SERVICE LIFE DESIGN GUIDANCE FOR UHPC LINK SLABS

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ABC-UTC Research Seminar

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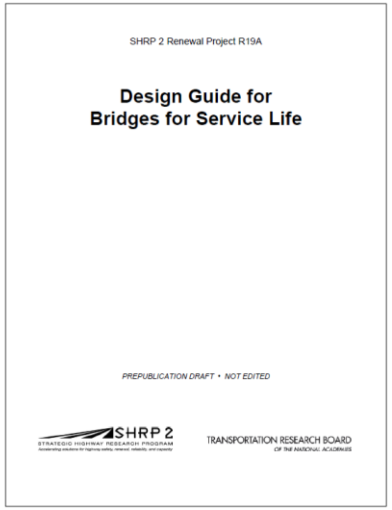
Service Life Design

- Develop longer lasting bridges
- Resistant to environment, maintainable, adaptable
- SHRP 2 R19A “Design Guide for Bridges for Service Life”
  - Consider Service Life at the design stage
  - Tailor methods to specific conditions
  - Materials, construction techniques, new technologies
- NCHRP 12-108 (web only document 269)
  - “Development of Guide Specification for Service Life Design of Highway Bridges”



SHRP 2 Renewal Project R19A

Design Guide for Bridges for Service Life

PREPUBLICATION DRAFT • NOT EDITED

SHRP 2

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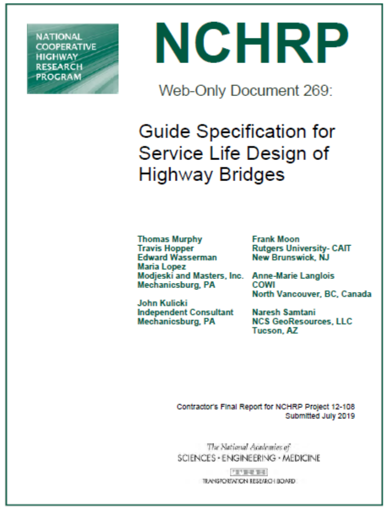

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP

Web-Only Document 269:

Guide Specification for Service Life Design of Highway Bridges

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Contractor's Final Report for NCHRP Project 12-108
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Expansion Joint Deterioration

Spalling and loss of steel armoring
Photo curtesy of Walt Peters

Offset of deck slabs and damage to joint seal
http://www.toledoblade.com/local/2011/07/08/Defective-bridge-expansion-joint-causes-I-75-delays.html

Beam End Deterioration

Spalling and discoloration of prestressed beam ends

Close-up of corrosion induced spalling

Substructure Deterioration

Corrosion and spalling on piers and pier caps likely resulting from water passing through the deck joint

Link Slabs

- Flexible slab continuous over piers – eliminate joints
- Allows rotation and simple span behavior
- Cracking under loading
- Debonded from beams and tied into deck slab
- First examined in 1980s and 1990s (Caner and Zia 1998)
  - Full-depth
  - Conventional concrete
  - Other materials have been used

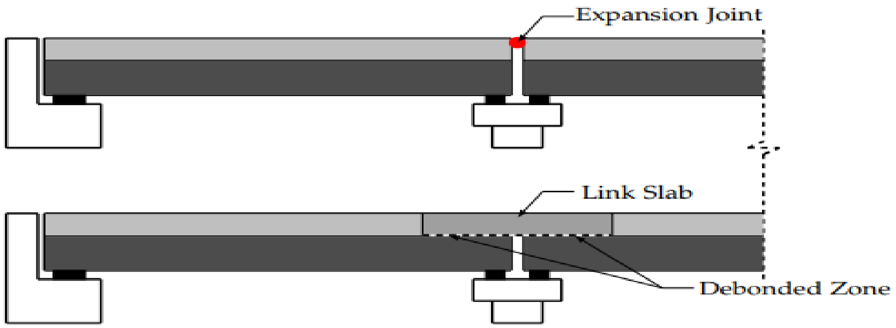


Illustration of link slab application (Haikal et al. 2019)

Ultra-High Performance Concrete (UHPC)

- Developed over the last 30 years
- Compressive strength typically greater than 21 ksi
- Post-cracking flexural strength greater than 0.72 ksi
- Very low to negligible permeability
- Resistant to freeze-thaw
- Strong bond to base concrete
- Short reinforcement development length
- Potential to increase service life

Illustration of the effect of fibers on failure

Ultra-High Performance Concrete (UHPC)

- Low w/cm
- Optimized particle packing
- High flowability
- Typically 2% by volume high strength steel fibers
- High mixing energy required

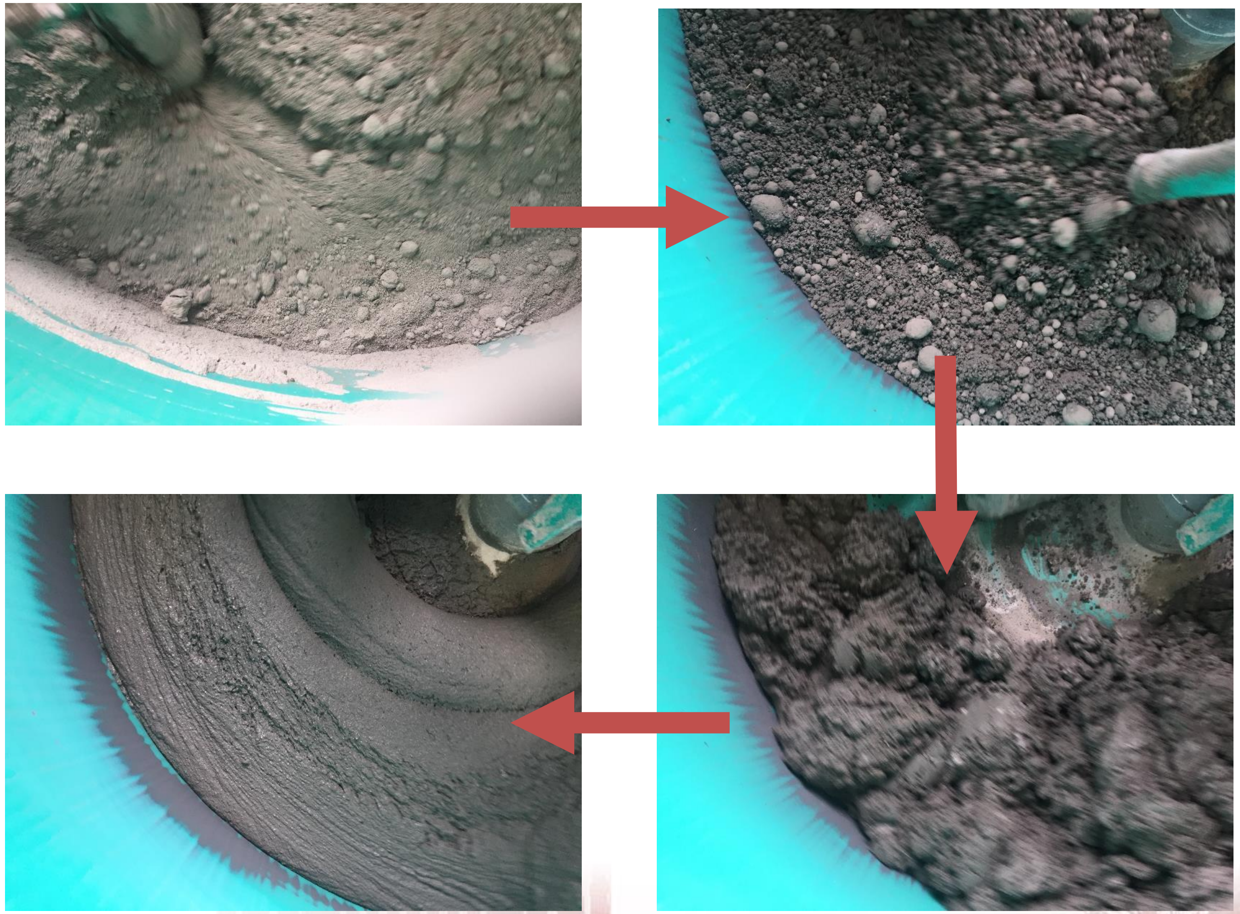


Illustration of the UHPC mixing process

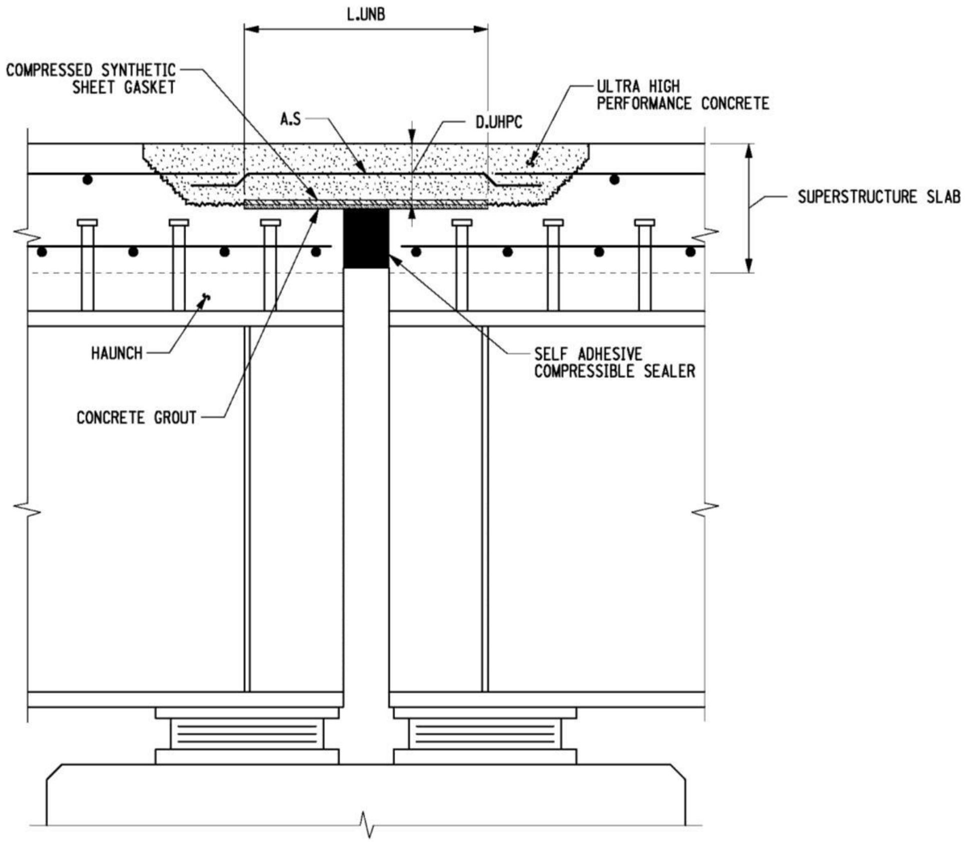
Non-Proprietary UHPC

Why?

