



Recent Advancements for the use of Ultra-High Performance Concrete as a Structural Material

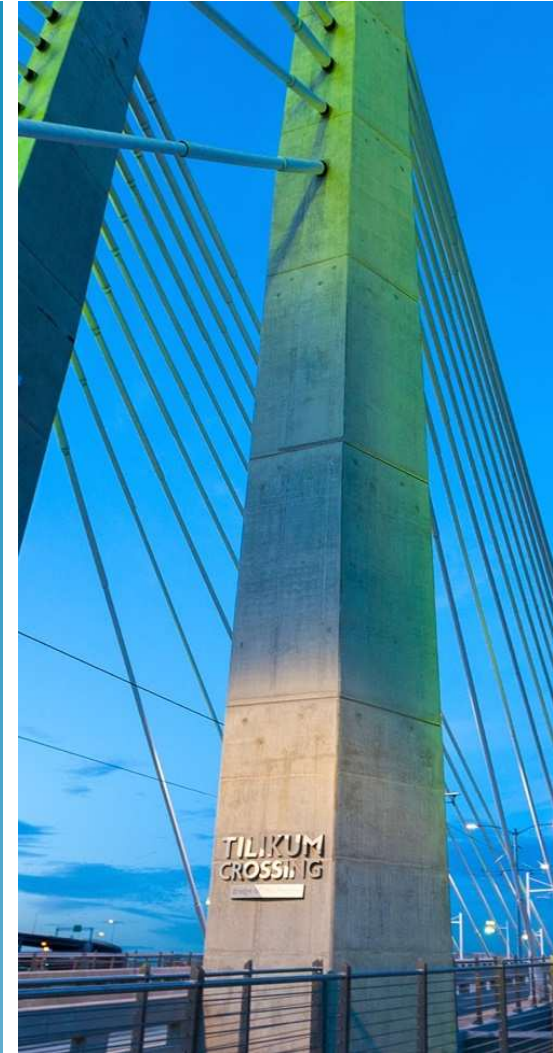
Presented by:

Andrew Foden, PhD, PE

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JCI-ACI Joint Seminar | July 17, 2025

What is UHPC?



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What is UHPC?

Cement-based composite material

- Self-consolidating
- Inherently ductile
- Highly durable

Composed of the following:

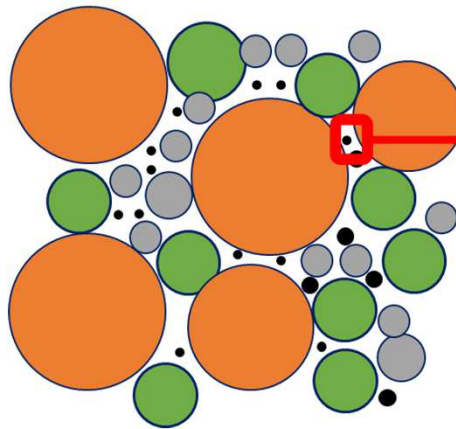
- Cementitious Materials
- Fine powders and sand
- Superplasticizers
- Steel fiber reinforcement
- Admixtures



What is UHPC?

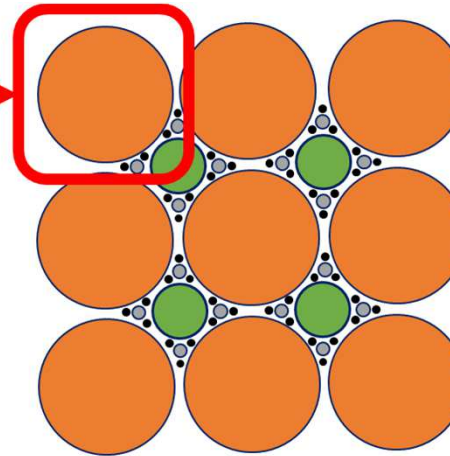
Conventional Concrete

All images Source: FHWA



- Aggregate (1/4 to 3/4 inch)
- Sand
- Cement

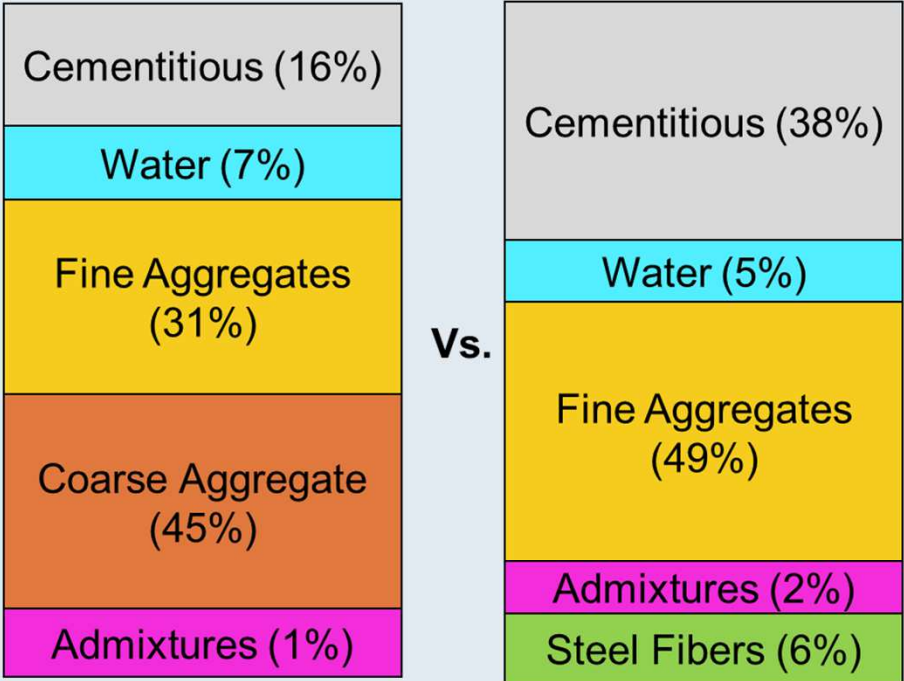
UHPC



- Sand (500 microns)
- Cement
- Quartz
- Silica Fume (1 micron)

How does UHPC compare to conventional concrete?

