Design Guidance for UHPC Connections of Precast Girders Made Continuous for Live Load

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ABC-UTC Research Seminar – July 28th, 2023

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Overview

Background

Previous Research and Implementation

Laboratory Testing

Results

Analysis

Conclusions

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Simple Span Bridges

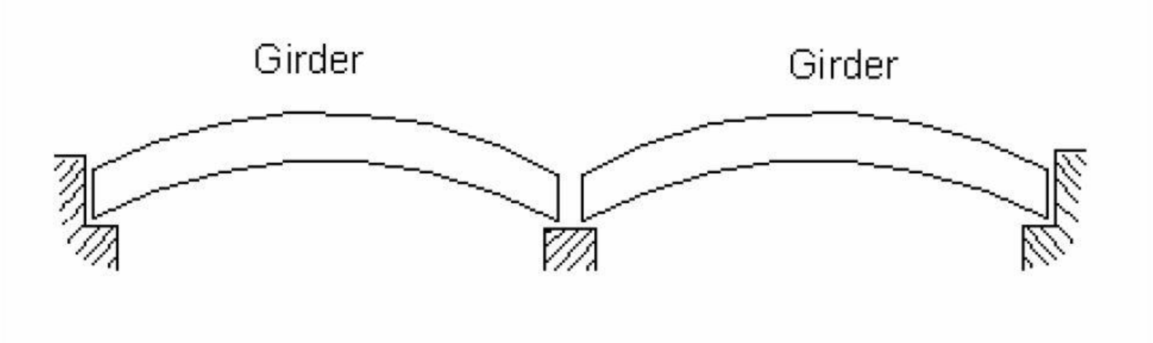

Illustration of simple span beams (Saadeghvaziri et al., 2004)

Expansion joint damage (http://www.toledoblade.com/local/2011/07/08/Defective-bridge-expansion-joint-causes-I-75-delays.html)

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Corrosion and Spalling of Simply Supported Girders

Examples of beam end deterioration in Oklahoma bridges

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Live Load Continuity

- Precast girders made continuous for live load (continuity connections)
  - Typical girder transport and placement
  - Reduce positive moments in span – longer spans, shallower girders, less prestressing
  - Reduce number of deck joints with potential for leakage
  - Potential for a smoother ride
  - Individual connections or full diaphragm
  - Amount continuity is considered in design varies
- Design concerns at the connections
  - Negative moment is resisted by the deck reinforcement
  - Positive restraint moments from creep and shrinkage

Live Load Continuity

Typical cracking in continuity connection on U.S. 283 over S. Canadian River (Photo courtesy of Walt Peters)

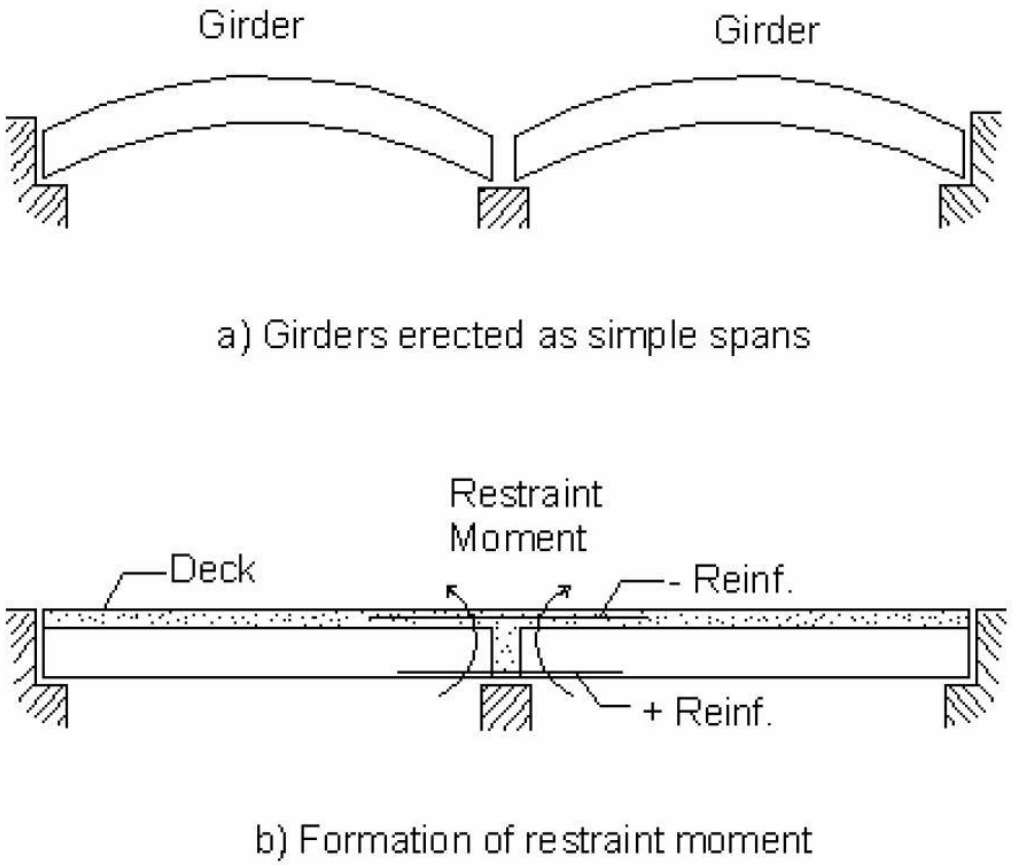

Illustration of restraint moment development (Saadeghvaziri et al., 2004)

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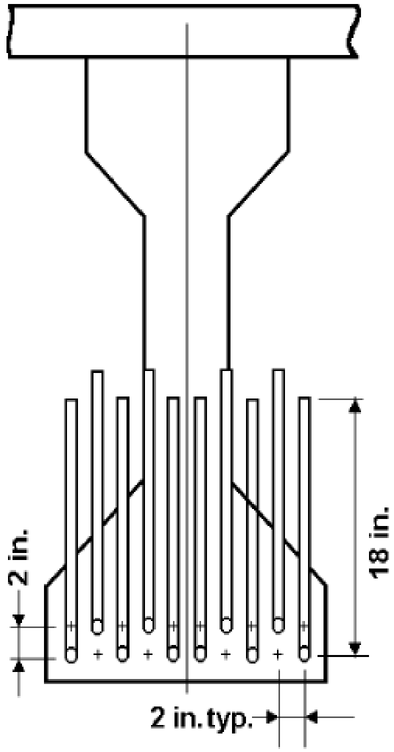
Continuity Connections

- Prestressed concrete girders became popular for use in U.S.A. bridges in the 1960's
  - Allowed longer spans
  - More efficient sections
- Continuity joints were also used
  - Allows live load to transfer
  - Protect the ends of girders
- Portland Cement Association
  - Conducted studies during the 1960's
  - Positive moment reinforcement required
  - Continuity could be lost



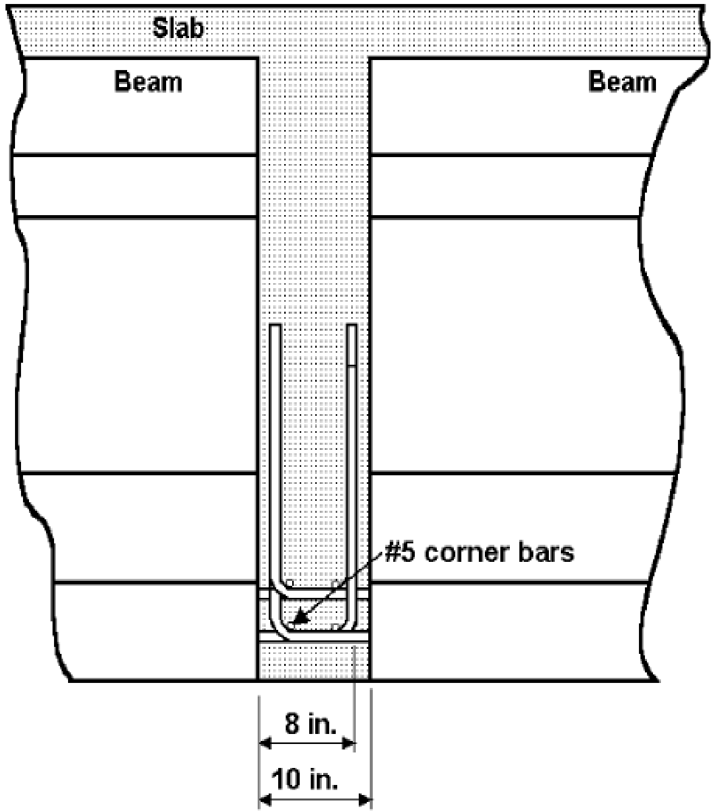


Illustration of typical positive moment reinforcement for live load continuity connection

Continuity Connection Research

NCHRP 322 (Oesterle et al. 1989)

- Analytical study on continuity joints in bridges
- Found no structural benefits
- Continuity joints created additional moments from end restraints

NCHRP 519 (Miller 2004)

- Conducted to further explore findings in NCHRP 322
- Full scale testing of continuity connections
- Concluded continuity joints were still useful

Full-scale load testing of a continuity connection by Miller (2004)

Current Design Practice (1)

- AASHTO LRFD Bridge Design Specifications (2017)
- Consider effect of restraint induced moments or wait 90 days (5.12.3.3.4)
- Minimum factored resistance for positive moment (5.12.3.3.4)
  - 90 day simplification
  - $\Phi M_n \geq 1.2 M_{cr}$
- Positive moment reinforcement either strands or mild steel (5.12.3.3.9)
  - Anchored in the connection
  - Strands shall not be debonded
  - Critical section for development at the face of the girder
- Deck reinforcement used for negative moment (5.12.3.3.8)
- M_{cr} based on beam section and non-prestressed (5.12.3.3.9)

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Current Design Practice (2)

- Requirements to consider the connection fully effective (5.12.3.3.5)
  - Bottom in compression with superimposed dead loads, time-dependent effects, and 50% live load applied
  - Contract documents require 90 days before establishing continuity when restraint moments are not determined
  - Otherwise considered partially effective
- Required positive moment resistance (5.12.3.3.9a)
  - Factored positive restraint moments
  - $0.6M_{cr}$
- Recommended that demand should be limited to $1.2M_{cr}$ (C5.12.3.3.9a)

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Current Design Practice (3)

- Positive moment reinforcement
- Mild steel (5.12.3.3.9b)
  - 90 degree hook or straight bar development (5.10.8)
- Prestressing Strand (5.12.3.3.9c)
  - 90 degree hook or development (5.9.4.3)
  - Strands project at least 8 in. before bend
  - $f_{psl} = \frac{(l_{dsh}-8)}{0.228}$ → max strand stress at the service limit state
  - $f_{pul} = \frac{(l_{dsh}-8)}{0.163}$ → max strand stress at the strength limit state
  - l_{dsh} → total length of extended strand (in.)

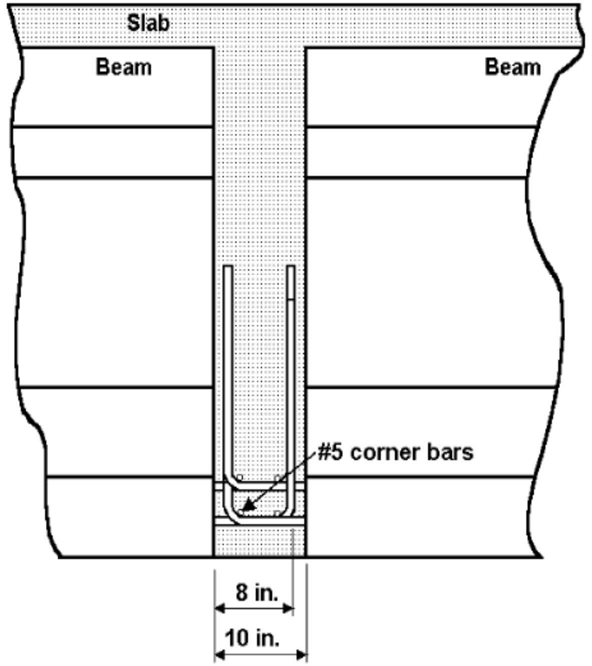

Illustration of hooked strands

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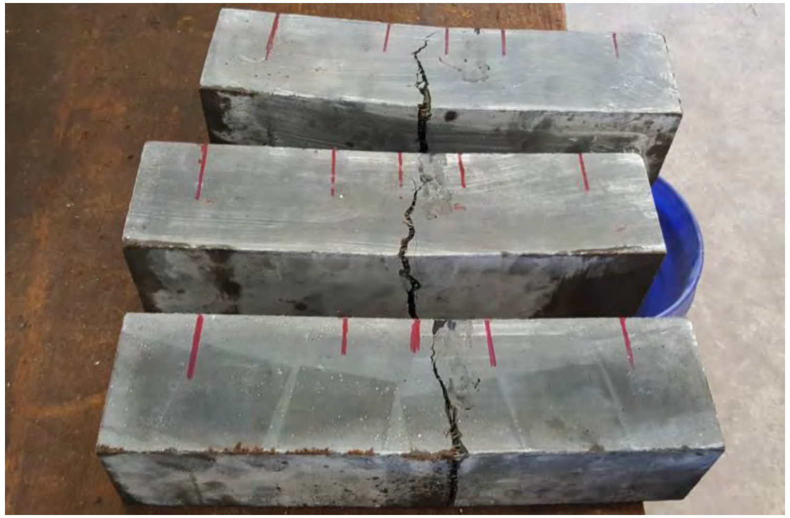
Ultra-High Performance Concrete (UHPC)

- Compressive strength typically greater than 18 ksi
- Fiber-reinforced UHPC can achieve post-cracking flexural strength greater than 0.72 ksi
- Strong bond to adjacent concrete
- Short reinforcement development length
- Potential to increase service life



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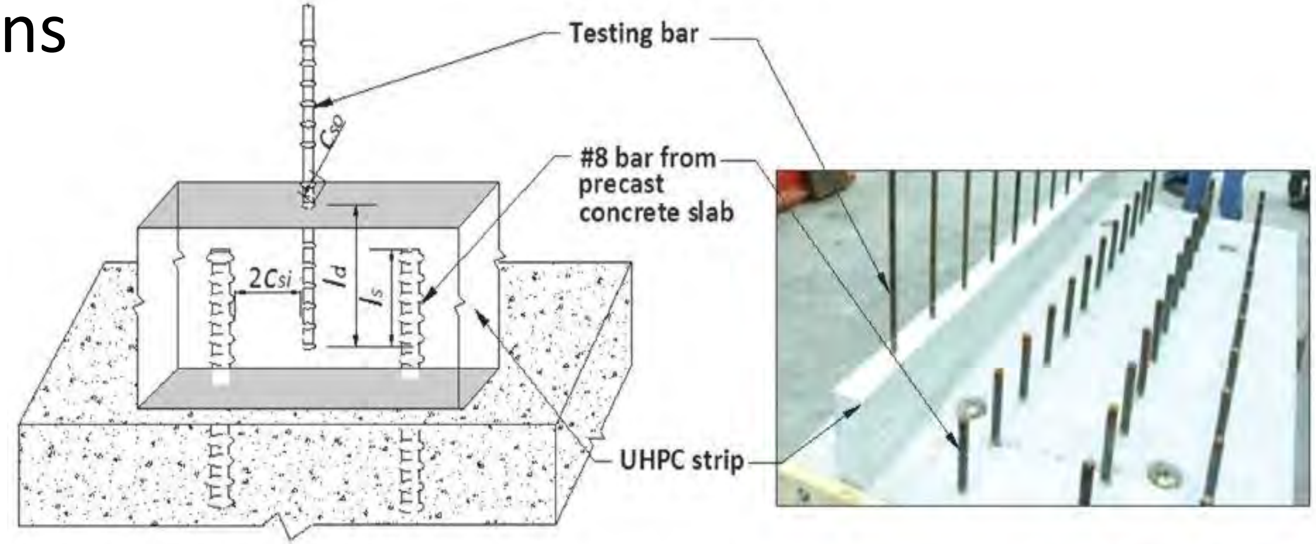
Bond Behavior of Reinforcement in UHPC

Study by Yuan and Graybeal (2014)

Minimum Design Recommendations

- $8d_b$ Embedment length
- $3d_b$ Side Cover
- $2d_b$ Bar spacing
- 13.5 ksi Compressive strength
- No. 4 – No. 8 Bar Sizes
- 75% of embedment length for lap splice length

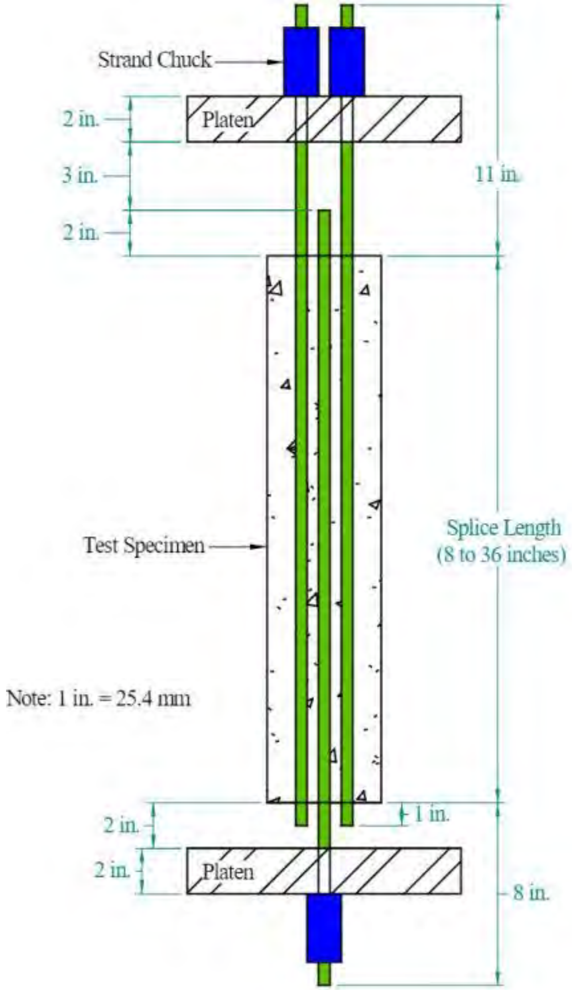


Note: c_{so}, side cover; $2c_{si}$, bar clear spacing to the adjacent No.8 bar; l_d, embedment length; l_s, lap splice length

Reinforcement pullout testing (Yuan and Graybeal 2014)