- High compressive strength of high end UHPC may not be needed in some applications such as field joints in bridge decks
- Tailor properties to need, which can lead to lower material cost
- Several DOTs see proprietary nature of UHPC lead to sole-sourcing and bidding issues

UHPC Link Slabs

- Can be partial depth
- UHPC allows for shorter connections and debonded length
- 5% of span + embedment vs. 2-3 ft total
- Small distributed cracks
- Relevant to ABC
  - Fast replacement/installation
  - High durability – limit repair



Example UHPC link slab detail for repair/retrofit application (Scarlata 2017)

Objectives

- Develop user friendly tools that will allow use of developed information specific to UHPC link slabs within the framework developed by SHRP2 R19A for service life design of bridges
- Examine effects of service level loads on durability
- Provide educational materials to help practitioners understand how to use this information
- Leverage other research by ABC-UTC and state DOTs

Project Status

- Multiple Covid-19 and equipment related delays
- Review of research and practice completed
- Large-scale testing still underway
  - Loading is complete
  - Specimens under preparation for freeze-thaw and corrosion testing
- Training material preparation underway
- ODOT planning for possible link slab implementation in 2022

Review of Research and Practice

- Typical proprietary UHPC properties (Graybeal 2014)

Characteristic	Average Result
Density	155 lb/ft^3 (2,480 kg/m^3)
Compressive Strength (ASTM C39, 28-Days)	24 ksi (165 MPa)
Modulus of Elasticity (ASTM C469, 28-Days)	7,000 ksi (48 GPa)
Direct Tension Cracking Strength	1.2 ksi (8.5 MPa)
Split Cylinder Cracking Strength (ASTM C496)	1.3 ksi (9.0 MPa)
Prism Flexure Cracking Strength (ASTM C1018)	1.3 ksi (9.0 MPa)
Long-Term Creep Coefficient (ASTM C 512,11.2 ksi (77MPa) Stress)	0.78
Long-Term Shrinkage (ASTM C 157, initial reading after set)	555 με
Total Shrinkage (embedded vibrating wire strain gage)	790 με
Coefficient of Thermal Expansion (AASHTO TP60-00)	8.2 x 10^{-6} in./in./°F (14.7 x 10^{-6} in./in./°C)
Chloride Ion Permeability (ASTM C1202, 28-day test)	360 coulombs
Chloride Ion Permeability (AASHTO T259, 0.5 in. (12.7 mm) depth)	<0.10 lb/yd^3 (<0.06 kg/m^3)
Scaling Resistance (ASTM C672)	No scaling
Abrasion Resistance (ASTM C944 2x Weight, ground surface)	0.026 oz. (0.73 g) lost
Freeze-Thaw Resistance (ASTM C666A, 600 cycles)	RDM = 99%
Alkali-Silica Reaction (ASTM C1260, tested for 28 days)	Innocuous

Review of Research and Practice

- Link slab behavior
  - Pin connection at slab
  - Point of rotation moved from bearings to slab
  - Prevent ingress of water and corrosive agents
  - Transmit thermal loadings
  - No cracks larger than 0.013 in. due to flexure

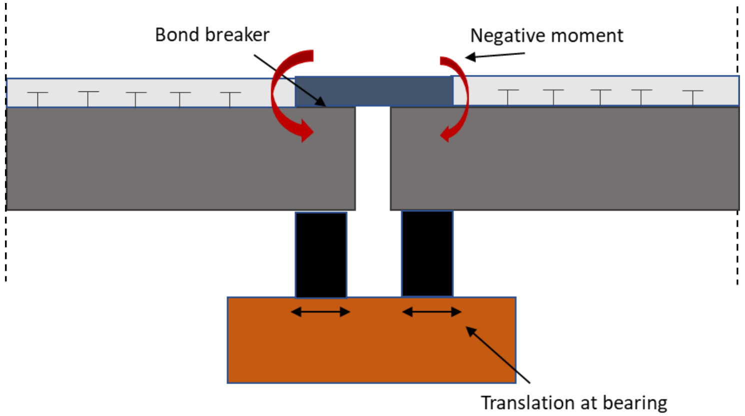
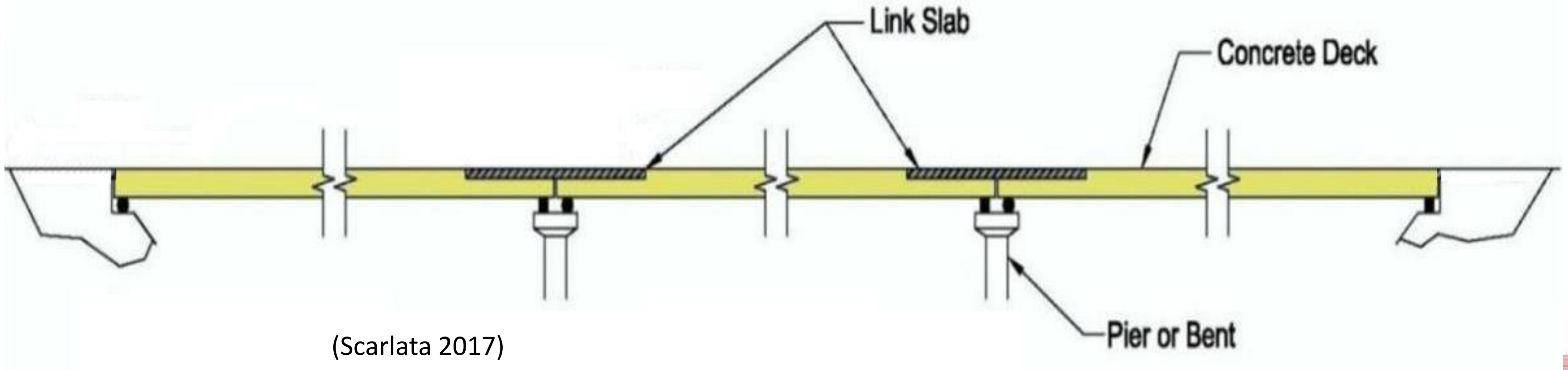


Illustration of link slab behavior



(Scarlata 2017)

Review of Research and Practice

- Approximately 30% of DOTs have implemented link slabs (Haikal et al. 2019, Thorkildsen and Pedersen 2020)

State	Research	Field Work	Specifications
Delaware	na	Yes	na
Florida	Yes	na	Yes
Georgia	Yes	na	na
Hawaii	Yes	na	na
Indiana	na	Yes	na
Iowa	Yes	na	na
Maryland	na	Yes	Yes
Massachusetts	na	Yes	Yes
Michigan	Yes	Yes	na
Missouri	na	Yes	na
Nebraska	Yes	na	na
New York	Yes	Yes	Yes
North Carolina	Yes	Yes	Yes
Tennessee	na	Yes	na
Utah	na	na	Yes
Virginia	Yes	Yes	Yes