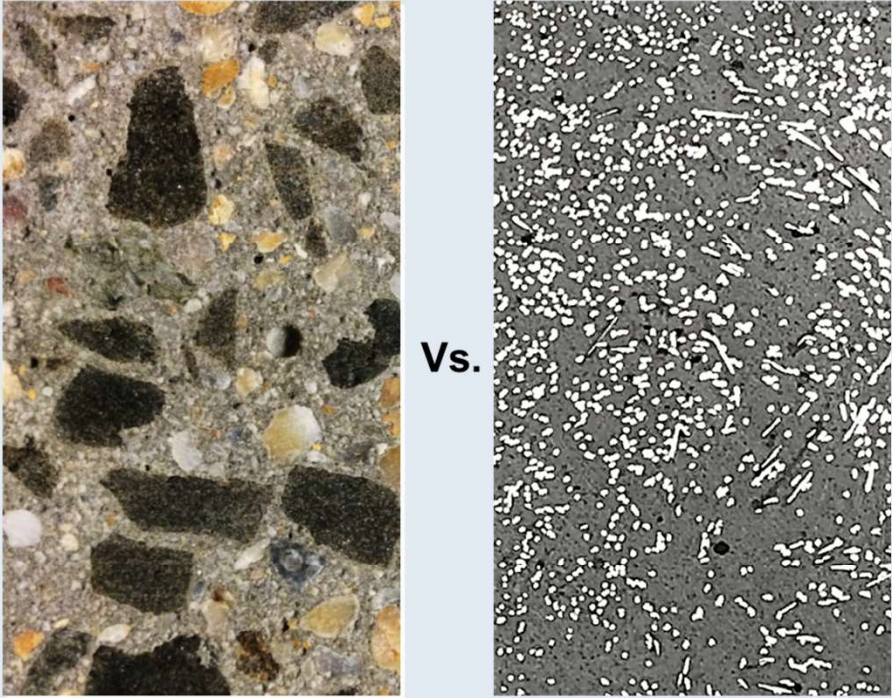
Mass Fraction



Concrete

UHPC

Composition

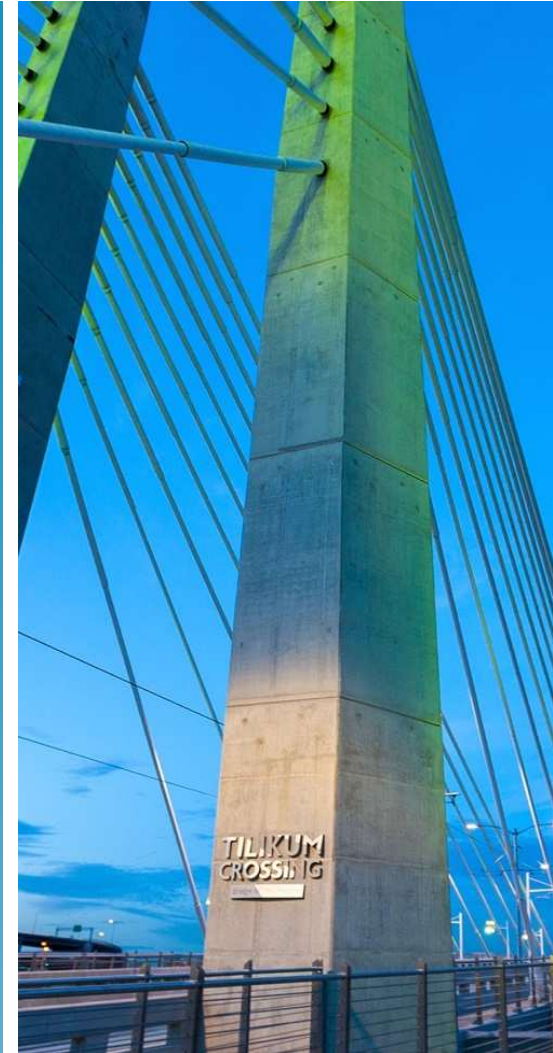


Concrete

UHPC

All images Source: FHWA

*Why should we use
UHPC?*

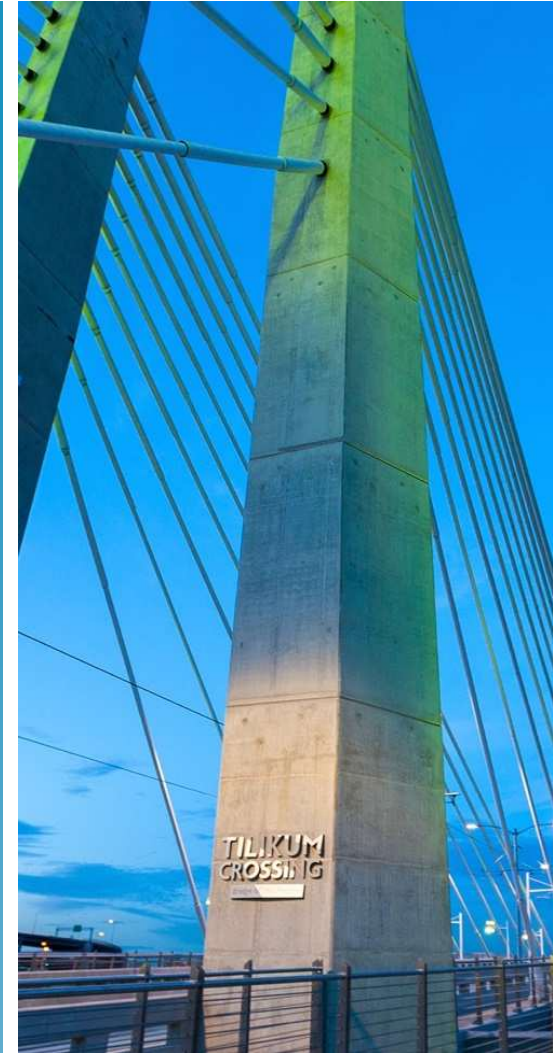


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Why should we use UHPC?

Property	UHPC	Concrete
Compressive Strength (Mature)	18 – 24 ksi	4 – 12 ksi
Direct tension Strength	0.7 – 2.0 ksi	0.0 – 0.5 ksi
Direct Tension Post-Cracking Strain Capacity	0.0025+	0.00
Elastic Modulus	6,500 ksi+	3,000 - 5,500 ksi
Bond Strength to Roughened Substrate Concrete	0.35 – 0.6 ksi	0.1 – 0.4 ksi
Long-Term Drying Shrinkage	300 – 1,200 microstrain	500 – 1,200 microstrain
Chloride Ion Permeability	50 – 500 Coulombs	1,500 to 2,500 Coulombs
Freeze-Thaw Resistance	RDM > 95%	RDM 75-80%

*Can we use it for
Primary Structural
Elements?*



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Why use UHPC Girders?

UHPC Prestressed Girders

Engineering benefits:

- Increased span length
- Decreased dead load
- Enhanced durability
- Reduced structural depth
- High possible slenderness

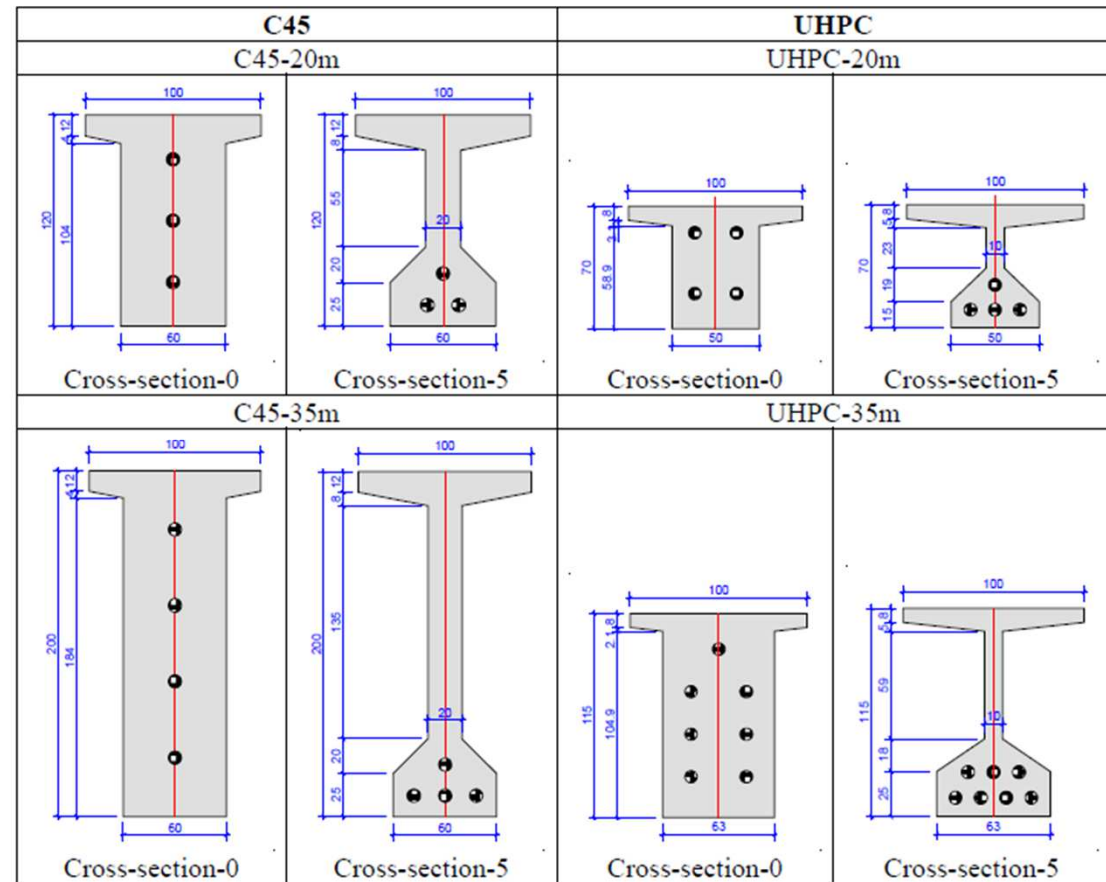
General benefits:

- Accelerated construction
- Lessened constriction at waterway crossings
- Reduced local environmental footprint.
- Lessened maintenance and disruption.