UHPC Lap Splice Performance

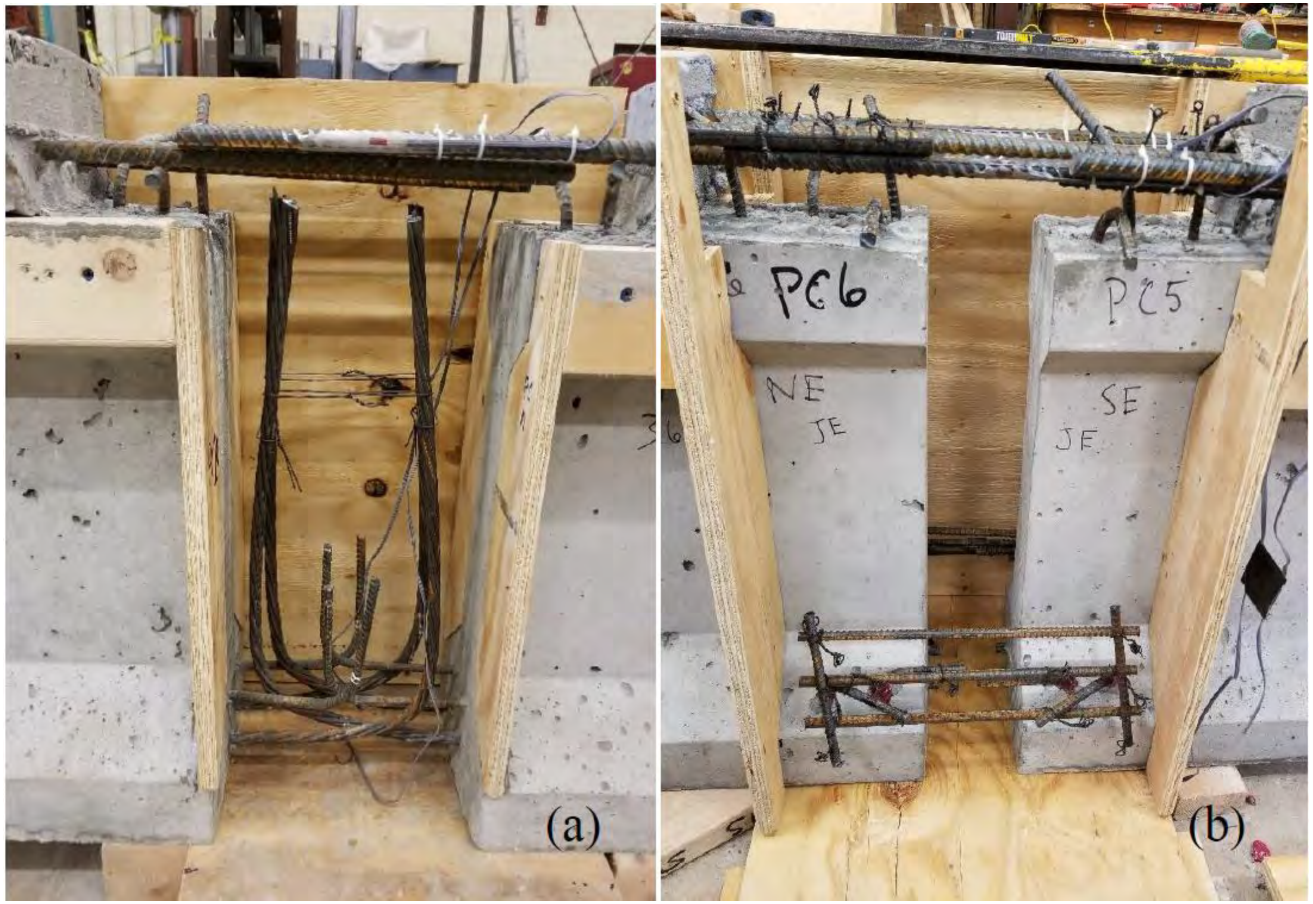
- Required length of non-contact lap splice was shorter than expected
- 0.5 in. diameter strands could be developed in 20 in.
- 0.6 in. diameter strands could be developed in 24 in.
- 16 in. lap splice may be possible with greater confinement



UHPC lap splice test (Graybeal 2014)

Previous Research at OU Sponsored by ODOT

- Studies by Casey (2019) and Looney et al. (2021)
- Using conventional concrete properties to design UHPC joints was found to be conservative
- UHPC is a viable retrofit material
- More research needed to optimize design



Continuity joint reinforcement for (a) new construction and (b) retrofit construction test specimens

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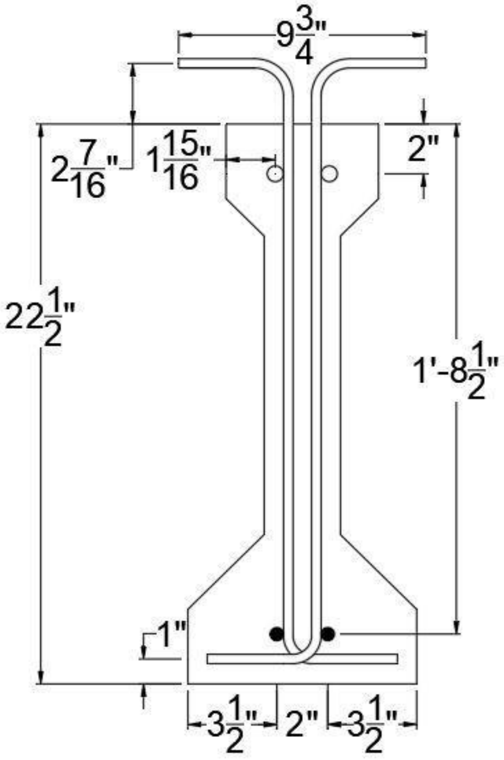
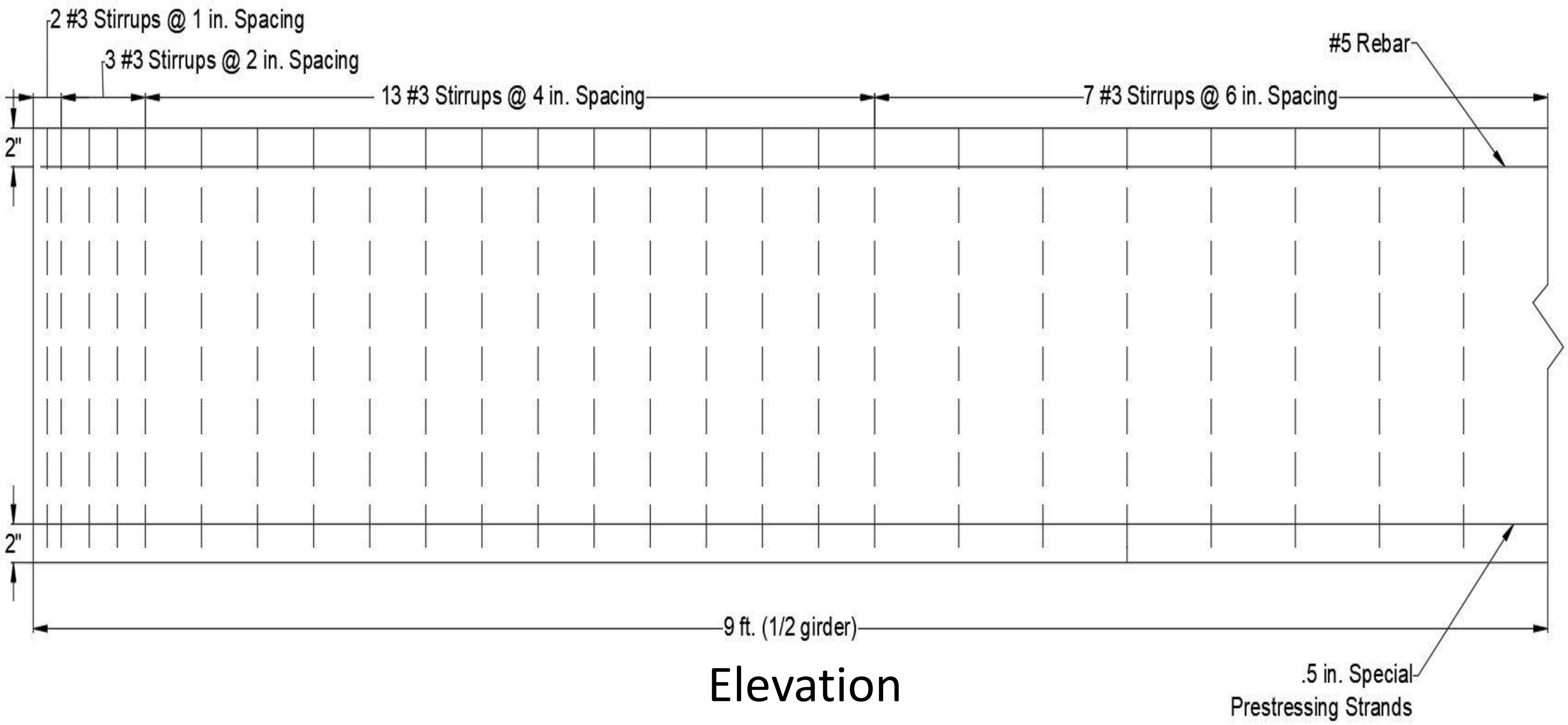
Laboratory Joint Girder Design

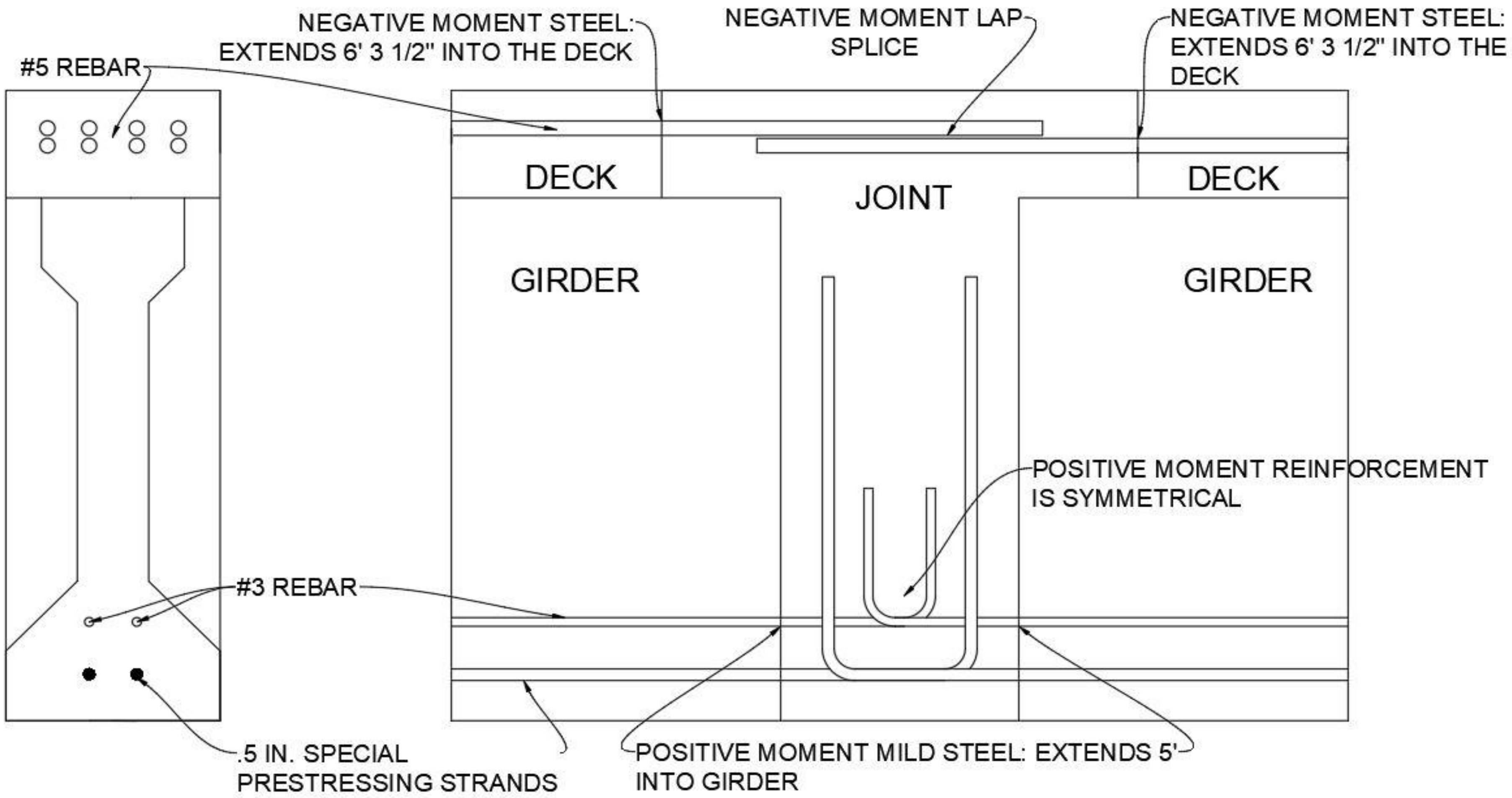


Cross-Section



Elevation

New Construction (NC) Continuity Joint



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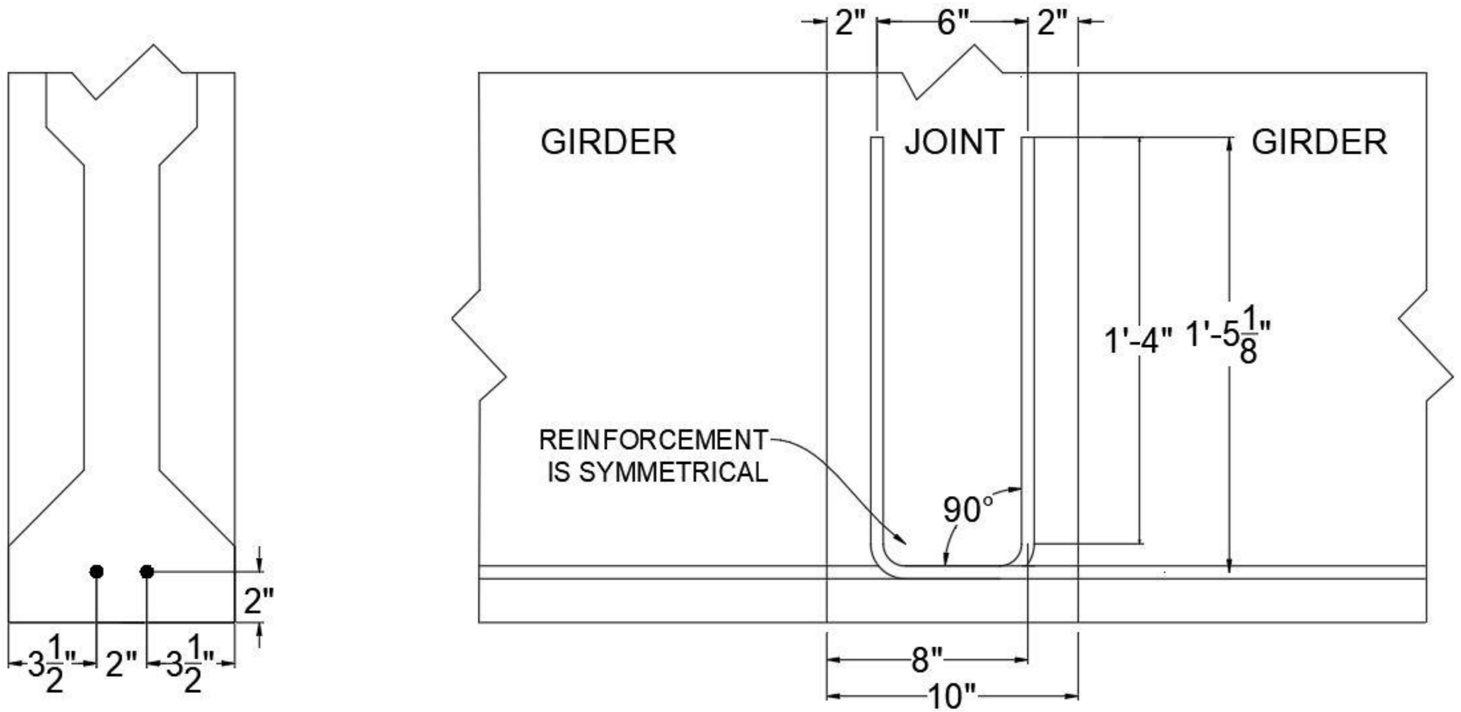
New Construction (NC) Continuity Joint

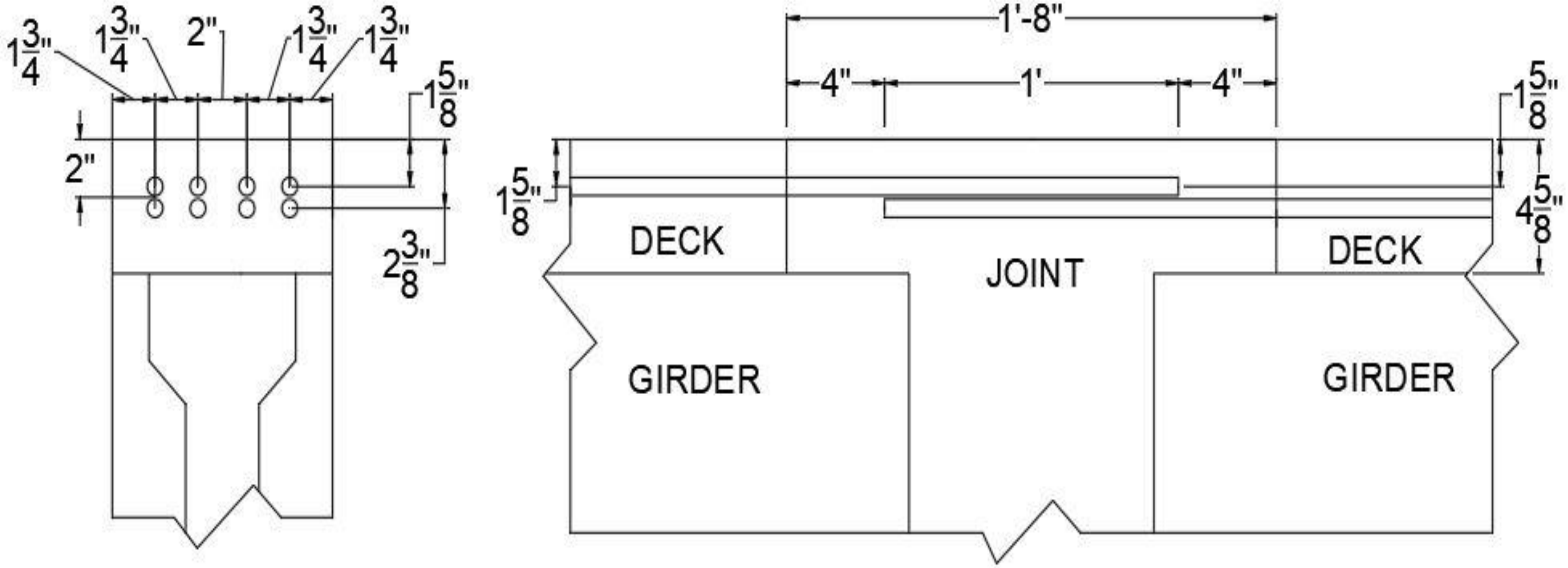
- Positive moment reinforcement
  - Designed using normal concrete properties
  - Followed AASHTO LRFD 2014
  - 90 days before continuity established
  - Strands plus 2 No. 3 bars with standard hooks



