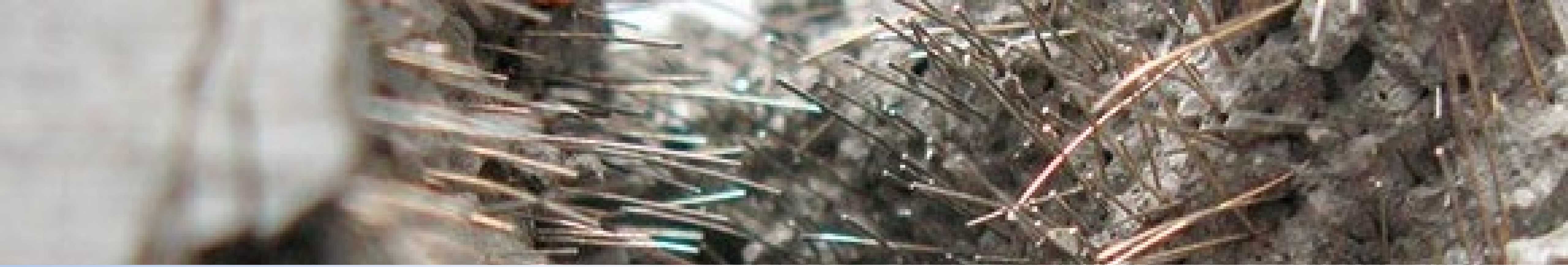


Ultrahigh Performance Concrete (UHPC): A Game Changing Technology

Sherif El-Tawil, PhD, PE, F.ASCE, F.SEI

Antoine E. Naaman Collegiate Professor of Civil Engineering

University of Michigan, Ann Arbor, MI

Outline of Workshop

- The UHPC workshop is about 4 hours
- It is comprised of sessions as follows
  - Session 1: History and Characteristics of UHPC
  - Session 2: Production of UHPC
  - Session 3: Qualification and Acceptance of UHPC
  - Session 4: Structural Design of Reinforced UHPC Structures
  - Session 5: Applications of UHPC Technology and its Potential
- Each session is about 35 minutes
- There will be a 10-minute break between sessions

About the Speaker

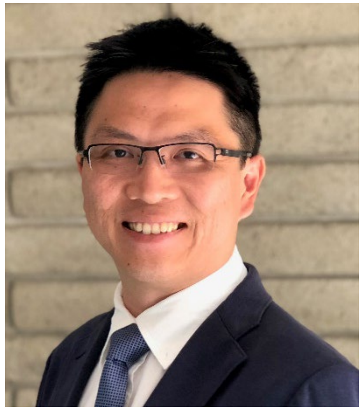
- Received PhD from Cornell University in 1996
  - Major Structural Engineering
  - Minor Theoretical and Applied Mechanics
- Assist Prof. at Univ. of Central Florida from 1996-2002
- Univ. of Michigan from 2002-Present
- PE in Michigan

- Particularly interested in the effects of extreme loading on structural systems
  - Material Modeling
- Long-sustained interest in the development of open-recipe UHPC and characterization of its short- and long-term properties.

Acknowledgement

Prof. Tony Naaman

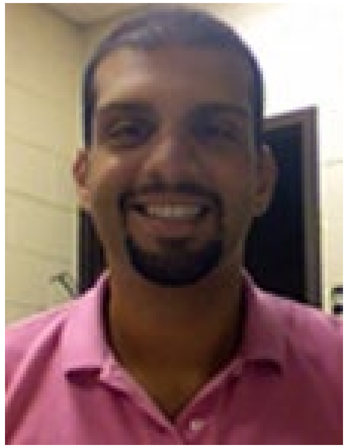
Prof. Andrew Tai



Prof. Chung-Chan Hung

Prof. Kay Wille

Prof. Sukhoon Pyo



Dr. Mo Alkaysi

HIPER FIBER

NSF

MDOT
Michigan Department of Transportation
BRIDGE FIELD SERVICES

Michigan Engineering

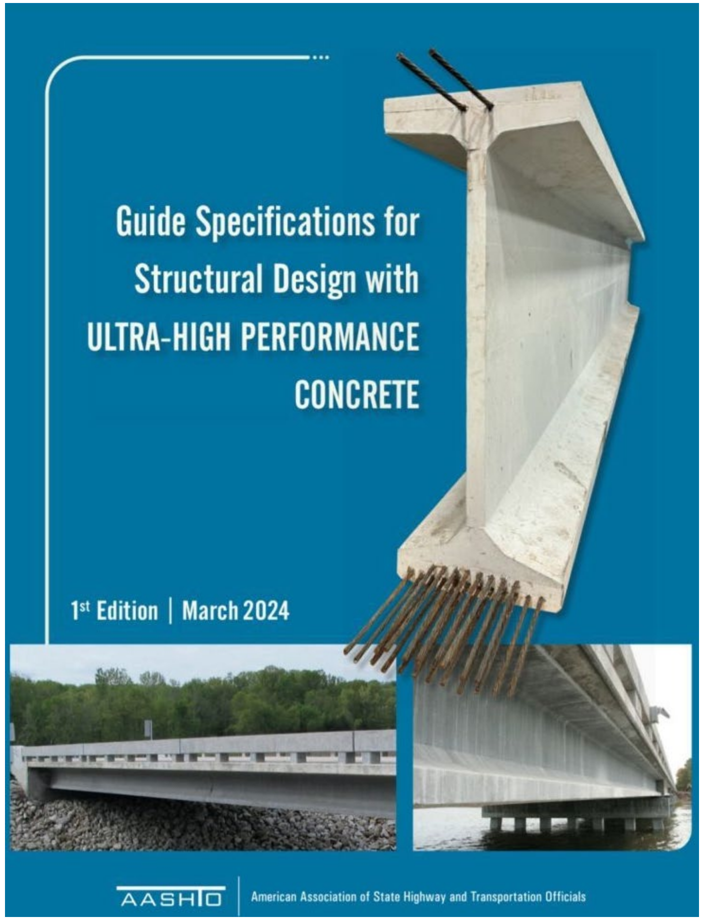
Session 1
History and Characteristics of UHPC

General Definition of UHPC

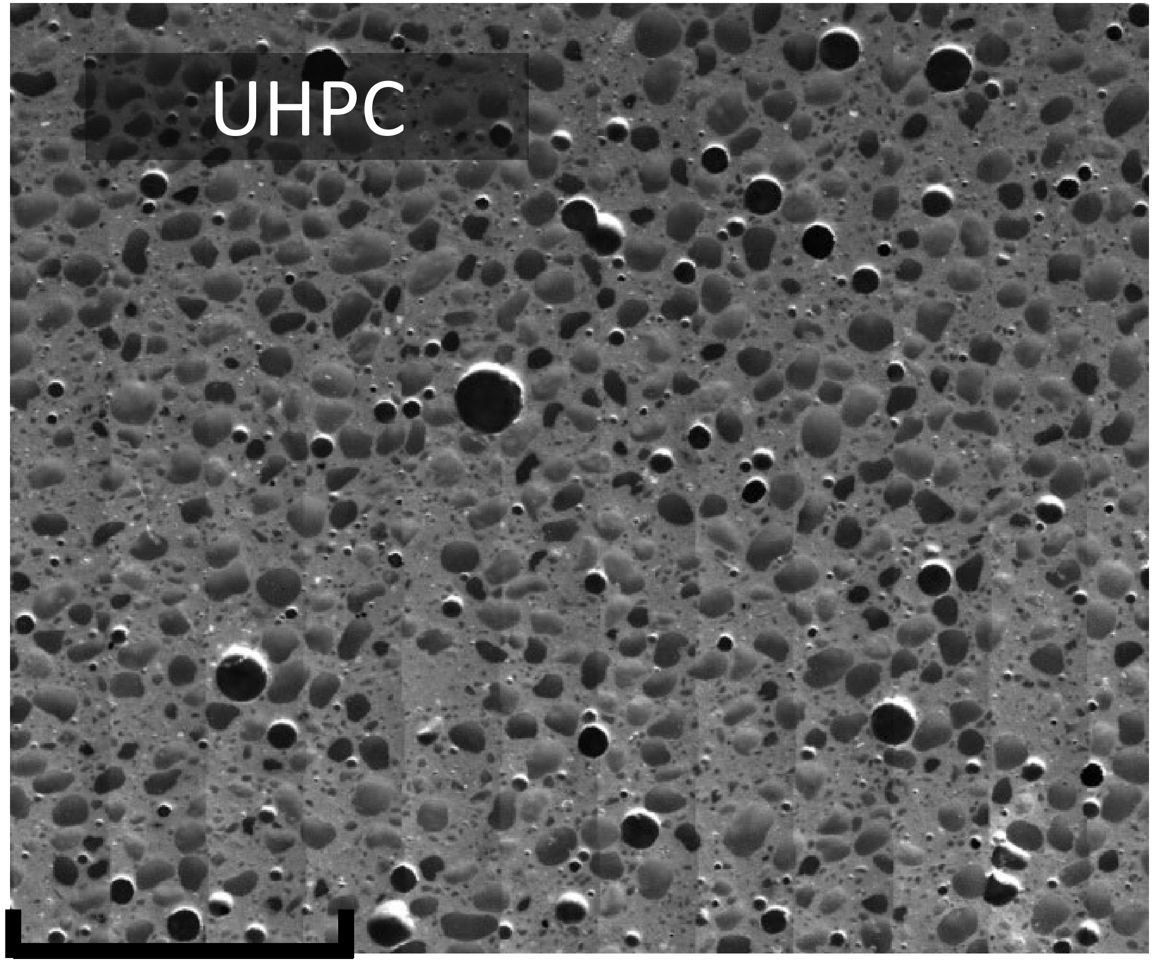
- It is a class of steel fiber reinforced cementitious materials with a suite of enhanced properties:
  - Fresh mix characteristics
  - Mechanical properties
  - Durability properties

What is UHPC: AASHTO Definition

- Exhibits a strain-hardening behavior, and has the following minimum property values:
  - A minimum compressive strength:
    - $f'_c > 17.5$ ksi
  - A minimum effective cracking strength:
    - $f_{t,cr} > 0.75$ ksi
  - A minimum crack localization strength:
    - $f_{t,loc} > f_{t,cr}$
  - A minimum crack localization strain:
    - $\varepsilon_{t,loc} > 0.0025$




Concrete
50 mm


UHPC
10 mm

The Road to UHPC

Early 1980s Macro defect free (MDF) concrete was introduced in the early 1980s

- Compressive strength in excess of 45 ksi

Mid 1980s Densified small particles (DSP) concrete was introduced in the mid 1980s

- Compressive strength of about 36 ksi

Mid 1990s Reactive powder concrete (RPC) was introduced in the mid 1990s

Mid 2000s These efforts represent early versions of what we now call UHPC

Proprietary versus *Open Recipe*

- One of the earliest patents on UHPC was that by Lafarge (now Holcim) for their trademark UHPC called Ductal
  - Patent ran out, but Ductal is still sold in the US
- Several other proprietary mixes are available on the market
  - Examples are CorTuf and Steelike in the US
- The high cost of proprietary products has created a demand for open recipe UHPC
  - The word ‘open’ implies that the formulae and methodologies for mixing are published (known) and conducive to further development by others
  - Many State DOTs have developed open mixes including Michigan, Montana, and Kansas.

Regulatory Documents

French Society of Civil Engineers 2003

2006 the Japanese Society of Civil Engineers (JSCE)

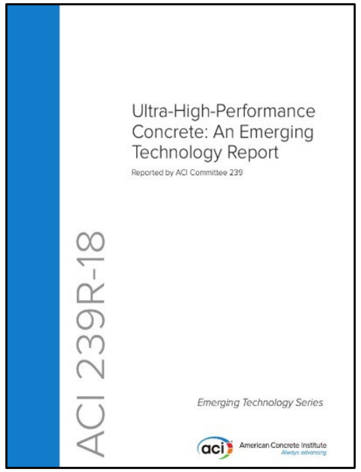
2013: FHWA “Design Guide for Precast UHPC Waffle Deck Panel Systems including Connections”.

2014: Swiss Society of Engineers and Architects (SIA) prSIA 2052: “UHPC: Material, Design and Construction”

2016: French Standards Institute - NF P 18-710: National addition to Eurocode

2017: ASTM C1856/1856M – 17 “Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete”

2018: ACI-239



2018: German Committee for Structural Concrete (Deutscher Ausschuss für Stahlbeton – DAfStb

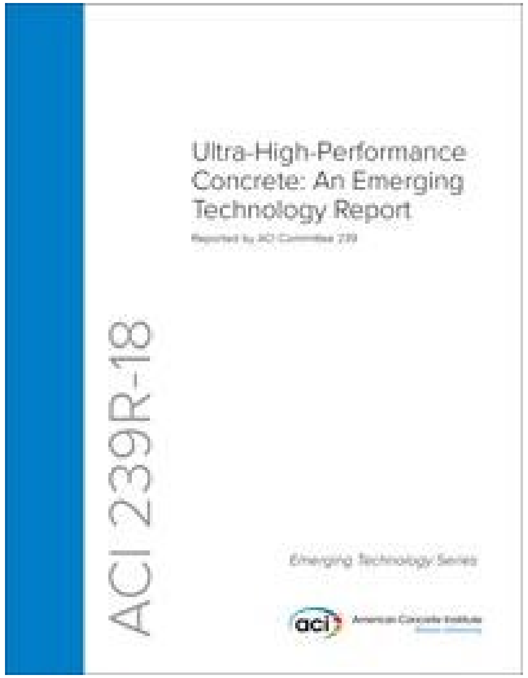
2018: Standards Australia Limited published DR AS 3600 “Concrete Structures”

2019: Spanish Guidelines for UHPC

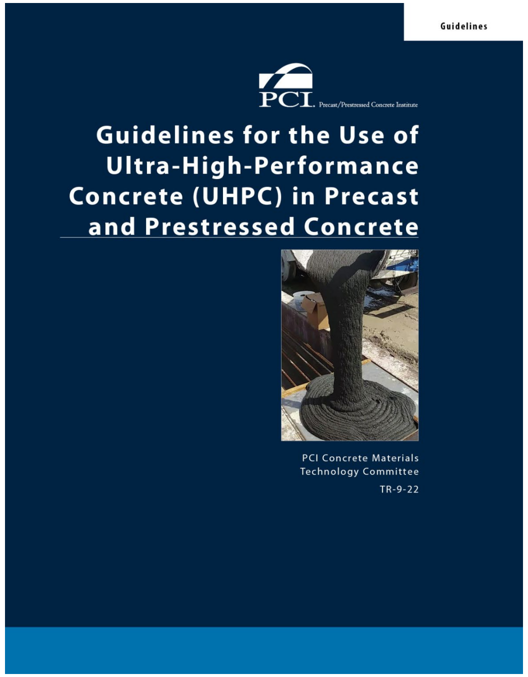
2019: Canadian CSA A23.1, Annex U and CSA S6, Annex 8

2003 2005 2007 2009 2011 2013 2015 2017 2019

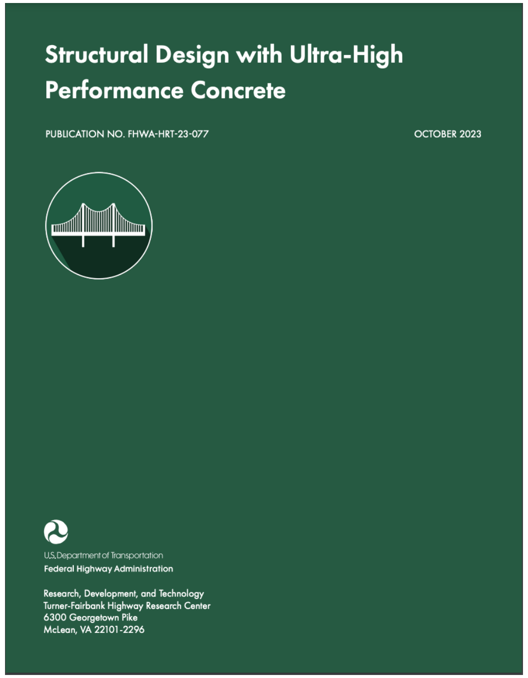
2018 → 2022 → 2023 → 2024



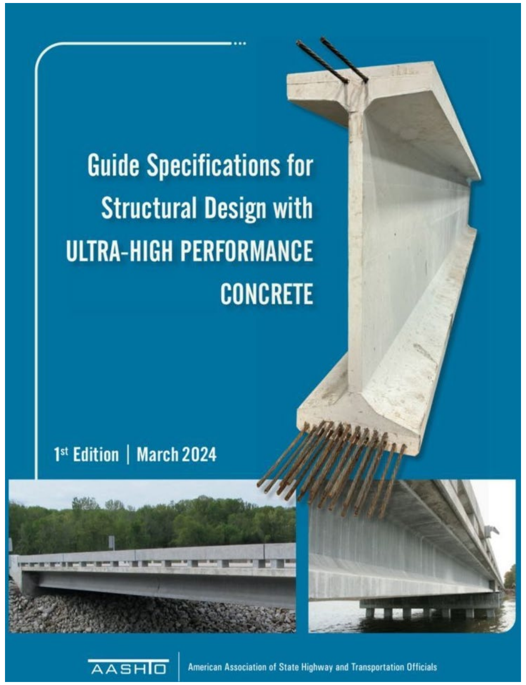
American Concrete Institute



Precast Concrete Institute



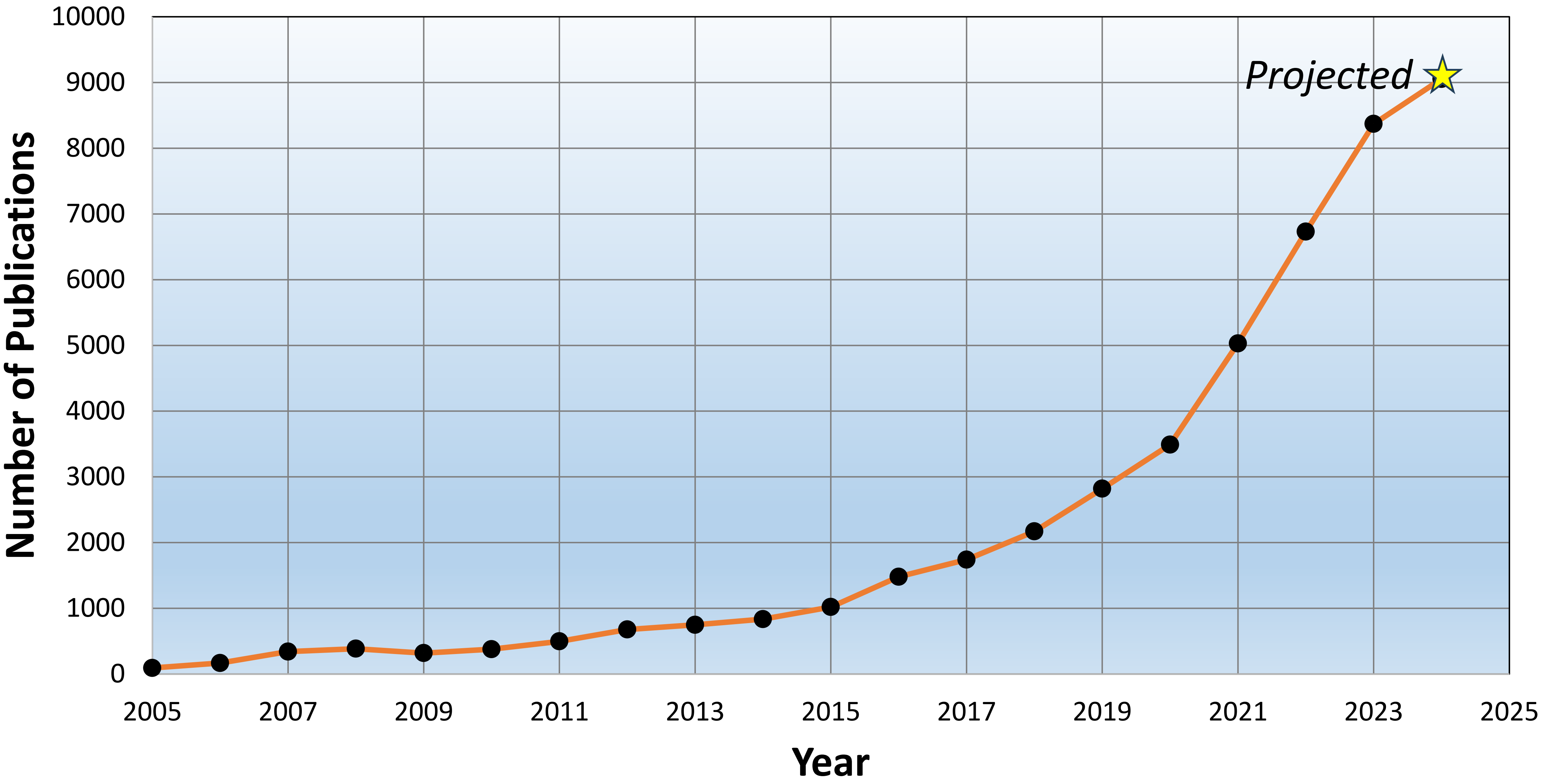
Federal Highway Administration



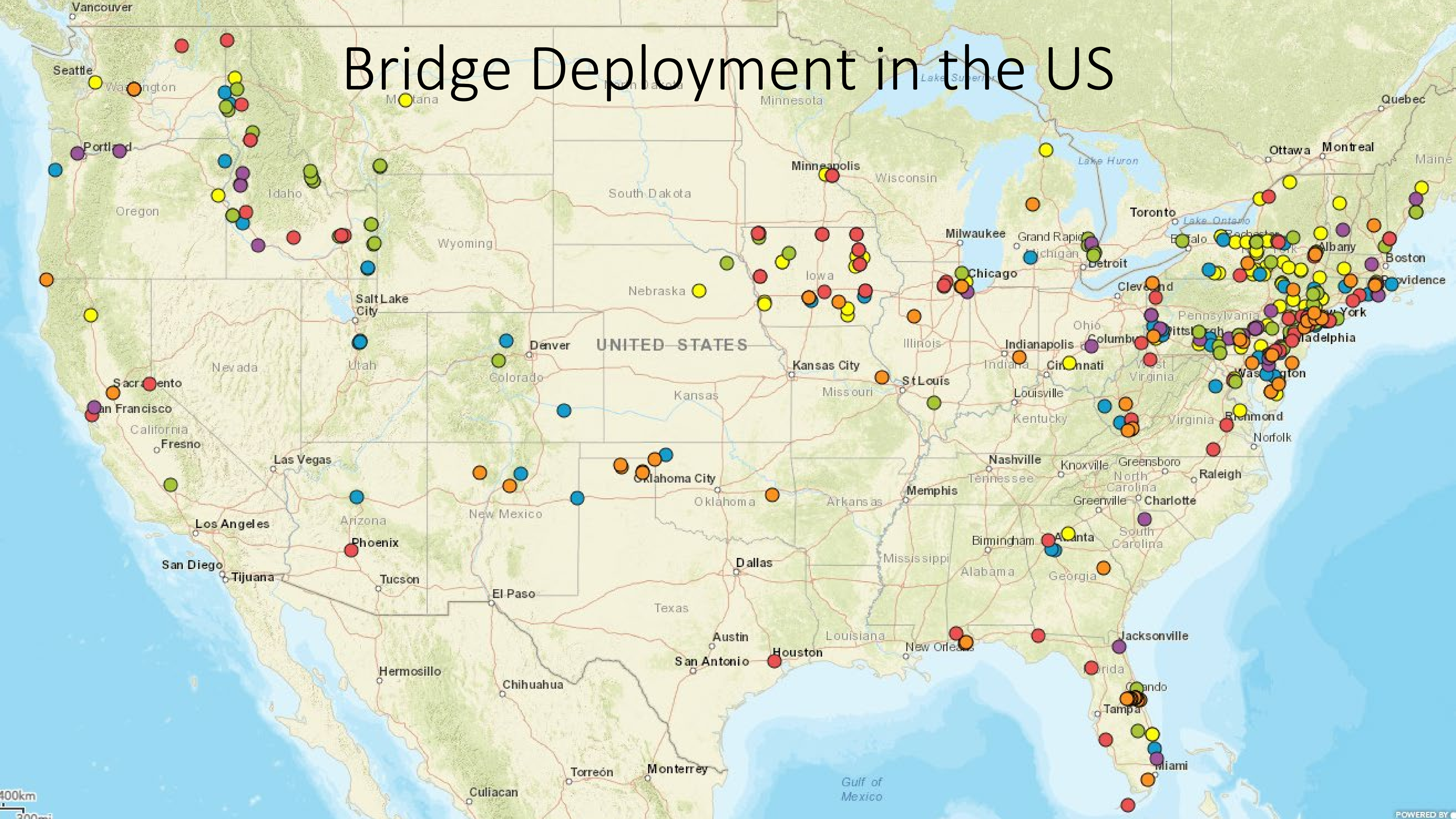
American Association of State Highway and Transportation Officials

A BIG DEAL! Movement towards material and structural performance NOT amount of steel fiber

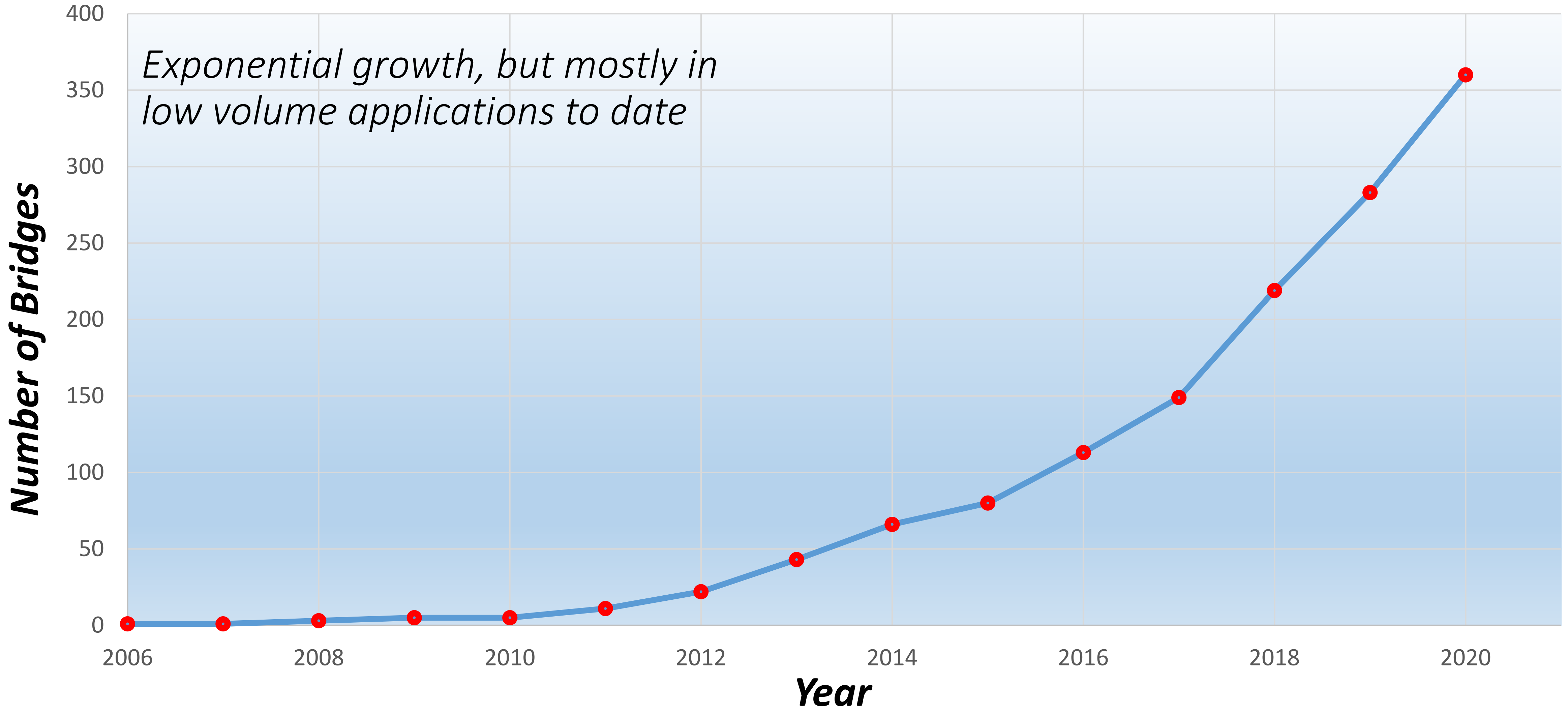
Approaching Maturity in UHPC Research



Bridge Deployment in the US



Growth in UHPC Bridge Applications

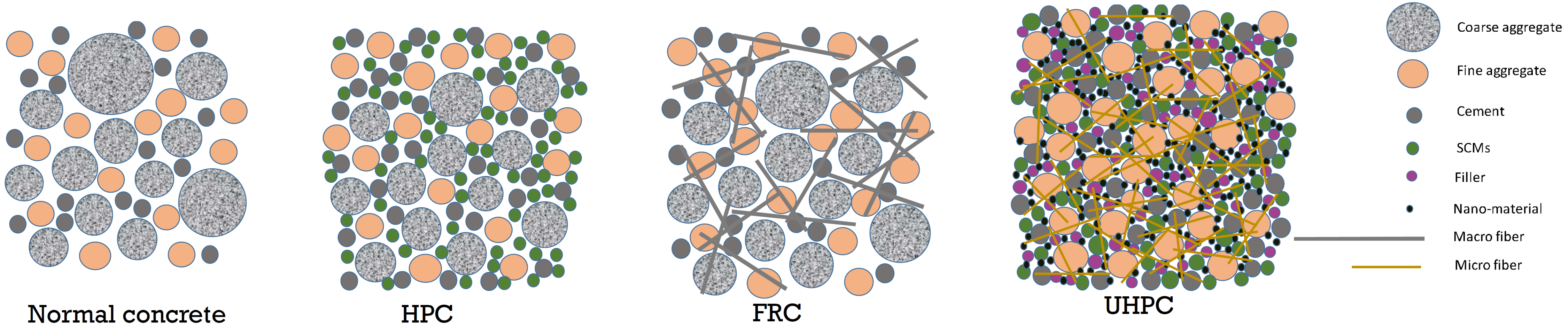


Typical Characteristics of UHPC

- Self consolidating
- Compressive strengths in the 22 ksi - 30 ksi range
- Direct tensile peak strength of 1.2 ksi -2 ksi
- Flexural tensile peak strength of 3 – 5.5 ksi
- Young’s modulus of 7,000 – 9,000 ksi
- Extremely high toughness and resistance to abrasion

Mix Components of UHPC

Typical Mix Design for Different Classes of Concrete



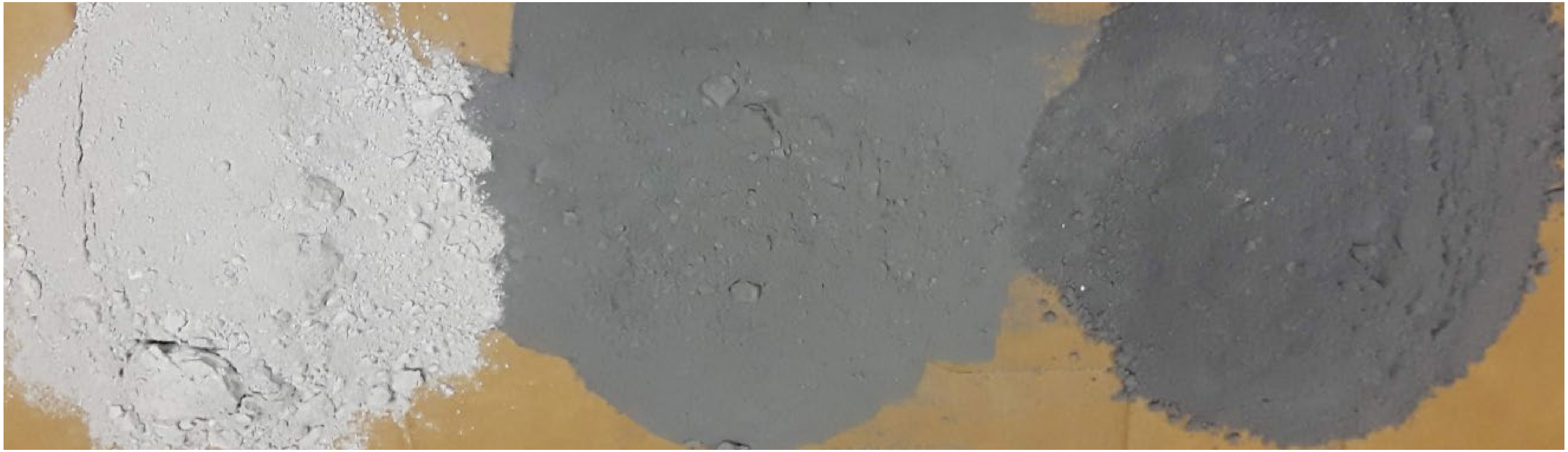
Mix	Normal PCC	HSC	FRC-L	FRC-M	UHPC
Cement	529	820	555	582	1200
SCMs	176	80	185	194	390
Filler	0	0	0	0	355
Coarse Aggregate	1650	1800	1570	1427	0
Fine Aggregate	1204	1140	1284	1427	1720
Water	261	261	274	287	218
Fibers	0	0	8	132	263
HRWR (fl oz/yd3)	56	290	84	112	745
w/b	0.37	0.29	0.37	0.37	0.22

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

MiUHPC: The Michigan Mix

Material (Weight in pounds)	UHPC				High Str. Concrete
Cement Blend	Mix A[1]	Mix B[1]	Mix C[1]	Mix D[1]	~ 9.5 ksi -
Ordinary Portland Type I	653				750 (Cement)
Slag Cement	653				-
Silica Sand					-
Sand I[2]	398	396	395	394	1400 (Sand)
Sand II[3]	1590	1586	1582	1577	1700 (Large Agg.)
Silica Fume	327				-
Water	276	272	268	264	248
High Range Water Reducer[4,5]	20	26	33	39	6
Steel Fibers[6]	265				-

Silica Fume

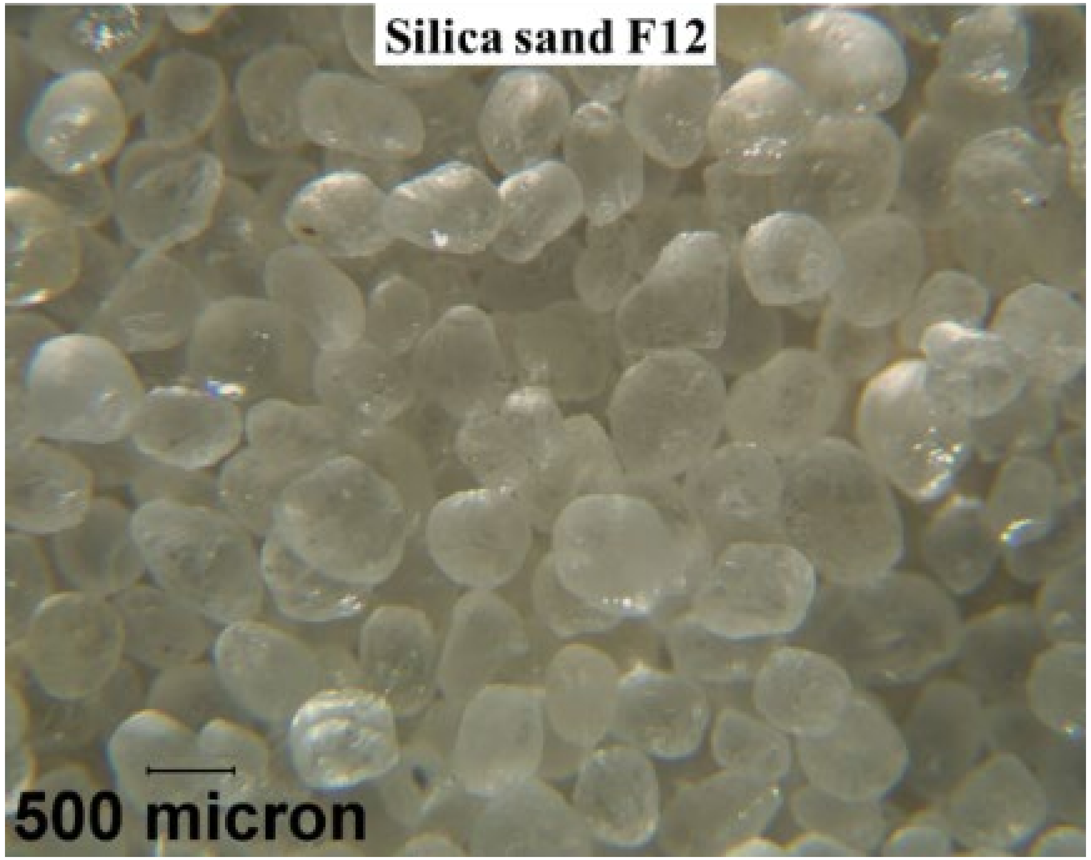


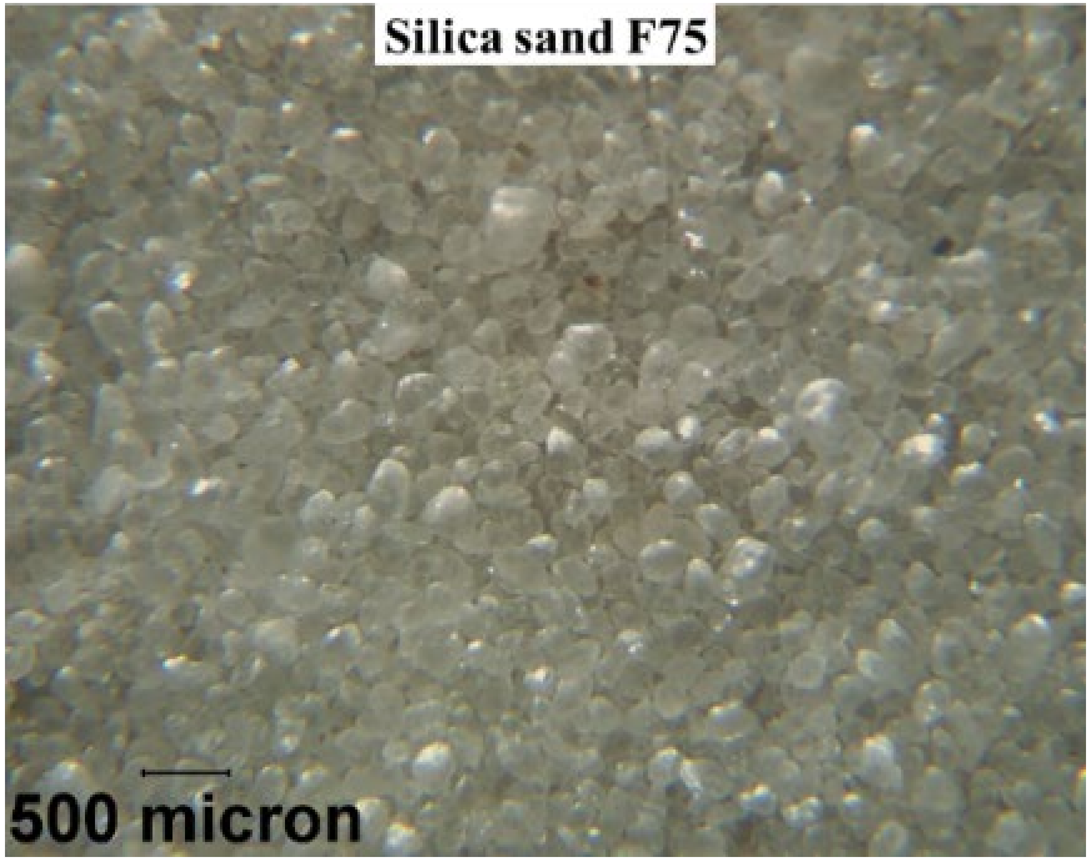
Carbon content influences color of silica fume
Need more HRWR to counter effect of carbon content

Open Recipe UHPC Components

Material (Weight in pounds)	UHPC				High Str. Concrete
Cement Blend	Mix A[1]	Mix B[1]	Mix C[1]	Mix D[1]	- 9.5 ksi -
Ordinary Portland Type I	653				750 (Cement)
Slag Cement	653				-
Silica Sand					-
Sand I[2]	398	396	395	394	1450 (Sand)
Sand II[3]	1590	1586	1582	1577	1800 (Large Agg.)
Silica Fume	327				-
Water	276	272	268	264	248
High Range Water Reducer[4,5]	20	26	33	39	6
Steel Fibers[6]	265				-

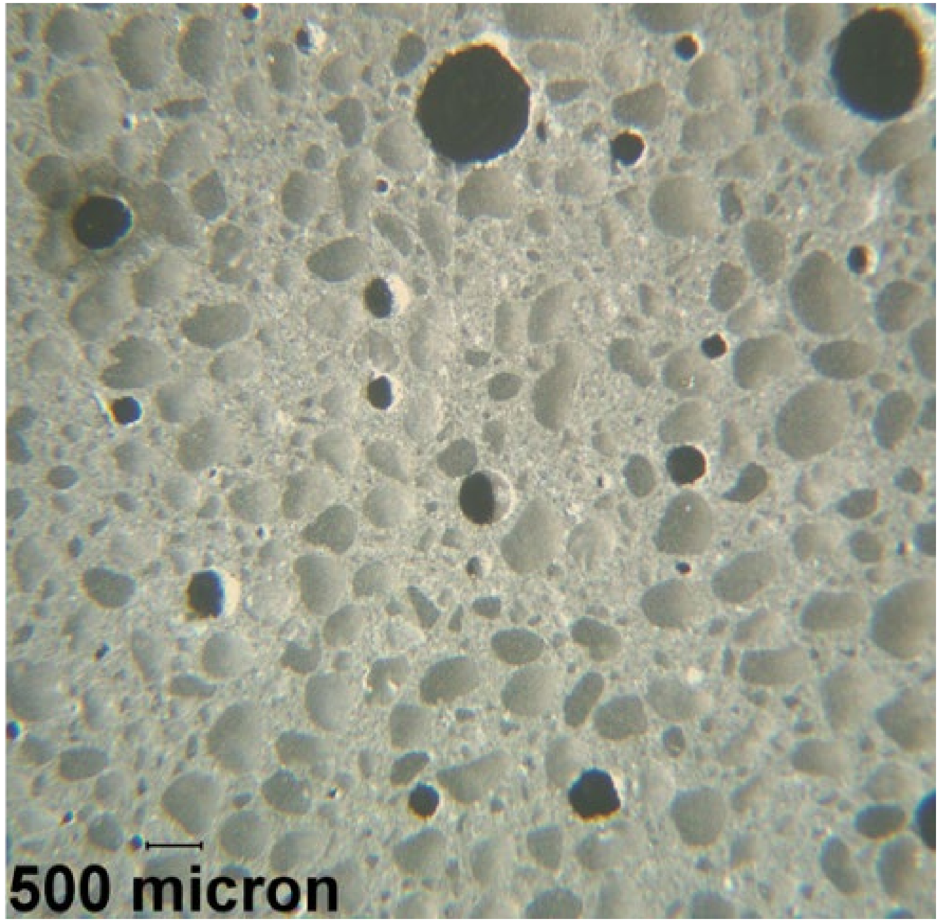
Sand I and Sand II





What gives UHPC its Unique Properties?