Note: na = not available to the author

Review of Research and Practice

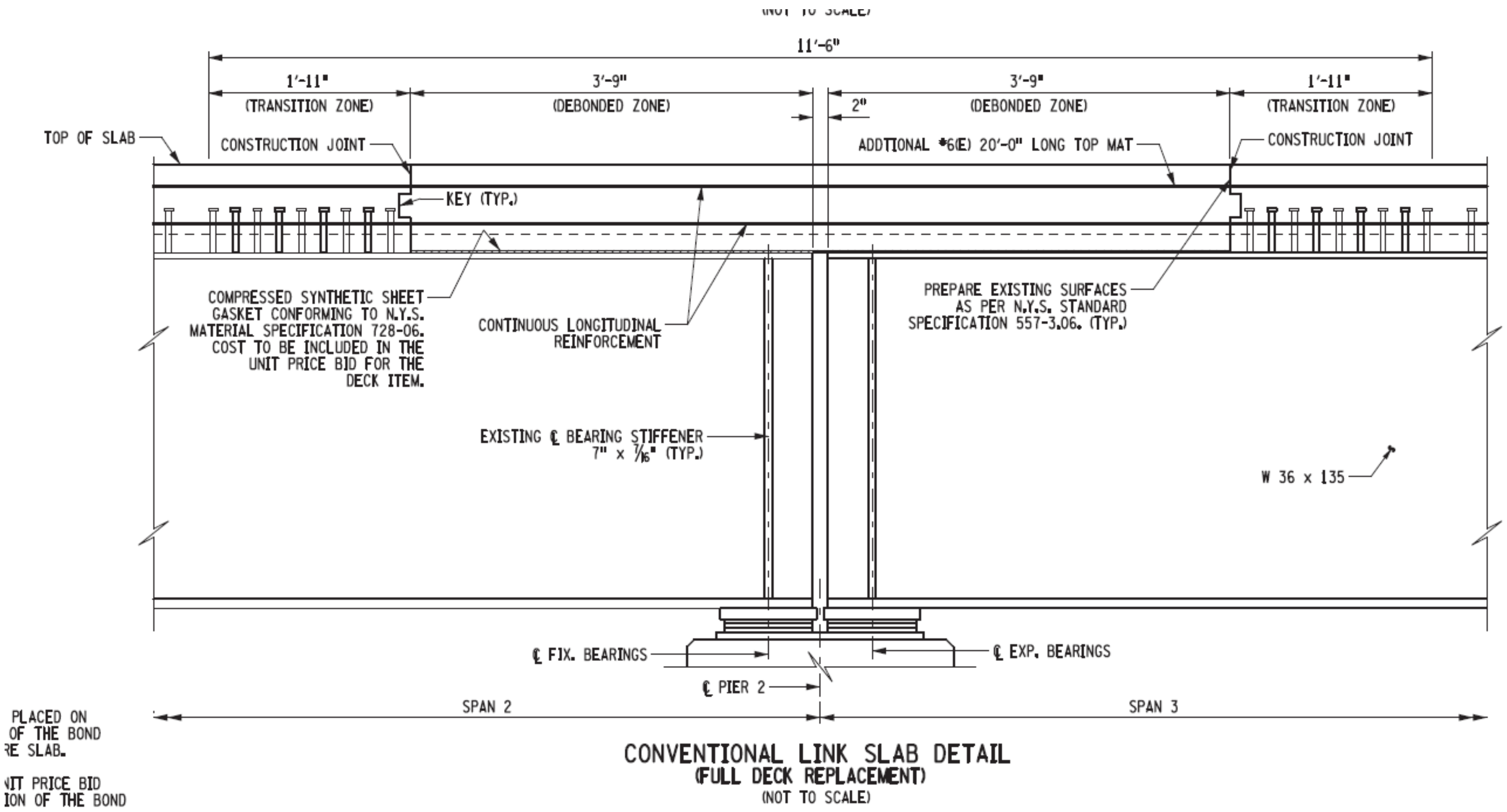
- Thorkildsen and Pedersen (2020) summarized typical design criteria by states using link slabs

Item	VDOT	MassDOT	NYSDOT (High Performance)	NYSDOT (UHPC)	MDTA
Number of Installed Slabs	227 bridges and 518 link slabs	30+ bridges and 50+ link slabs	Over 10	Over 50	1
Length of Link Slab	4 ft min.	5% to 7% of span length on either side of joint	Varies and is determined by specific analysis of the structure	2 - 3 ft – varies and is determined by specific analysis of the structure	3 - 4 ft
Other Concrete	>4 ksi, Low Shrinkage Class A4	High early strength	Internally cured concrete	UHPC	UHPC and ECC
Bond Breaker and Flexibility	Remove studs, ½ in. polystyrene	Remove studs, ¼ in. thick neoprene	Remove studs, Synthetic Sheet Gasket	Remove studs, Synthetic Sheet Gasket	Remove studs and Synthetic Sheet Gasket
Reinforcement in and Around Slab	Splice to existing	Splice to existing	Splice to existing	Splice to existing	Drill and grout longitudinal bars into existing deck
Also used on New Bridges	No	Yes. Particularly with ABC technique	No	Yes	No
Partial Depth Link Slab	Yes	No.	No	Yes	Yes
Skew Limits, (deg)	Not above 30	No restriction. Max bridge at 60 deg.	Not above 30.	Not above 30	No restriction. Max bridge at 43 deg
Design Procedure	Guidance provided in VDOT manual	Hand calcs, Excel spreadsheets	Automated file	Automated file	Excel spreadsheets

Design Process (NYSDOT)

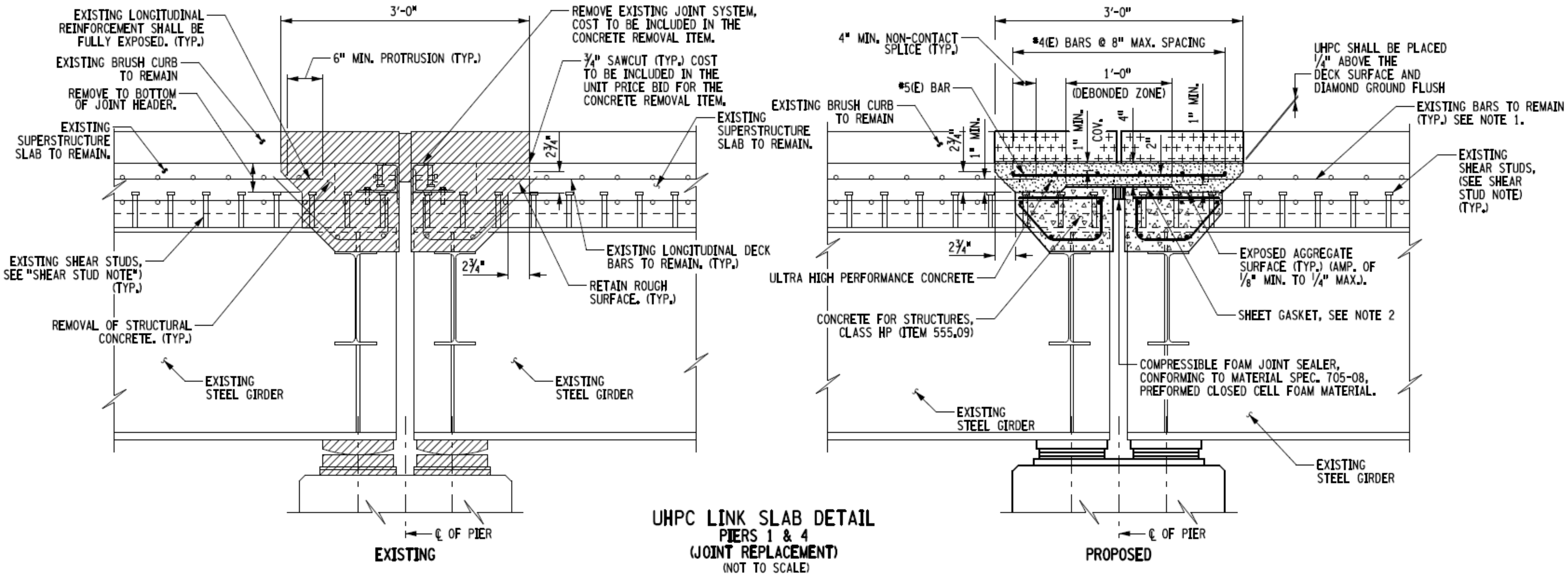
- Assume stresses distributed along debonded length
- Inputs
  - UHPC tensile cracking stress of 1.2 ksi
  - 3500 x 10^{-6} maximum UHPC tensile strain
  - UHPC allowable compressive stress of 14 ksi
- Sum internal forces considering UHPC tension resistance
- Determine UHPC and steel strain based on girder rotations and unbonded length
- Compare actual stresses to applied stresses

Review of Research and Practice



NYSDOT Conventional Link Slab Detail (full-depth)

Review of Research and Practice



NYSDOT UHPC Link Slab Detail (half-depth, joint replacement)

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Sources of Distress

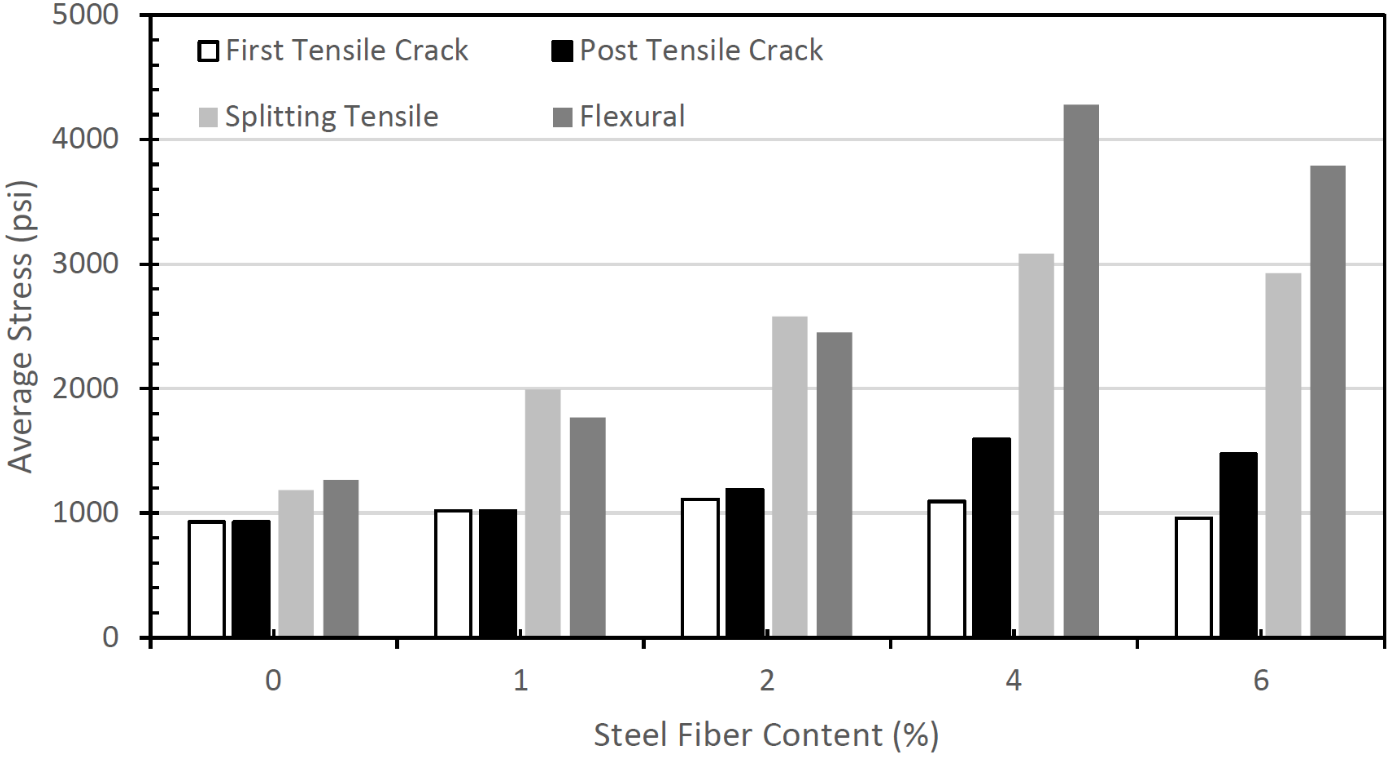
- Improper design of link slab stiffness
  - Arresting girder rotation can result in cracking in the link slab (Karim and Shafei 2021)
  - If link slab is stiffer than the deck slab, cracking may occur in the adjacent slab (Seibert and Corvez 2019)
- Inadequate debonded length can result in slab cracking (Lepech and Li 2009)