Reinforcement detail for prestressing strands in the bottom of the joint

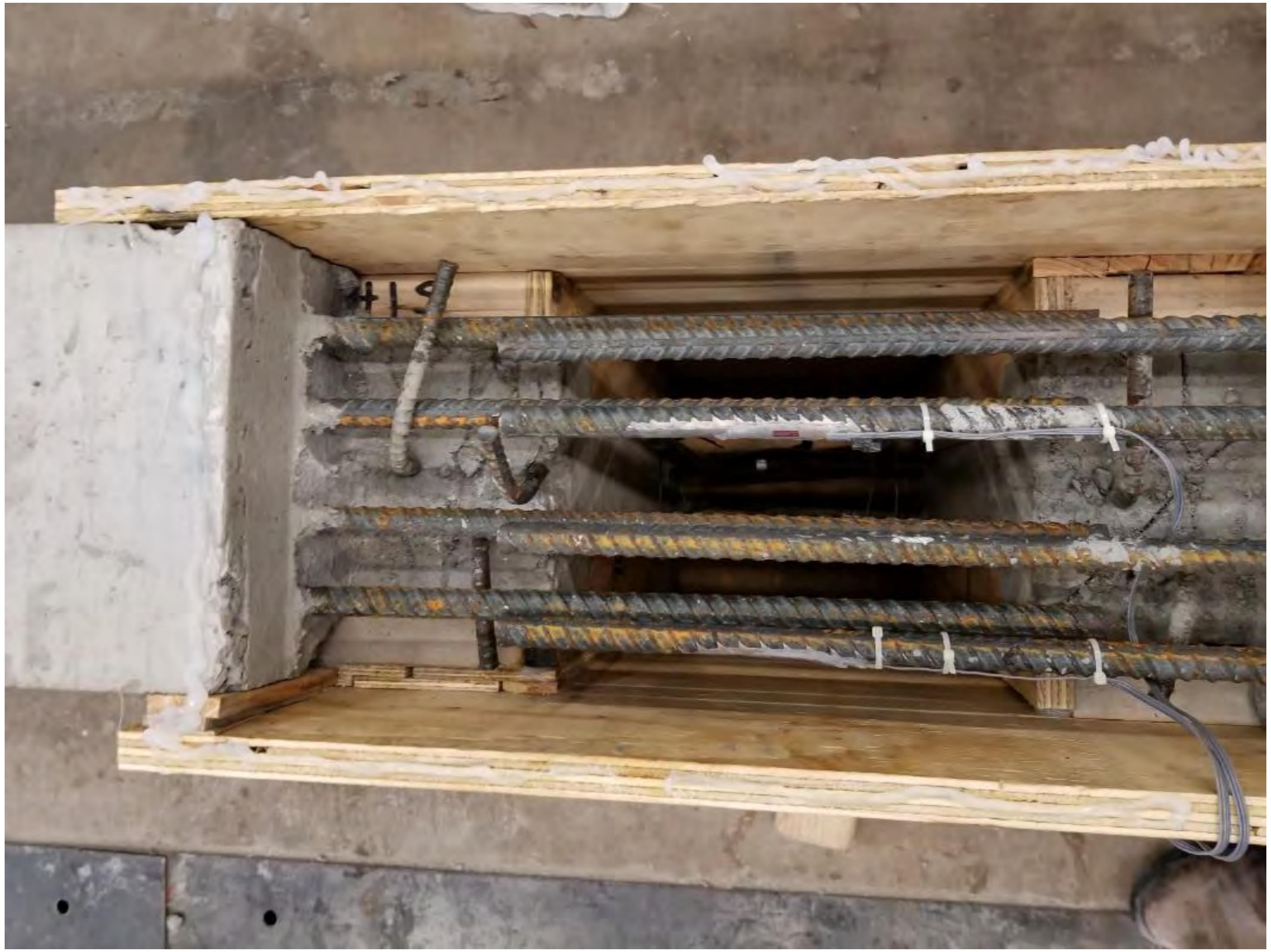
New Construction (NC) Continuity Joint

- Negative moment reinforcement
  - Designed using normal concrete properties
  - Point load applied to mid-span of each girder
  - RISA to model continuous span for max negative moment
  - Contact lap splice
    - Used UHPC recommendations



Reinforcement detail for mild steel in the deck

Continuity Joint Construction



New construction continuity joint reinforcement immediately before casting

Continuity Joint Construction

Retrofit construction continuity joint reinforcement immediately before casting

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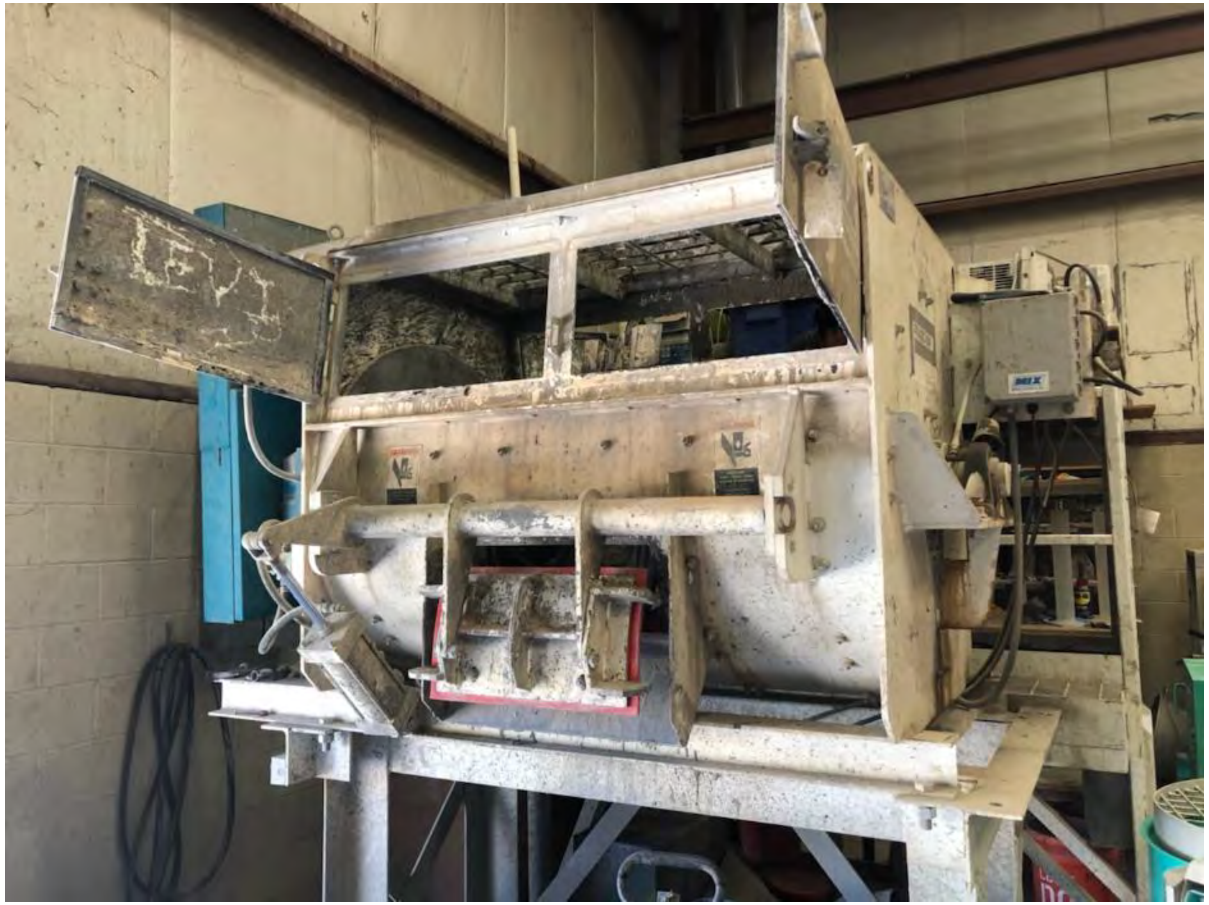
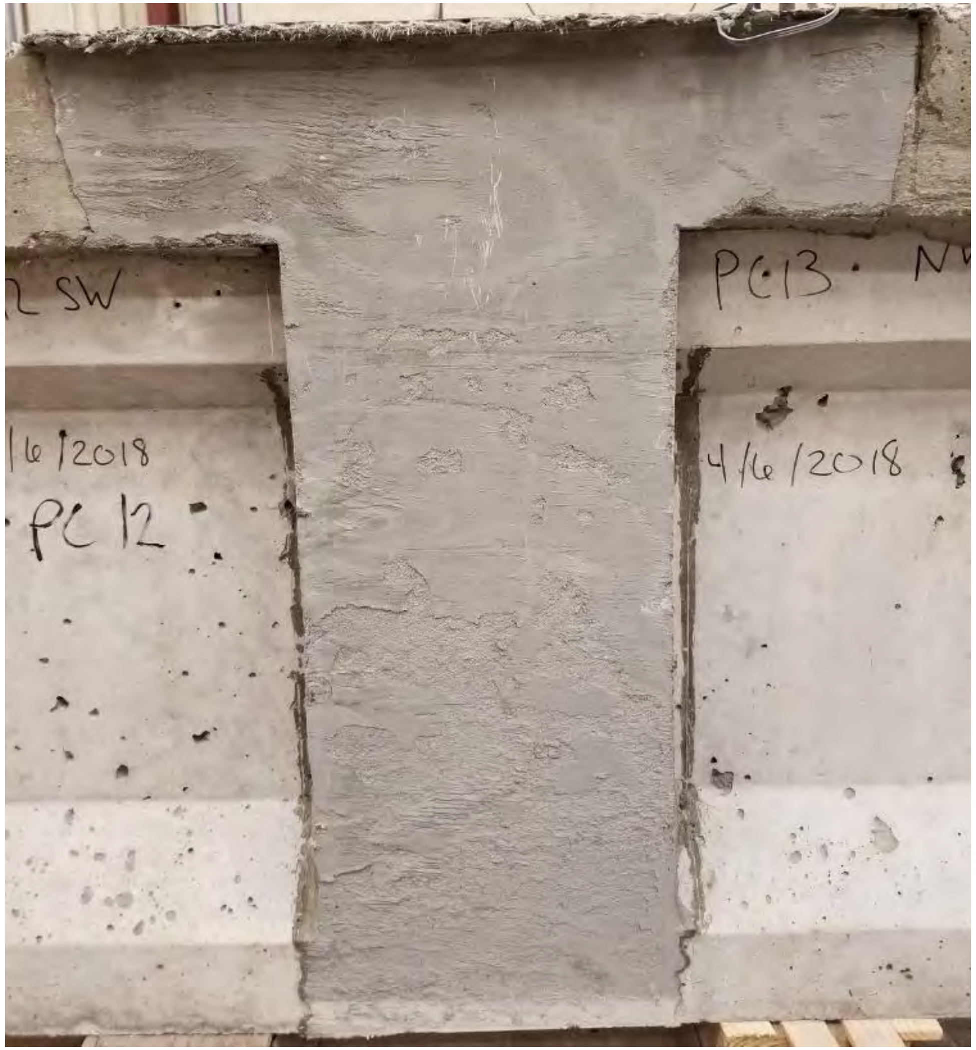
Continuity Joint Construction

- UHPC Mixing
  - Horizontal axis high-shear mixer
  - Two separate mixes of 10 ft^3
- Compressive Strength
  - New construction 24,760 psi
  - Retrofit 24,540 psi



Completed Continuity Joints



New construction continuity joint

Retrofit construction continuity joint

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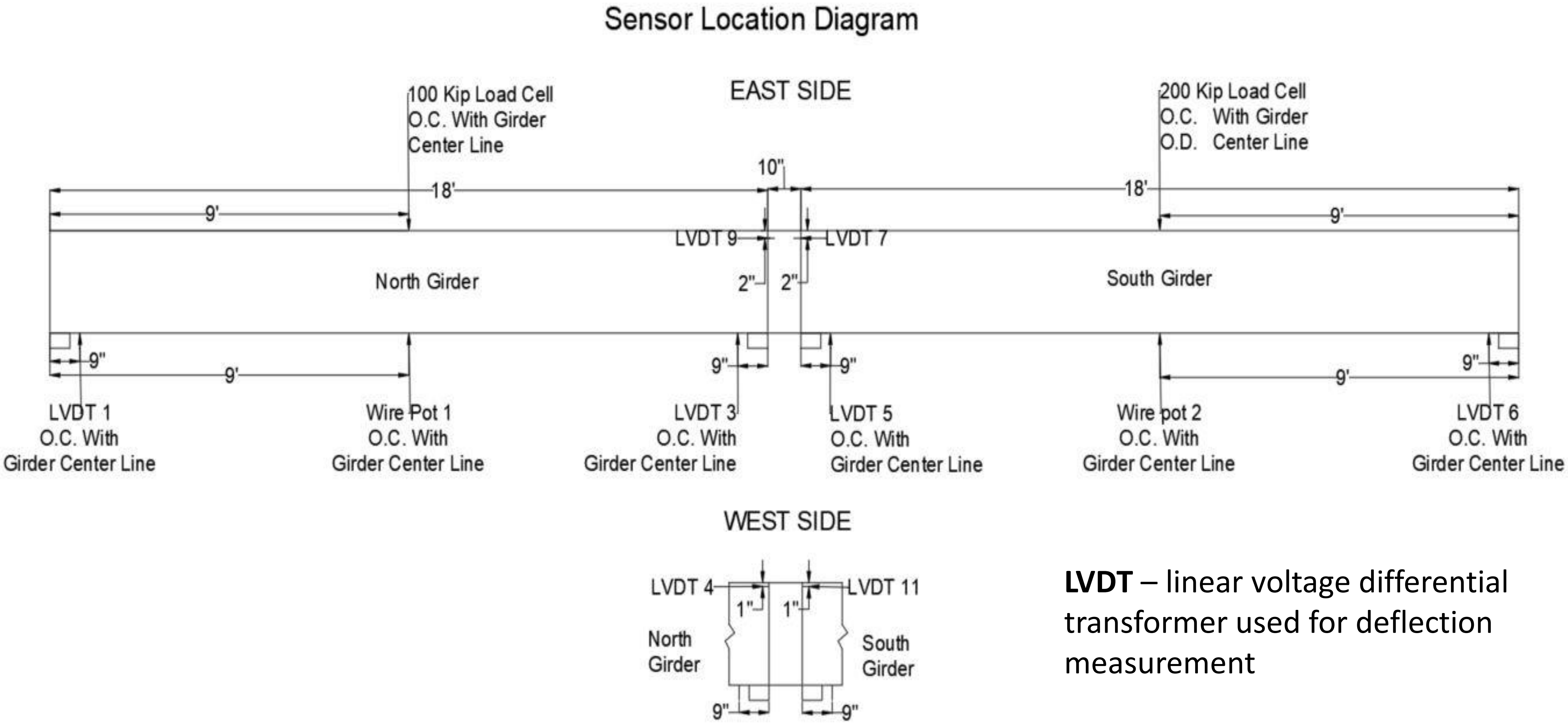
Specimen Test Setup



LVDT – linear voltage differential transformer used for deflection measurement

Wire Pot – wire potentiometer used for deflection measurement

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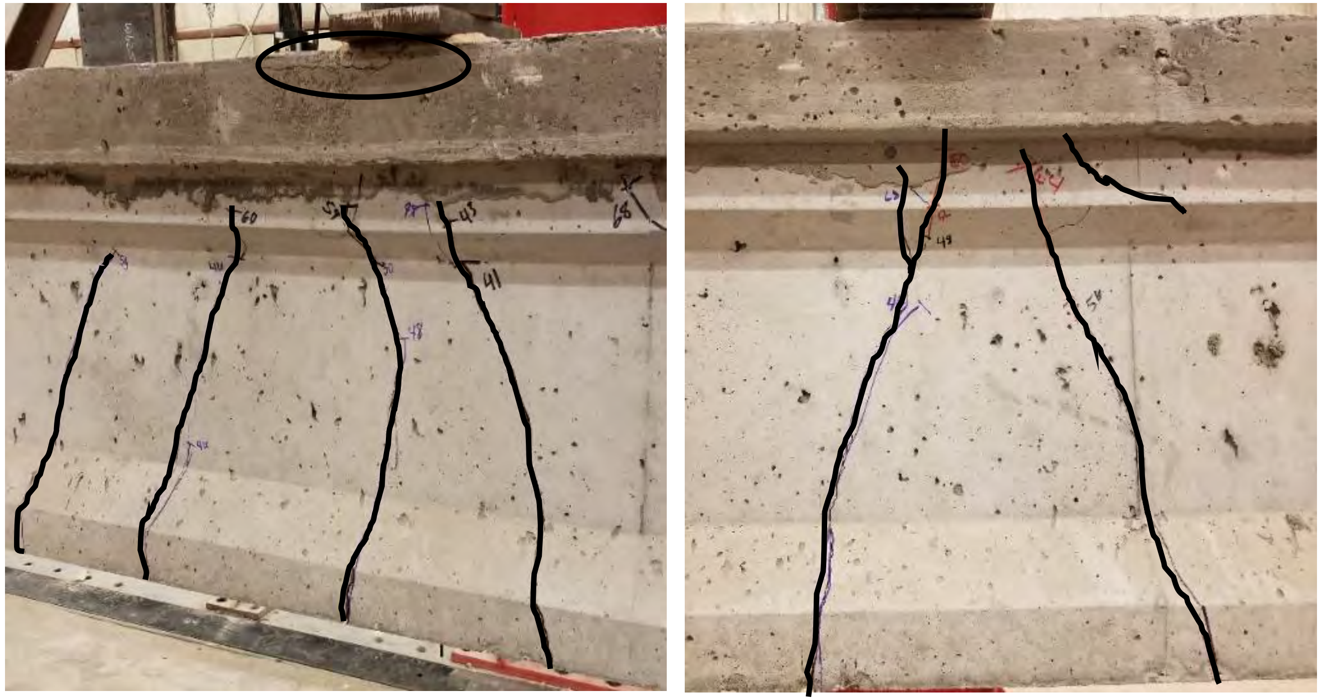
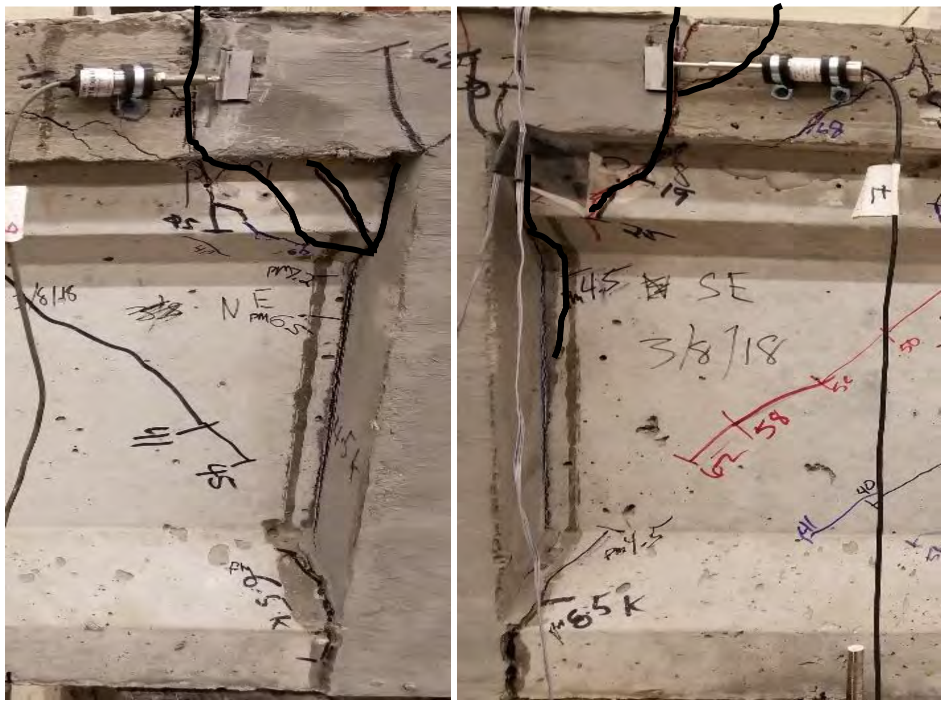
Testing Procedure