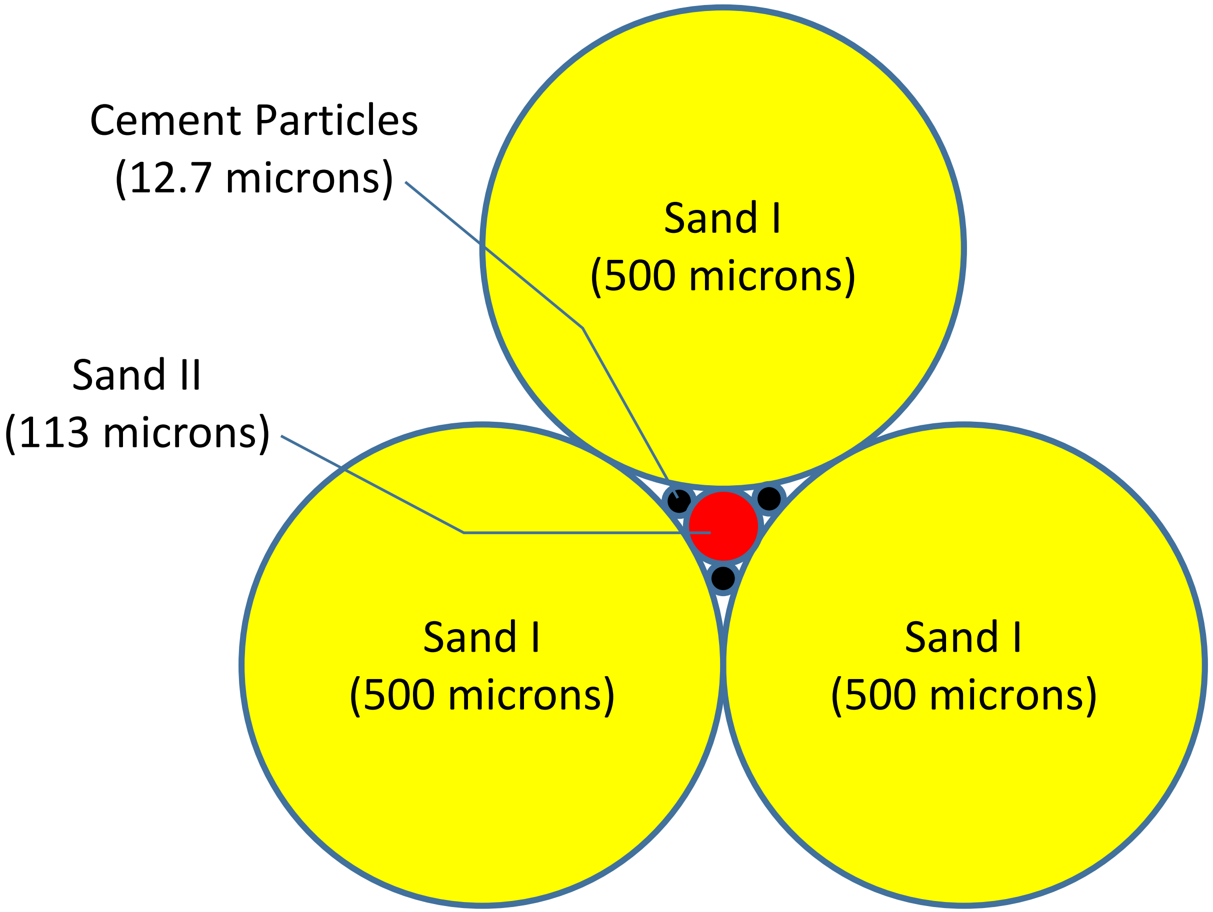
- High packing density
  - Achieved by carefully controlling the size and distribution of the constituent particles
- Discontinuous pore structure
  - Results from the uniformity of the matrix
  - Prevents water from entering the material, leading to its exceptional durability properties.
- Presence of steel fibers

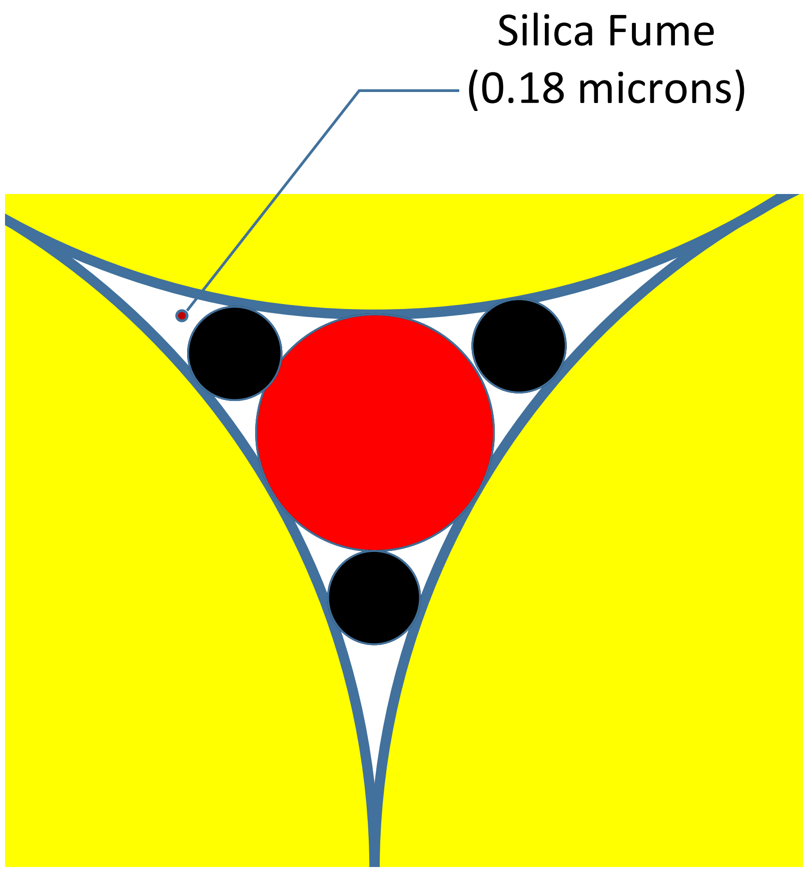


Secret of UHPC: High Packing Density

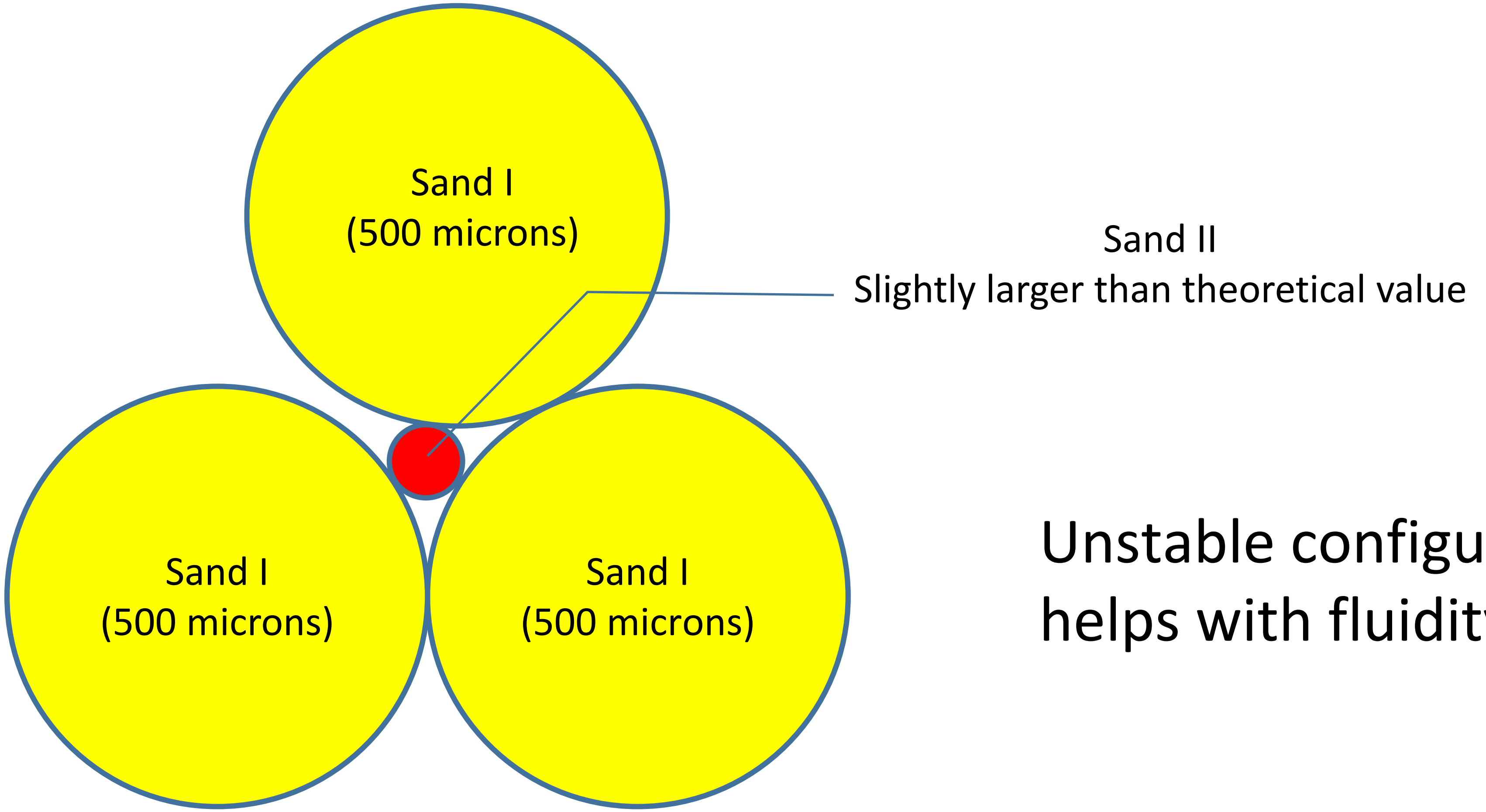
- Packing theory is the basis for designing UHPC
  - Proper application of packing theory can control the fresh and hardened properties of concrete
- A modified Andreassen and Andersen (A&A) is used to design UHPC
  - $P(D)(\%) = \left(\frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q}\right) \times 100\%$
- Optimum packing is obtained when *q* = 0.37
- However, for mixtures with a high amount of powders (<250 µm), a smaller *q* value is recommended in the range of 0.22~0.25

Secret of UHPC: High Packing Density



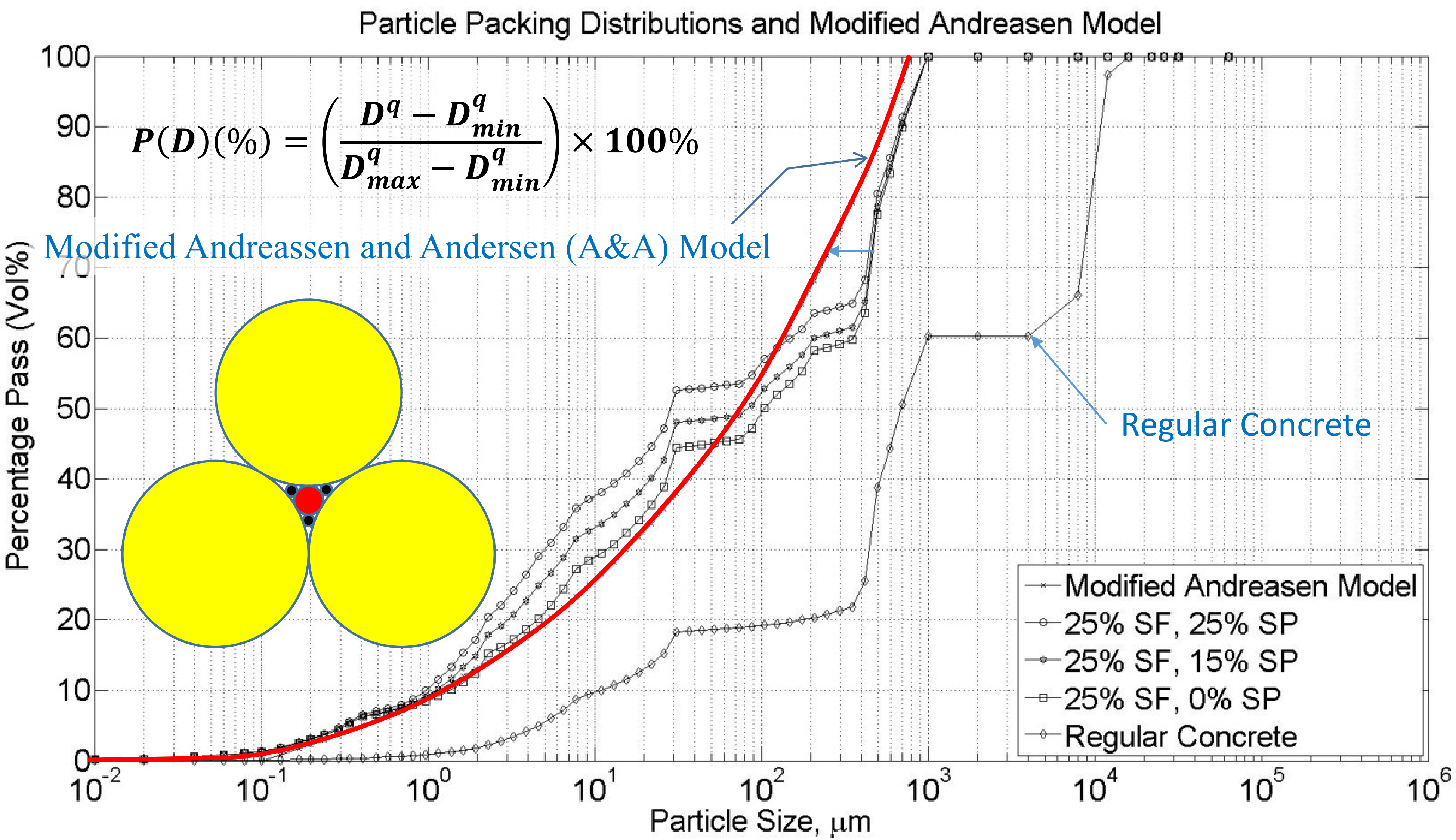


Secret of UHPC: High Packing Density



Unstable configuration helps with fluidity

Secret of UHPC: High Packing Density



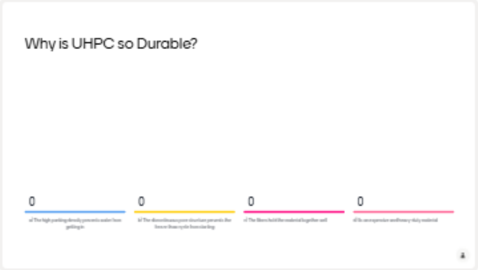
IS

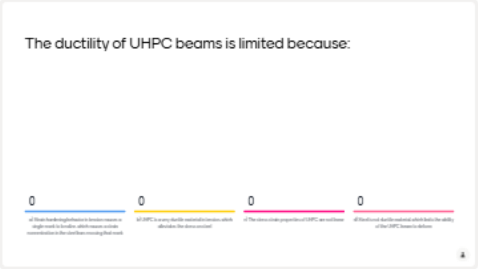
Menti

UHPC presentation

Choose a slide to present

Instructions





Menti

UHPC presentation

Choose a slide to present

Instructions

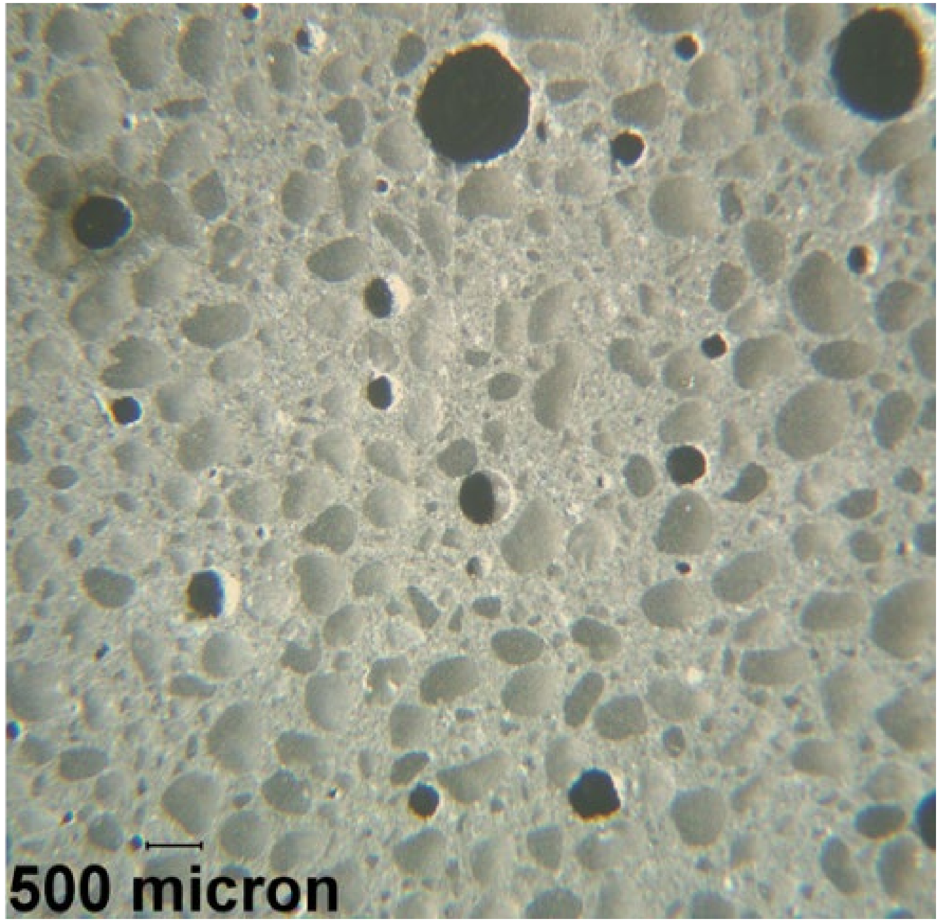
Why is UHPC so Durable?

The ductility of UHPC beams is limited because:

Recall This Slide?

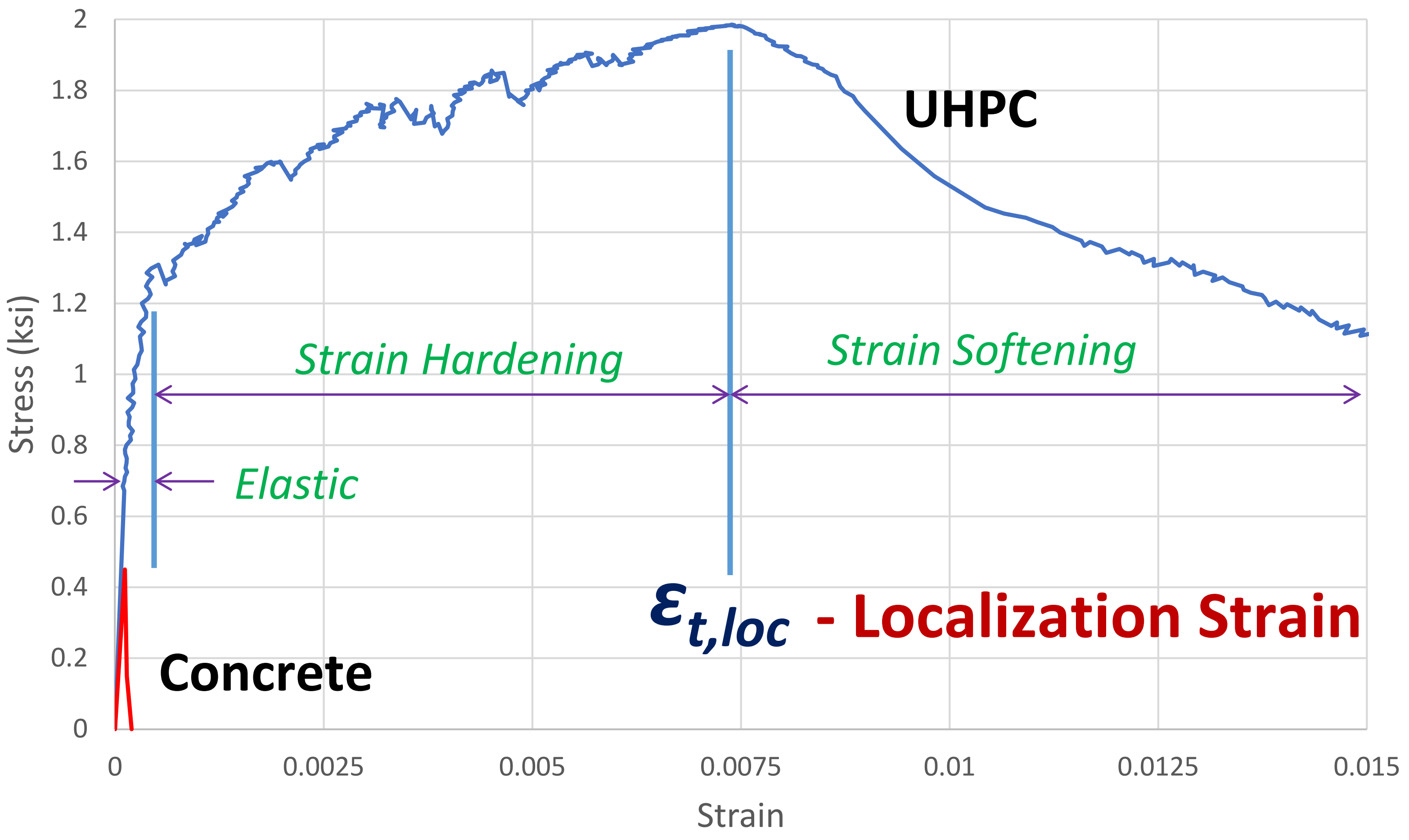
What gives UHPC its Unique Properties?

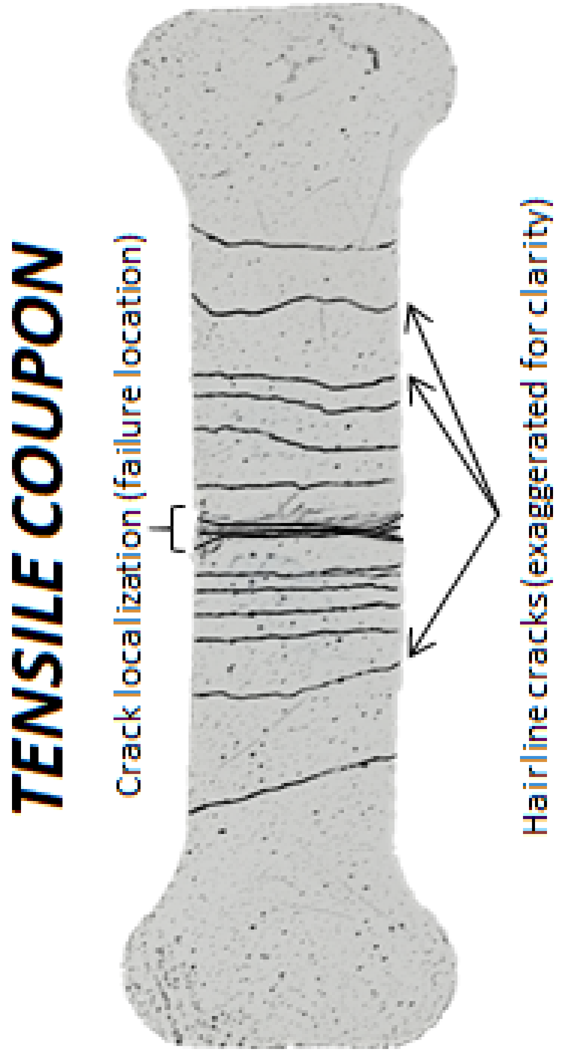
- High packing density
  - Achieved by carefully controlling the size and distribution of the constituent particles
- Discontinuous pore structure
  - Results from the uniformity of the matrix
  - Prevents water from entering the material, leading to its exceptional durability properties.
- Presence of steel fibers



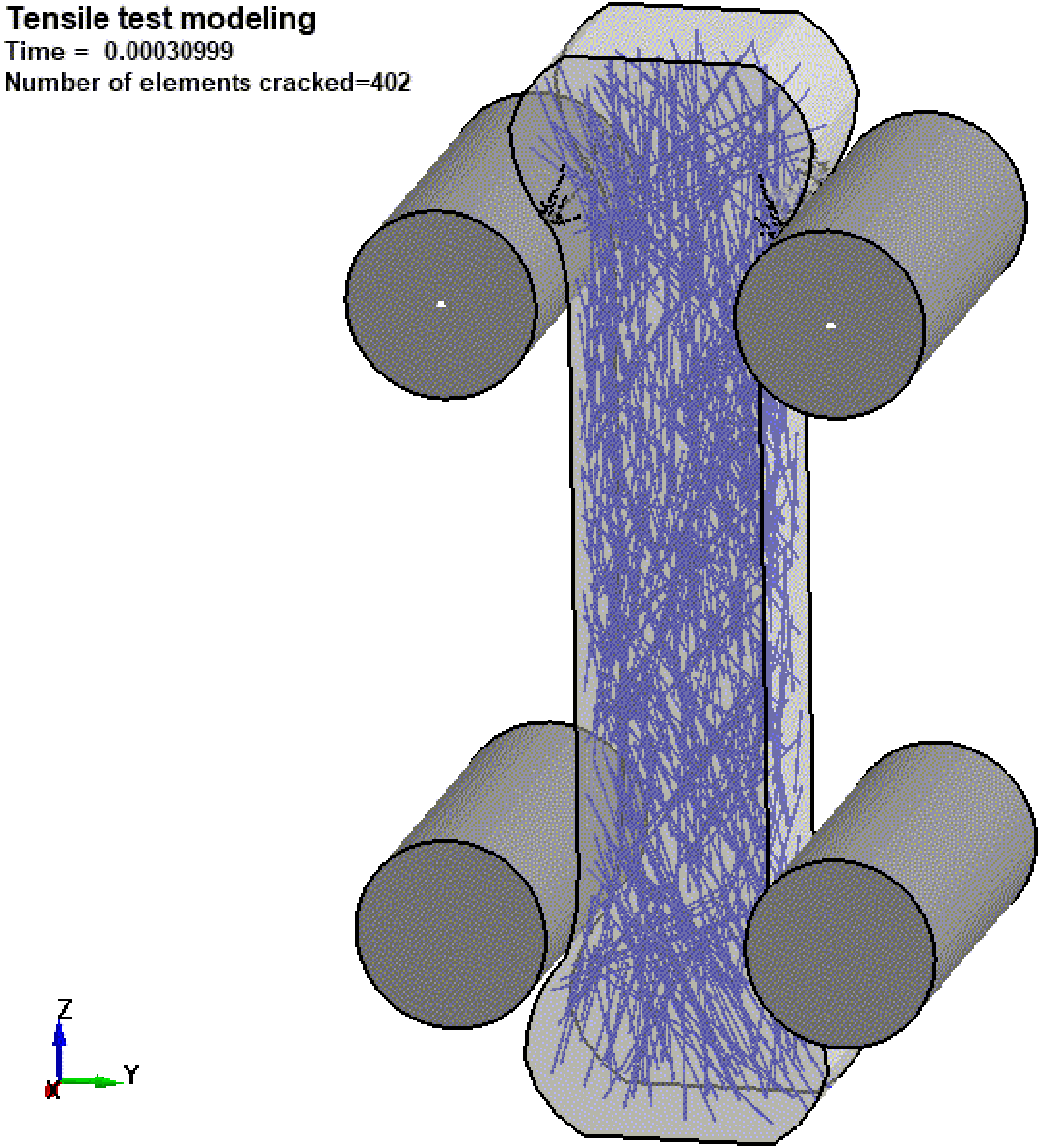
Material Properties of UHPC

Strain Hardening Response of UHPC in Tension

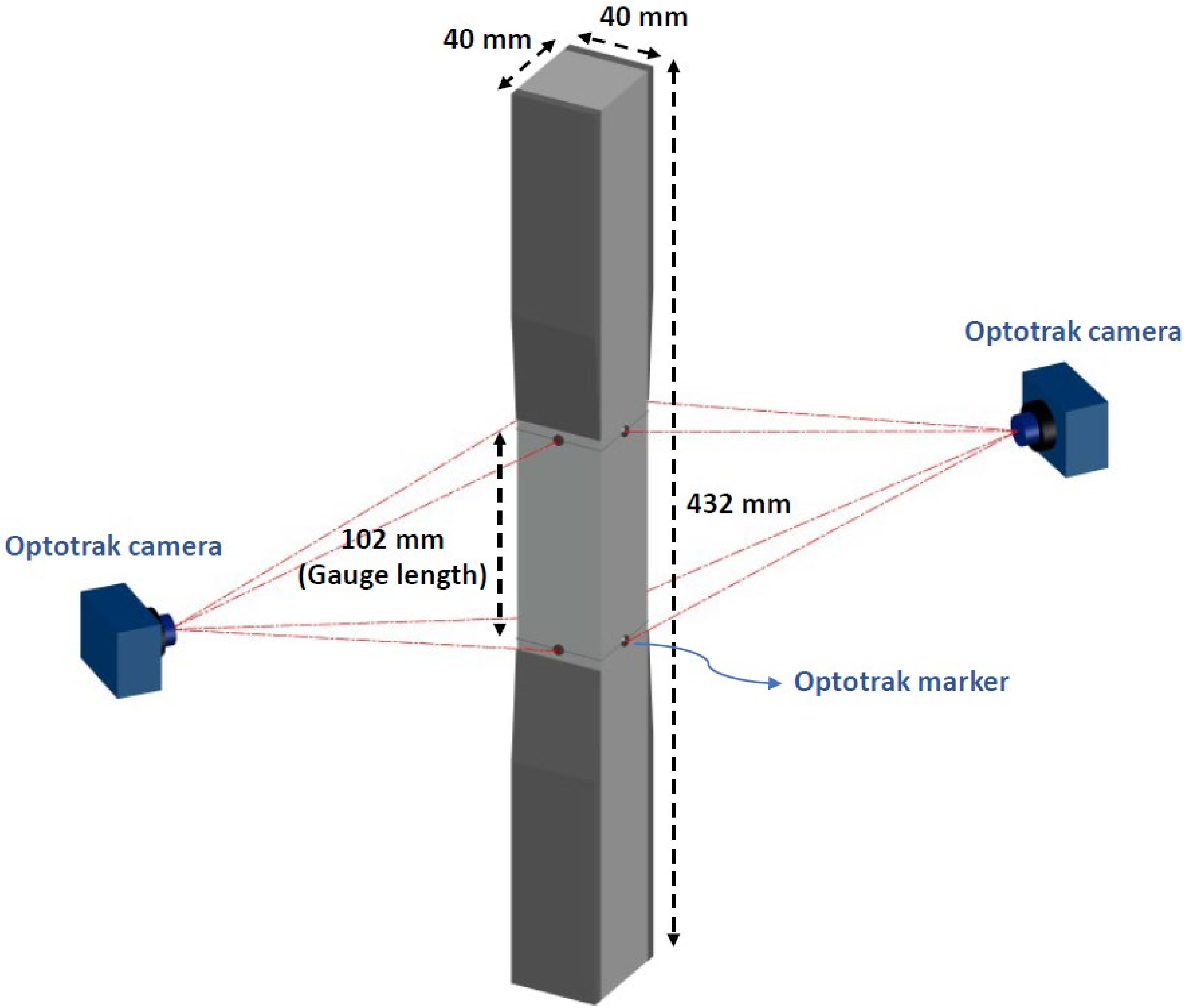




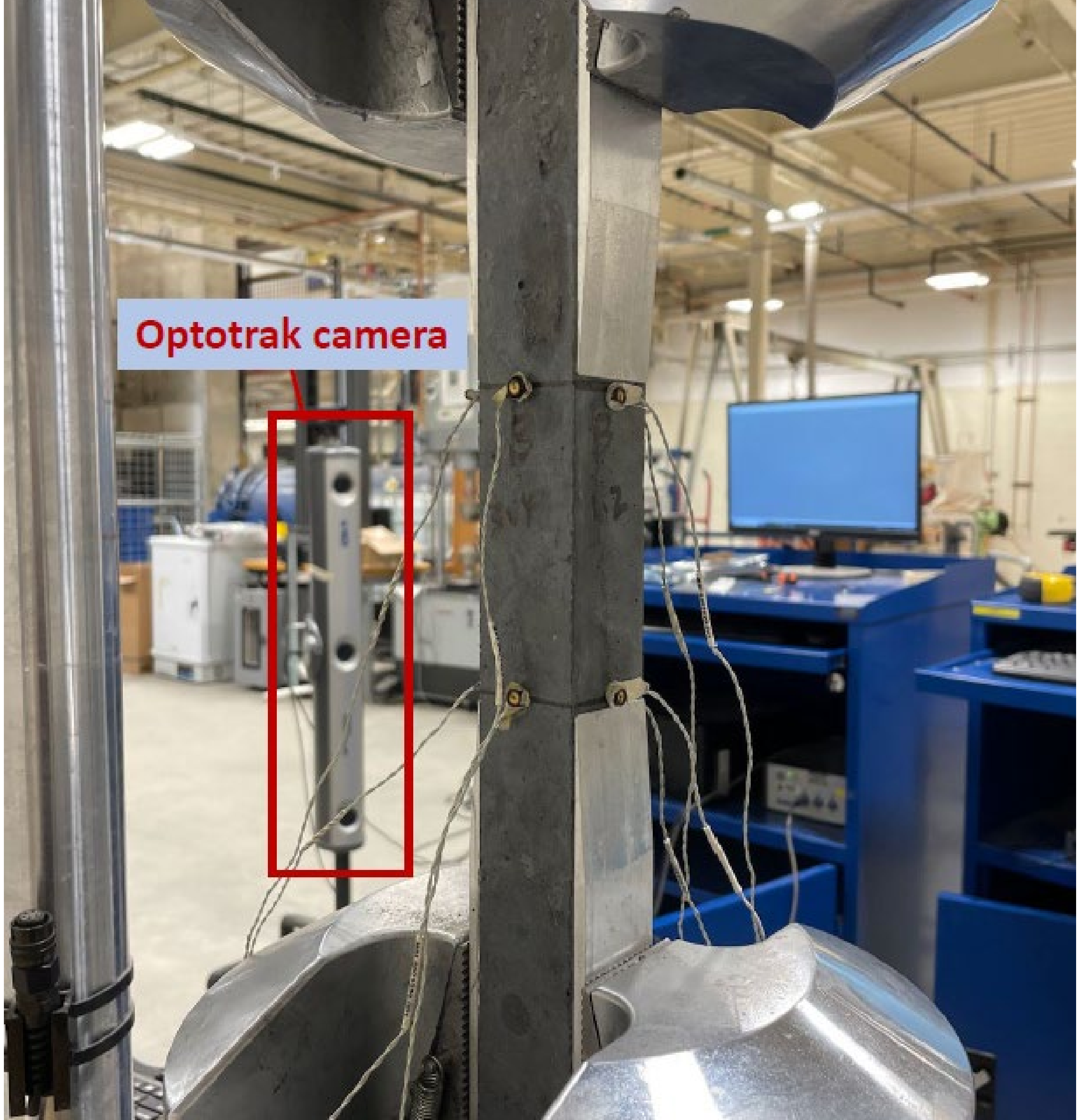
Simulation of Coupon Response

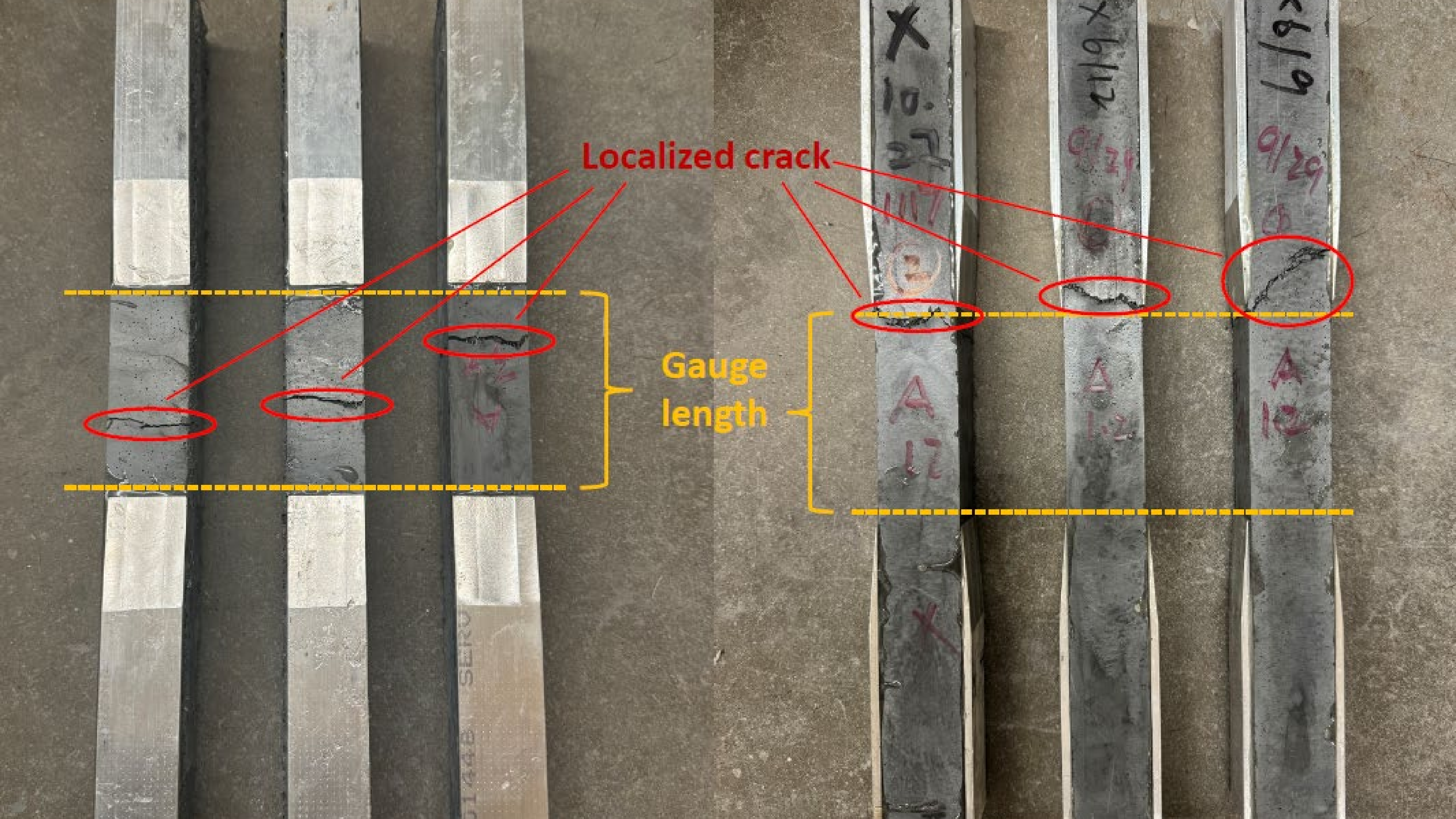


Tensile Properties
AASHTO T397-22



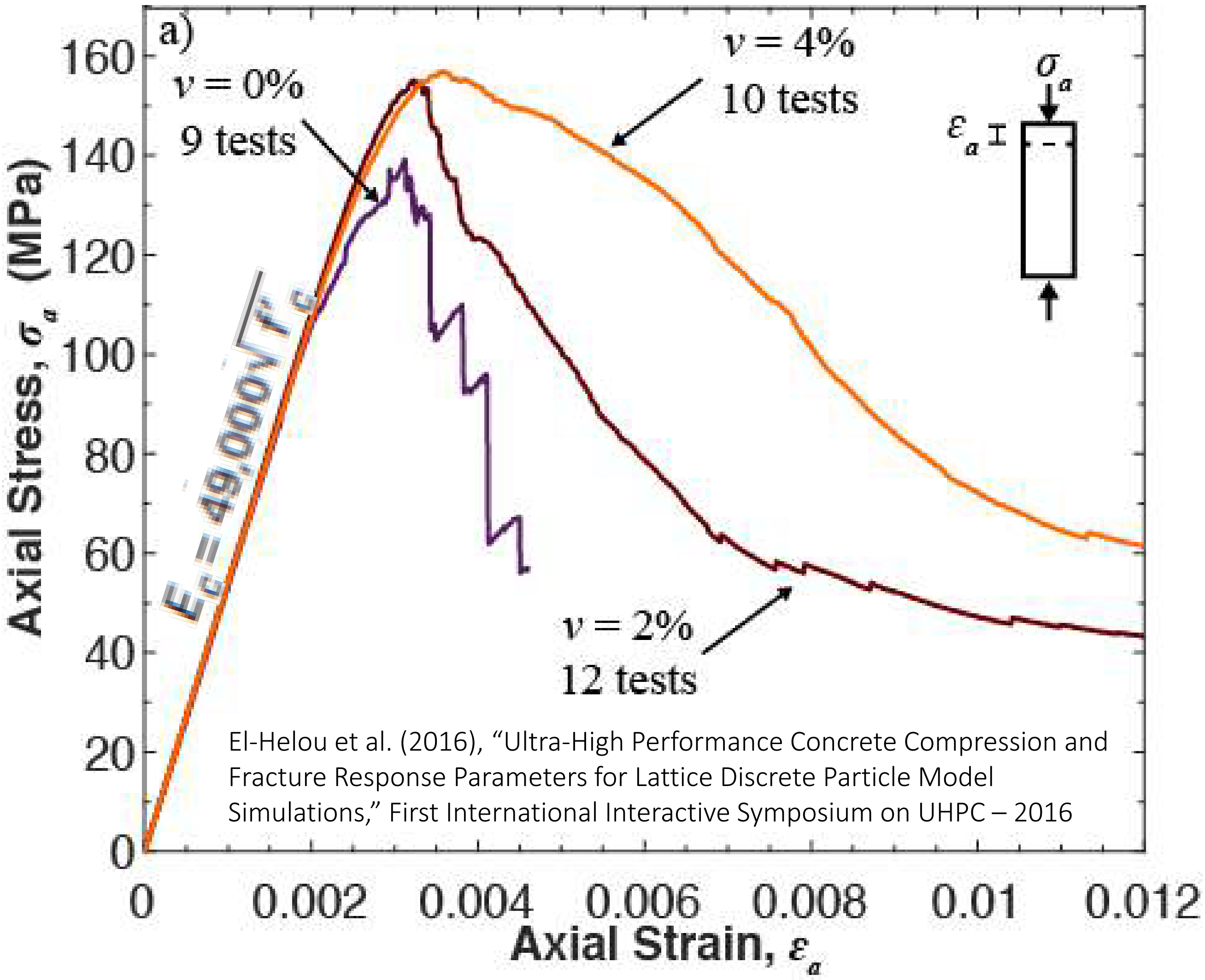
Tensile Properties
AASHTO T397-22




Localized crack
Gauge length

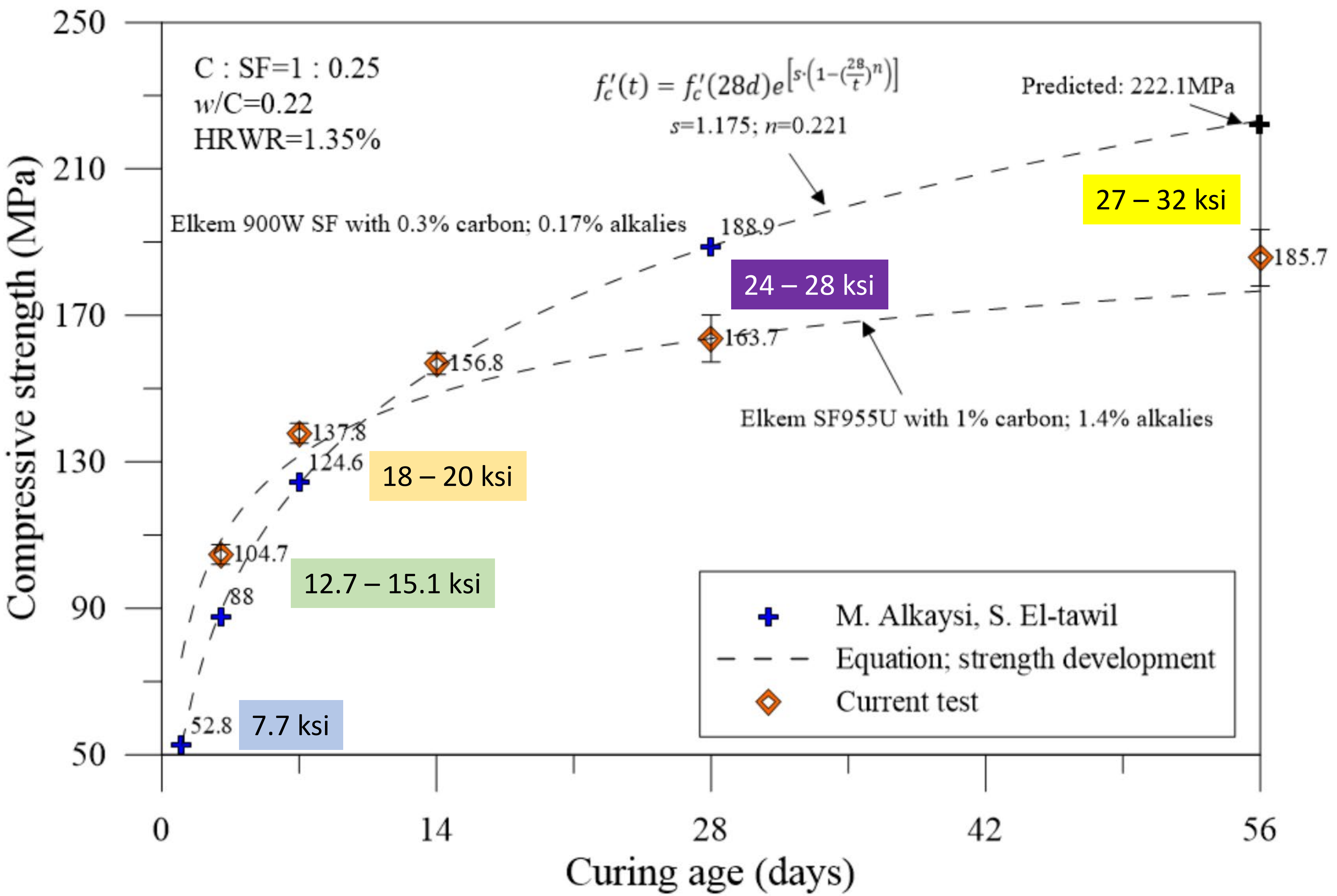
Compressive Testing
ASTM C109

Compression Response



El-Helou et al. (2016), "Ultra-High Performance Concrete Compression and Fracture Response Parameters for Lattice Discrete Particle Model Simulations," First International Interactive Symposium on UHPC – 2016