Sources of Distress

- Improper bearings at link slab locations (Gergess and Douaihy 2020)
  - Lateral movement and rotation should not be restrained
- Chloride ingress
- Freeze-thaw

Service Life Design Considerations

- J3 non-proprietary UHPC tensile strength



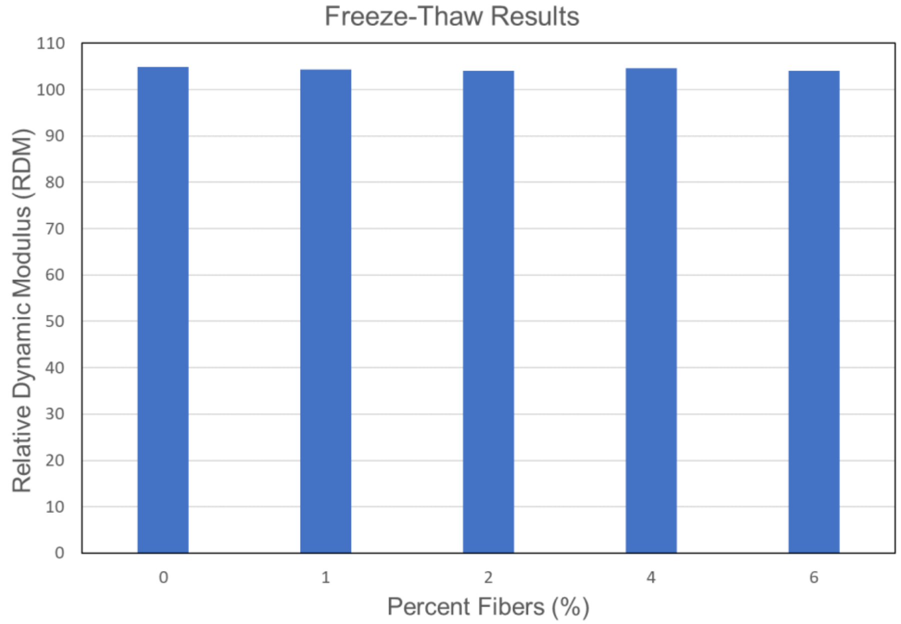
Comparison of results from direct tension, splitting tension, and flexural tension (MOR) tests

Service Life Design Considerations

- Freeze-thaw durability and chloride penetration
  - Conventional concrete (ODOT Class AA) and UHPC
  - J3 non-proprietary UHPC with varying fiber content
  - No fibers for Rapid Chloride testing

Summary of Measured Durability Properties

Property	AA	Proprietary UHPC	Non-Proprietary UHPC
Rapid Chloride (28-day)	2465 C	61 C	251 C
Rapid Chloride (56-day)	1832 C	28 C	63 C
Freeze-Thaw (350 cycles)	99.1%	102.5%	103.1%
Salt Scaling Rating (50 cycles)	1.75	1.25	0



Service Life Design Considerations

- Freeze-thaw durability
  - Composite UHPC and conventional concrete specimens
  - Varying fiber content

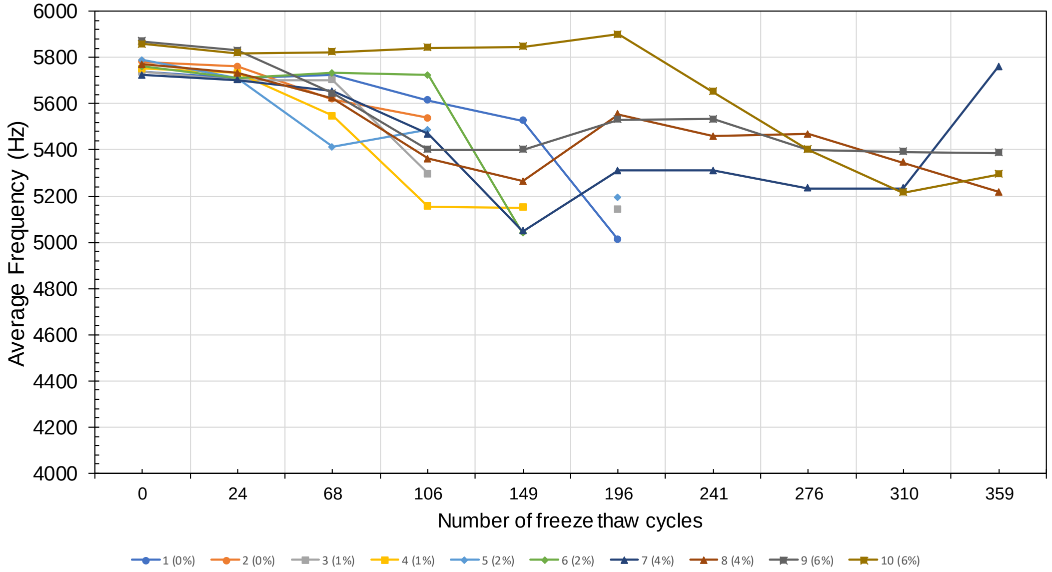
Exposed aggregate surface and completed specimen

0% fibers specimen after 150 cycles showing transverse cracks

0% fibers specimen after 350 cycles

Service Life Design Considerations

- Freeze-thaw durability
  - Composite UHPC and conventional concrete specimens
  - Varying fiber content

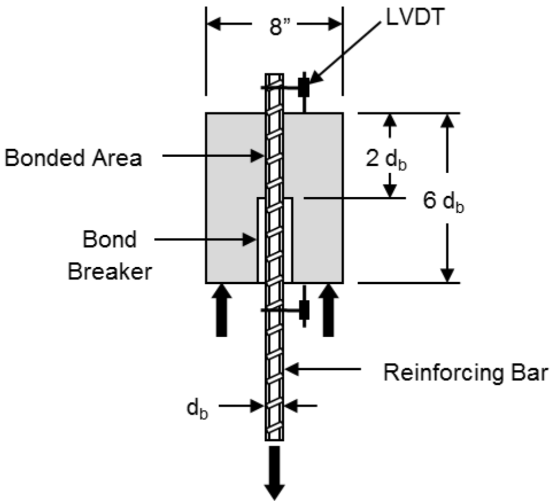


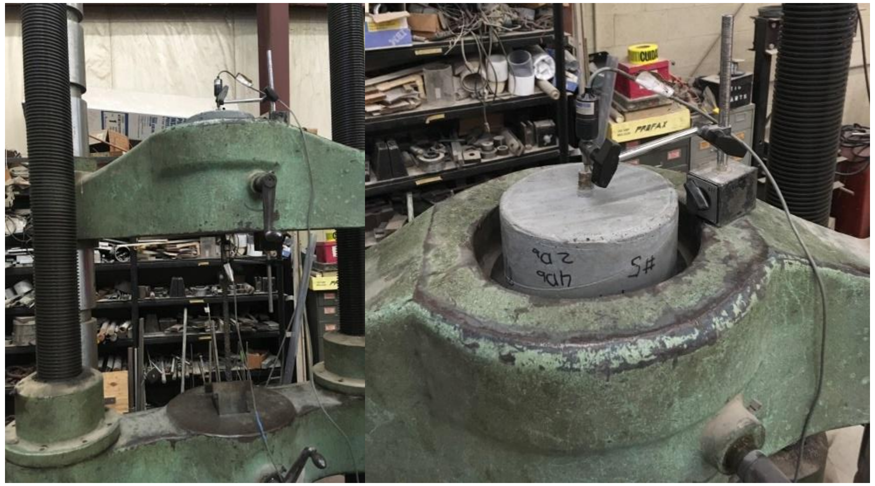
Change in specimen resonant frequency over time

Close-up showing no damage at interface after freeze-thaw testing

Service Life Design Considerations

- J3 non-proprietary UHPC bond strength
  - Comparative pull-out tests
  - Beam splice tests



