NATIONAL ACADEMIES *Sciences Engineering Medicine*

TRB TRANSPORTATION RESEARCH BOARD

Using Ultra-High Performance Concrete for Bridges

October 18, 2023

1:00 to 2:30 PM

Fundamentals and Application of PCI Ultra-High-Performance Concrete

e.construct
Structural Engineering Consultants
DUBAI · OMAHA · ORLANDO

Maher Tadros, PhD, PE

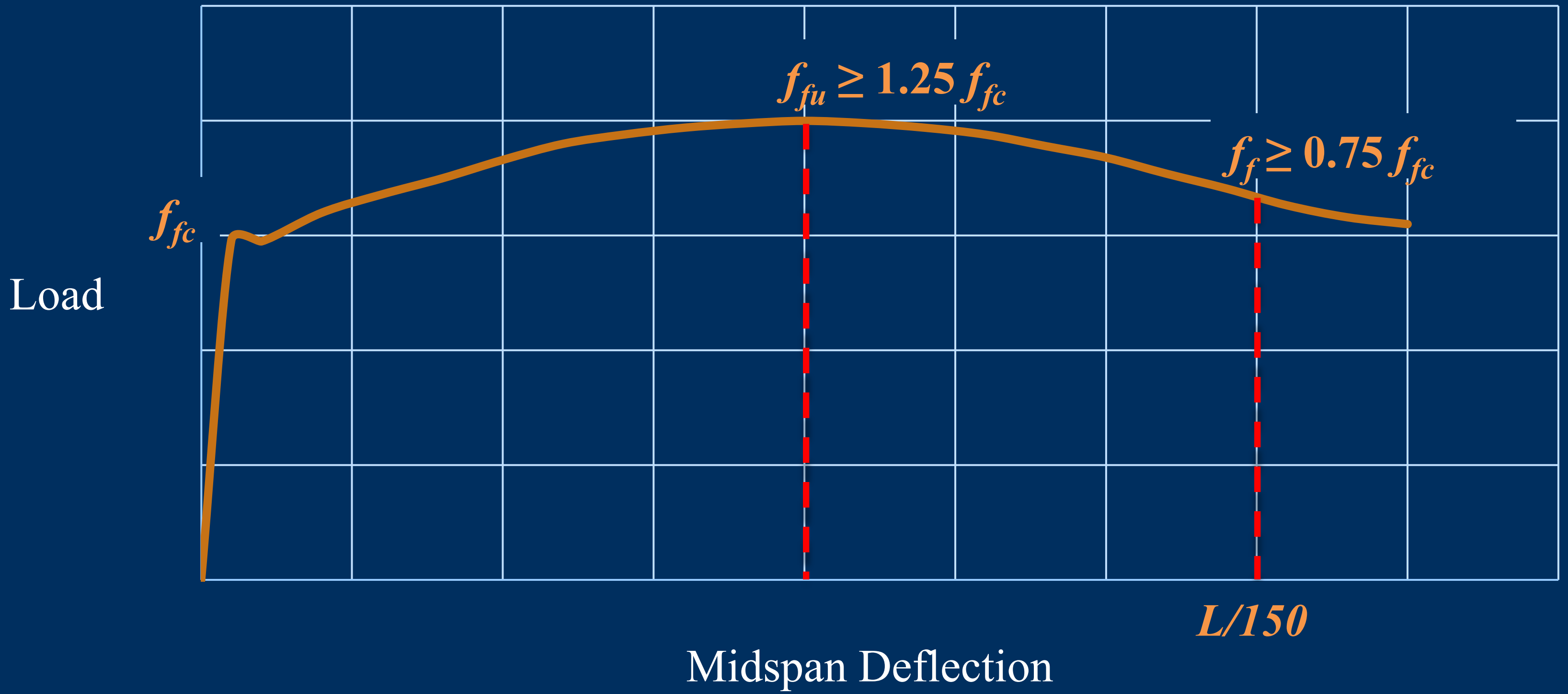
What is Ultra-High-Performance Concrete?

- Fiber-reinforced, cementitious composite
  - Low w/cm (typically < 0.20)

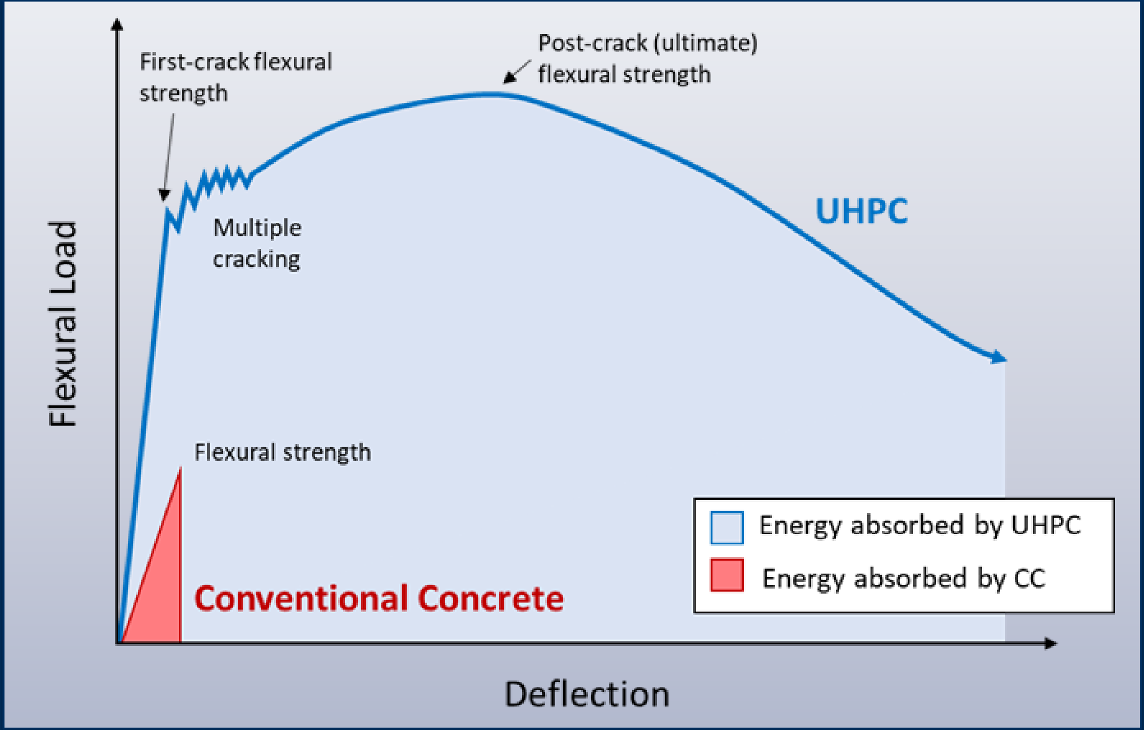
What is PCI-Ultra-High-Performance Concrete?

- Characterized by:
  - Higher compressive strength than currently in AASHTO LRFD-BDS
  - High pre- and post-cracking tensile strength
  - Ensured strain hardening to allow for exceptional flexural and shear behavior
  - Enhanced durability due to high density and discontinuous pore structure

Flexural Tension Requirements, using ASTM C1609 Standard Testing; 4”x4”x14” prism. IMPORTANT!



Tensile Strength and Ductility



Durability of PCI-UHPC vs. Conventional Concrete

Property	Conventional Concrete	UHPC
Electrical Indicator of Chloride Penetration Resistance, Coulombs	~4,000	32
Chloride Diffusion Coefficient, m^2/s	$\sim 5 \times 10^{-12}$	0.13×10^{-12}

Temperature and Flowability

- Goal is to have as much flow spread as possible without segregation: 8 to 11 inches at point of placement
- Temperature before placement should be as low as possible: 65 to 85° F, preferably close to 65!
- Temperature after placement and finishing should be as high as possible: 194° for 48 hours within 7 days of placement (PCTT).

Performance Achieved

Property	Target (PCI-UHPC)	Phase I (Box Beam)	Phase II (Decked I-Beam)
Compressive Strength			
28-days (lab-cured), psi	--	18,970 ✓	21,410 ✓
At service (match-cured), psi	≥ 17,400	19,780	22,290
Flexural Strength			
First-Peak, psi	≥ 1,500	1,960 ✓	1,770 ✓
Peak, psi	≥ 2,000	3,170	3,450
Peak, % of first peak	≥ 125%	162%	200%
Residual at L/150, % of first-peak	≥ 75%	137%	146%

Structural Design

Structural Design Guidelines

- Flexure, Creep, Shrinkage, Prestress Losses
- Vertical Shear
- Interface Shear
- Strand Bond
- End Zone Reinforcement

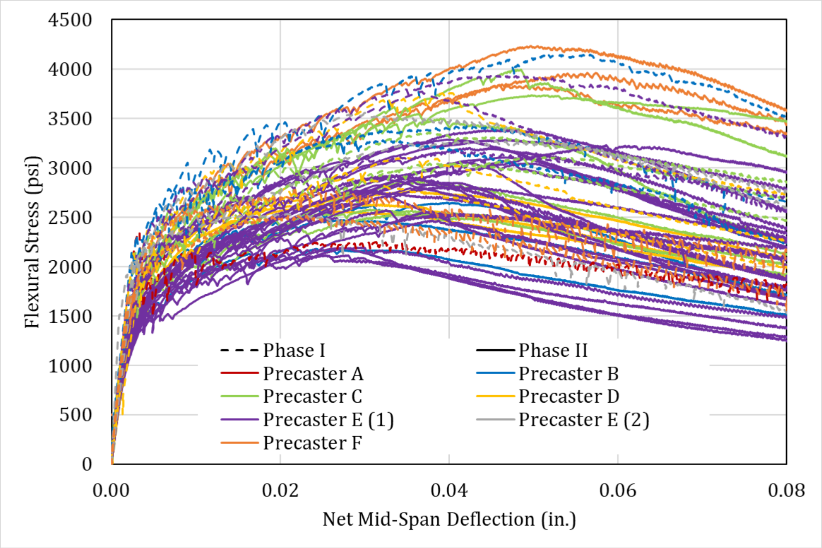
Flexure, Service Limit State

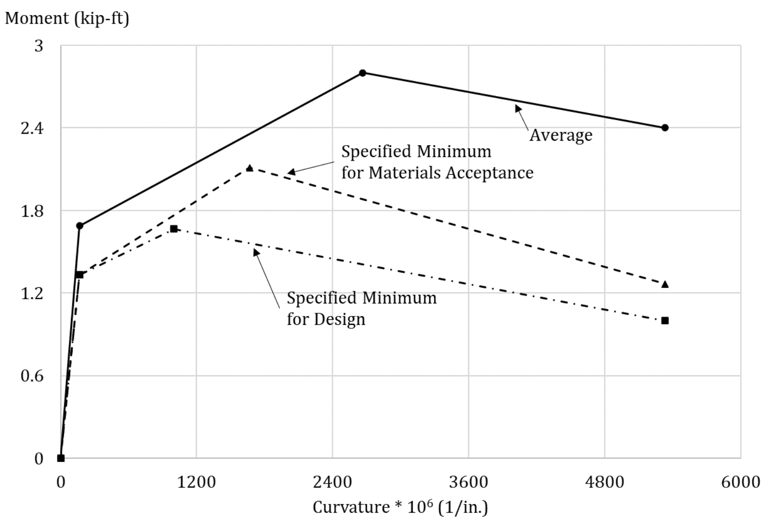
- Linear elastic uncracked section analysis, as currently in AASHTO LRFD Bridge Design Specifications (AASHTO)
- Concrete modulus, assumed = 6,500 ksi
- Initial Prestress Loss: same as in AASHTO
- Long Term Effective Prestress= 202.5-40.5 = 162 ksi
- Allowable compressive stress limits as currently in AASHTO
- Tensile stress at release to 0.75 ksi
- Tensile stress at service to 1.00 ksi

Flexure, Strength Limit State

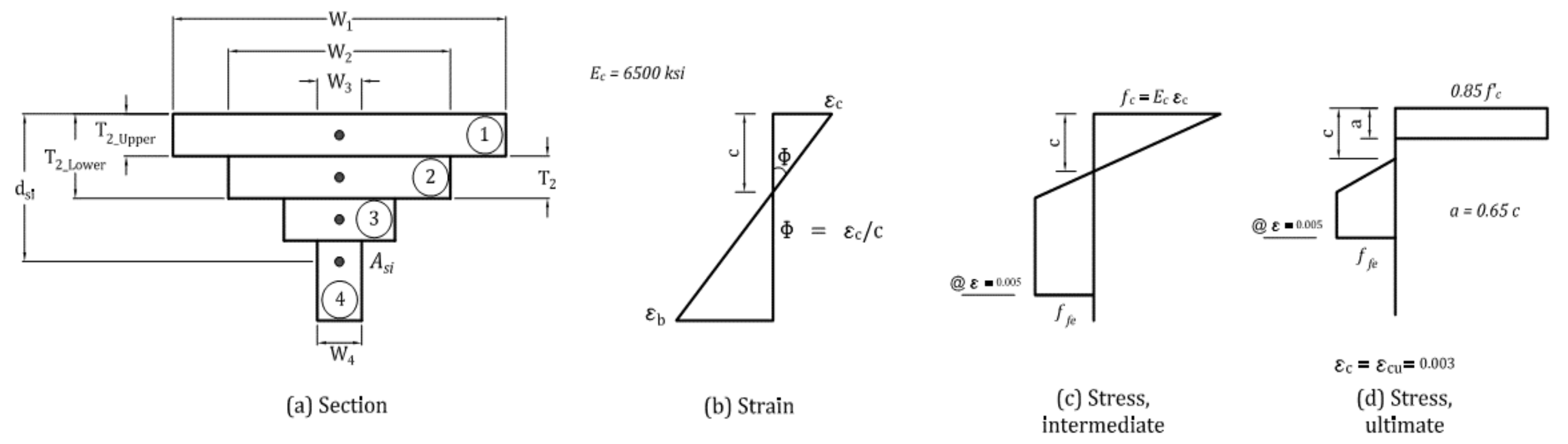
- Convert ASTM C1609 flexural stress minimum requirements to equivalent fiber tensile strength, using “inverse analysis”
- For the critical section, perform moment curvature analysis using provided spreadsheet
- Analysis includes contribution of fibers, rebars and strands
- Parametric studies in this research indicate that strands dominate in longitudinal direction…. Ignore fibers
- Parametric studies indicate that fibers may be adequate in T sections with flange in tension. Rebars may be needed in stems in tension.
- If fibers are counted on, a reduced resistance factor is proposed

Inverse Analysis





Flexural Strength Design Process



(a) Section (b) Strain (c) Stress, intermediate (d) Stress, ultimate

(a) Develop moment-curvature curve; Determine peak moment, M_{n1}

(b) Use ultimate strain of 0.003, and rectangular stress block to get M_{n2}

(c) The peak capacity is the larger of M_{n1} and M_{n2}

Example: Flexural Strength of Midspan Section of Prestressed Decked I-Beam

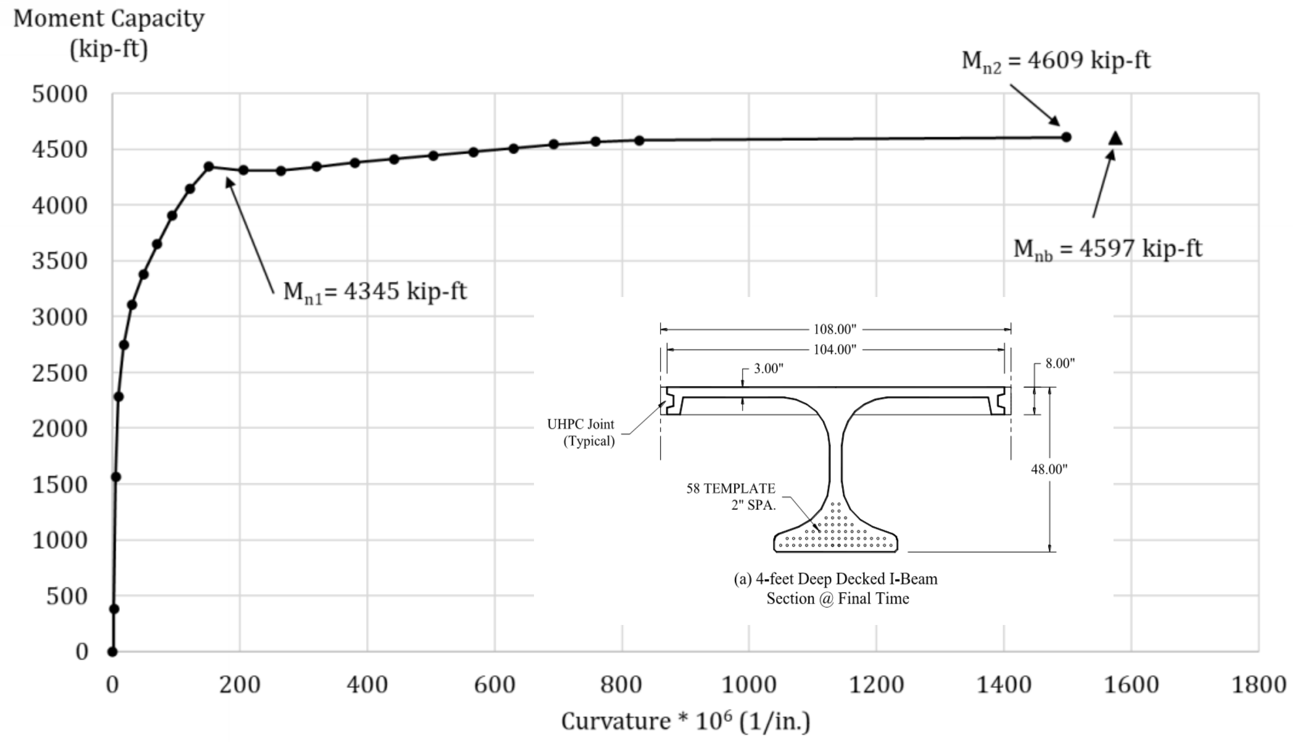
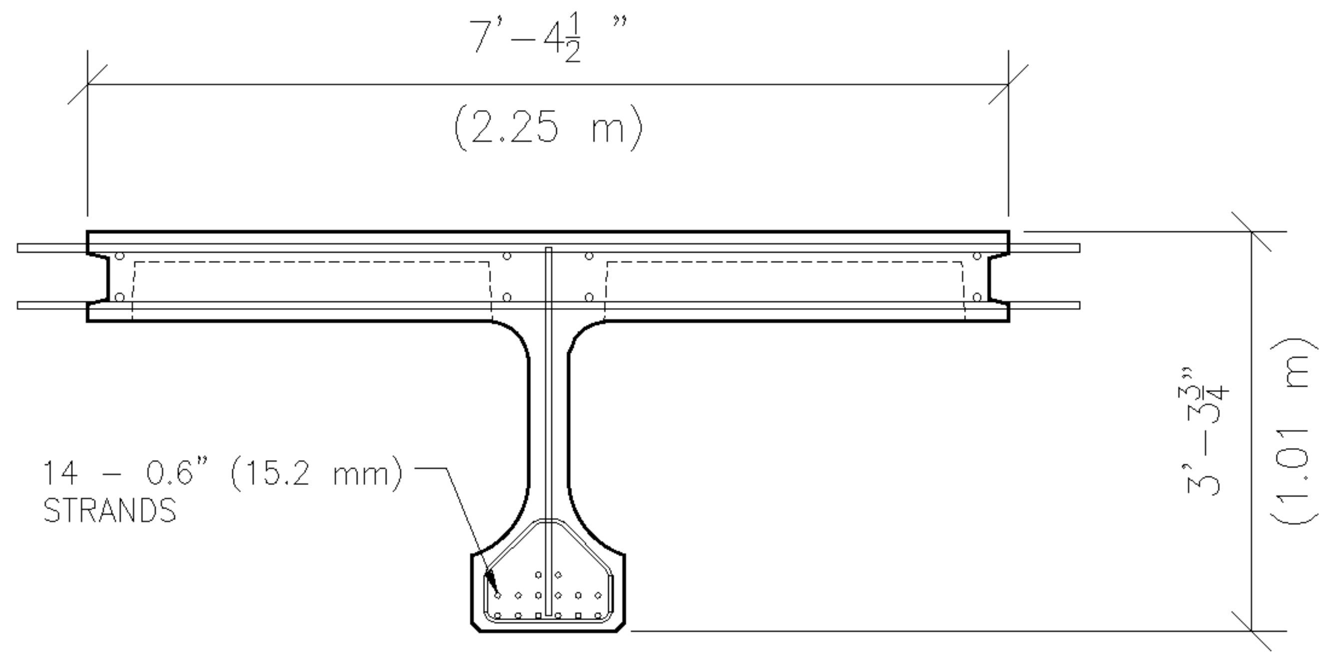