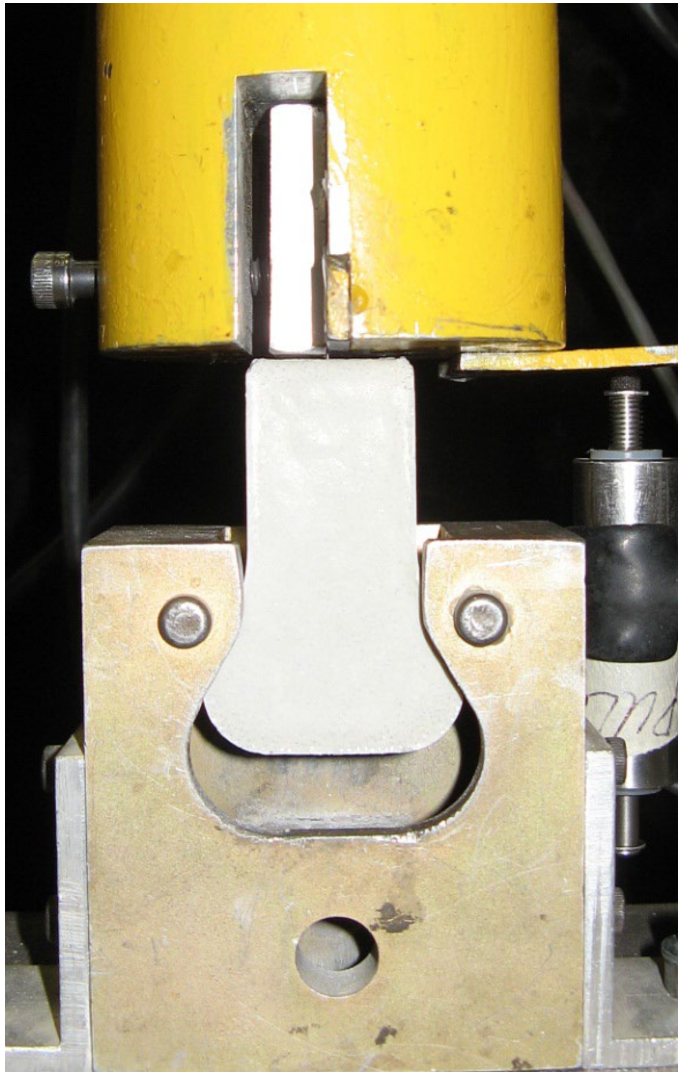
Strength Gain vs. Time

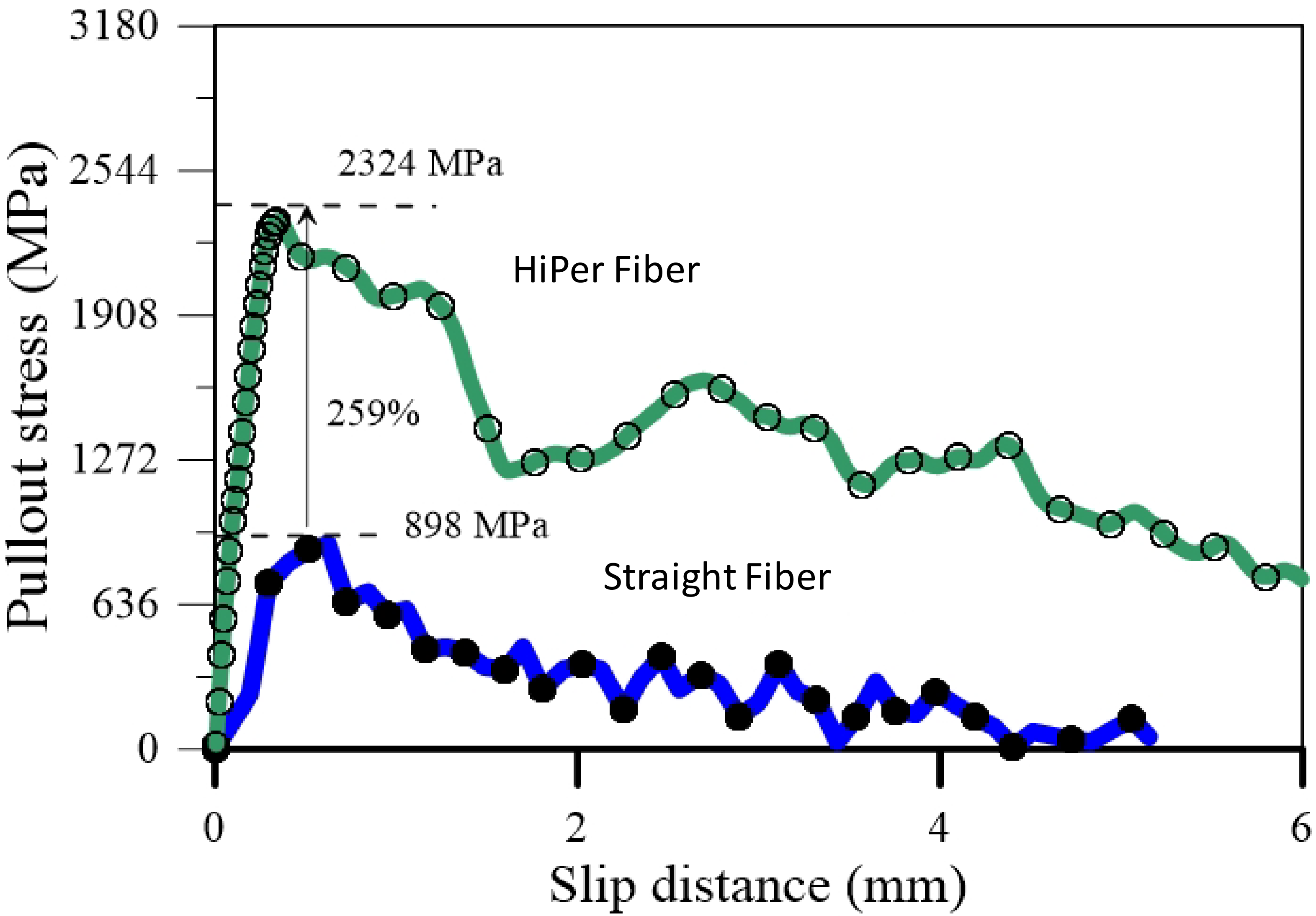


Role of Fibers

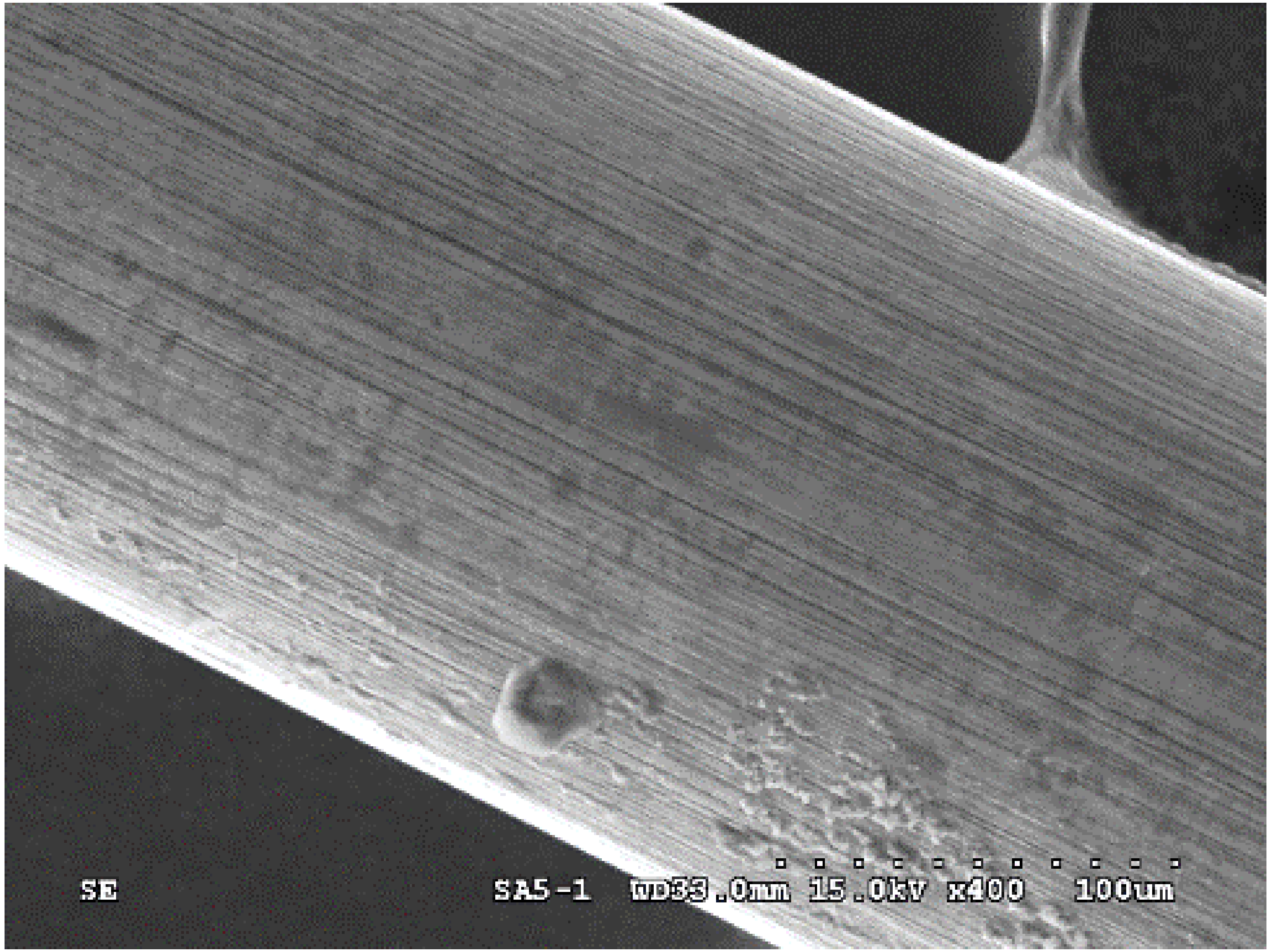
- Fibers ‘hold’ the material together
- The bond behavior between fibers and the UHPC matrix directly influences the mechanical properties in the composite level
- Bond behavior is activated when fibers bridge cracks that are trying to open further
- Fibers promote beneficial strain hardening tensile behavior
- Optimal UHPC response is achieved by carefully tailoring the fiber-matrix bond characteristics
  - Too high: promotes early fiber breakage and leads to brittle behavior
  - Too low: allows fibers to pull out easily, limiting their contribution
  - Must be just right!

Pullout Test to Determine Fiber Performance



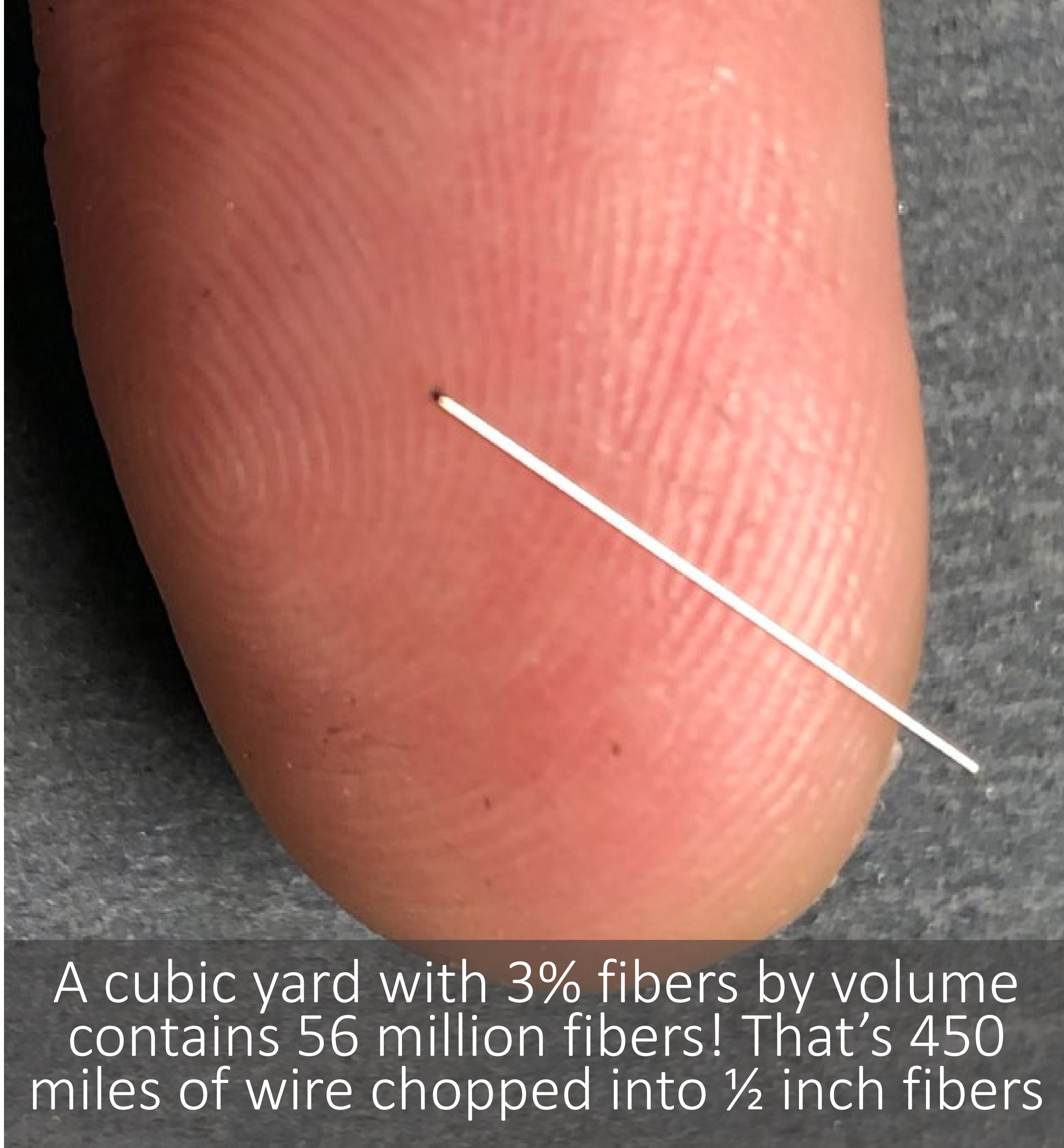


Fiber Pullout



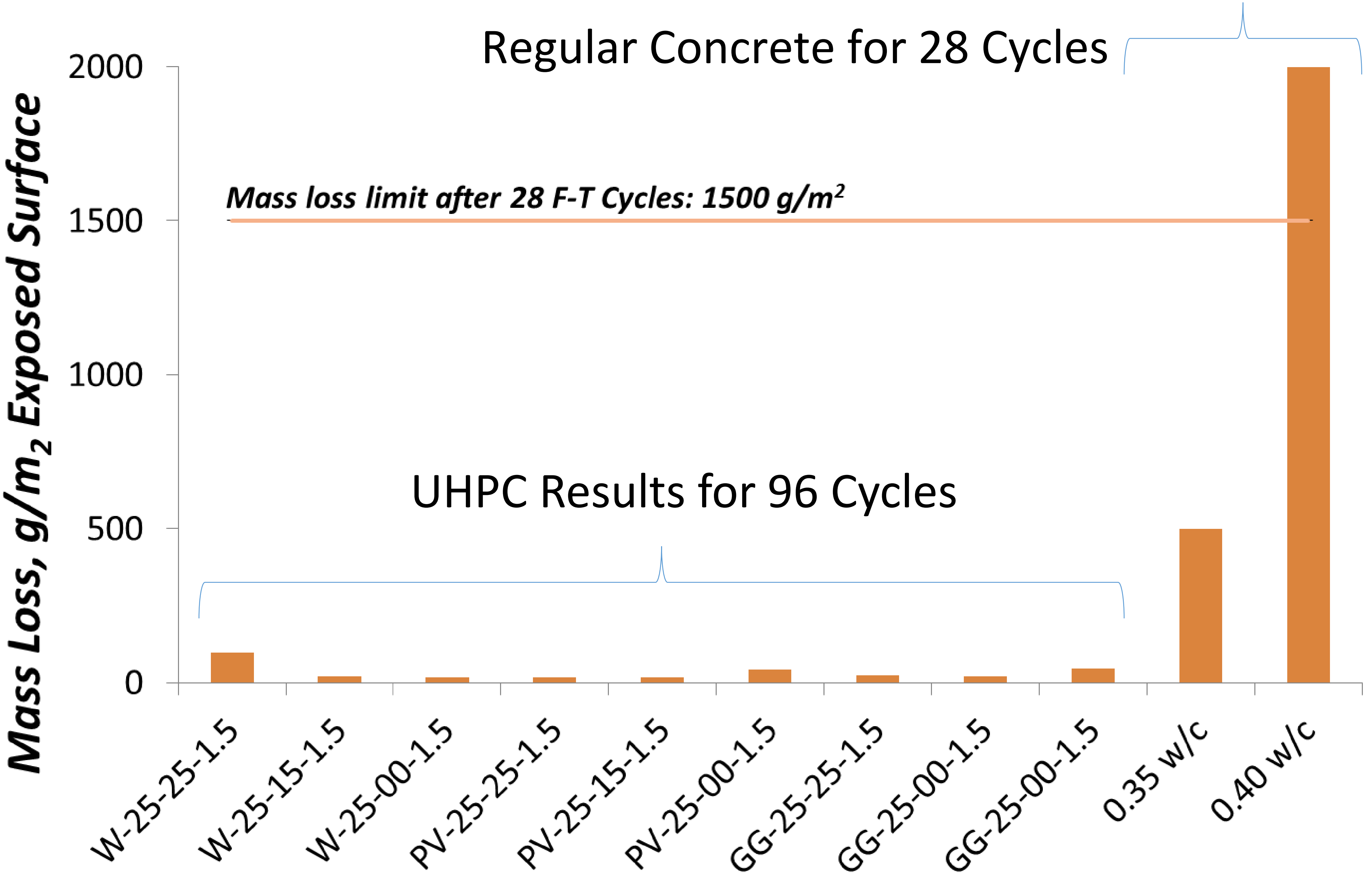
Research Results

- The result of thousands of single fiber pullout and coupon tests:
  - Thinner fibers are better
  - Longer fibers are better
  - However, longer fibers can lead to mixing problems, so there is a practical limit to length
  - Deformed fibers can lead to over-reinforcing
- Best, balanced performance achieved by straight, 13 mm x 0.2 mm OR 19 mm x 0.2mm fibers

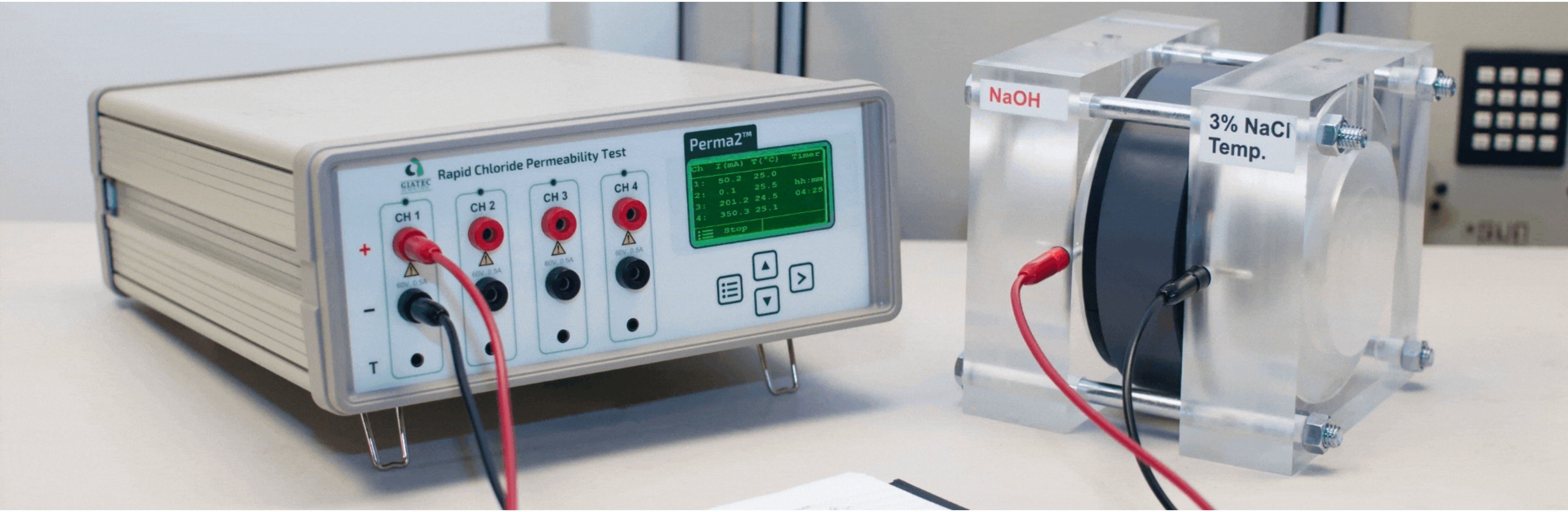


Freeze Thaw Performance

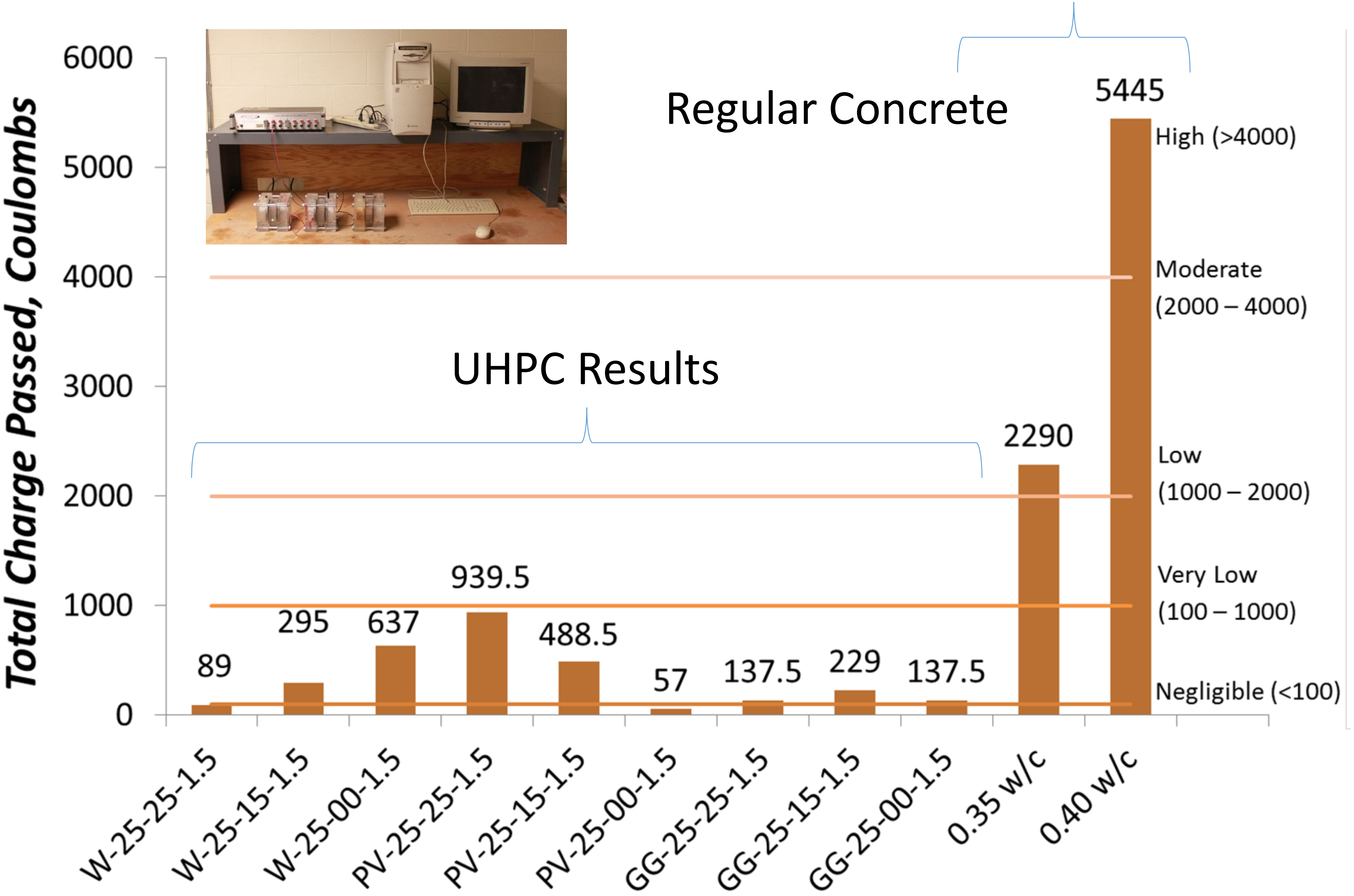
Freeze-Thaw Resistance
RILEM TC 176-IDC



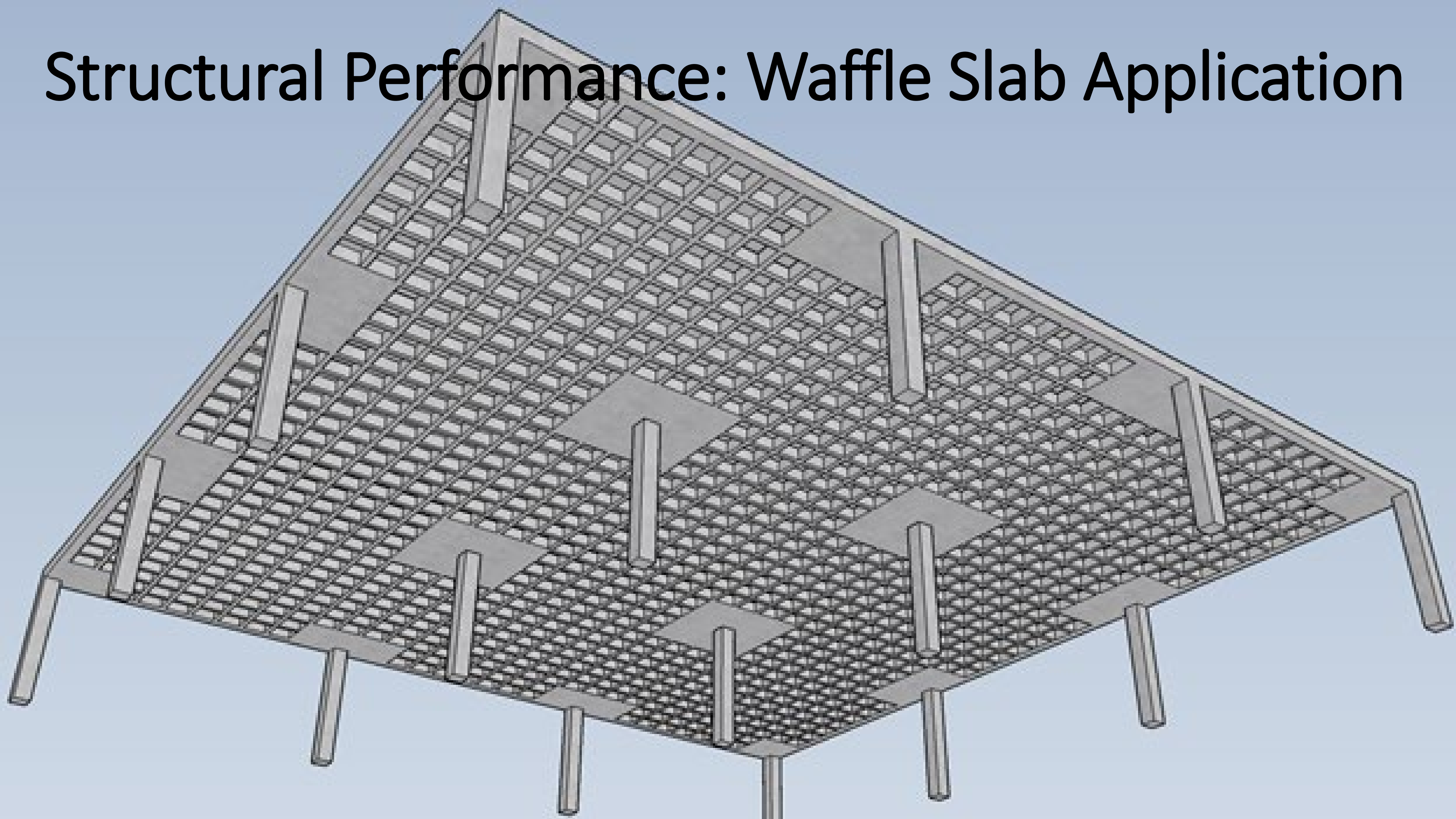
Rapid Chloride Penetration Test



Rapid Chloride Test (ASTM C1202-12)

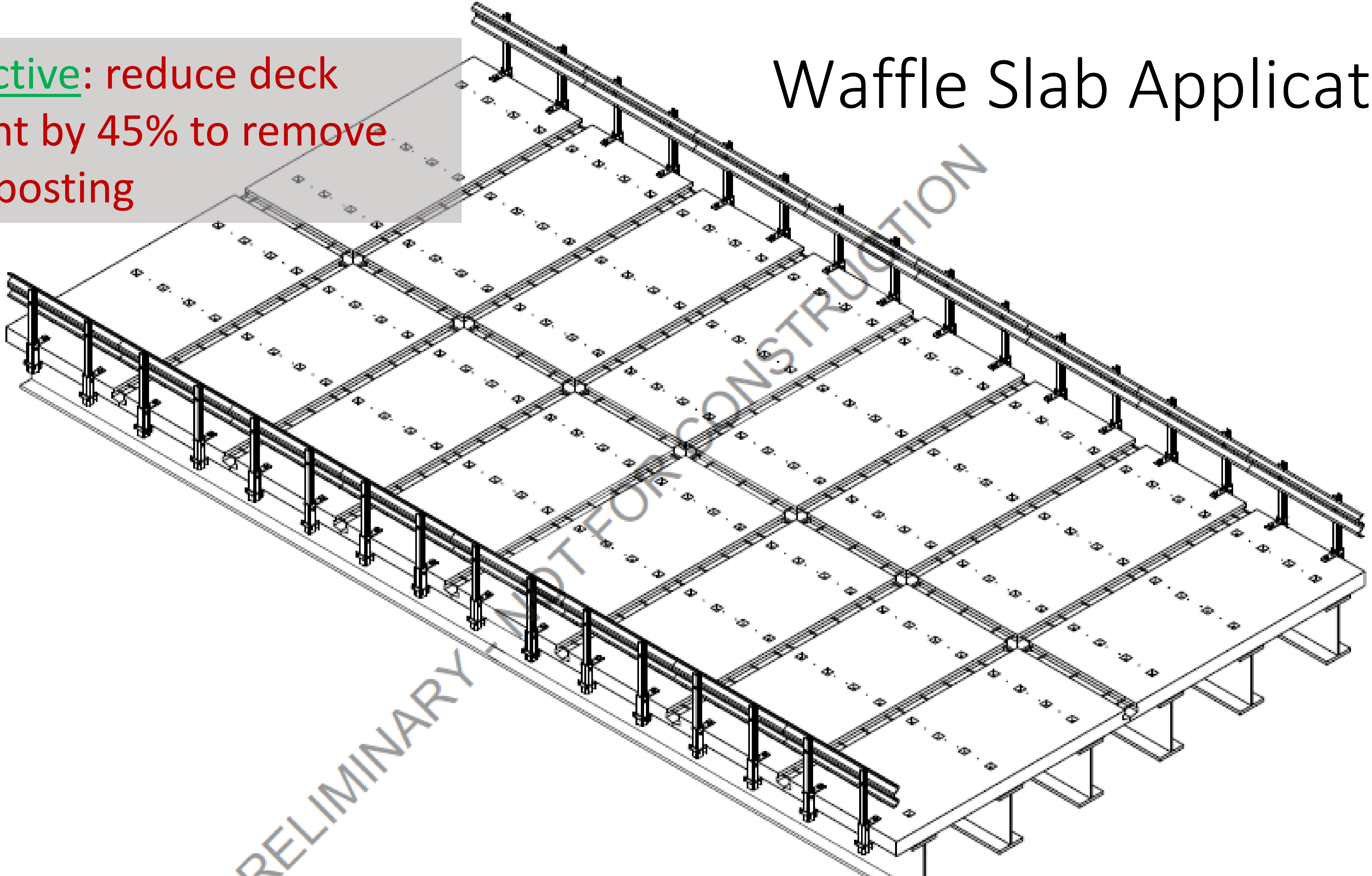


Structural Performance: Waffle Slab Application

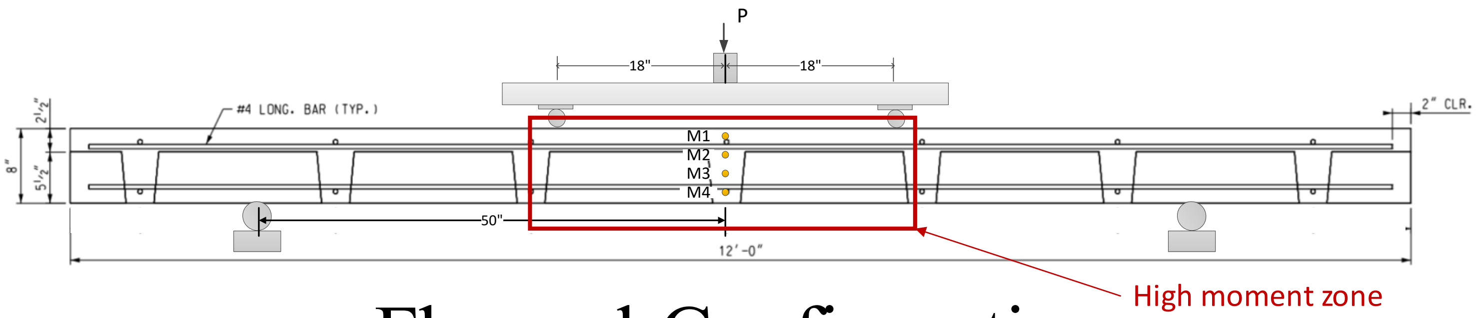


Waffle Slab Application

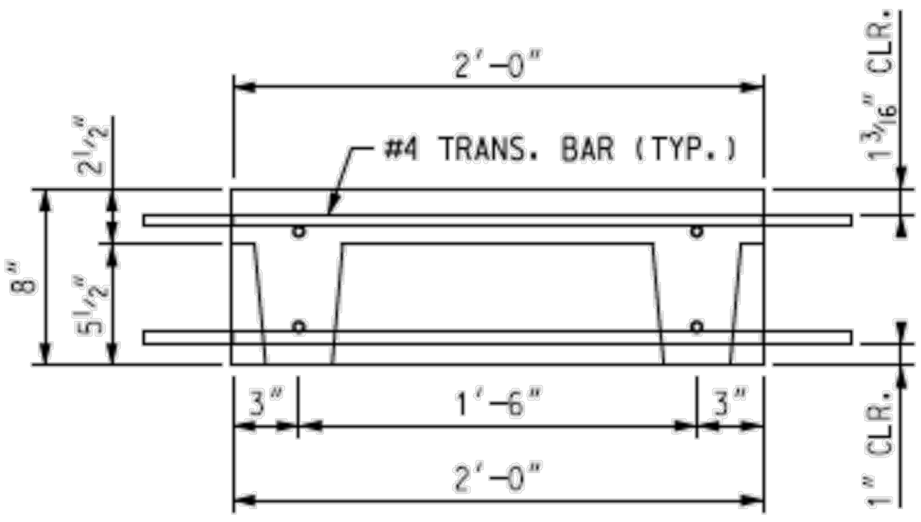
Objective: reduce deck weight by 45% to remove load posting



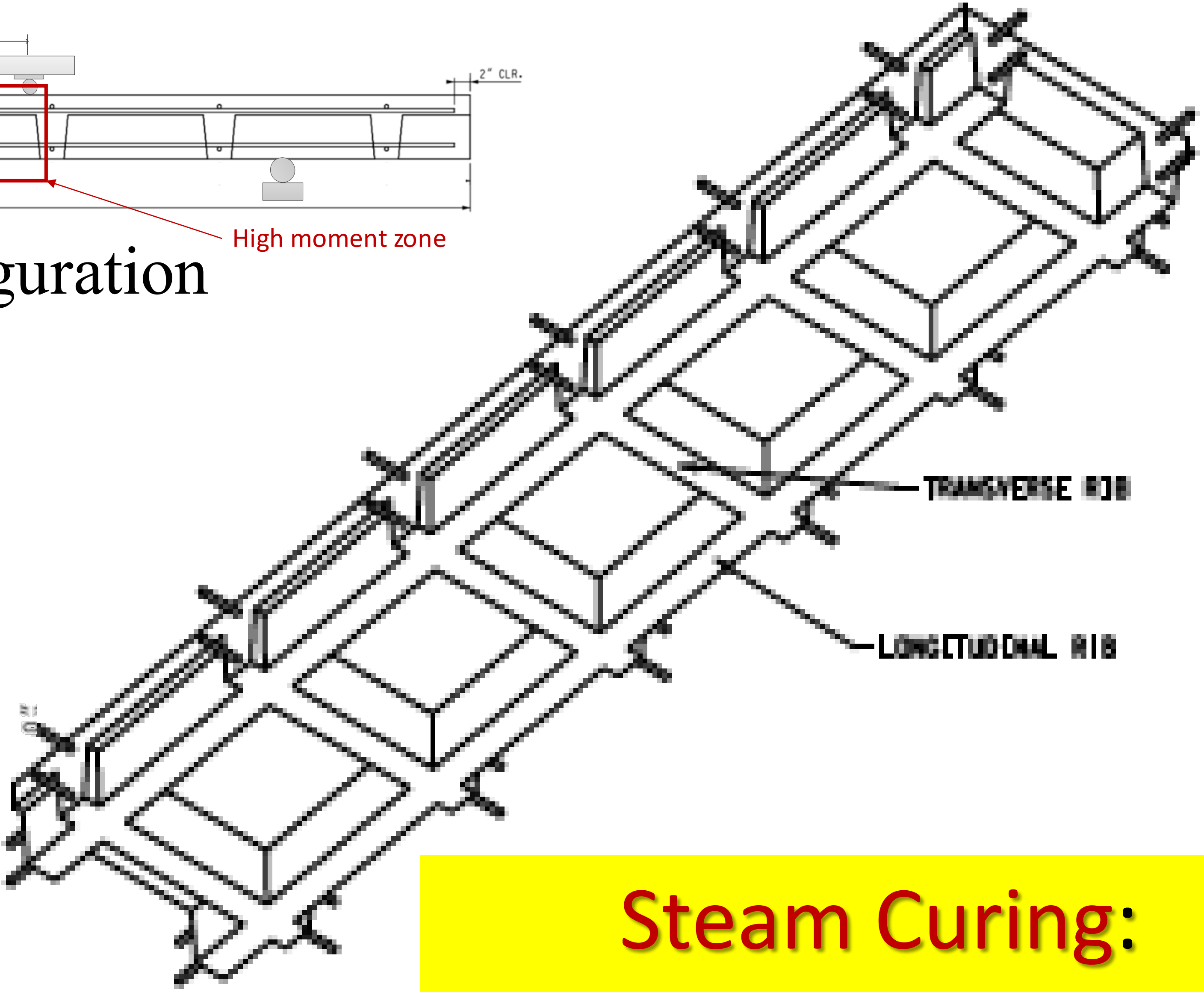
UHPC WAFFLE SLAB SAMPLE BRIDGE LAYOUT



Flexural Configuration



FRONT SECTION C-C



BOTTOM ISOMETRIC

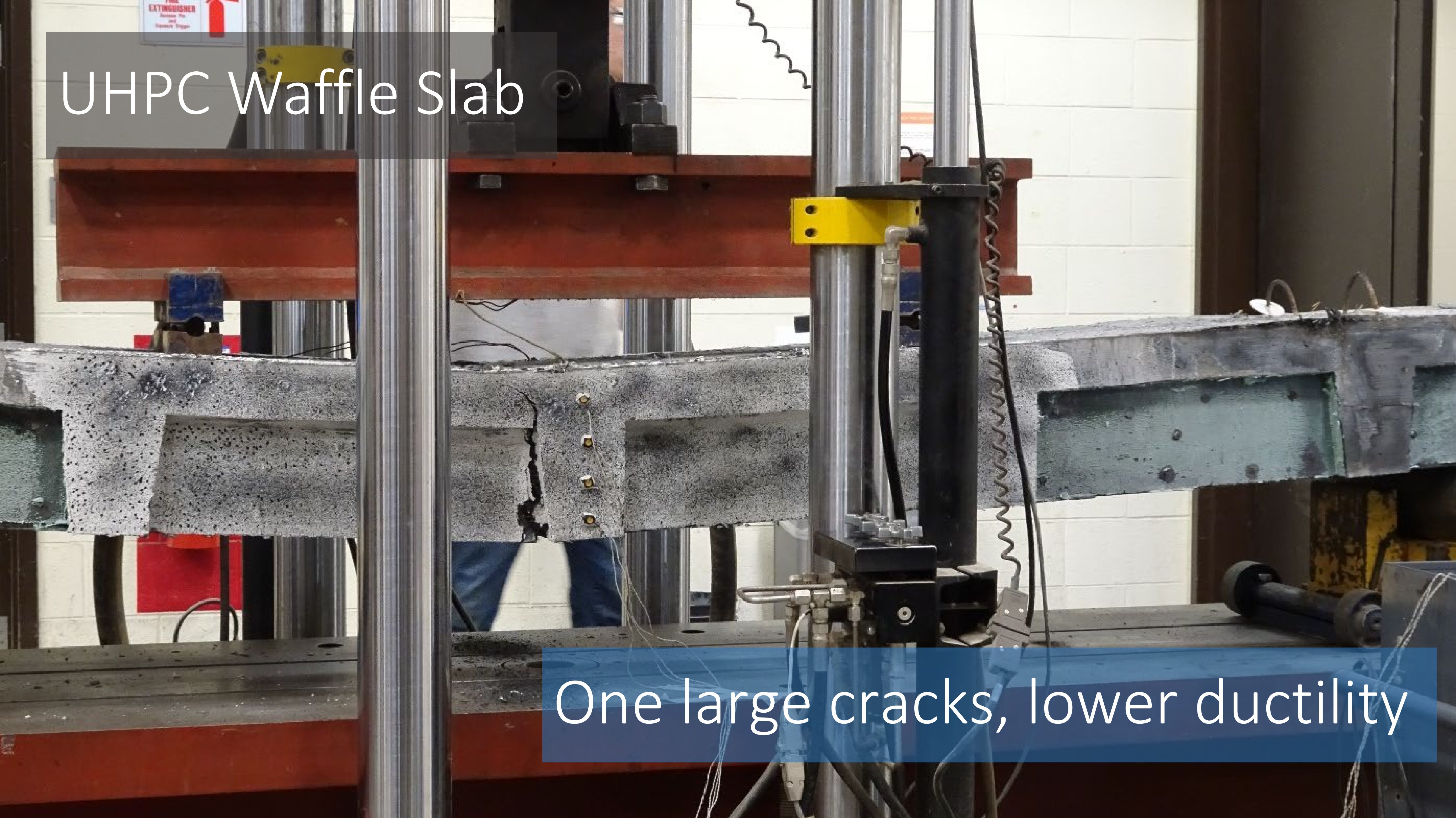
Steam Curing:

