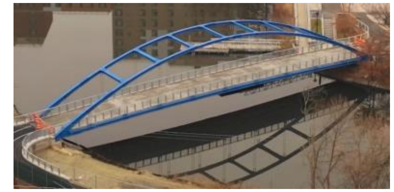
Office of Structures



Ultra-High Performance Concrete Link Slabs

Jim Scarlata, PE
Structures Design Bureau
Assistant Director

FIU ABC-UTC Monthly Webinar
April 18th, 2024

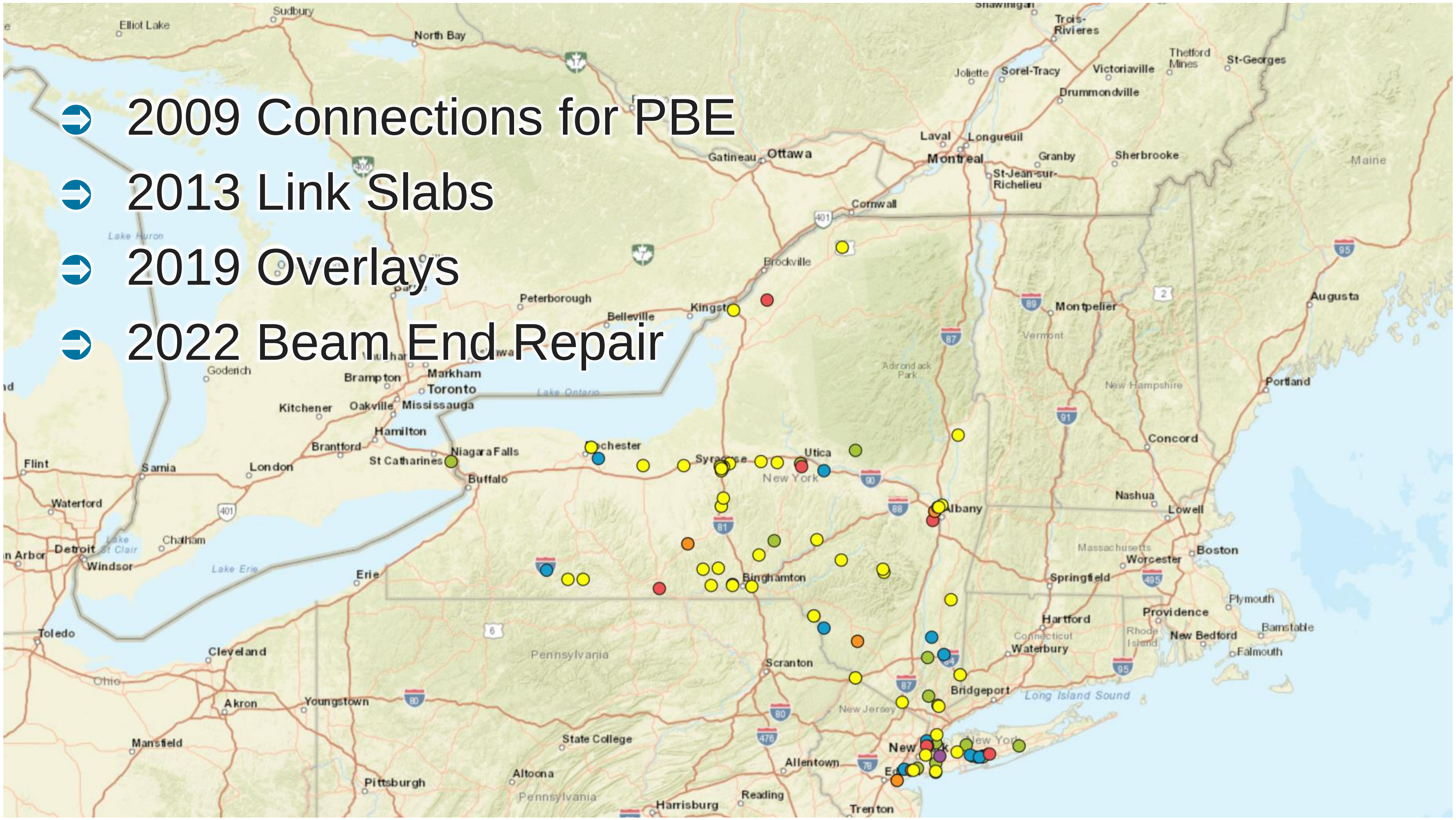
Presentation Topics

- **Joint Elimination**
  - Why Eliminate Joints
  - Current Practices in New York State
- **UHPC Link Slabs**
  - What, Why, and How
  - Evolution
  - What Makes a Good Candidate
  - Construction
  - Example Project
  - Question & Answer

Brooklyn Bridge – New York City

Bridges With UHPC in New York

- 2009 Connections for PBE
- 2013 Link Slabs
- 2019 Overlays
- 2022 Beam End Repair



Credit: FHWA UHPC Bridges Interactive Map

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Issues

- Require frequent maintenance
- Can be hazardous to traveling public
- Prone to leakage, exposing underlying components to moisture and chlorides
- Trickle-down deterioration reduces bridge service life

Joint Elimination Methods

Splicing of Girders

Concrete End Diaphragm

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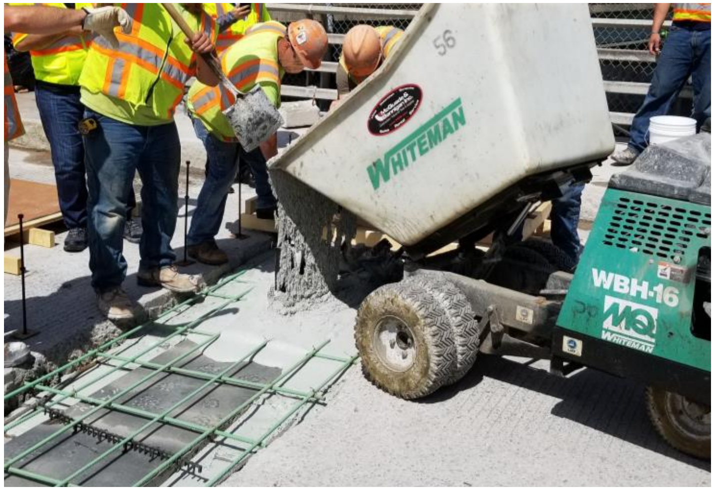
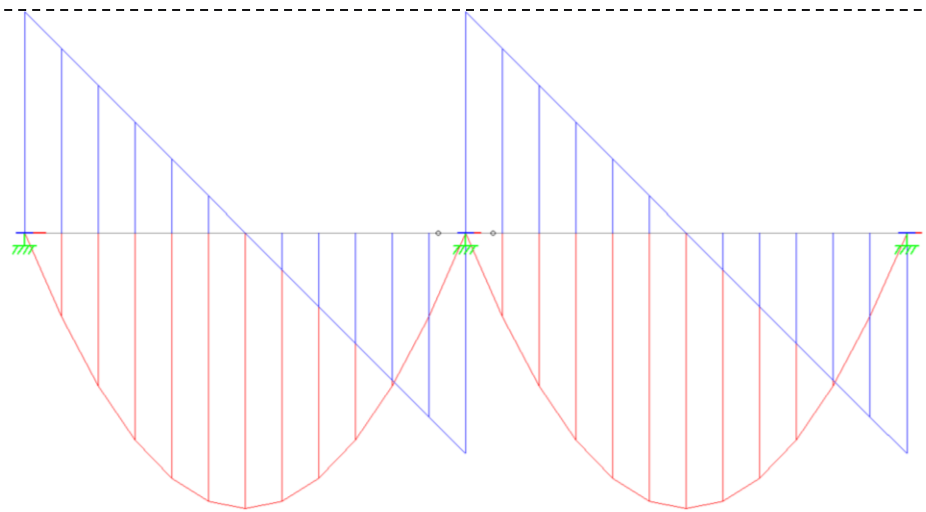
Joint Elimination Methods

Conversion to Integral Abutments

UHPC Link Slabs

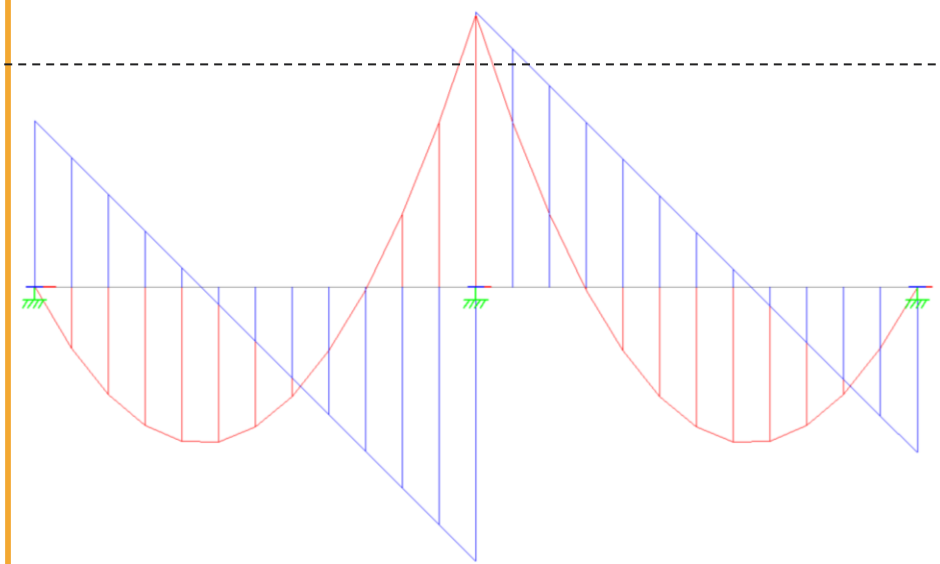


Without Continuity



Span 1 Span 2

With Continuity

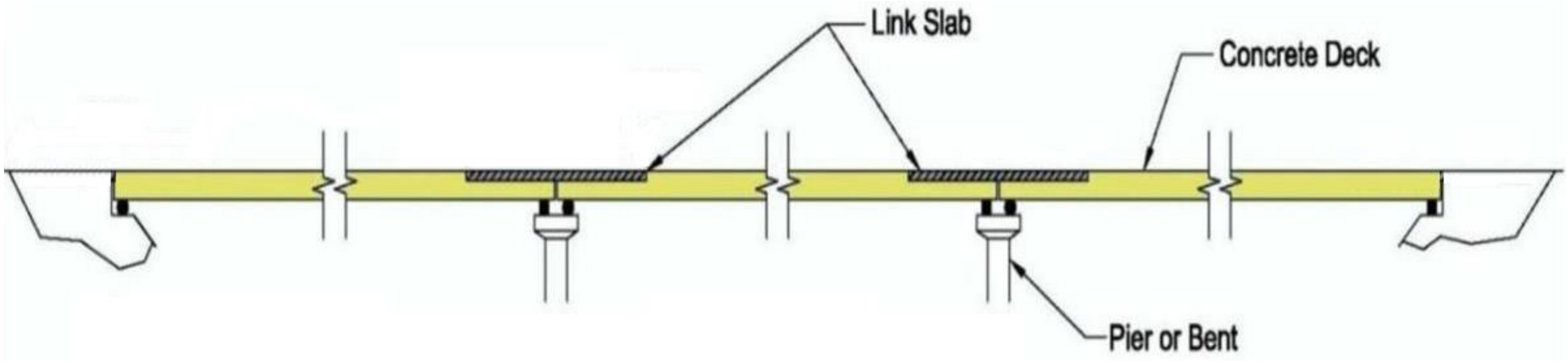


Span 1 Span 2

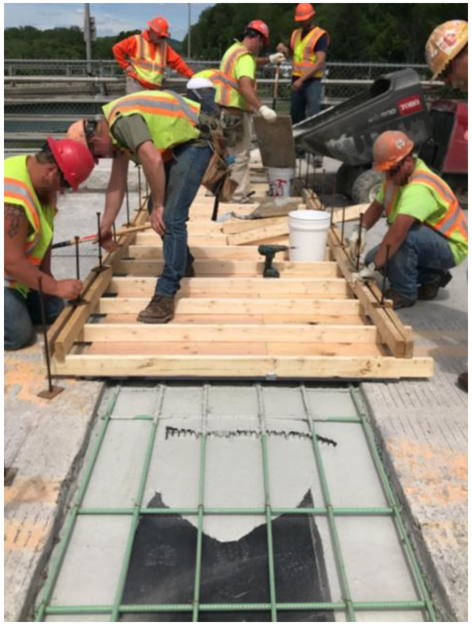
Joint Elimination with Link Slabs

- Economical means of joint elimination
  - Reduce design time, structural removal, and reconstruction work
  - Avoid undesirable negative moments and higher beam reactions
  - Long and maintenance free service life
- Versatile
  - Superstructure type
  - Geometry