Two-span loading configuration used for testing continuity joints showing loads applied at mid-span of each beam

Typical Cracking

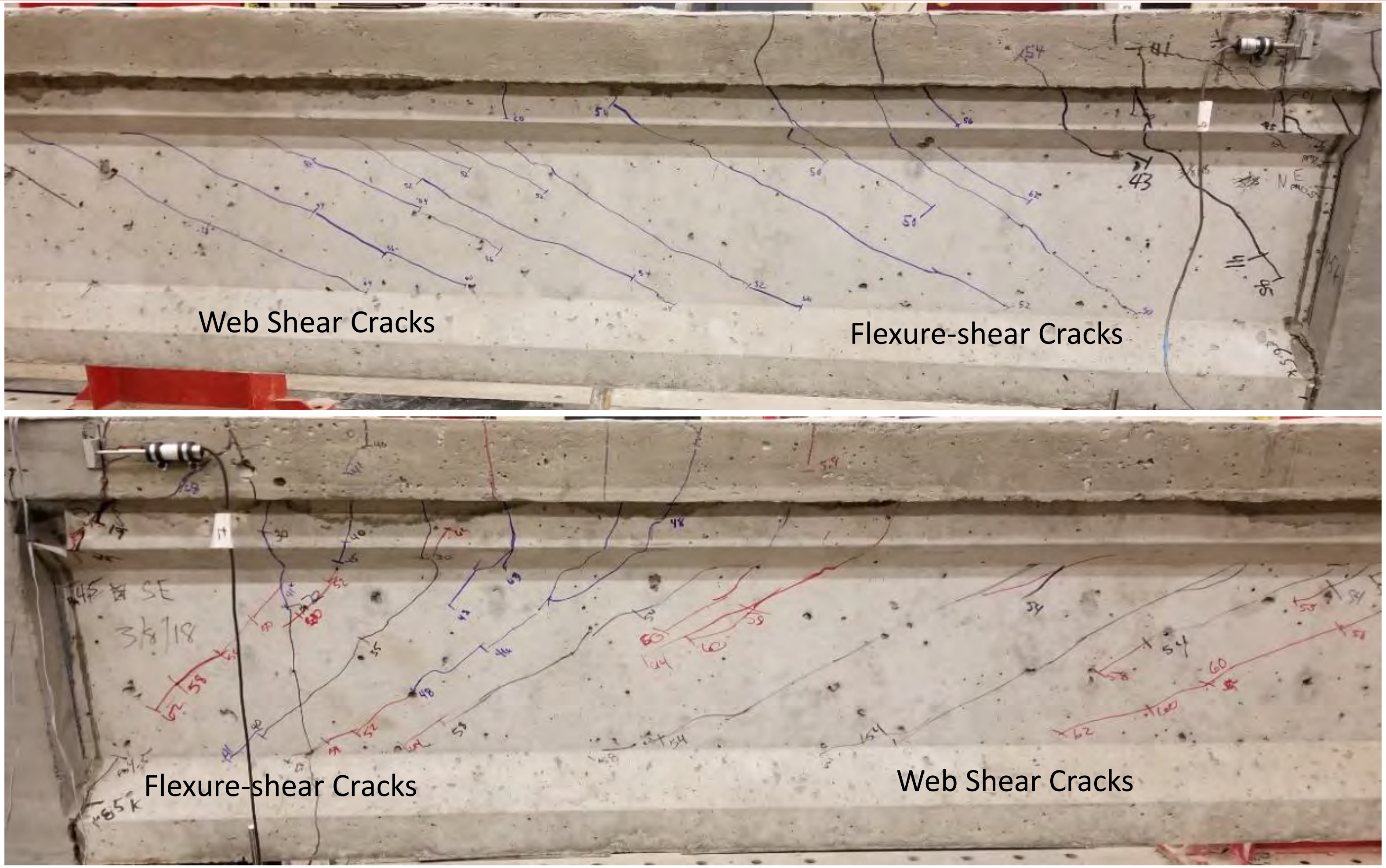


Flexural cracking under load point



Flexural and flexure-shear cracking at joint interface

Typical Cracking



Cracking between load point and joint on each side of the joint due to negative moment, top shows north beam and bottom shows the south beam

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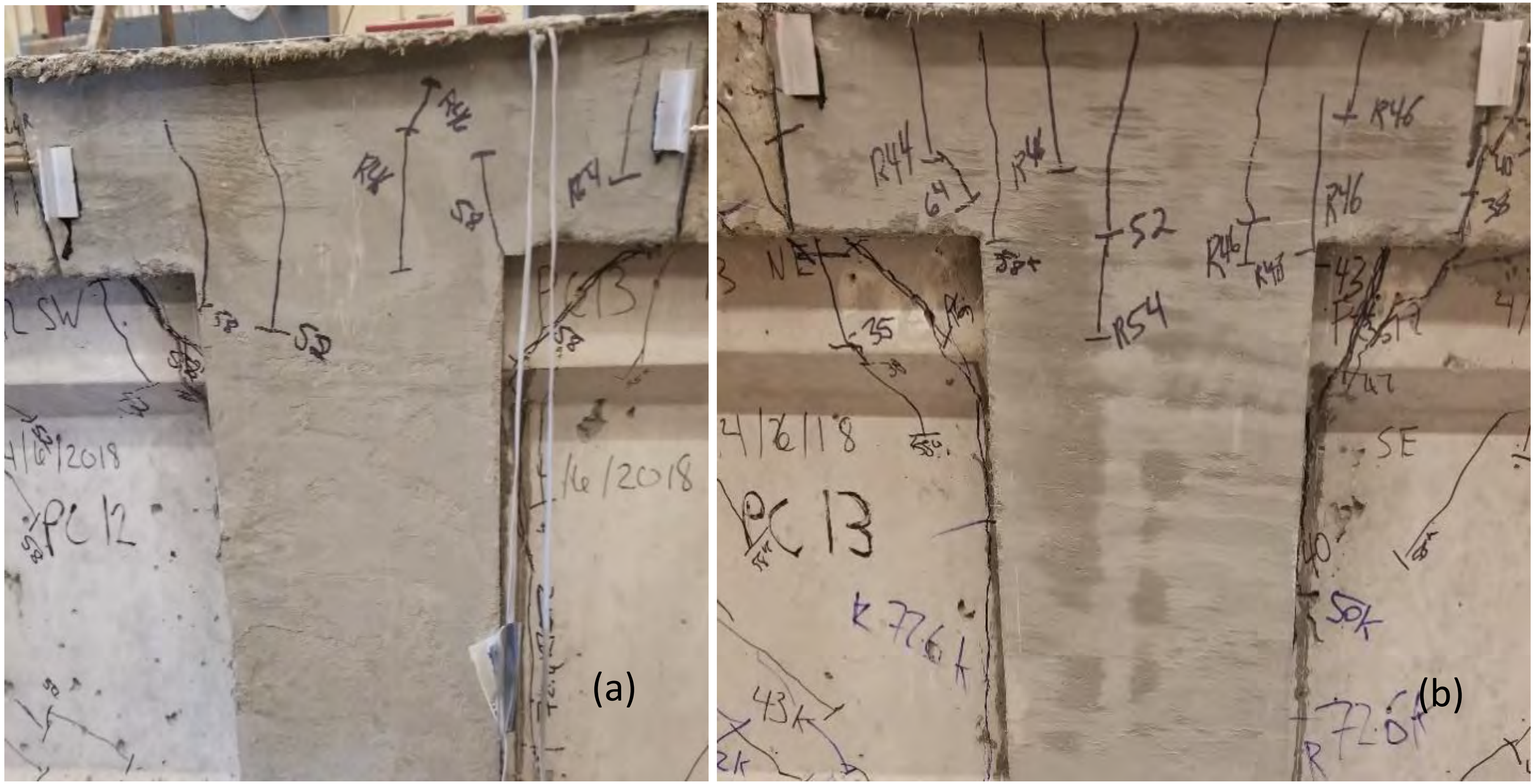
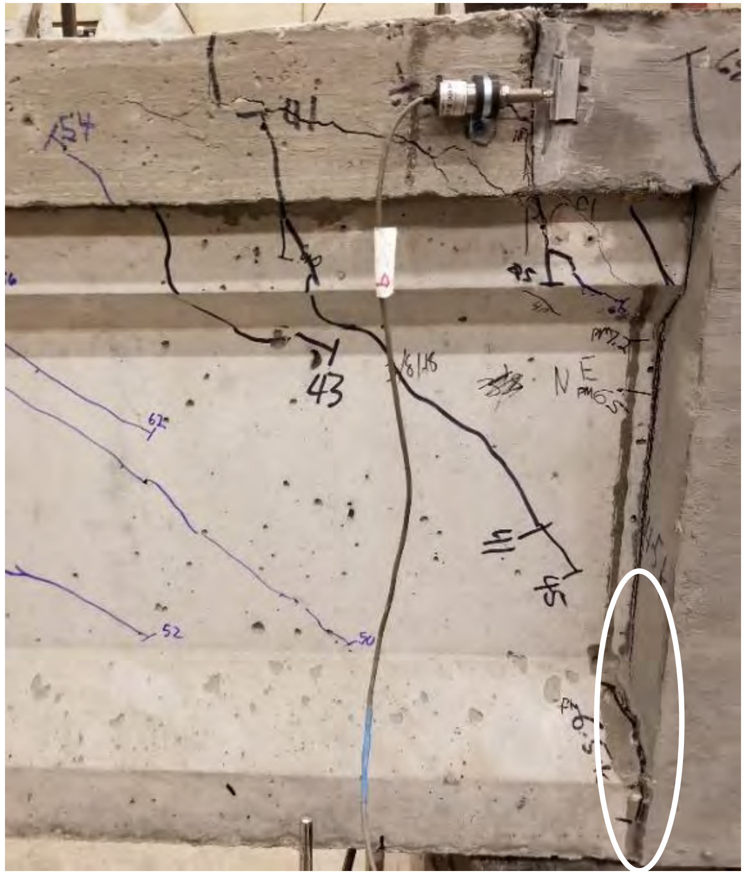
Typical Cracking in NC Continuity Joint



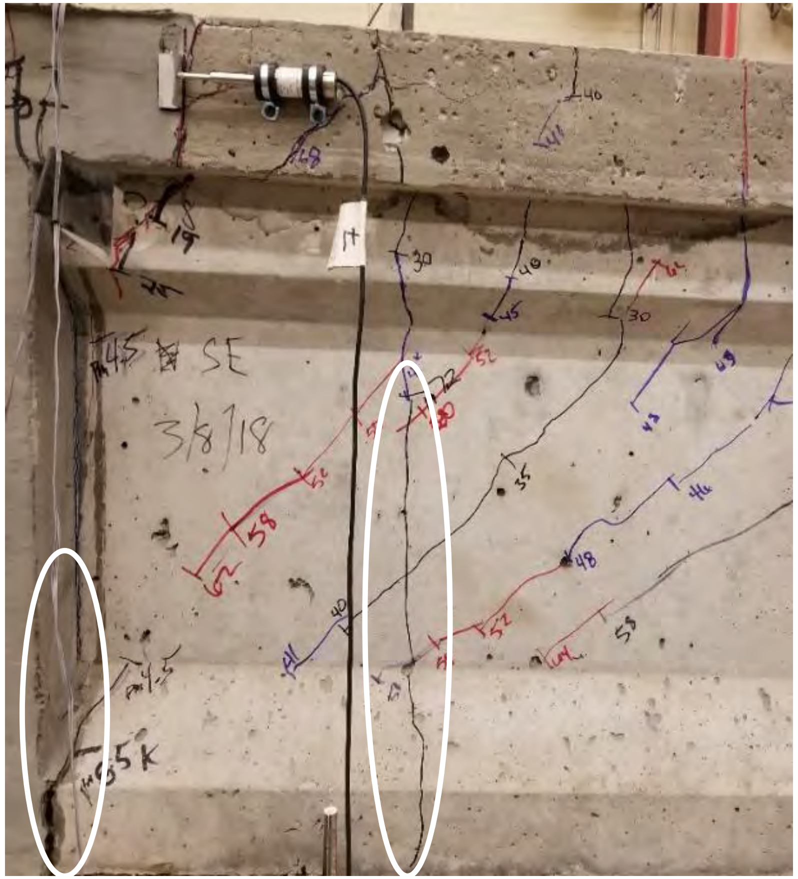
Small cracks in UHPC joint due to negative moment on each side of same UHPC joint for new construction detail

NC Positive Moment Test

- Initial test to induce positive moment
  - Removed supports at joint
  - Applied point loads
- Joint separation at bottom
- Flexural crack away from joint
- Followed by negative moment test