Figure 4.9.3-1. Moment-Curvature Relationship of the Decked I-Beam for Determination of M_n

Recommended Short Cut for Prestressed Members

- For prestressed concrete, strand is the dominant tension element
- No change to strain compatibility analysis in AASHTO
- Use available commercial software

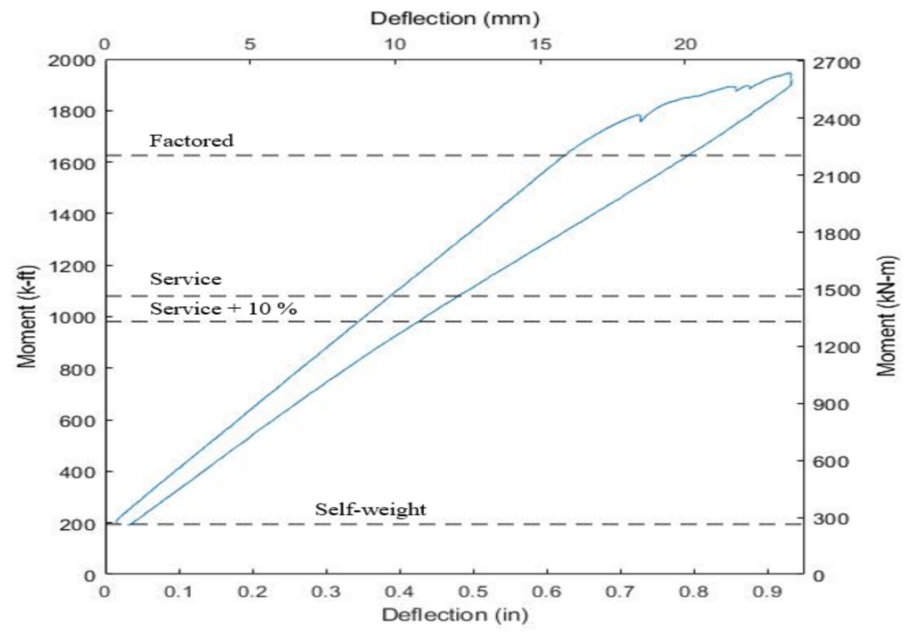
Product Testing in Flexure, PCI-UHPC Decked I-Beam



Decked I-Beam for FACCA, Inc, Ontario, Canada

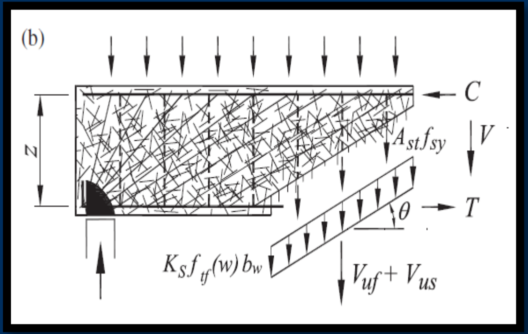
- 50’ long decked bridge girder
- Tests in flexure (3-pt), shear (both ends), and local deck and diaphragm tests

Flexure Testing



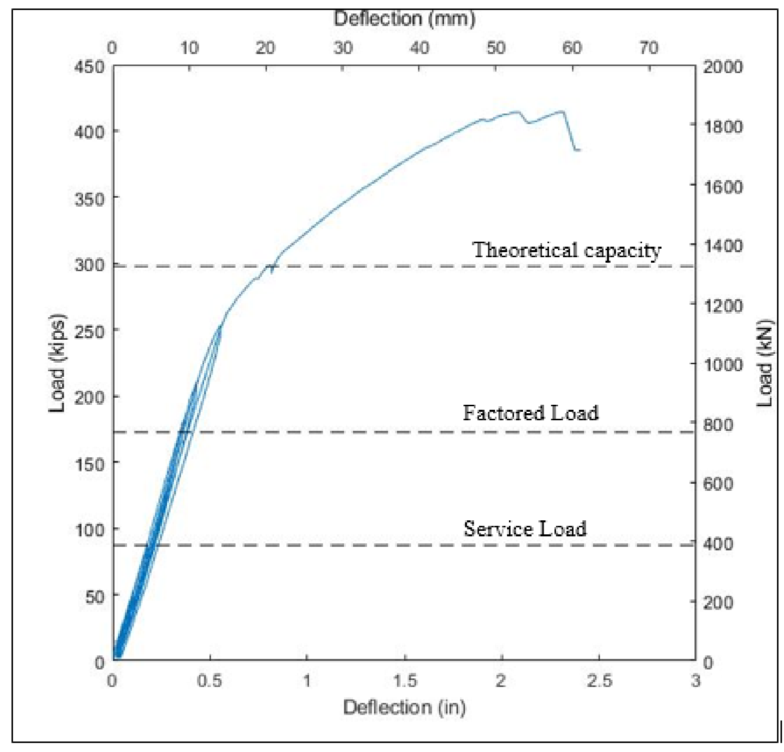
Vertical Shear

Shear Strength Design Recommendation

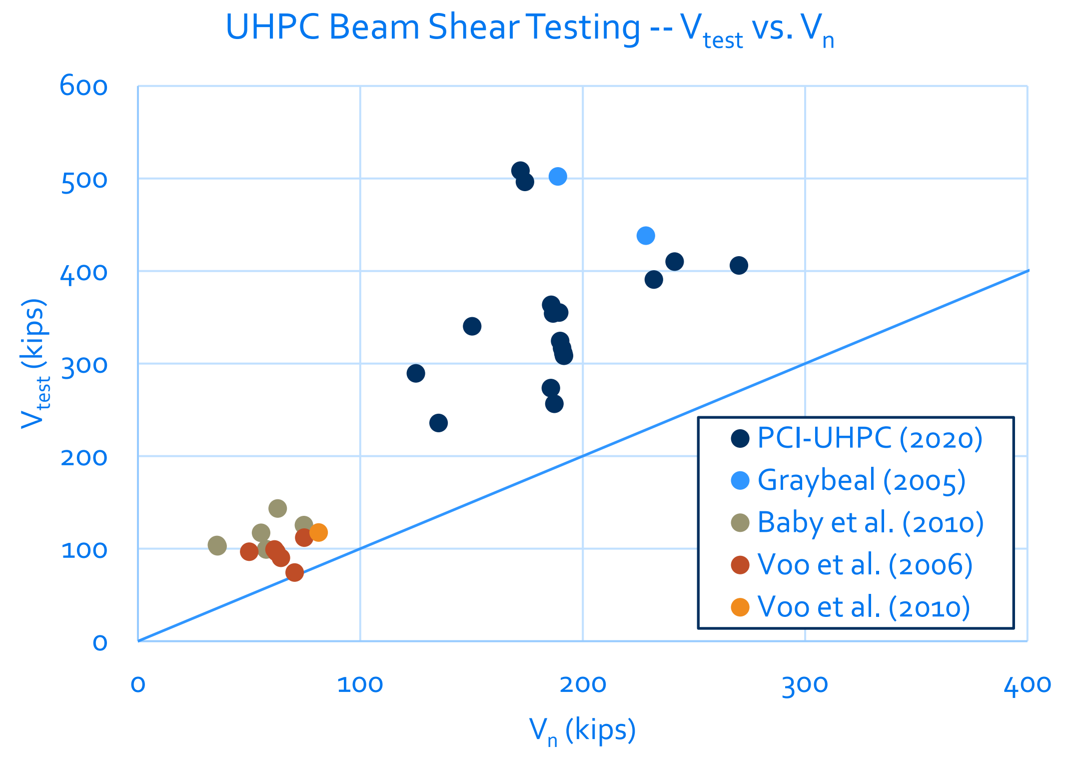


- Use AASHTO’s general MCFT, with modifications
- $V_n = V_c + V_s + \boldsymbol{V_f(\text{new})} + V_p$
  - $V_c = 0.0316\beta\sqrt{f_c'}b_v d_v$
  - $\varepsilon_s = \frac{(M_u/d_v)+(V_u-V_p)-P_e}{(E_s A_s+E_p A_{ps})}$
  - **Use negative strain** $\boldsymbol{\varepsilon_s = \frac{(M_u/d_v)+(V_u-V_p)-P_e}{(E_s A_s+E_p A_{ps}+E_c A_{ct})}}$
  - $\beta = 4.8/(1+750\varepsilon_s)$
  - $\theta = 29 + 3{,}500\varepsilon_s$
  - $\boldsymbol{V_f = f_{rr} \cot\theta\, b_v d_v}$ **,** where f_{rr} = residual rupture stress
  - Recommended: $\boldsymbol{V_f + V_c = 1.00\, ksi\, (\cot\theta\, b_v d_v)}$

DIB Shear Tests

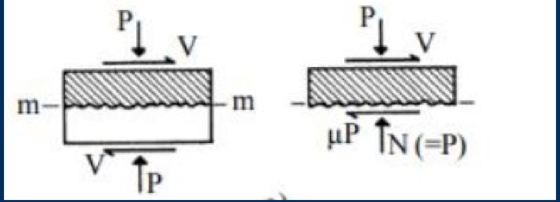


…Including Tests by Others

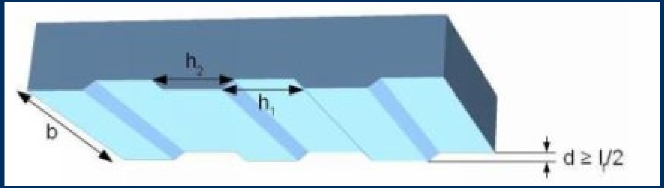


Interface Shear

Interface Shear Behavior



Shear Friction Hypothesis (Birkeland H. and Birkeland P., 1966)

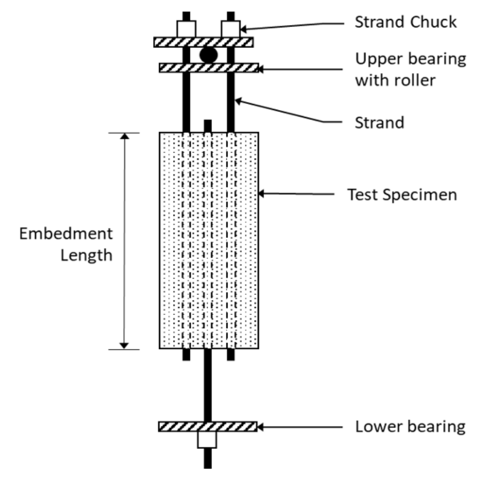


Fluted Joint Details as Specified by AFGC (2013)

Proposed Model

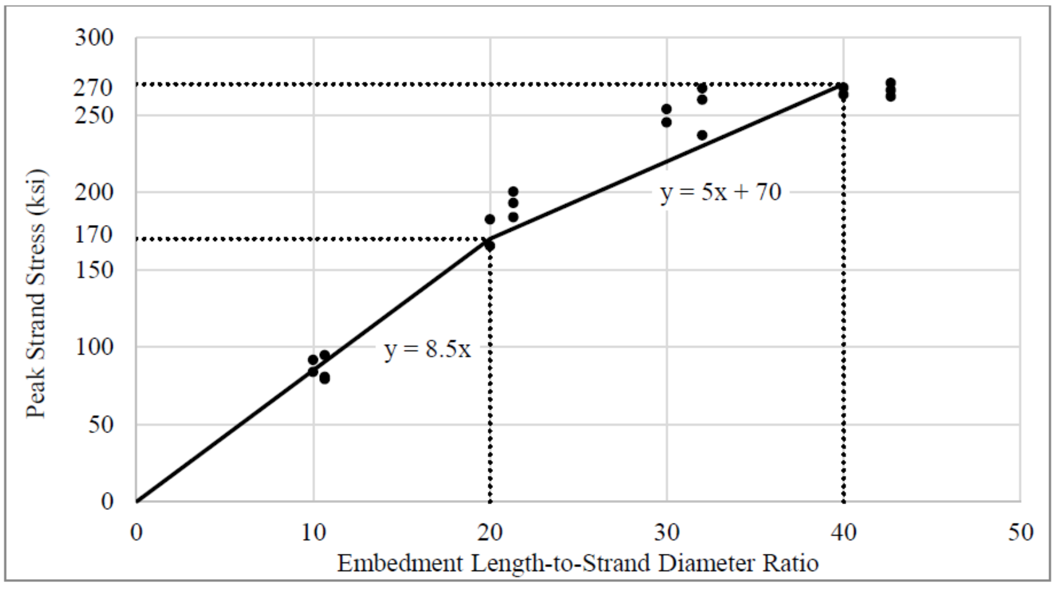
$$V_{ni} = cA_{cv} + \mu\, A_{vf}\, f_y$$

Strand and Bar Development



$$L_d = L_t + 0.2d(f_{ps} - f_{pe})$$

where $L_t = 20d_b$

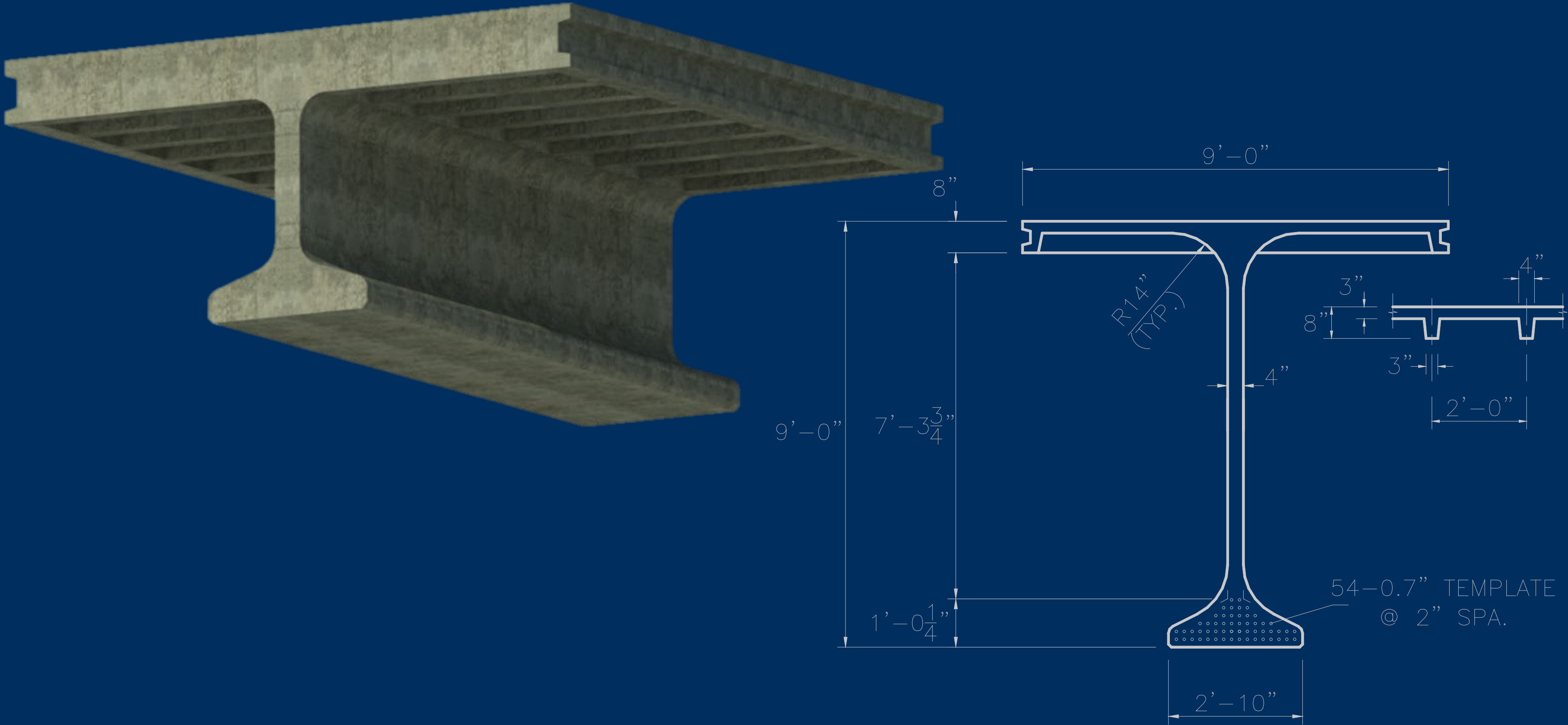


Confirming work by FHWA

Peak Strand Stress vs ℓ/d_b
(20 of 35 test results)

Optimized Products developed in the PCI-UHPC Program

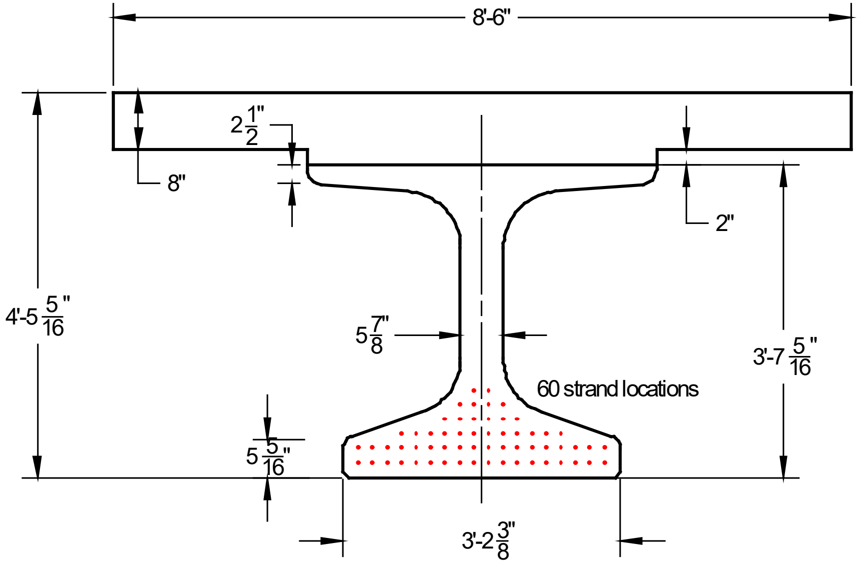
Decked I-Beams



Comparison with Conventional Concrete,

Span = 110 ft, Width = 50 ft, spacing = 8.5 ft.