Why use UHPC girders?

- Elimination of passive flexural and shear reinforcements possible
- Volume and weight reduced by 48%
- Depth reduced by 58%
- Cost/Benefit Analysis
 - Initial cost for girders higher
 - Reduced maintenance costs
 - Reduced substructure costs
 - Reduced ROW impacts

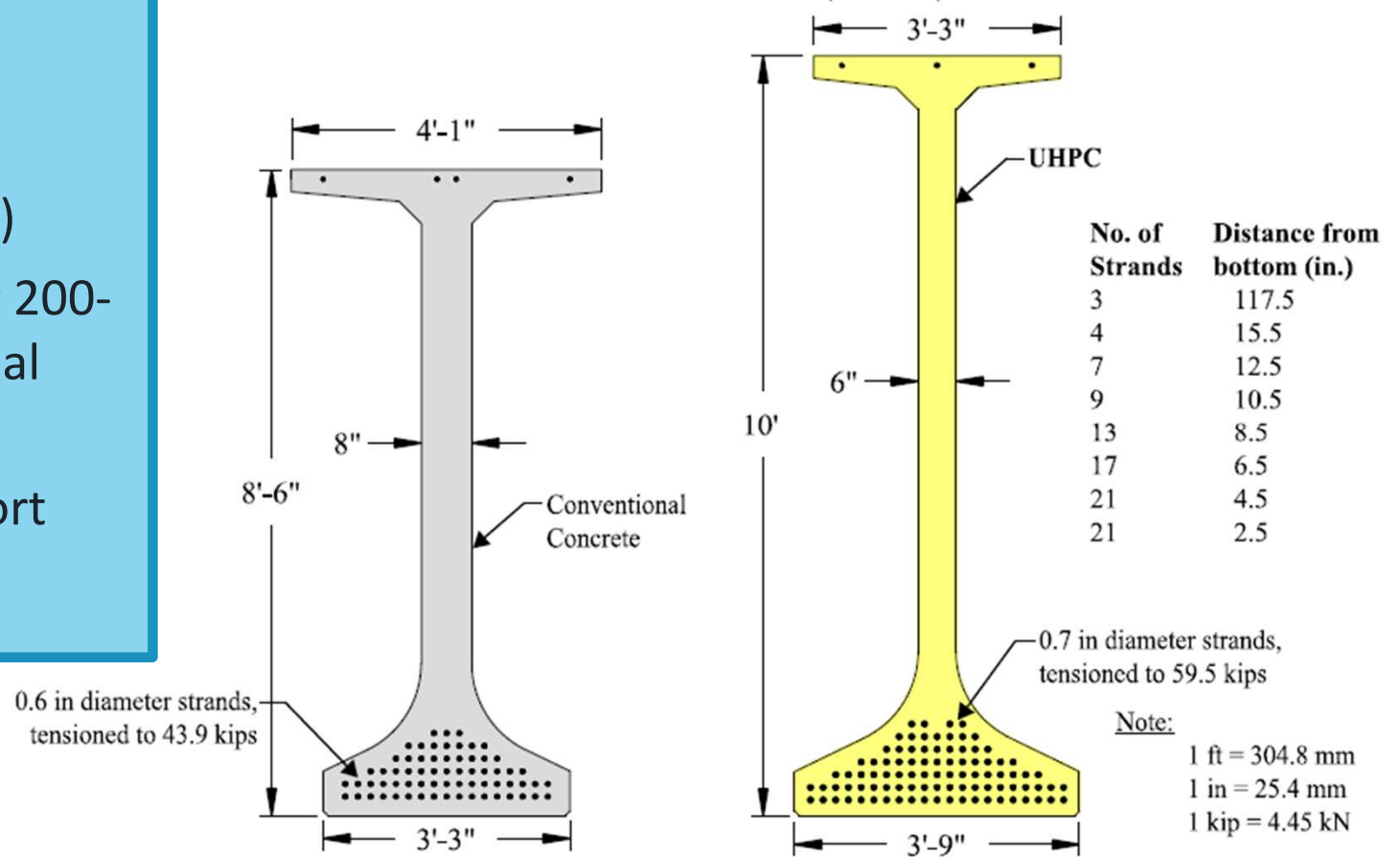


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How far can UHPC girders span?

Ultra Girder

- Research by FHWA
- 300-foot span (90 m)
- Modified an existing 200-ft (60 m) conventional concrete girder
- Challenge to transport



© El-Helou and Graybeal, 2022

Note:
 1 ft = 304.8 mm
 1 in = 25.4 mm
 1 kip = 4.45 kN

Have UHPC girders been used in the field?