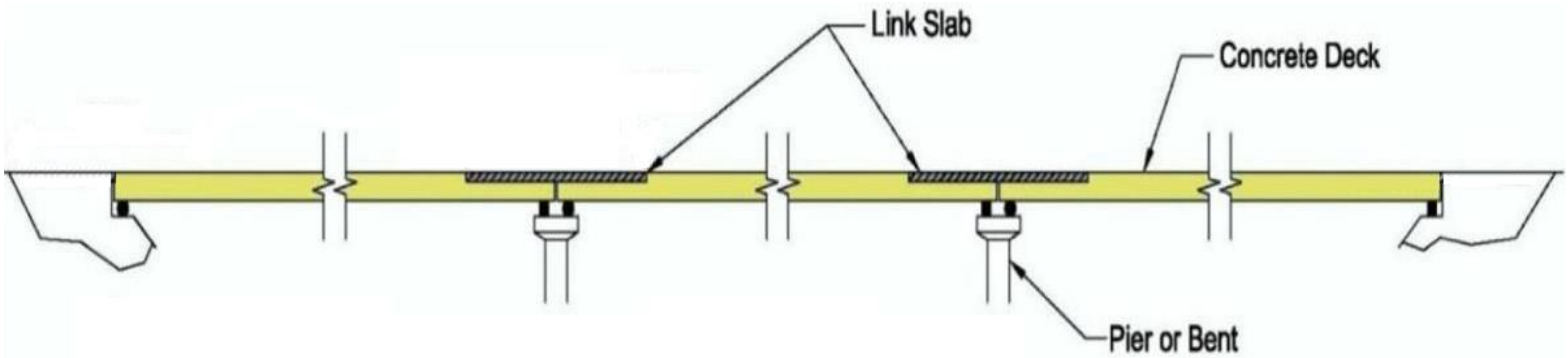
Link Slabs



3 Span With Link Slabs



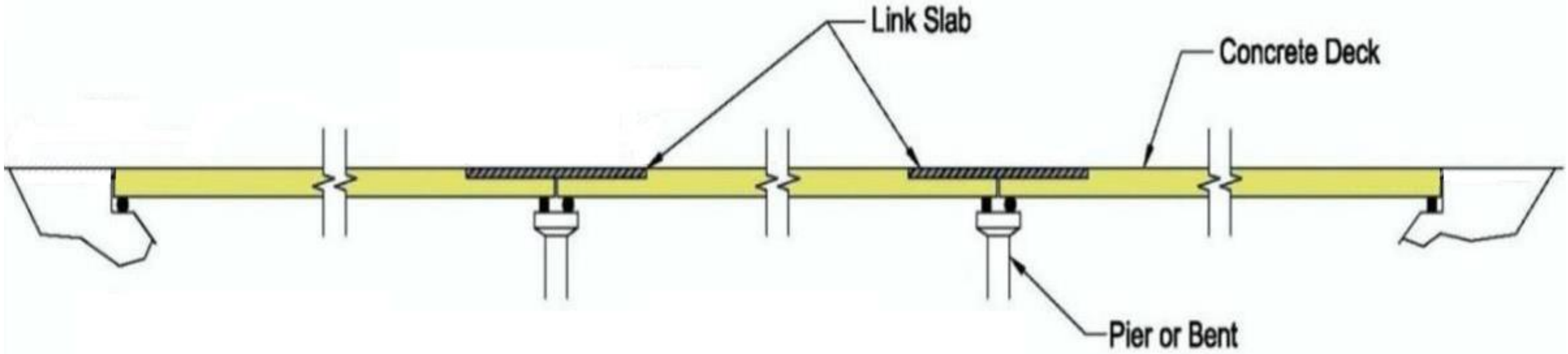
Link Slabs



3 Span With Link Slabs

- Joint Elimination

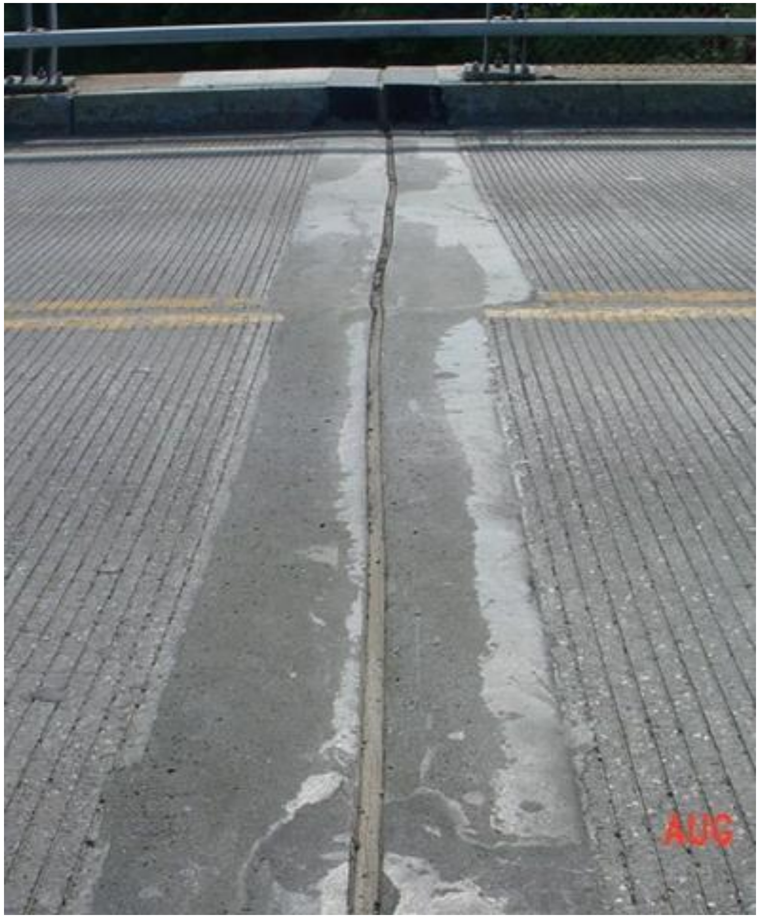
Link Slabs



3 Span With Link Slabs

- Accelerated construction
- Complex framing geometry
- Continuous span uplift
- Continuous span cracking over piers
- Reduce seismic vulnerability

UHPC Link Slabs



Before Link Slab

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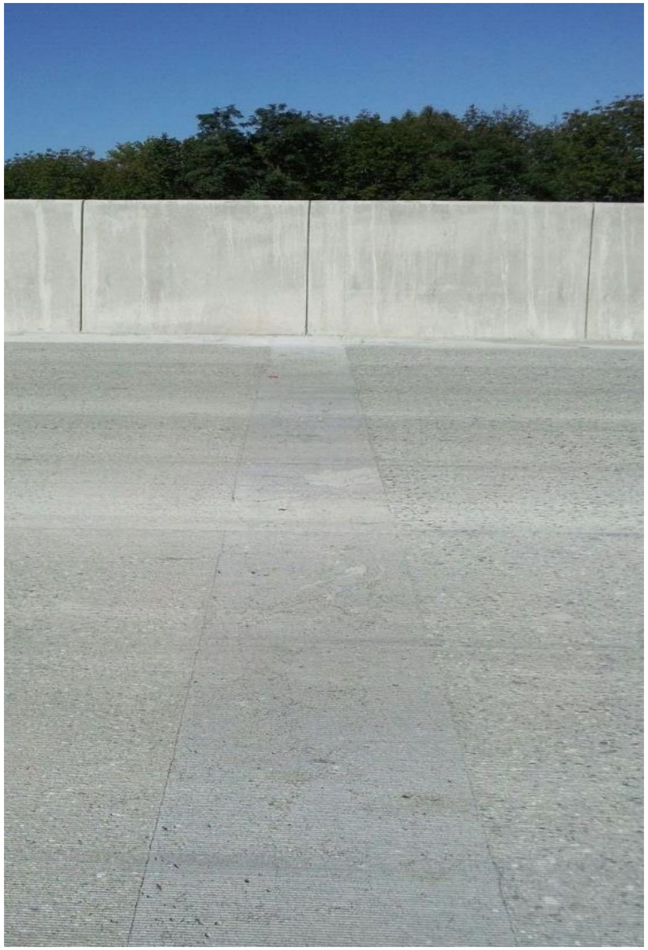
UHPC Link Slabs



After Link Slab

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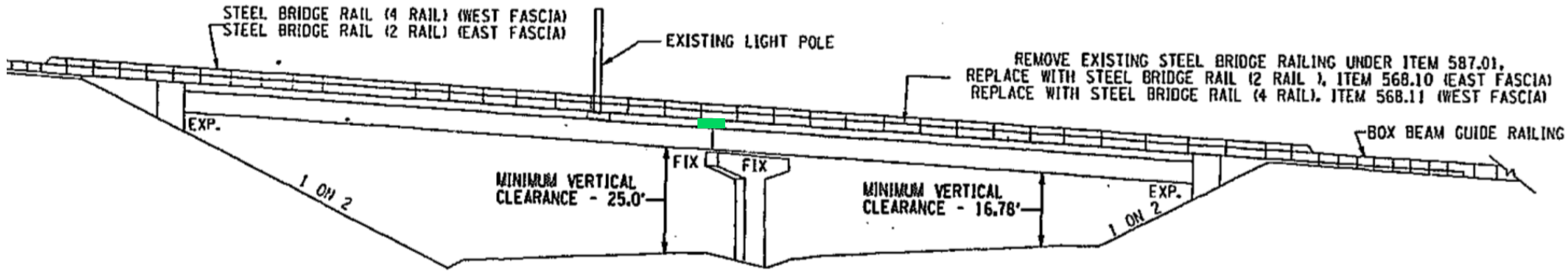
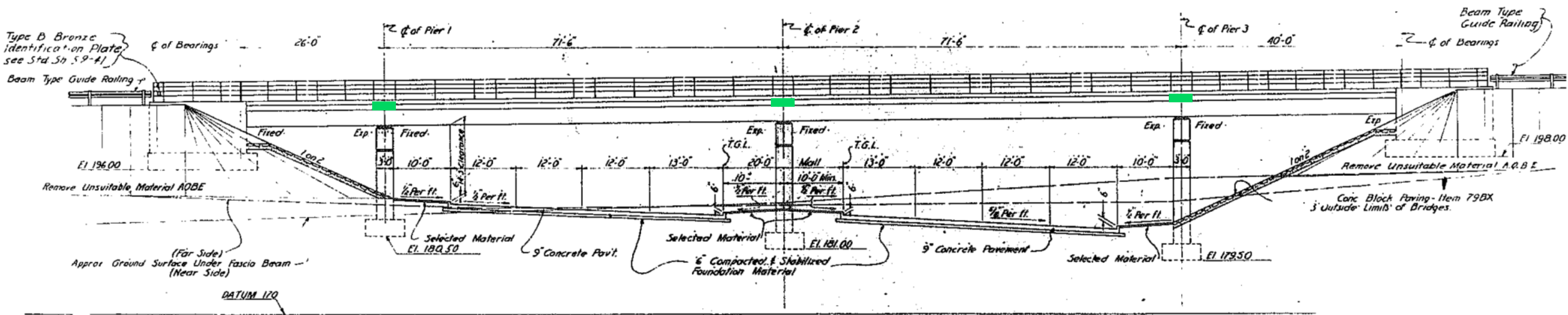
Evolution of UHPC Link Slab Usage



