test Setup Retrofit

DL produces M-



LL produces M+

Ti-NSM Retrofit: Mosier

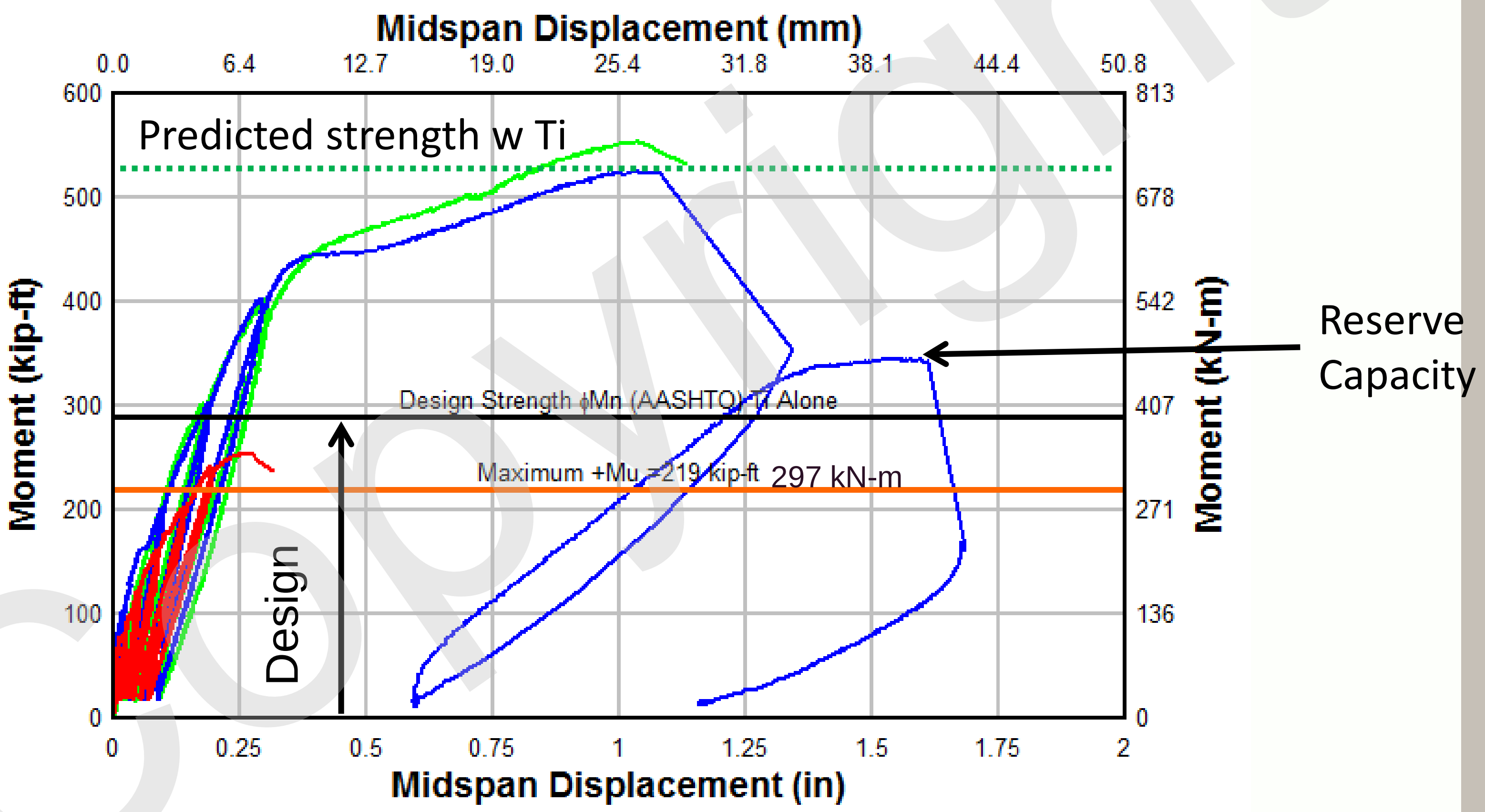
- 2 Ti bars on each side
  - 12 ft lengths
  - 6 in. long hooks
- Heat to 480-675 ˚C
- 2 in. diameter bend
- Epoxy in to 1 in. square grooves
- 6 in. deep, 3/4 in. dia. holes