Full strength in 2 days

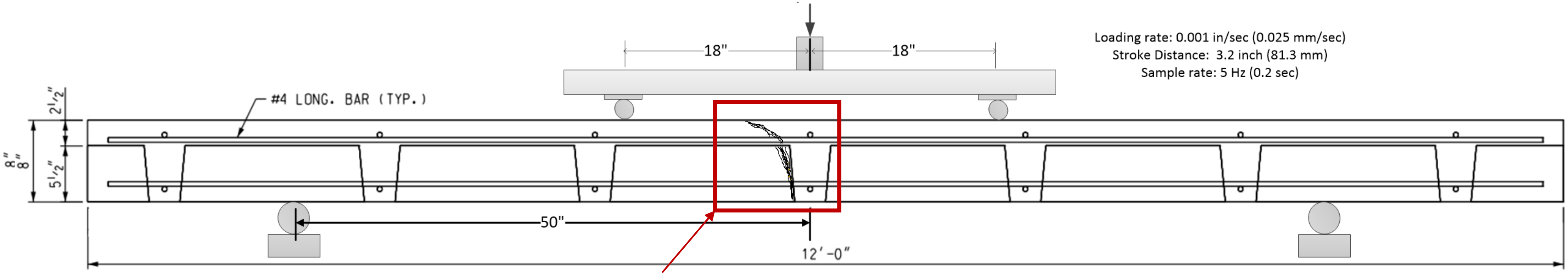
Waffle Slab Tests

FRC (17 ksi) Waffle Slab

Multiple large cracks, high ductility

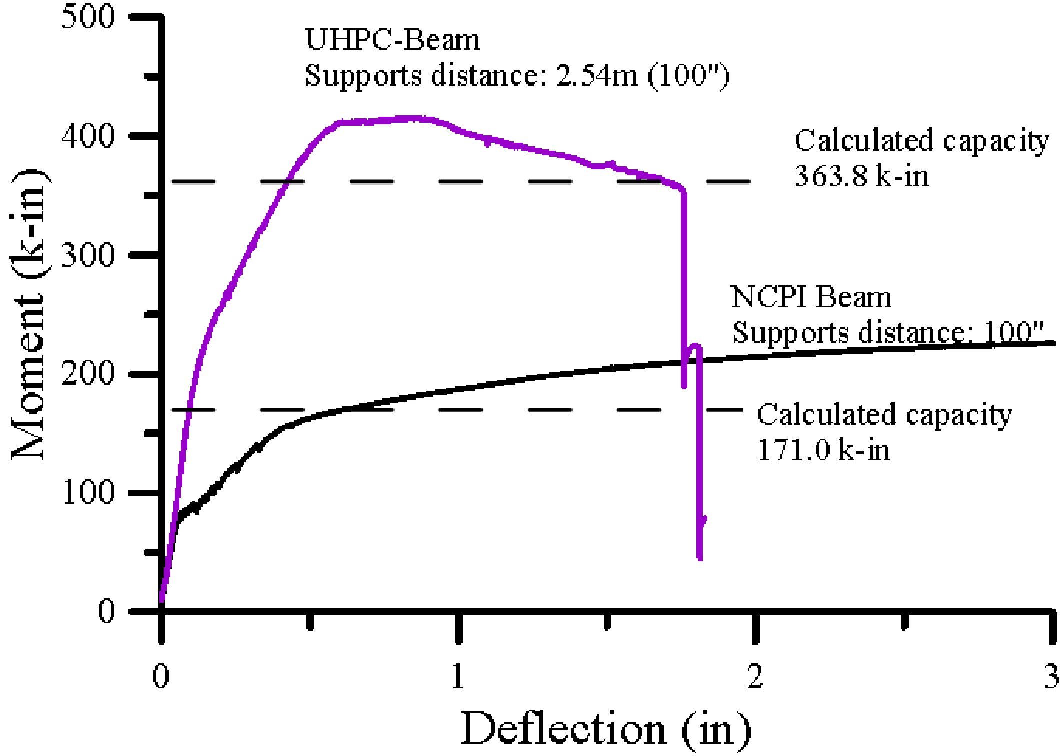

UHPC Waffle Slab
One large cracks, lower ductility

UHPC beam test and DIC results - FLEXURE

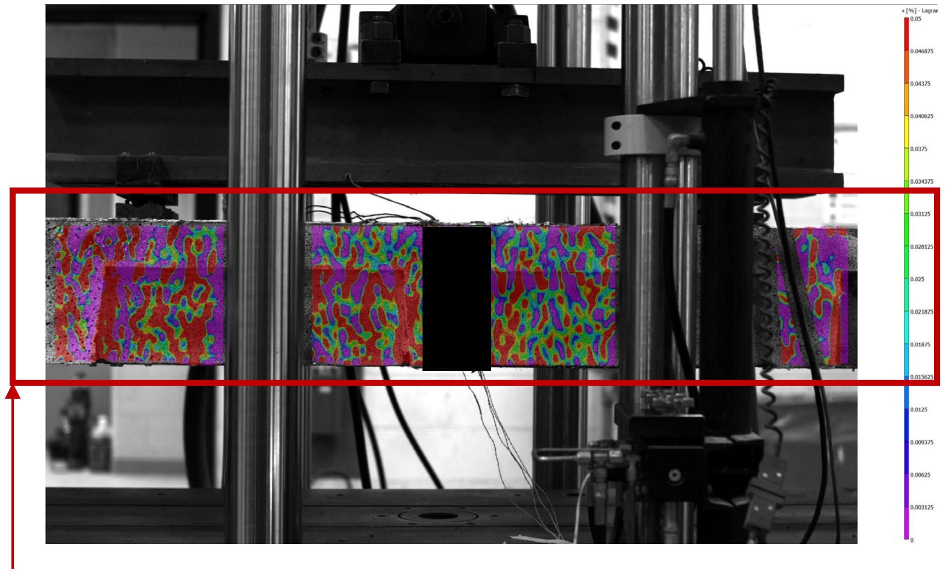


Loading rate: 0.001 in/sec (0.025 mm/sec)
Stroke Distance: 3.2 inch (81.3 mm)
Sample rate: 5 Hz (0.2 sec)

Single crack localization



M_{yield} ===> $\delta = 2.53\ mm$



Only micro-cracking at steel yield – excellent protection under service conditions

Ductile Material – Less Ductile Structures?

- Strain hardening causes cracks to localize in one spot
- High bond between bars and UHPC cause steel strain demands to become high at that location
  - Steel strain concentrates at the location of the crack leading to early fracture
- Disadvantage
  - Structural ductility is inhibited
- Advantage
  - Greater flexural strength
  - Micro-cracking is persistent up to steel yield
    - Steel rebars will be protected against corrosion up to steel yield
- What is an acceptable flexural design philosophy for UHPC beams?

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UHPC presentation

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Instructions

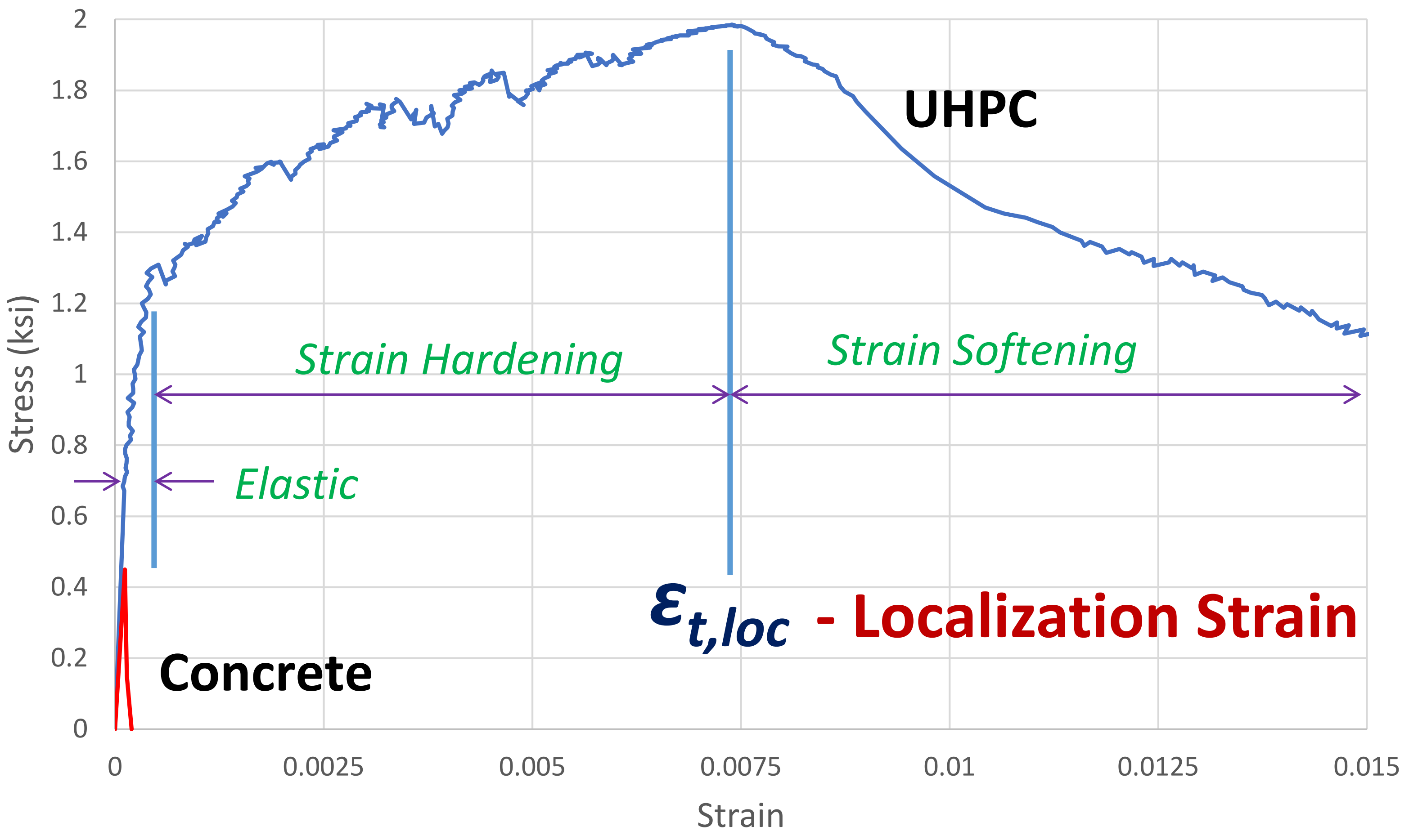
Why is UHPC so Durable?

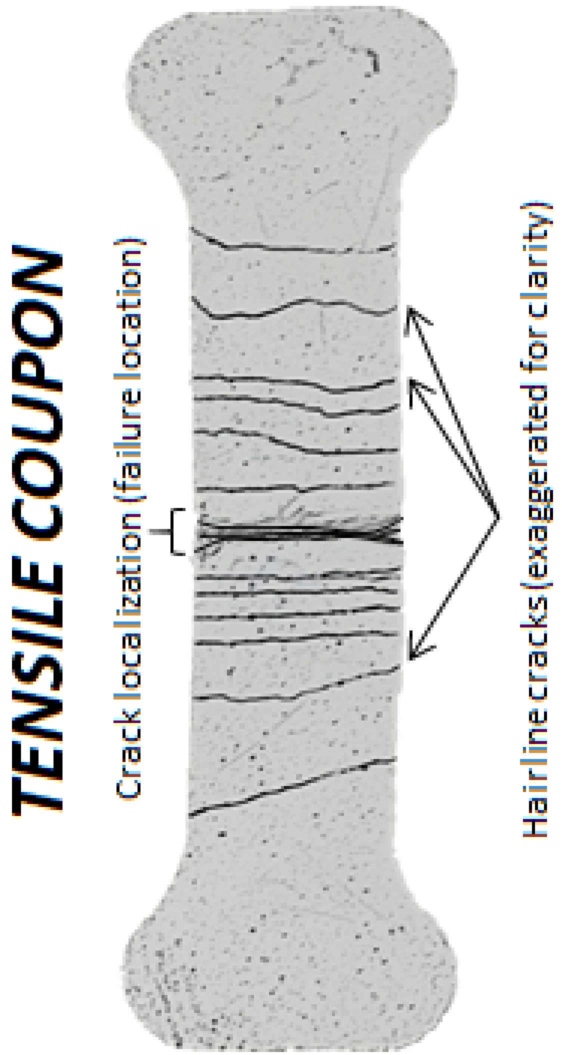
The ductility of UHPC beams is limited because:

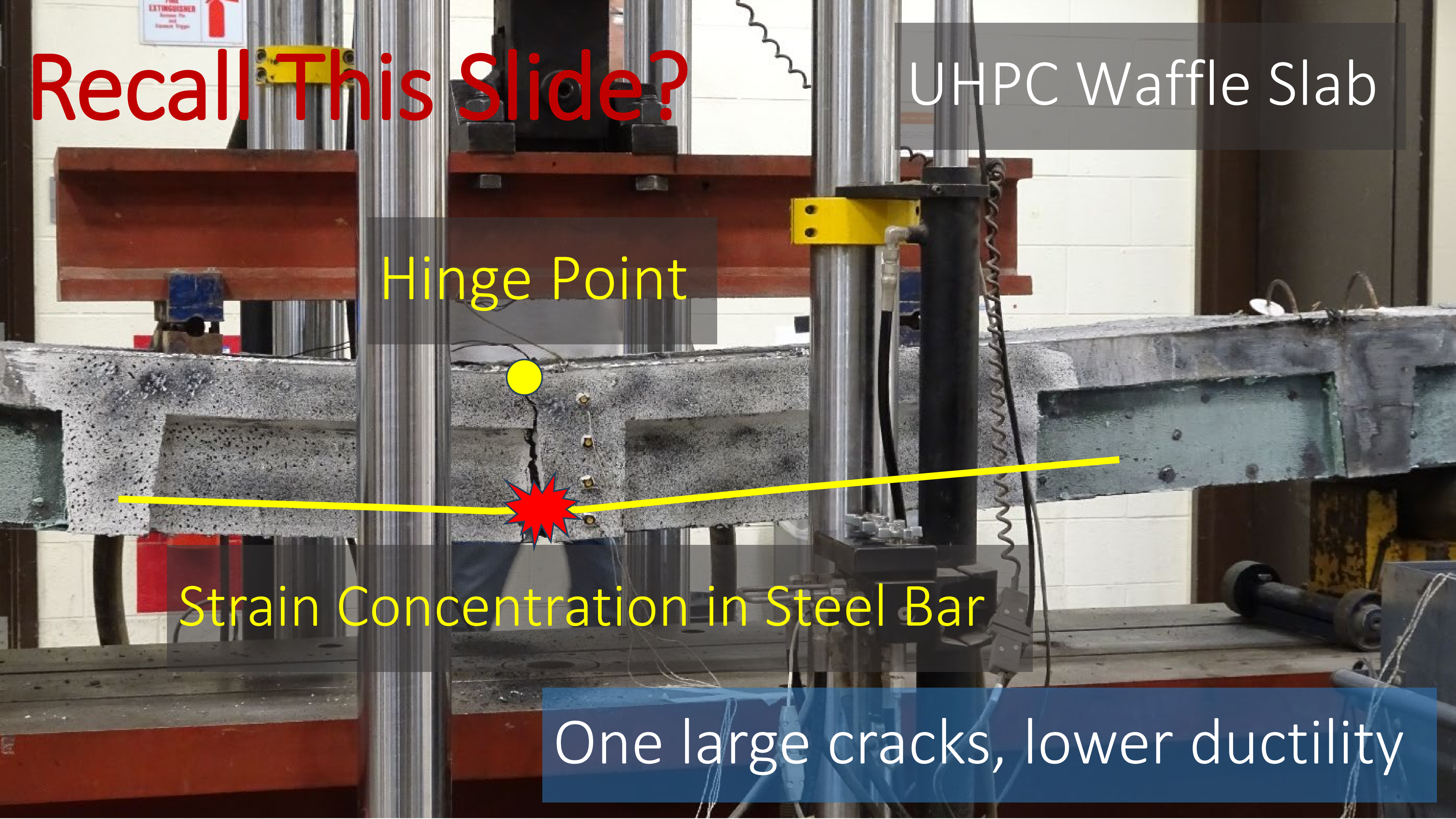
Fiber clumping is a sign of:

Recall This Slide?

Strain Hardening Response of UHPC in Tension






Recall This Slide?
UHPC Waffle Slab
Hinge Point
Strain Concentration in Steel Bar
One large cracks, lower ductility

Session 2
Production of UHPC

Mix Ingredients/Weights (for a Cubic Yard)

Cement (Portland Type I or IL): 653 lb
Slag Cement (GGBS 100): 653 lb
Silica fume: 327 lb
Water: 277 lb = 33.2 gallons
HRWR (3% using Sika ViscoCrete 2100): 39.2 lb (550 oz)
Steel fibers (2% by volume): 265 lb
Fine sand (grain size 100-300 micron): 396 lb
Coarse sand (grain size 400-900 micron): 1585 lb
Defoaming agent (like Air Out from Euclid or Sika Perfin 305): 4 lb

Note 1: Water/cement ratio is 0.23. If it is hot (say above 80 degrees ambient temperature), you could use ice (20% - 40% of water) to aid in mixing.
Note 2: If you use a light-colored silica fume, you may need to reduce the HRWR a bit
Note 3: Batch trial is recommended
Note 4: This information is not warrantied. You must conduct your own testing to ascertain performance.

Production of UHPC

The mix protocol is as follows:
Dry mix: 10 minutes
Add water and HRWR over 1 minutes
Wait for turnover (fluidity), which usually occurs within 5 minutes
Mix another 10 minutes after turnover.
Add fibers gradually over 2 minutes
Mix for ten minutes then cast.

Mixers
Can be mixed in most mixers including ready-mix trucks.

Production of UHPC

<u>Some Suggested Suppliers</u>

- Cement and slag can be obtained from St Mary or you can get them from any supplier.
- Elkem Silica fume: Type 965. Contact: Richard Wolf (Richard.wolf@elkem.com)
- Silica Sands: SHORT MOUNTAIN, Silica Sands 3070 (coarse sand) and glass sand (fine sand) respectively; Tom Rose; Email: trose43@msn.com
- Silica sand can also be obtained from US SILICA: The trade names are Flint 12 (coarse sand) and F75 (fine sand). Short Mountain is another supplier. HRWR (superplasticizer):
- Sika ViscoCrete 2100; burnett.doug@us.sika.com
- Steel fiber, Type X: HiPer fiber (sales@hiperfibersolutions.com)
- Defoaming agent can be obtained from Sika, or Euclid Chemical (air out): https://www.euclidchemical.com/products/admixtures/specialty-admixtures/air-detrainers/eucon-air-out/

STEPS

1. Batching
2. Mixing
3. Forming
4. Transporting and Placement
5. Finishing
6. Curing

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

1-BATCHING OF UHPC

a) Clean sand with controlled moisture (ASTM C133 or C144)

b) Dry stored cementitious materials (no hard lumps)

c) Dry and covered fibers to prevent oxidation

d) Chilled water or ice to control mixture temperature (50 – 80° F)

e) Admixtures within shelf-life and not exposed to freezing

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

Mixing Technology: Experimental Variables

- Material source
- Material quantities
- Mixer type
- Mixing speed

Mixing Equipment (Outside View)

(a) Rotating pan mixer (F1)

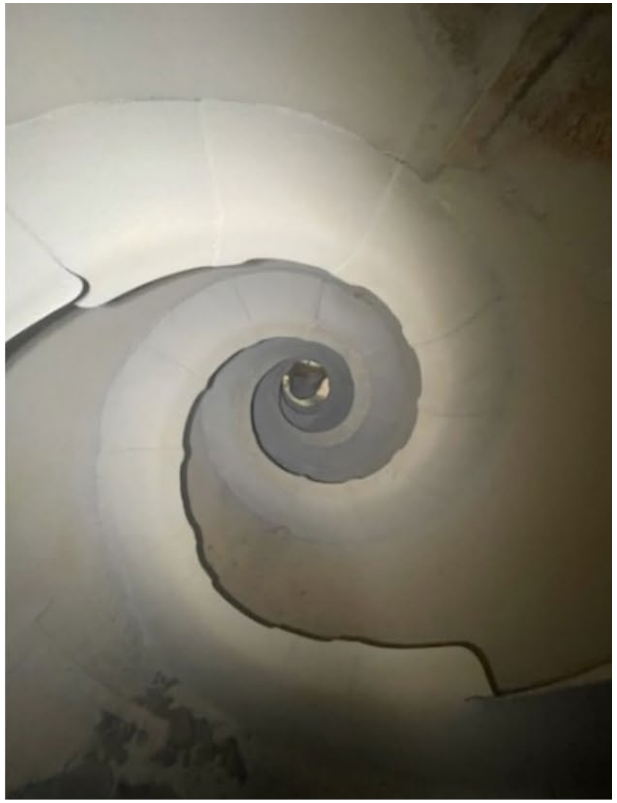
(b) Rotating drum mixer (F2)

(c) Truck mixer (T)

Mixing Equipment (Inside View)

(a) F1 mixer (note side scrapers and high shear ‘whirler’ blades)

(b) F2 mixer (note fixed blades)



(c) T mixer (note spiral blade)

Consistency of Well-Mixed UHPC

2-MIXING UHPC

- Failure to mix UHPC properly could result in:
  - Lack of workability
  - Clumping of fibers or paste
  - Fiber segregation

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Fiber Clumping

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

Fiber Segregation

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

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UHPC presentation

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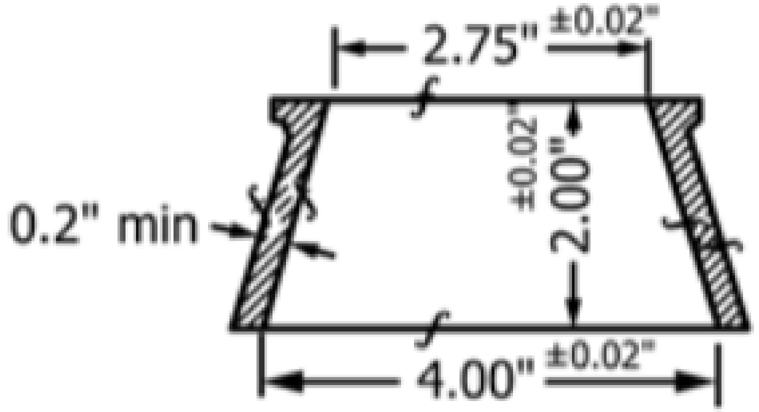
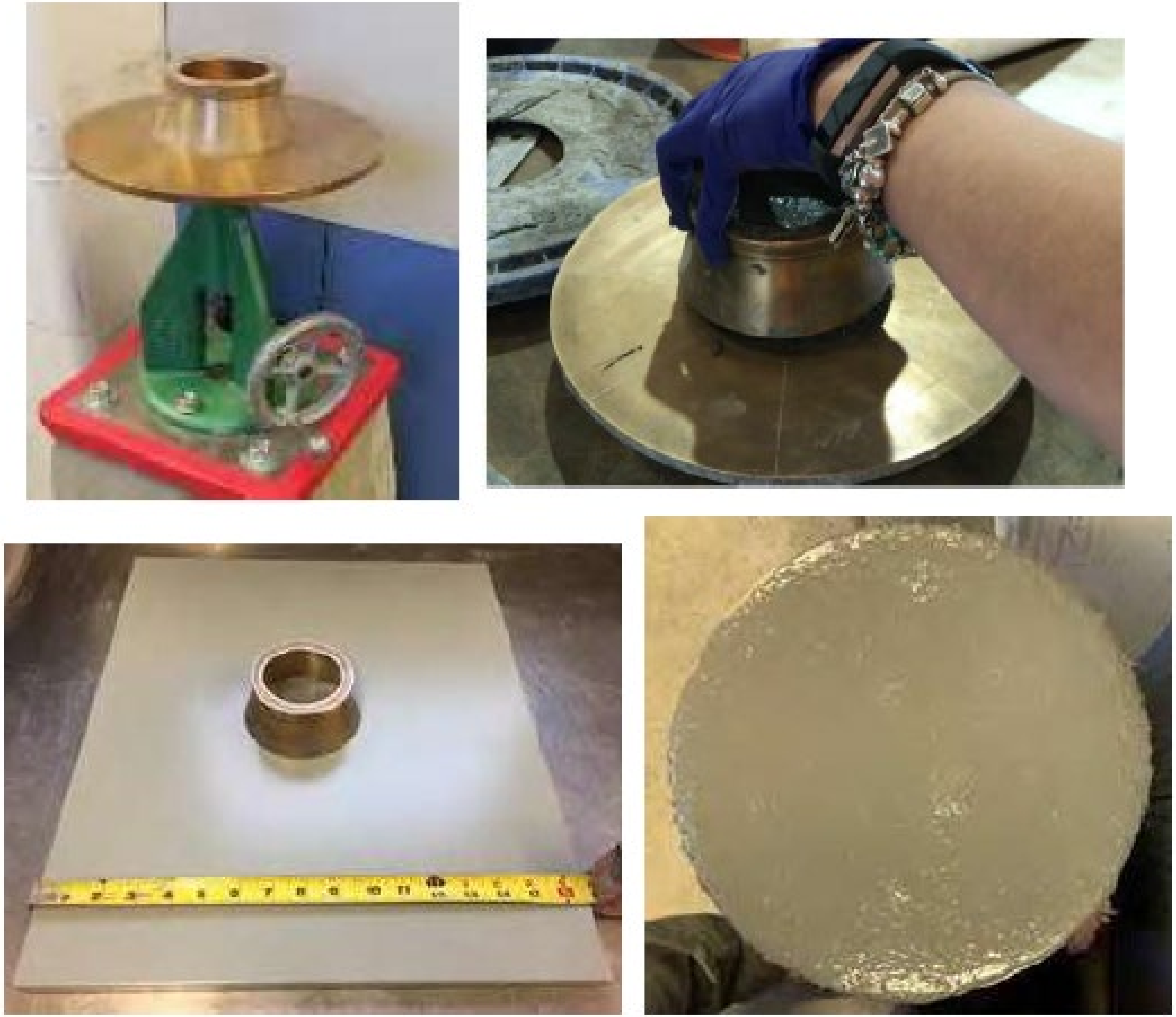
Why is UHPC so Durable?

The ductility of UHPC beams is limited because:

Spread Test for Quality (ASTM C1437)



Conical mold



From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

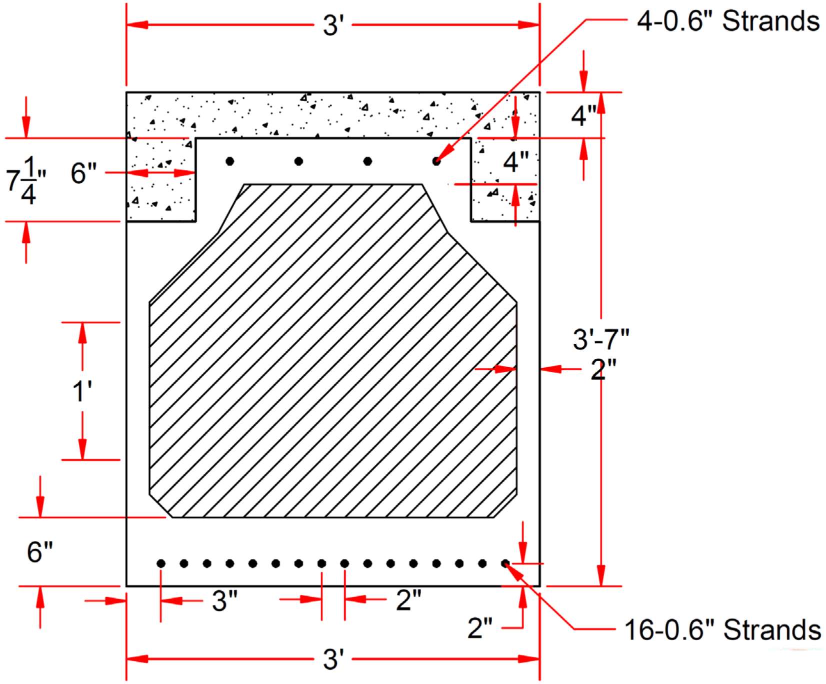
Spread Test Requirements

	ASTM C1856	FHWA	NYDOT	DCDOT	Caltrans	MDOT	GADOT	IADOT
Flow range (in)	8 to 10	7 to 10	7 to 10	7 to 10	7 to 10	7 to 12	7 to10	7 to 10

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

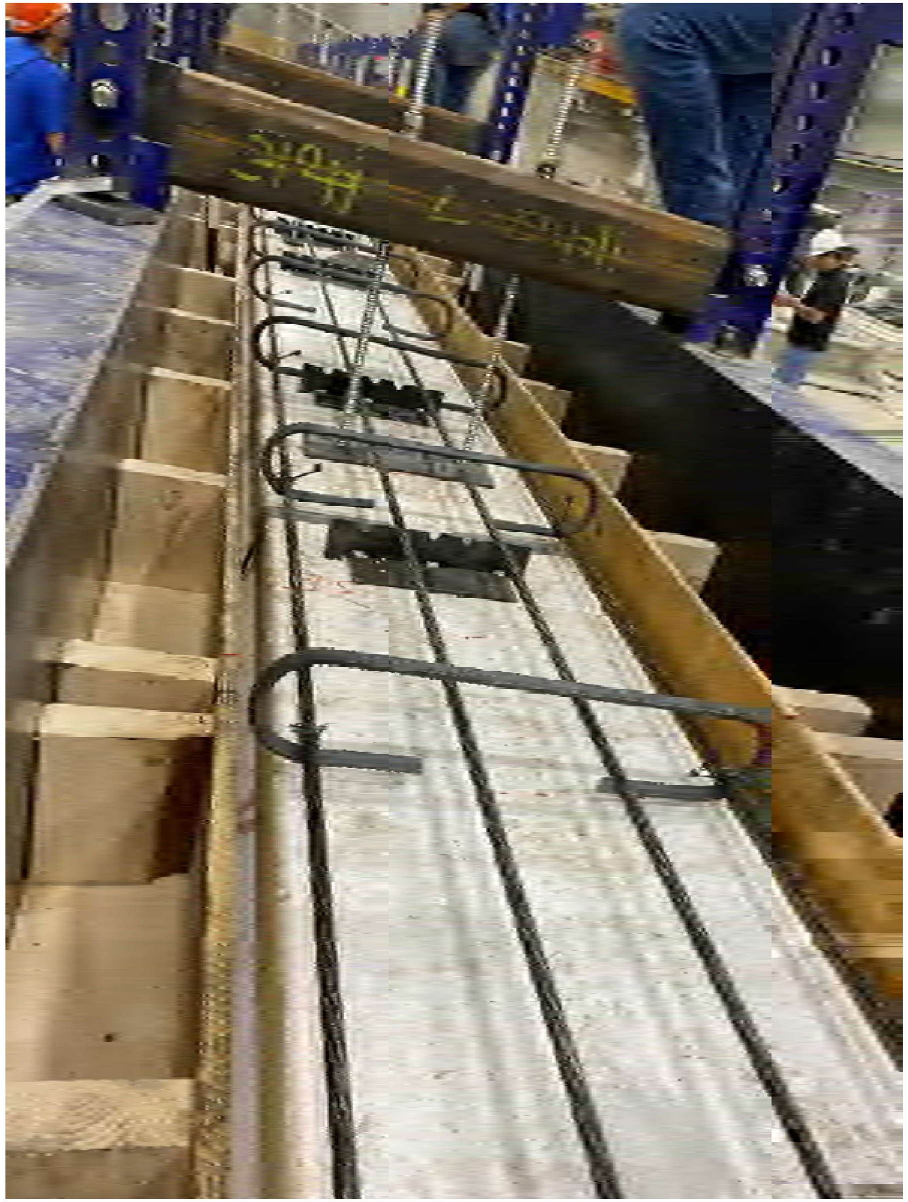
3-FORMING FOR UHPC

- Any forming material that is non-absorbing (plywood, steel, fiberglass, foam, concrete, etc.)
- Use chamfers, curves, and form release agents for ease of stripping
- Clear spacing between bars and formed surfaces is at least 1.5 x fiber length (min. ¾ in.)



From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

Full hydrostatic fluid pressure (use 160 pcf)



From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

Surface preparation of hardened concrete: Sandblasting or exposed aggregate plus pre-wetting

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Top form if sloped

Grout-tight forms

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

FORMING

- FHWA - UHPC is typically places in a closed form, or the form is closed immediately after placement. On flat surfaces exposed to air, UHPC should be in contact with the top formwork to minimize surface dehydration. Formwork that will be in contact to UHPC should have a non-absorbing finish.
- MIDOT - The forms must be water tight and coated to prevent absorption of water. The formwork must be resistant to the hydraulic pressure of the mix.
- DCDOT - medium density overlay plywood pre wetted just ahead of the UHPC material. They need to be hand removal.

U.S. Department of Transportation Federal Highway Administration

MDOT Michigan Department of Transportation

District Department of Transportation

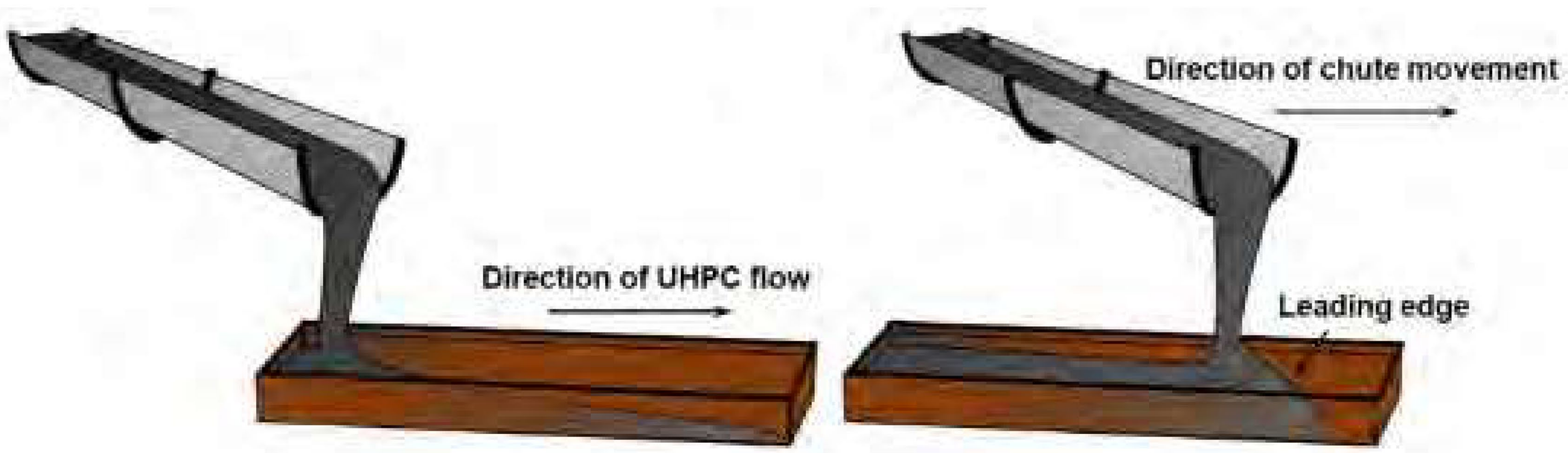
From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

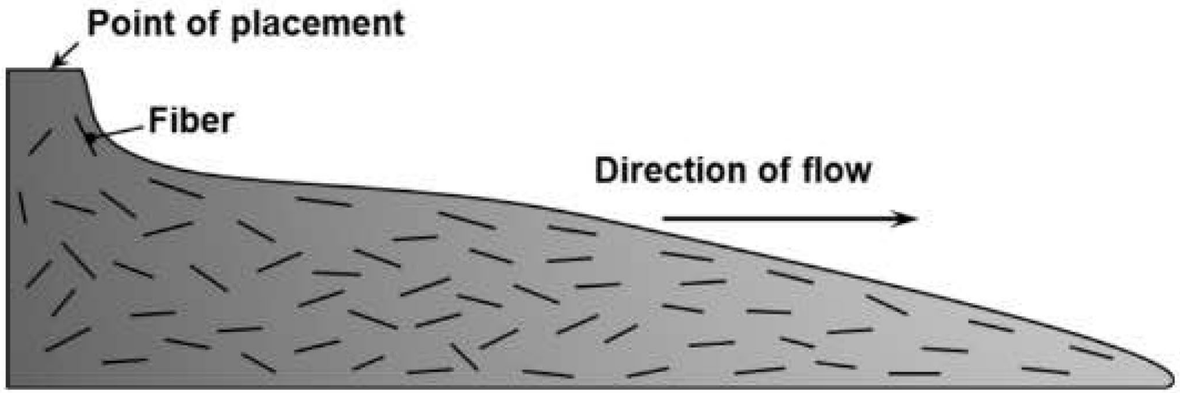
4-TRANSPORTING AND PLACEMENT

Any method that minimizes the following:

- Entrapment of air (cast from one side)
- Fiber segregation (no internal vibration)
- Forming cold joints/pour lines (min. time between lifts)
- Unfavorable alignment of fibers (direction of flow)
- Failure to fill the forms (add pressure head)
- Free Fall

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications





From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

CASTING

- FHWA - UHPC should not be internally vibrated because of the detrimental impact that this type of vibration has on the fiber reinforcement.
- Caltrans - UHPC does not free-fall more than 2 feet, there are no cold joints and steel fibers has to be uniformly distributed.
- MIDOT - Pumping Mi-UHPC is not permitted. Do no place concrete at ambient air temperatures below 40°F, nor above 90°F. The fresh mix must not be allowed to flow farther than 24 inches during placement. Start the casting process at one end of the joint and proceed to the other end at a speed comparable to the flow speed of the fresh mix. Once the other end of the joint is reached, reverse the casting process and proceed in the other direction to cast another layer of Mi-UHPC. Continue this process until the full depth of the joint has been cast. Vibrators may not be used.

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

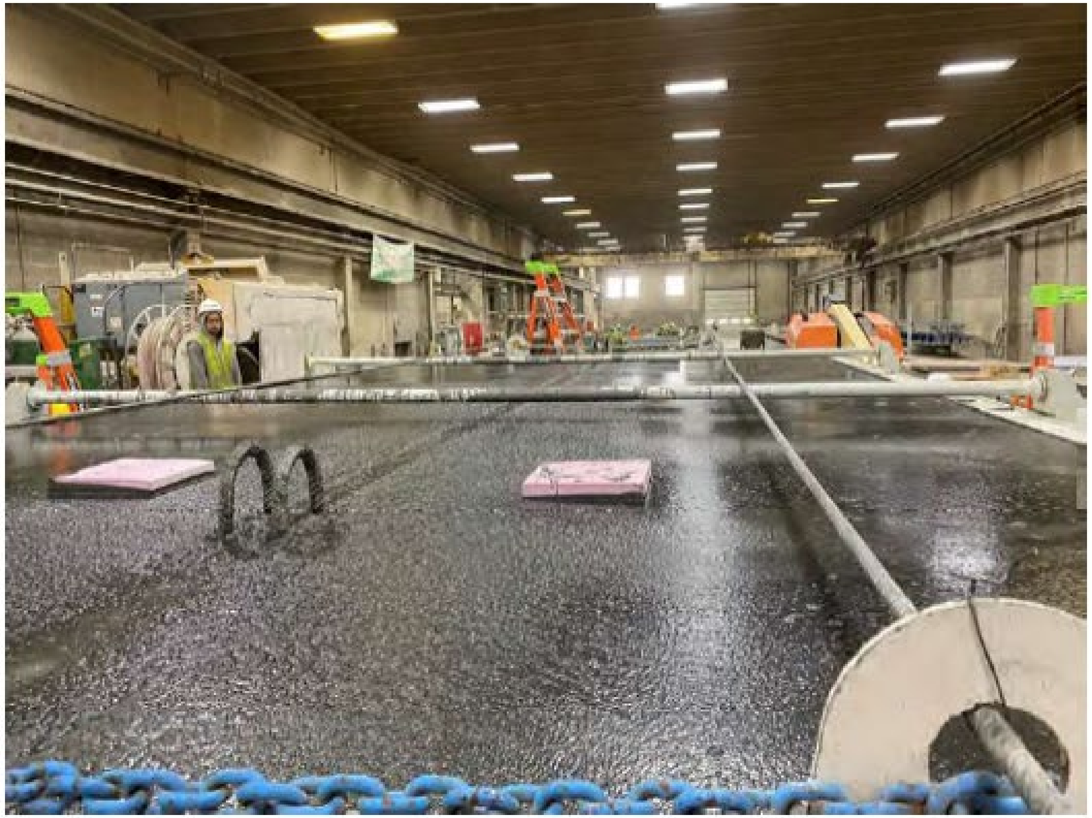
5-FINISHING

- Traditional finishing methods (screeding, raking, brooming) do not work with UHPC
- Spiked roller could be used to level the surface
- Vibratory screed is needed for stiff UHPC

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

5-FINISHING

- Highly flowable UHPC could result in smooth surface without intervention



From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

5-FINISHING

- Grinding of the UHPC surface can be performed when strength is at least 10 ksi, otherwise significant fiber pullout can happen.
- It is easier to grind joints when the strength is around 12 ksi than it is at full strength.