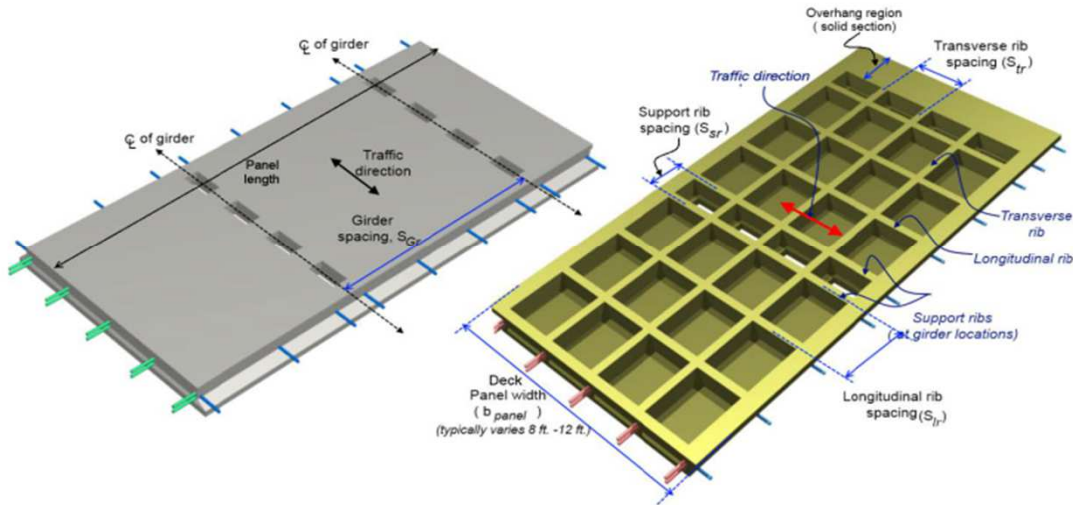


*What Type of Decks
Can We Make with
UHPC?*



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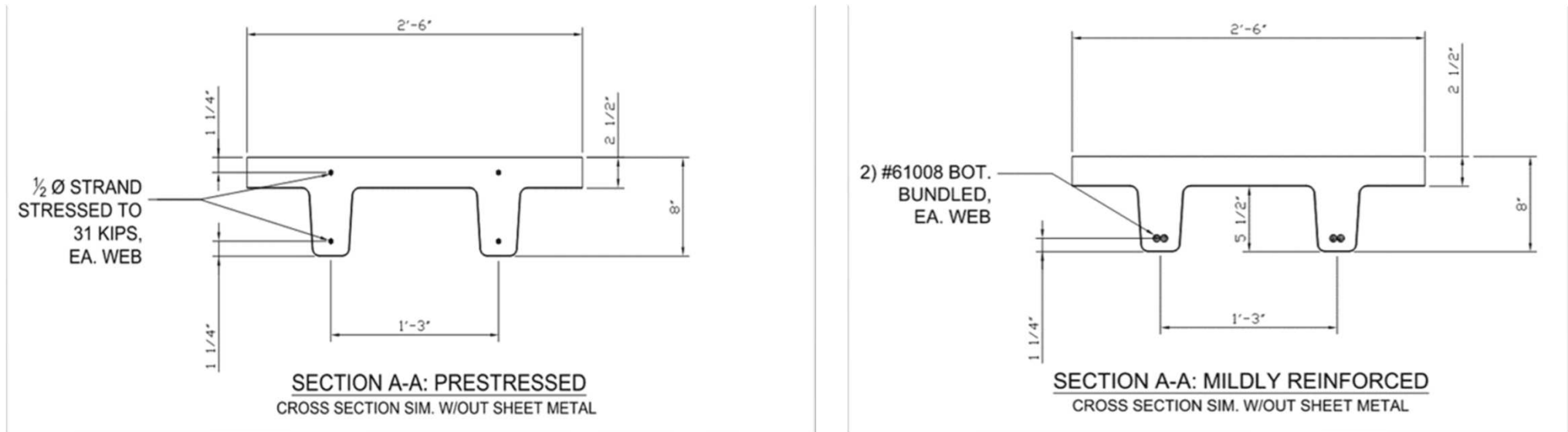
Why UHPC waffle deck?



- Utilize an innovative construction material to increase service life and decrease maintenance requirements/costs.
- Reduce DL on your superstructure and substructure! **Approximately 40% lighter than traditional decks.**
- Negative moment regions (if present) have reduced crack widths, can be considered composite due to strain hardening nature of UHPC material utilized.

Can we get rid of longitudinal ribs?

CORRUGATED UHPC DECK CROSS SECTION



Weight = < 50 psf

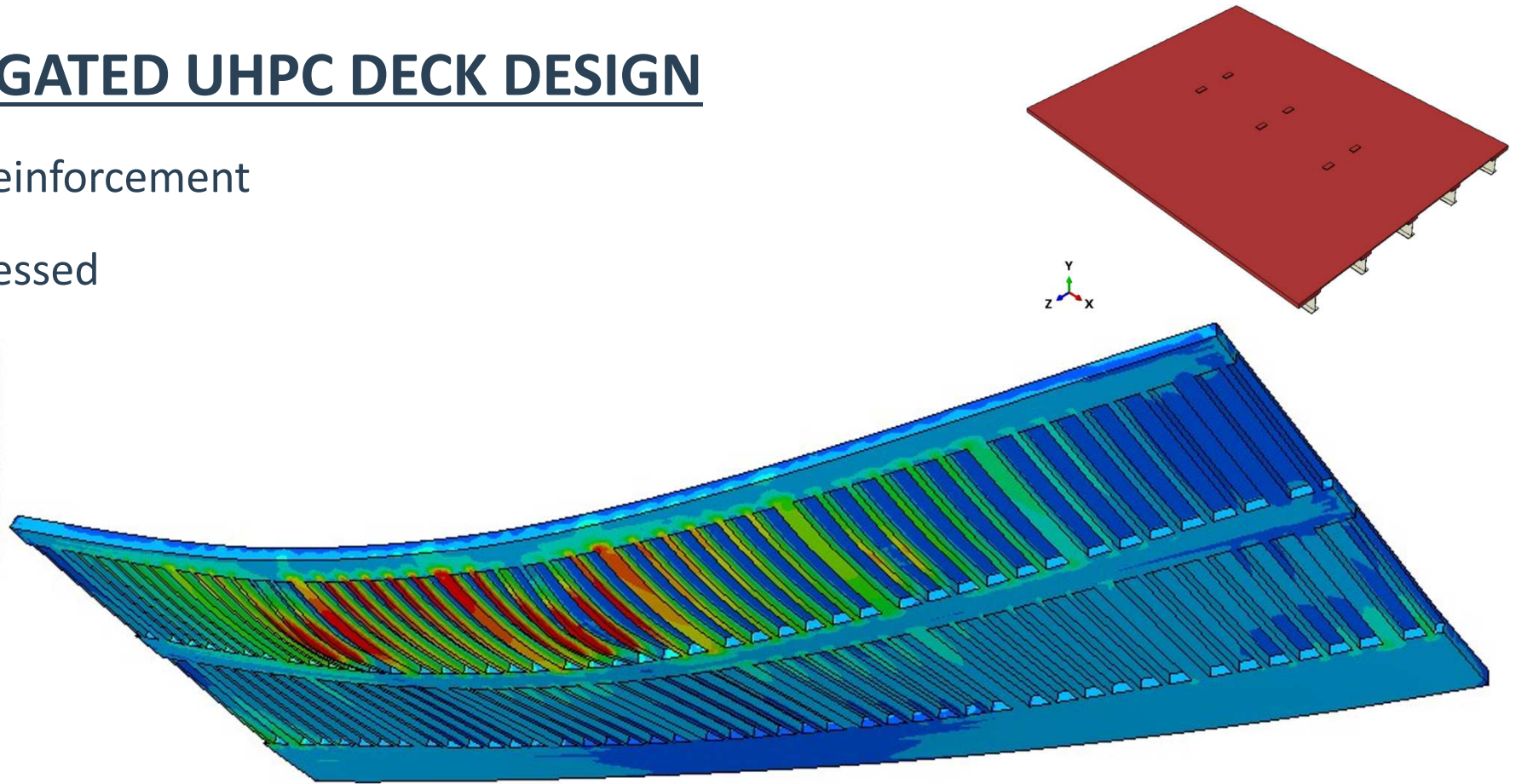
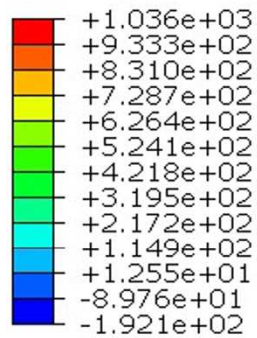
Spacing = 10 ft or less

Improved Stiffness can Reduce Girder Section

Can we get rid of longitudinal ribs?