Experimental Results: Mosier 3

Video 1

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

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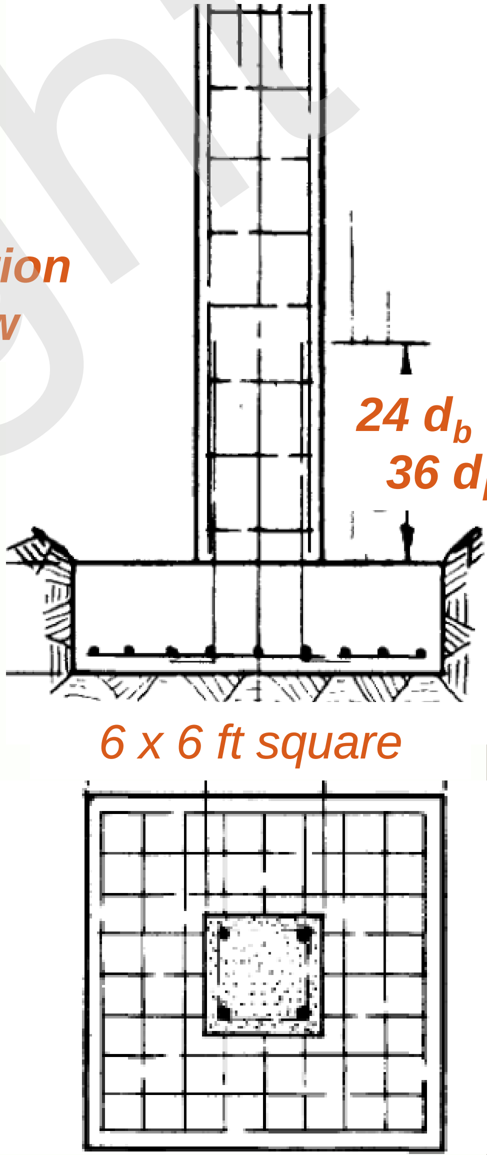
30% less expensive than CFRP

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)