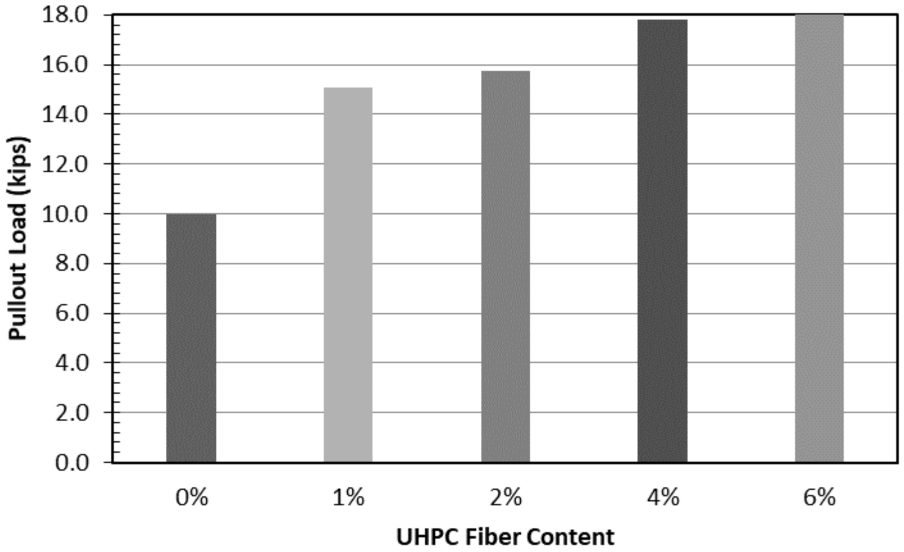


Pullout specimen details and test setup

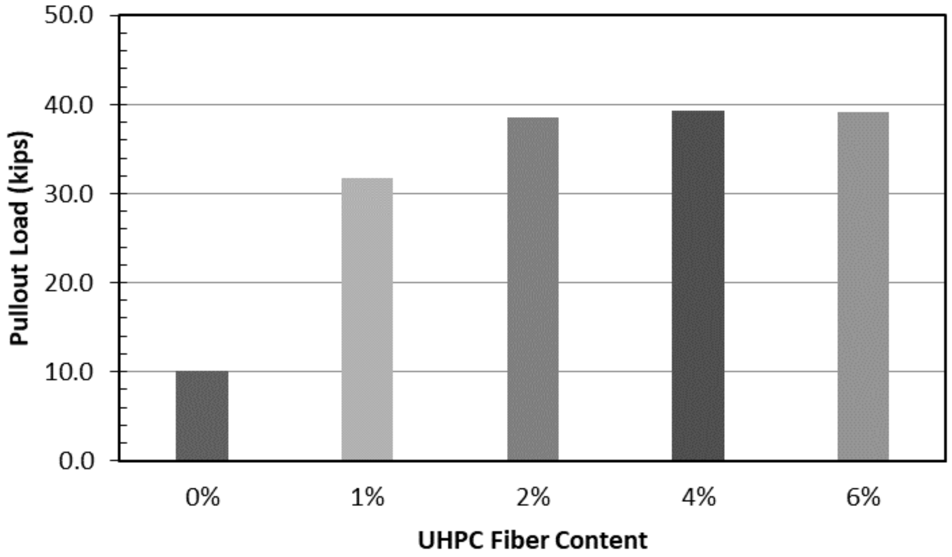
Splice beam testing arrangement

Service Life Design Considerations

- J3 non-proprietary UHPC bond strength – black steel



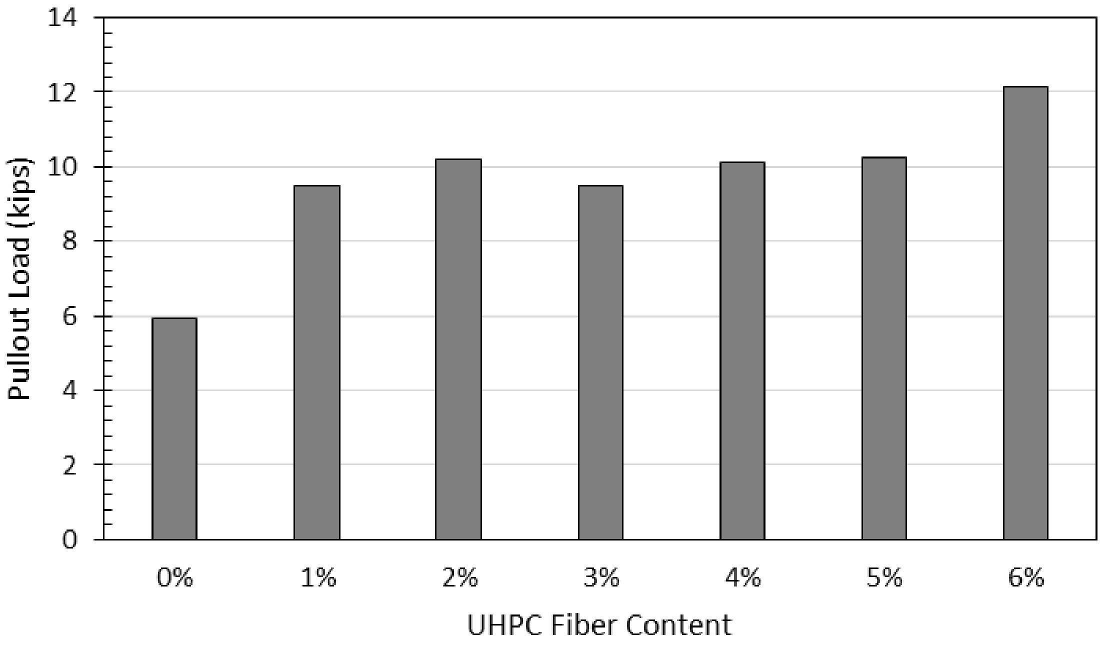
Average Pullout Loads for No. 5 Bars



Average Pullout Loads for No. 8 Bars

Service Life Design Considerations

- J3 non-proprietary UHPC bond strength – epoxy coated



Average Pullout Loads for No. 5 Bars

Service Life Design Considerations

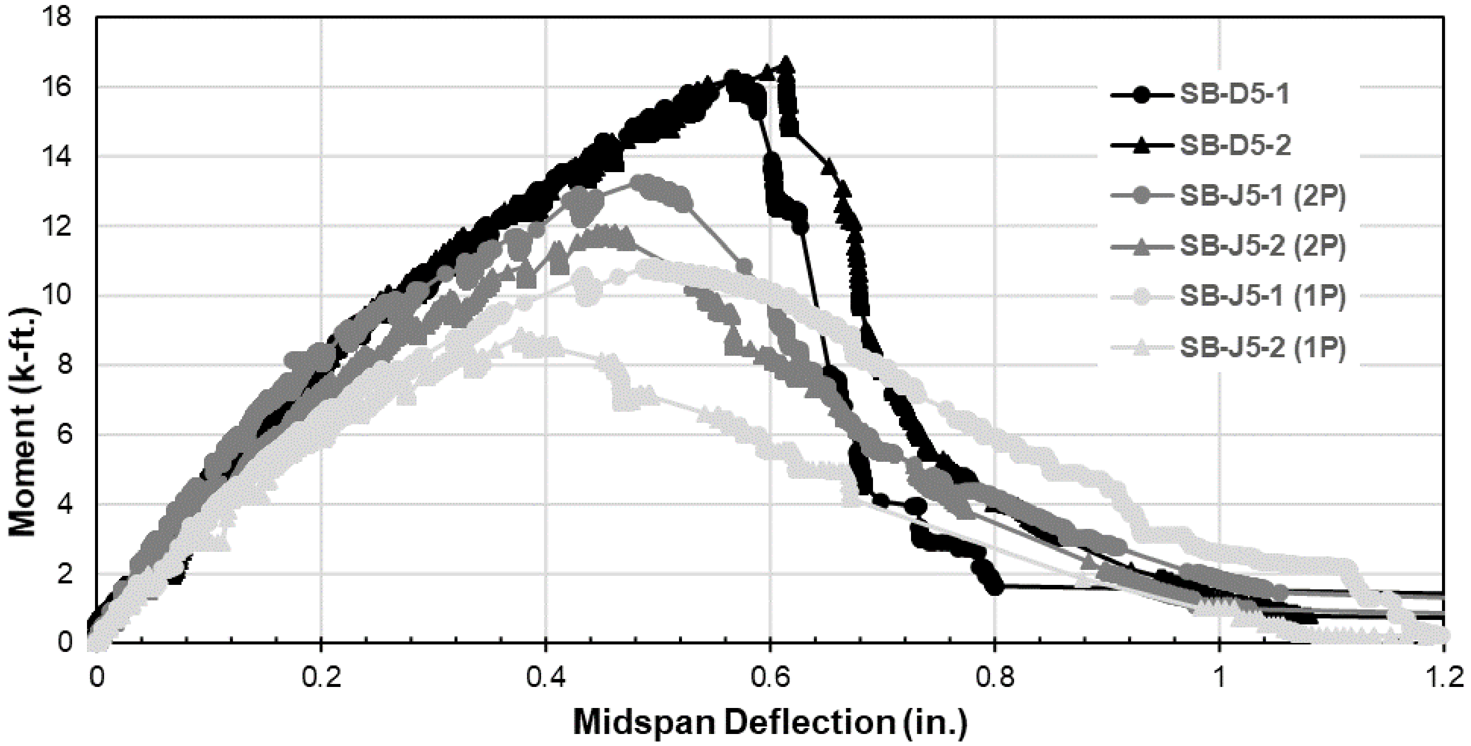
- J3 non-proprietary UHPC bond strength

J3 non-proprietary UHPC specimen showing distributed cracking at failure