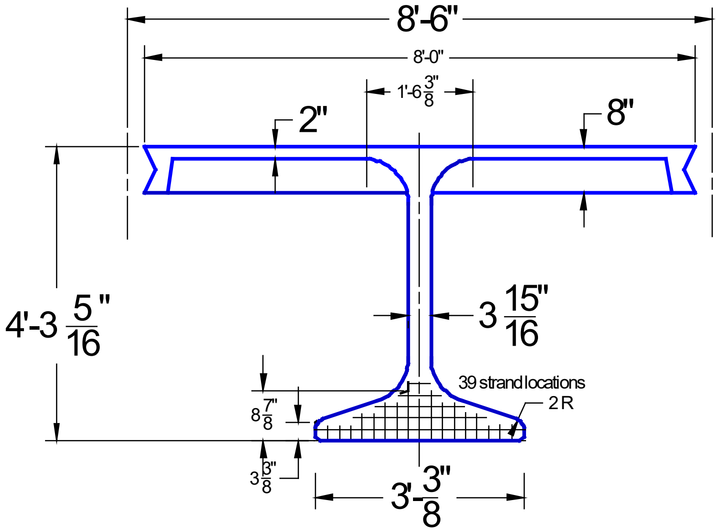
	Conventional NU 1100
Total depth (in.)	**53.31**
Compressive Strength at service, ksi	8
Compressive strength at release, ksi	6
Volume of beam, CY	20.00
Volume of deck, CY	25.80
Beam plus deck, CY	45.80
# of 0.7" Strands	**32**
Shear Reinforcement	YES
Deck Reinforcement	Both Directions



Nebraska NU 1100 (43.31") with 8" conventional deck

One-Stage Decked I Beam- Best Solution

	UHPC Decked-I-Beam	Percent reduction due to use of UHPC
Total depth (in.)	**51.31**	
Compressive Strength at service, ksi	18	
Compressive strength at release, ksi	10	
Volume of beam, CY	23.85	-
Volume of deck, CY	1.35	-
Beam plus deck, CY	25.20	**45%**
# of 0.7" Strands	**24**	
Shear Reinforcement	NO	
Deck Reinforcement	Transverse Only	Significant

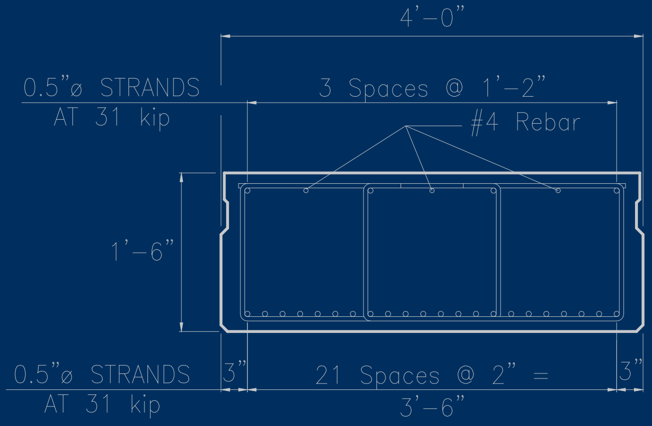


UHPC Decked I-Beam based on NU1100

UHPC Box Slab

CC Solid Slab

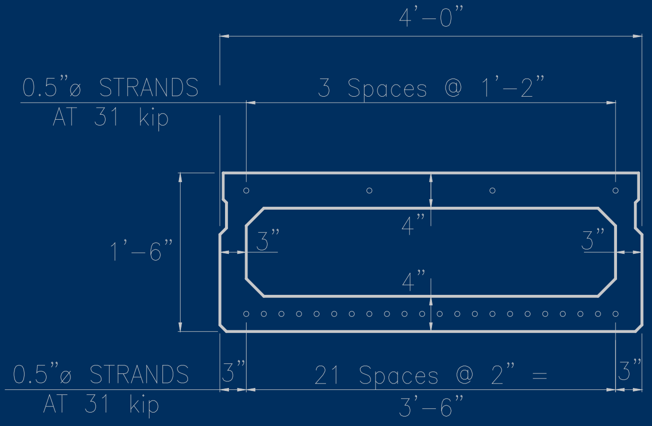
Proj. No. 18032-110



CC Weight = 920 lb/ft

Gr. 60 Reinf. = 745 lb (Total)

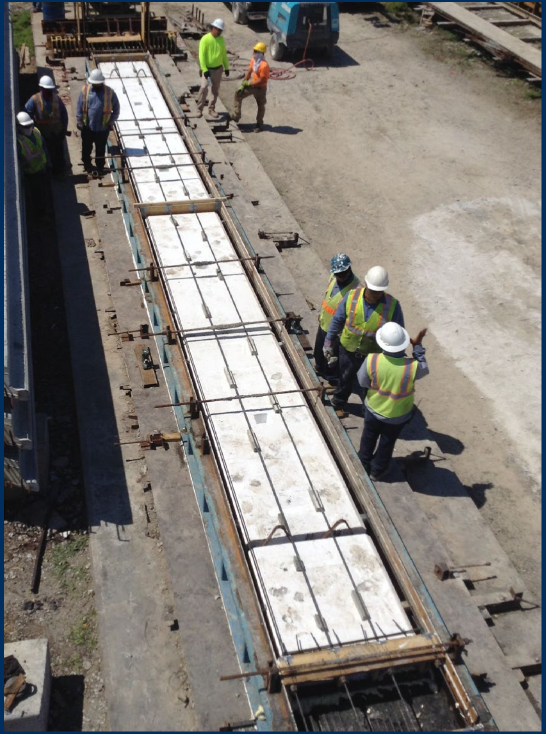
UHPC Box Slab



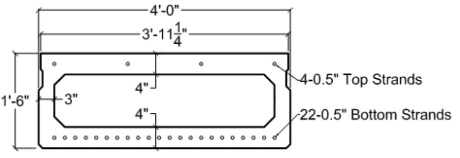
UHPC Weight = 480 lb/ft

Gr. 60 Reinf. = 24 lb (Total)

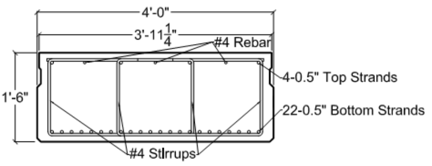
UHPC Box Slab vs. Florida Conventional Concrete Solid Slab

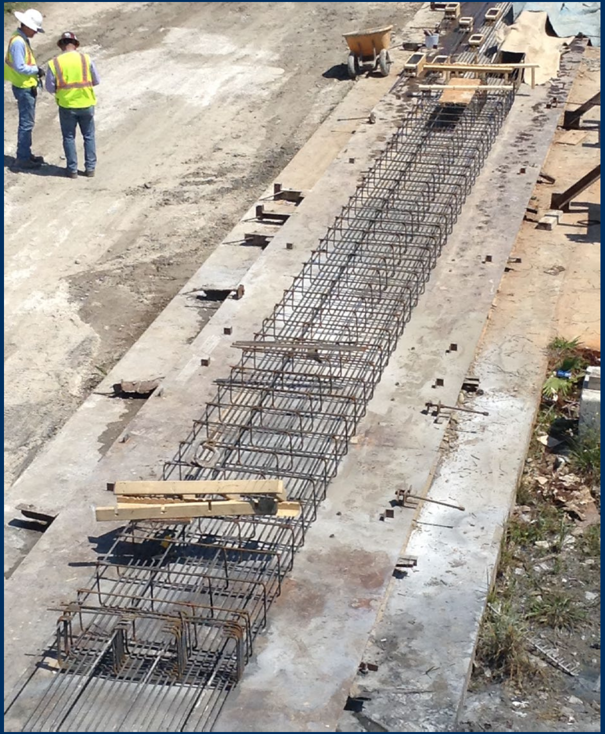


UHPC



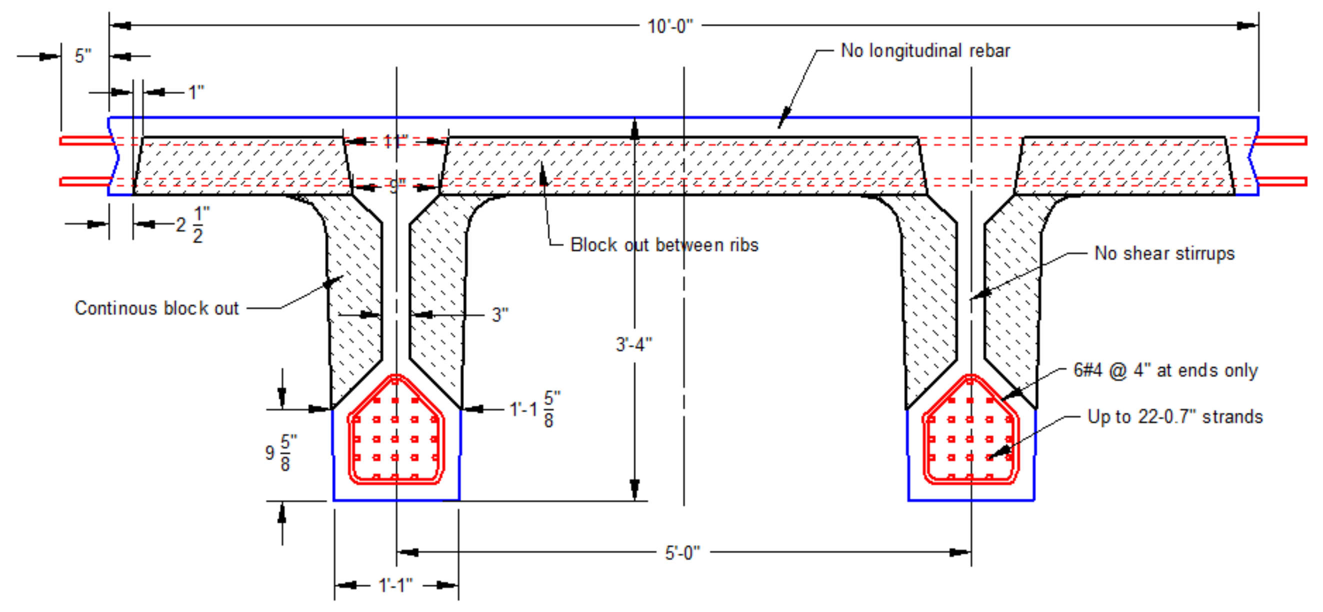
Conventional

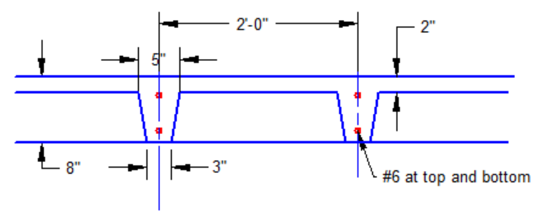




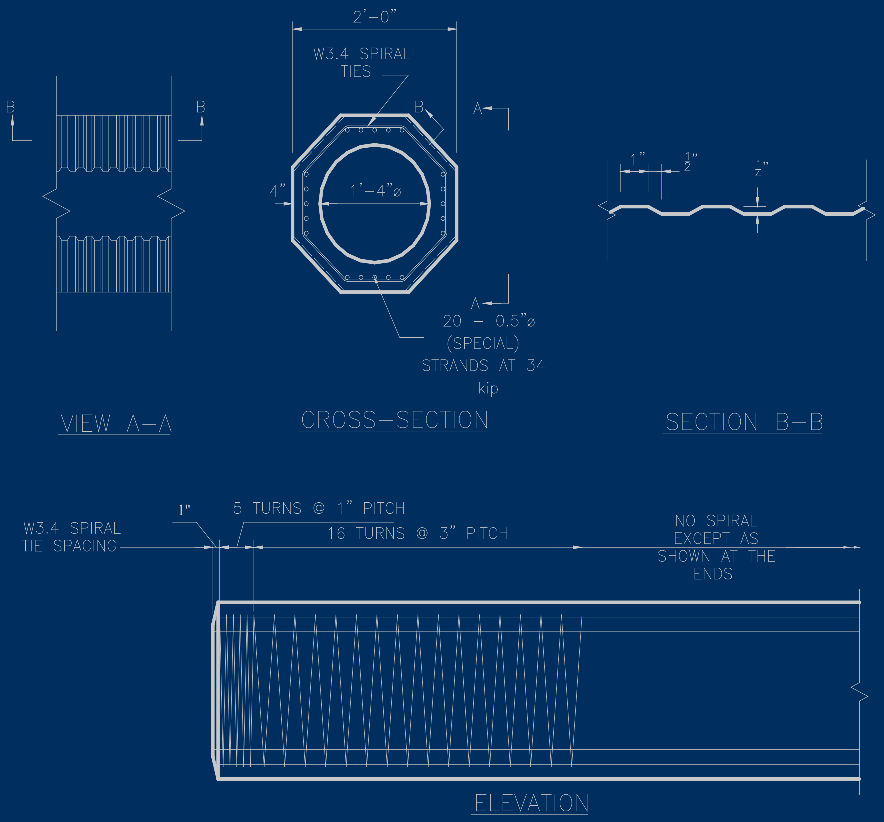
Optimization of Northeast Extreme Tee (NEXT)

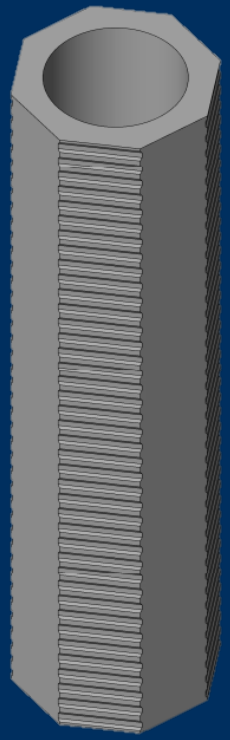
Volume reduced from 43 to 23 cubic yards for a 90 ft long piece



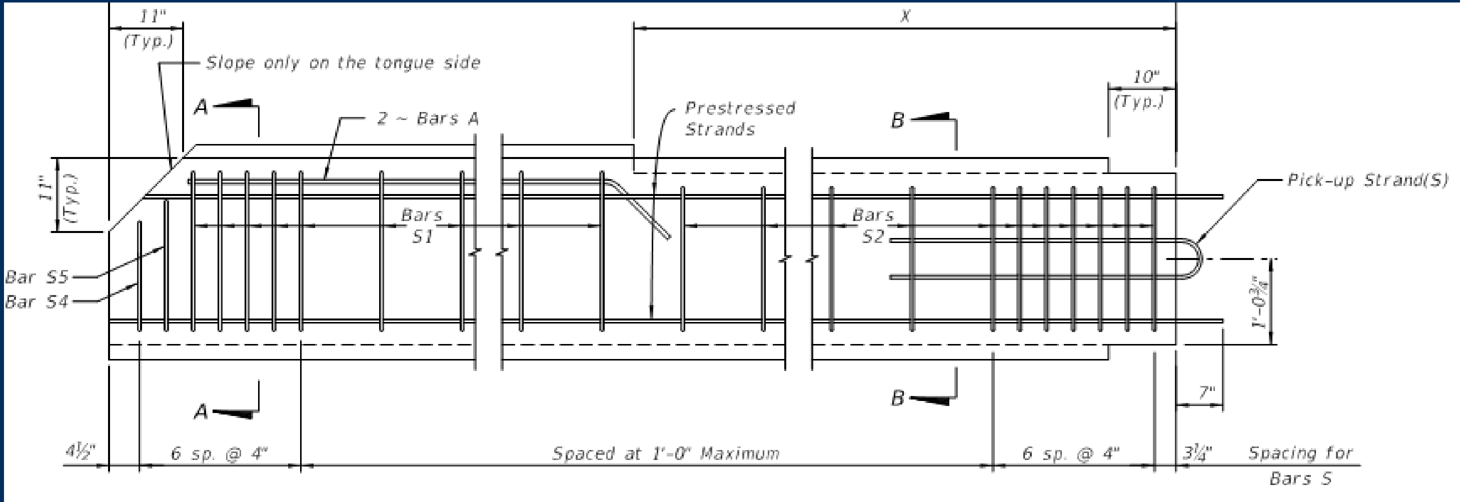


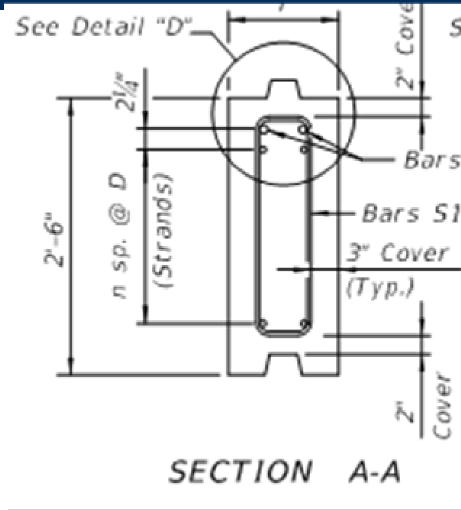
Optimization of Square Piles





Typical Conventional Concrete Sheet Pile, 10-12" Thick





Sheet Pile in the Netherlands: UHPC (a) versus Conventional concrete (b)

(Grünewald 2004)
(Walraven and Schumacher 2005, Walraven 2007)
(Walraven 2007)

When can we start designing with PCI-UHPC?

The time is NOW!

Recipe for Success

1. Start with something simple
2. Many spans; relatively short 60-80 ft spans
3. Preferably aggressive environment site
4. Simple cross section; the Florida box slab is a top candidate
5. Aim for 50 percent reduction in conventional concrete volume
6. Aim for 80 percent reduction in rebars
7. Be conservative in your design

Florida Department of Transportation - Advancements on the Application of UHPC

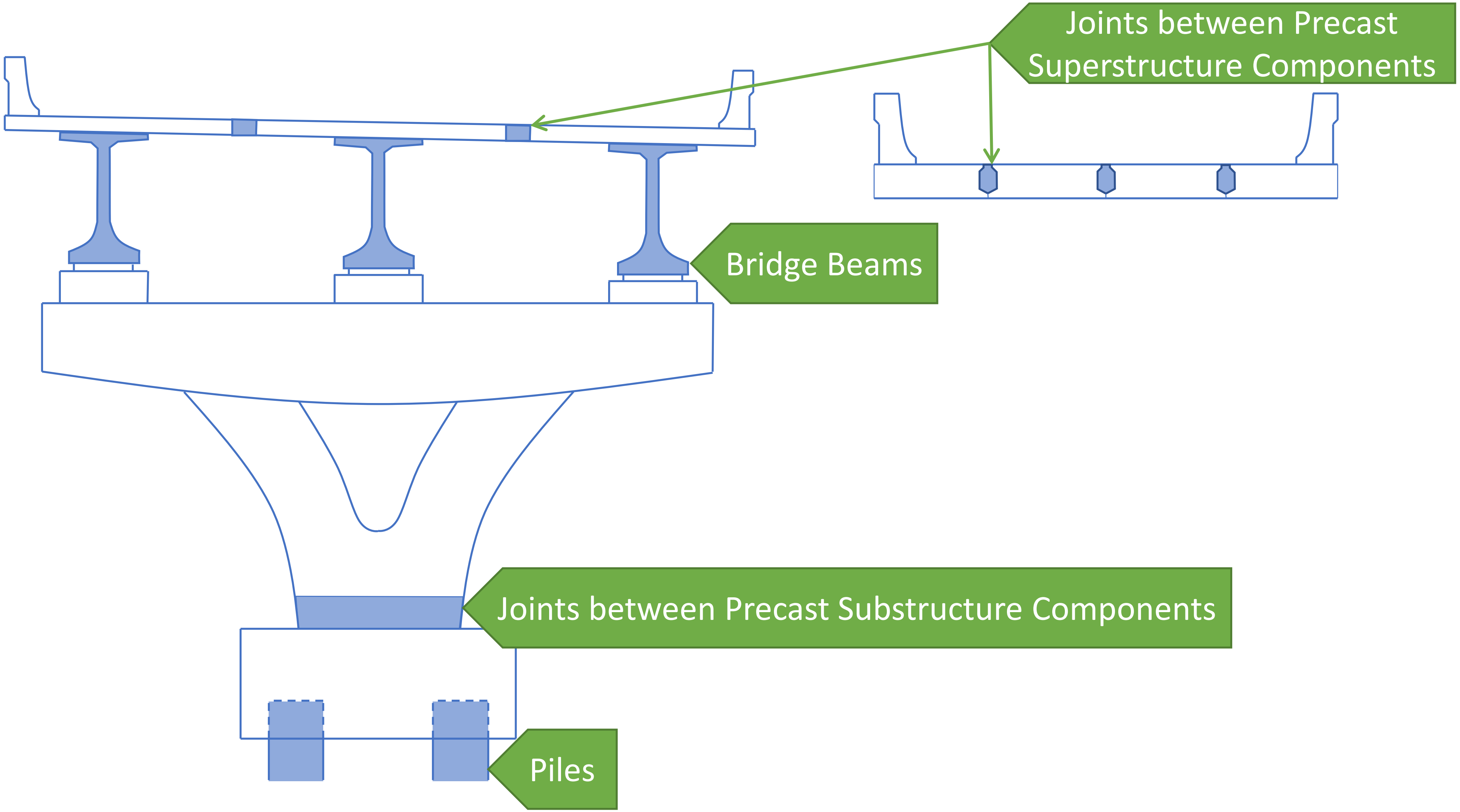
Presented By: Christina Freeman

Structures Research Center

- Large Scale Structures Research
  - In-House
  - University/Consultant
- Bridge Load Testing/Rating and Monitoring

What is UHPC?