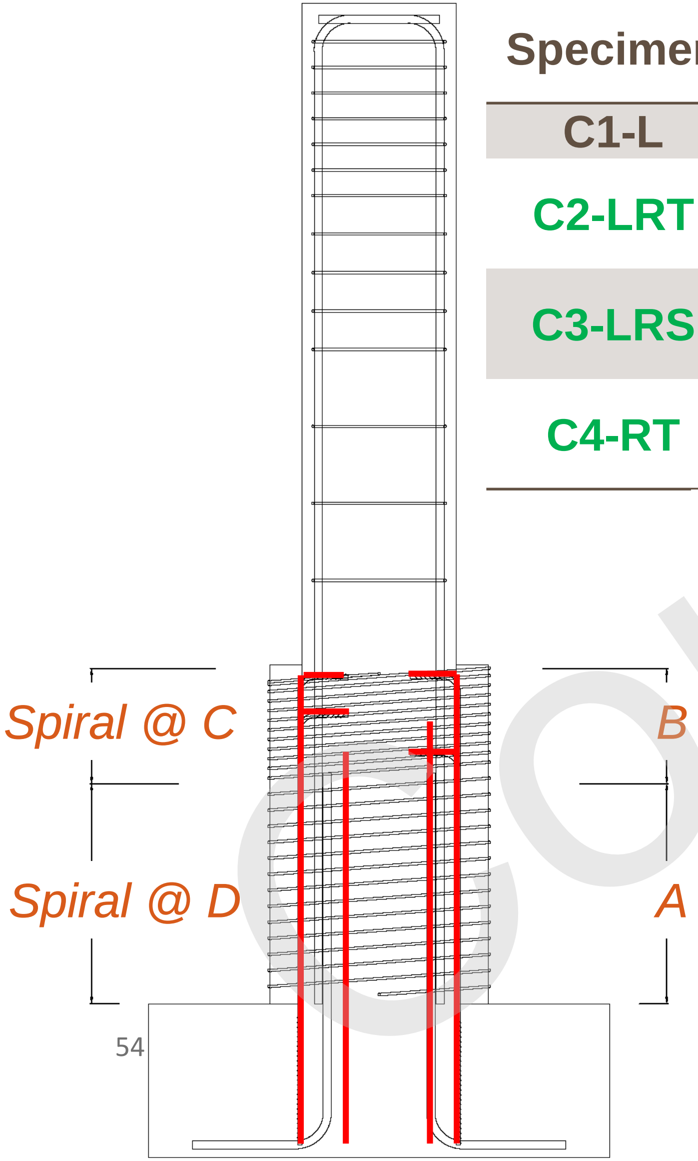
Common Approach for Retrofitting

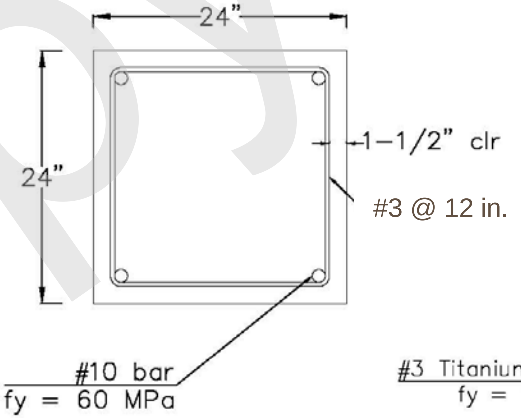
Fiber reinforced (FRP) laminates (Confinement)

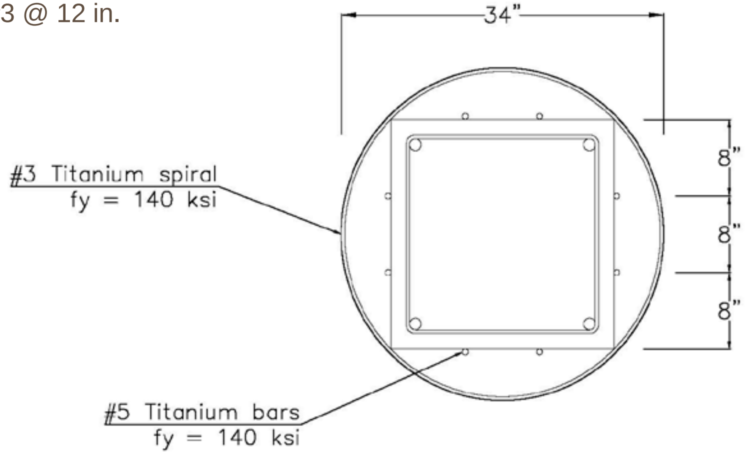
- High-strength
- Surface preparation
- Non-ductile
- Degradation concerns
- Not inspectable