CORRUGATED UHPC DECK DESIGN

- Mild reinforcement
- Prestressed



Max. Principal Stress (psi) – UHPC Deck, Service III

*What Guidance is
Available for UHPC
Structural Design?*

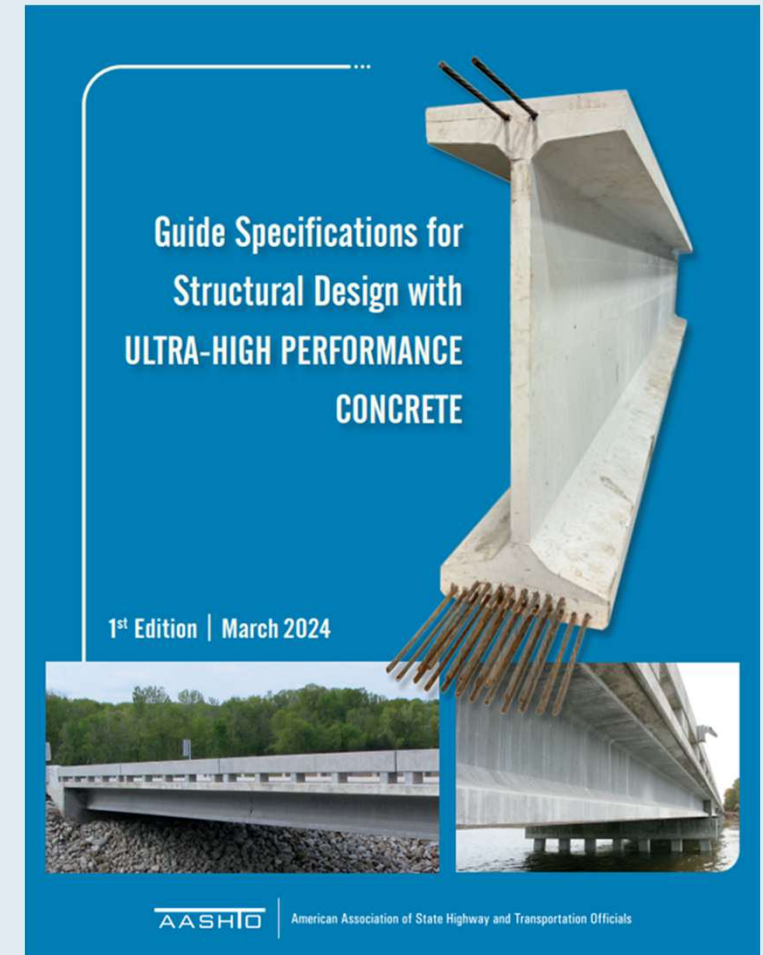


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What is the available design guidance for UHPC?

UHPC Design Guide Specification

- Is a stand-alone document.
- Counterparts section 5 of the AASHTO LRFD Bridge Specifications: “Concrete Structures”*
- Covers key aspects of structural design with UHPC
- FHWA developed the document in consultation with, and for consideration by, AASHTO CBS T-10
- AASHTO COBS balloted and passed an AASHTO guide specification document in May 2023



UHPC Structural Design Framework

- Incorporates UHPC mechanical properties into existing structural analysis methods using a familiar, AASHTO LRFD- based design framework*
- Is based on the physical behaviors of UHPC structural elements
- Is validated against data from experimental tests
- Is founded on work that is being published in peer-reviewed journals

Guide Specification for Structural Design with Ultra-High Performance Concrete TABLE OF CONTENTS

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*AASHTO. 2020. *LRFD Bridge Design Specifications, 9th edition*. Washington, DC: AASHTO.

What are the assumptions?

Conventional Concrete:

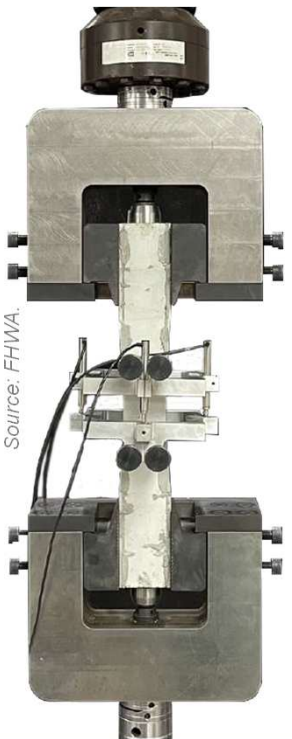
- Engineering mechanics is fundamental.
- Postcracking tensile resistance ignored.
- Creep behaviors can be empirically predicted from a data set with significant scatter.
- Flexural ultimate limit states include:
 - Concrete compression crushing strain.
 - Tensile reinforcement rupture strain.
- Shear ultimate limit state is dependent on reinforcement yield strength and concrete aggregate interlock.

UHPC:

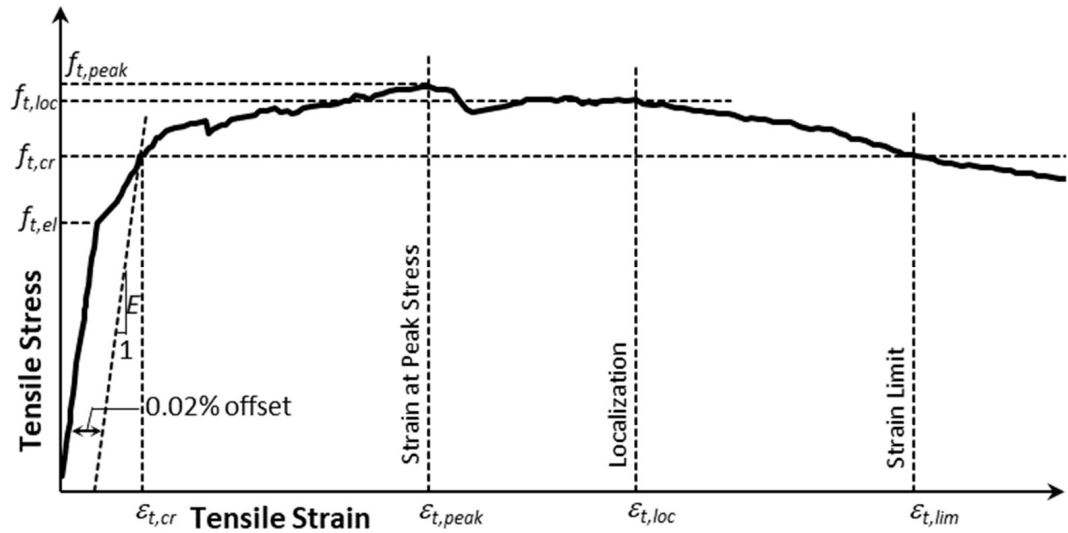
- Engineering mechanics is fundamental.
- Postcracking tensile resistance offers major benefits but also changes member response.
- Data on creep behaviors are limited.
- Flexural ultimate limit states include:
 - Concrete compression crushing strain.
 - Tensile reinforcement rupture strain.
 - UHPC tensile strain capacity.
- Shear ultimate limit state is dependent on reinforcement strain and UHPC tensile resistance.

What are the tension design models?

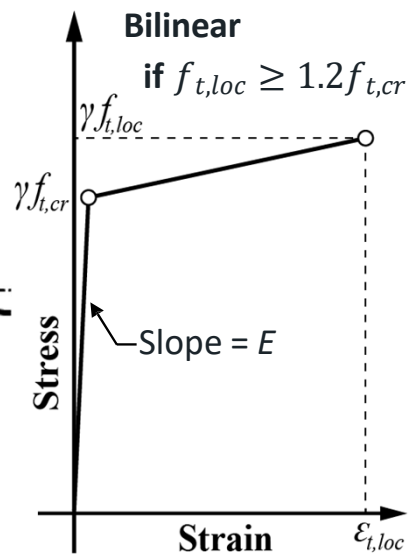
Tension Design Models*



Source: FHWA.

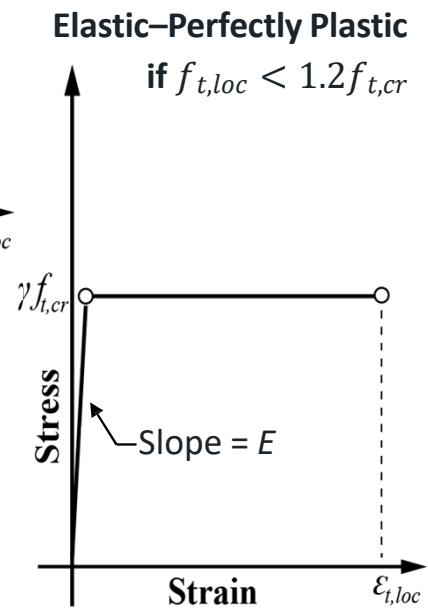


Source: FHWA.



Source: FHWA.

Article 1.4.2.5



Source: FHWA.