- Portland Cement Product
- Very High Early Strength
- Fiber Reinforced (2%)
- Water to cementitious ratio < 0.25
- Compressive Strength > 17.5 ksi
- Tensile Strength > 0.75 ksi
- Enhanced Durability
- Flowable
- Expensive


Joints between Precast Superstructure Components

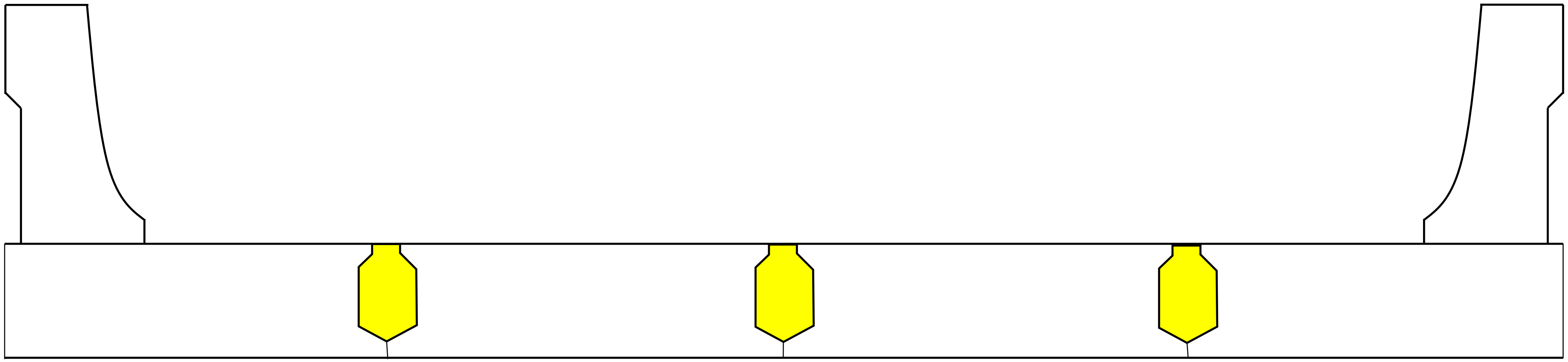
Bridge Beams

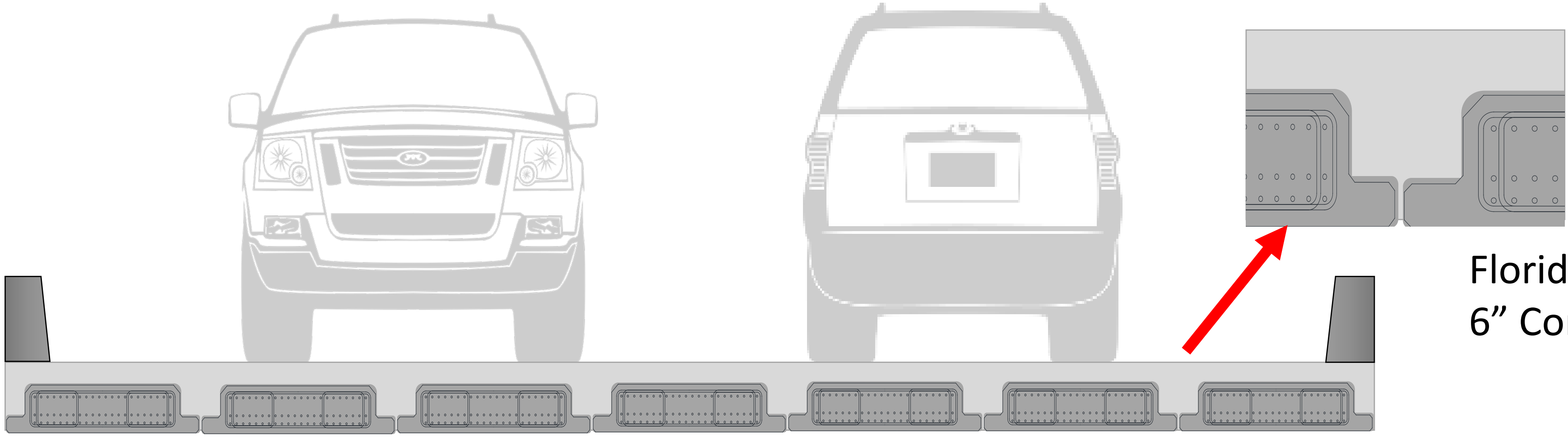
Joints between Precast Substructure Components