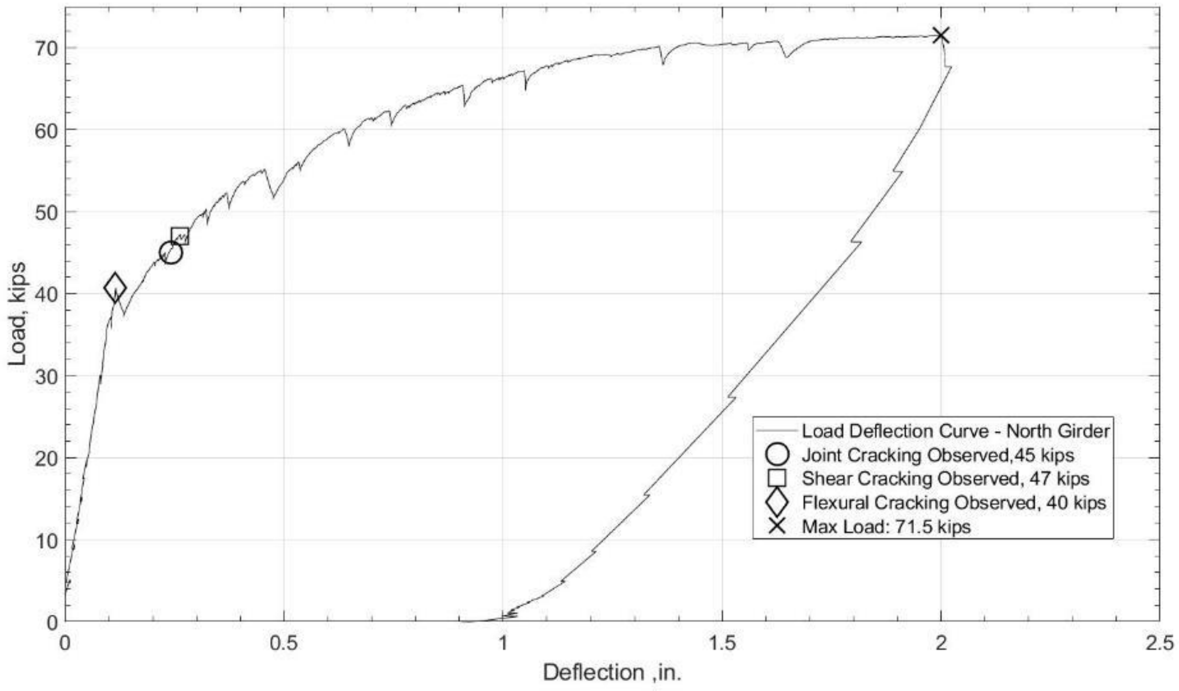


North girder

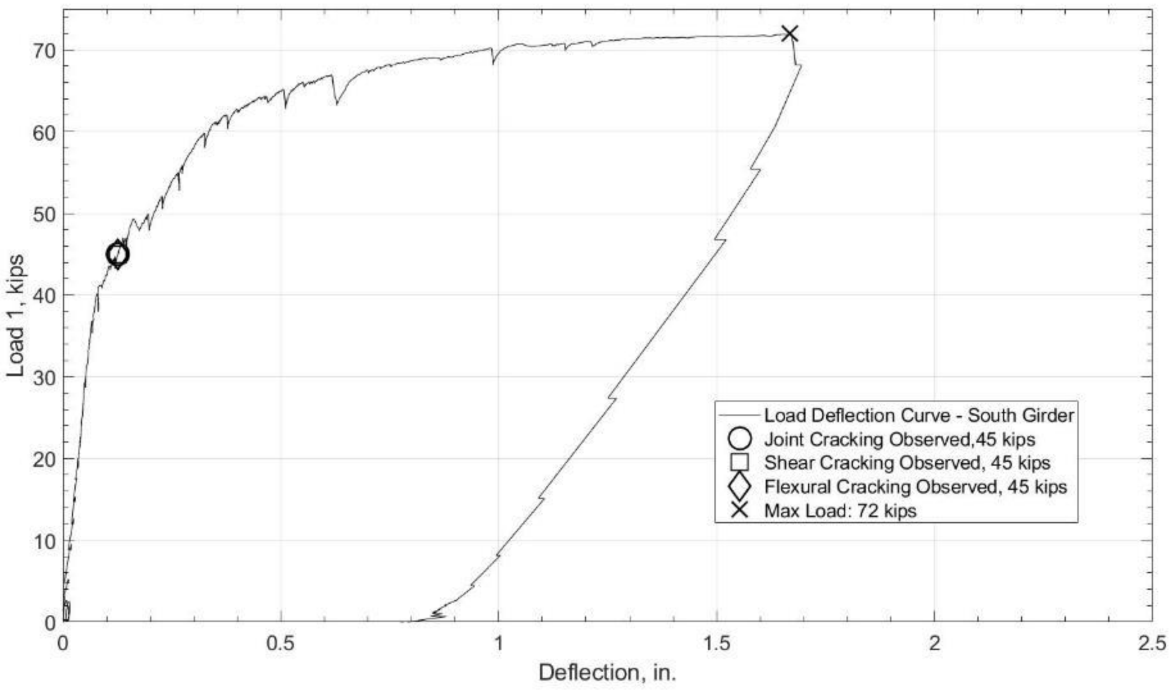


South girder

Typical NC Load vs. Deflection



North girder



South girder

NC Summary

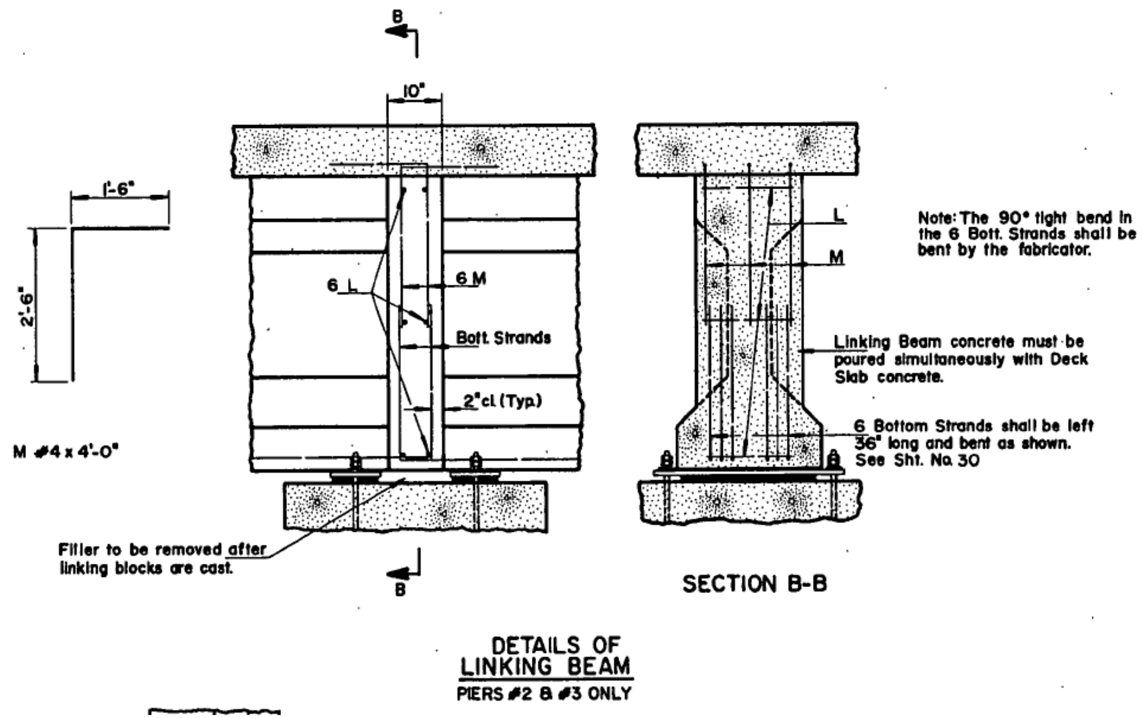
Specimen	NC1		NC2		NC3	
Girder	NC1-N	NC1-S	NC2-N	NC2-S	NC3-N	NC3-S
Experimental Max Load w/ Continuity Joint, kips	72.5	73.8	71.5	72	69.8	70.2
Theoretical Max Moment w/ Continuity Joint, kip-ft	211.9	215.6	208.9	210.4	204	205.1
M_n single span girder, kip-ft	145.7		145.7		145.7	
Moment percentage increase w/Continuity Joint	31.2	32.4	30.3	30.8	28.6	29.0

RC Summary

Specimen	RC1		RC2		RC3	
Girder	RC1-N	RC1-S	RC2-N	RC2-S	RC3-N	RC3-S
Experimental Max Load w/ Continuity Joint, kips	76	75.9	74.12	74.18	76.1	73.31
Theoretical Max Moment w/ Continuity Joint, kip-ft	217.2	216.9	211.8	212	217.5	209.6
M_n single span girder, kip-ft	145.7		145.7		145.7	
Moment percentage increase w/Continuity Joint	32.9	32.8	31.2	31.3	33.0	30.5

U.S. 183/412 Bridge over Wolf Creek, Fort Supply, OK

- Five 85 ft spans, three continuous
    - AASHTO Type IV prestressed beams spaced at 9.25 ft
    - Composite 9.25 in. deck
    - Constructed in 1985
    - Significant agricultural truck traffic to pork processing plant
- After cracking of continuity connections considered as simply supported for load rating



Continuity connection detail for U.S. 183/412 over Wolf Creek (Courtesy of Walt Peters)

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Featured in December 2022 ABC-UTC Monthly Webinar
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U.S. 183/412 Bridge over Wolf Creek, Fort Supply, OK

Panoramic view of U.S. 183/412 Bridge over Wolf Creek, Fort Supply, OK

Close-up view of continuity connection

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U.S. 183/412 Bridge over Wolf Creek, Fort Supply, OK

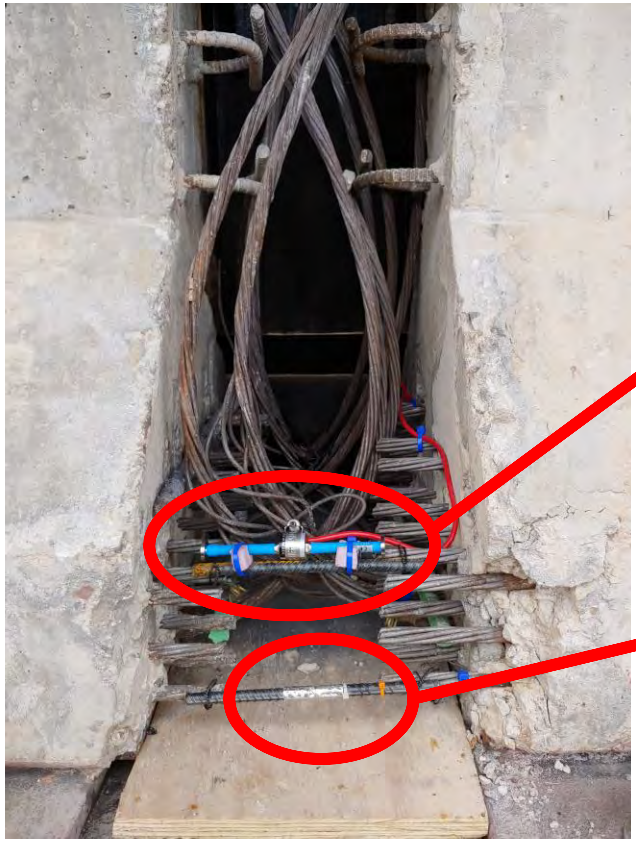
In-service condition (April 2019)

Cracking in continuity connections on U.S. 183/412 Bridge over Wolf Creek, Fort Supply, OK

Field Implementation

Joint demolition (November 2019)

Exposed reinforcement after joint demolition



Instrumentation for UHPC joint

Vibrating wire strain gauge tied to #3, Grade 60 rebar tied to exposed prestressing strand

Foil strain gauge on #3, Grade 60 rebar

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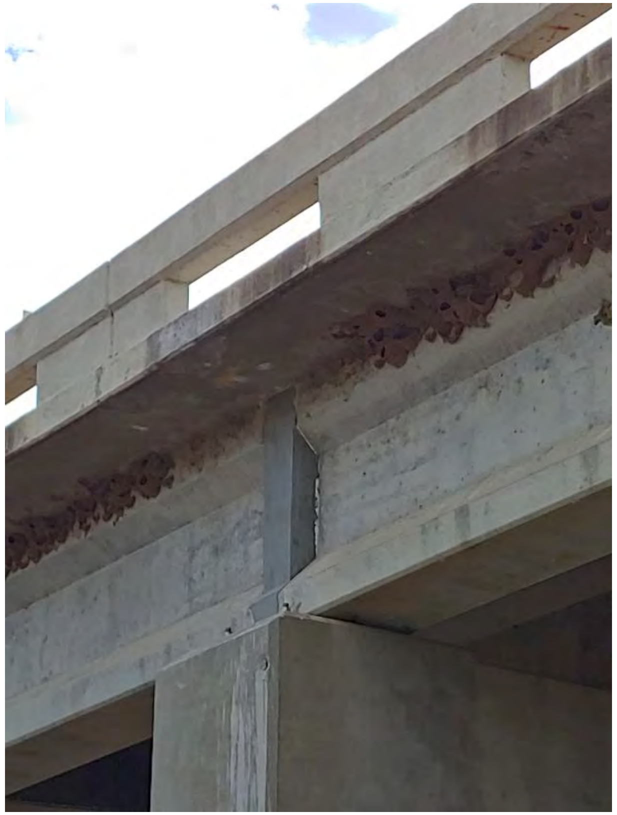
Field Implementation

Joint construction (November 2019)

UHPC Placement through the deck



Completed UHPC joint

Joint Condition After 1 Year (December 2020)

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Joint Condition After 3 years (October 2022)

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Current Research Objectives

- Examine current design details and literature
- Compare the performance of two different UHPC materials
  - J3, a UHPC mix design developed at the University of Oklahoma
  - Commercially available premixed UHPC product donated from completed bridge project
  - Inadvertent examination of effect of fiber distribution
- Analyze the capacity of straight strands vs. hooked strands
- Test both negative and positive moment bending
- Produce recommendations for future design

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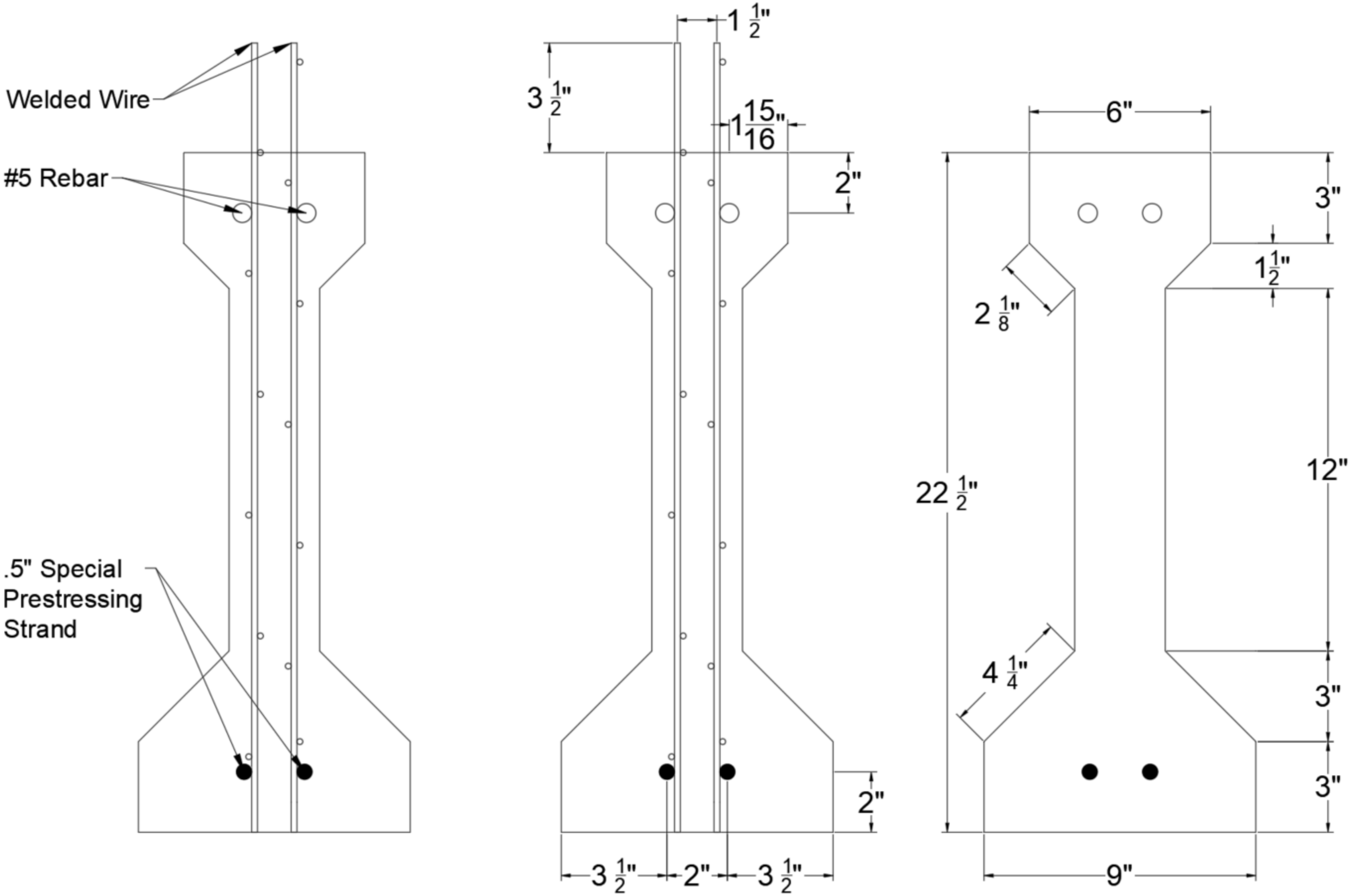
Girder Design



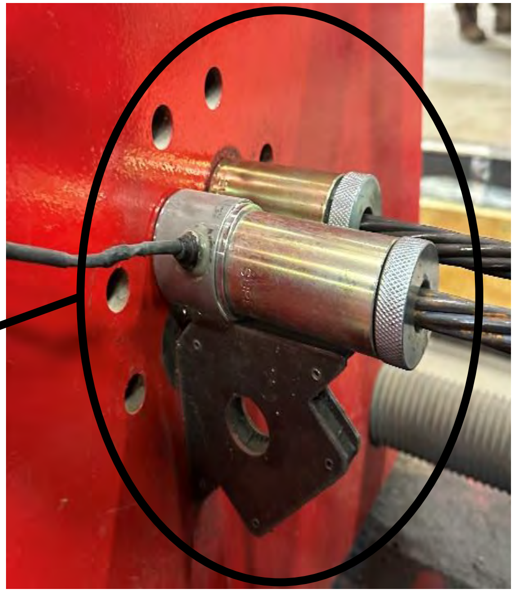
Girder Construction

Beam formwork and reinforcement in place on the prestressing bed

Prestressing Abutments and Load Cell

Dead end abutment

Live end abutment showing nuts (blue) used to hold the prestress



Load cell used to measure prestress

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Girder Construction (Cont'd)

Completed girder specimens in place on the prestressing bed

Gap between the two specimen ends

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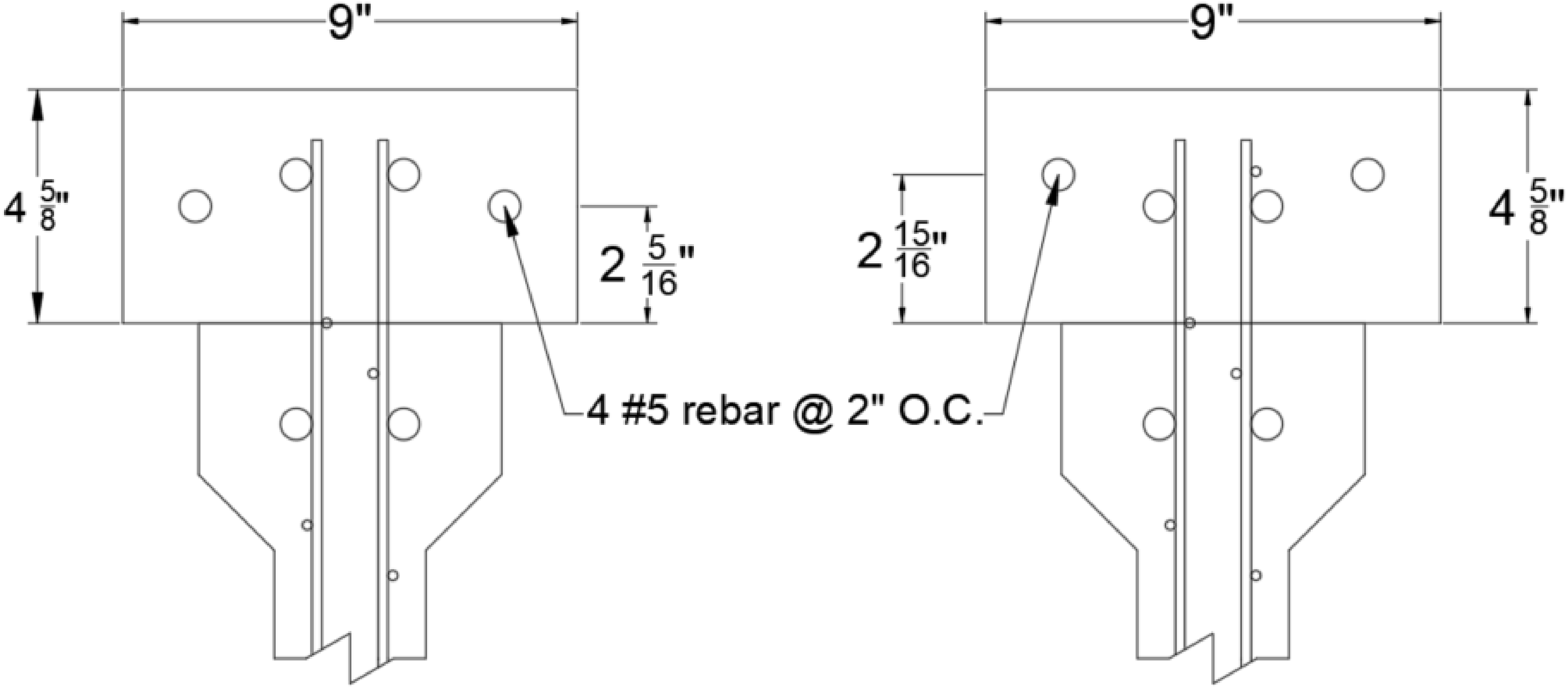
Deck Construction



Deck reinforcement showing alternating bar locations to facilitate splice

Deck Construction (Cont'd)