*El-Helou, R. G., B. A. Graybeal, and Z. A. Haber. 2022. "Mechanical Behavior and Design Properties of Ultra-High Performance Concrete." *ACI Materials Journal*. 119(1).

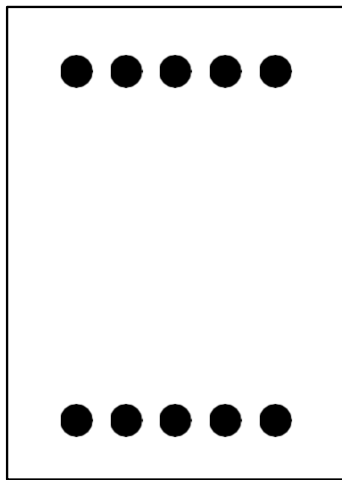
What are the flexural design assumptions?

Flexural Behavior*

Article 1.6.3.1,
Article 1.6.3.2

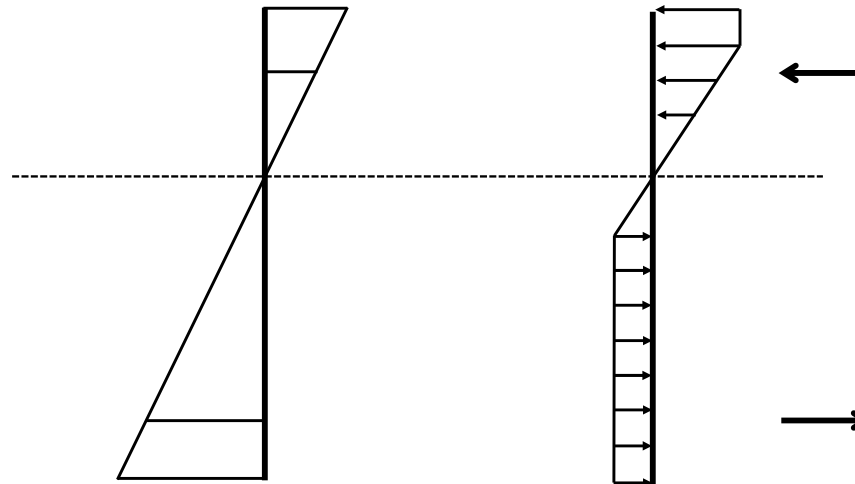
The proposed mechanical models for UHPC in compression and tension are utilized in a strain compatibility framework.

UHPC Cross Section

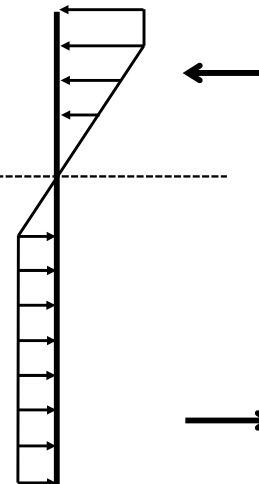


Source: FHWA.

Strain Compatibility



Stress Diagram



Failure modes:

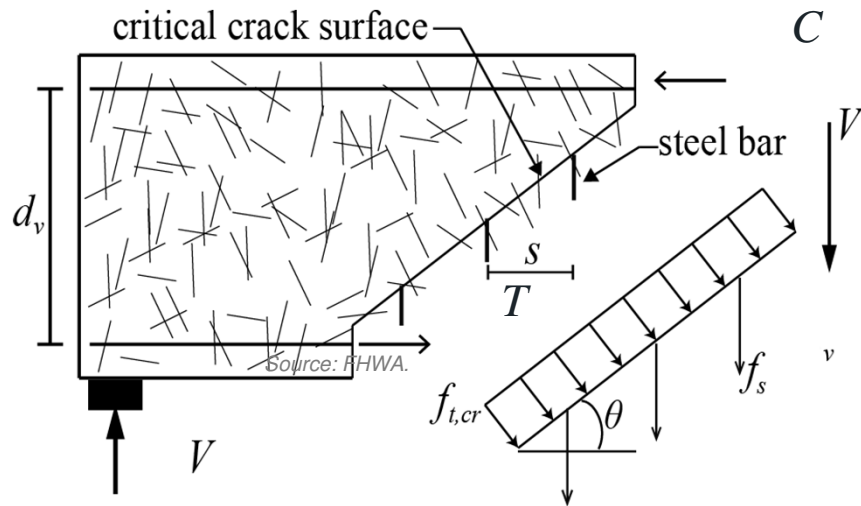
- Crushing
- Crack localization
- Rupture of reinforcing steel

*El-Helou, R. G., and B. A. Graybeal. 2022. "Flexural Behavior and Design of Ultrahigh-Performance Concrete Beams." *Journal of Structural Engineering*, 148(4).

What are the shear design assumptions?

Shear Design Model*

Article 1.7.3.3



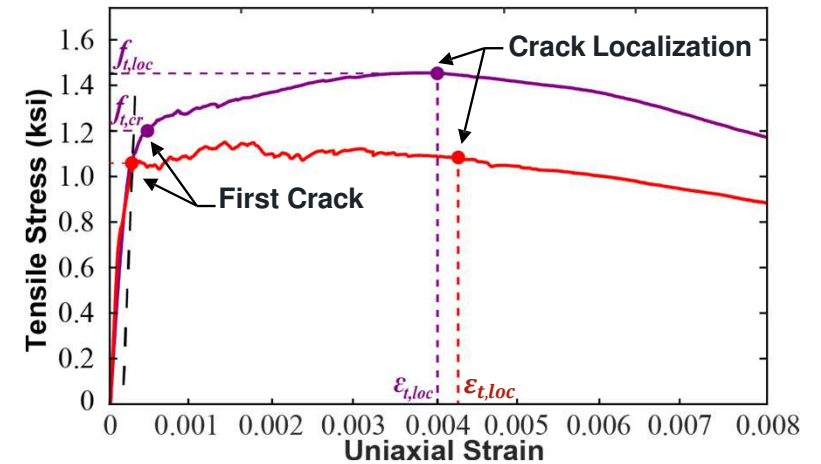
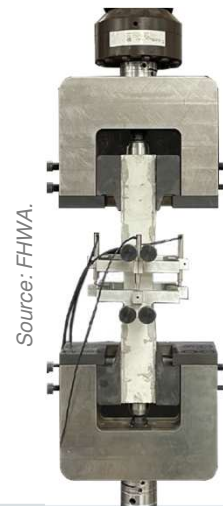
- Localization Stress, $f_{t,loc}$
- Inclination angle, θ
- Steel stress at failure, f_v

$$V_n = V_{UHPC} + V_s$$

$$V_{UHPC} = \gamma f_{t,loc} b_v d_v \cot \theta$$

$$V_s = \frac{A_v f_v}{s} d_v \cot \theta$$

Direct Tension Test



Source: FHWA.

*El-Helou, R. G., and B. A. Graybeal. Submitted and under review. "Shear Design of Strain-Hardening Fiber Reinforced Concrete Beams." *Journal of Structural Engineering*.