Piles

UHPC for Bridges

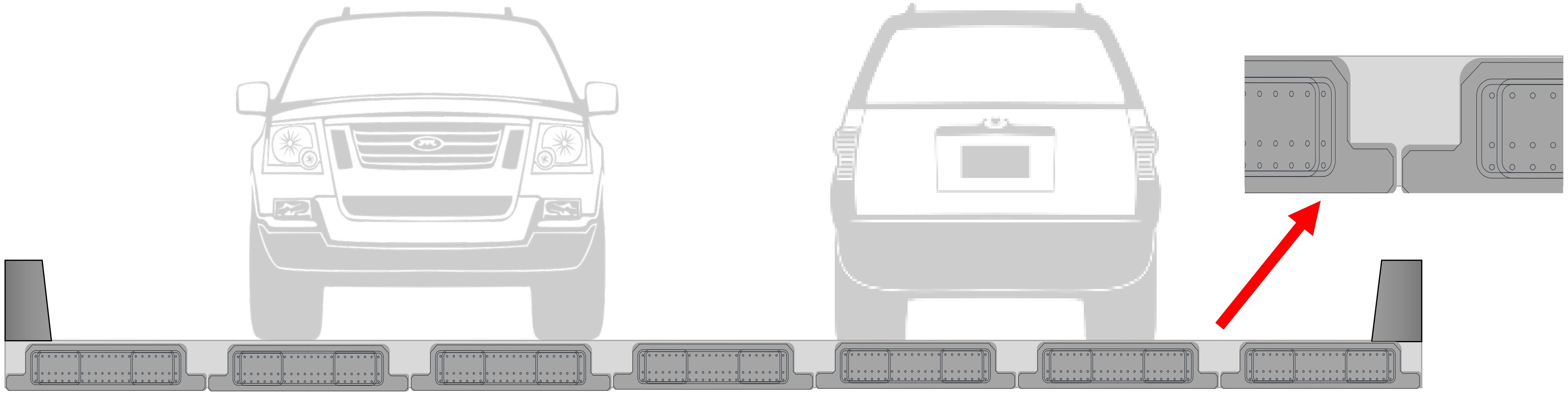
Connecting Flat Slab Beams





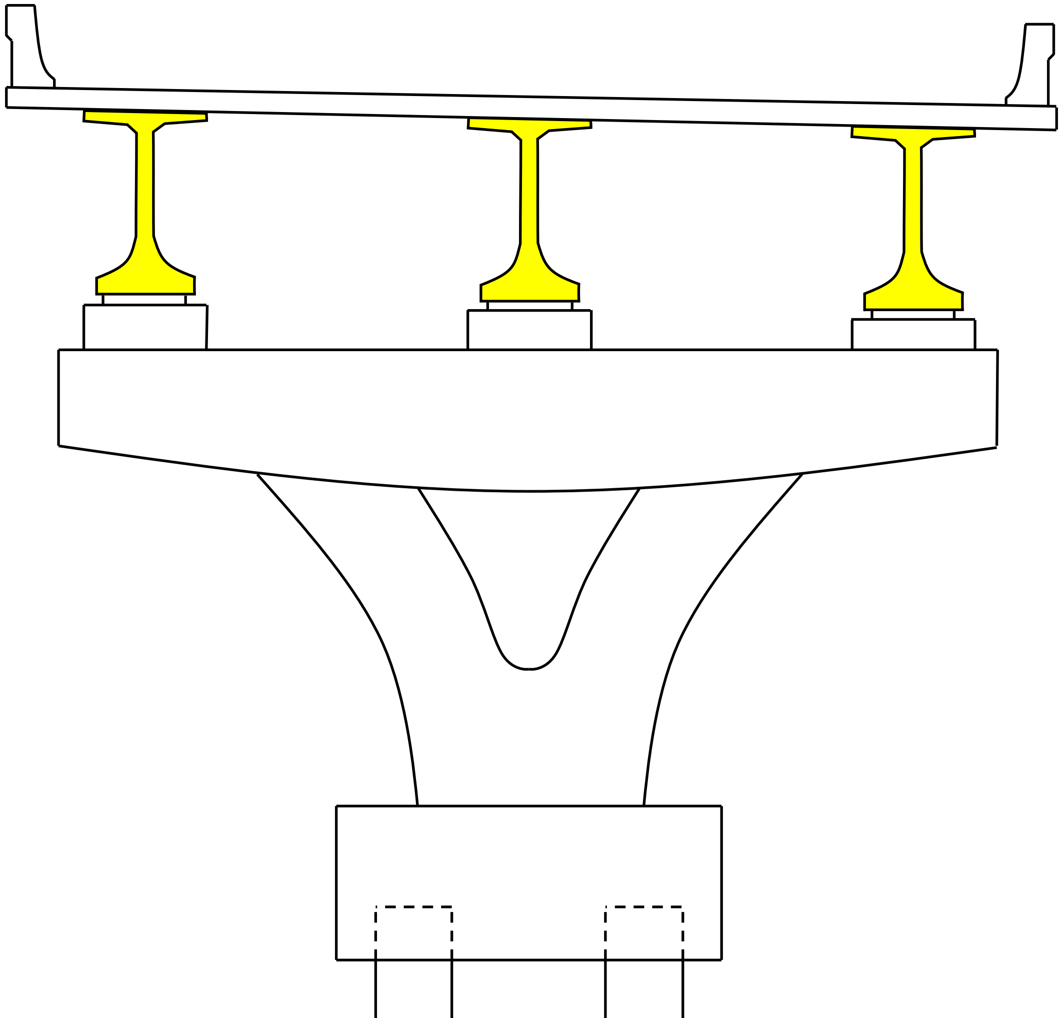
Florida Slab Beam with
6” Concrete Deck

Florida Slab Beam with
UHPC Closure Pour

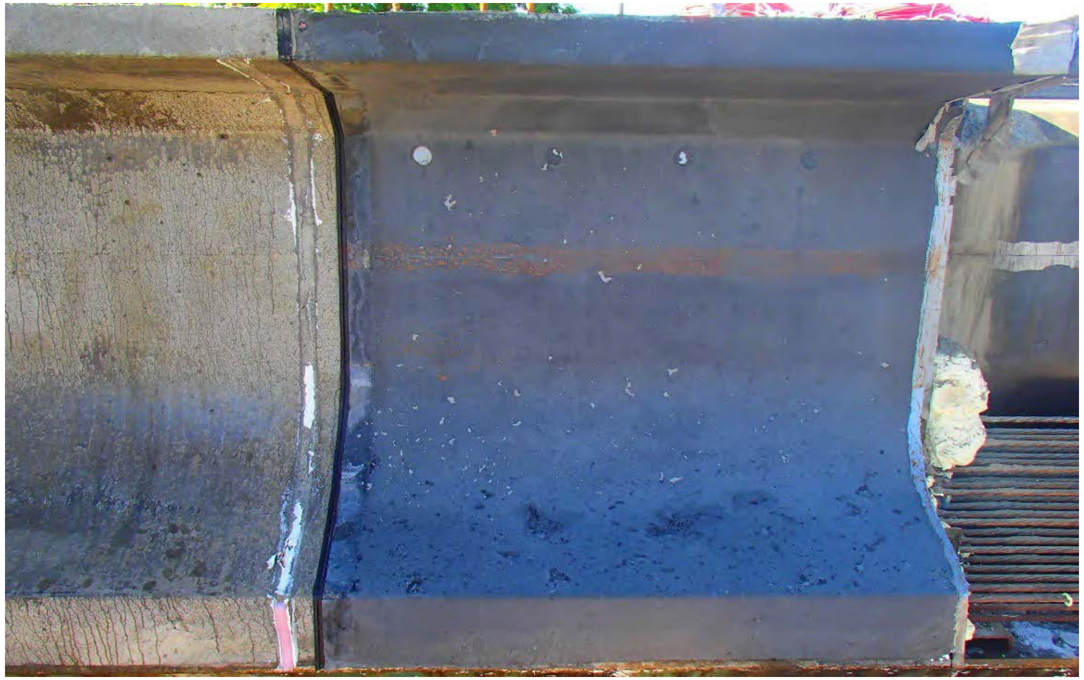


Source: Garber & Chitty Presentation, SRUT 2017

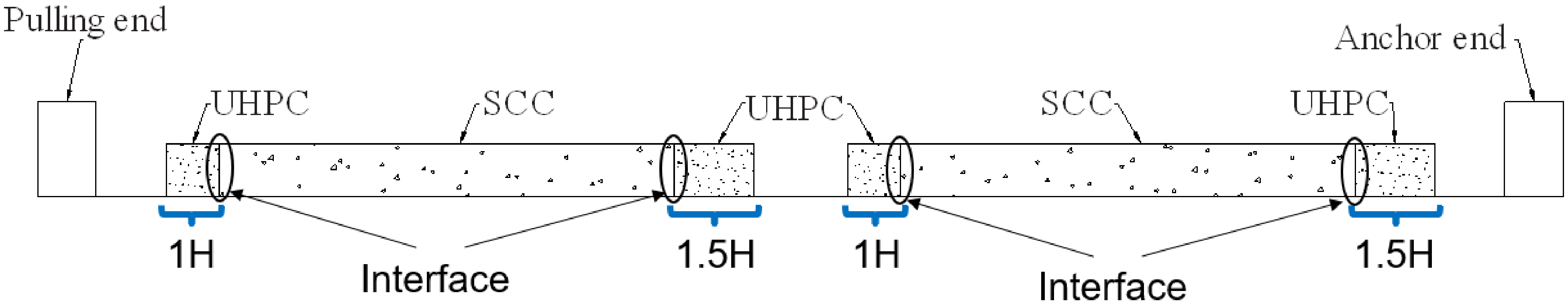
UHPC Beams

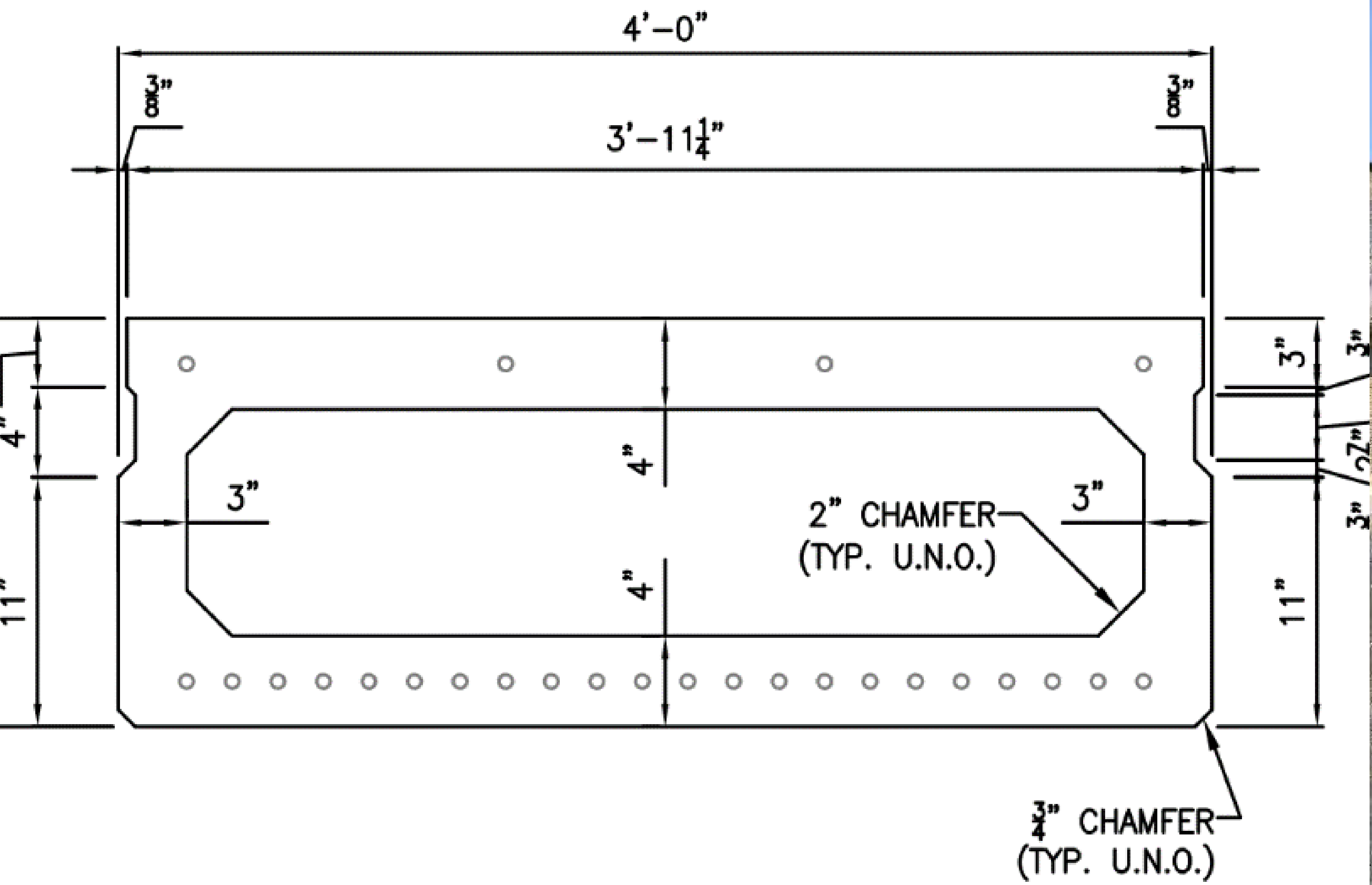


Hybrid Prestressed Concrete Girders Using UHPC



Hybrid Prestressed Concrete Girders Using UHPC

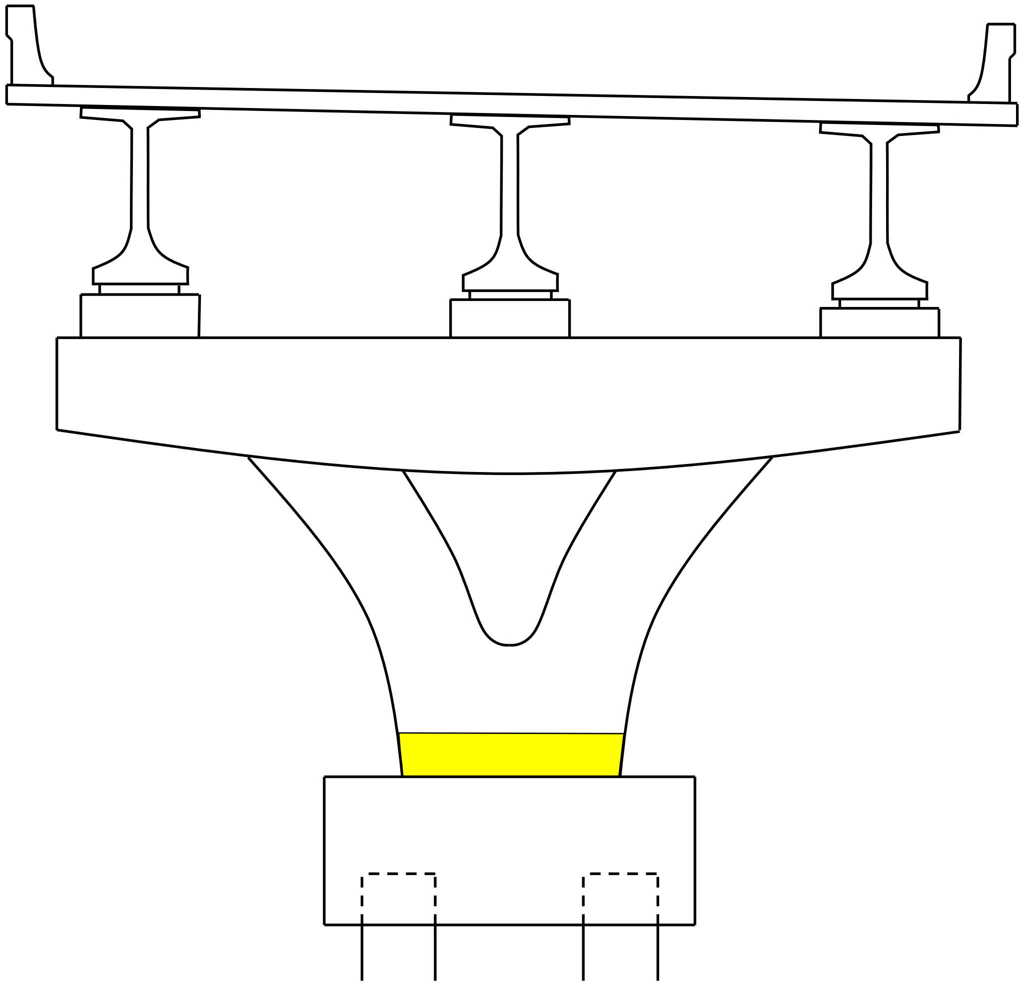


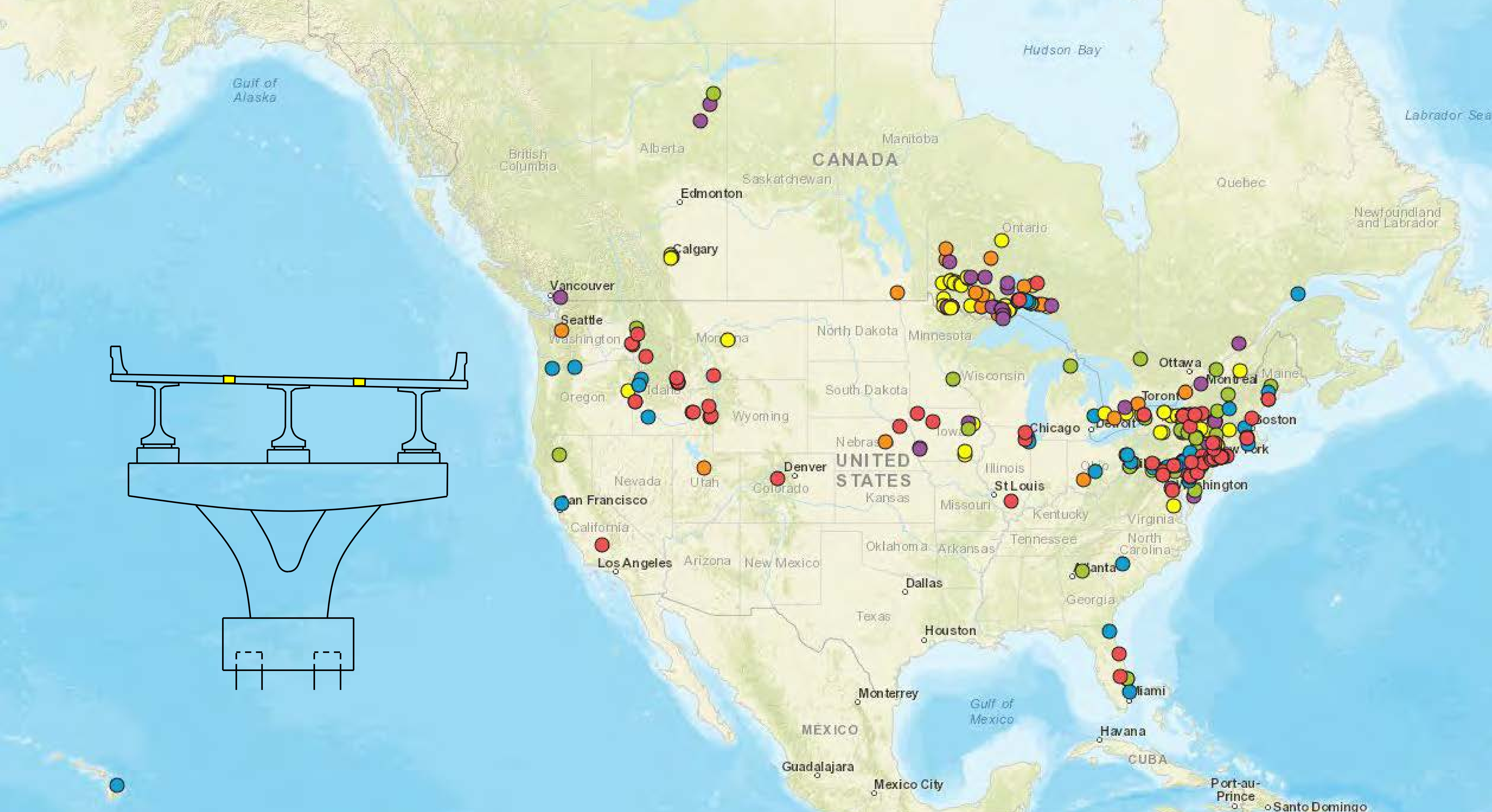


UHPC Box Beam

SCP STANDARD CONCRETE PRODUCTS

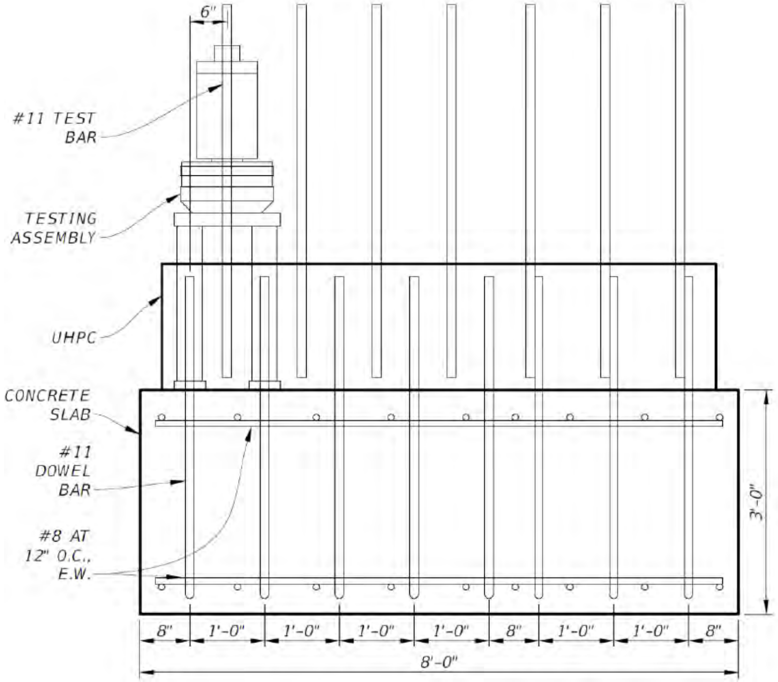
Connecting Foundation Components

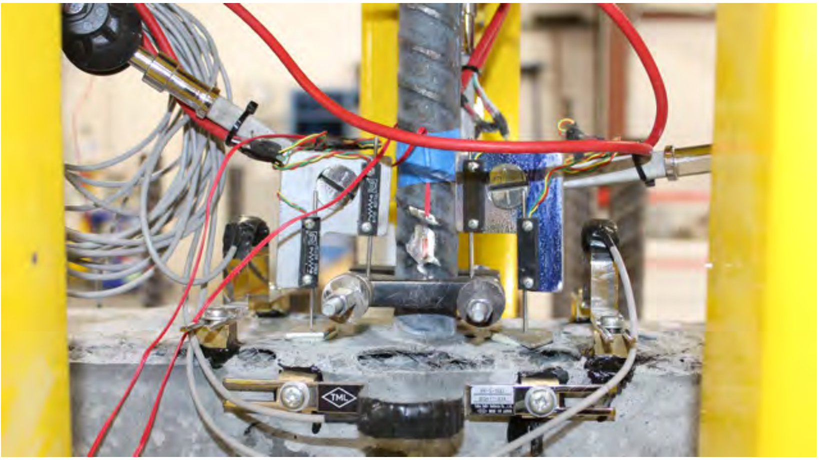


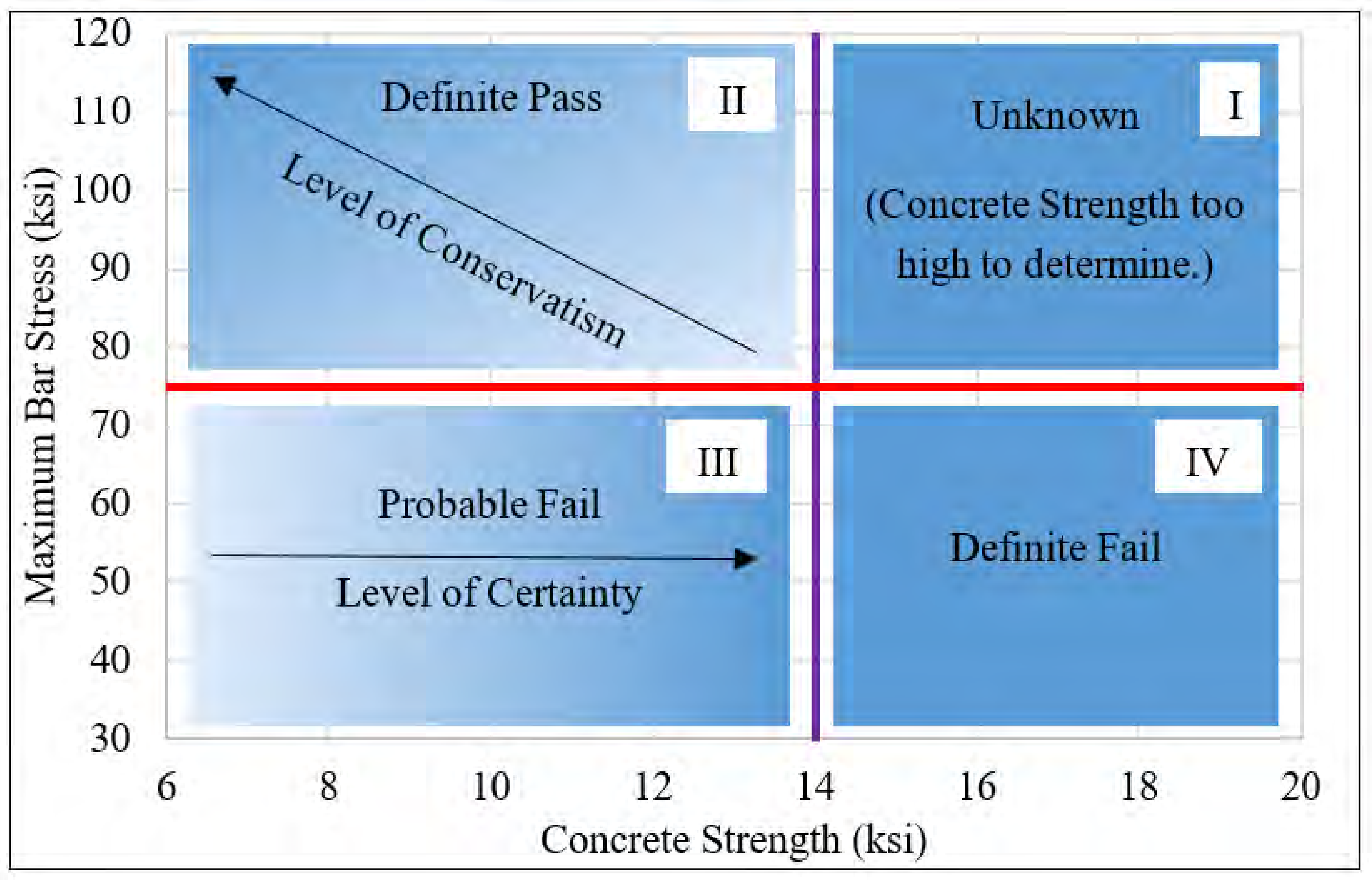


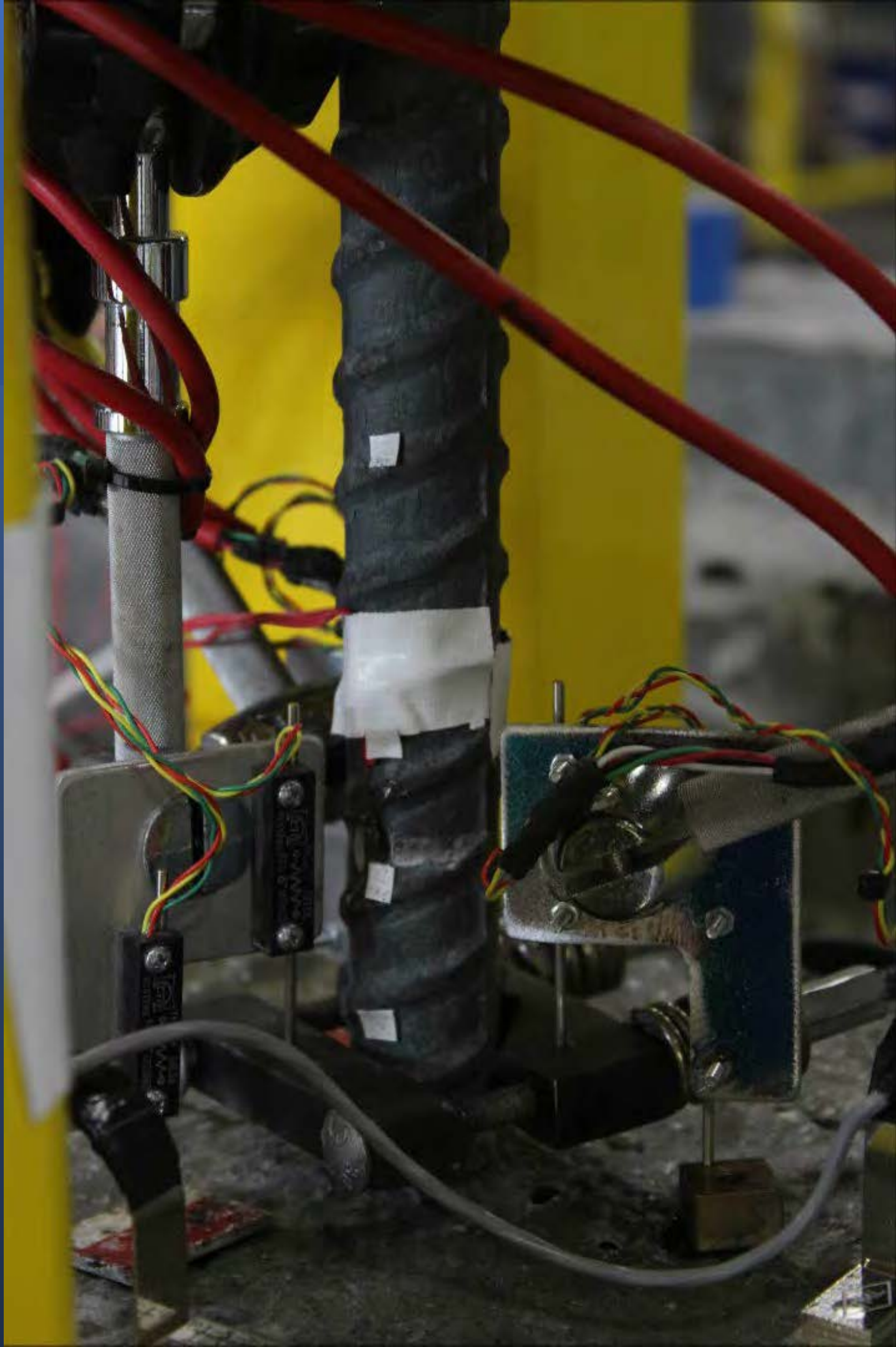
Source: www.fhwa.dot.gov

Large Reinforcing Bars Spliced in UHPC





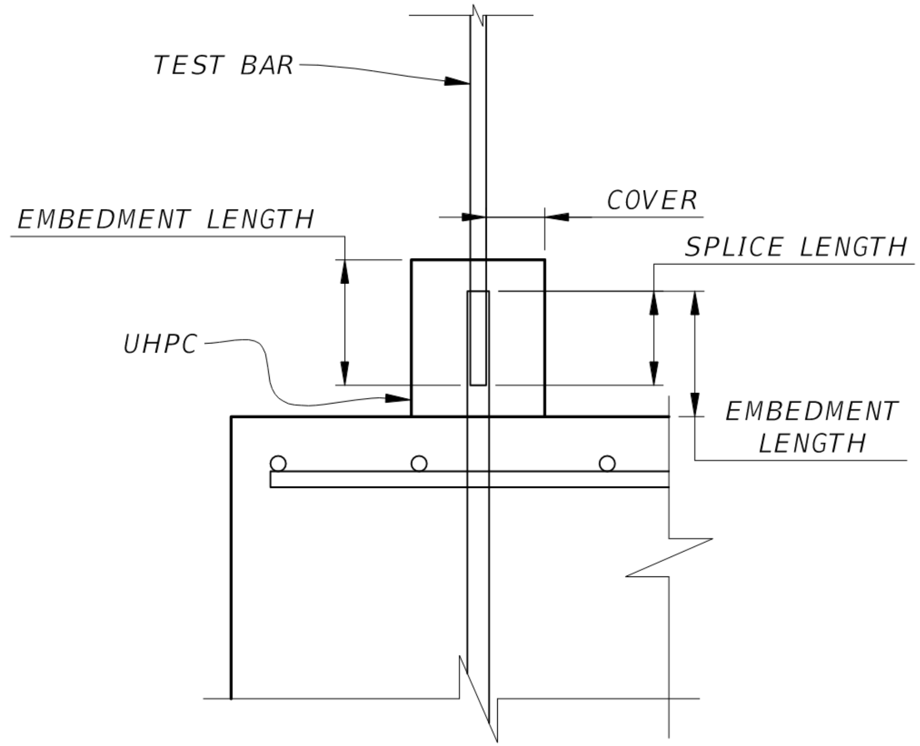

120
110
100
90
80
70
60
50
40
30
Maximum Bar Stress (ksi)
6
8
10
12
14
16
18
20
Concrete Strength (ksi)
Definite Pass
II
Level of Conservatism
Unknown
I
(Concrete Strength too high to determine.)
III
Probable Fail
Level of Certainty
IV
Definite Fail