Deck reinforcement in place for casting

Reinforcement splice alignment

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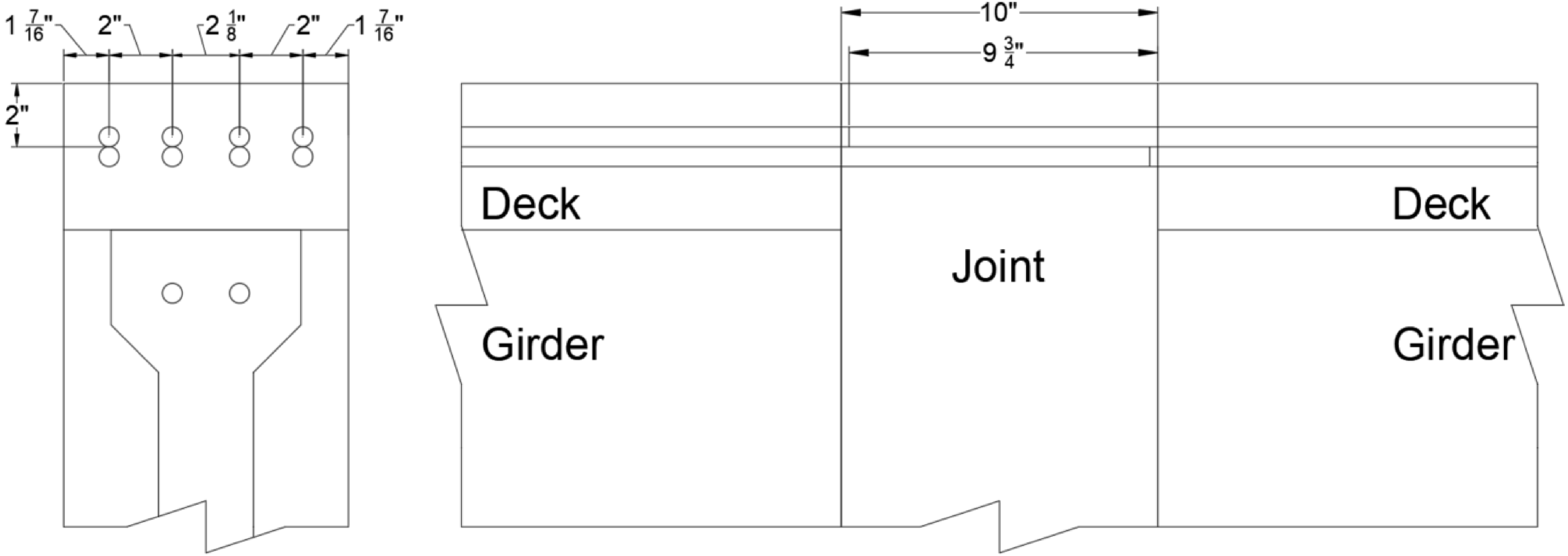
Deck Construction (Cont’d)

Completed specimen including the deck

Negative Moment Contact Lap Splice Detail



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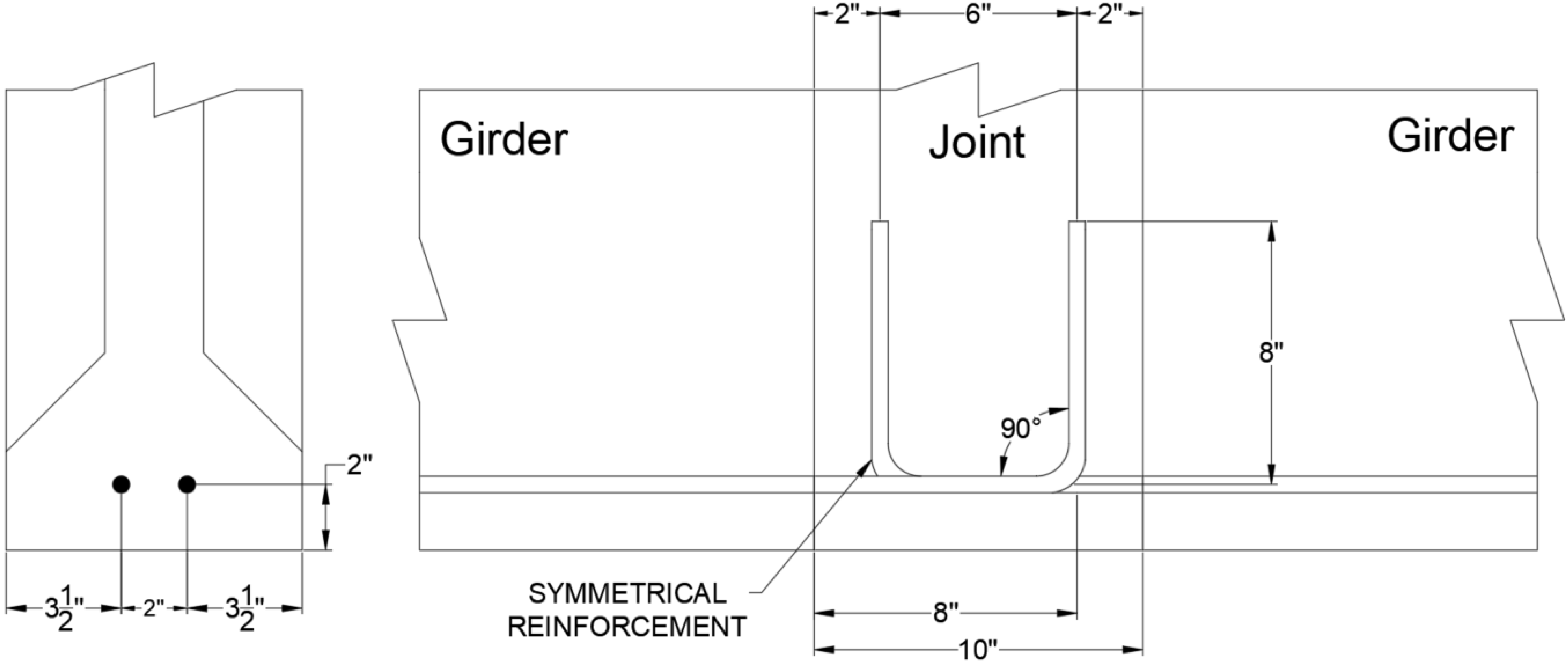
Positive Moment Hooked Strand Detail



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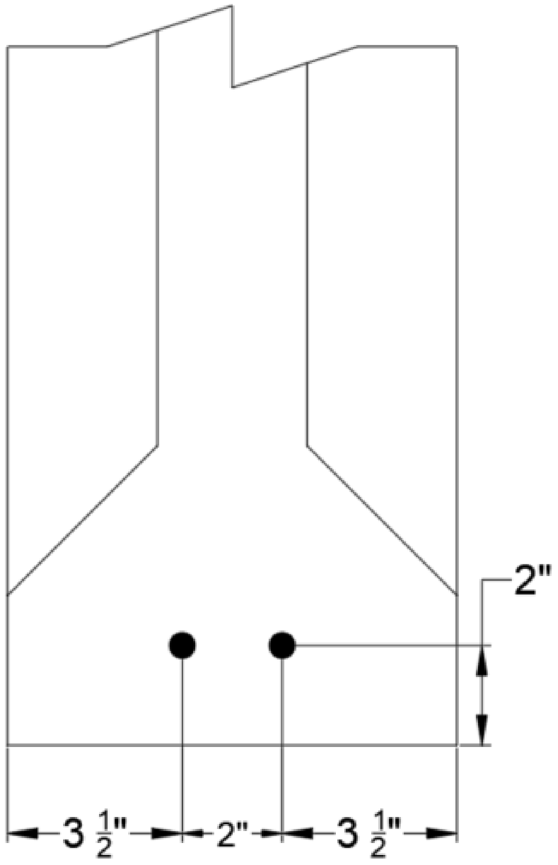
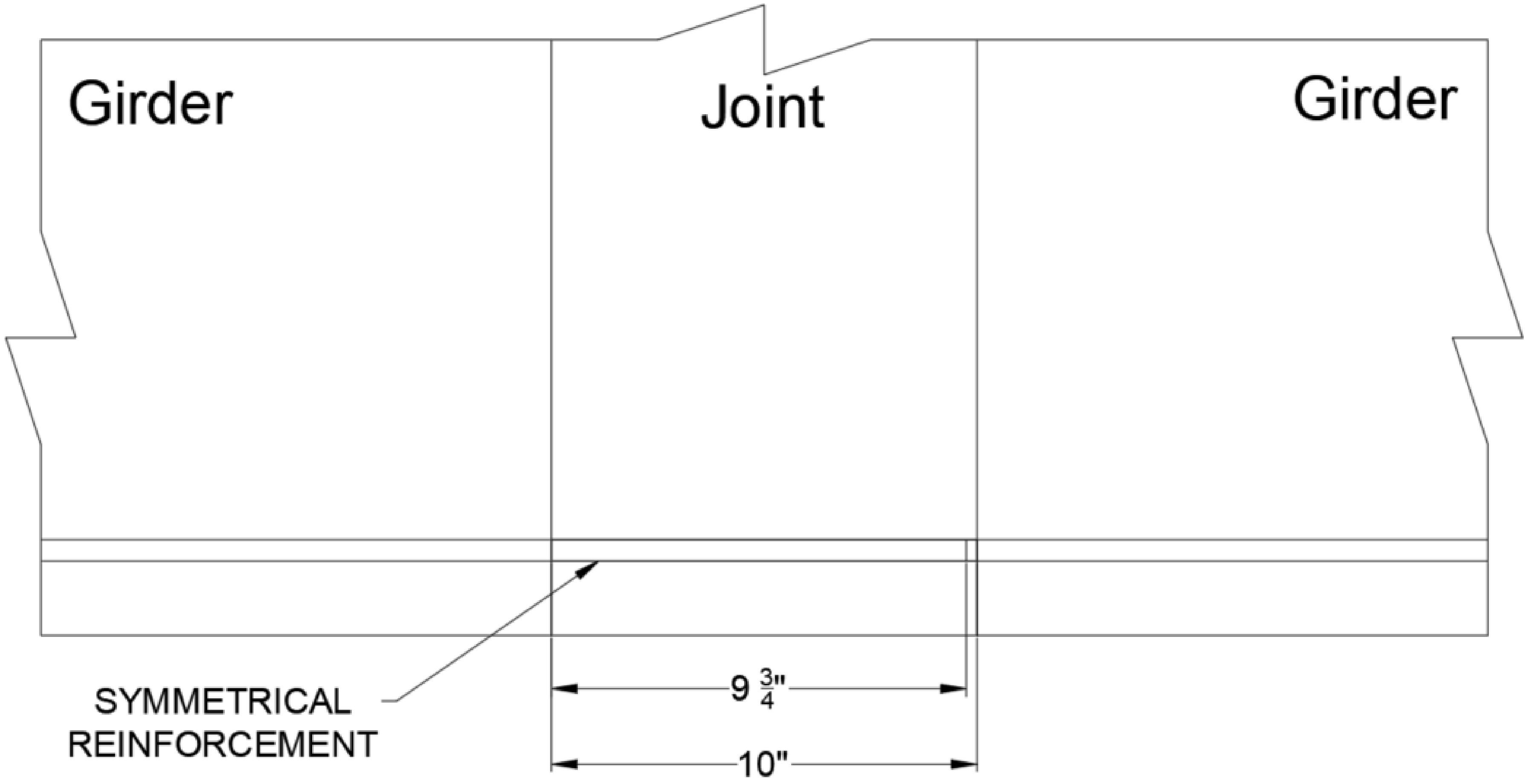
Positive Moment Straight Strand Detail





Joint Details

Hooked strands

Straight strands

Deck reinforcement splice

ABC-UTC Non-Proprietary UHPC

- Developed through ODOT and ABC-UTC support
- 8-10 in. flow
- Compressive strength of 18 ksi
- Approximately 1 ksi post-cracking tensile strength
- Cost approximately $\$800/yd^3$
- Excellent bond strength
- Very low to negligible permeability
- High freeze-thaw resistance

Constituent	Mix Proportion
Type I Cement	0.6
Silica Fume	0.1
Slag Cement	0.3
Masonry Sand (1:1 agg/cm)	1.0
w/cm	0.2
Steel Fibers	2% by Volume
HRWR	20-28 oz/cwt

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Completed Joints

Joint formwork

Completed UHPC connection

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Completed Specimen

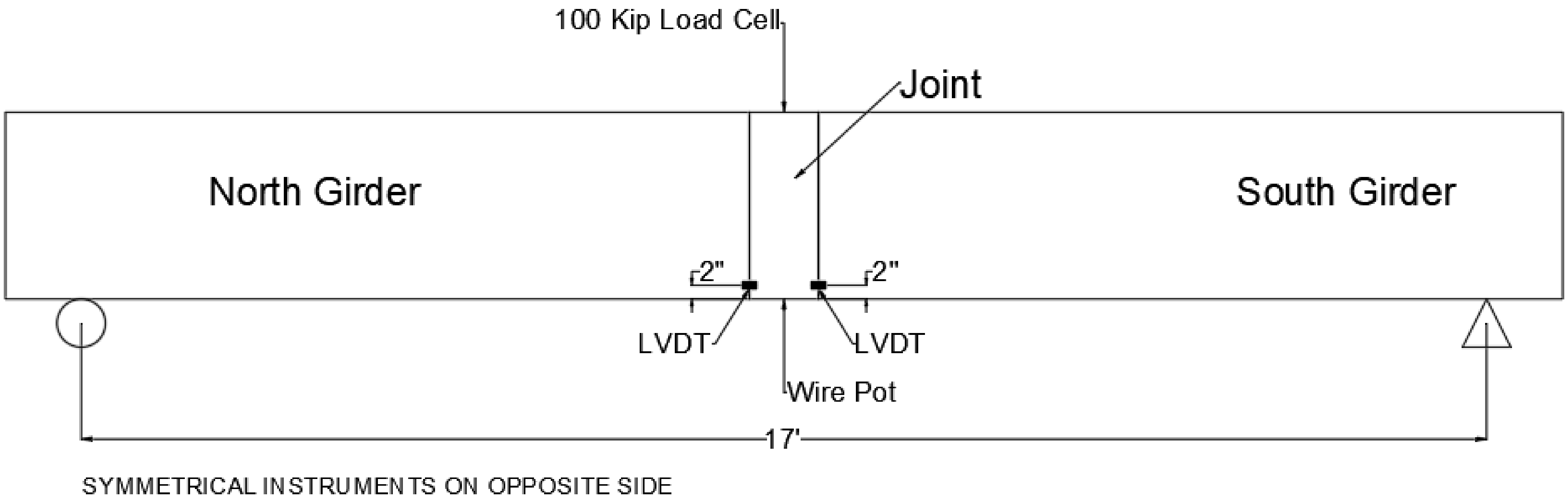
Completed connection specimen including two half-length beams and UHPC joint

UHPC Observations

- High flow – 10 in.
- High compressive strengths
  - 19,500 psi for non-proprietary UHPC
  - 29,500 psi for proprietary UHPC
- Errors in construction for proprietary UHPC specimens
  - Reinforcement cover was less than intended
  - Uneven fiber distribution likely due to improper mixing/admixture dosage
  - Provided excellent opportunity to examine effects of fiber distribution on bar development

Specimen Test Setup

- Simply-supported 17 ft span
- 4 LVDTs used to monitor joint separation
- 2 wire pots to monitor deflection at the joint
- 100K load cell to monitor applied load



LVDT – linear voltage differential transformer

Wire Pot – wire potentiometer

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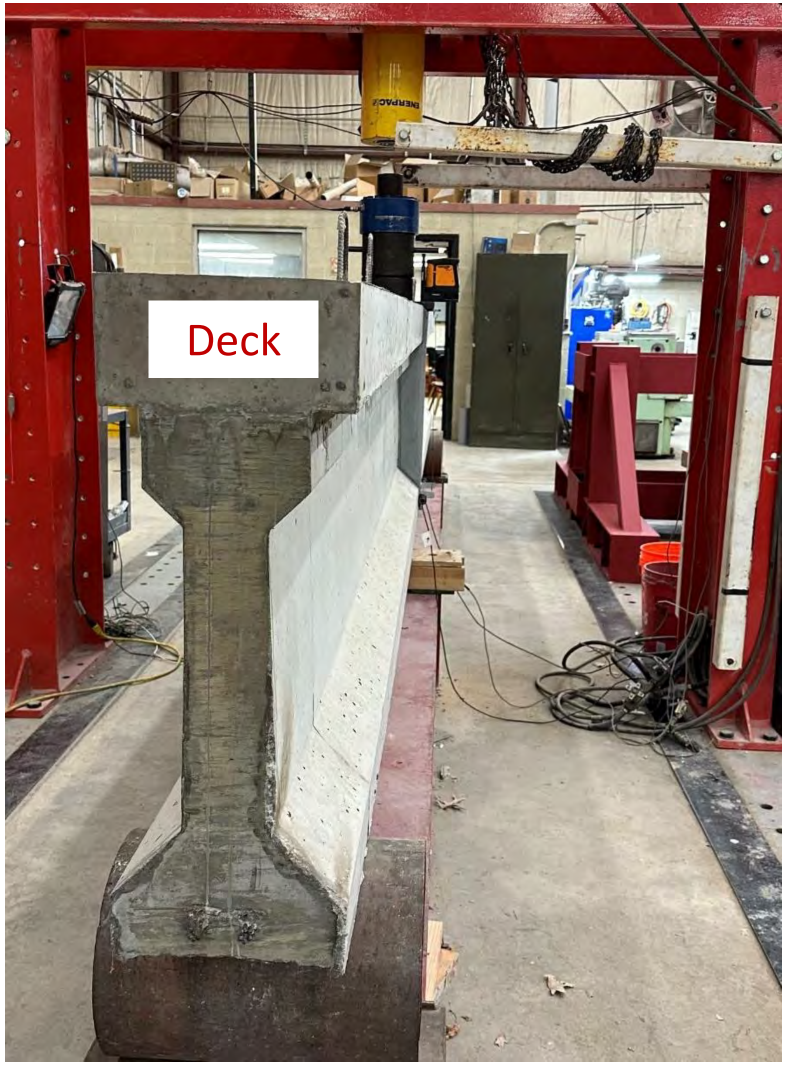
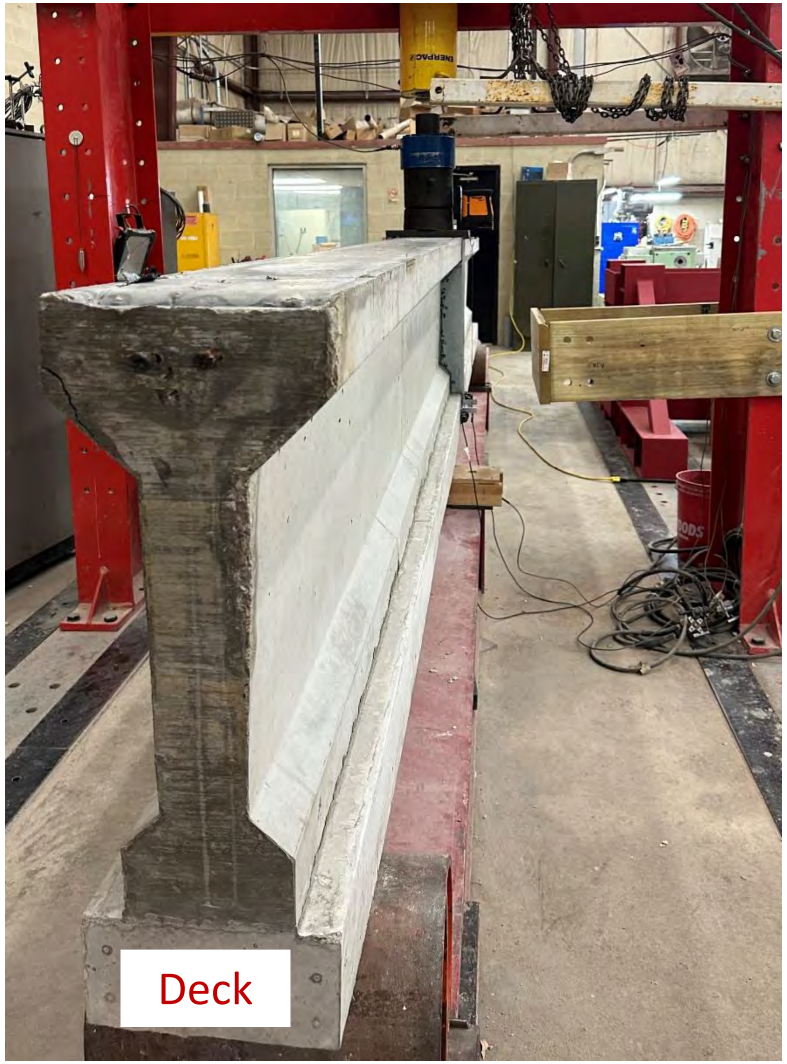
Testing Orientation