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications

6. Curing (and Heat Curing)

- The low w/c can cause surface drying and affect its hardening properties
  - Cover the surface of the specimen with plastic sheets as quickly as possible after pouring to prevent moisture loss.
- Onsite or laboratory manufactured specimen should be cured according to the ASTM C31/C31M and ASTM C192/C192M, respectively
- Heat treatment for 48 hours after demolding can lead to extremely rapid strength gain
  - The curing conditions are a temperature of 90 ° C (195 ° F), and relative humidity of 95%.

Heat Curing (Full Strength in 2 Days)


Curing in cold temperature (1 day)

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UHPC presentation

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Instructions

Why is UHPC so Durable?

The ductility of UHPC beams is limited because:

Fiber clumping is a sign of:

Overview of UHPC Production

UHPC Truck Mixing

Production Steps

a) Forms ready for casting

b) Loading of sand into ready-mix truck

c) Loading of water and water reducer

d) Loading steel fibers

a) Casting of UHPC materials in form

b) Casting of UHPC materials in form

c) Finished panel

d) Wrapped and curing panel


Jackson

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Session 3

Qualification and Acceptance of UHPC

Structural Design with Ultra-High Performance Concrete

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

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

Table A1-1. Typical and minimum mechanical properties for UHPC.

Property	Test Method	Typical Values	Minimum Value
Modulus of elasticity, E_c (ksi)	ASTM C1856/C1856M (ASTM 2017a)	6,500–9,400	N/A
Compressive strength, f'_c (ksi)	ASTM C1856/C1856M (ASTM 2017a)	20.0–36.0	17.5
Ultimate compressive strain, ε_{cu}	ASTM C1856/C1856M (ASTM 2017a)	0.003–0.005	N/A
Poisson's ratio	ASTM C1856 (ASTM 2017a)	0.1–0.2	N/A
Effective cracking strength, $f_{t,cr}$ (ksi)	AASHTO T 397 (AASHTO 2022b)	0.90–1.80	0.75
Crack localization strength, $f_{t,loc}$ (ksi)	AASHTO T 397 (AASHTO 2022b)	0.90–1.80	$\geq f_{t,cr}$
Crack localization strain, $\varepsilon_{t,loc}$	AASHTO T 397 (AASHTO 2022b)	0.003–0.008	0.0025

N/A = not applicable.

Modulus of Elasticity of UHPC

- The modulus of elasticity, Ec, may be determined by physical tests in accordance with ASTM C1856/C1856M (ASTM 2017a).
- In the absence of more detailed information, Young's modulus shall be taken as:

$$E_c = 2{,}500\, K_1\, f_c'^{\,0.33}$$

Correction factor for modulus of elasticity to be taken as 1.0 unless determined by physical test, and as approved by the owner

Compressive strength of UHPC for use in design (ksi)

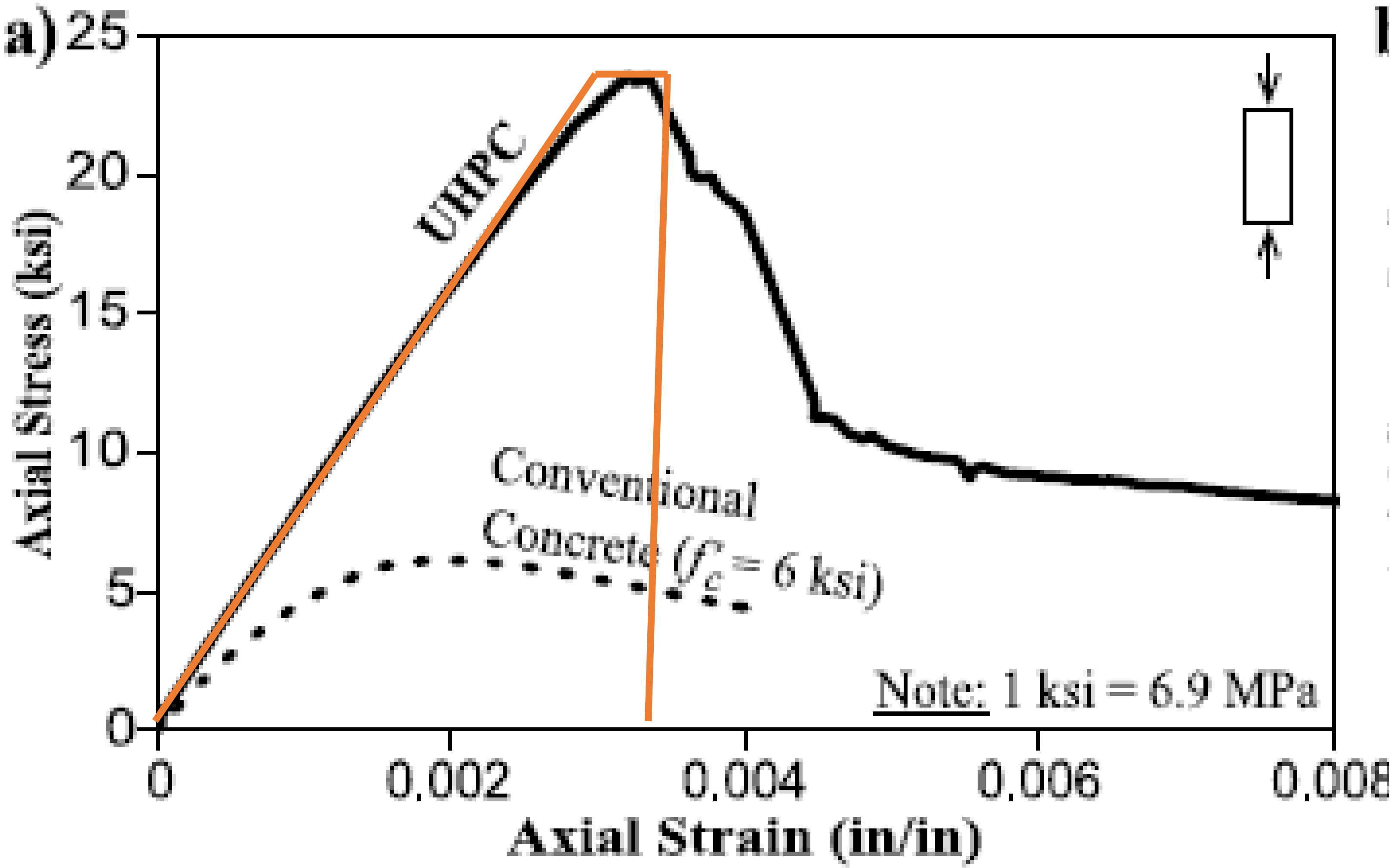
Compressive Strength and Ultimate Strain

- The compressive strength of the UHPC, f'_c, is obtained from testing cylinders (typically 3” x 6”)
  - ASTM C1856/C1856M (ASTM 2017a).
- The ultimate compressive strain of UHPC, ε_{cu}, is the greater of the elastic compressive strain limit, ε_{cp}, or 0.0035.

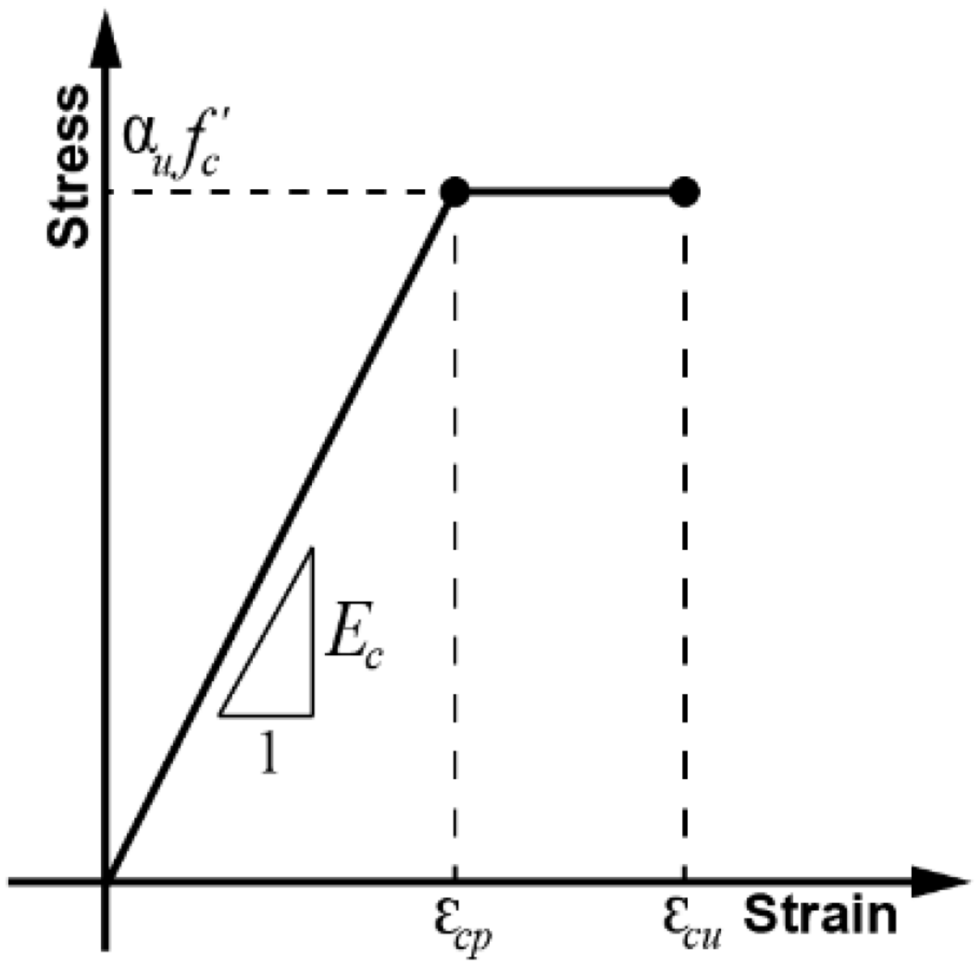
Reduction factor to account for the nonlinearity of the compressive stress-strain response <0.85

$$\varepsilon_{cp} = \frac{\alpha_u f_c'}{E_c}$$

Recall the compressive response of UHPC



Compressive Model

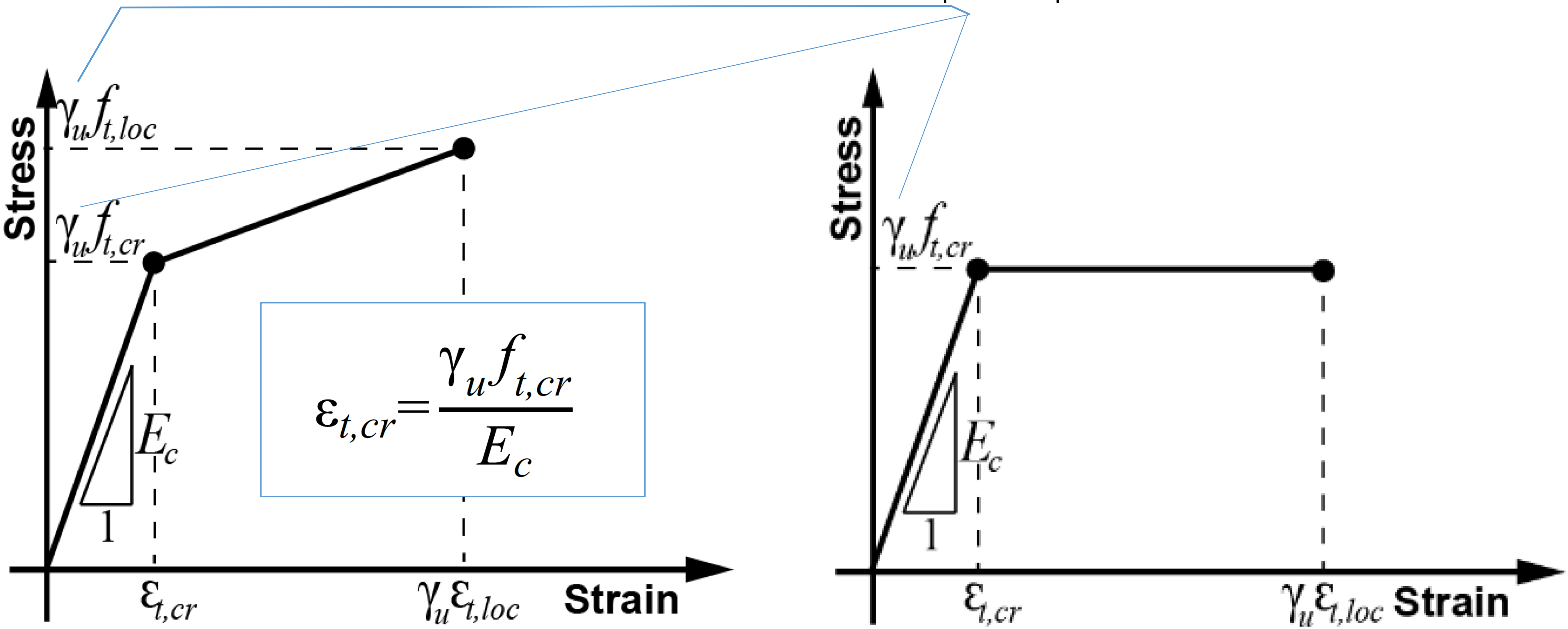


Tensile Properties

- The effective cracking strength for use in design, $f_{t,cr}$
  - Stress at the onset of the formation of the first crack under uniaxial loading
- The crack localization strength for use in design, $f_{t,loc}$
  - First tensile stress value at which the tensile stress continuously decreases with increasing strain - OR
  - Permanently drops below the value of the effective cracking strength, whichever occurs first
- Both values are determined from the direct tension test
  - AASHTO T 397
- $f_{t,loc} = f_{t,cr}$ if $f_{t,loc} < 1.2\, f_{t,cr}$
- The crack localization strain for use in design, $\varepsilon_{t,loc}$, is the strain corresponding to the crack localization strength, $f_{t,loc}$

Tensile Properties

The factor γ_u accounts for the cases in which the values of the tensile properties of the UHPC placed in the structural components are expected to be lower than their respective qualified values



$$\varepsilon_{t,cr} = \frac{\gamma_u f_{t,cr}}{E_c}$$

Compliance of Mix Components

- The hydraulic cement shall be compliant with the requirements of ASTM C150, ASTM C595
- Fine aggregates shall be compliant with ASTM C33 or ASTM C144
- Silica fume shall be compliant with ASTM C1240
- Slag cement shall be compliant with ASTM C989
- Liquid and frozen water shall be compliant with ASTM C1602
- Chemical admixtures shall be compliant with ASTM C494
- Steel fiber reinforcement shall be compliant with ASTM A820

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Instructions

Why is UHPC so Durable?

The ductility of UHPC beams is limited because:

Fiber clumping is a sign of:

Qualification vs. Acceptance

- In concrete testing, qualification and acceptance serve different purposes in ensuring concrete meets project specifications and standards
- Qualification testing
  - Ensures a mix is suitable before construction begins
- Acceptance testing
  - Ensures delivered and placed concrete complies with project specifications

Qualification Testing

- Purpose:
  - Conducted before concrete is used in a project to verify that the mix design meets the required specifications.
- Scope:
  - Evaluates the proposed mix design, materials, and properties (e.g., compressive strength, workability, durability).
- Testing Includes:
  - Laboratory trial batches
  - Compressive strength tests at various ages
  - Tensile properties
- Outcome:
  - A qualified mix design can be used for production, ensuring it meets performance criteria.

Acceptance Testing

- Purpose:
  - Conducted during construction to verify that the delivered concrete meets project requirements.
- Scope:
  - Evaluates actual batches of concrete as placed in the structure.
- Testing Includes:
  - Laboratory trial batches
  - Compressive strength tests at various ages
  - Tensile properties
- Outcome:
  - If results meet specified criteria, the concrete is accepted for use; if not, corrective actions may be required (e.g., rejection, removal, or adjustments in future batches).

Qualification

- Qualification testing is performed to determine the suitability of a particular UHPC mixture
- Material qualification should be based on field-test specimens that represent materials, mixture proportions, batching procedures, and climatic conditions similar to those expected during the fabrication of UHPC elements
- A complete set of material qualification testing shall be completed at an interval not to exceed 3 years.

Qualification – Fresh Properties

- Flow is measured for each batch from which specimens for qualification testing are cast in accordance with ASTM C1856/1856M.
- Susceptibility to fiber segregation shall be measured according to ASTM C1712.
- Unit weight shall be measured and recorded according to ASTM C138-17a

Qualification - Compressive Strength

- The qualified design value shall be determined from the results of a minimum of 15 cylinders (ASTM C1856/C1856M)
- A test result shall not be discarded, except that if any cylinder shows evidence of improper sampling, molding, or testing
- Specimens shall be sampled from at least three separate batches

Average compressive strength $$\bar{f}'_{cQ} = \frac{1}{n_{cQ}} \sum_{i=1}^{n_{cQ}} f'_{c,i}$$

Standard deviation $$s_{cQ} = \sqrt{\frac{\sum_{i=1}^{n_{cQ}} \left(f'_{c,i} - \bar{f}'_{cQ}\right)^2}{n_{cQ} - 1}}$$

COMPRESSIVE STRENGTH (ASTM C1856 & ASTM C39)

End Grinder

Test Setup

- 3″ x 6″
- 145±7 psi/sec.

8.1 *Compressive Strength:*

8.1.1 Determine the compressive strength in accordance with Test Method C39/C39M, with the exceptions described in this section.

8.1.2 Only 75 mm [3 in.] diameter by 150 mm [6 in.] long cylindrical specimens shall be used for compressive strength testing.

NOTE 4—If molds in SI units are required and not available, the inch-pound mold should be permitted.

8.1.3 Prior to testing, all cylinders shall be end ground such that the ends do not depart from perpendicularity to the axis by more than 0.5° (approximately equivalent to 1 mm in 100 mm [0.05 in. in 5 in.]). The ends of the cylinders shall be ground plane to within 0.050 mm [0.002 in.].

8.1.4 Capping compounds and unbonded neoprene pads shall not be used.

8.1.5 The diameter used for calculating the cross-sectional area of a cylindrical test specimen shall be determined on each cylinder to the nearest 0.1 mm [0.04 in.].

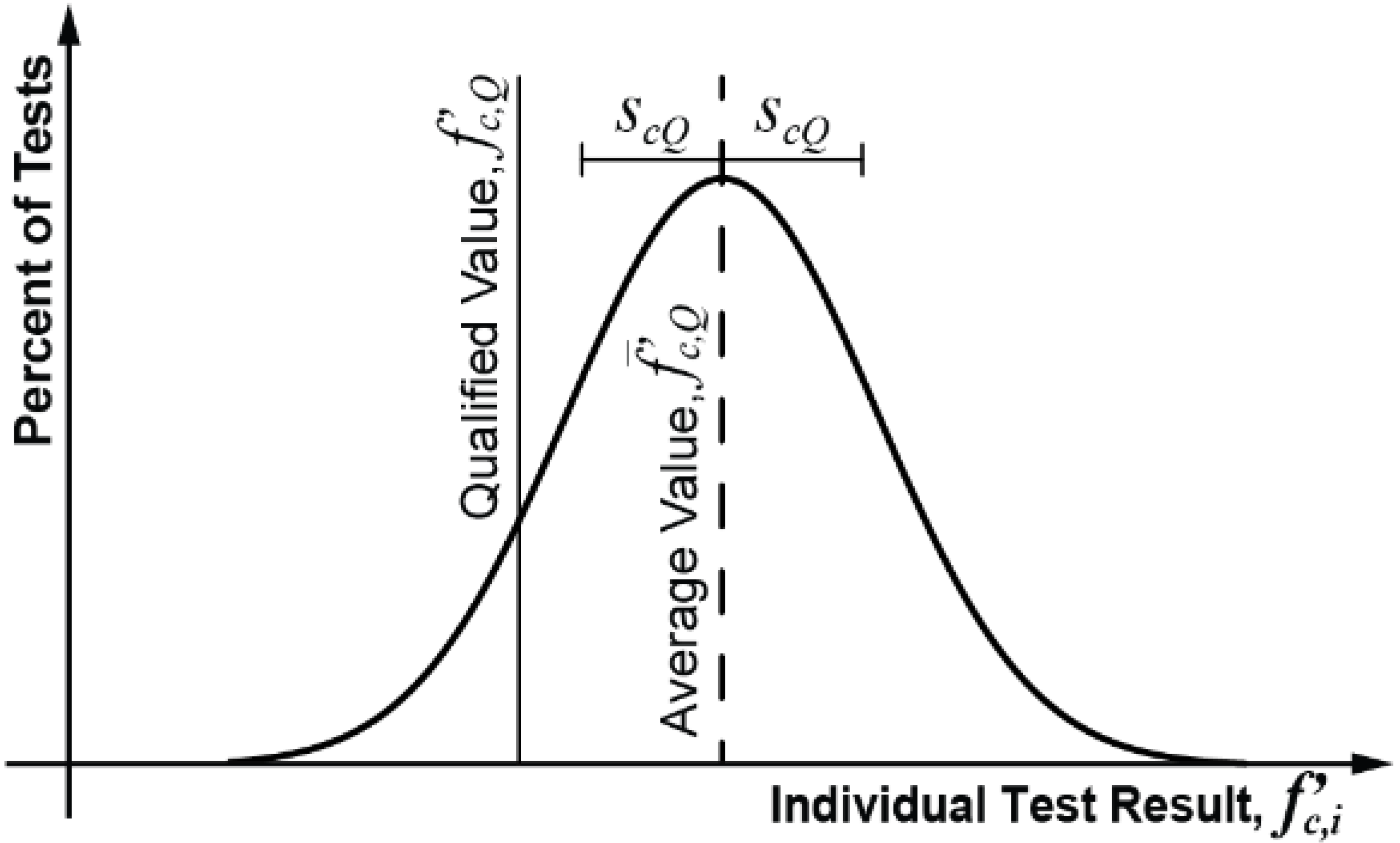
NOTE 5—The diameter is measured to a greater accuracy than Test Method C39/C39M.

8.1.6 *Rate of Loading*—The load shall be applied at a rate of movement (platen to crosshead measurement) corresponding to a stress rate on the specimen of 1.0 ± 0.05 MPa/s [145 ± 7 psi/s].

NOTE 6—Conventional load rates as specified in Test Method C39/C39M would require approximately 15–20 min to complete a test.

NOTE 7—For a 75-mm [3 in.] diameter specimen, the loading rate is 265 ± 13 kN/min [61 500 ± 3 000 lb/min].

From: Hu and Morcous, U. of Nebraska, Workshop on Production of Cast-in-Place UHPC for Bridge Applications



Percent of Tests
Qualified Value, $f'_{c,Q}$
s_{cQ}
s_{cQ}
Average Value, $\bar{f}'_{c,Q}$
Individual Test Result, $f'_{c,i}$

Compressive Strength Qualification

- The qualified design value of the compression strength shall be determined as the lesser of the following:

Qualified design value of the compression strength

Modification factor for the total number of compression strength test – Reflects confidence in the data

$$f'_{cQ} = \overline{f'}_{cQ} - 1.34\, k_{cQ}\, s_{cQ}$$

$$f'_{cQ} = 1.11\, \overline{f'}_{cQ} - 2.59\, k_{cQ}\, s_{cQ}$$

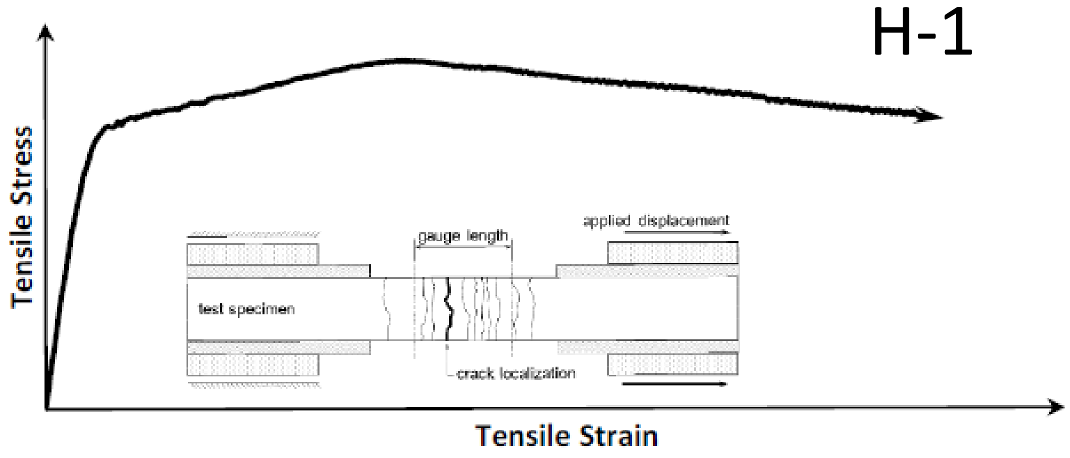
Standard deviation

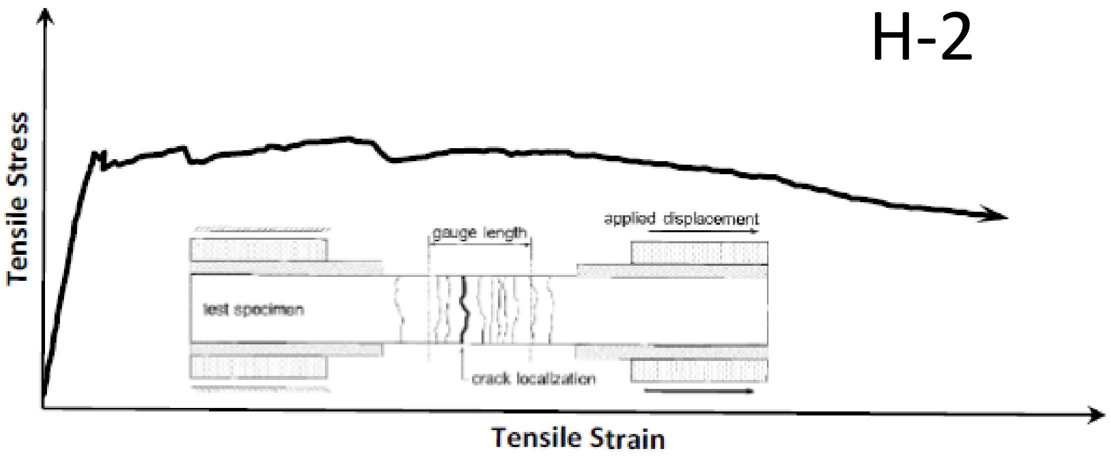
Total Number of Tests Considered	*k*-Factor for Increasing the Sample Standard Deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Based on ACI 301 that ensures that no more than **one test in 100** (1%) falls below the specified strength ($f'c$).

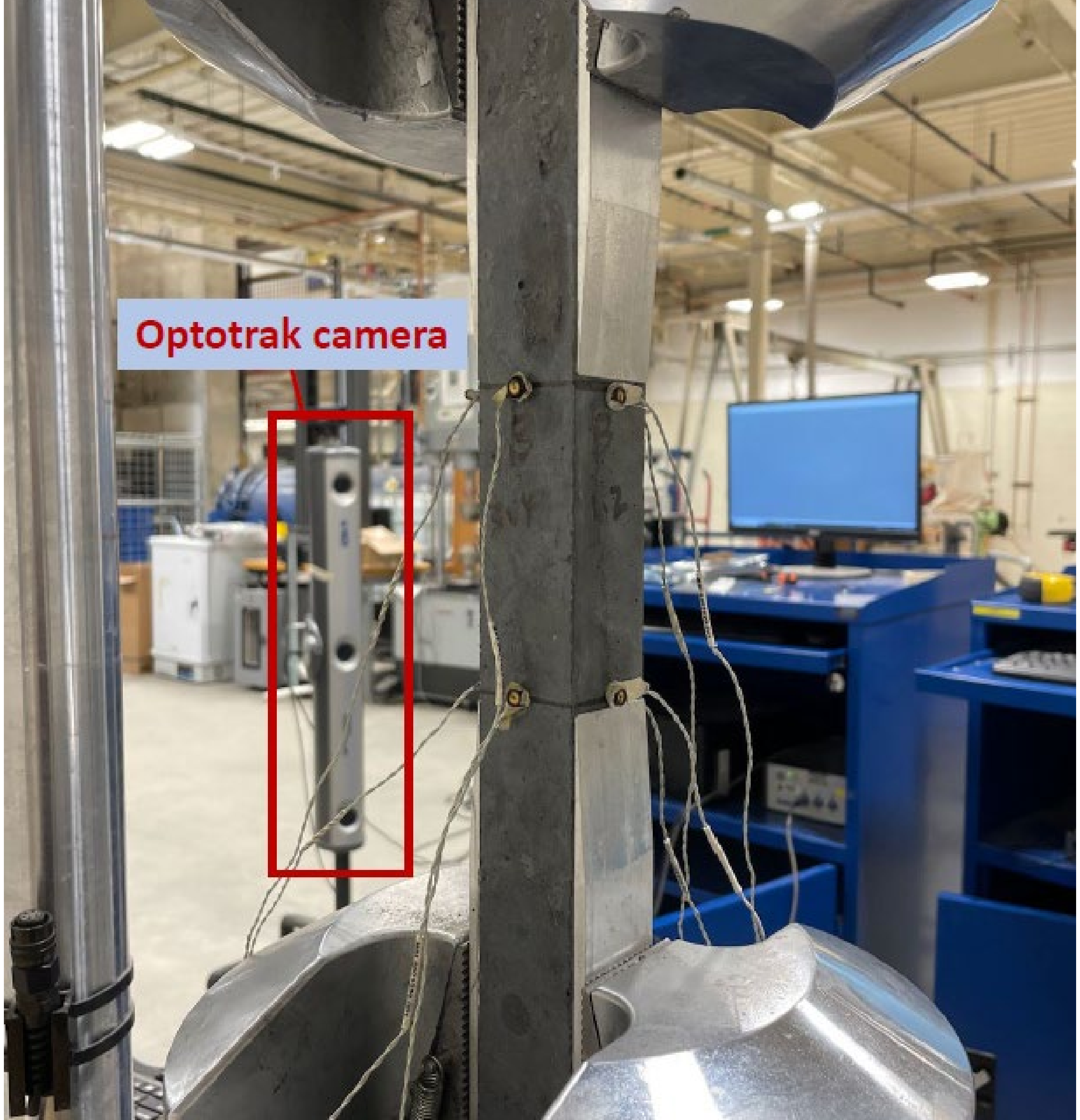
Tensile Properties Qualification

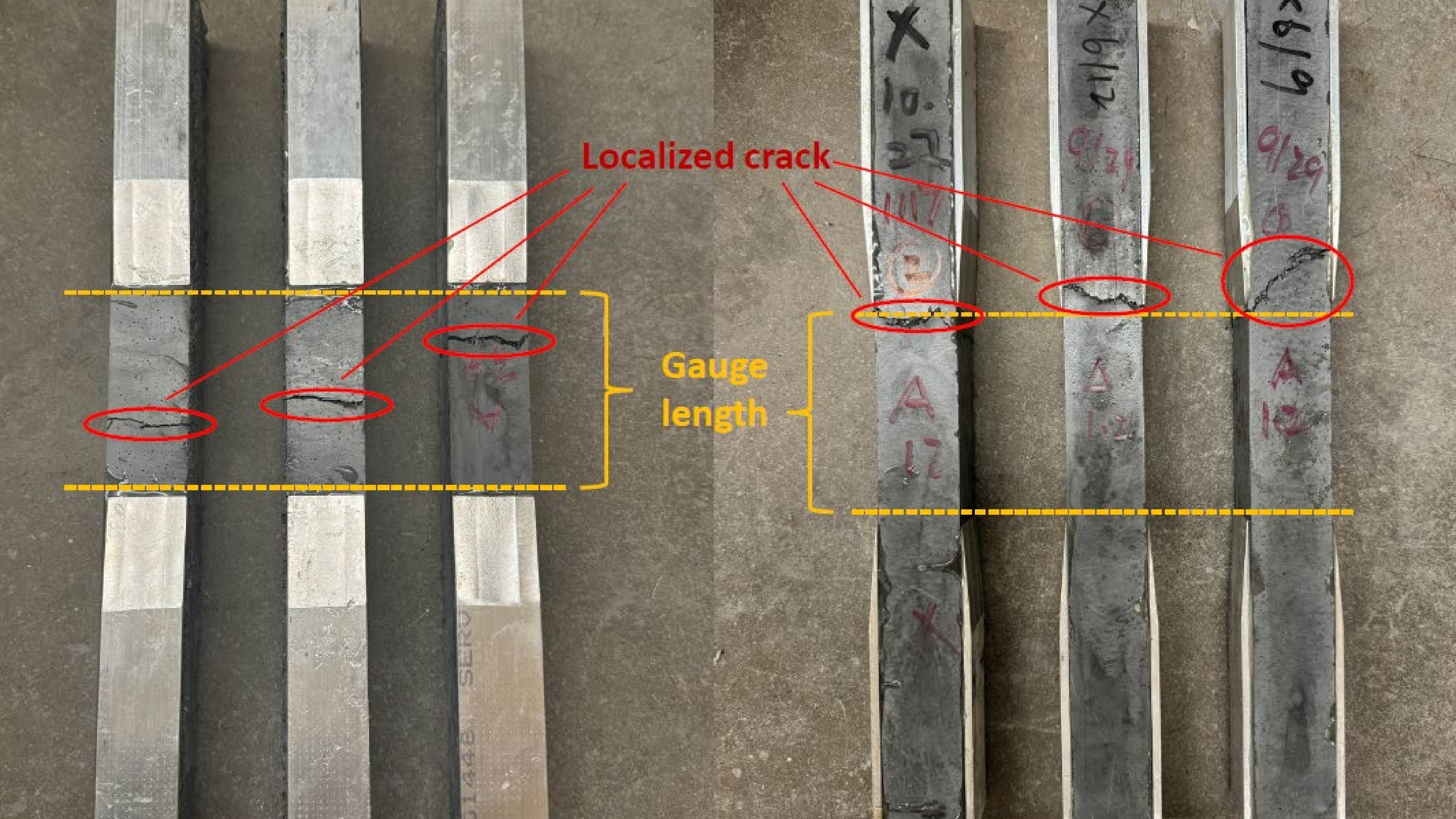
- The qualified design values of the effective cracking strength, $f_{t,crQ}$, the design crack localization stress, $f_{t,locQ}$, and the design crack localization strain, $\varepsilon_{t,locQ}$, of a UHPC mixture shall be determined from a minimum of 15 tension response test results classified as Type H-1 or H-2, as defined in AASHTO T 397



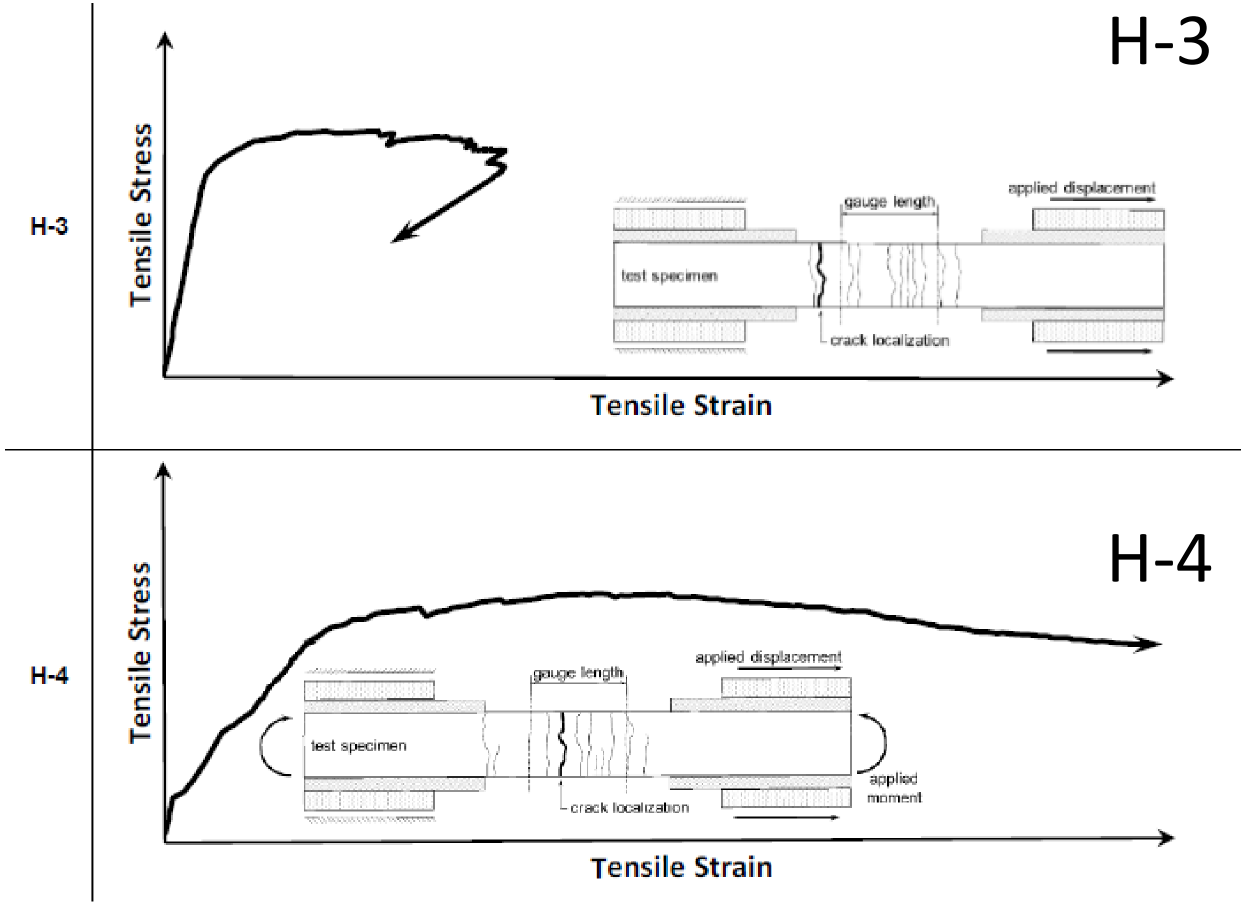


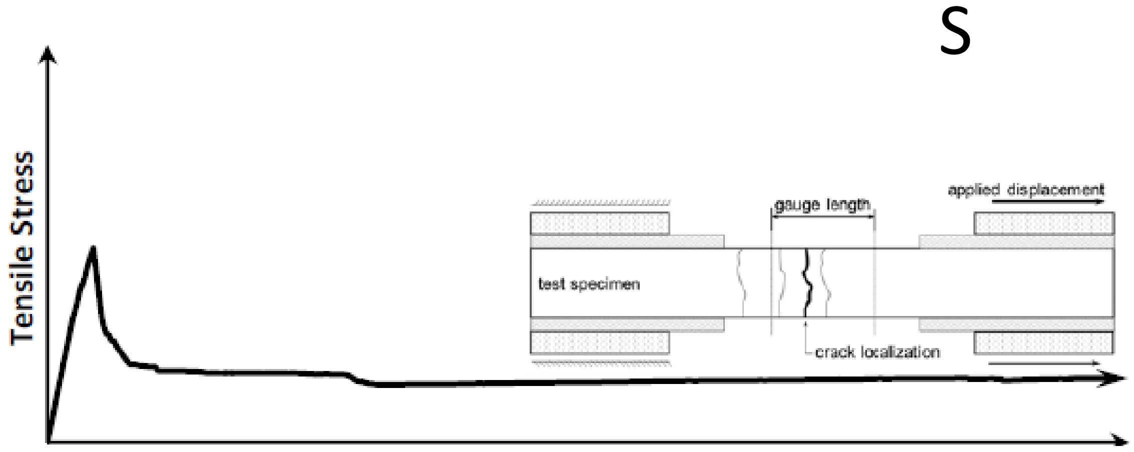
Tensile Properties
AASHTO T397-22

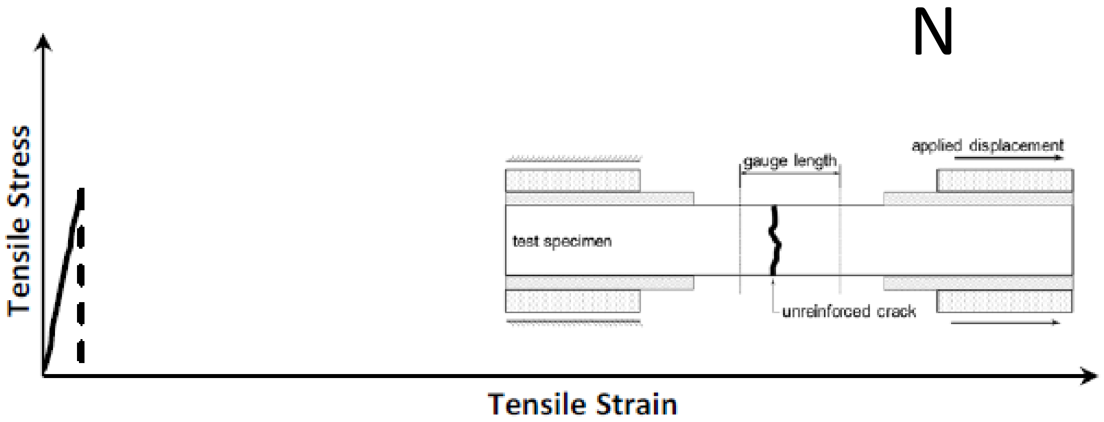



Localized crack
Gauge length

Poor Responses in T-397 Tensile Tests







Tensile Strength Qualification

- Specimens shall be sampled from at least three separate batches
  - A minimum of 10 to 14 specimens are recommended to be sampled from each batch
- A minimum of two but not more than half of the tested specimens used for qualification, i.e., exhibiting tensile behavior of Type H-1 or H-2, as defined in AASHTO T 397, shall be obtained from a single batch
  - To ensure that all batches provide good strain hardening behavior
- If more than one out of five tested specimens from a single batch result in tension responses classified as Type S, as defined in AASHTO T 397, all specimens sampled from the same batch shall not be used for qualification
  - This is likely a poorly mixed batch
- A UHPC mixture shall be disqualified if more than one out of five tested specimens from two or more batches result in a tension response of Type S or if any tested specimen from any batch results in a tension response of Type N, as defined in AASHTO T 397
  - The mix is not a strain hardening one, i.e., it is poorly designed

Tensile Strength Qualification

Effective Cracking Strength

Average tensile strength

$$\bar{f}_{t,crQ} = \frac{1}{n_{tQ}} \sum_{i=1}^{n_{tQ}} f_{t,cr,i}$$

Standard deviation

$$s_{t,crQ} = \sqrt{\frac{\sum_{i=1}^{n_{tQ}} \left(f_{t,cr,i} - \bar{f}_{t,crQ}\right)^2}{n_{tQ} - 1}}$$

Total number of tensile test results exhibiting tension responses of Types H-1 or H-2

Localization Strength

$$\bar{f}_{t,locQ} = \frac{1}{n_{tQ}} \sum_{i=1}^{n_{tQ}} f_{t,loc,i}$$

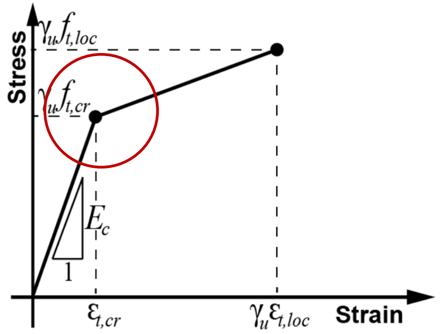
$$s_{t,locQ} = \sqrt{\frac{\sum_{i=1}^{n_{tQ}} \left(f_{t,loc,i} - \bar{f}_{t,locQ}\right)^2}{n_{tQ} - 1}}$$

Localization Strain

$$\bar{\varepsilon}_{t,locQ} = \frac{1}{n_{tQ}} \sum_{i=1}^{n_{tQ}} \varepsilon_{t,loc,i}$$

$$s_{\varepsilon t,locQ} = \sqrt{\frac{\sum_{i=1}^{n_{tQ}} \left(\varepsilon_{t,loc,i} - \bar{\varepsilon}_{t,locQ}\right)^2}{n_{tQ} - 1}}$$

Tensile Strength Qualification - Effective Cracking Strength



- The qualified design value of the effective cracking strength shall be determined as the lesser of the following:

Modification factor for the total number of tensile strength test – Reflects confidence in the data

Qualified design value of the tensile strength

$$f_{t,crQ} = \bar{f}_{t,crQ} - 1.34\, k_{tQ}\, s_{t,crQ}$$

$$f_{t,crQ} = 1.11\, \bar{f}_{t,crQ} - 2.59\, k_{tQ}\, s_{t,crQ}$$

Standard deviation

Total Number of Tests Considered	*k*-Factor for Increasing the Sample Standard Deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Based on ACI 301 that ensures that no more than **one test in 100** (1%) falls below the specified strength ($f'c$).