ELEVATION A-A
1"=20'



ELEVATION
Scale: 1"=10'-0"

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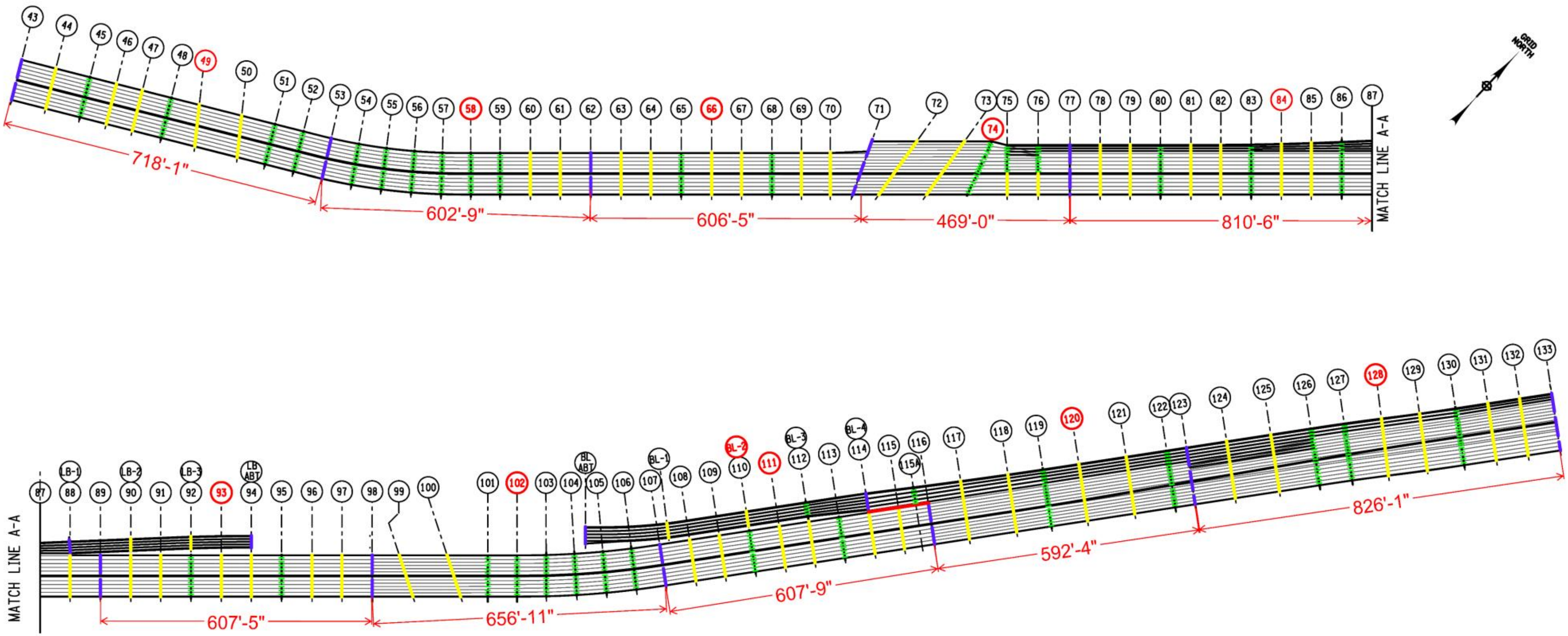
Evolution of UHPC Link Slab Usage



DECK REPLACEMENT - KEY PLAN
NOT TO SCALE

NOTES:

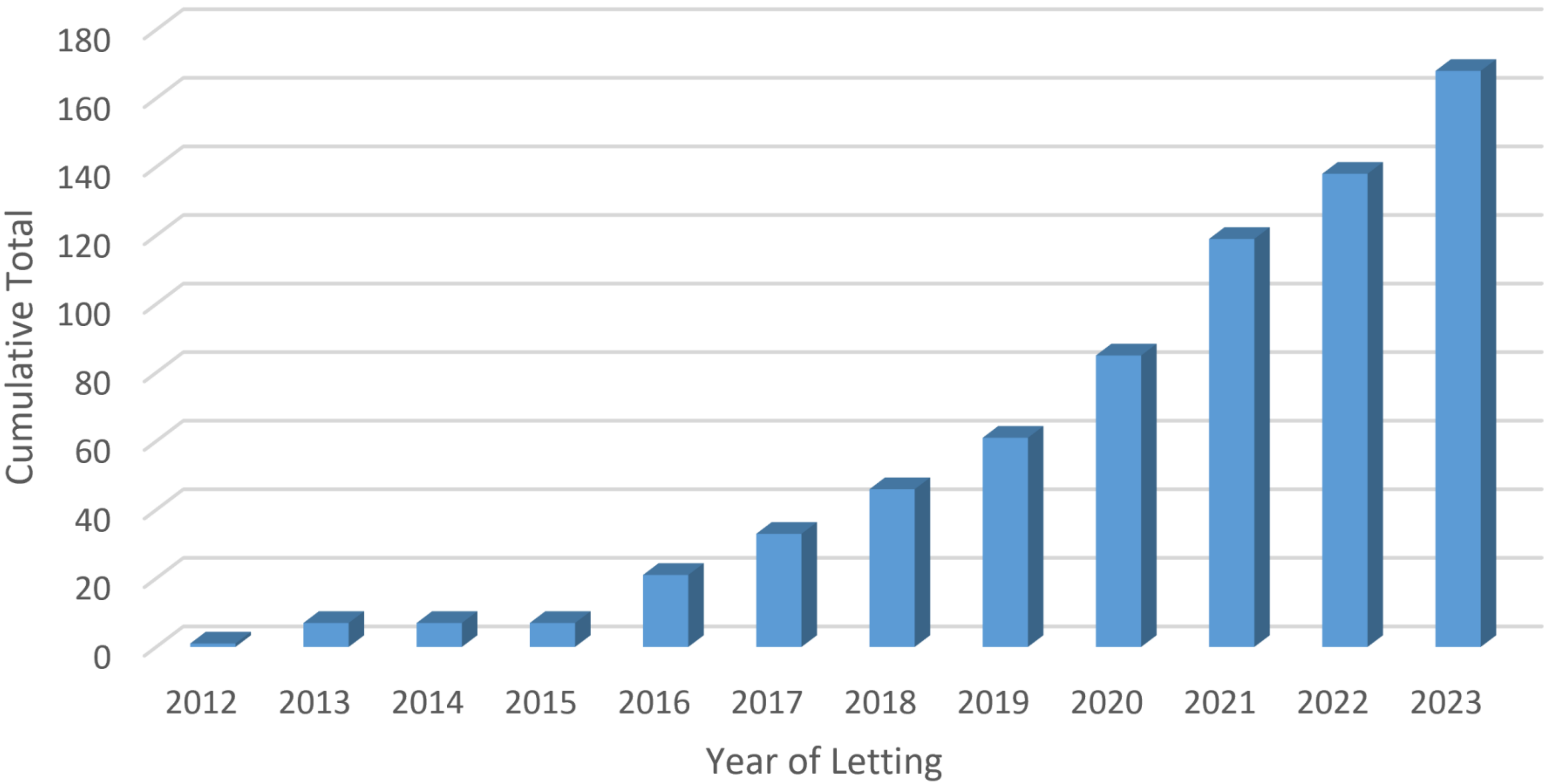
EXISTING NUMBER OF TRANSVERSE JOINTS ON MAINLINE = 44
PROPOSED NUMBER OF TRANSVERSE JOINTS ON MAINLINE = 11
APPROXIMATE REDUCTION IN NUMBER OF TRANSVERSE JOINTS = 75%

EXISTING NUMBER OF CONTINUOUS SPANS = 74
EXISTING NUMBER OF SIMPLE SPANS = 17

LEGEND:

- (XX) PIER NUMBER
- (XX) PIER NUMBER (FIXED BEARINGS)
- LINK SLAB
- EXPANSION JOINT
- FULL DECK CONTINUITY
- LONGITUDINAL JOINT

New York State UHPC Link Slab Usage



UHPC Link Slabs	
Built	138
Planned	30
Total	168

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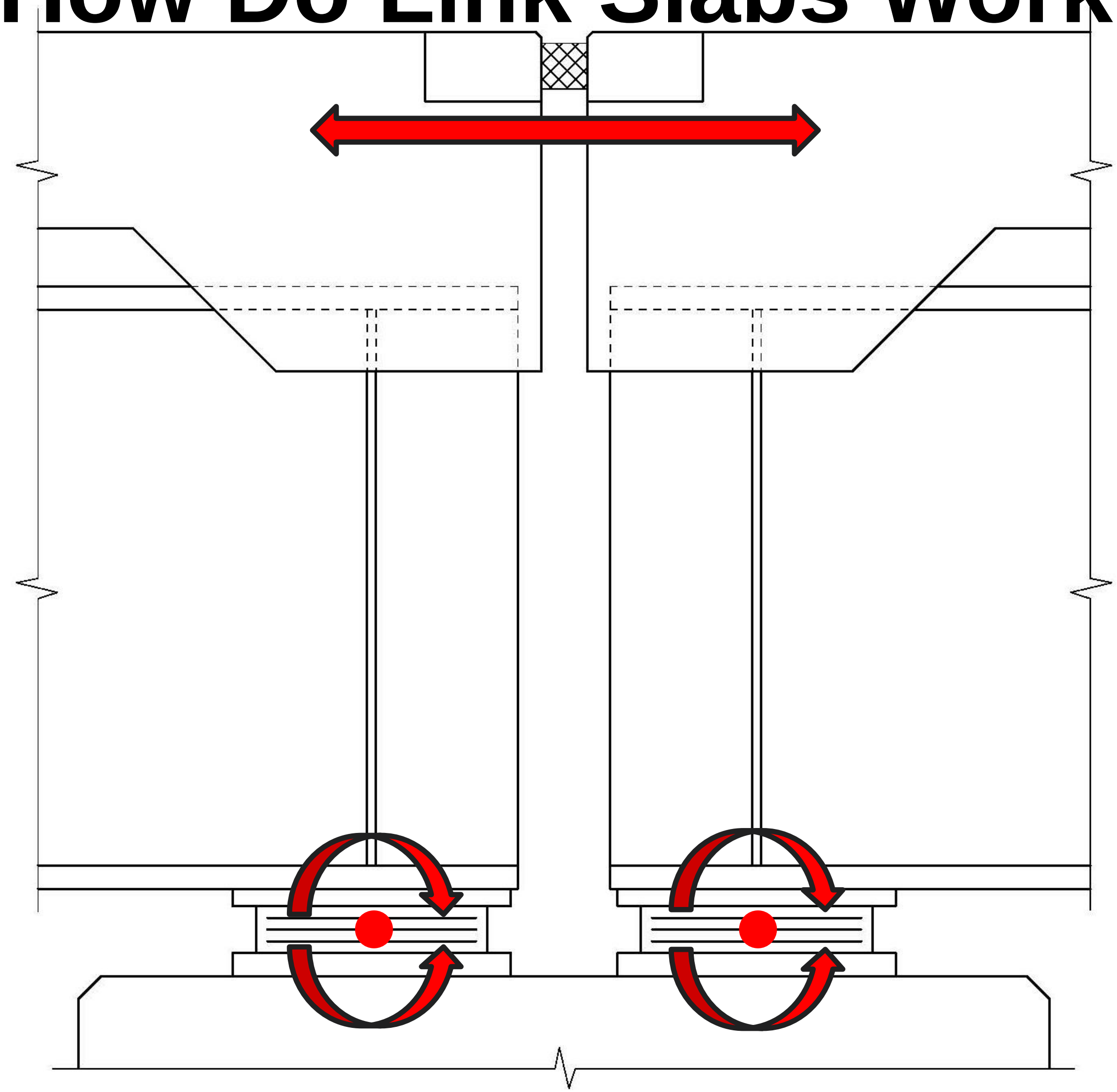
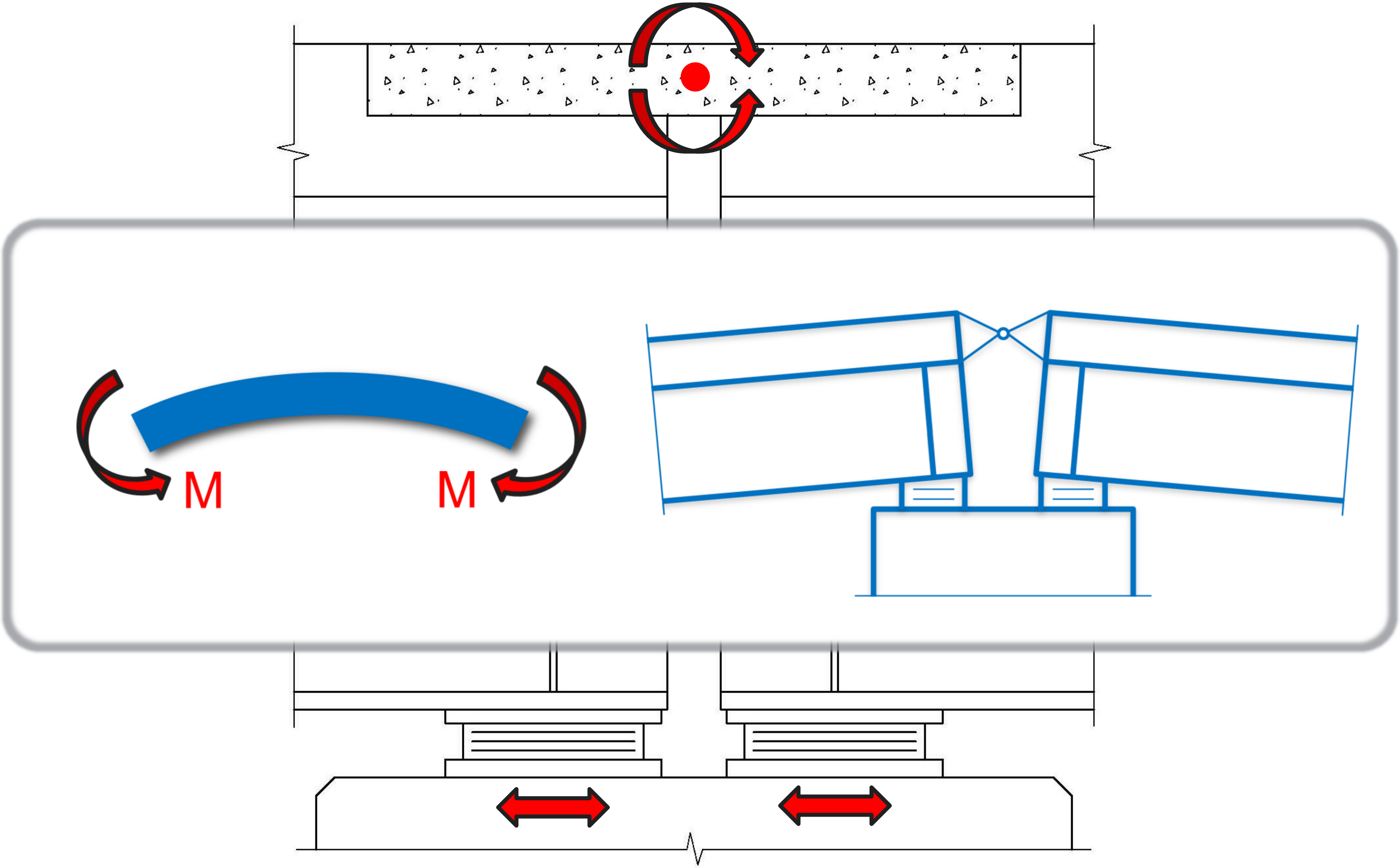
How Do Link Slabs Work?