Results

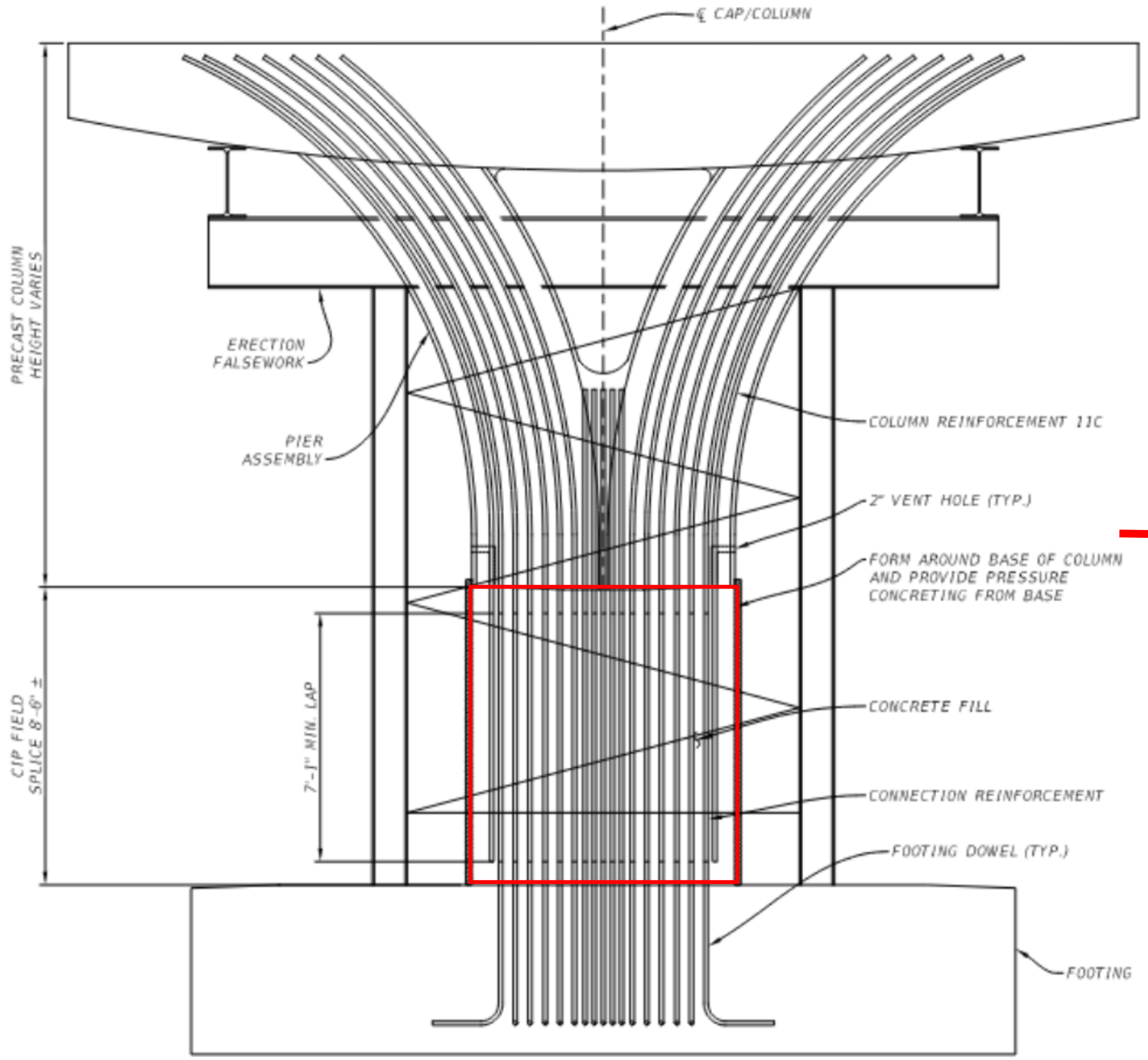
Required Embedment Length (M, D) in Inches					
		Bar Size			
		No. 8 (Per FHWA)	No. 9	No. 10	No. 11
Cover	1.75 inch	8	11	15	18.25
	2.75 inch	-	-	-	16
	3.75 inch	8	9	11	13

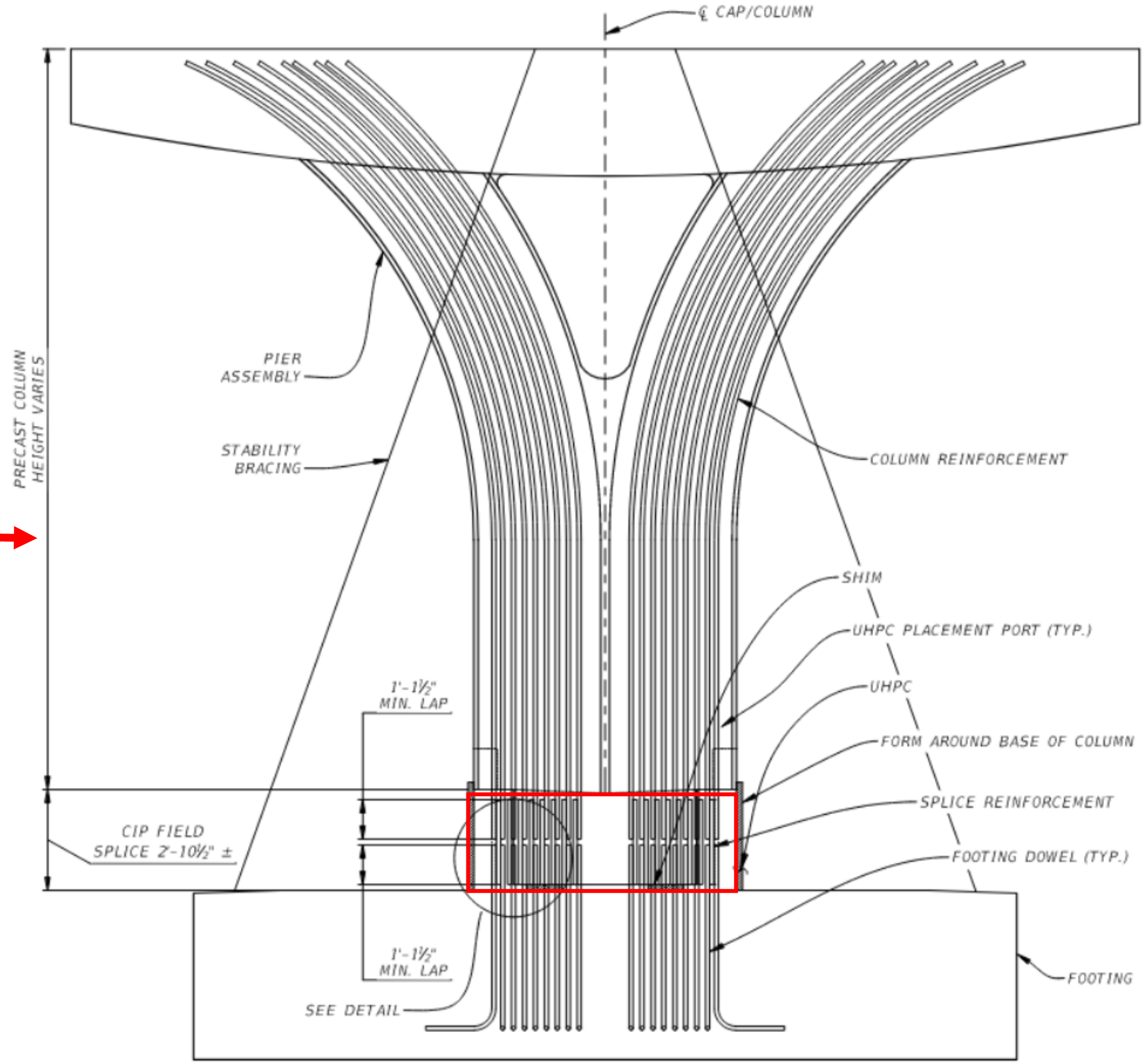
Required Splice Length (C) in Inches					
		Bar Size			
		No. 8 (Per FHWA)	No. 9	No. 10	No. 11
Cover	1.75 inch	6	8.5	12.5	15.75
	2.75 inch	-	-	-	13.5
	3.75 inch	6	6.75	8.5	10.5



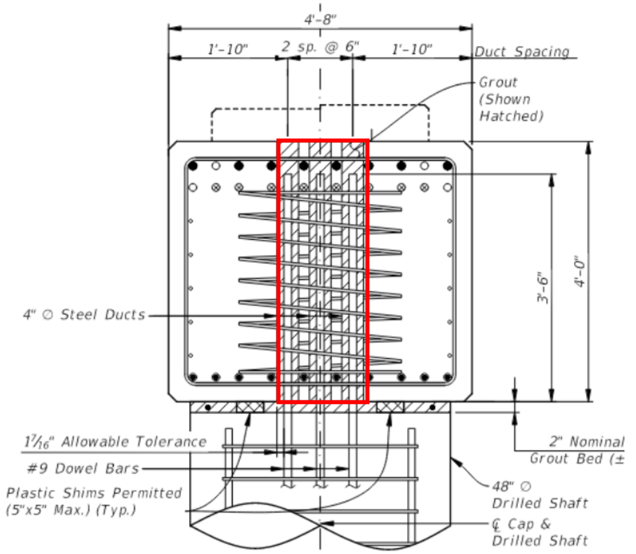
https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/structures/structuresresearchcenter/final-reports/2023/large-reinforcing-bars-spliced-in-uhpc.pdf

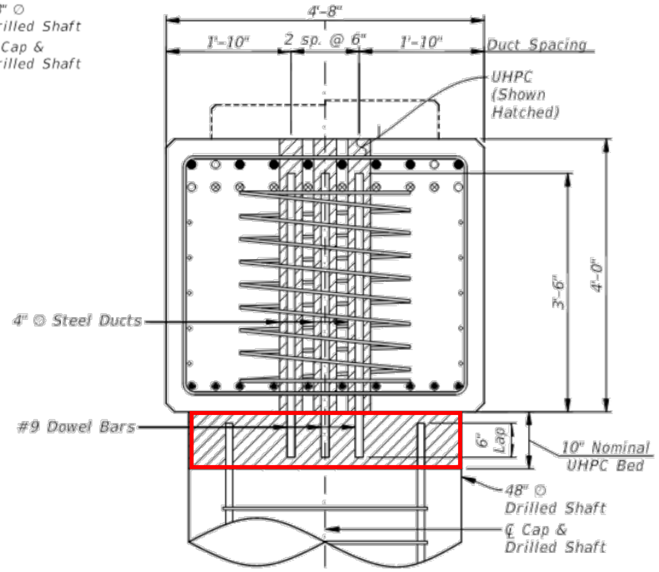
Large Reinforcing Bars Spliced in UHPC: Application

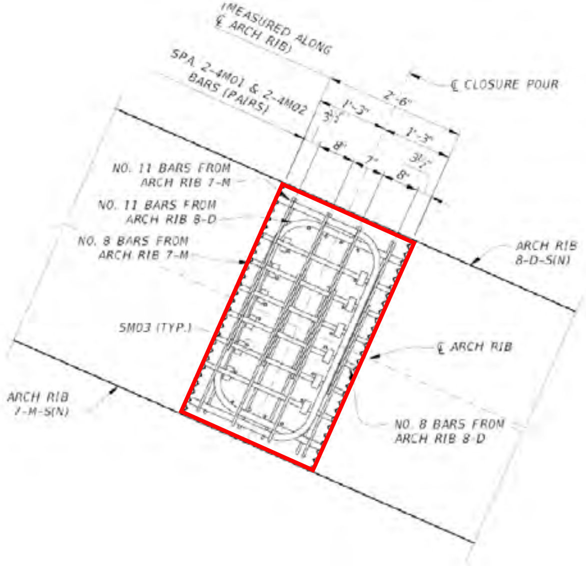


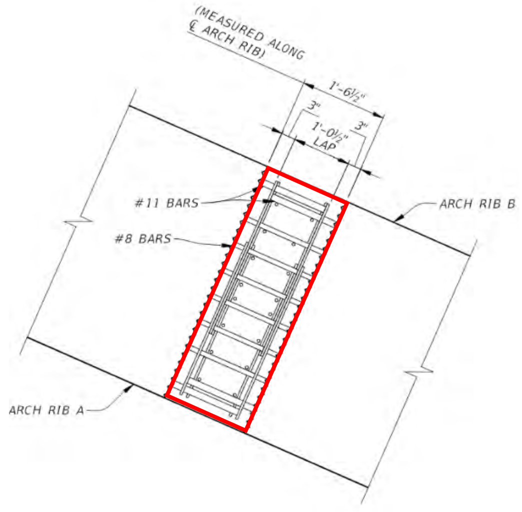


Large Reinforcing Bars Spliced in UHPC: Application

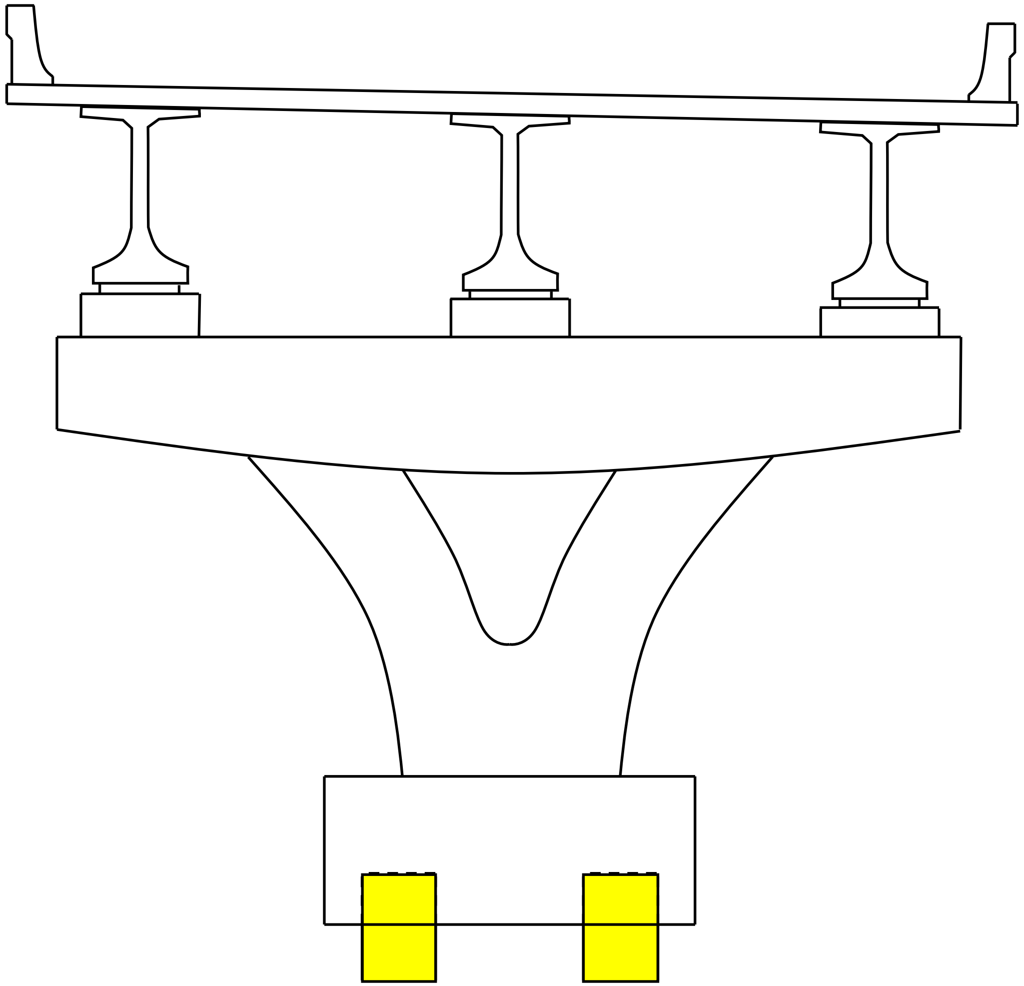








UHPC Piles



SCP STANDARD CONCRETE PRODUCTS

DURA-STRESS Inc.

UHPC Piles: Structural Testing

UHPC Piles: Driving Demonstration

DURA-STRESS
Inc.

Upcoming Research

- Bond Performance Between Precast UHPC Substrates and Field Cast UHPC Connections
- Acceptable Crack Width Limit for UHPC Structural Members Under Coastal and Marine Environment
- Assessment and Optimization of the Casting Procedure for Precast UHPC
- Evaluation of Ultra-High Performance Concrete (UHPC) Pile Splices

Questions?

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www.fdot.gov/structures

Recent Advancements for the use of Ultra-High Performance Concrete in Infrastructure Applications

Presented by:

Andrew Foden, PhD, PE

HNTB

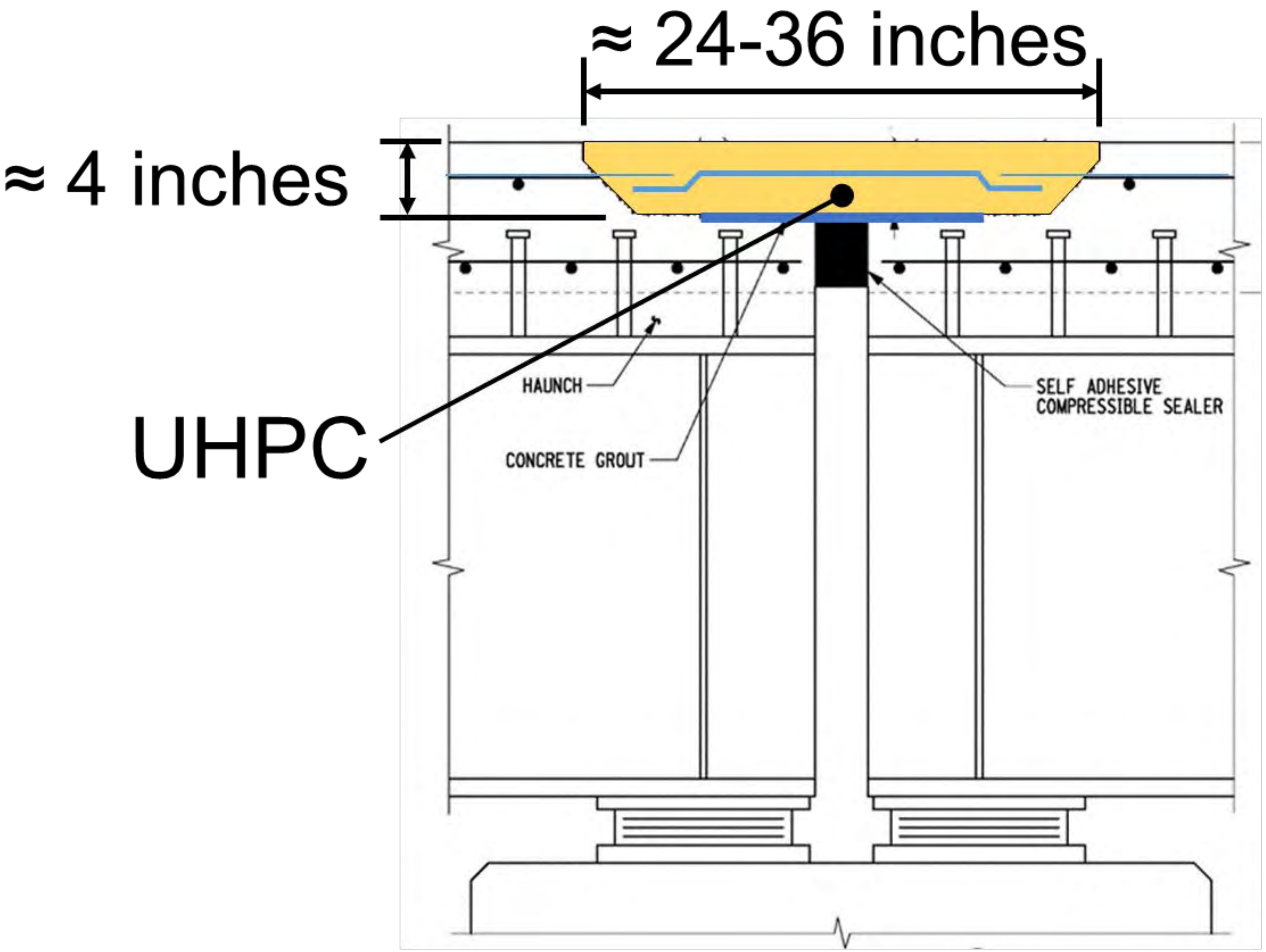
TRB Webinar
October 18, 2023

What can we do with UHPC for bridge preservation and repair?