Proprietary UHPC specimen showing limited cracking at failure

Service Life Design Considerations

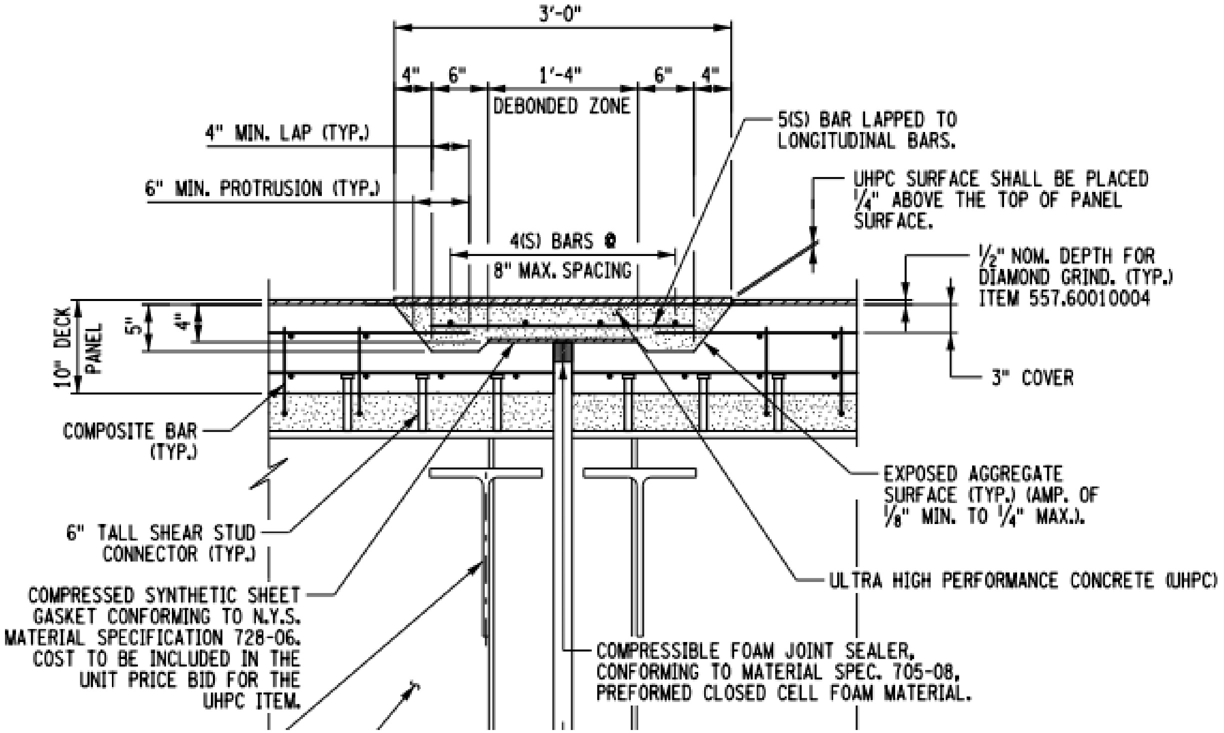
- J3 non-proprietary UHPC bond strength



Load-deflection behavior for No. 5 bar splice beam test specimens

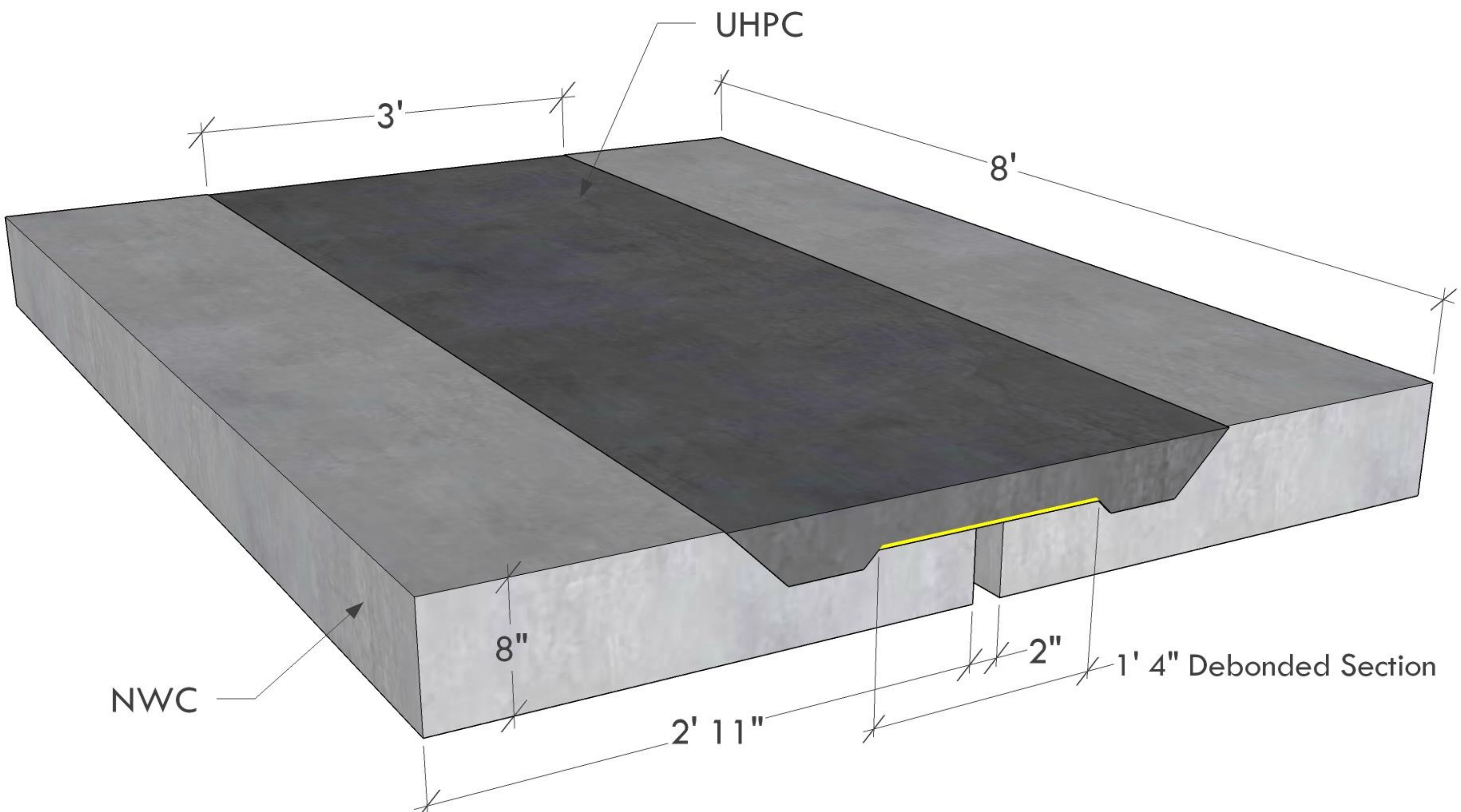
Specimen Preparation – Design

- Four connection specimens
  - Two Class AA
  - Two J3 non-proprietary UHPC
- NYSDOT connection design
  - Partial depth of deck
  - Debonded section
- Modified 10-inch deck from detail to an 8-inch deck for testing



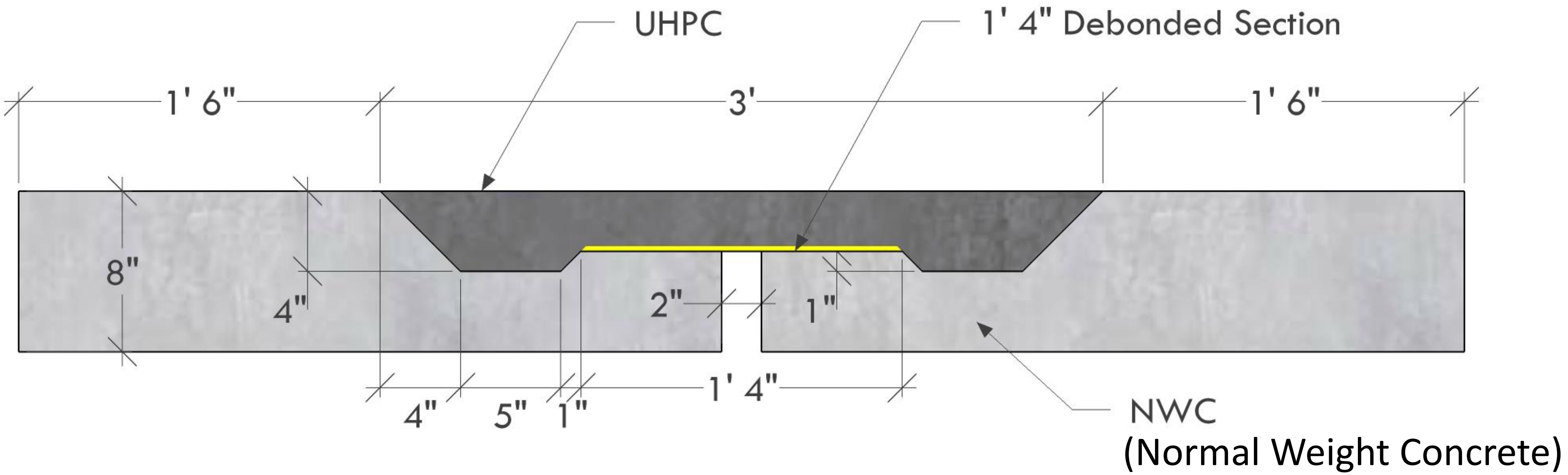
NYSDOT UHPC Link Slab Detail (half-depth, new construction)