Do the tension Equations Look Familiar?

Compressive Strength Qualification

- The qualified design value of the compression strength shall be determined as the lesser of the following:

Qualified design value of the compression strength

Modification factor for the total number of compression strength test – Reflects confidence in the data

$$f'_{cQ} = \overline{f'}_{cQ} - 1.34\, k_{cQ}\, s_{cQ}$$

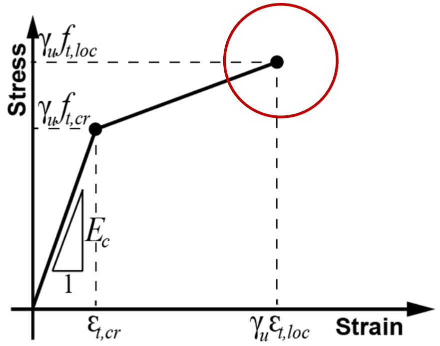
$$f'_{cQ} = 1.11\, \overline{f'}_{cQ} - 2.59\, k_{cQ}\, s_{cQ}$$

Standard deviation

Total Number of Tests Considered	*k*-Factor for Increasing the Sample Standard Deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Based on ACI 301 that ensures that no more than **one test in 100** (1%) falls below the specified strength ($f'c$).

Tensile Strength Qualification – Crack Localization Strength



- The qualified design value of the crack localization strength shall be determined as the lesser of the following:

Qualified design value of the crack localization strength

Modification factor for the total number of tensile strength test – Reflects confidence in the data

$$f_{t,locQ} = \bar{f}_{t,locQ} - 1.34\, k_{tQ}\, s_{t,locQ}$$

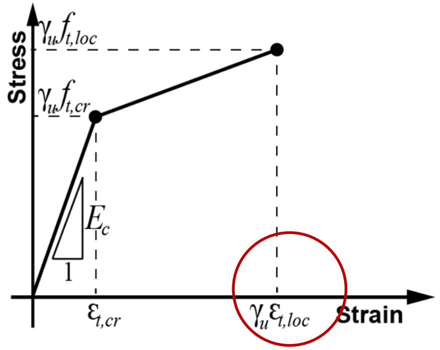
$$f_{t,locQ} = 1.11\, \bar{f}_{t,locQ} - 2.59\, k_{tQ}\, s_{t,locQ}$$

Standard deviation

Total Number of Tests Considered	*k*-Factor for Increasing the Sample Standard Deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Based on ACI 301 that ensures that no more than **one test in 100** (1%) falls below the specified strength ($f'c$).

Tensile Strength Qualification – Crack Localization Strain



- The qualified design value of the crack localization strength shall be determined as the lesser of the following:

Modification factor for the total number of tensile strength test – Reflects confidence in the data

Qualified design value of the crack localization strain

$$\varepsilon_{t,locQ} = \bar{\varepsilon}_{t,locQ} - 1.34\, k_{tQ}\, s_{\varepsilon t,locQ}$$

$$\varepsilon_{t,locQ} = 1.11\bar{\varepsilon}_{t,locQ} - 2.59\, k_{tQ}\, s_{\varepsilon t,locQ}$$

Standard deviation

Total Number of Tests Considered	*k*-Factor for Increasing the Sample Standard Deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Based on ACI 301 that ensures that no more than **one test in 100** (1%) falls below the specified strength ($f'c$).

Material Acceptance

- Material acceptance testing shall be conducted on the UHPC material being used to construct structural components

Property	Article	Minimum Frequency
Flow	2.7.2.1	Every batch.
Fiber segregation	2.7.2.2	First batch each day. Whenever compression or tension test specimens are cast.
Temperature	2.7.2.3	Every batch.
Compressive strength	2.7.3.2	One set per element cast. If element volume exceeds 25 yd^3, once per 25 yd^3 cast.
Tensile response: *Option 1*	2.7.3.3.1	One set per element cast. If element volume exceeds 25 yd^3, once per 25 yd^3 cast.
Tensile response: *Option 2*	2.7.3.3.2	One set per element cast. If element volume exceeds 25 yd^3, once per 25 yd^3 cast.

Material Acceptance - General

- Each hardened property shall be acceptable if both of the following criteria are met:
  - Every average of three consecutive test results equals or exceeds their respective required value.
  - No single property test result falls below their respective required value by more than 10 percent.

Required Compression Strength

- Use at least three cylinders from a single batch of UHPC
- Four cylinders must be made for each acceptance requirement
- The required value of the compressive strength is the greater of:

Total Number of Tests Considered	*k*-Factor for Increasing the Sample Standard Deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Modification factor for the total number of compression strength test results

Required average value of the compressive strength

$$f'_{cR} = f'_c + 1.34\, k_{cQ}\, s_{cQ} \leq f'_{cQ}$$

$$f'_{cR} = 0.90\, f'_c + 2.33\, k_{cQ}\, s_{cQ} \leq f'_{cQ}$$

Qualified design value of the compressive strength

Sample standard deviation of the compressive strength for the mixture obtained from the qualification testing

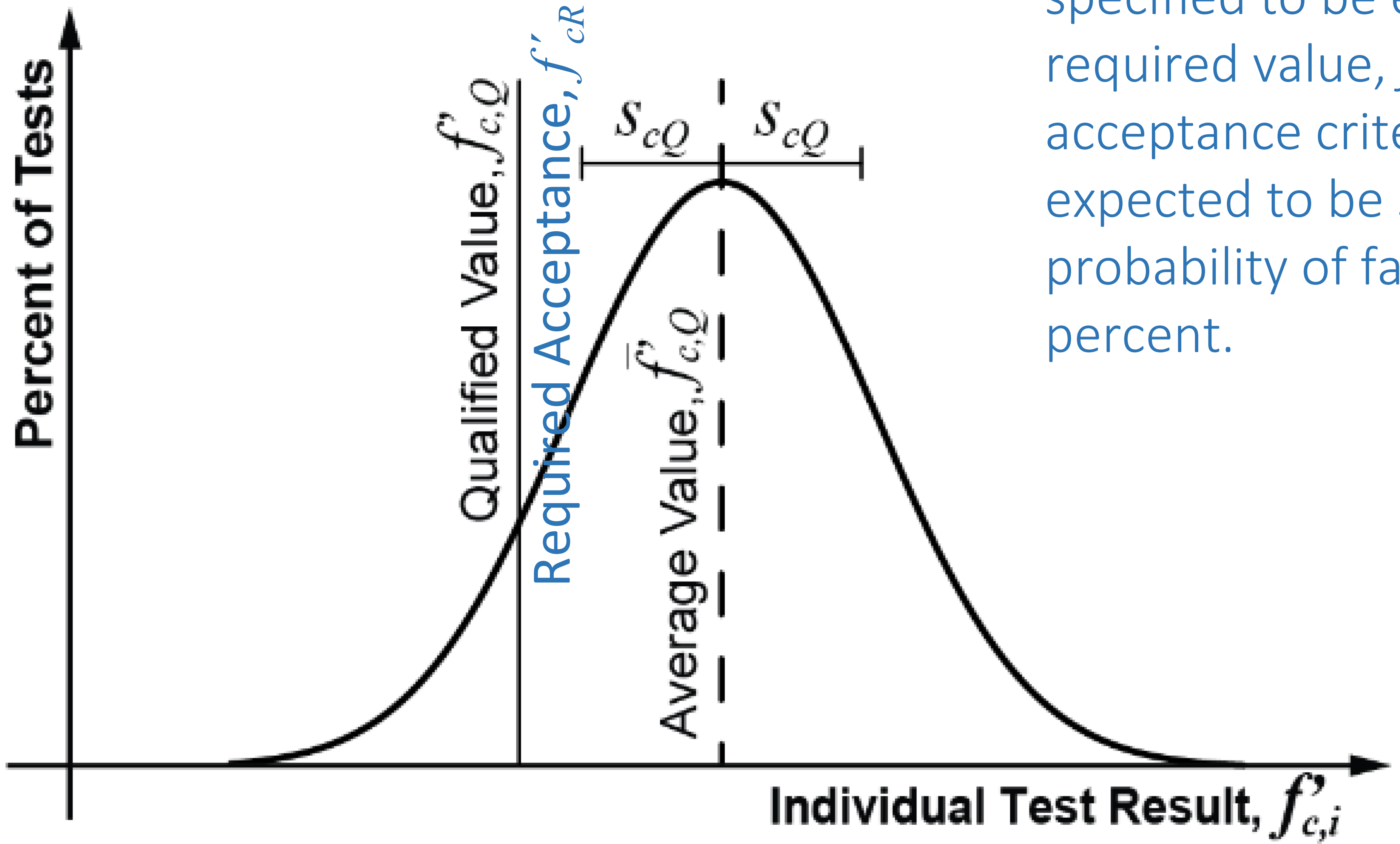
Statistical properties from qualification testing

Design values

$$f'_{cR} = f'_c + 1.34\, k_{cQ}\, s_{cQ} \leq f'_{cQ}$$

$$f'_{cR} = 0.90\, f'_c + 2.33\, k_{cQ}\, s_{cQ} \leq f'_{cQ}$$

This consideration is intended to restrict the average compression strength values obtained from acceptance testing from being significantly lower than their qualified values obtained during qualification of the same UHPC mixture



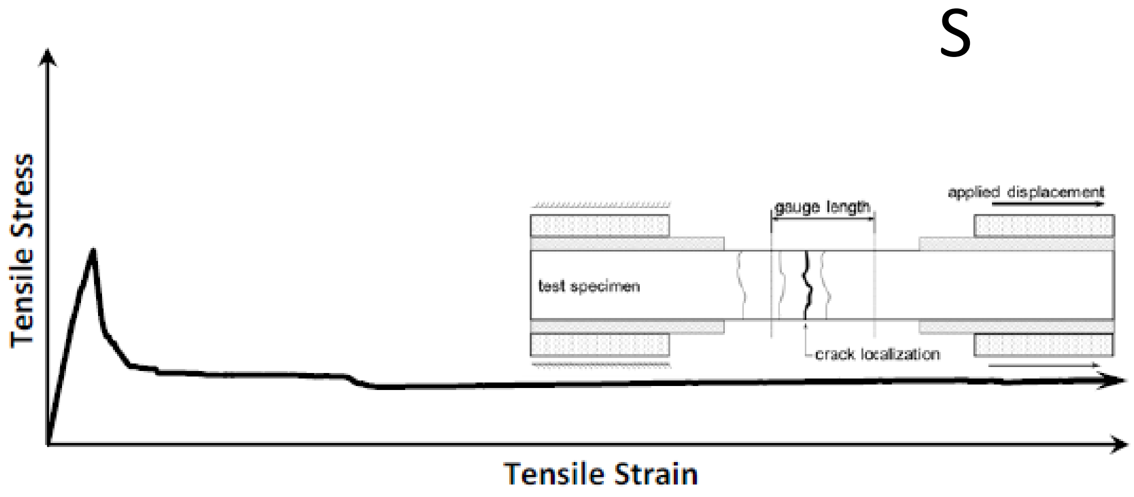
When the acceptance value of the compressive strength is specified to be equal to the required value, f'_{cQ}, the acceptance criteria are expected to be satisfied with a probability of failure of 1 percent.

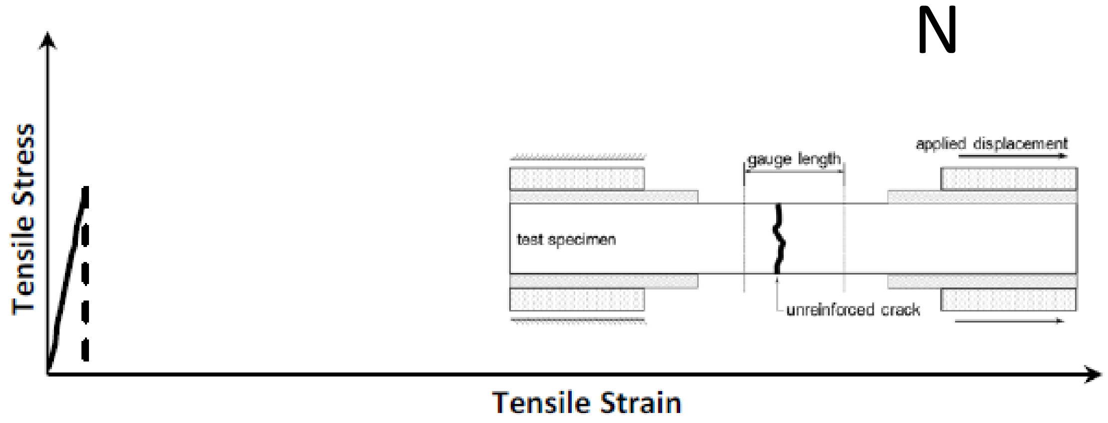
Acceptance of Tensile Properties

- The tensile properties for acceptance are: 1) effective cracking strength, 2) crack localization stress, and 3) crack localization strain
- Results are obtained from the tension response test results of at least three specimens taken from a single batch of UHPC
- The tension response test result of each specimen used to determine the tensile properties must be classified as Type H-1 or H-2 as defined in AASHTO T 397
- A minimum of six specimens shall be sampled for each tension response acceptance requirement
- A specimen exhibiting behavior other than H-1 or H-2 cannot be used for acceptance

Acceptance of Tensile Properties

- If more than one out of every six tested specimens from a single batch result in a tension response of Type S, or
- If any tested specimen resulted in a tension response of Type N as defined in AASHTO T 397, the mixture shall be considered as not meeting the acceptance criteria.





Required Cracking Tensile Strength

Total Number of Tests Considered	*k*-Factor for Increasing the Sample Standard Deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Modification factor for the total number of cracking tensile strength test results

Cracking tensile strength for use in design

Required value of the cracking tensile strength

$$f_{t,crR} = f_{t,cr} + 1.34\, k_{tQ}\, s_{t,crQ} \leq f_{t,crQ}$$

$$f_{t,crR} = 0.90\, f_{t,cr} + 2.33\, k_{tQ}\, s_{t,crQ} \leq f_{t,crQ}$$

Qualified design value of the cracking tensile strength

Sample standard deviation of the cracking tensile strength for the mixture obtained from the qualification testing

When the acceptance value = qualification value, the acceptance criteria are satisfied with 1% probability of failure

Required Crack Localization Strength

Modification factor for the total number of crack localization strength test results

Crack localization strength for use in design

Required value of the crack localization strength

$$f_{t,locR} = f_{t,loc} + 1.34\, k_{tQ}\, s_{t,locQ} \leq f_{t,locQ}$$

$$f_{t,locR} = 0.90\, f_{t,loc} + 2.33\, k_{tQ}\, s_{t,locQ} \leq f_{t,locQ}$$

Qualified design value of the crack localization strength

Sample standard deviation of the crack localization strength for the mixture obtained from the qualification testing

Total Number of Tests Considered	*k*-Factor for Increasing the Sample Standard Deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

When the acceptance value = qualification value, the acceptance criteria are satisfied with 1% probability of failure

Required Crack Localization Strain

Total Number of Tests Considered	*k*-Factor for Increasing the Sample Standard Deviation
15	1.16
20	1.08
25	1.03
30 or more	1.00

Modification factor for the total number of crack localization strain test results

Crack localization strain for use in design

Required value of the crack localization strain

$$\varepsilon_{t,locR} = \varepsilon_{t,loc} + 1.34\, k_{tQ}\, s_{\varepsilon t,locQ}$$

$$\varepsilon_{t,locR} = 0.90\, \varepsilon_{t,loc} + 2.33\, k_{tQ}\, s_{\varepsilon t,locQ}$$

Qualified design value of the crack localization strain

Sample standard deviation of the crack localization strain for the mixture obtained from the qualification testing

When the acceptance value = qualification value, the acceptance criteria are satisfied with 1% probability of failure

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UHPC presentation

Choose a slide to present

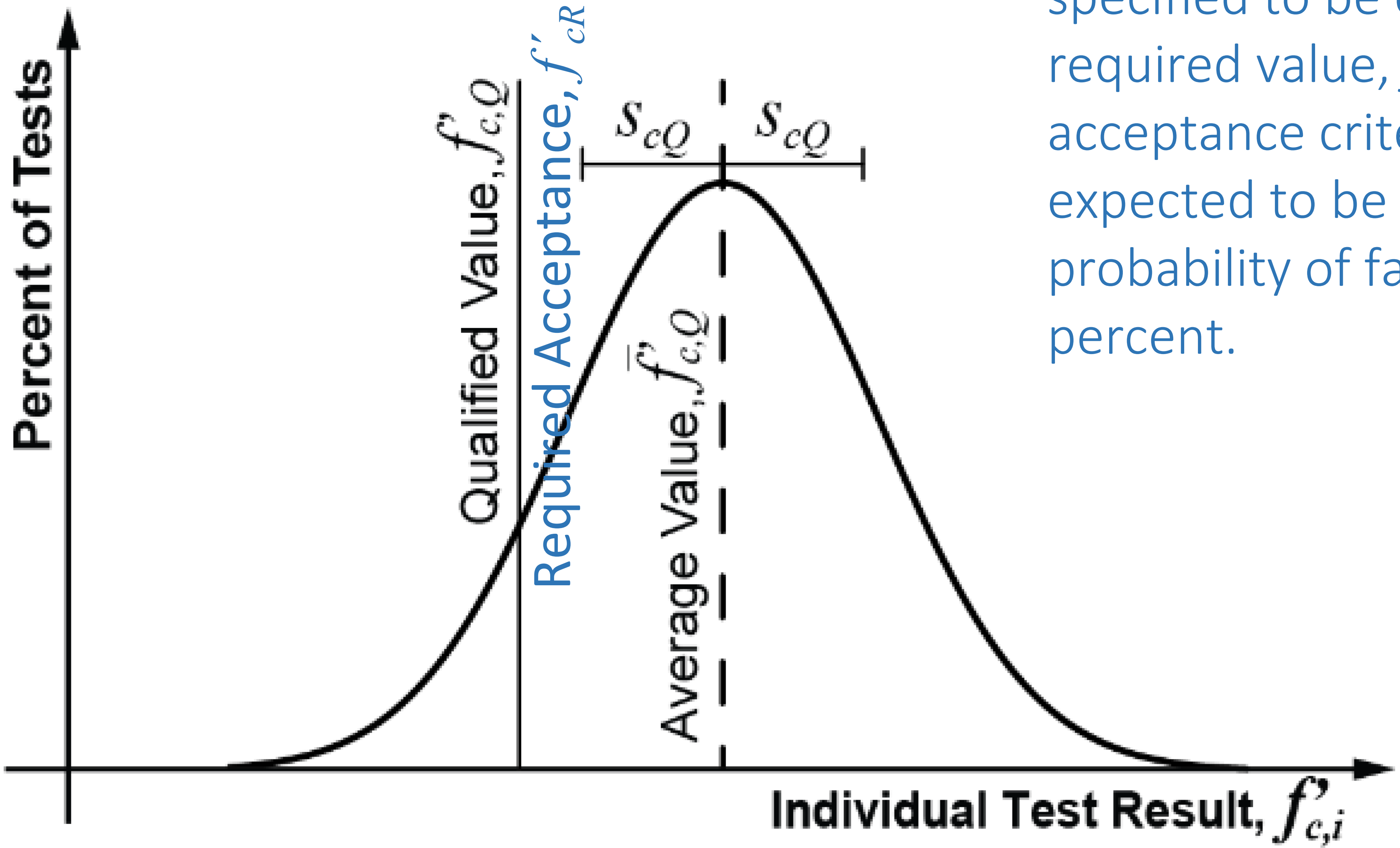
Instructions

Why is UHPC so Durable?

The ductility of UHPC beams is limited because:

Fiber clumping is a sign of:

Let's Review Why?



When the acceptance value of the compressive strength is specified to be equal to the required value, f'_{cQ}, the acceptance criteria are expected to be satisfied with a probability of failure of 1 percent.

Session 4

Structural Design of Reinforced UHPC Structures

Guide Specifications for Structural Design with ULTRA-HIGH PERFORMANCE CONCRETE

1st Edition | March 2024

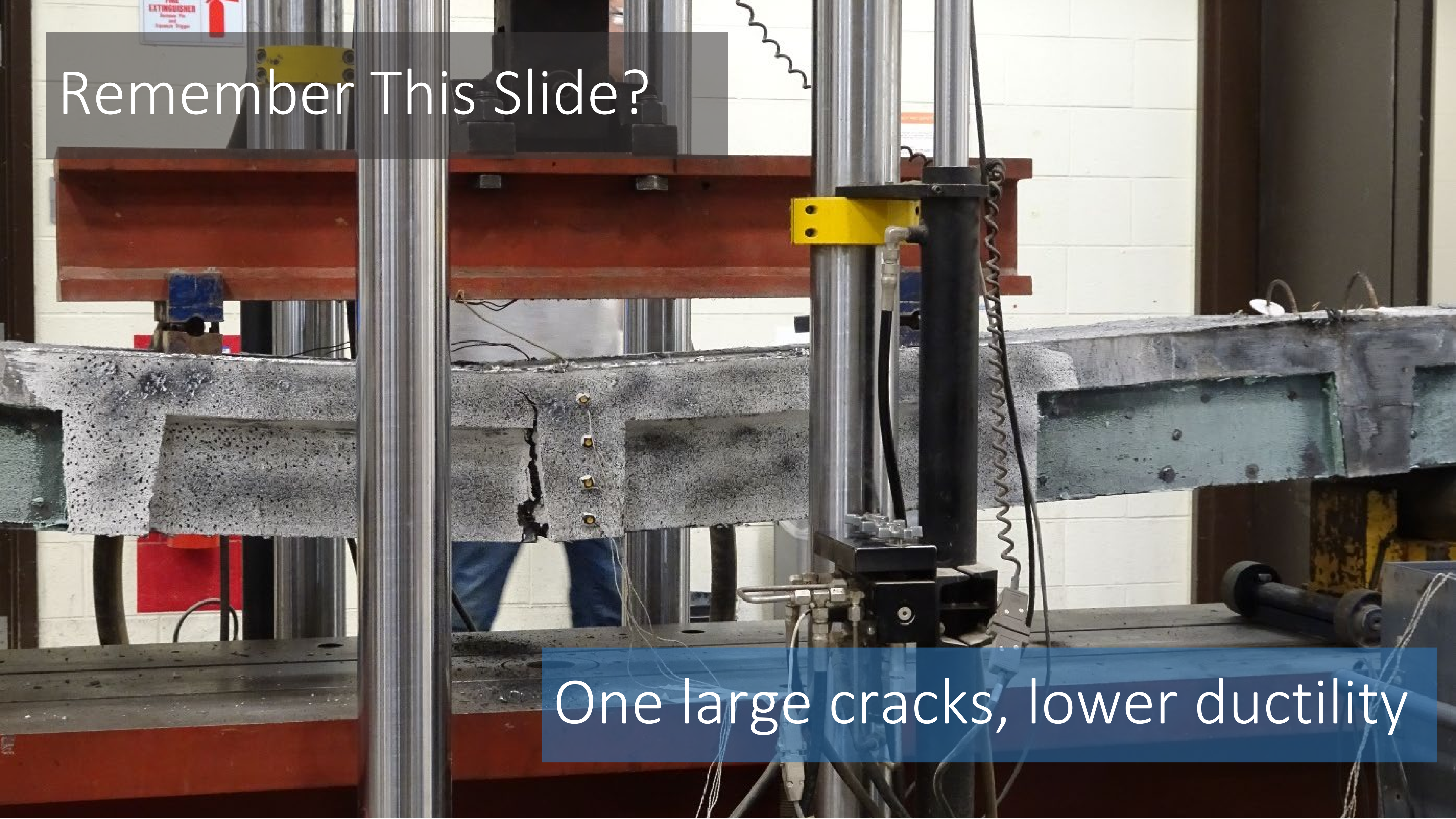
AASHTO | American Association of State Highway and Transportation Officials

Explicitly Defines UHPC

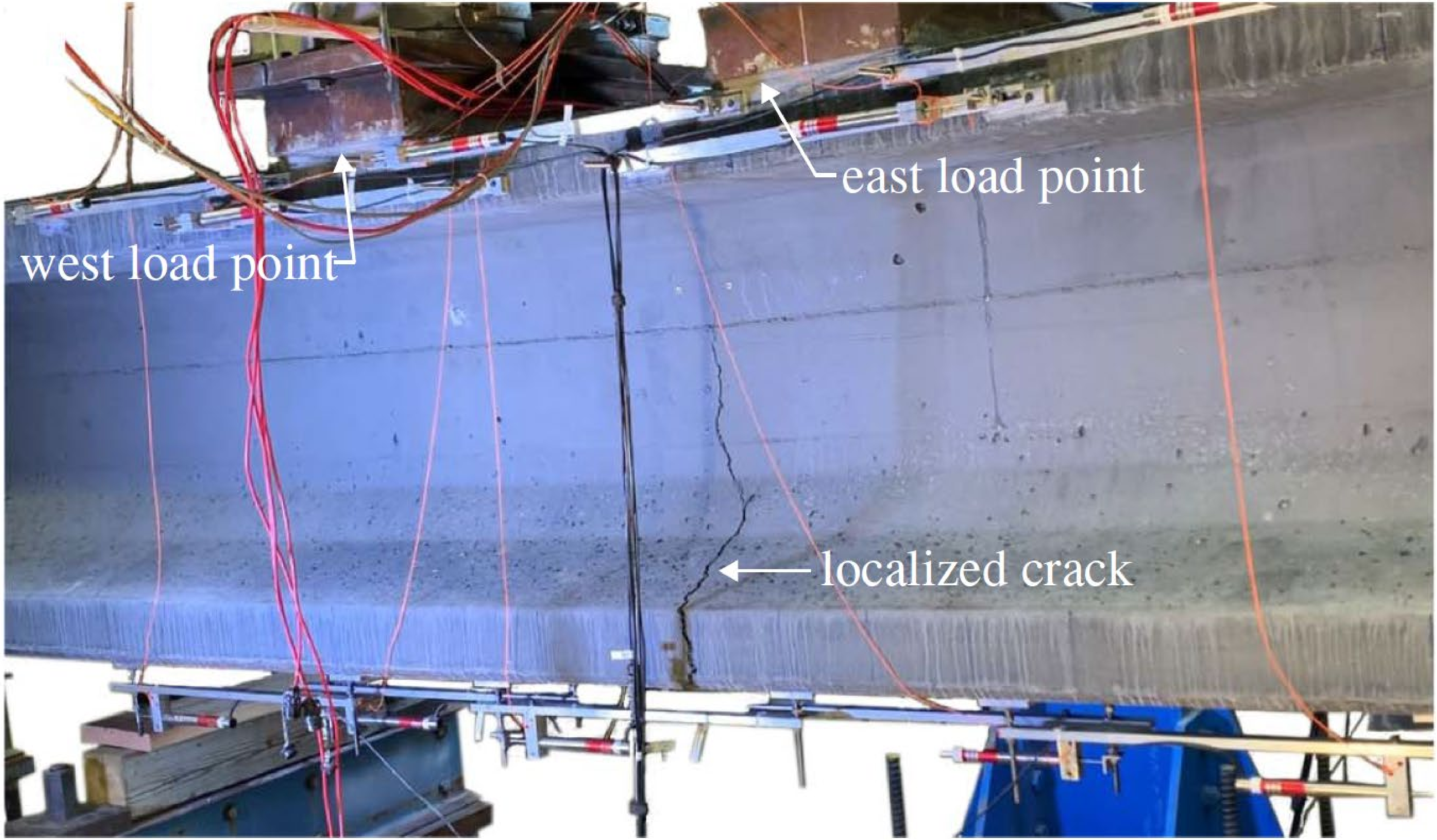
- UHPC shall be a Portland cement composite with a discontinuous pore structure and reinforced with steel fiber reinforcement.
- Other non-steel fiber reinforcements may be included as supplements, but shall not be the primary fiber reinforcement.
- Minimum properties:
  - Compressive strength, f'_c, of 17.5 ksi
  - Effective cracking strength, $f_{t,cr}$, of 0.75 ksi
  - Crack localization strength, $f_{t,loc}$, greater than or equal to the effective cracking strength, $f_{t,cr}$
  - Crack localization strain, $\varepsilon_{t,loc}$, of 0.0025

DESIGN FOR FLEXURE

Remember This Slide?



One large cracks, lower ductility

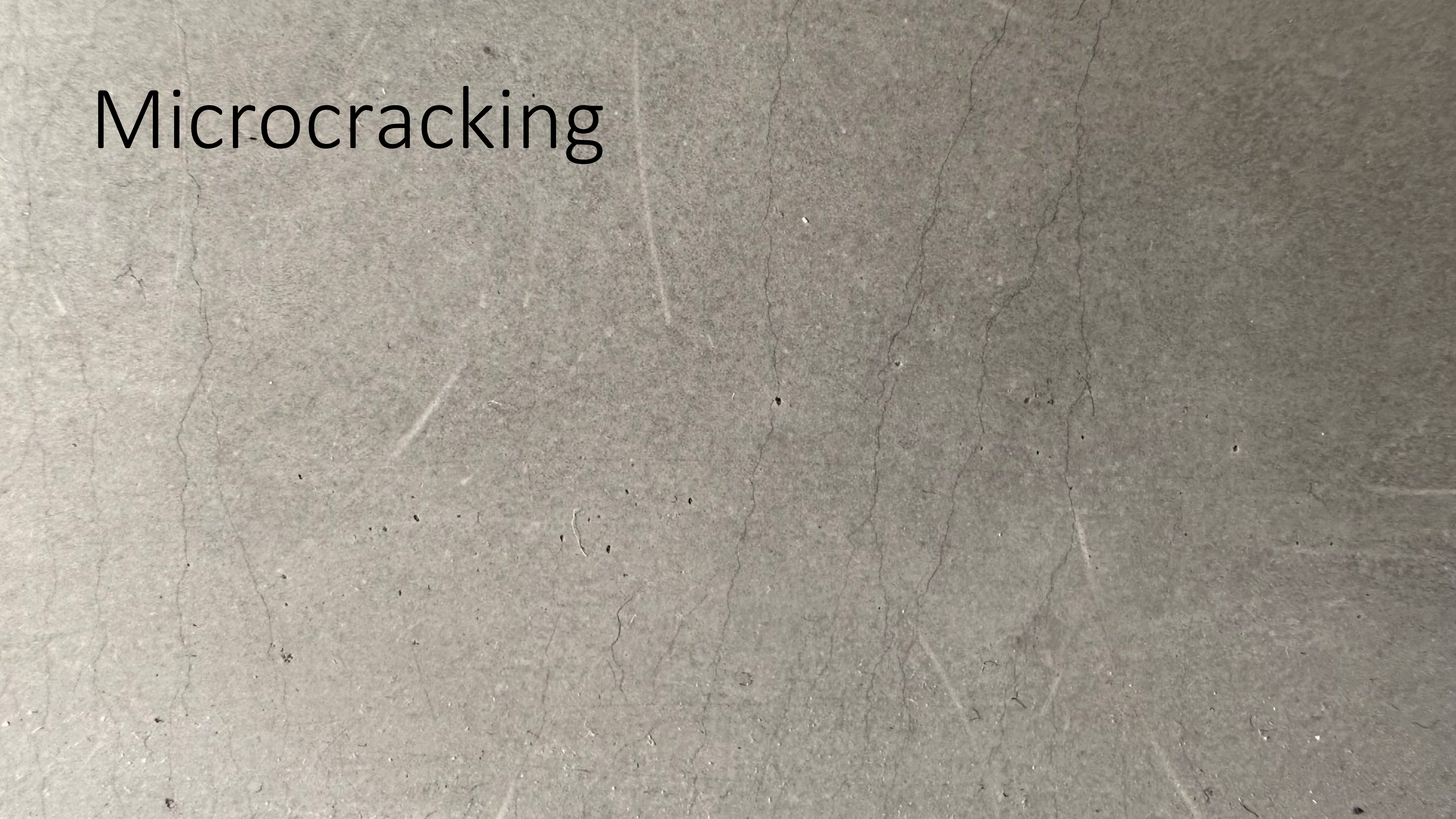


J. Struct. Eng., 2022, 148(4): 04022013 Prestressed UHPC Beam

Service Limit State

- The strain in the UHPC at extreme tension fiber shall not exceed the lesser of $0.25\gamma_u\varepsilon_{t,loc}$ or 0.001, where $\varepsilon_{t,loc}$ is the crack localization strain
  - Why? See next slide!
- The compressive stress at extreme compression fiber shall not exceed $0.45f'_c$ due to permanent loads and $0.60\phi_w f'_c$ due to permanent and transient loads, as well as during shipping and handling.
- The principal tensile stresses in webs of components shall not exceed $\gamma_u f_{t,cr}$ when the superstructure element is subjected to loadings of Service I load combination.
  - No cracking in the web!
- The stress limit for steel reinforcement in non-prestressed components shall be taken as $0.80f_y$, where f_y is the steel yielding stress.

Microcracking



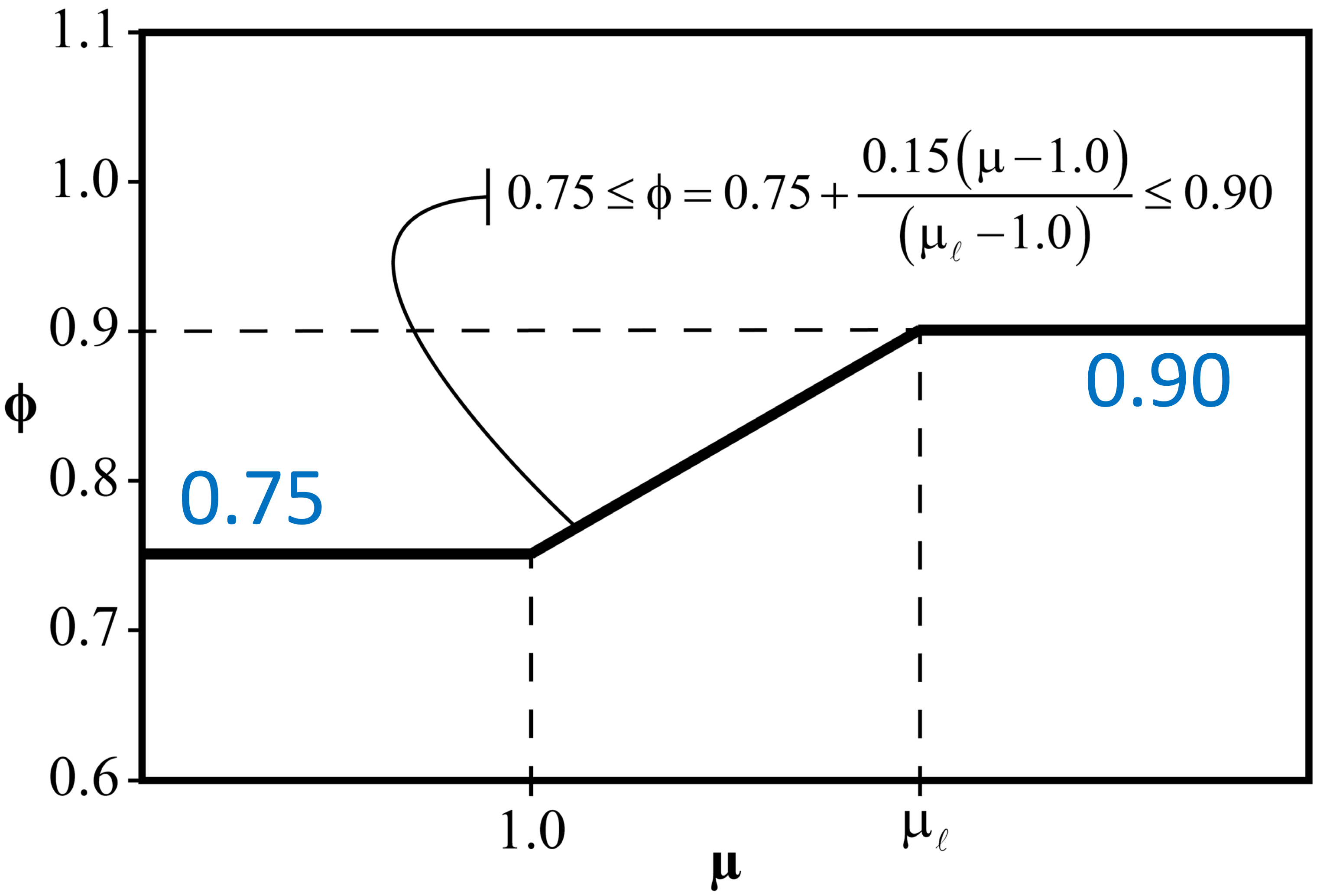
Fatigue Limit State

- Discrete steel elements embedded in UHPC must be checked using AASHTO LRFD provisions
- All steel elements must be checked to ensure their stress ranges in the uncracked section remain less than the fatigue threshold
  - Although the sections are uncracked, the steel stress may be higher than in regular concrete because the compressive and tensile strengths of UHPC are greater than that of conventional concrete
    - Certain design scenarios may elevate the stress ranges in discrete steel elements more than if they were embedded in the same design of conventional concrete.

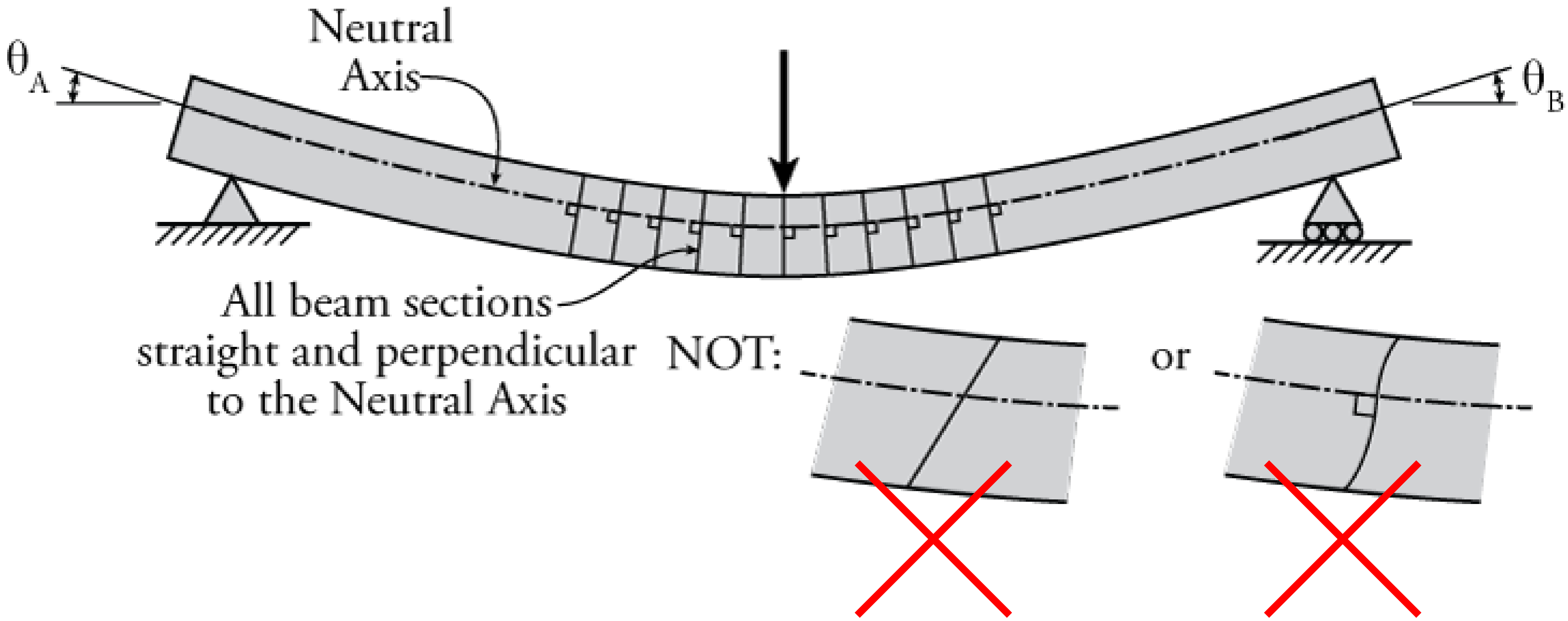
Strength Reduction Factor (□

- For compression members: 0.75
- For tension members and members subjected to combined tension and flexure: 0.75
- For shear and torsion in reinforced and unreinforced sections: 0.90
- For bearing on UHPC: 0.70
- For resistance during pile driving: 1.00

Flexural Strength Reduction Factor (□

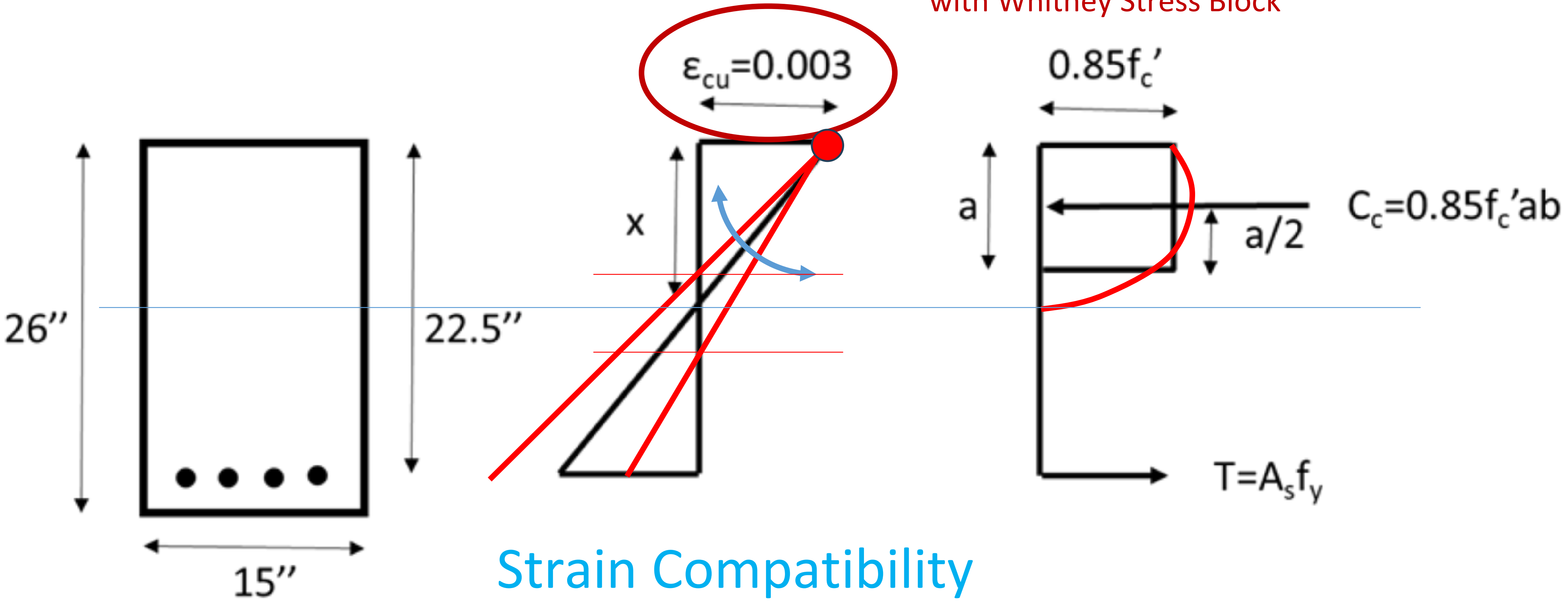


Strain Compatibility



Recall: Flexural Design of RC Sections

Actual Concrete Response Replaced with Whitney Stress Block



Strain Compatibility

UHPC Flexural Behavior: Strain Compatibility

- Euler-Bernoulli applies
- The maximum usable strain at extreme UHPC compression fiber = ε_{cu}
- The maximum usable strain at extreme UHPC tensile fiber = $\gamma_u \varepsilon_{t,loc}$

$\gamma_u \varepsilon_{t,loc}$

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UHPC presentation

Choose a slide to present

Instructions

Why is UHPC so Durable?