Positive Moment



Negative Moment



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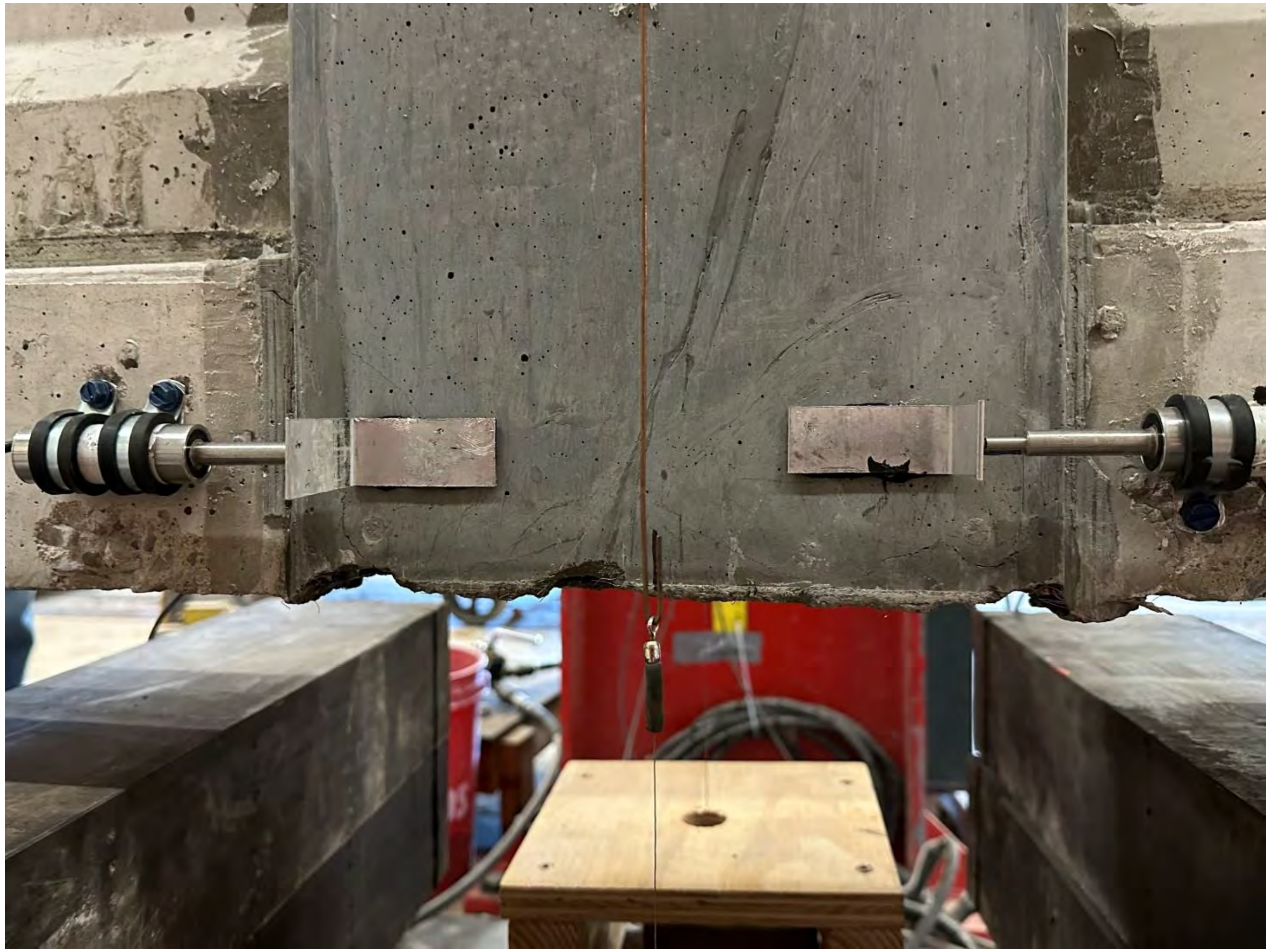
Testing Instrumentation



LVDTs used to measure opening at the UHPC-girder interface

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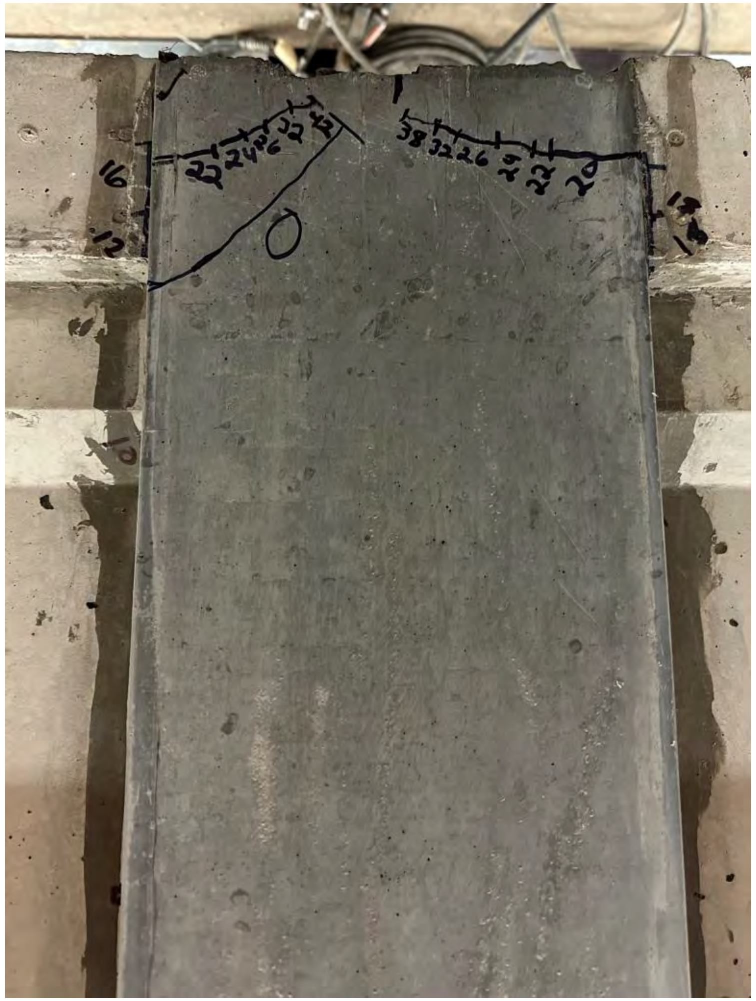
Typical Positive Moment Failure

Typical separation at the interface between the girder and UHPC connection

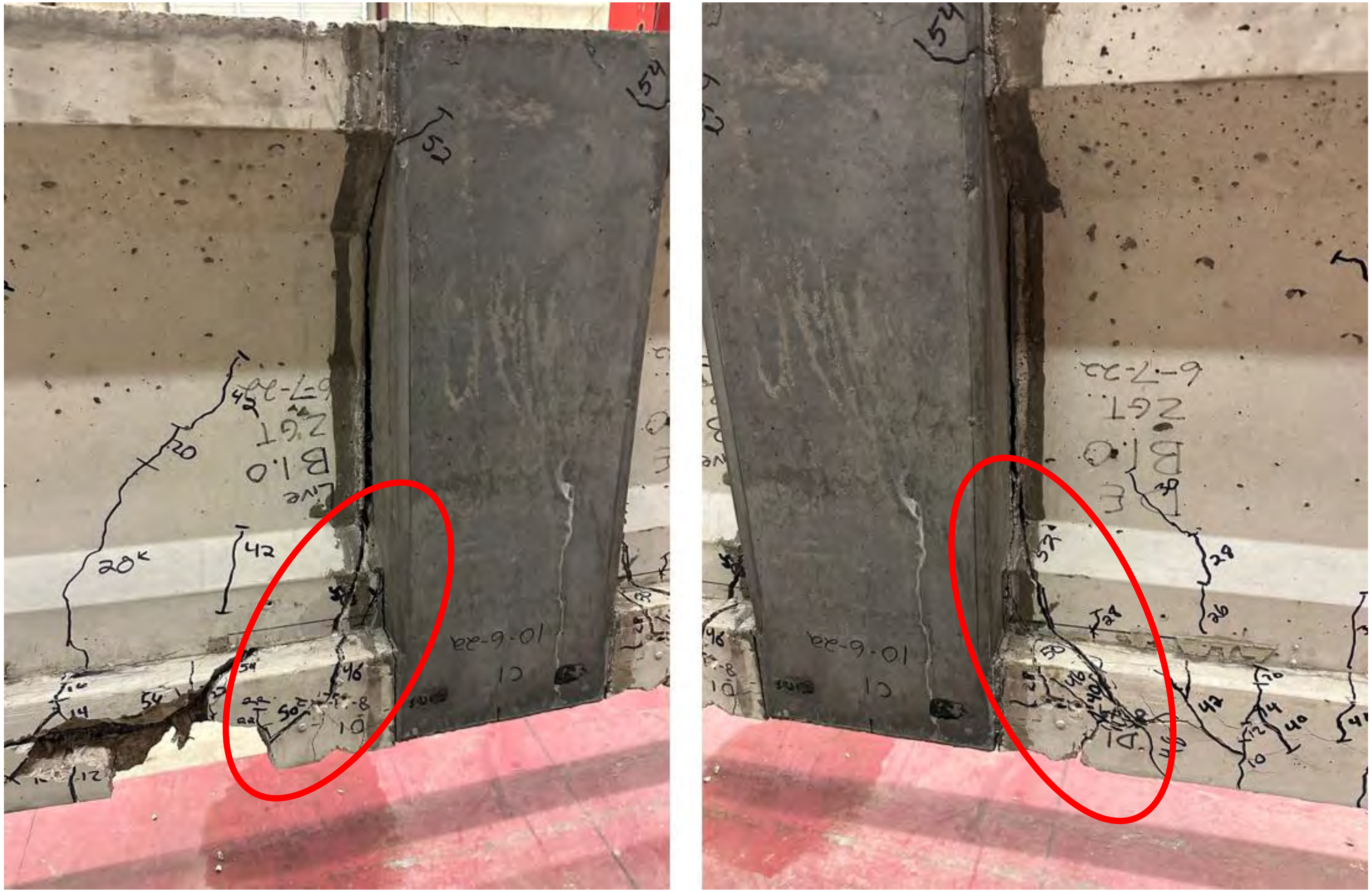


Cracking in the compression zone

Typical Negative Moment Failure

Flexural cracking in test with specimen loaded upside down to induce tension at the top of the connection

Unusual Negative Moment Failure (HSJ3-1)



Flexural cracking deviating from the interface of the girder and UHPC

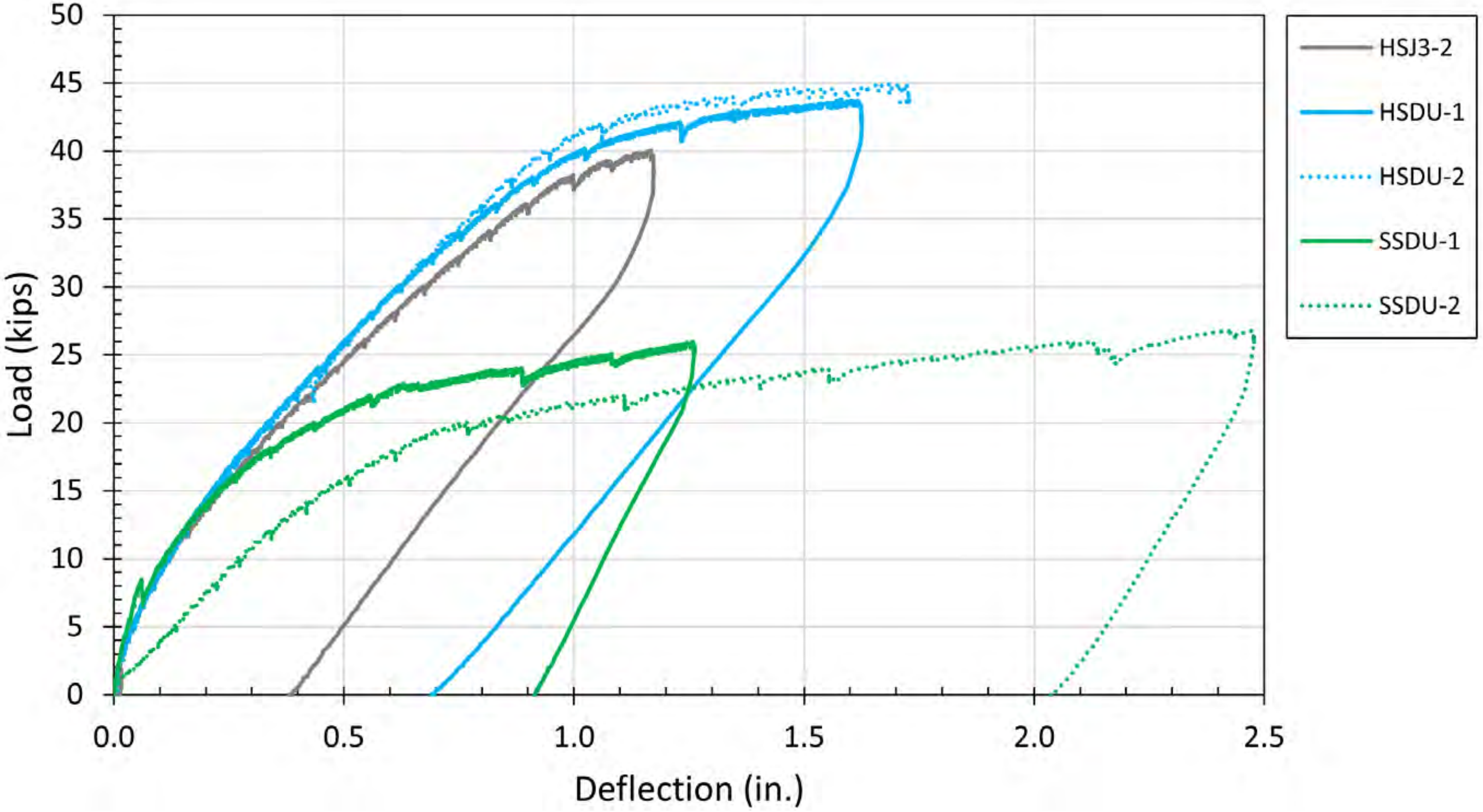
Specimen Nomenclature

- Example: SSDU-2 N

Label	Meaning
HS	Hooked Strand
SS	Straight Strand
J3	Non-proprietary UHPC
DU	Proprietary UHPC
1 or 2	Number of Specimen (in a set)
N or S	Interface Location (North or South)

Load-Deflection Curves for Positive Moment Tests

- Hooked strands displayed a significantly higher capacity than straight strands
- All specimens followed a similar curve



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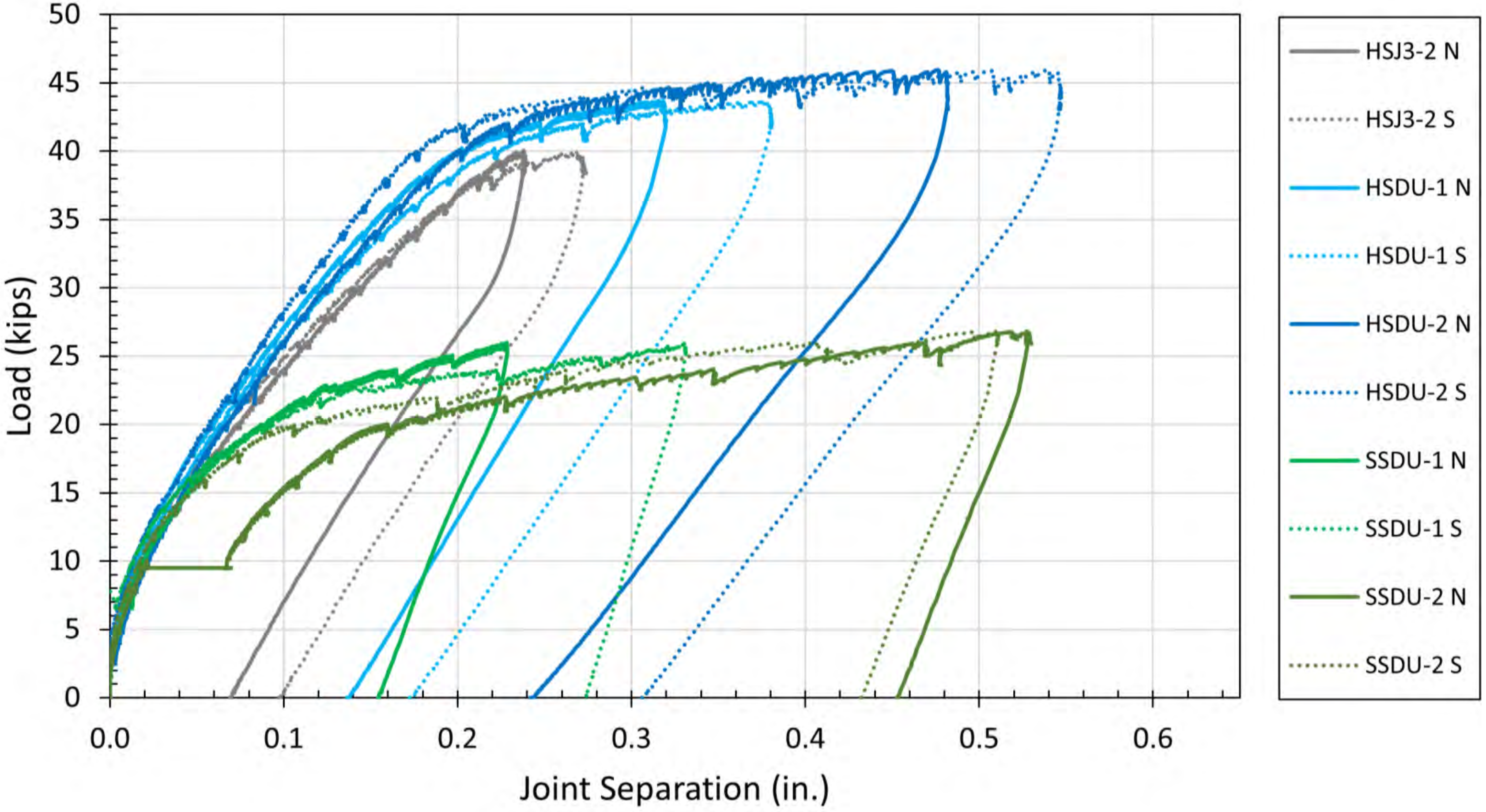
Load-Joint Separation Curves for Positive Moment Tests