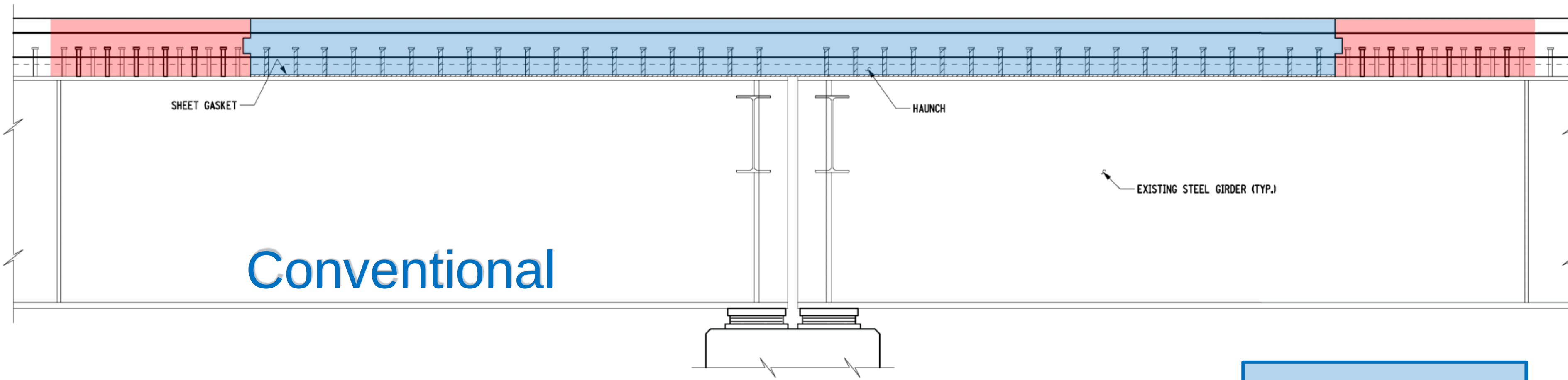


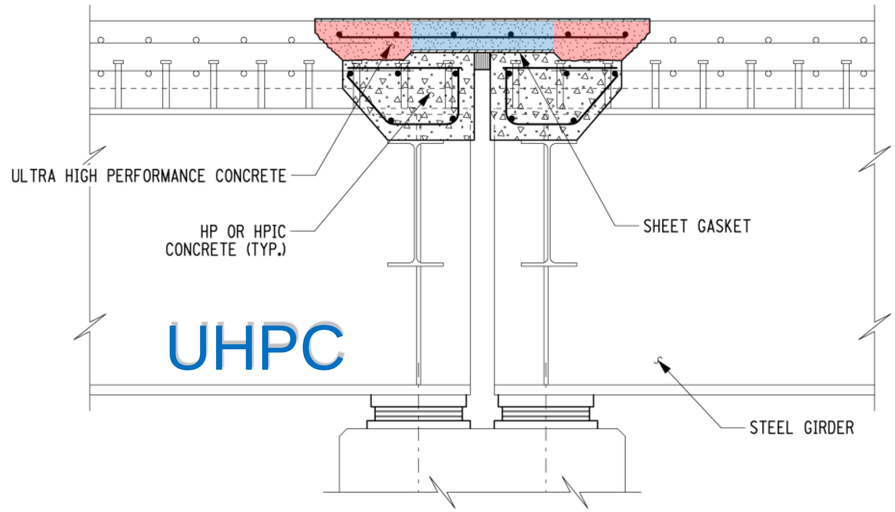
Deck Joint



Link Slab

Conventional vs. UHPC Link Slab





Debonded Zone

Anchor Zone

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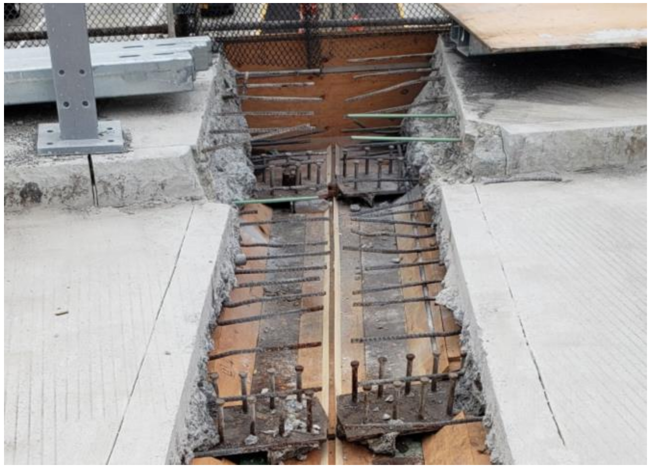
Benefits of UHPC Link Slabs

- Only require reconstruction of deck ends
- Reduce construction duration
- Are highly durable and inherently ductile



Credit: MDPI Sustainability Journal

The UHPC Difference

- Only 2’ - 3’ long, 4” thick, nominal reinforcement
  - Ultimate tensile strain 7,000 με (HPC = 200 με)
  - Widespread micro-cracking due to steel fiber matrix
  - Compressive strength 18 ksi (NYSDOT Spec)
- Strong bond to existing concrete
- Exceptional durability

Design Assumptions

- UHPC Material Design Allowables
  - Tensile strain: 3,500 $\mu\varepsilon$
  - Tensile cracking stress: 1.2 ksi
  - Compressive stress: 14 ksi
  - Compressive modulus: 8000 ksi
- Flexural design with adjoining spans simultaneously loaded with HL-93 live load
- Displacement based analysis
- Stresses equally distributed within debonded length

User Inputs

$f_y := 60\ \text{ksi}$ reinforcement yield strength

$E_s := 29000\ \text{ksi}$ reinforcement modulus of elasticity (LRFD 5.4.3.2)

$A_s := \frac{0.31\ \text{in}^2}{8\ \text{in}} = 0.47\ \frac{\text{in}^2}{\text{ft}}$ area of longitudinal reinforcement per ft. in debonded zone (this reinforcement must be centered vertically within the link slab's debonded zone or the results of this worksheet will be invalid)

$d_{bf} := 6.32\ \text{ft}$ vertical distance from top of deck to bottom of bottom flange

$L_{dz} := 16\ \text{in}$ debonded zone length (1'-0" minimum, adjust to determine the shortest length that satisfies all design checks)

$f_a := 0.2\ \text{ksi}$ Strength I applied axial stress (tension +, compression -)

Unfactored Girder End Rotations

Left Span	*Right Span*	
$\theta_{DC2.L} := 0.0\ \text{rad}$	$\theta_{DC2.R} := 0.0\ \text{rad}$	superimposed dead load rotation
$\theta_{DW.L} := 0.00070\ \text{rad}$	$\theta_{DW.R} := 0.00070\ \text{rad}$	future wearing surface rotation
$\theta_{LL.L} := 0.00445\ \text{rad}$	$\theta_{LL.R} := 0.00445\ \text{rad}$	maximum HL-93 live load plus impact rotation

Password Protected Area

Note: The following inputs are standard and not editable by the user.