The ductility of UHPC beams is limited because:

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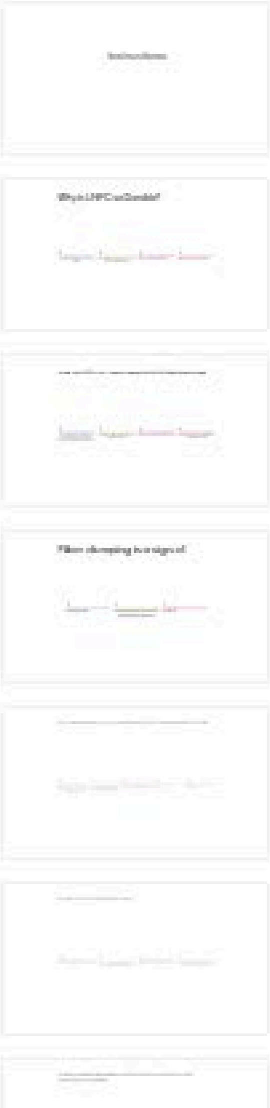
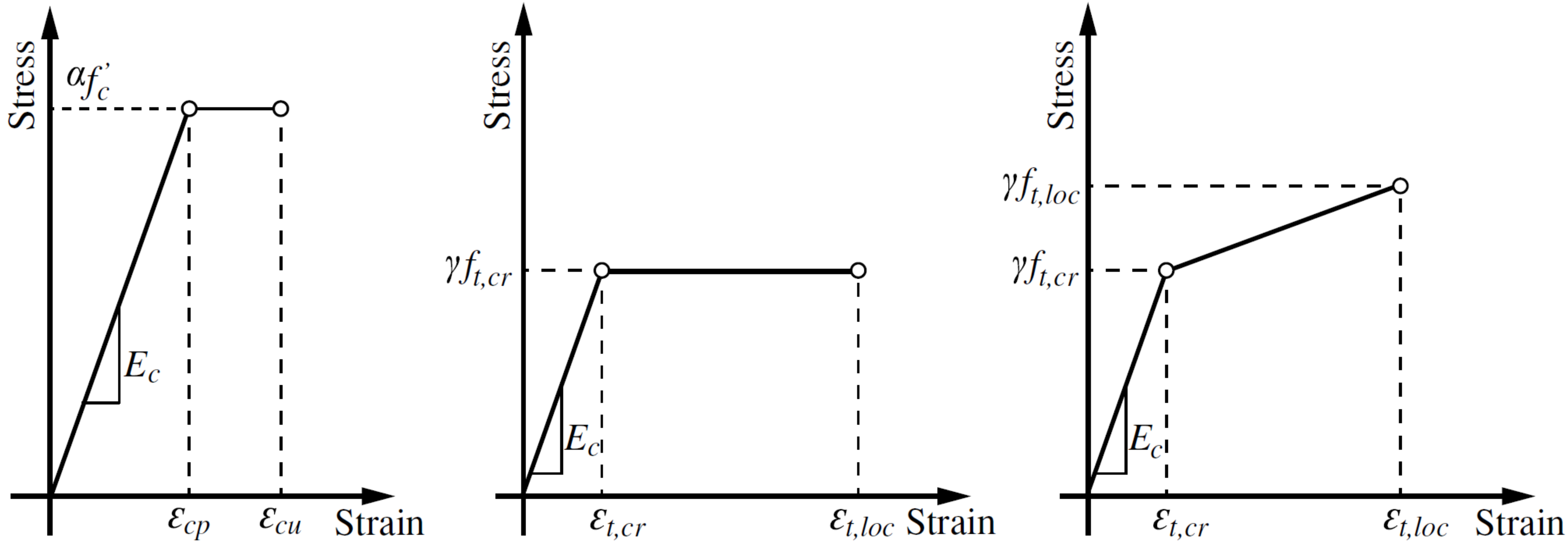
UHPC presentation

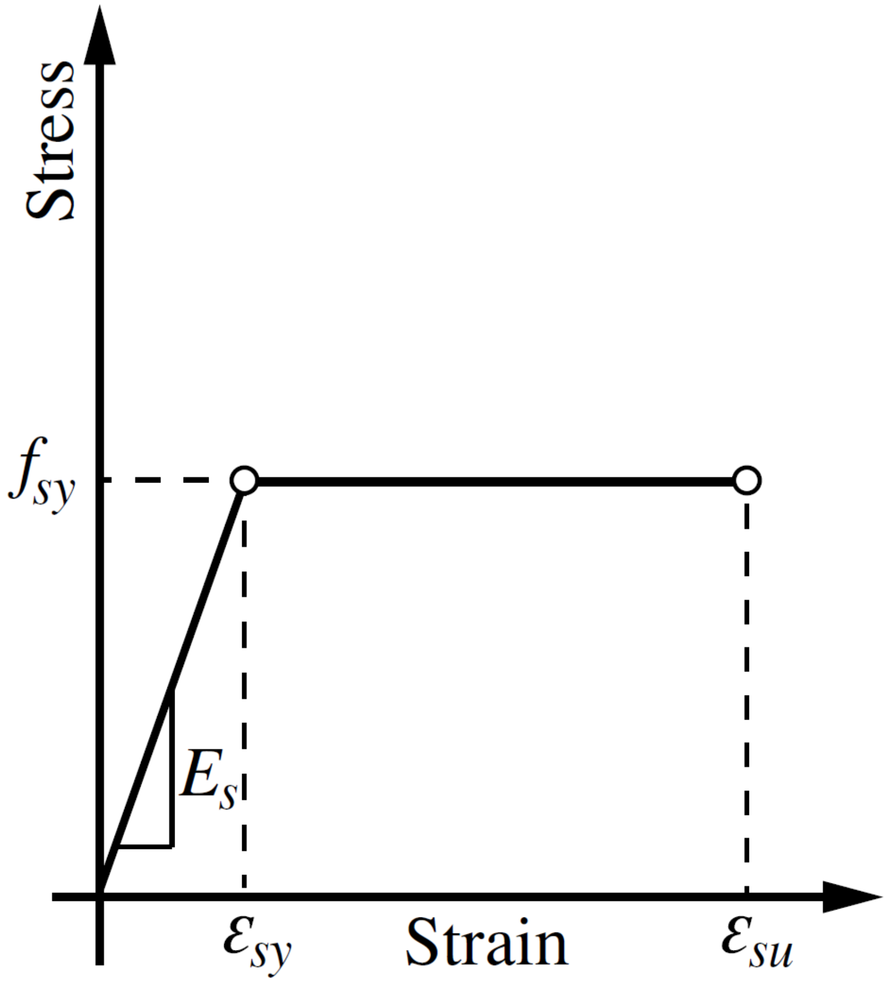
Choose a slide to present



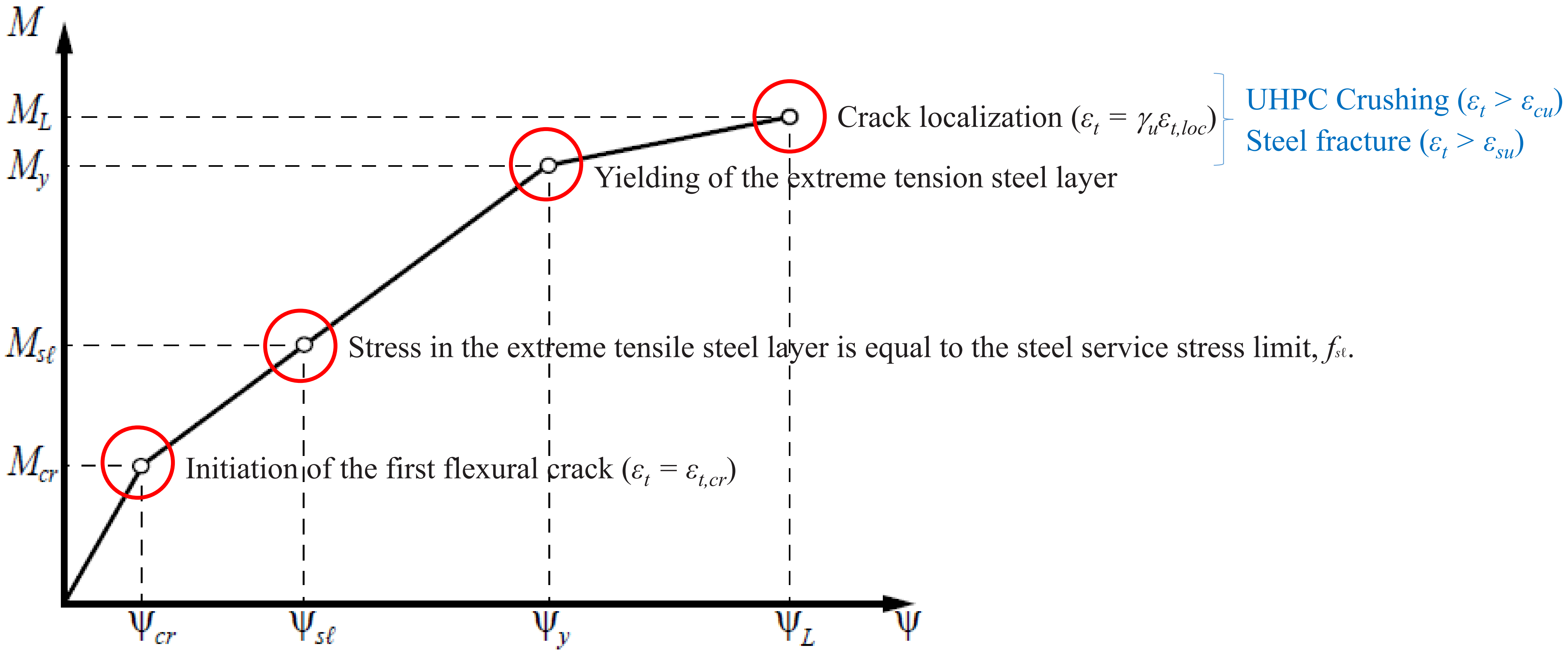
UHPC Stress-Strain Responses



Steel Stress Strain Response



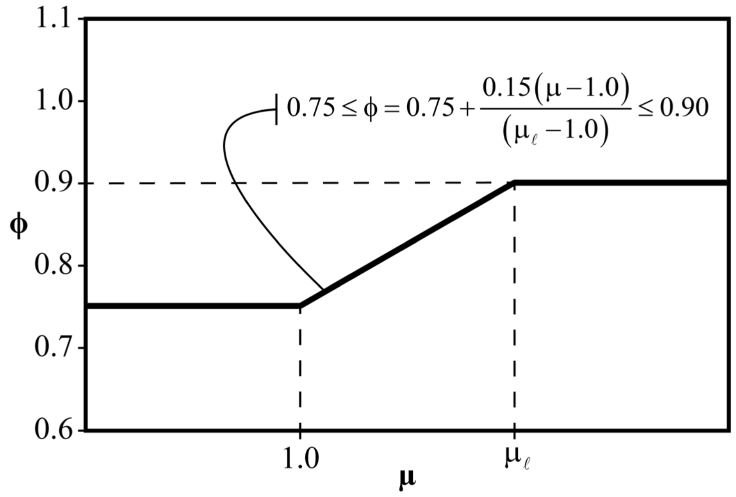
Moment-Curvature Response: Key States



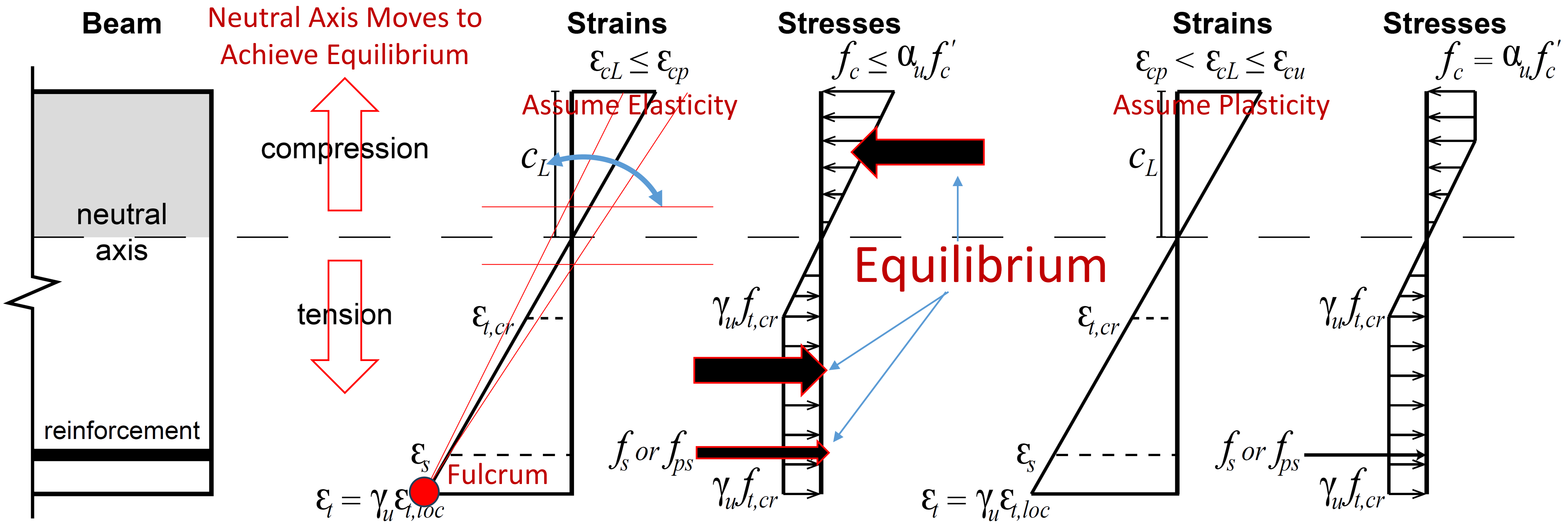
Moment Curvature Analysis - Procedure

- Draw the strain diagram corresponding to each state
- Get the strain in any given layer of the UHPC, prestressing steel, and/or non-prestressed reinforcement
- Get the stress from the stress–strain models (next slides)
- Satisfy the conditions of force equilibrium in the section
- Compute the nominal flexural strength

$$M_r = \phi M_n$$



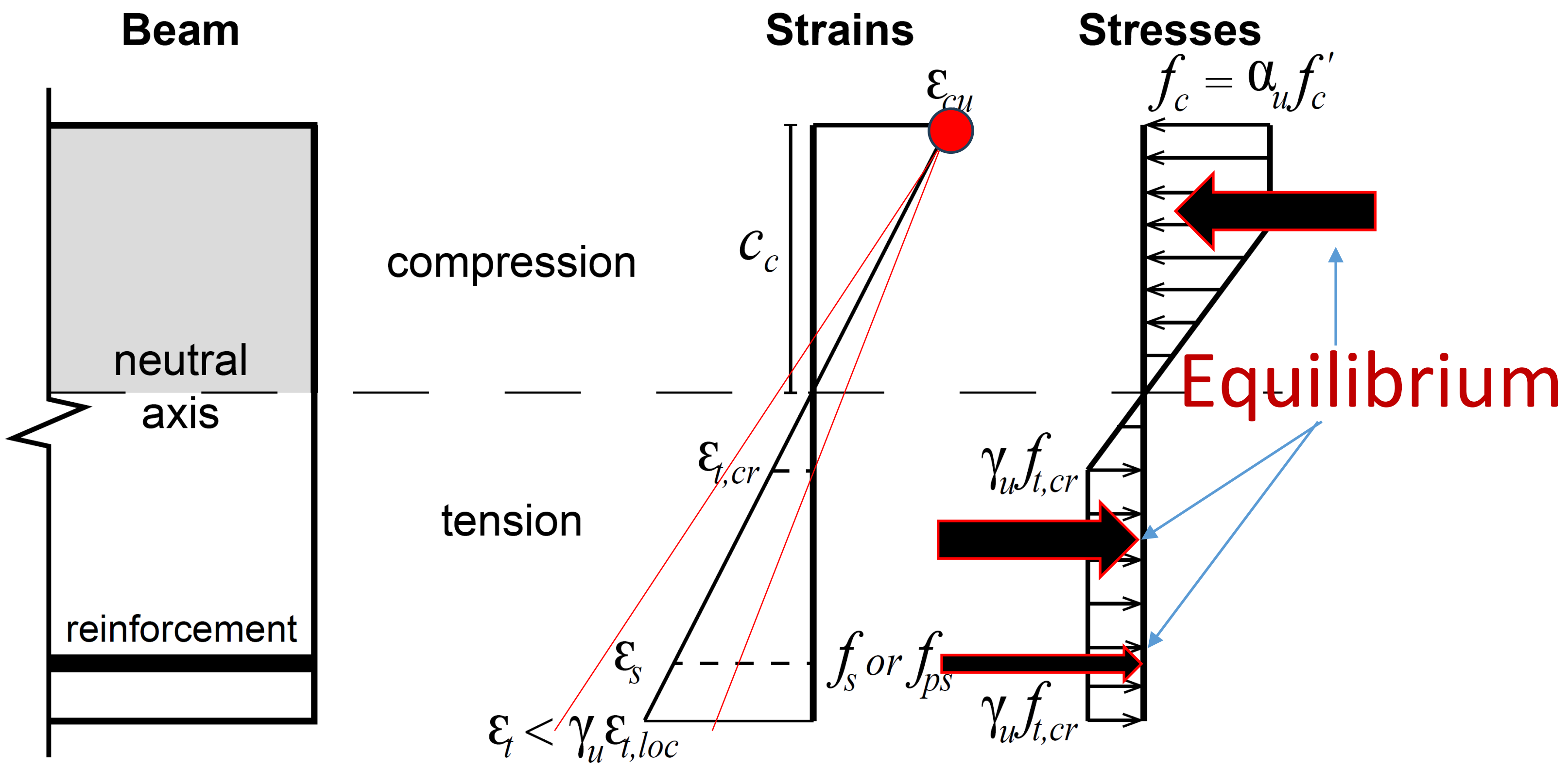
Strain Compatibility in Flexure – Onset of Crack Localization



(a) Elastic stresses in compression

(b) Plastic stresses in compression

Strain Compatibility in Flexure – UHPC Crushing



Curvature Ductility Ratio

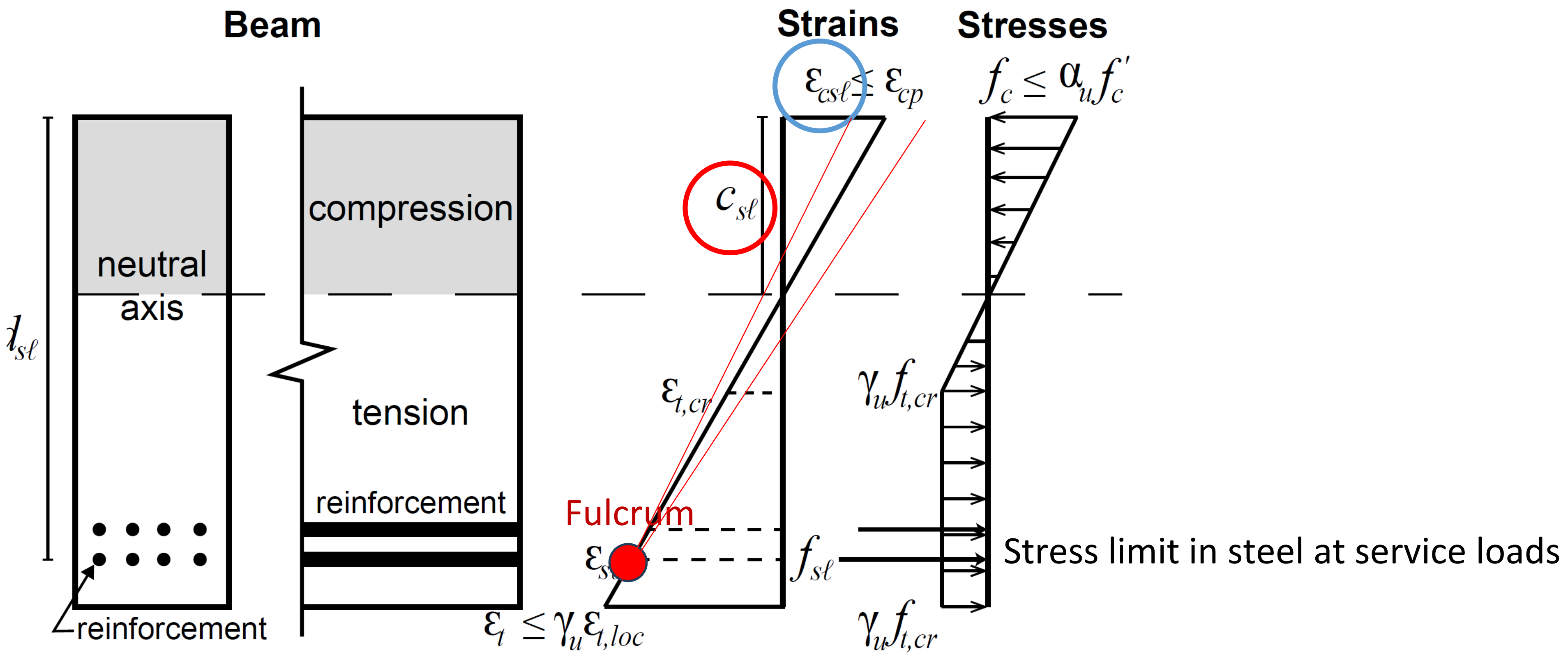
- Ratio of the sectional curvature at the nominal moment resistance to the baseline sectional curvature

$$\mu = \frac{\psi_n}{\psi_{s\ell}}$$

- The baseline sectional curvature is when the stress in the extreme tension steel is equal to 80 percent of the yielding stress of the reinforcement
- Originates from the ‘service curvature’ for prestressed members

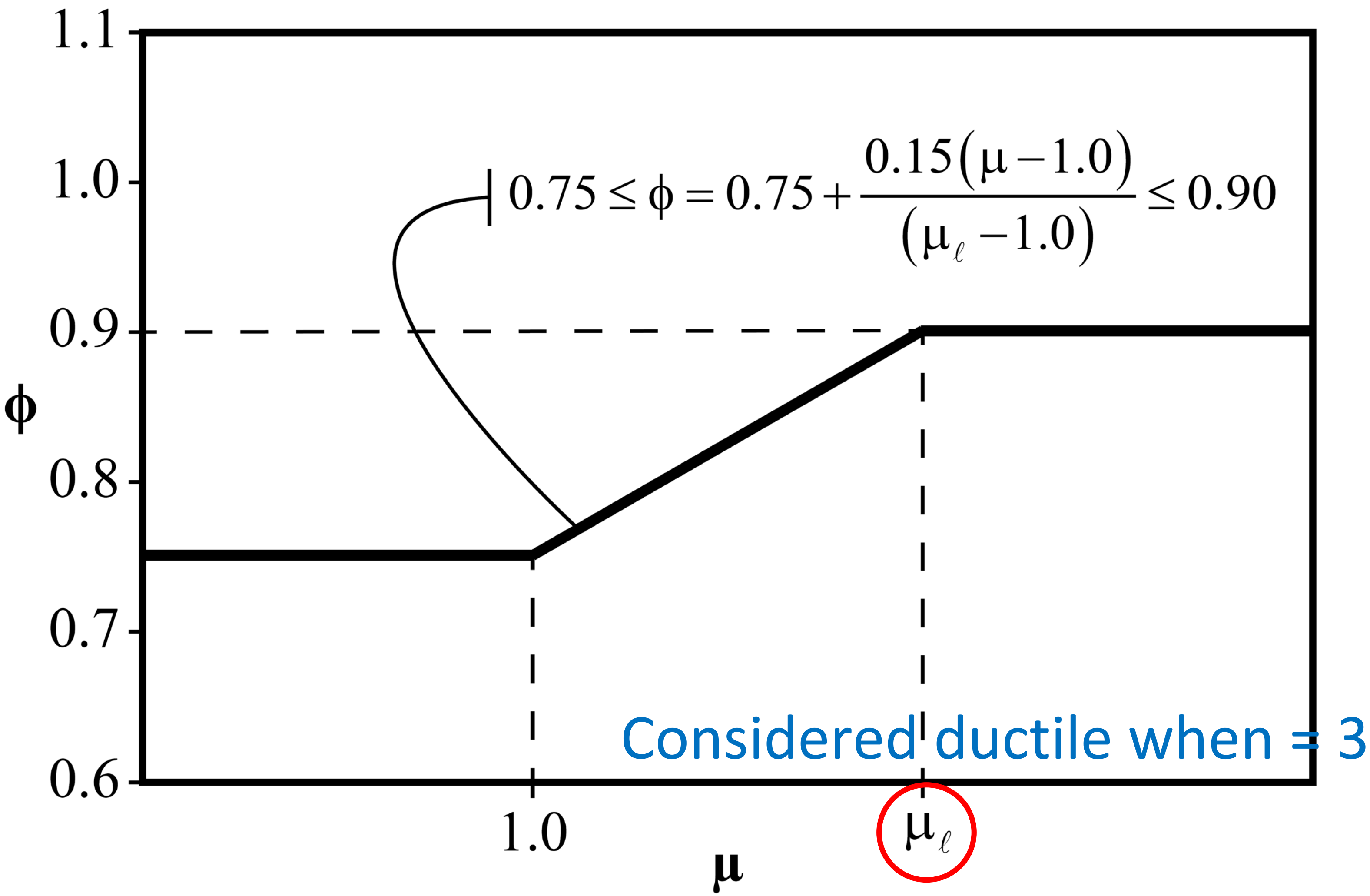
Baseline Sectional Curvature

$$\psi_{s\ell} = \frac{\varepsilon_{cs\ell}}{c_{s\ell}}$$



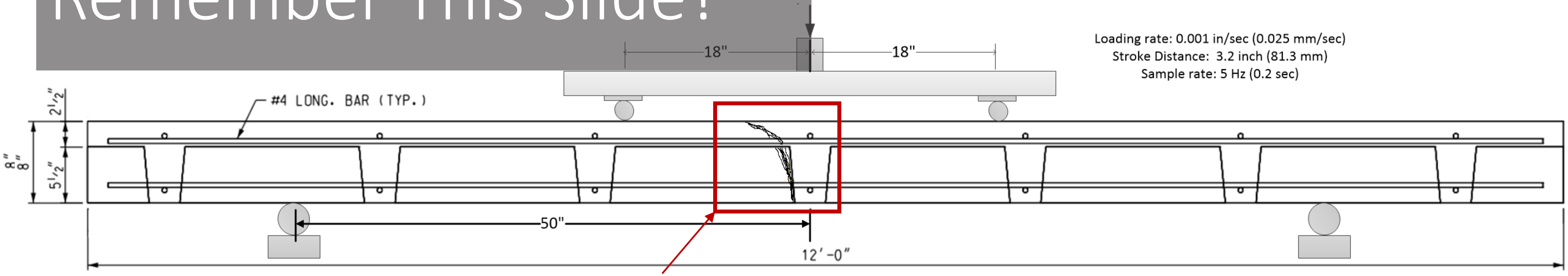
Stress in the extreme tension steel is equal to the service stress limit, $f_{s\ell}$

Flexural Strength Reduction Factor (

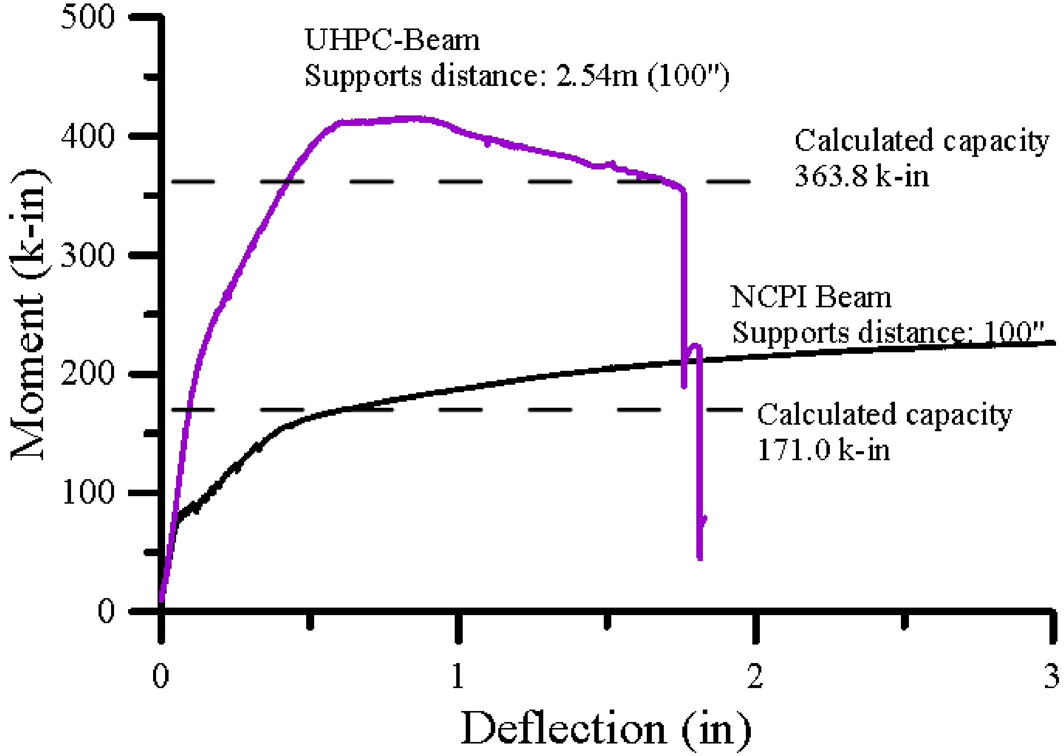


UHPC beam test and DIC results - FLEXURE

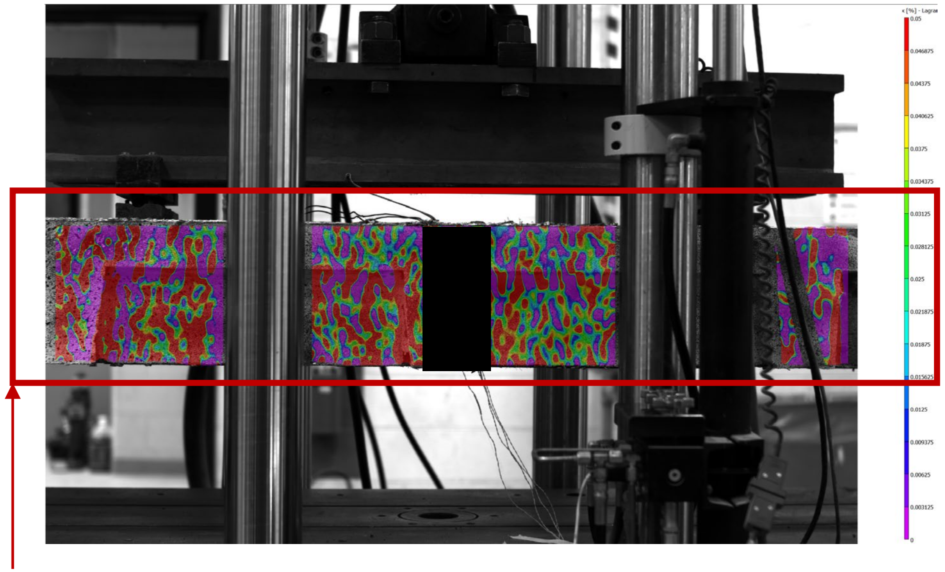
Remember This Slide?



Single crack localization



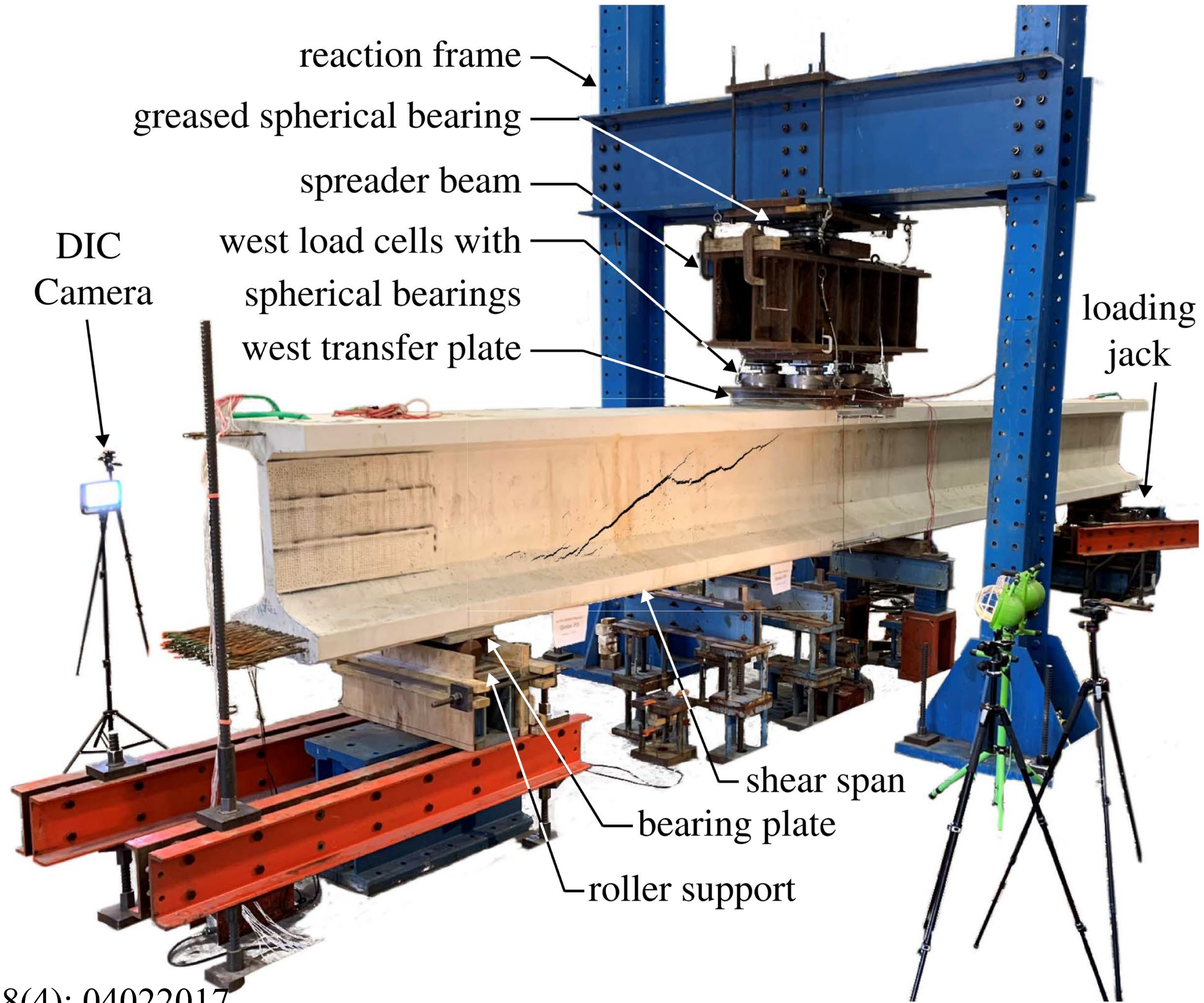
M_{yield} ===> $\delta = 2.53\ mm$



Only micro-cracking at steel yield – excellent protection under service conditions

DESIGN FOR SHEAR

B-Regions



J. Struct. Eng., 2022, 148(4): 04022017

Relationship to AASHTO-LRFD

- The Guide specification provide explicit guidance on how its provisions should be used with AASHTO-LRFD provisions

When is Transverse Reinforcement Needed?

Nominal shear resistance of the UHPC

$$V_u > \phi(V_{UHPC} + V_p)$$

Resistance factor = 0.9

Component of prestressing force in the direction of the shear force; positive if resisting the applied shear

- Full-scale shear tests on UHPC girders show significant post-cracking ductility.
- This is due to the fibers.
- Therefore, transverse steel reinforcement is not required unless this condition is satisfied.
- Unlike Concrete!

Minimum Transverse Reinforcement

- Transverse shear reinforcement need not be provided where not required.

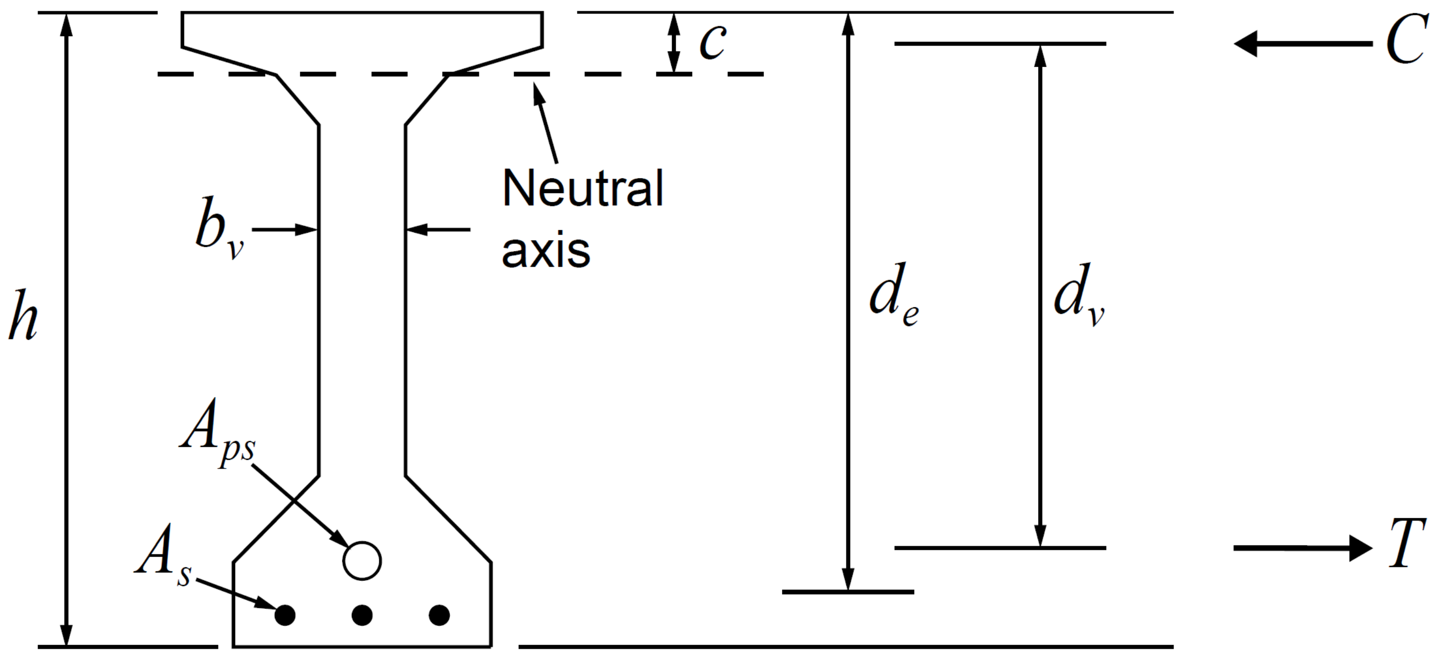
Maximum Spacing of Shear Reinforcement

$$s_{max} = 0.25 d_v \cot \theta \leq 24.0 \text{ in.}$$

Effective shear depth

Angle of inclination of diagonal compressive stresses

Effective Shear Depth



- d_v is the distance between the tensile and compressive resultants
- d_v < Max(0.9d_e or 0.72h)

Shear Stress on UHPC

Zero in reinforced UHPC

$$v_u = \frac{\left| V_u - \phi V_p \right|}{\phi b_v d_v}$$

Effective web width taken as the minimum web width

Nominal Shear Resistance

V_n is the smaller of

$$0.25 f'_c b_v d_v$$

Intended to capture the failure mode in which the UHPC in the web of the beam crushes prior to or at the development of the critical crack

$$V_{UHPC} + V_s$$

Based on the Modified Compression Field Theory (MCFT), originally developed for conventional concrete by Vecchio and Collins (1986)

Nominal Shear Resistance

'Shear' Capacity

Web Area

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

Angle of inclination of diagonal compressive stresses

Nominal Shear Resistance

Stress in the transverse shear reinforcement at nominal shear resistance

$$V_s = \frac{A_v f_{v,\alpha} d_v \cot\theta}{s}$$

Angle of inclination of diagonal compressive stresses

Simplified Procedure

- The parameters θ and $f_{v,\alpha}$ are determined by iteratively solving a set of equations to achieve equilibrium in shear
- Simplified procedure can be used if certain conditions are met
  - $E_c \geq 6{,}500$ ksi and $f_{t,loc} \leq 1.80$ ksi
  - $f_y \leq 75.0$ ksi, $\rho_{v,\alpha} \leq 3.0\%$, and $\alpha = 90$ (vertical stirrups)
- Need to compute the strain in the steel: ε_s

Compute ε_s

Area of UHPC on the flexural tension side of the member

Net longitudinal tensile strain in the section at the centroid of the tension reinforcement

$$\varepsilon_s = \frac{\left(\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{ps}f_{po} - \gamma_u f_{t,cr} A_{ct}\right)}{E_s A_s + E_p A_{ps}}$$

(In the equation, the terms $0.5N_u$, V_p, $A_{ps}f_{po}$ and E_p are crossed out with red X marks.)