- Hooked strand proprietary UHPC specimens performed the best
- Clear relationship between hooked vs. straight strands



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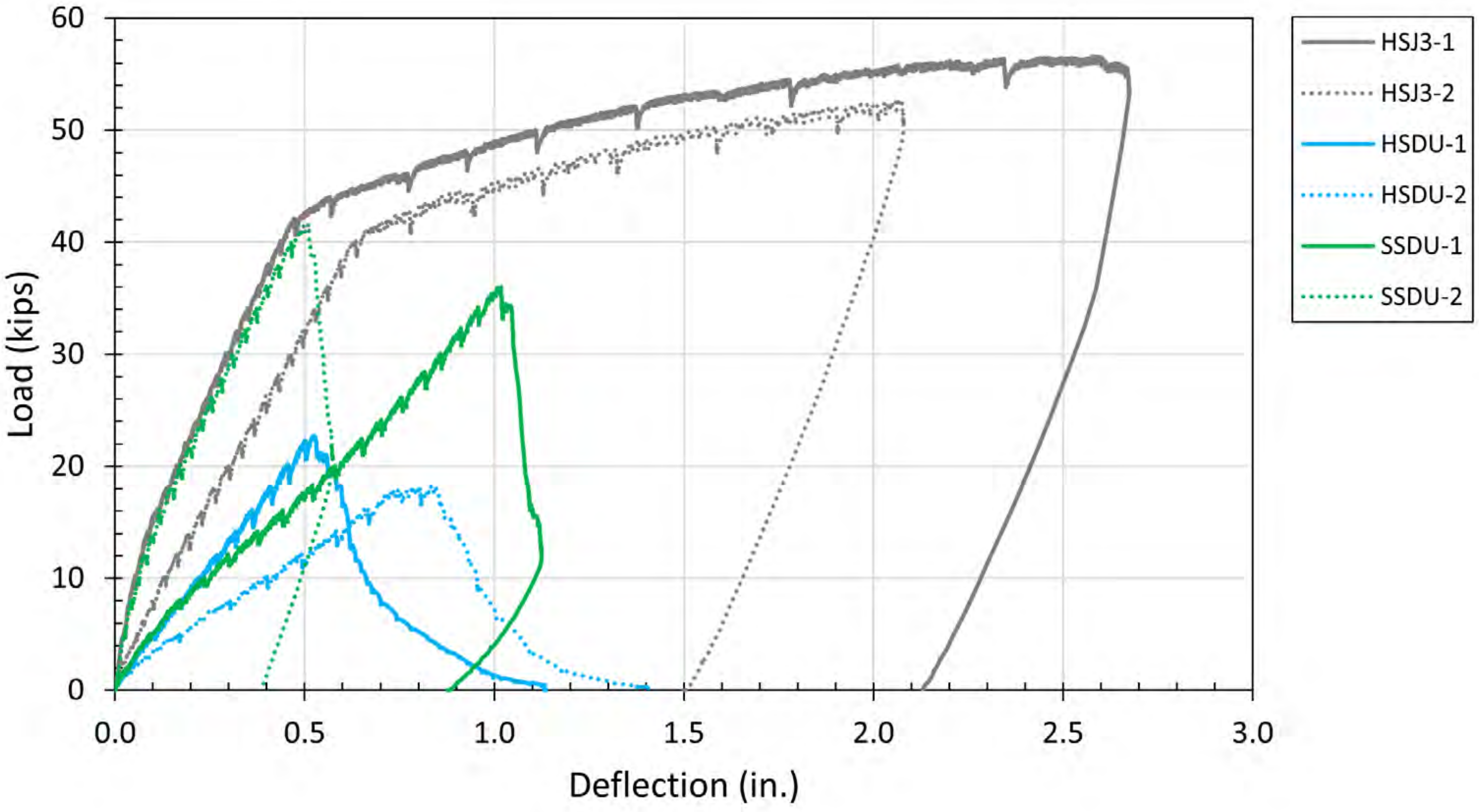
Load-Deflection Curves for Negative Moment

- Non-proprietary UHPC specimens showed greater capacity and gradual loss of stiffness
- UHPC with limited fibers around mild steel showed lower load carrying capacity and a sudden loss of stiffness



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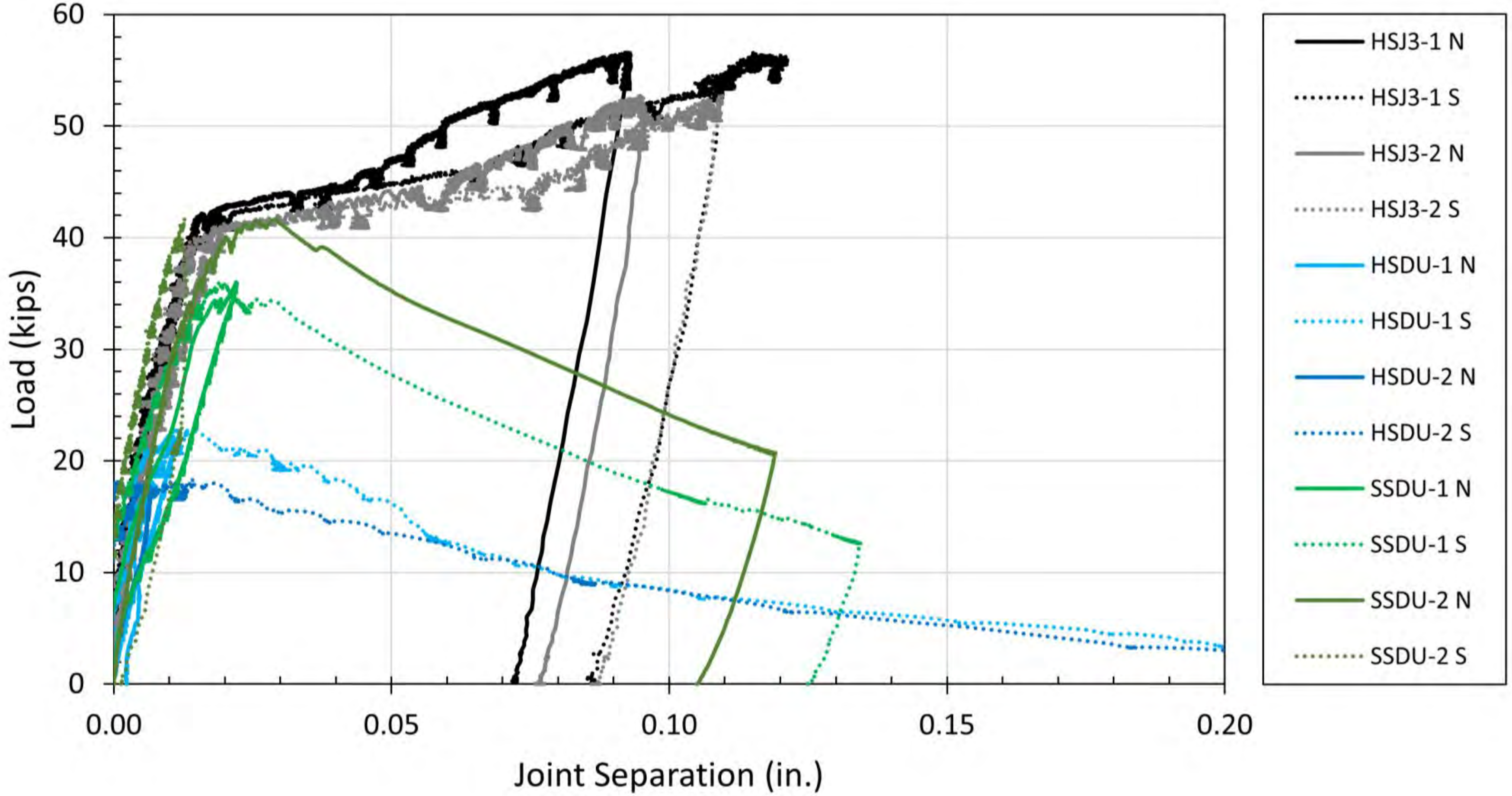
Load-Joint Separation Curves for Negative Moment

- Non-proprietary UHPC specimens showed significant joint separation at both interfaces
- Proprietary UHPC specimens showed joint separation at a single interface



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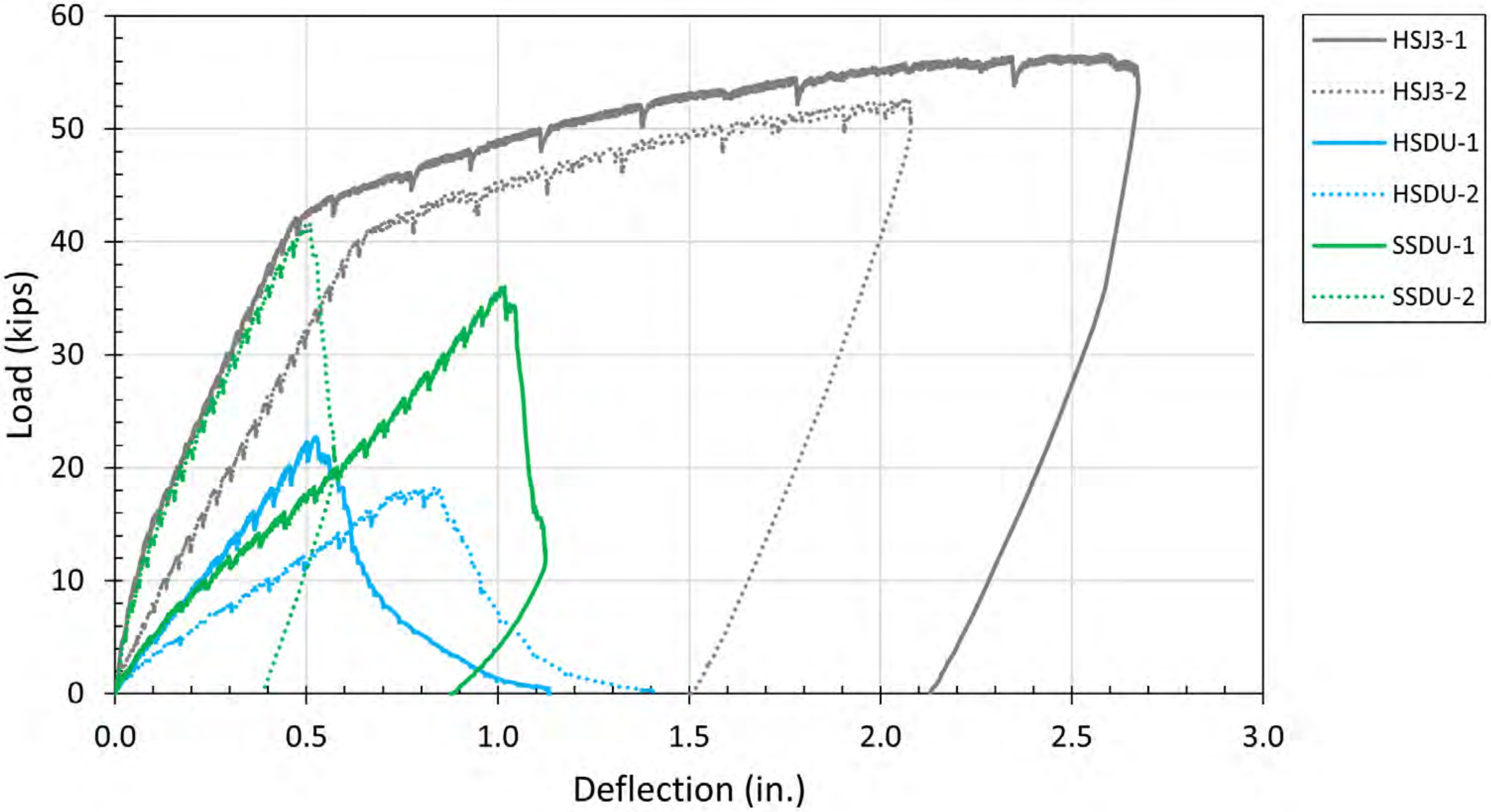
Calculated Stress in Deck Steel During Negative Moment Test

- Based on strain compatibility using ultimate loads

Specimen	Stress in Steel (ksi)
HSJ3-1	89.7
HSJ3-2	83.6
HSDU-1	35.4
HSDU-2	28.4
SSDU-1	56.6
SSDU-2	65.5

Load-Deflection Curves for Negative Moment



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As-Cast Top Face of Joint Without Fibers

Horizontal cracking and spalling of UHPC with no fibers during negative moment test

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Calc. Stress in Prestressing Steel During Positive Moment Test

- Based on strain compatibility using ultimate loads

$$Bond\ Stress = \frac{Applied\ Load}{Bond\ Length * \pi * Strand\ Diamater}$$

Specimen	Stress in Steel (ksi)	Bond Stress (ksi)
HSJ3-2	236.8	--
HSDU-1	259.1	--
HSDU-2	273.8	--
SSDU-1	152.3	1.17
SSDU-2	157.2	1.20

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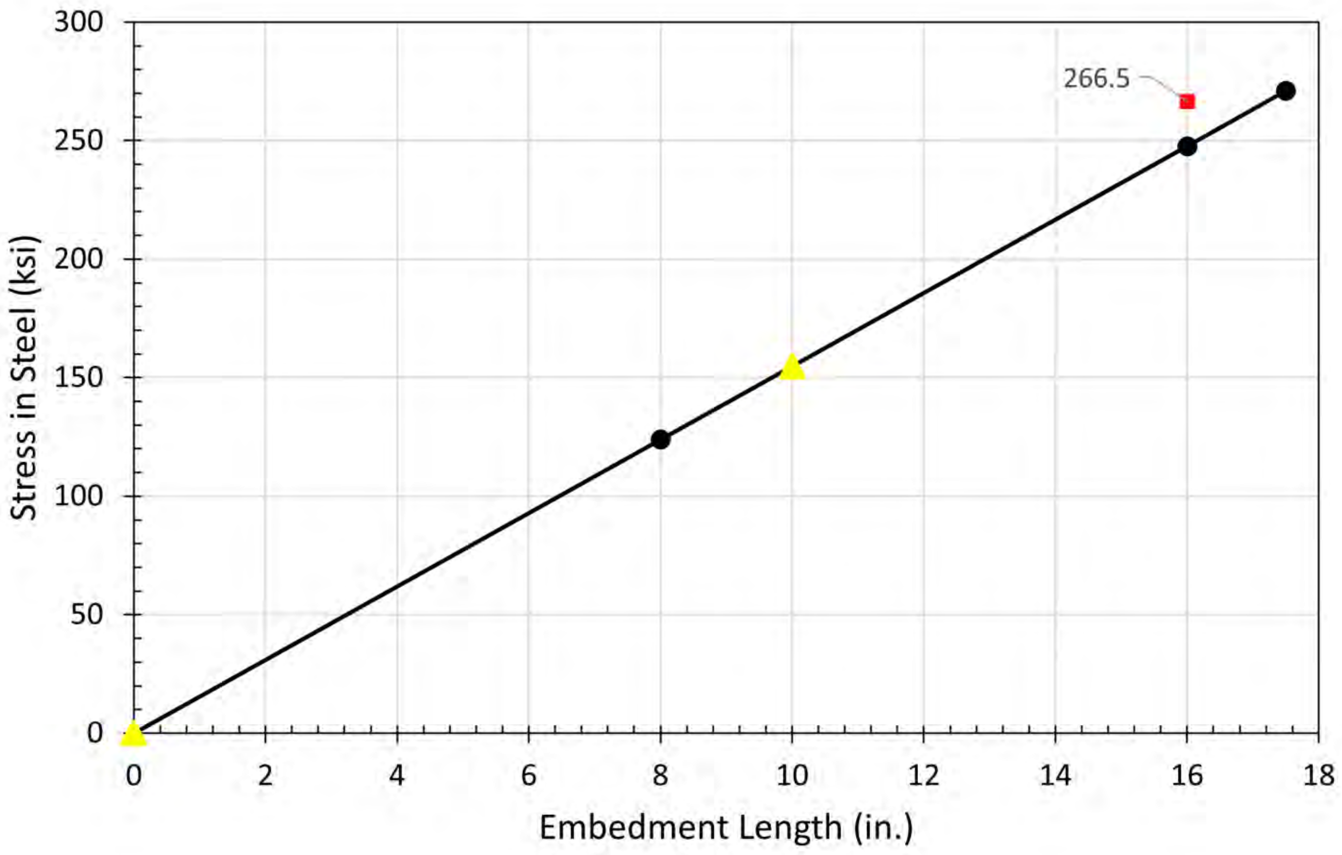
Assumed Linear Relationship

- Based on 10 in. straight strand proprietary UHPC specimens
  - Yellow triangle indicates values from straight strand specimen
  - Red square from hooked strand specimen
  - Others extrapolated

Embedment Length (in.)	Stress in Steel (ksi)
0	0
8	123.8
10	154.8
16	247.7
17.5	270.9



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Lessons Learned

- Bond strength, resistance to cracking, and fiber distribution contribute more to joint performance than compressive strength alone
- Testing each connection in both positive and negative moment likely influenced the results of the second test for several specimens
- Proper material storage and mixing are critical to ensure UHPC performance
- Joints should be overfilled to ensure adequate reinforcement cover
- Beam ends should be roughened to increase the bond to UHPC joint material
- High stiffness of the UHPC joint may lead to more cracking in the beam ends than for conventional concrete joints

Conclusions

- Previous research indicates UHPC connections designed using current AASHTO provisions provide required capacity and are effective for establishing continuity
- All UHPC hooked strand specimens showed very similar performance during positive moment testing where fibers were adequately distributed around the reinforcement
- Providing a hook significantly increased capacity with the same horizontal strand embedment
- Extrapolated data indicates that hooked strands provide similar capacity to a straight strand of an equal total length

Design Recommendations

- Current AASHTO provisions with modifications for UHPC properties
- Previous research and AASHTO Guide Specification for Structural Design with Ultra-High Performance Concrete (e.g. El-Helou and Graybeal (2022))
  - UHPC material property models
  - Flexural capacity of the UHPC connection
- Bar and strand development in UHPC continuity connections verified or developed during the current research
  - $8d_b$ or $10d_b$ for deformed bars based on Graybeal (2014a)
  - Hooked strand with 20 in. (0.5 in.) or 24 in. (0.6 in.) total embedment and 8 in. horizontal projection

Recommendations for Future Work

- Beam end pullout testing to further evaluate strand connection details
  - Provide a variety of embedment and hook lengths
  - Test each specimen for only one type of moment

- Investigate non-contact lap splice connections for both positive and negative moment details

- Model effects of connection stiffness to evaluate effects on girder behavior/design and potential for moving cracking from the joint to the girder

Implementation

- Upcoming ABC-UTC Guide for Design of UHPC Continuity Connections

- References to past research
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