$E_c := 8000\ \text{ksi}$ UHPC compressive modulus of elasticity

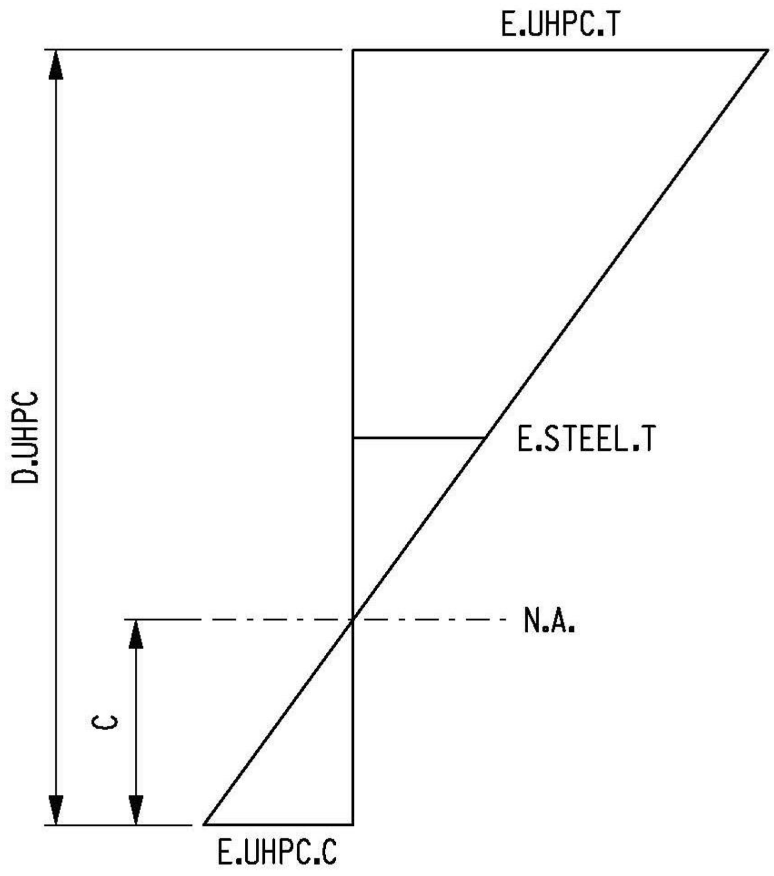
$f_{uhpc.t.all} := 1.2\ \text{ksi}$ UHPC tensile cracking stress

$f_{uhpc.c.all} := -14\ \text{ksi}$ maximum allowable UHPC compressive stress

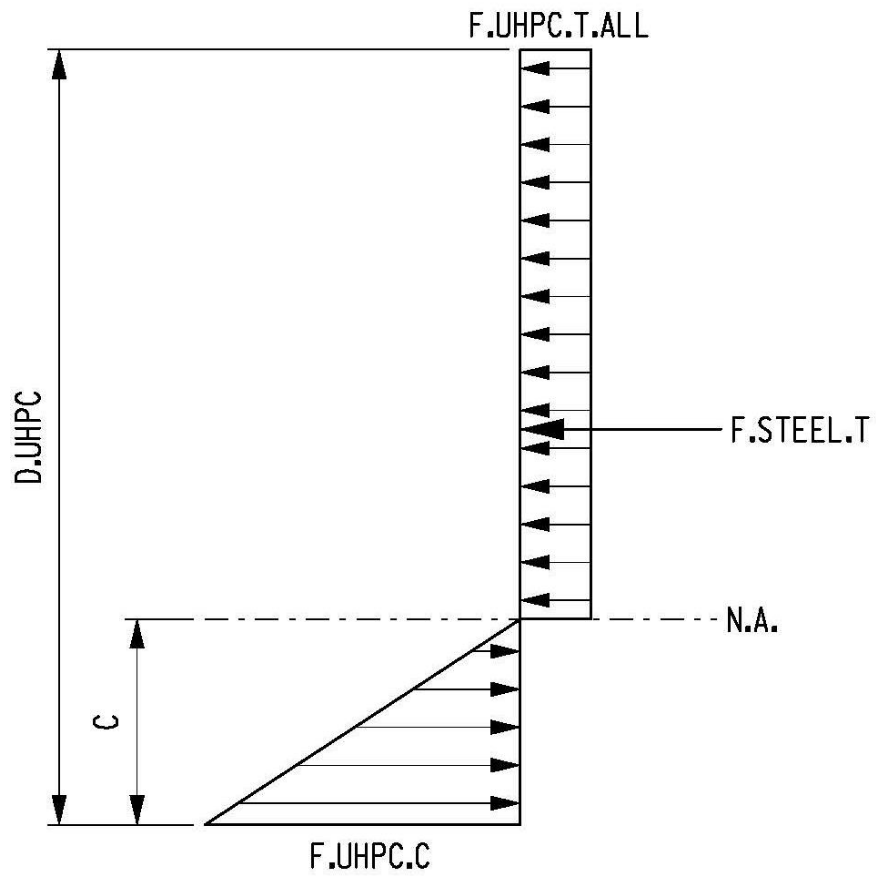
$\varepsilon_{uhpc.t.all} := 3500 \cdot 10^{-6}$ maximum allowable UHPC tensile strain

$d_{uhpc} := 4\ \text{in}$ depth of UHPC within debonded zone

Strain Diagram



Stress Diagram



Flexural Analysis of Link Slab

$b := 1\ \text{ft}$ width of design section

$h := d_{uhpc} = 4.0\ \text{in}$ depth of UHPC

$A_s := A_s \cdot b = 0.47\ in^2$ area of reinforcement

$f_t := f_{uhpc.t.all} = 1.2\ \text{ksi}$ maximum tensile stress of UHPC

$\theta := 1.25 \cdot \text{mean}\left(\theta_{DC2.L}, \theta_{DC2.R}\right) + 1.50 \cdot \text{mean}\left(\theta_{DW.L}, \theta_{DW.R}\right) + 1.75 \cdot \text{mean}\left(\theta_{LL.L}, \theta_{LL.R}\right) = 0.51\ \text{deg}$ Strength I girder end rotation

Sum Forces: $C := \frac{c \cdot f_c \cdot b}{2}$ $T := f_t \cdot (h - c) \cdot b + \frac{A_s \cdot E_s \cdot eci \cdot \left(\frac{h}{2} - c\right)}{c}$

Equation Solver: $c := \frac{\sqrt{A_s^2 \cdot E_s^2 \cdot eci^2 + f_c \cdot A_s \cdot E_s \cdot b \cdot h \cdot eci + b^2 \cdot f_t^2 \cdot h^2} + b \cdot f_t \cdot h - A_s \cdot E_s \cdot eci}{b \cdot f_c + 2 \cdot b \cdot f_t}$

Check: $C := \frac{c \cdot f_c \cdot b}{2} = 61.64 \cdot \text{kip}$ $T := f_t \cdot (h - c) \cdot b + \frac{A_s \cdot E_s \cdot eci \cdot \left(\frac{h}{2} - c\right)}{c} = 61.64 \cdot \text{kip}$

Assume UHPC Strain: $eci := 1200\ 10^{-6}$

Assumed vs. Calc. Strain: $\varepsilon_{uhpc.c} := \frac{-2 \cdot \theta \cdot c}{L_{unb}} = -1207 \cdot 10^{-6}$

Mathcad Worksheet

$$
c := \left|
\begin{array}{l}
eci \leftarrow 1 \cdot 10^{-6} \\
ec \leftarrow 1 \\
i \leftarrow 1 \\
\text{while } eci < |ec| \\
\quad \left| \begin{array}{l}
fc \leftarrow eci \cdot E_c + f_a \\
c \leftarrow \dfrac{\sqrt{A_s^{\,2} \cdot E_s^{\,2} \cdot eci^2 + fc \cdot A_s \cdot E_s \cdot b \cdot h \cdot eci + b^2 \cdot f_t^{\,2} \cdot h^2} + b \cdot f_t \cdot h - A_s \cdot E_s \cdot eci}{b \cdot fc + 2 \cdot b \cdot f_t} \\
ec \leftarrow \dfrac{-2 \cdot \theta \cdot c}{L_{dz}} \\
eci \leftarrow eci + 0.1 \cdot 10^{-6} \\
i \leftarrow i + 1
\end{array} \right. \\
\text{if } (c < 0 \cdot \text{in}) \vee (c > d_{uhpc}) \vee \left(\dfrac{\max(|ec|, eci)}{min(|ec|, eci)} - 1 > 5\% \right) \\
\quad \left| \ out \leftarrow \text{“Error”} \right. \\
\text{else} \\
\quad \left| \ out \leftarrow c \right. \\
\text{return } out
\end{array}
\right.
$$

eci = assumed UHPC compressive strain
ec = computed UHPC compressive strain
fc = UHPC compressive stress

iterative algorithm to determine distance from bottom of section to neutral axis

$c = 1.03\ in$ distance from bottom of section to neutral axis

$$\varepsilon_{uhpc.t} := \frac{2 \cdot \theta \cdot (d_{uhpc} - c)}{L_{dz}} = 3283 \ 10^{-6}$$ tensile strain in UHPC

$$\varepsilon_{s.t} := \frac{2 \cdot \theta \cdot \left(\frac{d_{uhpc}}{2} - c\right)}{L_{dz}} = 1074 \ 10^{-6}$$ tensile strain in reinforcement

$$f_{s.t} := \varepsilon_{s.t} \cdot E_s = 31.14 \ ksi$$ tensile stress in reinforcement

$$\varepsilon_{uhpc.c} := \frac{-2 \cdot \theta \cdot c}{L_{dz}} = -1136 \ 10^{-6}$$ compressive strain in UHPC

$$f_{uhpc.c} := \varepsilon_{uhpc.c} \cdot E_c = -9.09 \ ksi$$ compressive stress in UHPC

$$d_{gap.min} := 2 \cdot \theta \cdot (d_{bf} - (d_{uhpc} - c)) = 1.29 \ in$$ minimum required girder end gap

Analysis Results

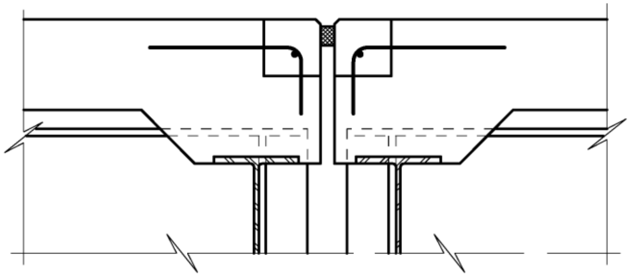
$R =$

"Analysis Criteria"	"Actual"	"Allowable"	"Design Ratio"	"Pass/Fail"
"Tensile Strain in UHPC (με)"	3283.09	3500.00	1.07	"Pass"
"Stress in Reinforcement (ksi)"	31.14	60.00	1.93	"Pass"
"Compressive Stress in UHPC (με)"	−9.09	−14.00	1.54	"Pass"
"Minimum Girder End Gap (in)"	"---"	1.29	"---"	"---"
"Debonded Zone Length (in)"	16.00	"---"	"---"	"---"

Bridge Deck Joints

Structural Functions

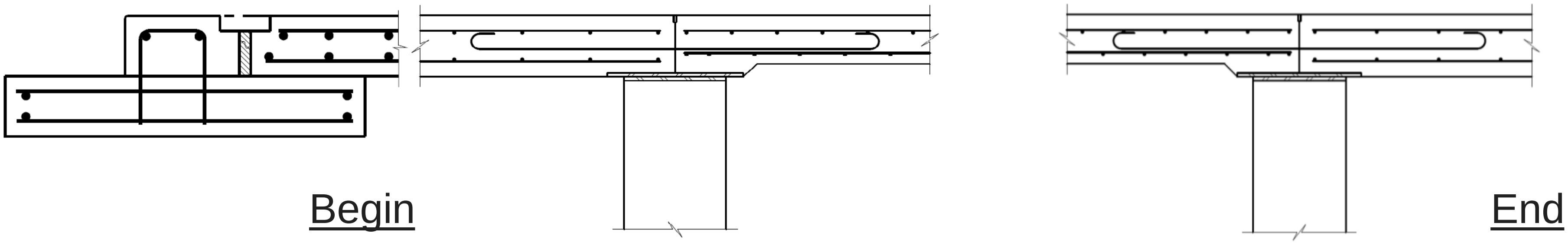
- Allow for unrestrained beam rotations
- Simplest way to accommodate superstructure's thermal movements
- Provide discrete superstructure segments, simplifying horizontal load distribution to substructures

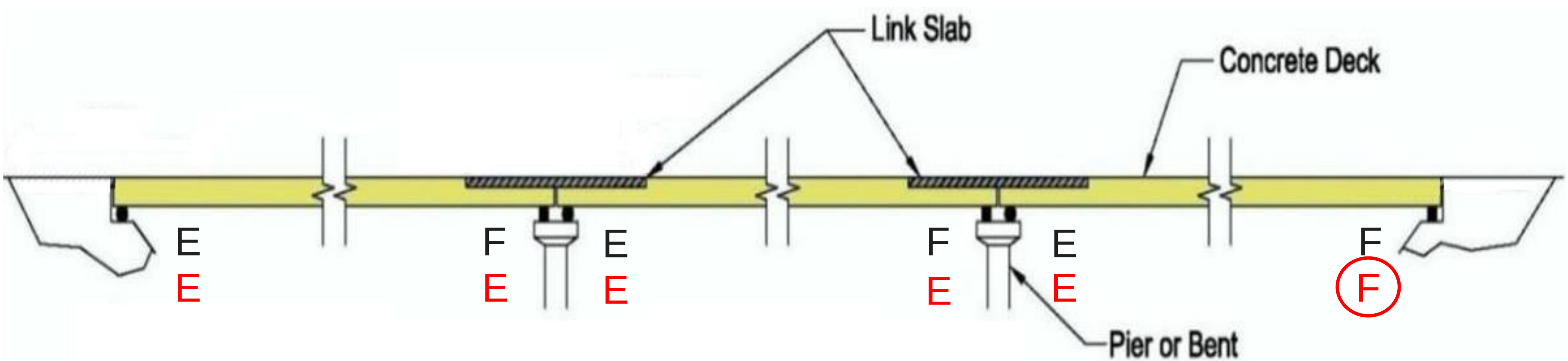


Joints Replaced With Link Slabs

Global Structural Changes

- Beam rotations still assumed to be unrestrained
- Superstructure’s thermal movements altered
- No longer have discrete superstructure segments - Link Slabs create contiguous segments, resulting in more complex horizontal load distribution to substructures