Specimen Preparation – Design



Link Slab Test Specimen – General View

Specimen Preparation – Design



Link Slab Test Specimen - End Elevation

Specimen Preparation – Mix Design

- Class AA Concrete
  - Standard ODOT mix for bridge decks
  - 0.37 w/cm
  - Coarse aggregate up to 1.5”
  - Includes sand, air entrainer

- J3 non-proprietary UHPC
  - Mix developed at OU
  - 0.33 w/cm
  - No coarse aggregate
  - Includes masonry sand, silica fume, slag, high range water reducer
  - 2% steel fibers

Specimen Preparation – Design

- Reinforcement
  - Rebar in all concrete bodies
    - No. 5 – connected spans, longitudinal connection rebar
    - No. 4 – transverse connection bars
    - Grade 60 for all rebar

Formwork for connected panel with installed rebar

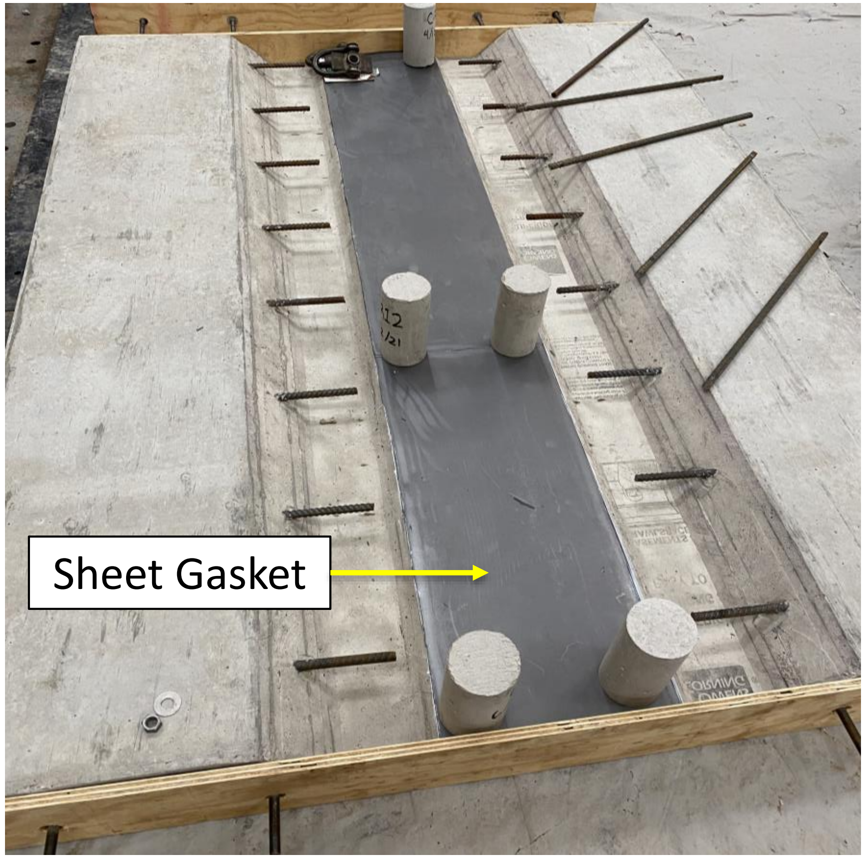
Specimen Preparation – Construction

Concrete panel removed from formwork and flipped

Concrete panel with foam insert removed, exposed rebar

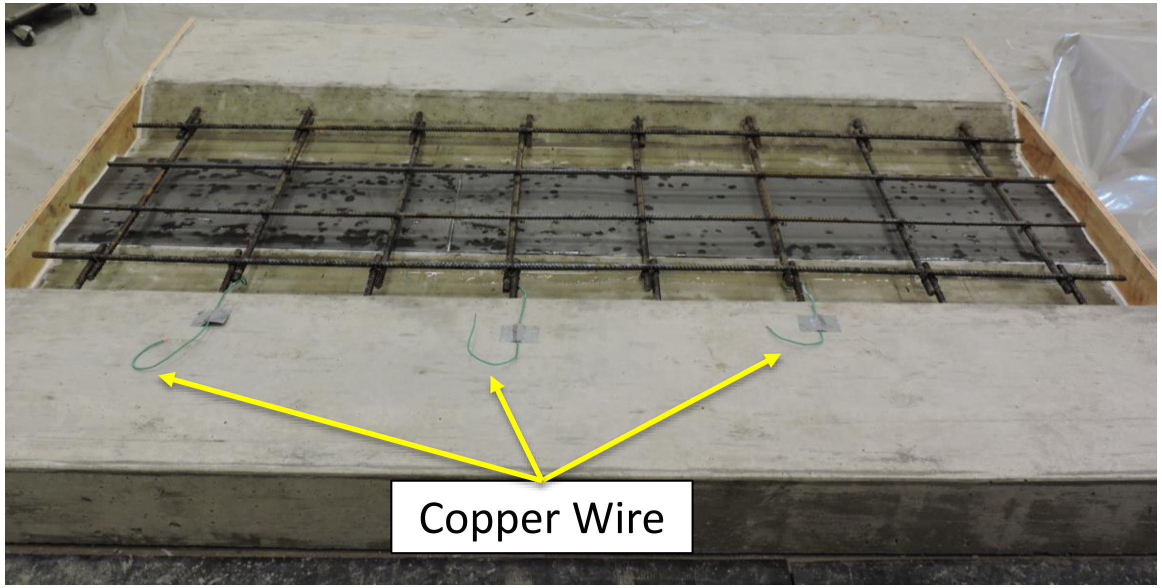
Specimen Preparation – Construction

Adjacent panels set up for connection with 2-inch spacer

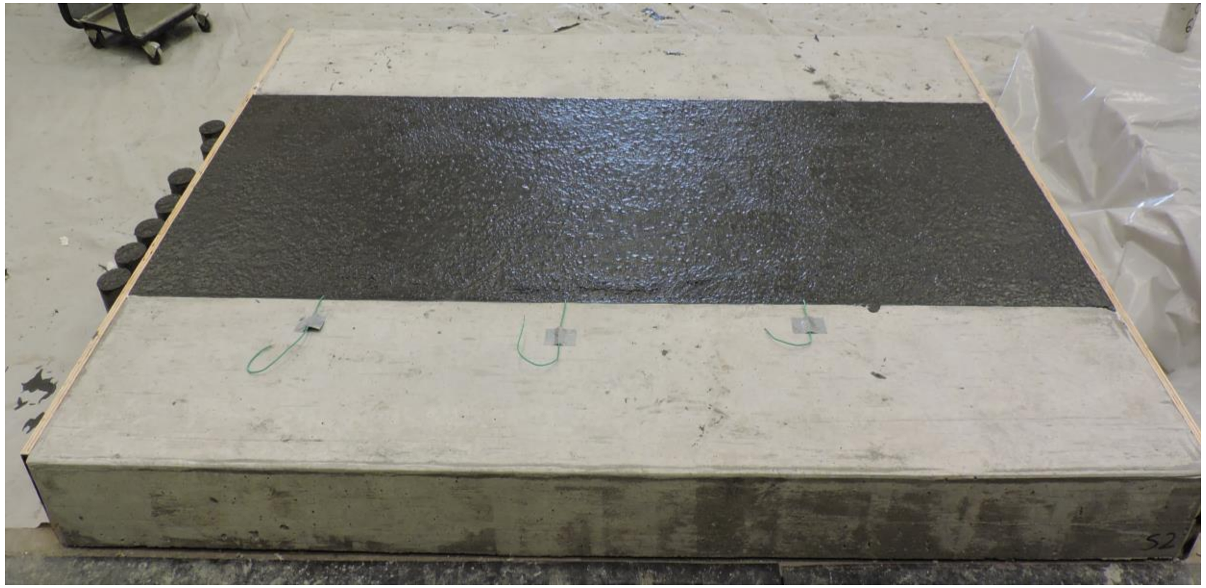


Adjacent panels set up for connection with sheet gasket placed as bond breaker

Specimen Preparation – Construction



Connection formwork with installed bond breaker and rebar



Connection after J3 non-proprietary UHPC is poured

Specimen Preparation – Cyclic Loading

- One specimen of each material
  - One Class AA ODOT
  - One J3 non-proprietary UHPC
- Tension loading
  - Load distributed along connection width
  - 100,000 cycles
    - 5,000 lb peak load
    - 1,000 lb minimum load

J3 non-proprietary UHPC link slab in tension loading (upside down of service orientation)