- Connection Repairs
- Seismic Retrofit
- Column Repairs
- Concrete Patching
- Shotcrete
- Headers
- **Steel Girder Strengthening and Repair**
- **Bridge Deck Overlays**
- **Link Slabs**

Can UHPC fix this?

Yes, it can!



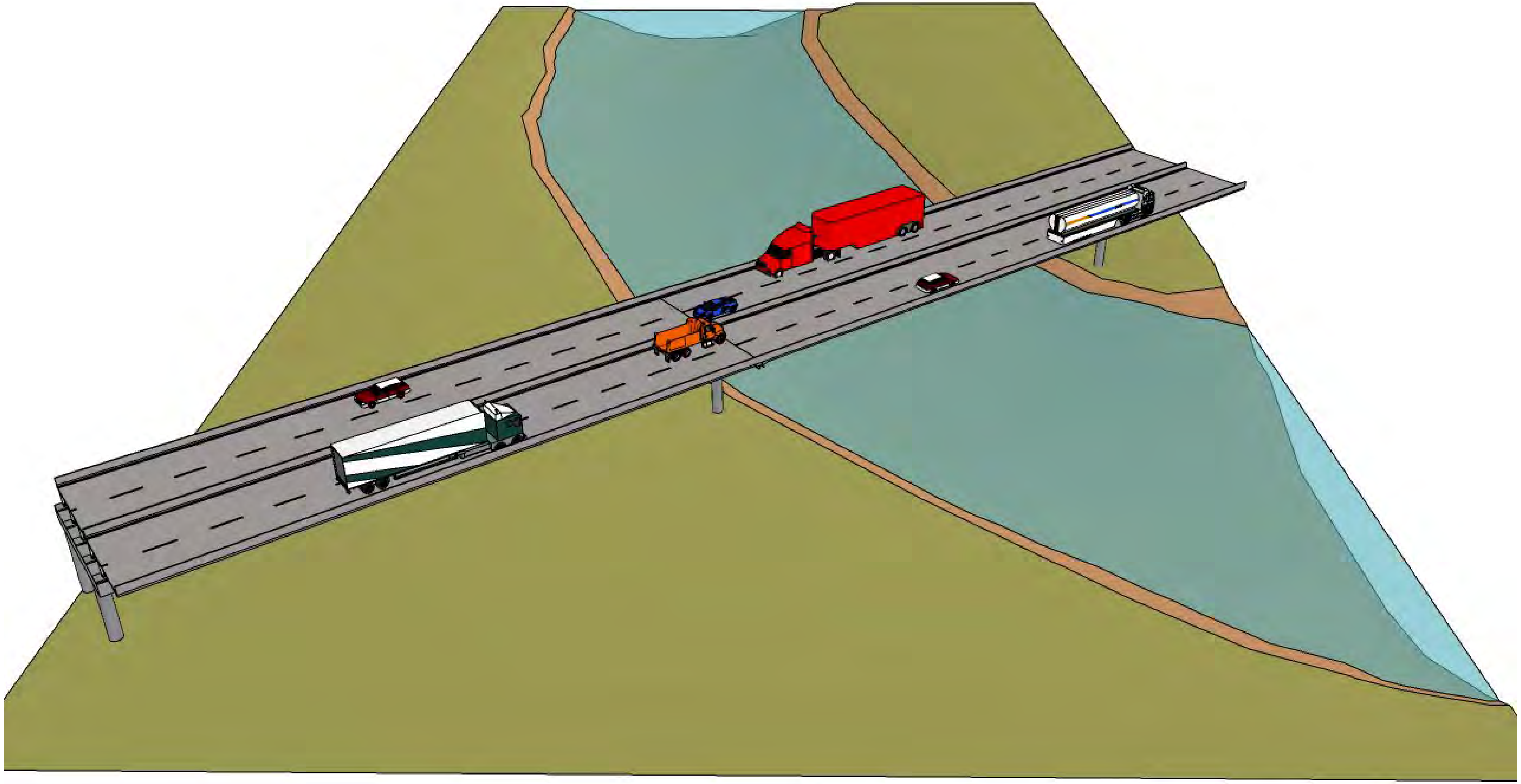
UHPC Link Slab Detail

Source: NYSDOT

OK, but can UHPC fix this?

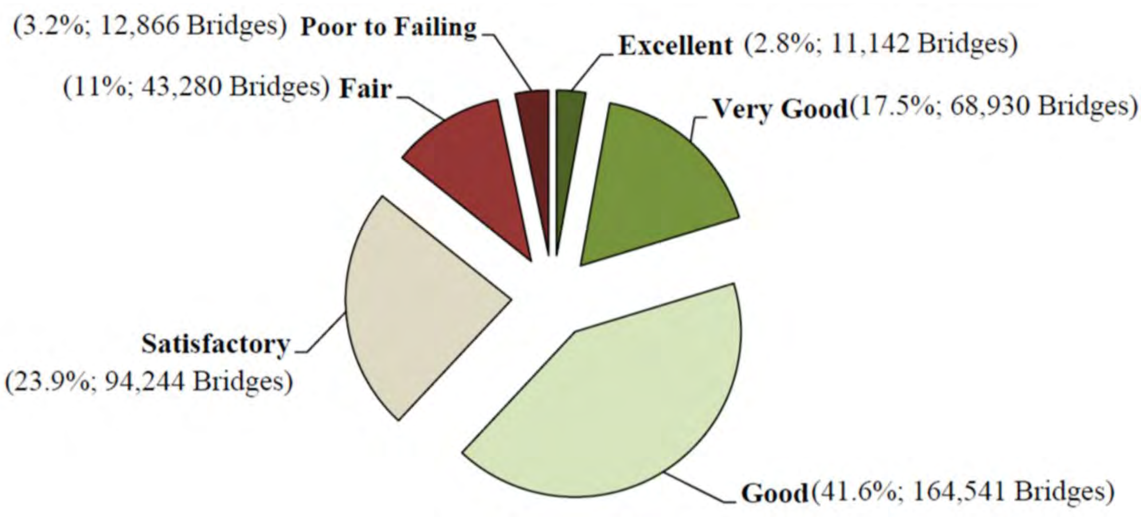
Credit: A. Zaghi, University of Connecticut

Yes, it can!



© Arash Zaghi, University of Connecticut

Can UHPC Fix this?



Of course, it can!

How do you keep UHPC from flowing to the gutter line?

Source: FHWA

Is there guidance for preservation and repair applications?

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

- FHWA-HRT-22-065
- Background on UHPC
- Design Guidance for:
  - Bridge Deck Overlays
  - Link Slabs
  - Steel Girder End Repair
- Construction Inspection
- Deployments
- Emerging applications

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

PUBLICATION NO. FHWA-HRT-22-065

MAY 2022

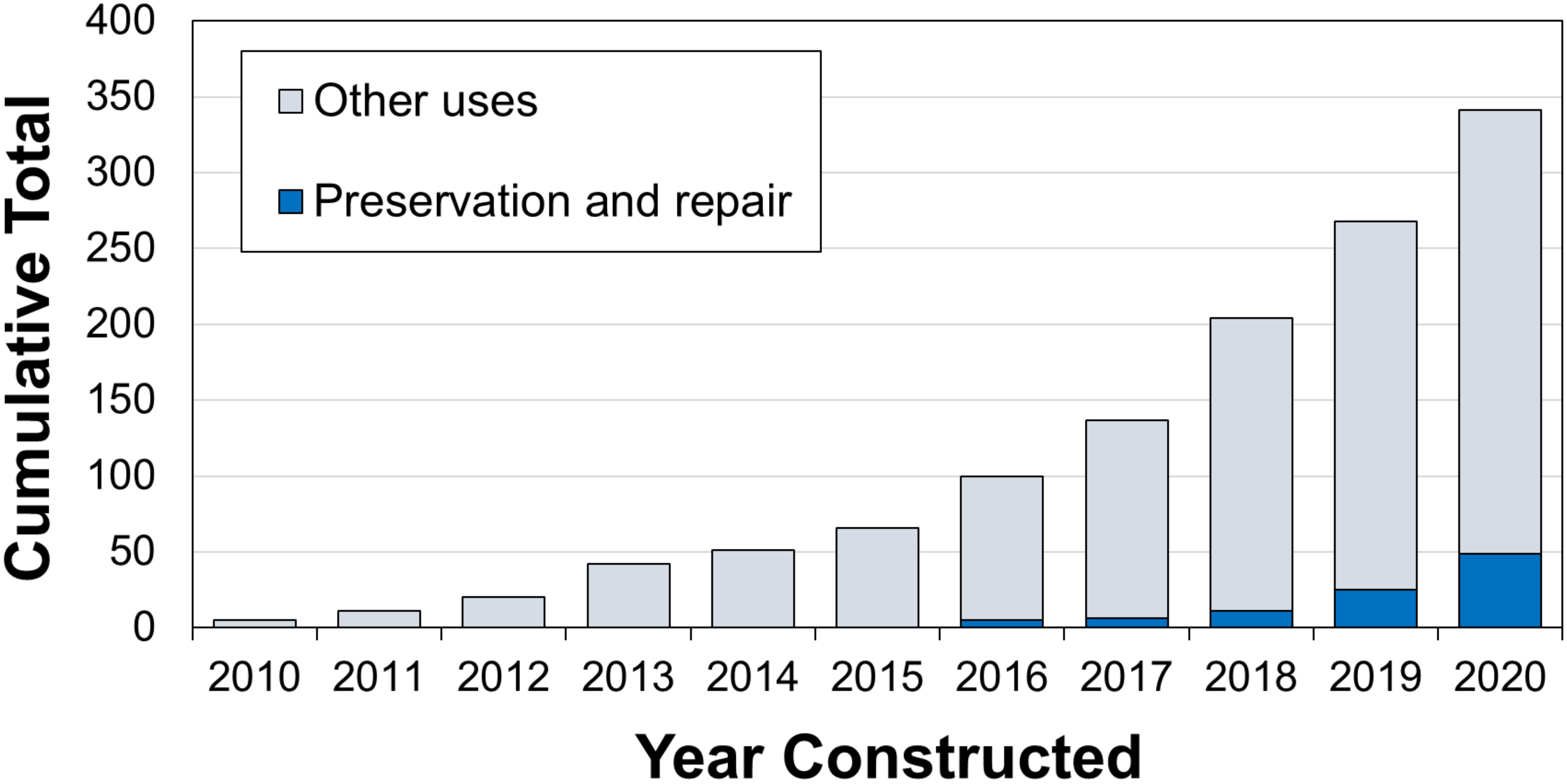
Source: FHWA

But isn't UHPC expensive?

Material	Approximate Cost per yd^3
Portland Cement Grouts	$1,000 to $2,000
Repair Mortars	$1,500 to $3,000
Epoxy Grouts	$4000 to $5,000
Commercial UHPC	$2,500 to $3,500
Open-Source UHPC*	$1,000 to 1,200

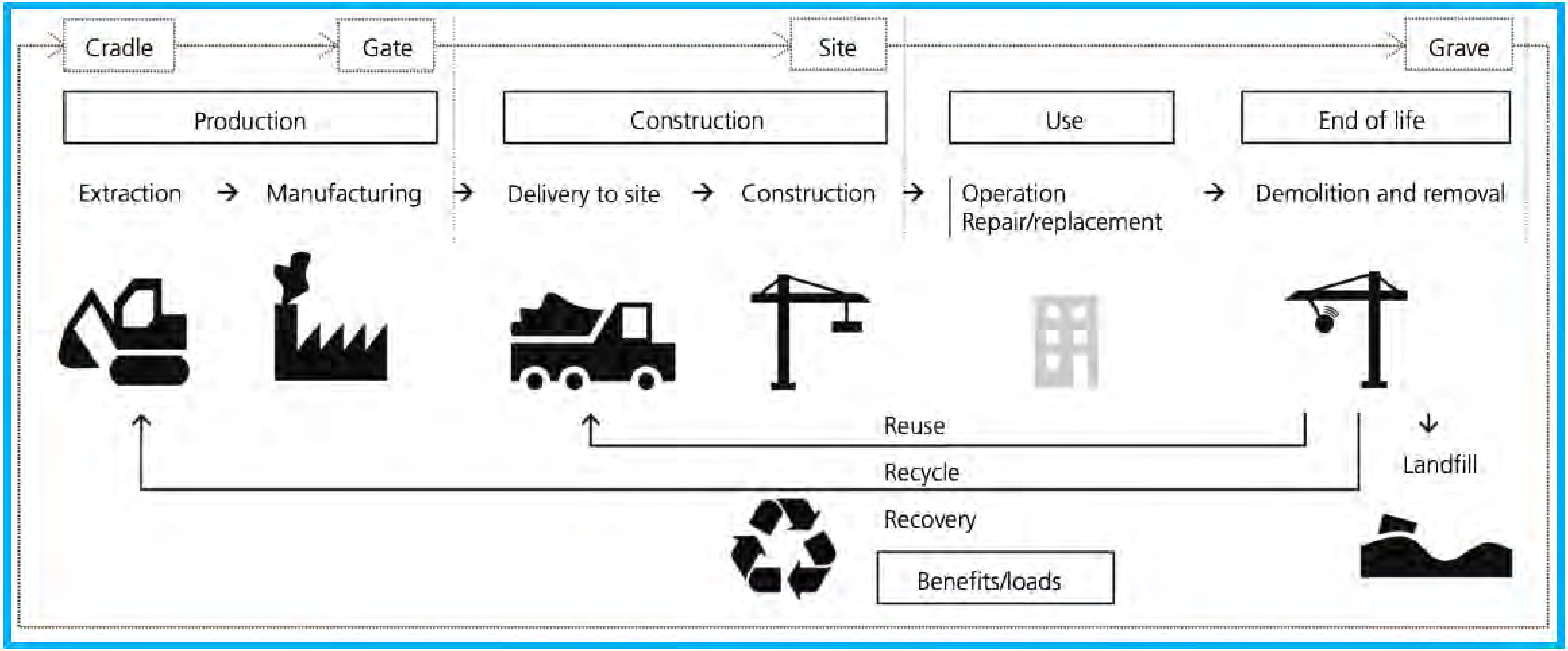
*Additional costs required for research and development (R&D), blending, packaging, and quality assurance/quality control.

Are people using this stuff?



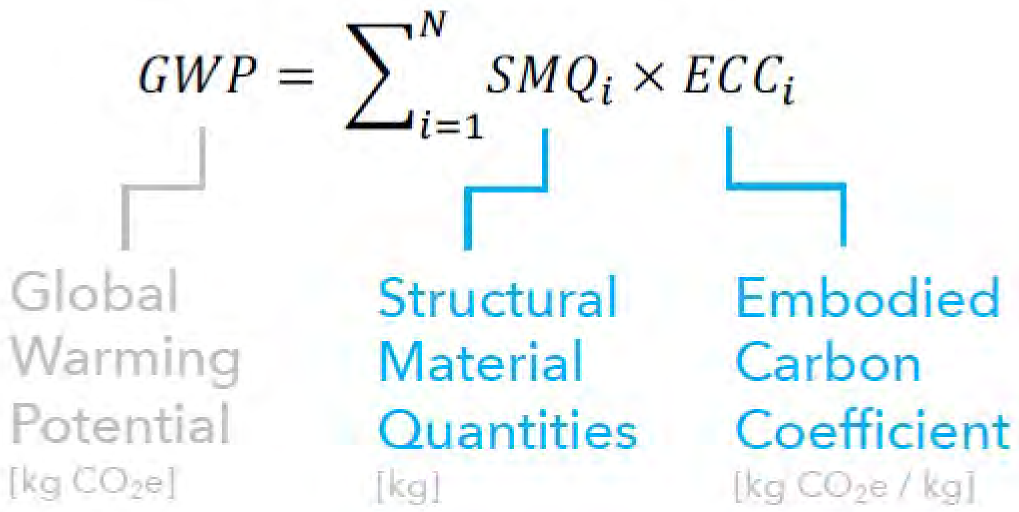
But is it sustainable?

But is it sustainable?



But is it sustainable?

How do we quantify embodied carbon in structural systems?



$$GWP = \sum_{i=1}^{N} SMQ_i \times ECC_i$$

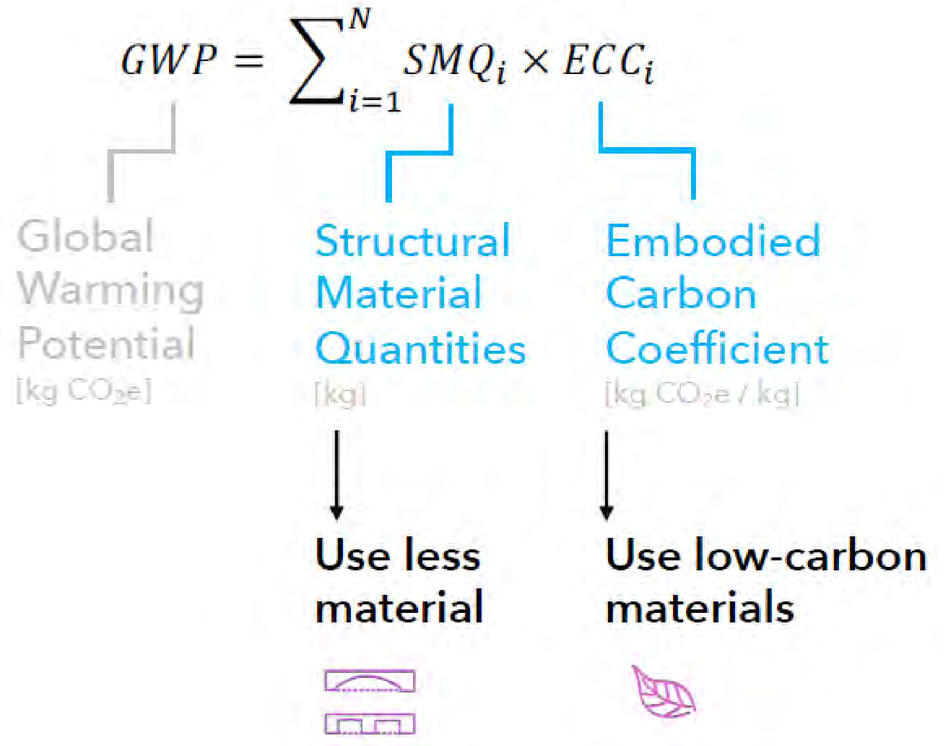
Global Warming Potential [kg CO_2e]

Structural Material Quantities [kg]

Embodied Carbon Coefficient [kg CO_2e / kg]

But is it sustainable?