Black = Existing Bearings

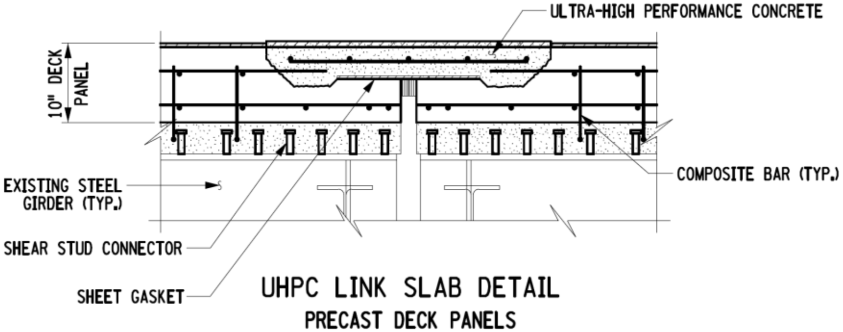
Red = New Bearings, Type EB

3 Span with Link Slabs

UHPC Link Slabs for Joint Elimination

Scoping Considerations

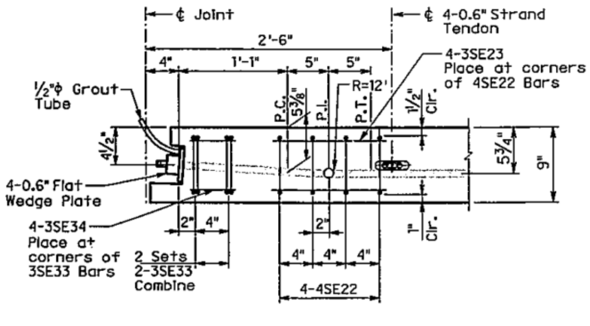
- Ideal Conditions
  - Deck in fair or better condition
  - Precast deck replacement
  - No skew or slight skew
  - Weekend closure permitted
  - Bearings deteriorated and/or unstable

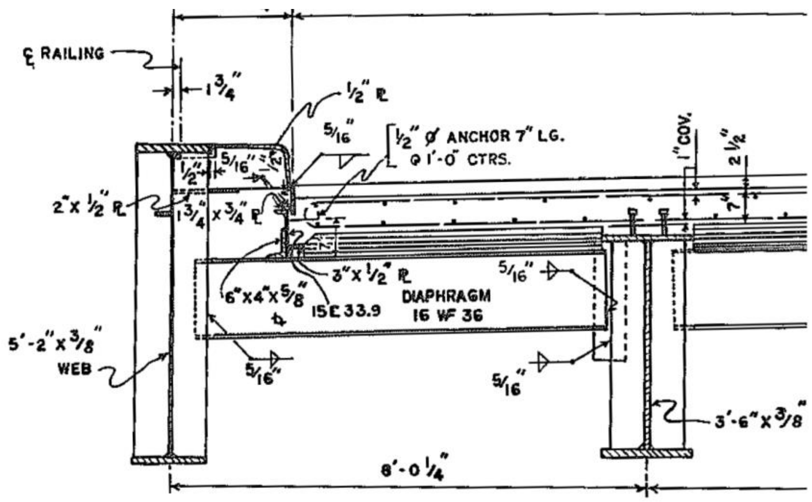


UHPC Link Slabs for Joint Elimination

Scoping Considerations

- Obstacles
  - Highly skewed supports - bearing layout, horizontal load distribution
  - Railing mounted on top flange
  - Post-tensioned deck
  - Joint over Pin & Hanger

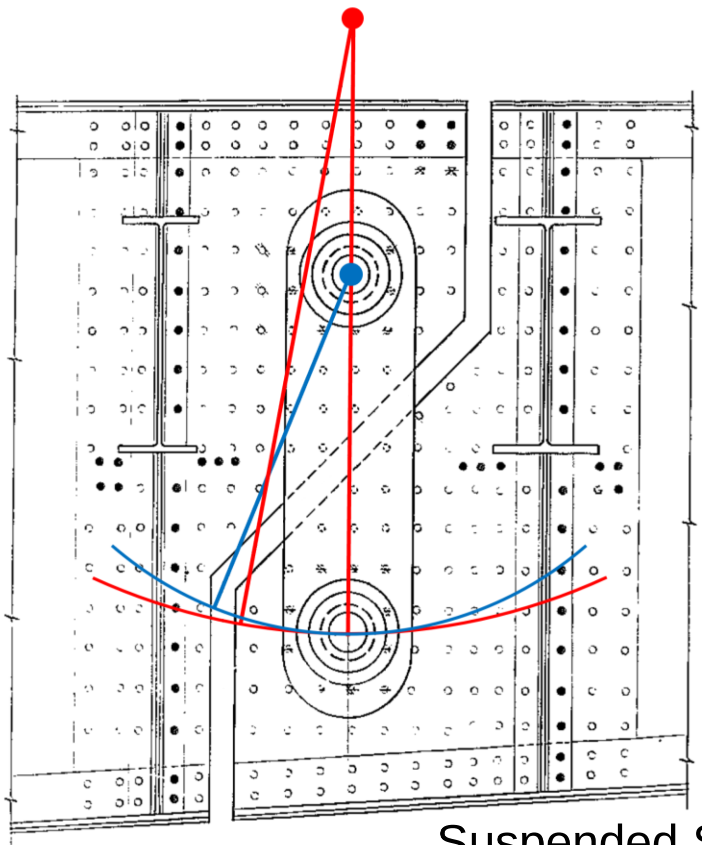




UHPC Link Slabs for Joint Elimination

Pin and Hanger

- Theorized tension increase in pin and hanger



Cantilever Span

Suspended Span

UHPC Link Slabs for Joint Elimination

Pin and Hanger

- Sling Retrofit – Vulnerability removed, joint retained

UHPC Link Slabs for Joint Elimination

Pin and Hanger

- MassDOT Ship Lap Joint Detail

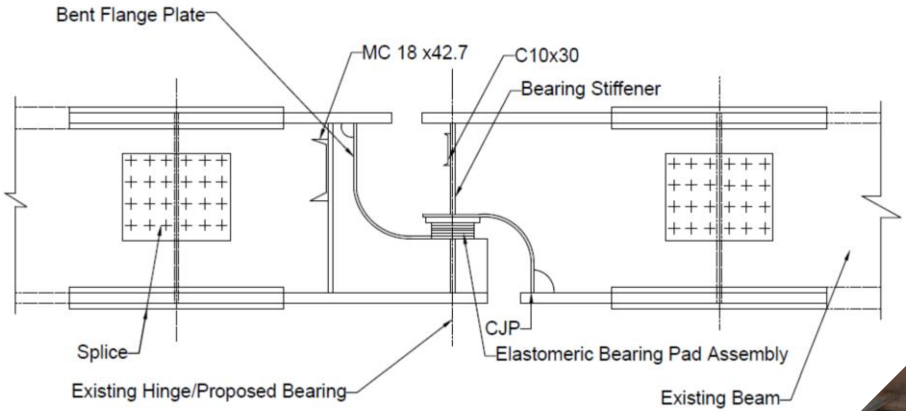


Figure 3.8 Ship lap joint detail (Mass DOT, 2014)

Credit: MassDOT

Construction and Lessons Learned

- Bearing replacements & temporary blocking
- Bearing and span alignment

Construction and Lessons Learned

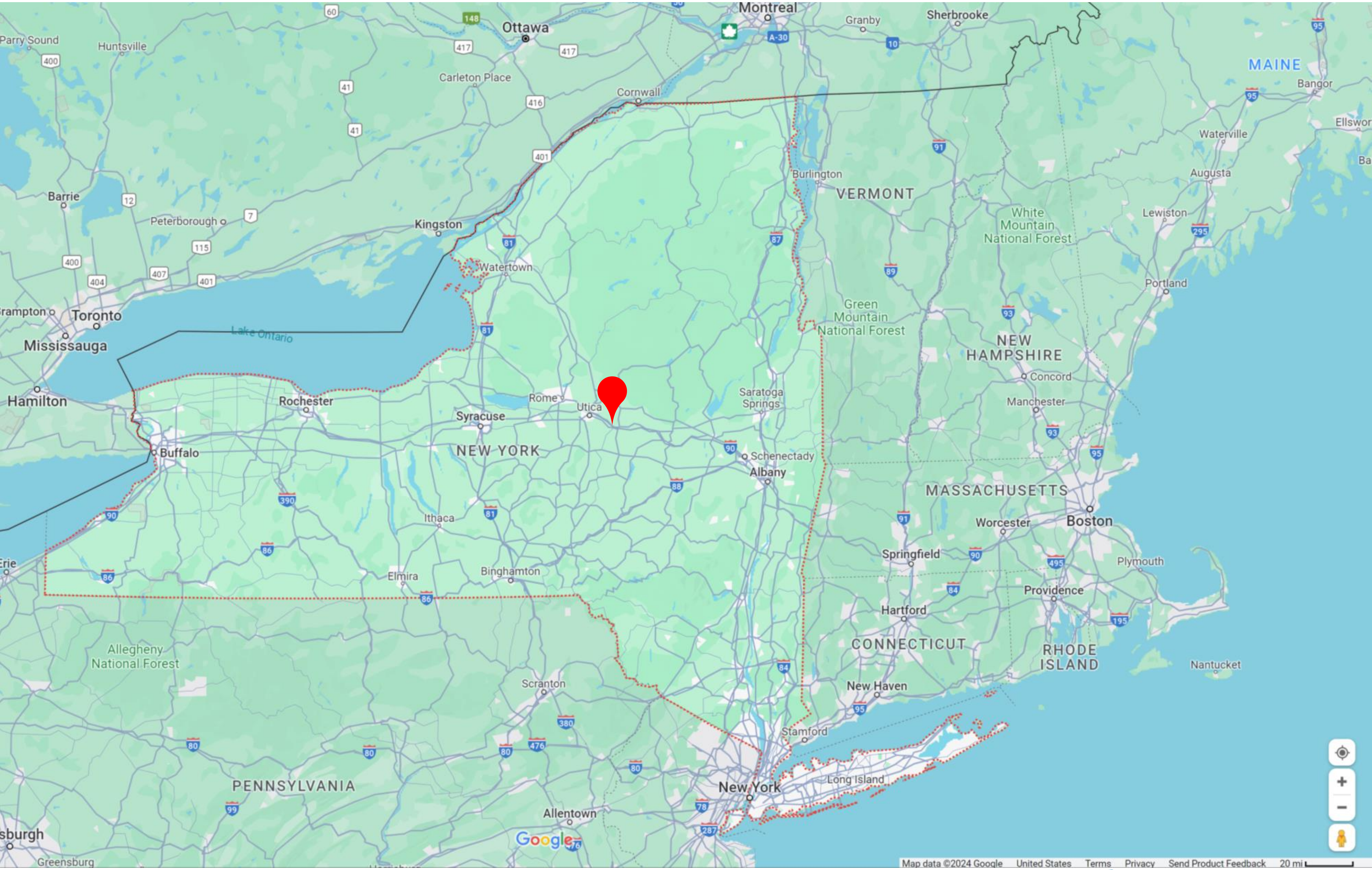
- Sealed formwork
- Surface preparation
  - Exposed aggregate finish / chip hammer
  - Saturated Surface Dry (SSD)
- Distribution of steel fibers (next slide)
- Flow of UHPC, orientation of steel fibers
- Overfilled cavity