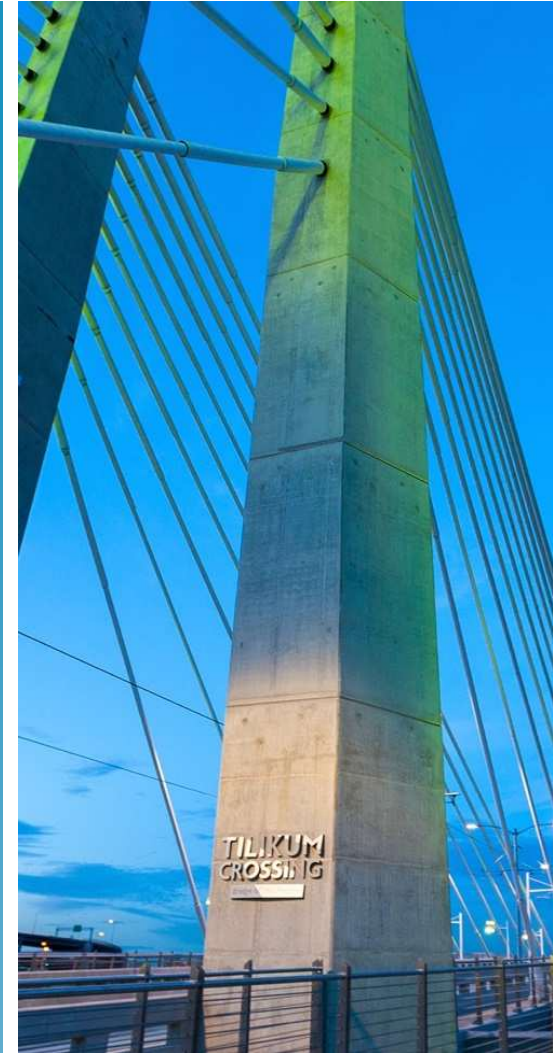
How do we test it?

Standard Method of Test for Uniaxial Tensile Response of UHPC

- UHPC tensile behavior is different than conventional
 - concrete tensile behavior
- A new standard test method was necessary to obtain the engineering parameters needed for design
- FHWA developed a test method to address this need
- FHWA worked with [AASHTO COMP TS-3c](#) to finalize and deliver a test method to the community
- [AASHTO COMP](#) balloted and passed a new standard method in October 2021

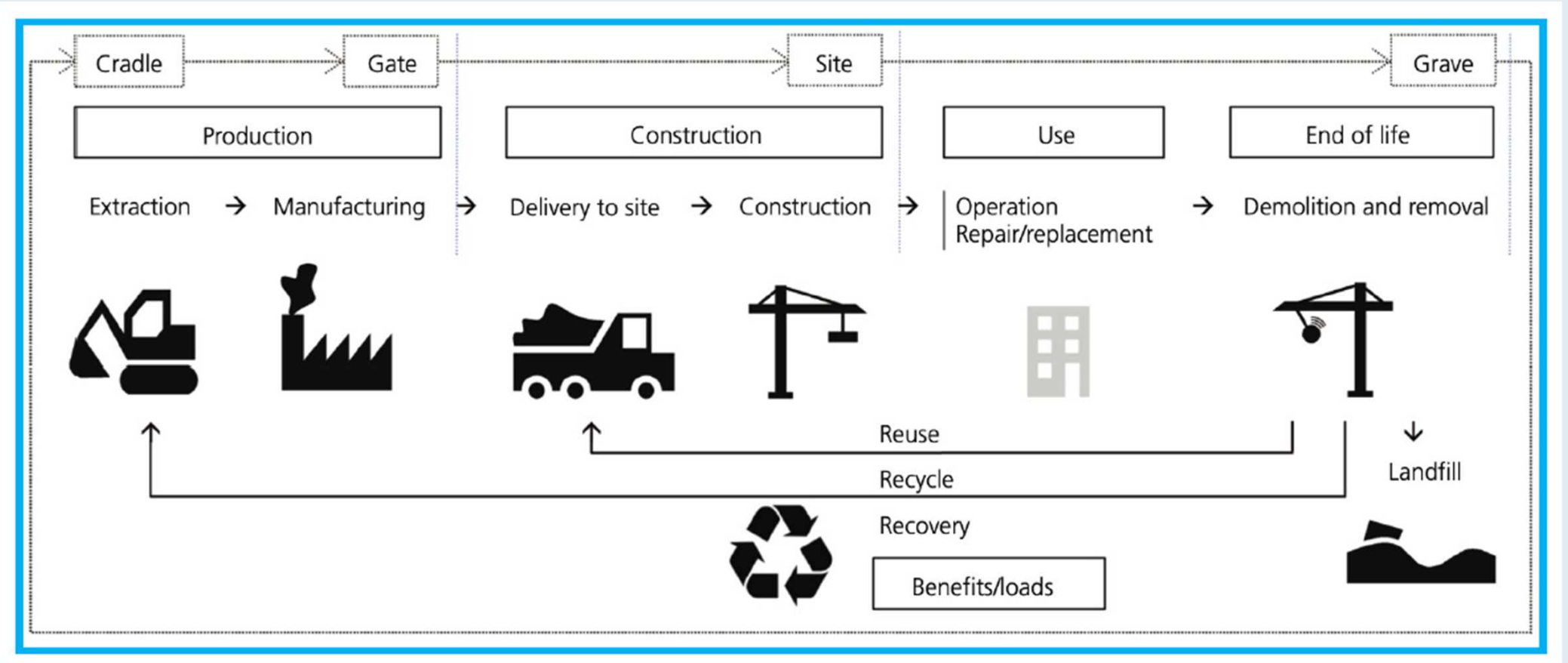


But is it sustainable?



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But is it sustainable?



But is it sustainable?

How do we quantify embodied carbon in structural systems?

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

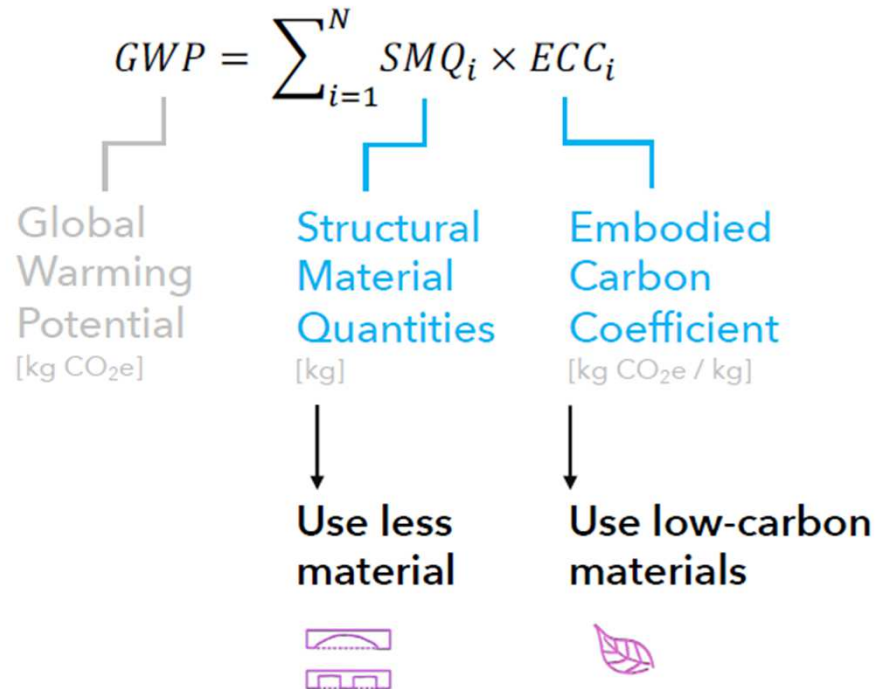
Global Warming Potential [kg CO₂e]

Structural Material Quantities [kg]

Embodied Carbon Coefficient [kg CO₂e / kg]

But is it sustainable?

How do we **reduce** embodied carbon in structural systems?



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.