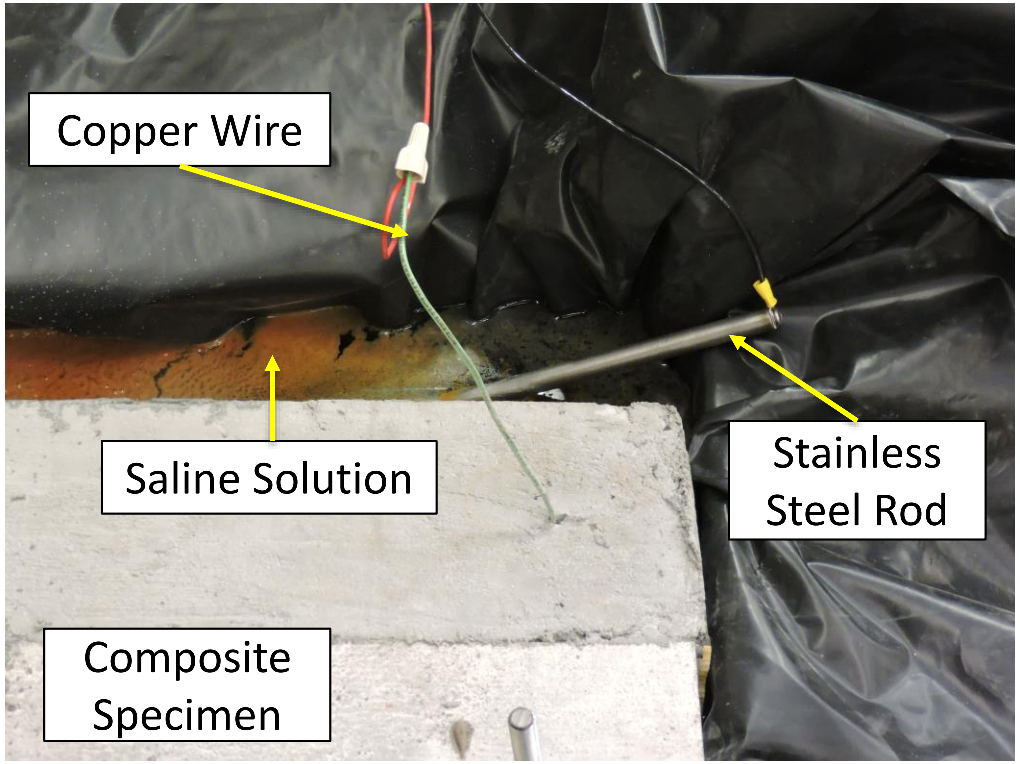
Specimen Preparation – Cyclic Loading

- Compression loading
  - Load distributed perpendicular to connection width
  - 20 cycles
    - 18,000 lb peak load
    - 1,000 lb minimum load

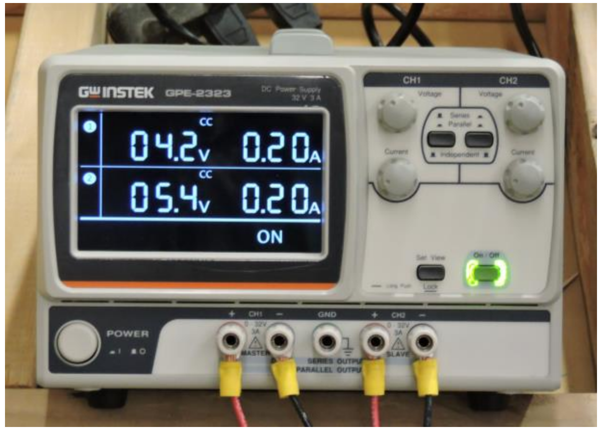
J3 non-proprietary UHPC link slab in compression loading

Durability Testing – Corrosion

- Sections from full-scale link slabs
- 5% saline solution bath, partially submerged
- Electric current through solution and rebar via copper wire



Testing setup for accelerated corrosion specimen section



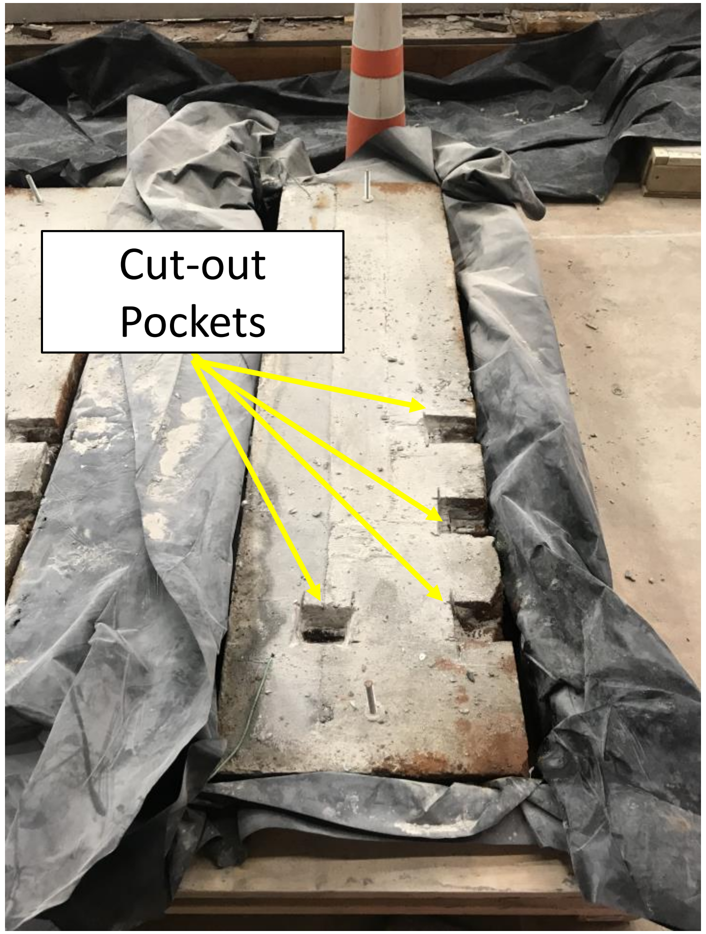
DC power supply for accelerated corrosion testing

Durability Testing – Corrosion

- Interval corrosion checks
- Exposed surface placed down to be submerged in solution
- Visual examination
  - Loaded vs. unloaded
  - AA ODOT vs. UHPC

Composite specimens in saline solution during accelerated corrosion testing

Corrosion Testing – Previous Research



Class AA composite specimen post-corrosion testing with pockets cut out to observe rebar

J3 non-proprietary UHPC composite specimen post-corrosion testing with pockets cut out to observe rebar

Corrosion Testing – Previous Research

Class AA composite specimen post-corrosion testing: cut-out pocket at interface

J3 non-proprietary UHPC composite specimen post-corrosion testing: cut-out pocket at interface

Durability Testing – Freeze-Thaw

- Sections from full-scale link slabs
- ASTM C666
  - Specimens fully submerged in water
  - 300 cycles
    - Between 0 and 40°F (-18 and 4°C)
    - Cycle length: 2-5 hours

UHPC specimen sections in freeze-thaw machine

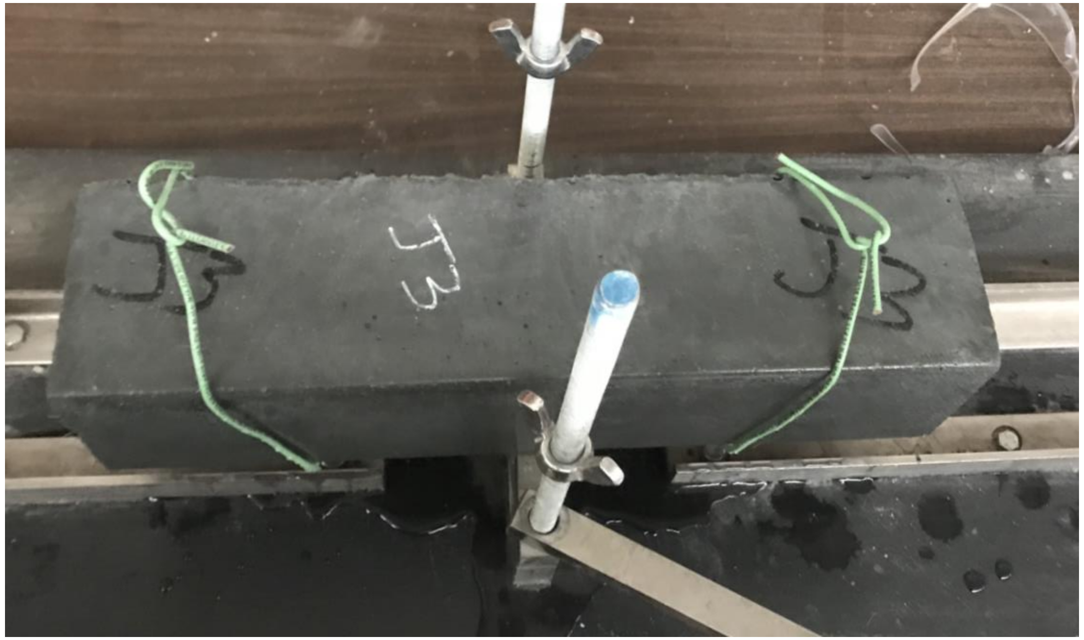
Durability Testing – Freeze-Thaw

- Transverse frequency
  - Taken within every 36 cycles
  - Used to determine modulus of elasticity
- Visual examination
  - Loaded vs. unloaded
  - AA ODOT vs. UHPC

UHPC specimen set up for determining its fundamental transverse frequency

Freeze-Thaw Testing – Previous Research

Class AA specimen section after freeze-thaw testing



J3 non-proprietary UHPC specimen section after freeze-thaw testing

Education Module and Guide

- Education Module
  - Materials for training design professionals
  - Pre-recorded videos explaining important considerations
  - Example of design alternatives
- “Guide for Design of UHPC Link Slabs”
  - Service life considerations and incorporation into service life framework
  - UHPC mix designs

Conclusions

- UHPC link slab specimens exhibited less cracking than conventional concrete link slab specimens
- UHPC link slab requires less concrete removal in existing bridges and smaller connections for new construction
- UHPC has negligible chloride ion permeability and excellent freeze-thaw resistance
- Non-proprietary UHPC showed no halo corrosion in accelerated testing

Future Work

- Complete on-going freeze-thaw and corrosion testing
  - Slab cutting is underway
  - Testing beginning in the next week
- Complete training materials including design example
  - After testing is complete
- Work with ODOT to find implementation opportunities in Oklahoma

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