Distribution of Steel Fibers

Construction and Lessons Learned

- Maturity Testing
  - Real-time compressive strength
  - Validated with compressive tests
  - Form removal 10 ksi
  - Opening to traffic 12 ksi
- Diamond grinding
- Longitudinal grooving
- Interface and crack sealing with high molecular weight methacrylate

Ilion UHPC Link Slab Project



Ilion UHPC Link Slab Project

Route 51 over Erie Canal, CSX, and Route 5

Ilion, New York

Originally Built 1968
Rehabbed 2018

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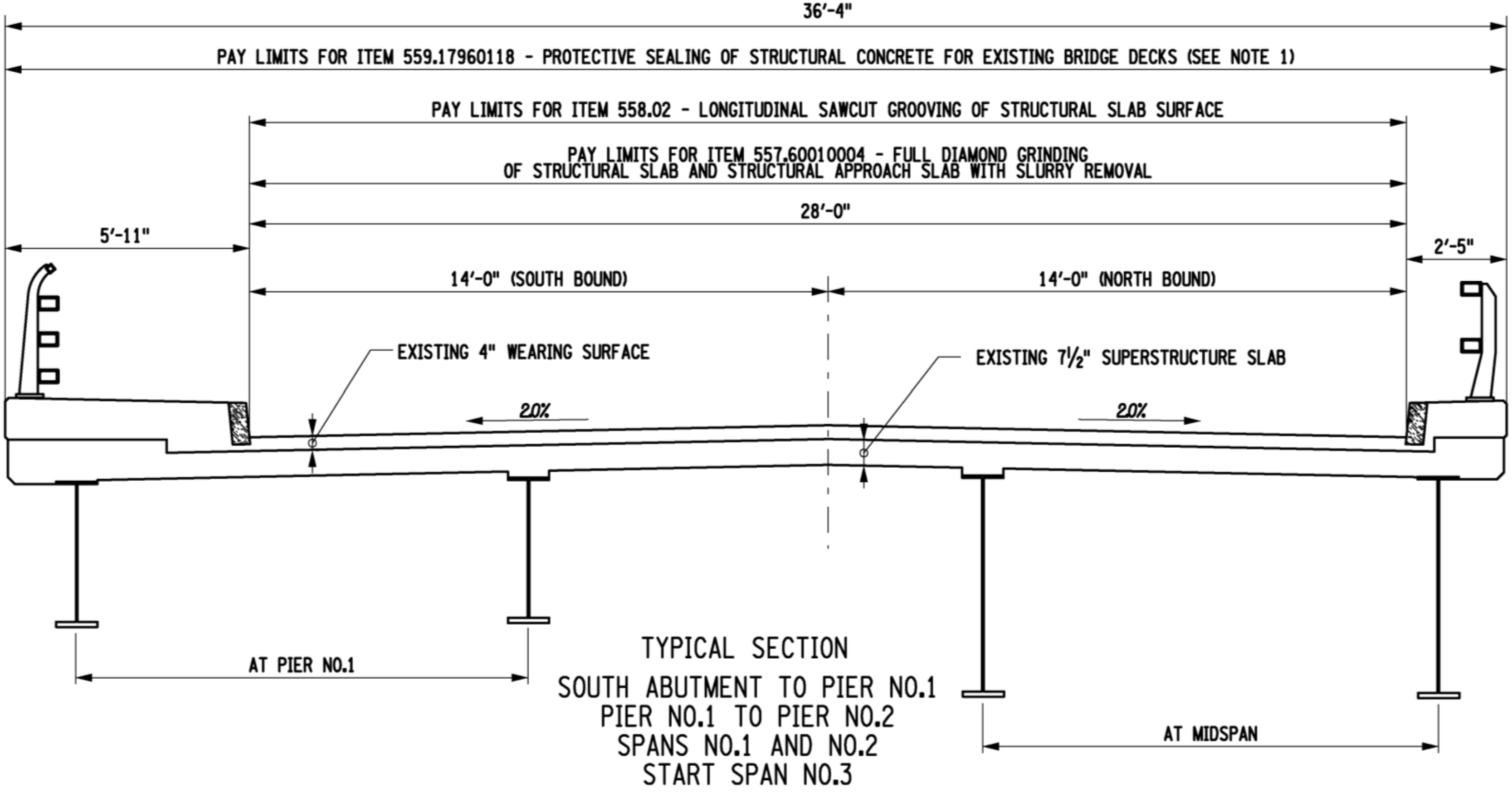
Typical Section



Existing Conditions

Existing Conditions

Scope of Work

- Pier column and cap replacements
- Substructure and girder repairs
- New pedestals and bearings
- New approach and sleeper slabs
- Overlay resurfacing
- Elimination of 9 deck joints with UHPC link slabs
- 3 remaining deck joints replaced

Contract Info

- Design Bid Build - Economy Paving
- Total Bid $4.6M, UHPC $9,550/CY

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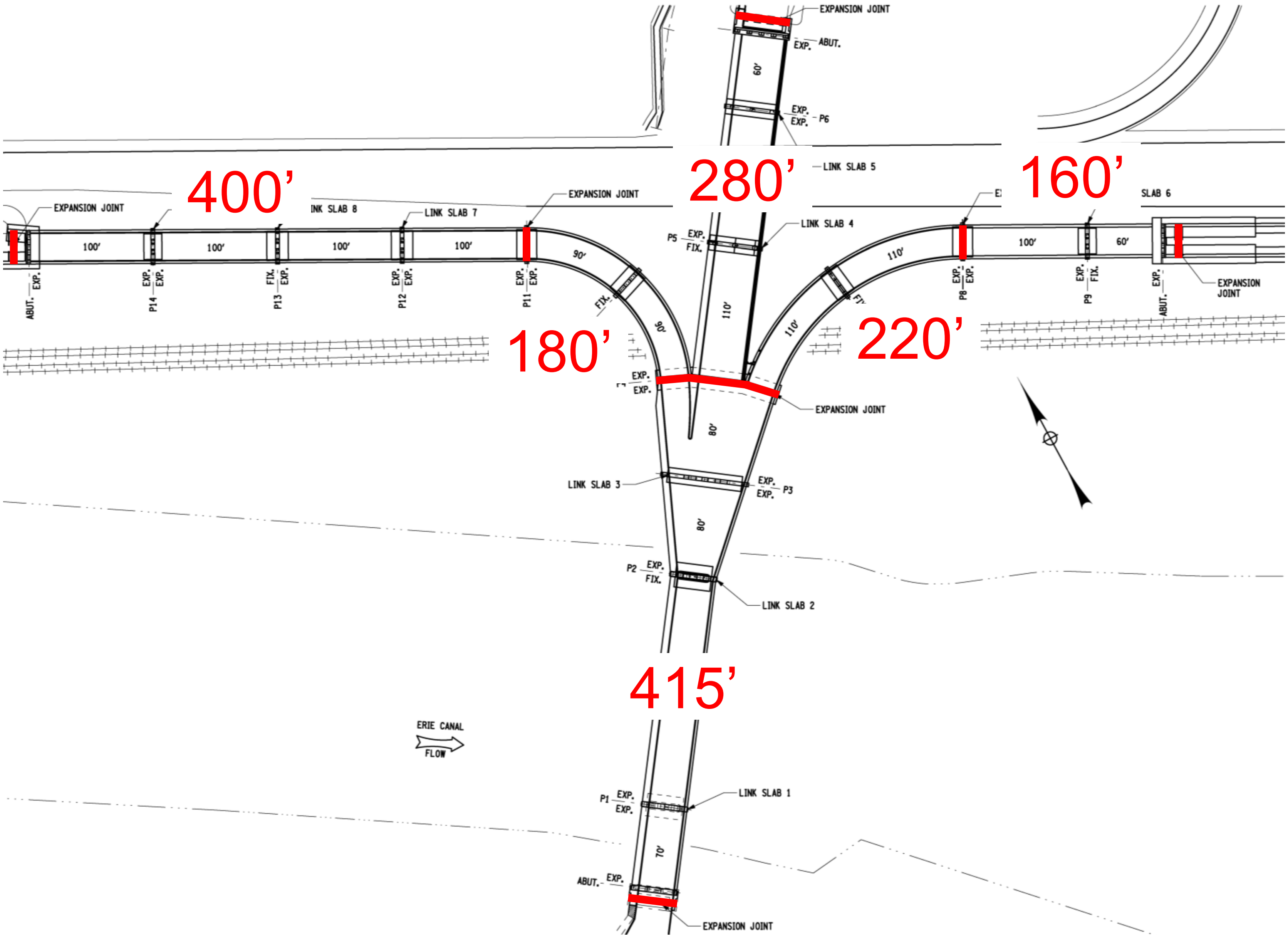
Comparison of Material Costs

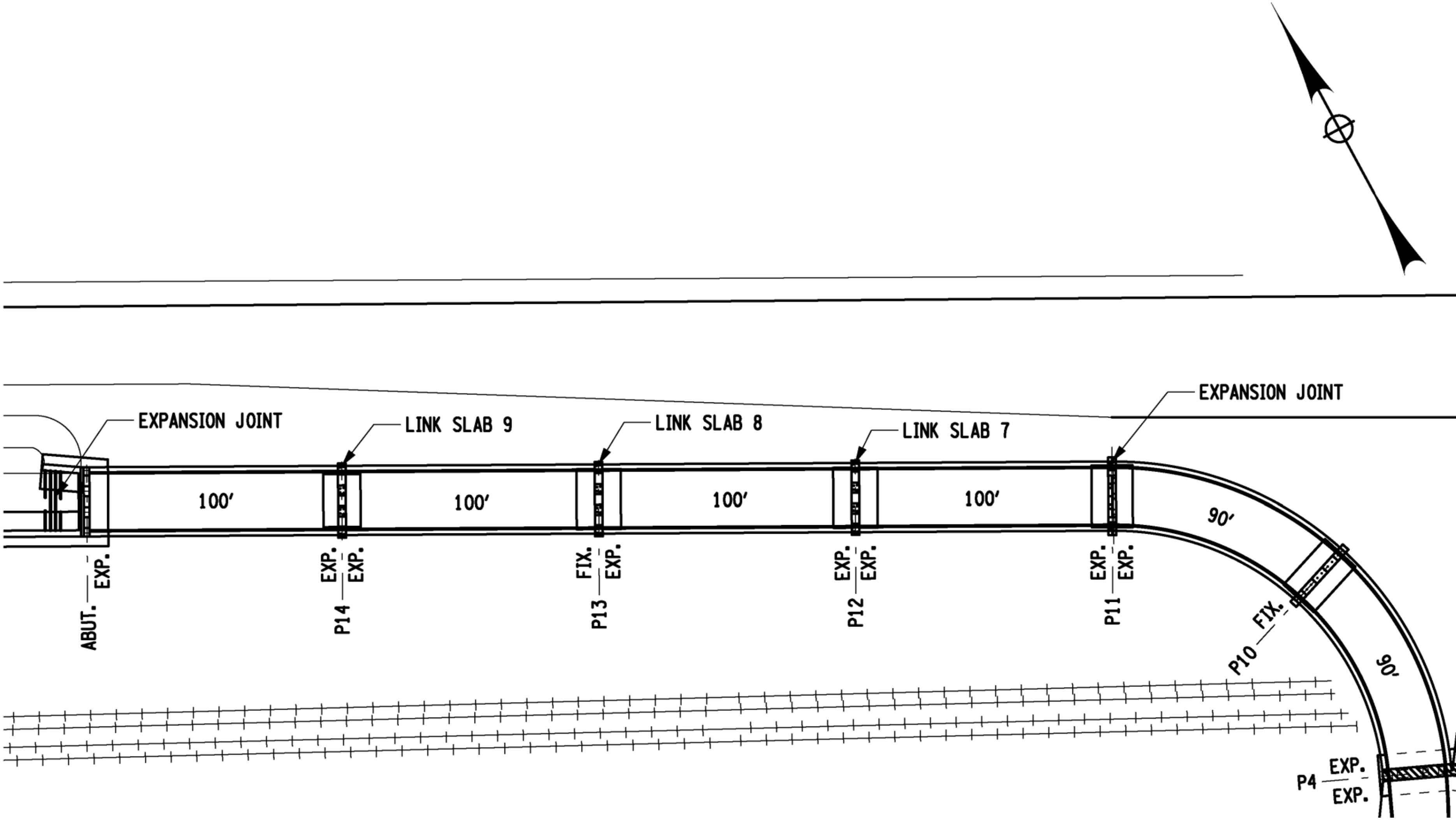
Material	Approx. Cost / CY
Conventional Concrete	$250
Portland Cement Grout	$1,500
Epoxy Grout	$5,000
Polymer Concrete	$2,300
UHPC	$3,000