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

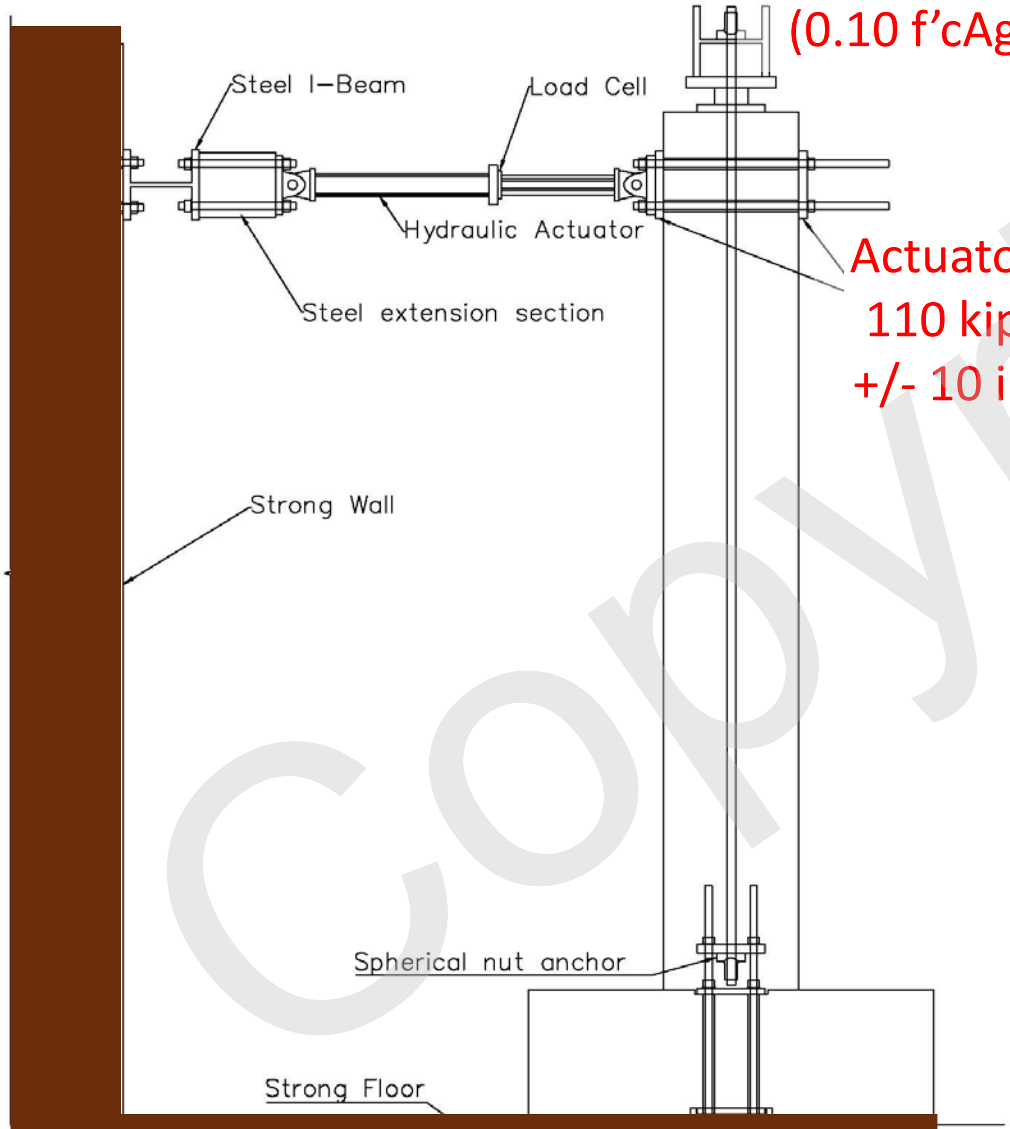






Experimental Set-Up

Axial load
200 kip
(0.10 f’cAg)