How do we reduce embodied carbon in structural systems?



$$GWP = \sum_{i=1}^{N} SMQ_i \times ECC_i$$

Global Warming Potential [kg CO_2e]

Structural Material Quantities [kg]

Embodied Carbon Coefficient [kg CO_2e / kg]

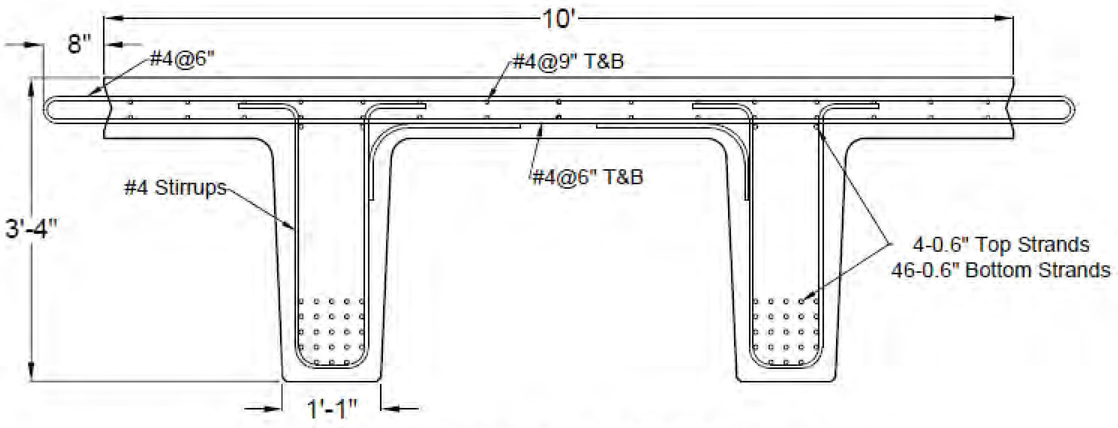
Use less material

Use low-carbon materials

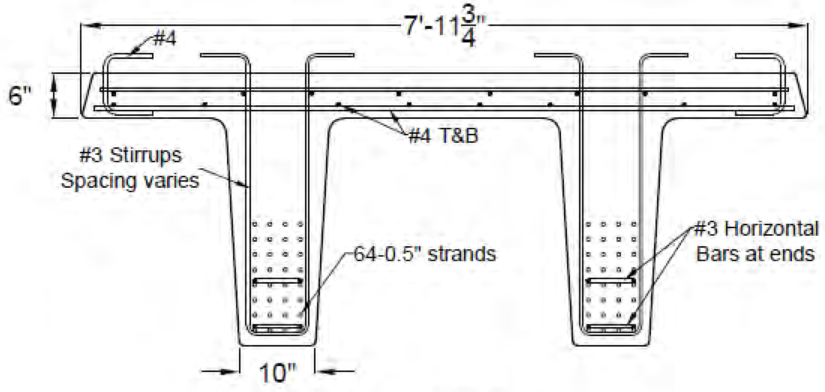
But is it sustainable?

- Reduced Material Consumption
  - UHPC offers remarkable design flexibility, allowing for innovative and efficient structural solutions.
  - Compared to conventional concrete, UHPC requires smaller cross-sectional dimensions, resulting in decreased raw material extraction, transportation, and energy consumption during construction.
- Extended Service Life
  - The exceptional durability of UHPC contributes to longer service life for structures, reducing the need for frequent repairs and replacements.
- Lower Carbon Footprint
  - Although UHPC typically has higher embodied carbon per unit volume, by optimizing the design and extending the service life sustainability benefits can be shown to outweigh this initial impact.

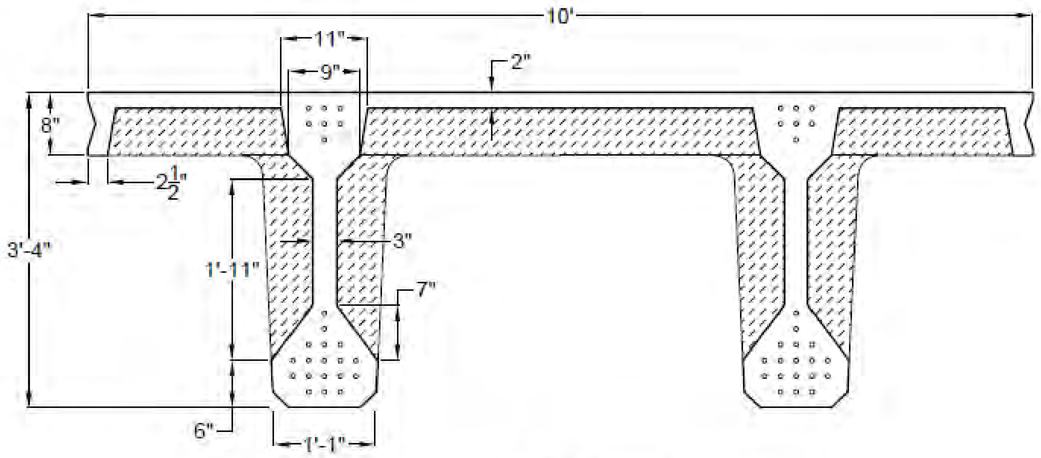
But is it sustainable?



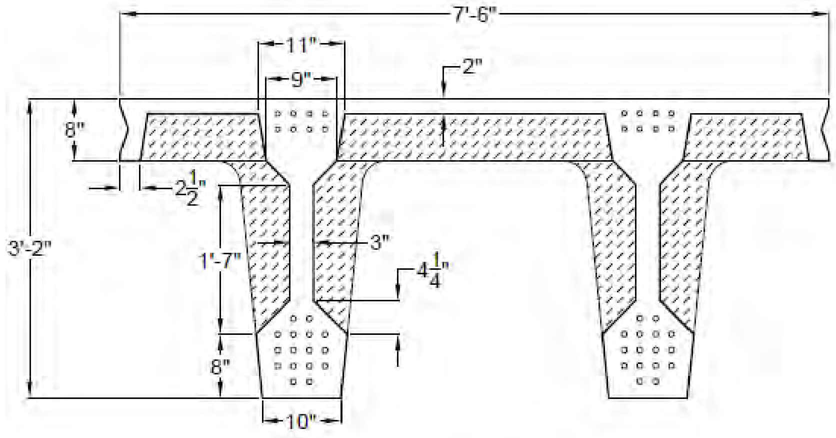
(a) Northeast NEXT D Section



(b) Texas DT Section



(a) Optimized NEXT D Beam



(b) Optimized Texas DT Beam

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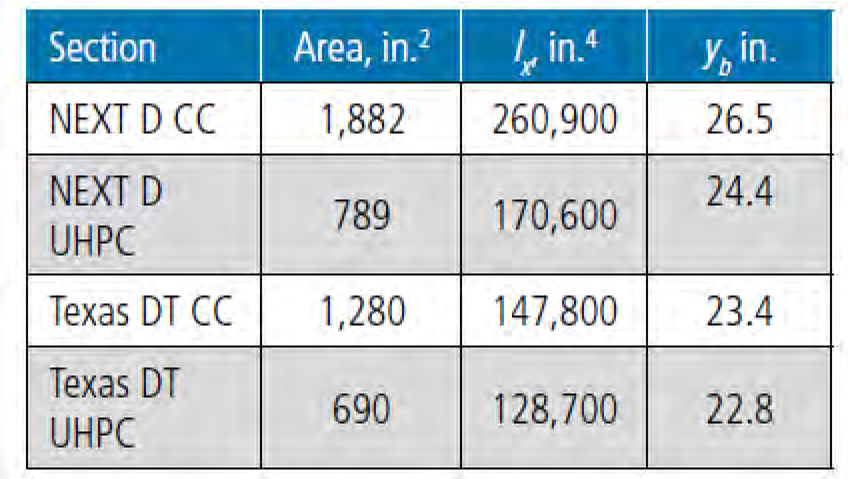
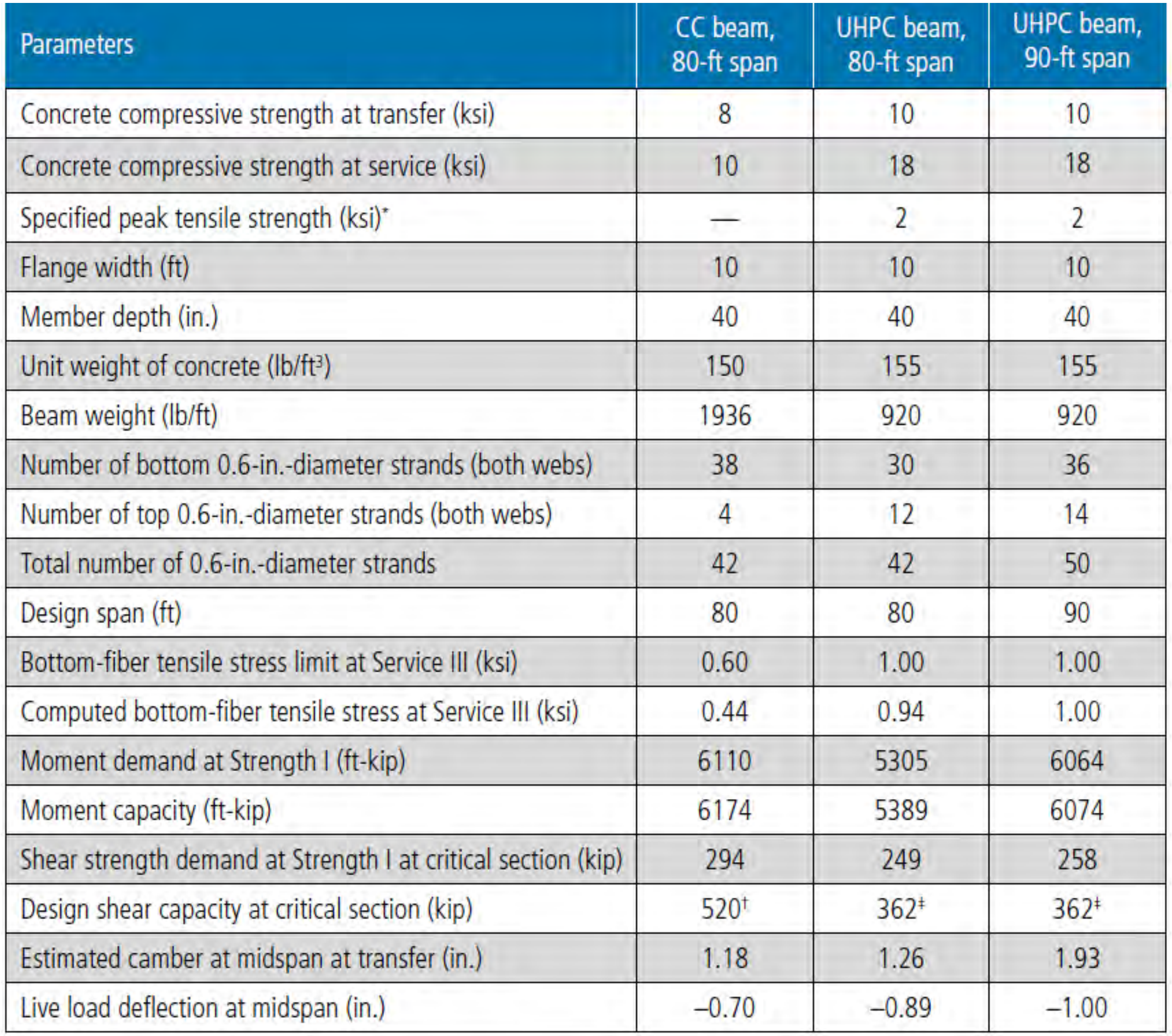
But is it sustainable?



Section	Area, in.^{2}	I_x, in.^{4}	y_b, in.
NEXT D CC	1,882	260,900	26.5
NEXT D UHPC	789	170,600	24.4
Texas DT CC	1,280	147,800	23.4
Texas DT UHPC	690	128,700	22.8



Parameters	CC beam, 80-ft span	UHPC beam, 80-ft span	UHPC beam, 90-ft span
Concrete compressive strength at transfer (ksi)	8	10	10
Concrete compressive strength at service (ksi)	10	18	18
Specified peak tensile strength (ksi)[*]	—	2	2
Flange width (ft)	10	10	10
Member depth (in.)	40	40	40
Unit weight of concrete (lb/ft^3)	150	155	155
Beam weight (lb/ft)	1936	920	920
Number of bottom 0.6-in.-diameter strands (both webs)	38	30	36
Number of top 0.6-in.-diameter strands (both webs)	4	12	14
Total number of 0.6-in.-diameter strands	42	42	50
Design span (ft)	80	80	90
Bottom-fiber tensile stress limit at Service III (ksi)	0.60	1.00	1.00
Computed bottom-fiber tensile stress at Service III (ksi)	0.44	0.94	1.00
Moment demand at Strength I (ft-kip)	6110	5305	6064
Moment capacity (ft-kip)	6174	5389	6074
Shear strength demand at Strength I at critical section (kip)	294	249	258
Design shear capacity at critical section (kip)	520[†]	362[‡]	362[‡]
Estimated camber at midspan at transfer (in.)	1.18	1.26	1.93
Live load deflection at midspan (in.)	–0.70	–0.89	–1.00

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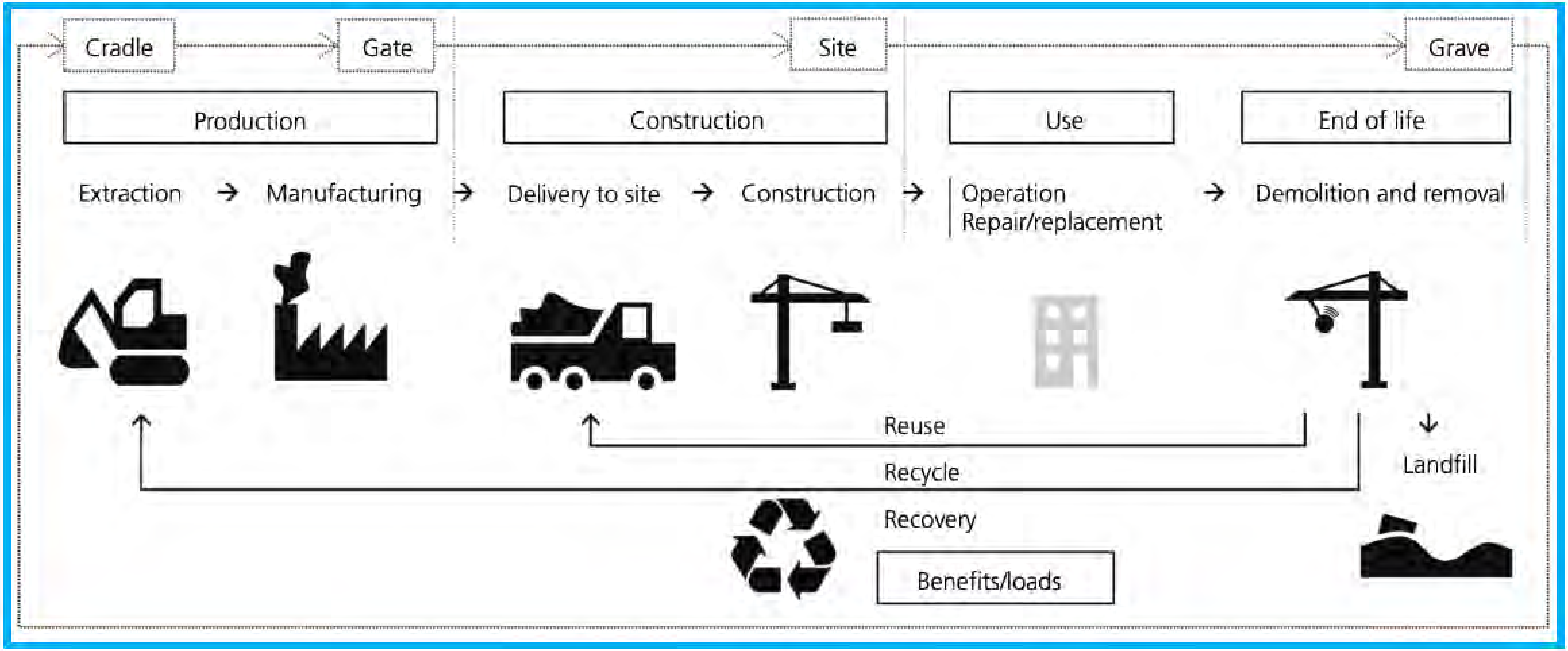
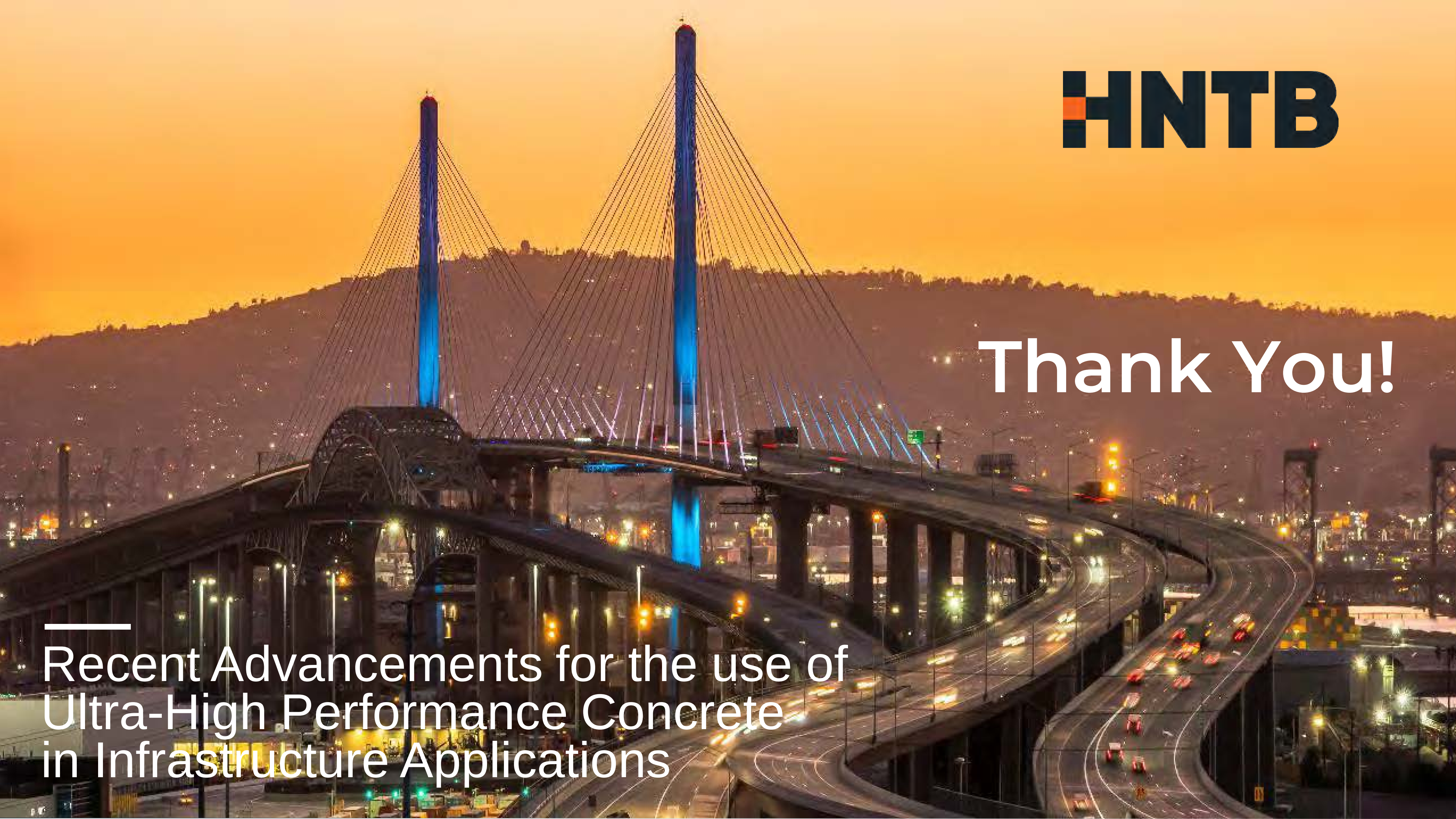
Bonus, it also costs less!

- Cost of CC NEXT D
    - about $360/FT
- Cost of Corresponding UHPC Beam
    - About $280/LF

But is it sustainable?





Thank You!

Recent Advancements for the use of Ultra-High Performance Concrete in Infrastructure Applications