Statewide Average Installed Costs

Material	Approx. Cost / CY
HP Concrete	$1,600
Polymer Concrete	$7,000
UHPC	$10,000



6 Contiguous Segments



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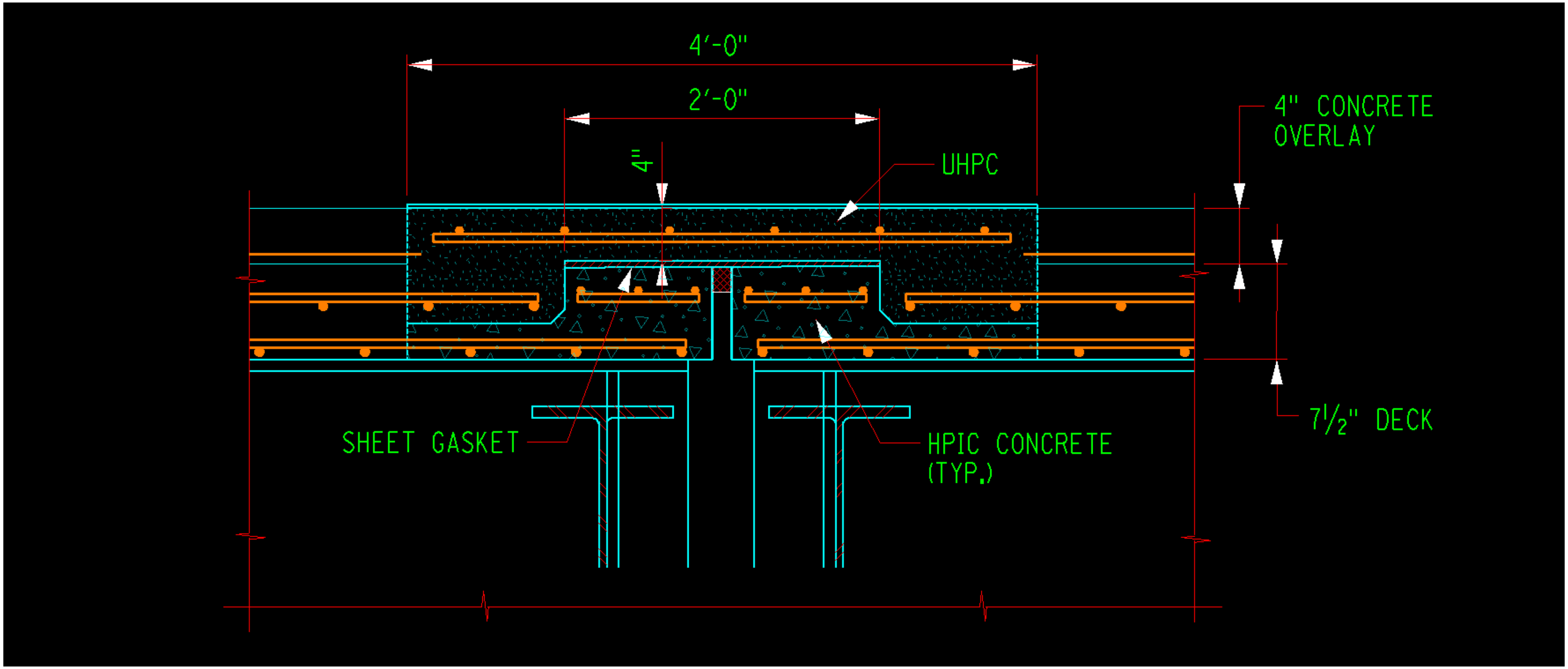

UHPC Link Slab Detail

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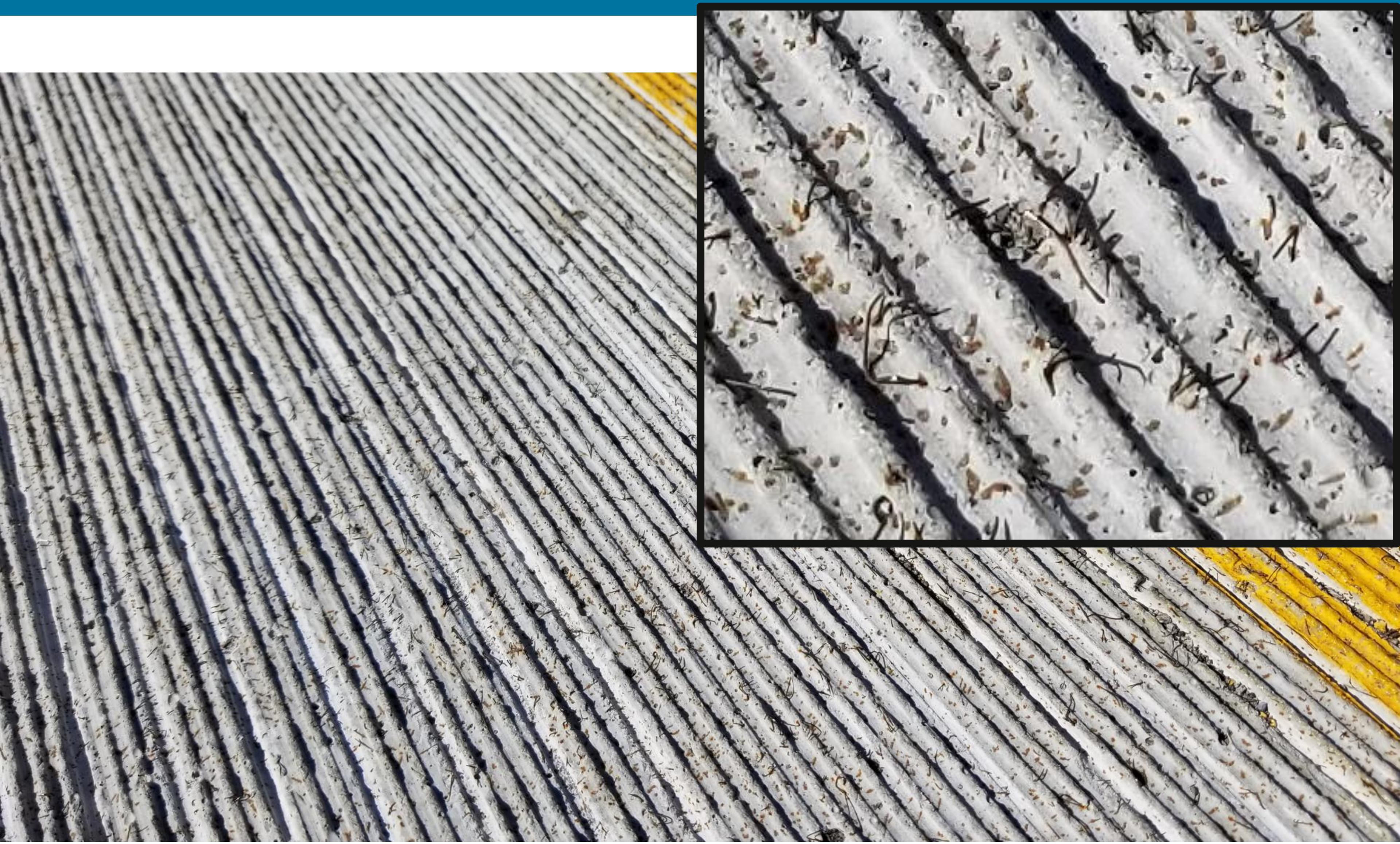
PACKAGED ICE
CRYSTAL CLEAR ICE
ICE
ICE
ICE
Milton CAT
POWER
CAT
Ductal
397
2010
1689


Ductal
Ductal
Dramix


56
WHITEMAN
WBH-16
WHITEMAN



Pier 1
5 Years After Installation of Link Slab

UHPC Link Slab Resources

- Federal Highway Administration

Design and Construction of UHPC-Based Bridge Preservation and Repair Solutions

PUBLICATION NO. FHWA-HRT-22-065 MAY 2022

Ultra-High Performance Concrete (UHPC) Link Slab Design Example

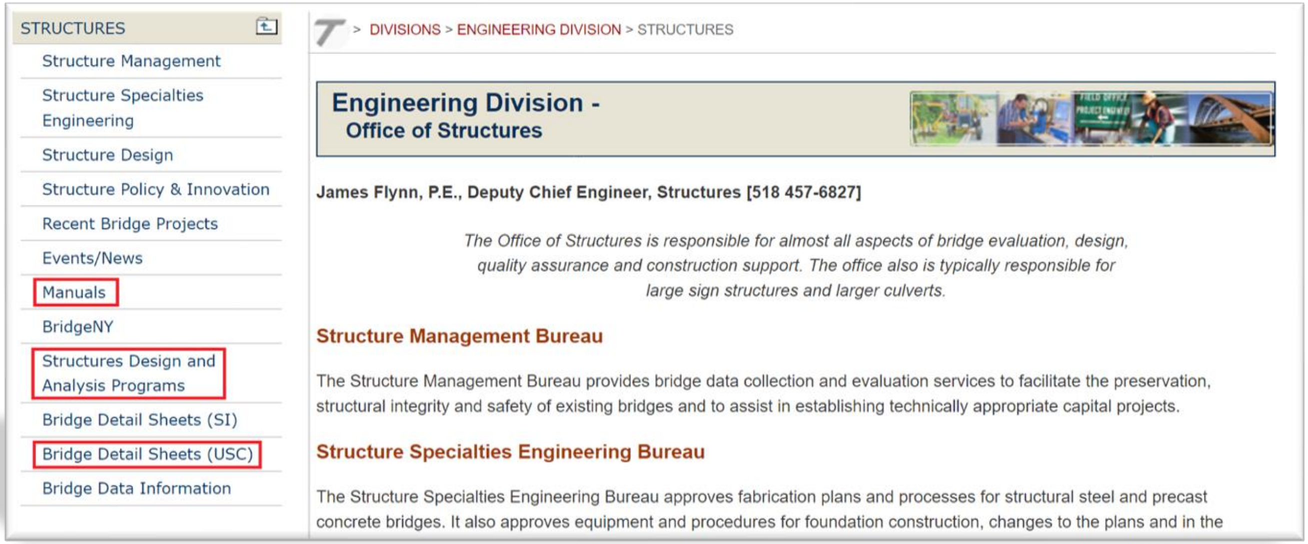
Publication No. FHWA-RC-23-0004 November 2023

Structural Design with Ultra-High Performance Concrete

PUBLICATION NO. FHWA-HRT-23-077 OCTOBER 2023

UHPC Link Slab Resources

- New York State DOT
  - In the near future policies, design guidance, Mathcad worksheets, examples, and details will be available on the Office of Structures website



dot.ny.gov/divisions/engineering/structures

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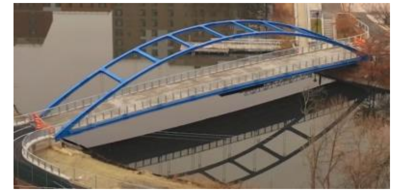
UHPC Link Slab Resources

- New York State DOT
  - Currently, most of our link slab information can be found on our Design-Build website

    [*dot.ny.gov/main/business-center/designbuild*](dot.ny.gov/main/business-center/designbuild)



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