Actuator
110 kip
+/- 10 in

Elevation View

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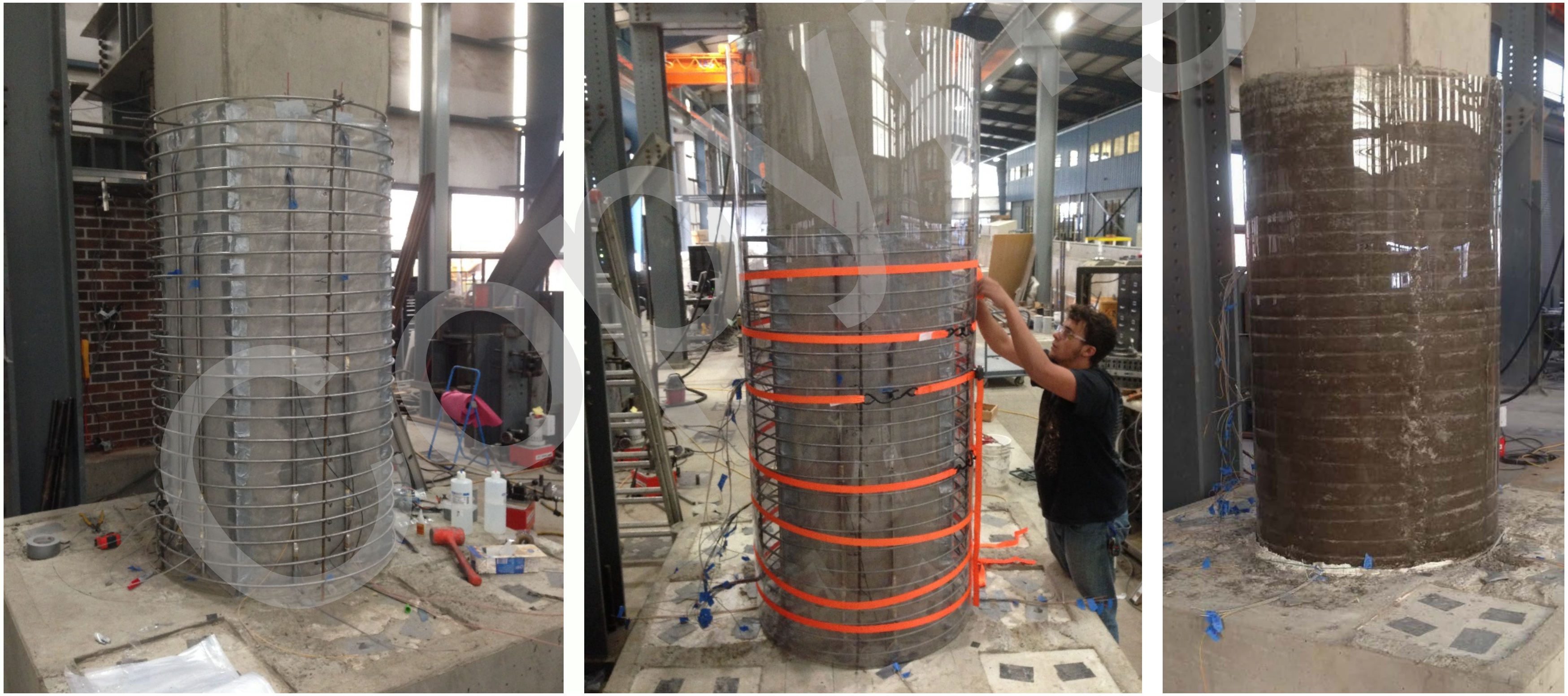
TiAB Spiral Reinforced Concrete Shell

- 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



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

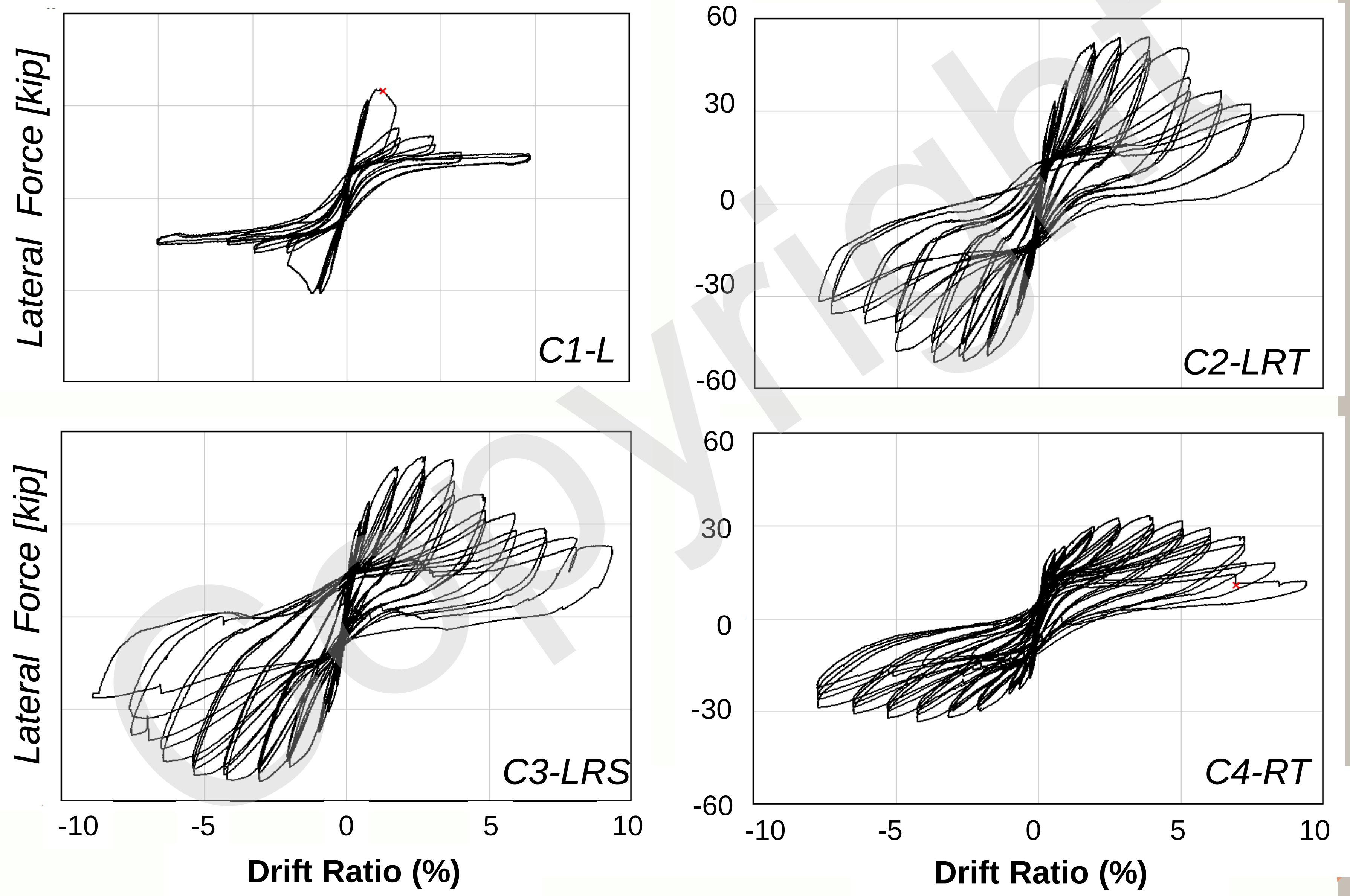
Retrofitted specimens: corner spalling progression