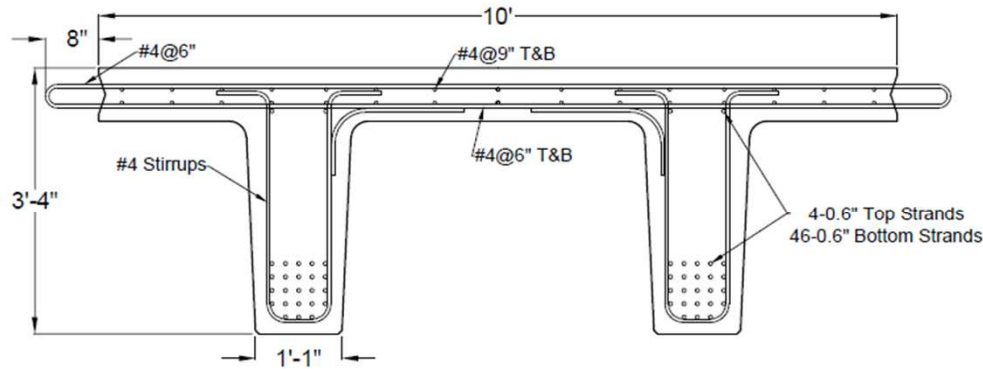
Extended Service Life

- The exceptional durability of UHPC contributes to longer service life for structures, reducing the need for frequent repairs and replacements.

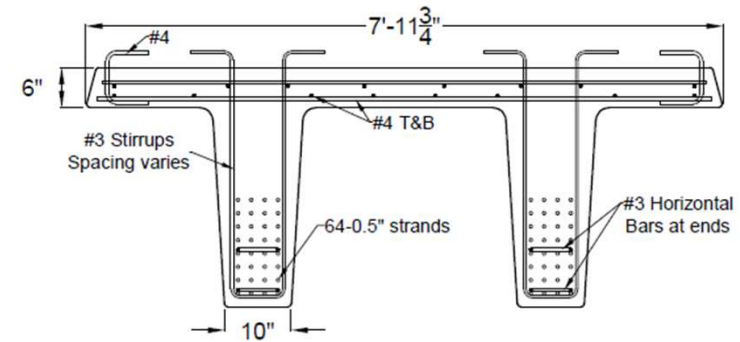
Lower Carbon Footprint

- 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.

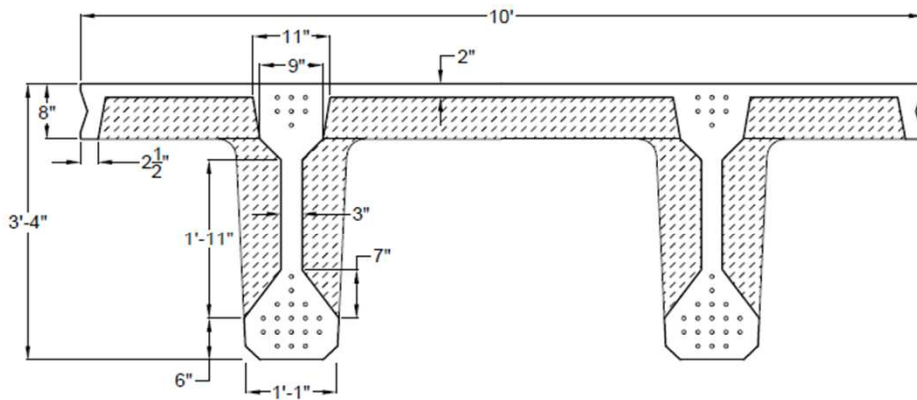
But is it sustainable?



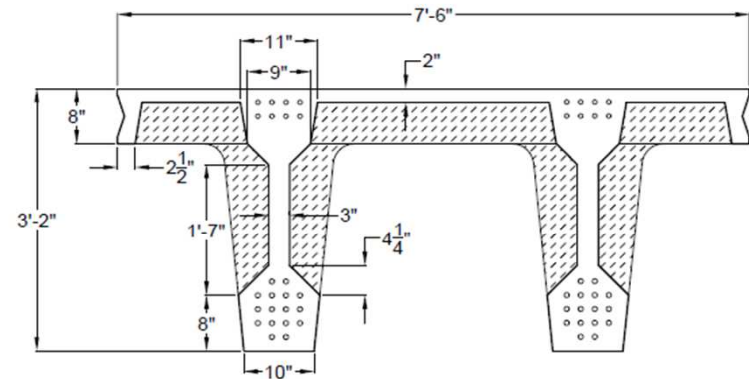
(a) Northeast NEXT D Section



(b) Texas DT Section



(a) Optimized NEXT D Beam



(b) Optimized Texas DT Beam

Gee et al. *Aspire Winter 2020*

But is it sustainable?

Bonus, it also costs less!

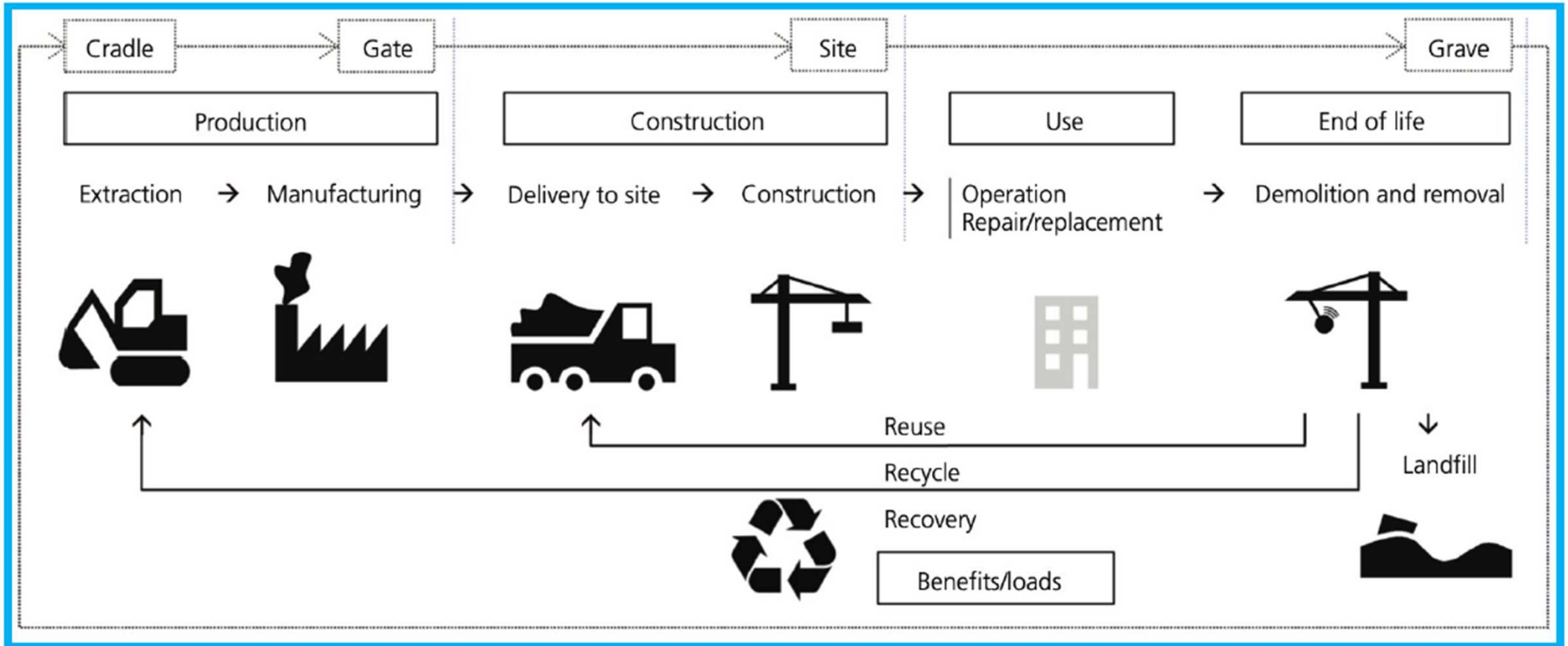
- Cost of CC NEXT D
 - about \$360/FT
- Cost of Corresponding UHPC Beam
 - About \$280/LF

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

Gee et al. Aspire Winter 2020

But is it sustainable?



Questions?



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