Observed Performance

Retrofitted specimens with lap splices (similar performance):

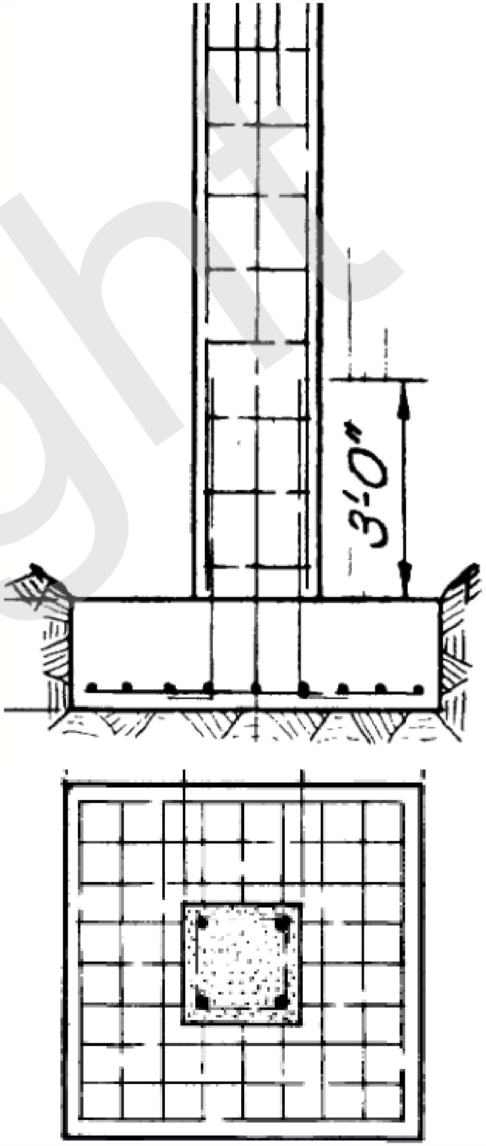
- Ductile withdrawal of hooked anchorages
- Footing concrete spall cones
- Rocking column behavior

Load-Deformation Response



Fuse Seismic Forces Imparted on Footing

- Spread footing
- Timber pile



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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