X — Effect of prestressing

Values of θ (Degrees) and Upper Limit of $f_{v,\alpha}$ (ksi) for Sections with Transverse Reinforcement with $\rho_{v,\alpha} \leq 0.5$ Percent

$\varepsilon_s \times$ 1,000	Parameter	$\gamma_u \varepsilon_{t,loc} \times$ 1,000											
		≥2.5	≥3.0	≥3.5	≥4.0	≥4.5	≥5.0	≥5.5	≥6.0	≥6.5	≥7.0	≥7.5	≥8.0
≤ −1.0	θ (deg.)	31.8	31.2	30.8	30.4	29.9	29.3	28.8	28.4	28.0	27.6	27.3	27.0
	$f_{v,\alpha}$ (ksi)	≤39.0	≤49.6	≤60.4	≤71.2	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤ −0.5	θ (deg.)	33.5	32.7	32.1	31.6	31.0	30.4	29.9	29.4	28.9	28.5	28.1	27.7
	$f_{v,\alpha}$ (ksi)	≤37.6	≤48.1	≤58.7	≤69.4	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤0.0	θ (deg.)	35.4	34.4	33.6	32.9	32.3	31.6	30.9	30.4	29.9	29.4	29.0	28.6
	$f_{v,\alpha}$ (ksi)	≤35.9	≤46.2	≤56.8	≤67.4	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤0.5	θ (deg.)	37.5	36.2	35.2	34.3	33.6	32.8	32.1	31.5	30.9	30.4	29.9	29.4
	$f_{v,\alpha}$ (ksi)	≤33.9	≤44.2	≤54.6	≤65.2	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤1.0	θ (deg.)	40.0	38.3	37.0	35.9	35.0	34.1	33.3	32.6	32.0	31.4	30.8	30.3
	$f_{v,\alpha}$ (ksi)	≤31.7	≤41.8	≤52.2	≤62.8	≤73.4	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤1.5	θ (deg.)	42.8	40.6	38.9	37.6	36.6	35.6	34.6	33.8	33.1	32.4	31.8	31.3
	$f_{v,\alpha}$ (ksi)	≤29.1	≤39.2	≤49.5	≤60.0	≤70.7	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤2.0	θ (deg.)	45.9	43.1	41.1	39.5	38.2	37.1	36.0	35.1	34.3	33.5	32.9	32.3
	$f_{v,\alpha}$ (ksi)	≤26.2	≤36.2	≤46.5	≤57.0	≤67.7	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤2.5	θ (deg.)	49.5	45.9	43.4	41.5	39.9	38.7	37.5	36.5	35.5	34.7	34.0	33.3
	$f_{v,\alpha}$ (ksi)	≤22.8	≤32.8	≤43.2	≤53.7	≤64.4	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤3.0	θ (deg.)	–	49.1	45.9	43.6	41.8	40.4	39.0	37.9	36.8	35.9	35.1	34.4
	$f_{v,\alpha}$ (ksi)	–	≤29.1	≤39.6	≤50.1	≤60.8	≤71.7	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤3.5	θ (deg.)	–	–	48.7	46.0	43.8	42.1	40.7	39.4	38.2	37.2	36.3	35.5
	$f_{v,\alpha}$ (ksi)	–	–	≤35.6	≤46.2	≤57.0	≤67.9	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤4.0	θ (deg.)	–	–	–	48.5	46.0	44.0	42.4	40.9	39.6	38.5	37.5	36.7
	$f_{v,\alpha}$ (ksi)	–	–	–	≤42.1	≤52.9	≤63.9	≤74.9	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤4.5	θ (deg.)	–	–	–	–	48.3	46.0	44.1	42.5	41.1	39.9	38.8	37.9
	$f_{v,\alpha}$ (ksi)	–	–	–	–	≤48.6	≤59.6	≤70.7	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤5.0	θ (deg.)	–	–	–	–	–	48.1	46.0	44.2	42.7	41.3	40.1	39.1
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	≤55.1	≤66.3	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤5.5	θ (deg.)	–	–	–	–	–	–	47.9	46.0	44.3	42.8	41.5	40.4
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	≤61.7	≤73.0	≤75.0	≤75.0	≤75.0	≤75.0
≤6.0	θ (deg.)	–	–	–	–	–	–	–	47.8	46.0	44.3	42.9	41.7
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	≤68.2	≤75.0	≤75.0	≤75.0	≤75.0
≤6.5	θ (deg.)	–	–	–	–	–	–	–	–	47.7	45.9	44.4	43.0
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	–	≤74.8	≤75.0	≤75.0	≤75.0
≤7.0	θ (deg.)	–	–	–	–	–	–	–	–	–	47.5	45.9	44.4
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	–	–	≤75.0	≤75.0	≤75.0
≤7.5	θ (deg.)	–	–	–	–	–	–	–	–	–	–	47.4	45.8
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	–	–	–	≤75.0	≤75.0
≤8.0	θ (deg.)	–	–	–	–	–	–	–	–	–	–	–	46.6
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	–	–	–	–	≤75.0

Note: Values for θ and $f_{v,\alpha}$ where ε_s is greater than $\gamma_u \varepsilon_{t,loc}$ are not relevant. These combinations are indicated by cells containing the "–" symbol.

Values of θ (Degrees) and Upper Limit of $f_{v,\alpha}$ (ksi) for Sections with Transverse Reinforcement with $\rho_{v,\alpha} \leq 0.5$ Percent

$\varepsilon_s \times 1{,}000$	Parameter	$\gamma_u \varepsilon_{t,loc} \times 1{,}000$											
		≥2.5	≥3.0	≥3.5	≥4.0	≥4.5	≥5.0	≥5.5	≥6.0	≥6.5	≥7.0	≥7.5	≥8.0
≤ −1.0	θ (deg.)	31.8	31.2	30.8	30.4	29.9	29.3	28.8	28.4	28.0	27.6	27.3	27.0
	$f_{v,\alpha}$ (ksi)	≤39.0	≤49.6	≤60.4	≤71.2	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤ −0.5	θ (deg.)	33.5	32.7	32.1	31.6	31.0	30.4	29.9	29.4	28.9	28.5	28.1	27.7
	$f_{v,\alpha}$ (ksi)	≤37.6	≤48.1	≤58.7	≤69.4	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤0.0	θ (deg.)	35.4	34.4	33.6	32.9	32.3	31.6	30.9	30.4	29.9	29.4	29.0	28.6
	$f_{v,\alpha}$ (ksi)	≤35.9	≤46.2	≤56.8	≤67.4	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤0.5	θ (deg.)	37.5	36.2	35.2	34.3	33.6	32.8	32.1	31.5	30.9	30.4	29.9	29.4
	$f_{v,\alpha}$ (ksi)	–	–	–	–	≤48.6	≤59.6	≤70.7	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤5.0	θ (deg.)	–	–	–	–	–	48.1	46.0	44.2	42.7	41.3	40.1	39.1
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	≤55.1	≤66.3	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤5.5	θ (deg.)	–	–	–	–	–	–	47.9	46.0	44.3	42.8	41.5	40.4
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	≤61.7	≤73.0	≤75.0	≤75.0	≤75.0	≤75.0
≤6.0	θ (deg.)	–	–	–	–	–	–	–	47.8	46.0	44.3	42.9	41.7
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	≤68.2	≤75.0	≤75.0	≤75.0	≤75.0
≤6.5	θ (deg.)	–	–	–	–	–	–	–	–	47.7	45.9	44.4	43.0
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	–	≤74.8	≤75.0	≤75.0	≤75.0
≤7.0	θ (deg.)	–	–	–	–	–	–	–	–	–	47.5	45.9	44.4
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	–	–	≤75.0	≤75.0	≤75.0
≤7.5	θ (deg.)	–	–	–	–	–	–	–	–	–	–	47.4	45.8
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	–	–	–	≤75.0	≤75.0
≤8.0	θ (deg.)	–	–	–	–	–	–	–	–	–	–	–	46.6
	$f_{v,\alpha}$ (ksi)	–	–	–	–	–	–	–	–	–	–	–	≤75.0

Note: Values for θ and $f_{v,\alpha}$ where ε_s is greater than $\gamma_u \varepsilon_{t,loc}$ are not relevant. These combinations are indicated by cells containing the "–" symbol.

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UHPC presentation

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Instructions

Why is UHPC so Durable?

The ductility of UHPC beams is limited because:

Fiber clumping is a sign of:


No stirrups!

Session 5

Application of UHPC Technology and its Potential

Cost of a Cubic Yard of Open Recipe UHPC

- Commercially available UHPC costs between $2,000 to $3,000 a cubic yard (*Ready Mixed Concrete Association, Feb. 2020*)
- Open recipe UHPC costs about ~ 1/3 of this price on average (~ 2/3 savings)

Ingredient	Cement	SF	GGBS	Sand I	Sand II	Steel Fiber	SP (3%)	Total Price
$/pound	0.06	0.26	0.06	0.07	0.07	1.96	1.83	
$/yard^3	42	85	39	28	112	519	72	896
2019 Prices								

Cost of a Cubic Yard of Open Recipe UHPC in 2023

- Cost of Open Recipe:
  - Glass Sand; 0.165/lb X 394 = $65.01
  - Fine Sand: .165/lb X 1577 = $260.2
  - Cement; 0.11/lb X 653 = $71.83
  - Slag; 0.09/lb X 653 = $58.77
  - Water Reducer; 5.45/gal X 4.7 = $25.62
  - Silica Fume; 0.45/lb X 326 = $146.7
  - Fiber; 2.45/lb X 264 = $646.8
  - Total: $1215

Reducing the Cost with Replacement Sand and Reduced Steel Dosage – More to Come!

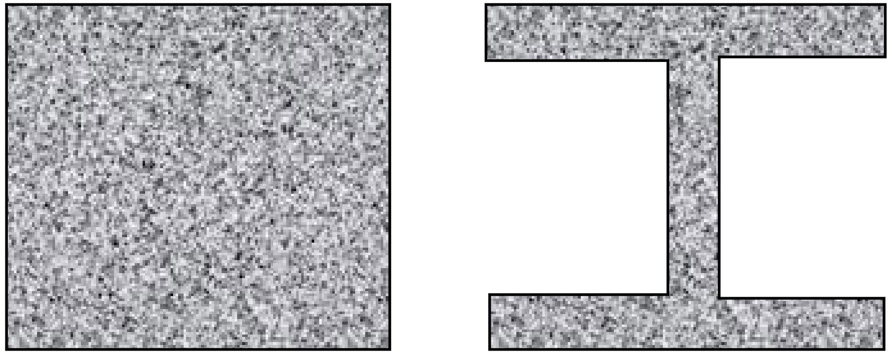
- Glass Sand; 0.165/lb X 394 = $65.01
- Fine Sand: .007/lb X 1577 = $11
- Cement; 0.11/lb X 653 = $71.83
- Slag; 0.09/lb X 653 = $58.77
- Water Reducer; 5.45/gal X 4.7 = $25.62
- Silica Fume; 0.45/lb X 326 = $146.7
- Fiber; 2.45/lb X 200 = $490

- Total: $869

The Cost Argument

- The cost of a cubic yard of construction grade concrete is X ~ $120
- A cubic yard of concrete does not exist in isolation
  - Several hundred dollars in design, construction and furnishing costs must be expended to get that cubic yard into place
- A lane-mile of highway costs $1M to construct in 2019 dollars
  - That's $500 per placed cubic yard of concrete
  - Suggests that other costs are about $380 per cubic yard ($500-$120)
- Cost of a placed cubic yard of concrete in a prestressed concrete girder is about $1,000 in 2019 dollars
  - Means that other costs are $880 per cubic yard
- **Therefore**: 'Other' costs range from 3X to 7X

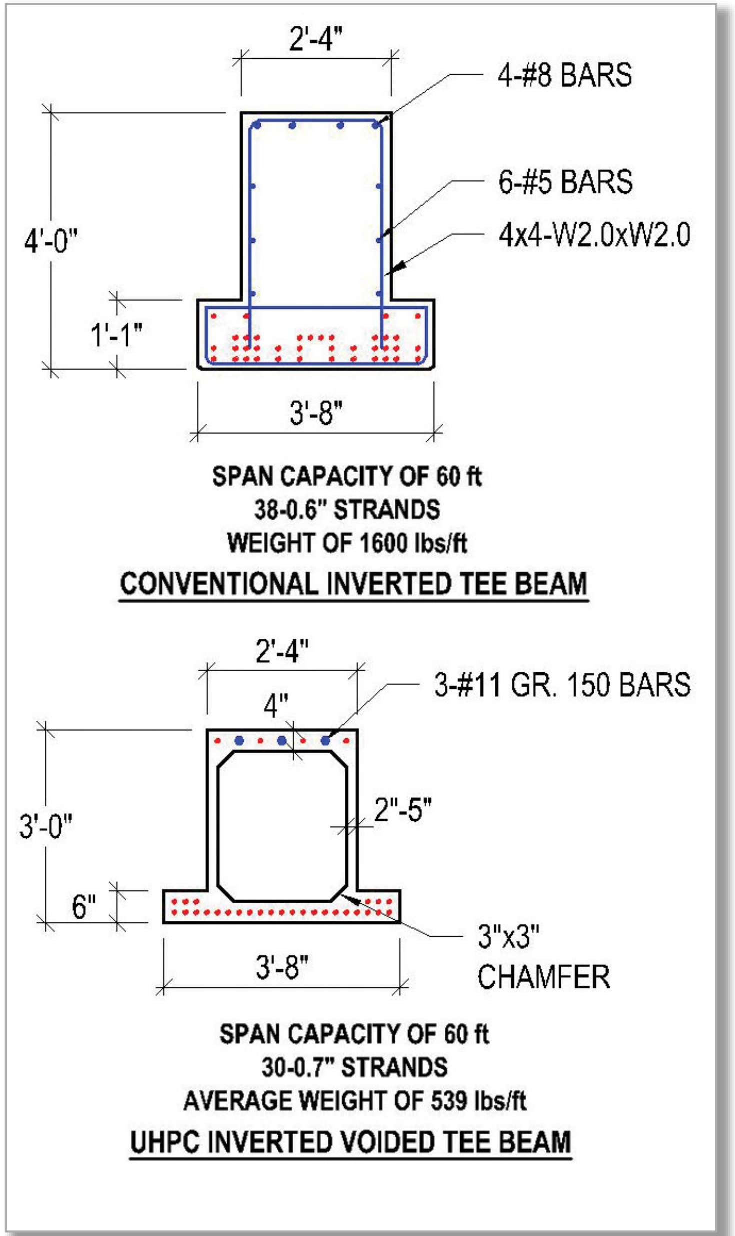
UHPC Reduces Material Volume



Y: reduction in volume due to the use of UHPC

Z: reduction in ‘other’ costs for the replaced product

Recall: X ~ $120



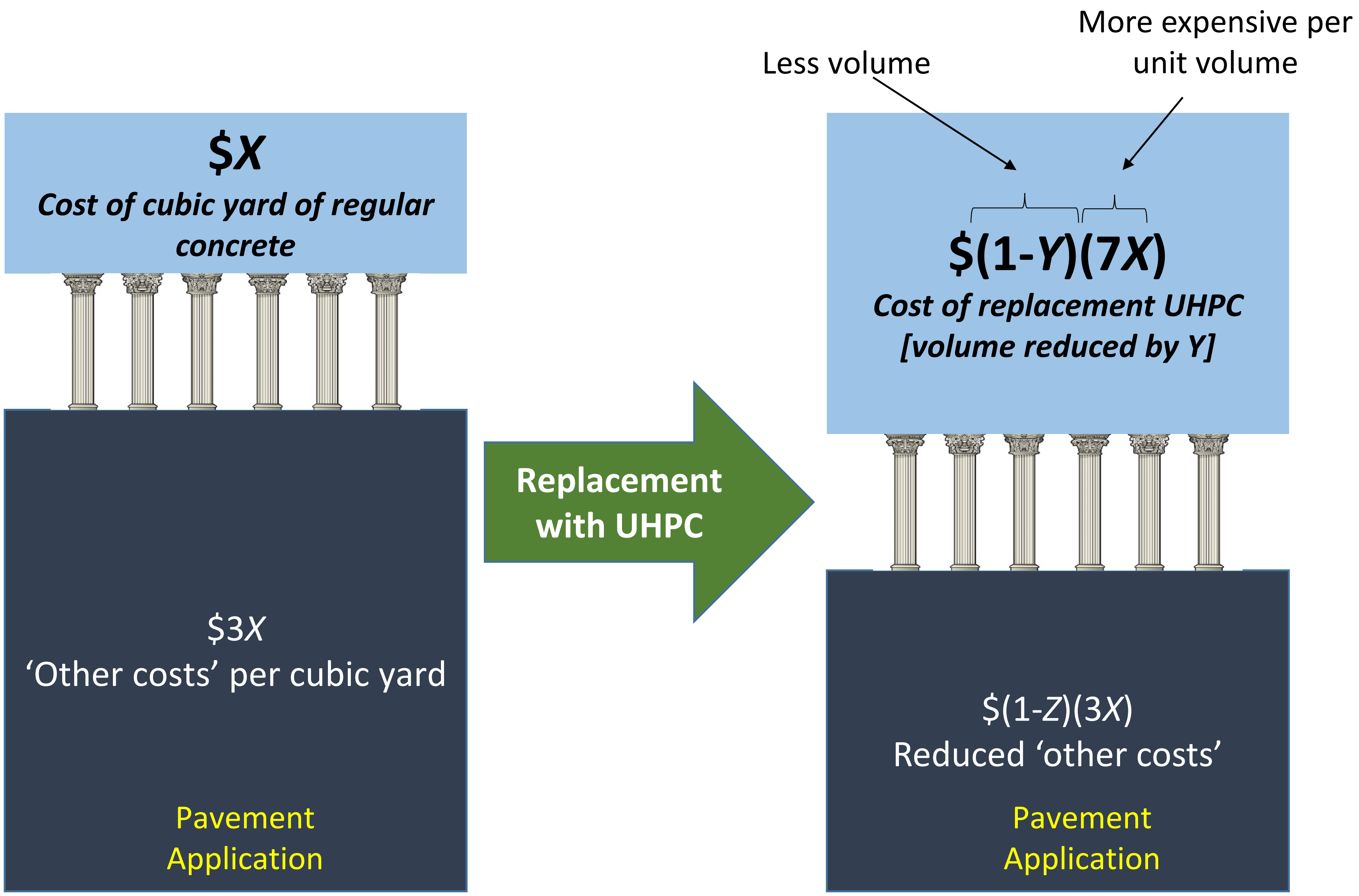
One foot shallower and 65% lighter

Tadros et al. (2019), Ultra-High-Performance Concrete, Structure Magazine, April 2019

Cheaper Z ('Other' Costs)

- Cheaper transportation cost
- Easier and cheaper handling (needs smaller cranes on construction site)
- Lighter and cheaper superstructure
- Lighter and cheaper substructure

The Cost Argument



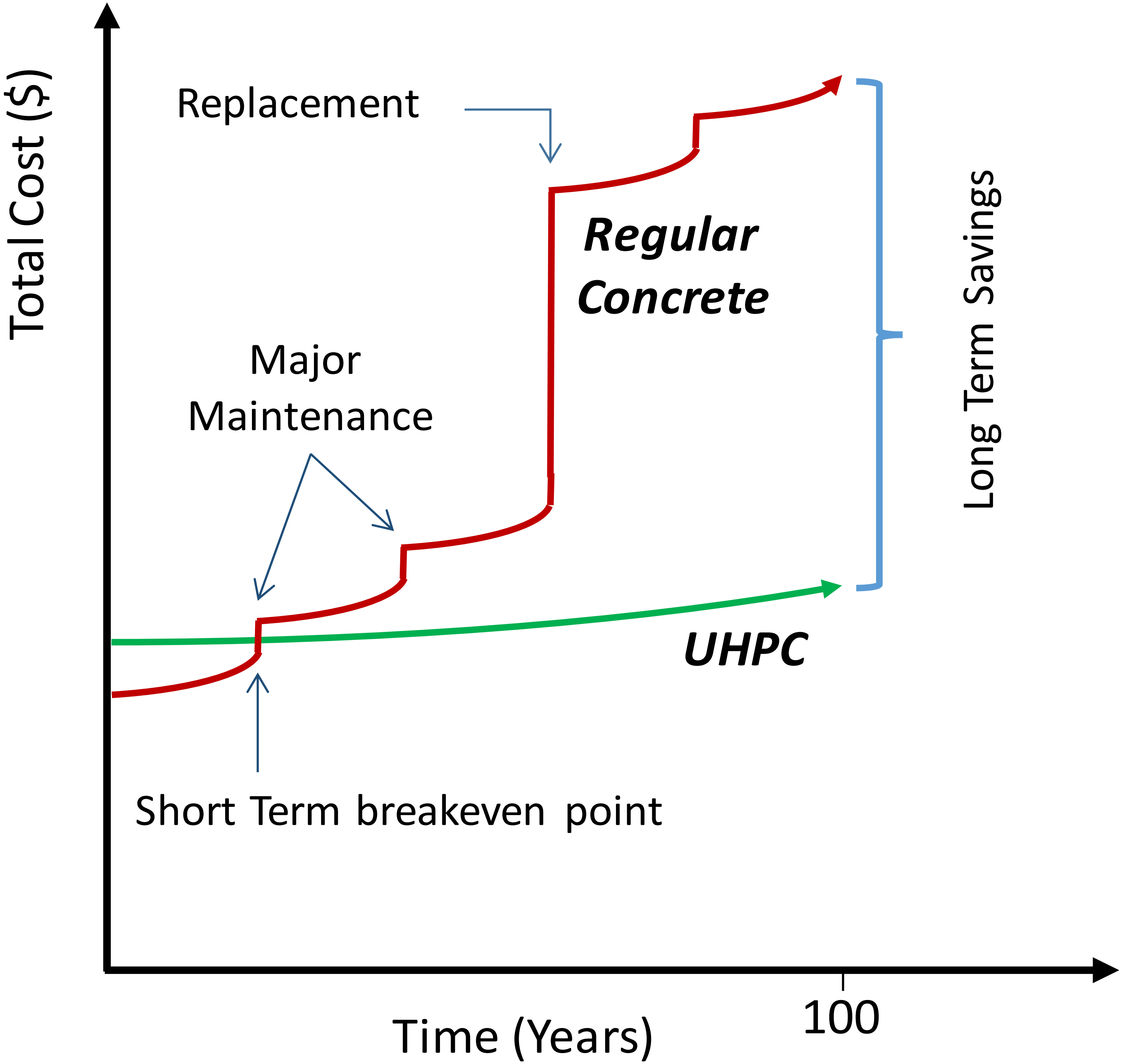
Prestressed Concrete Girders	Increase in Total Cost					
Y \ Z	0.2	0.3	0.4	0.5	0.6	0.7
0.4	23	14	5	-4	-13	-21
0.5	14	5	-4	-13	-21	-30
0.6	5	-4	-13	-21	-30	-39
0.7	-4	-13	-21	-30	-39	-48

Pavement Concrete	Increase in Total Cost					
Y \ Z	0.2	0.3	0.4	0.5	0.6	0.7
0.4	65	58	50	43	35	28
0.5	48	40	33	25	18	10
0.6	30	23	15	8	0	-8
0.7	13	5	-2	-10	-18	-25

Y: reduction in volume due to the use of UHPC

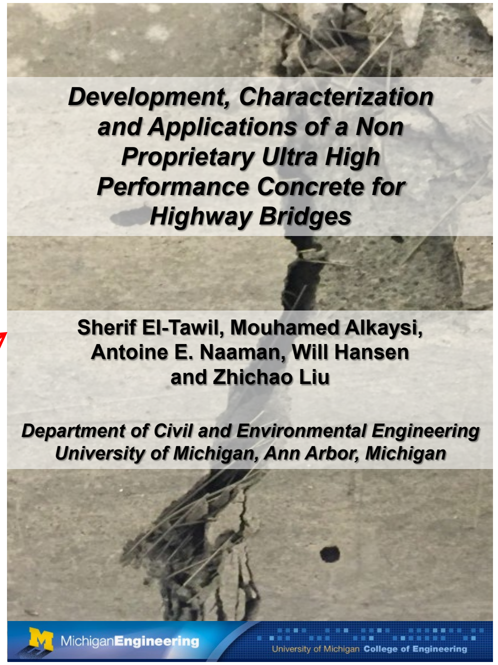
Z: reduction in 'other' costs for the replaced product

Real Opportunity for Cost Savings



UHPC Usage in Michigan

- Michigan is a pioneer in UHPC technology
- MDOT funded a pair of studies at the University of Michigan that produced a non-proprietary UHPC that is the basis for much of the research ongoing across the US on this topic.
- The State is host to several firsts in UHPC usage:
  - First bridge with open-recipe UHPC closure pour (Dewayne Rogers, St. Clair County 2018)
  - First bridge with open-recipe UHPC composite deck (Dewayne Rogers, Clare County 2022)
  - First bridge with open-recipe UHPC full deck (Bill Hazelton, St. Clair County 2022)
- Other users
  - Art Buck, Midland County (closure pour, 2022)



RECOMMENDED SPECIAL PROVISION
FOR
PRODUCTION OF MICHIGAN ULTRA HIGH PERFORMANCE CONCRETE (MI – UHPC)

a. Description. This special provision addresses the production of Michigan Ultra High Performance Concrete (Mi-UHPC). Mi-UHPC must be used at locations specified on the plans. All work must be in accordance with the standard specifications, except as modified herein.

b. Materials. The concrete mixture must contain the following materials per cubic yard. Four mixes are listed with different amounts of High Range Water Reducers (HRWR). Other amounts of HRWR and alternative material proportions may be used if the resulting mix is shown to achieve the performance outlined in section h of this special provision and approved by the Engineer.

Material	**Weight [lb/yd^3]**			
Cement Blend	Mix A[1]	Mix B[1]	Mix C[1]	Mix D[1]
Portland Type I	653			
Slag Cement	653			
Silica Sand				
Fine Sand[2]	398	396	395	394
Coarse Sand[3]	1590	1586	1982	1577
Silica Fume	327			
Water	276	272	268	264

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UHPC presentation

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Instructions

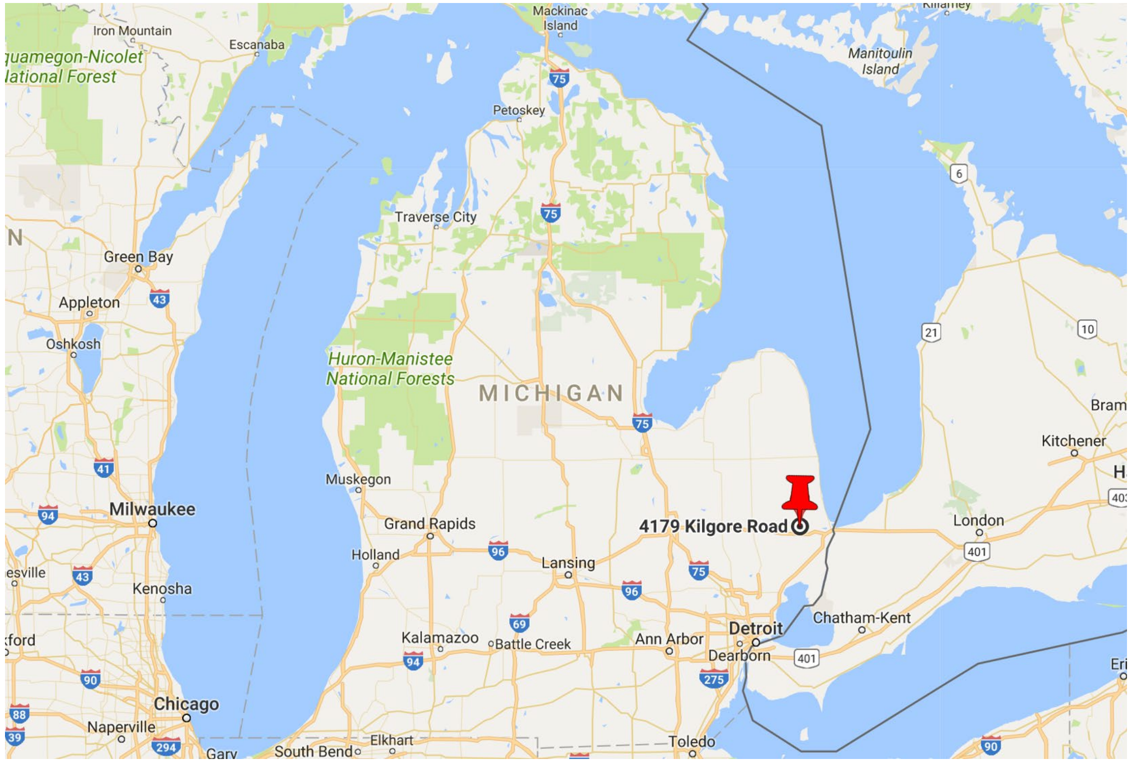
Why is UHPC so Durable?

The ductility of UHPC beams is limited because:

Fiber clumping is a sign of:

Example 1: First Open Recipe UHPC Bridge:

Kilgore Road over the Pine River, Kenockee Township, MI



(a) Location of UHPC deployment in the State of Michigan

(b) Bridge site

(a) Addition of ingredients

(b) Dry mix

c) Addition of liquid with cubed ice

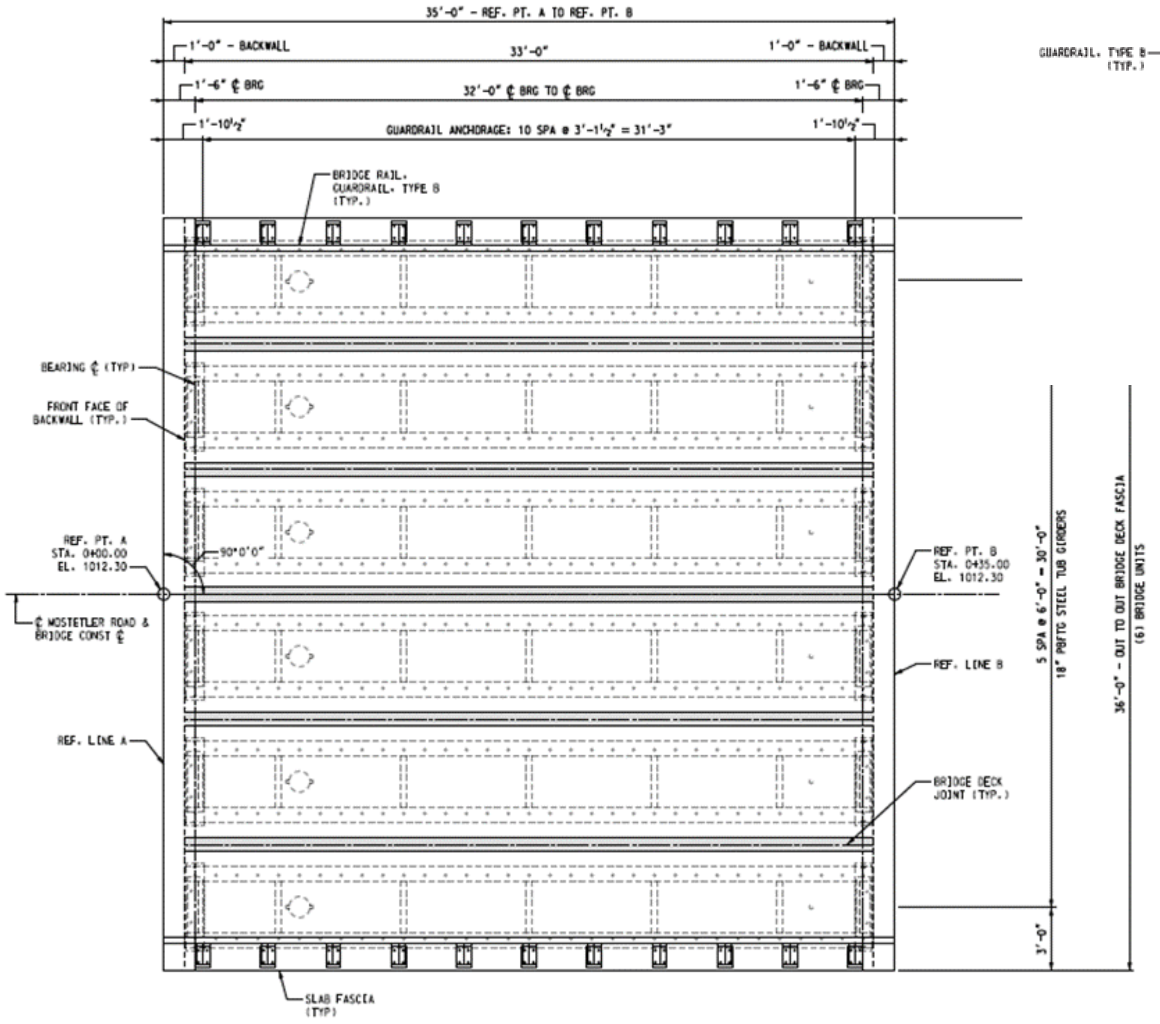
(d) Mix dispersion and homogenization

(e) Addition of steel fibers

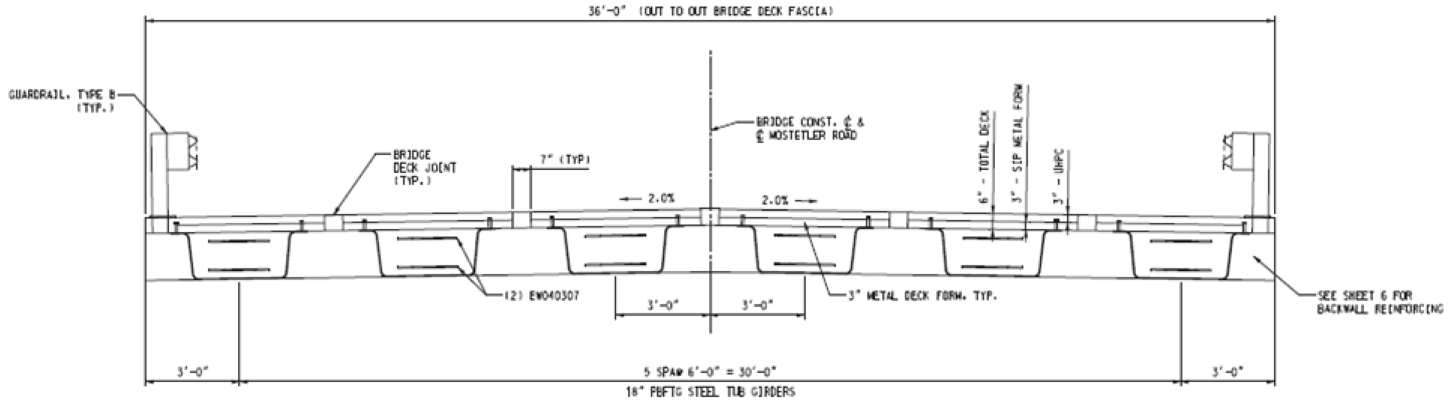
(f) Flow test on UHPC

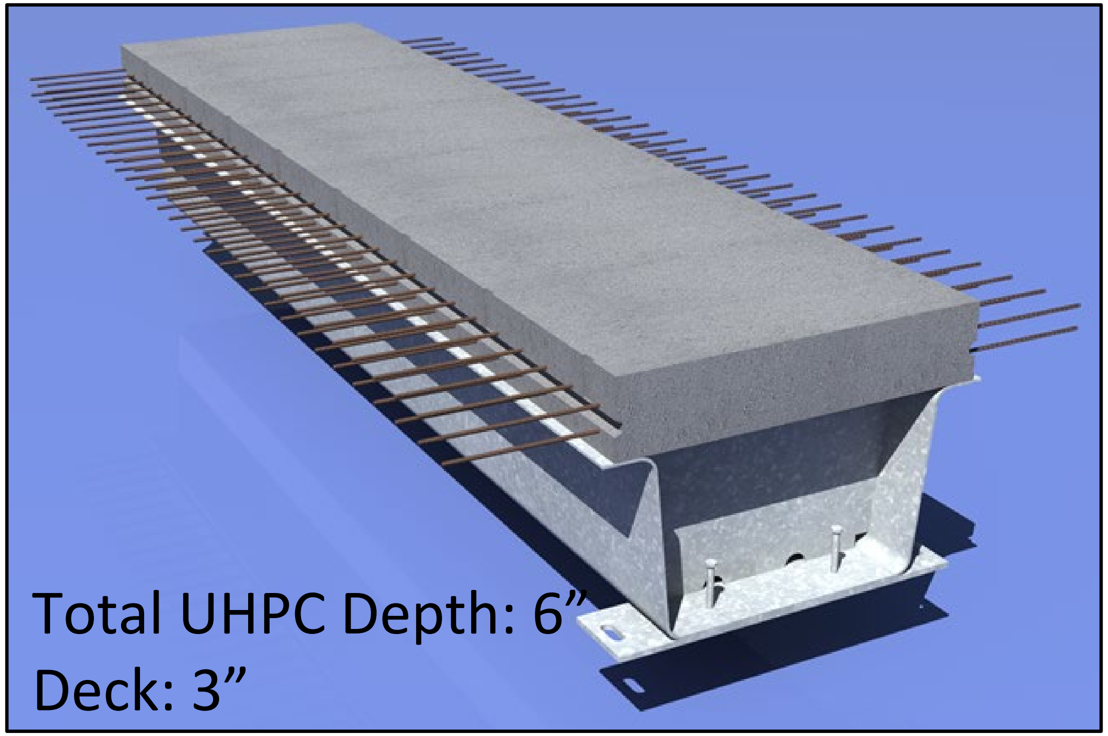
First bridge in the US to use open-recipe UHPC (2018)
Kilgore Road over the Pine River (Structure No. 10091), Kenockee Township, MI

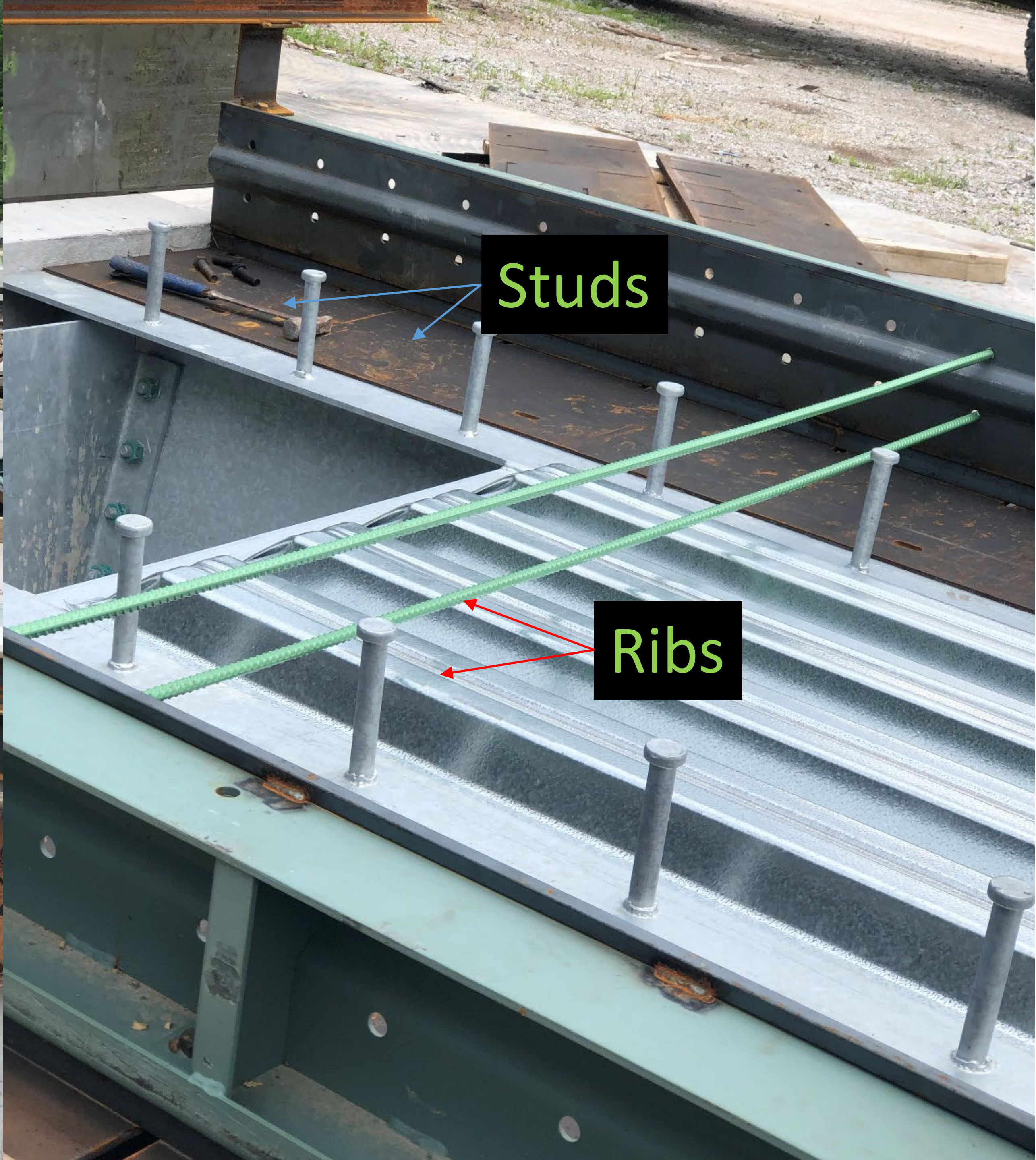
Example 2: First bridge in the US with UHPC Deck Composite Tub Girders: Mostetler Road over Mostetler Creek Bridge



Courtesy Guy Nelson, Valmont Engineering






Studs
Ribs

UHPC was mixed in a truck


Clare County Bridge (Dewayne Rogers)
First bridge in the US with Open Recipe UHPC Deck Composite Tub Girders

Clare County Bridge (Dewayne Rogers)
First bridge in the US with Open Recipe UHPC Deck Composite Tub Girders

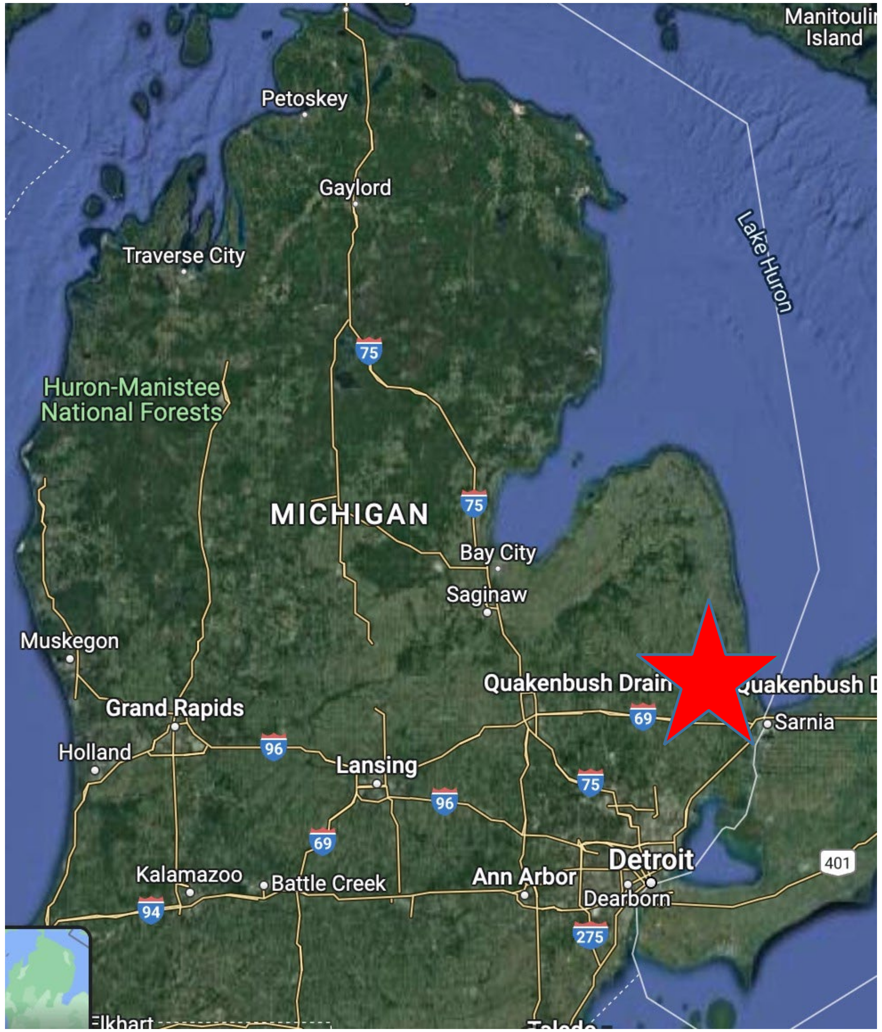
<u>Guy Nelson</u>: The installation was also made more efficient by the light weight of the UHPC/PBTG PBU’s. The completed PBU’s required only a third of the concrete in a conventional bridge superstructure, and less than a quarter of the weight of a concrete PBU.

100-year maintenance-free service life

Substantial Short Term Savings

- MDOT bridge worksheet cost is $788,000
- Clare County bridge cost $534,000
  - Includes guardrail, paving, and epoxy overlay
- Short Term Savings: $254,000 (32.2%)
- Long Term Savings: Discussed Later
- Dewayne Rogers: "*Could have definitely saved money, but that's the learning curve. More to do with our experience than UHPC.*"

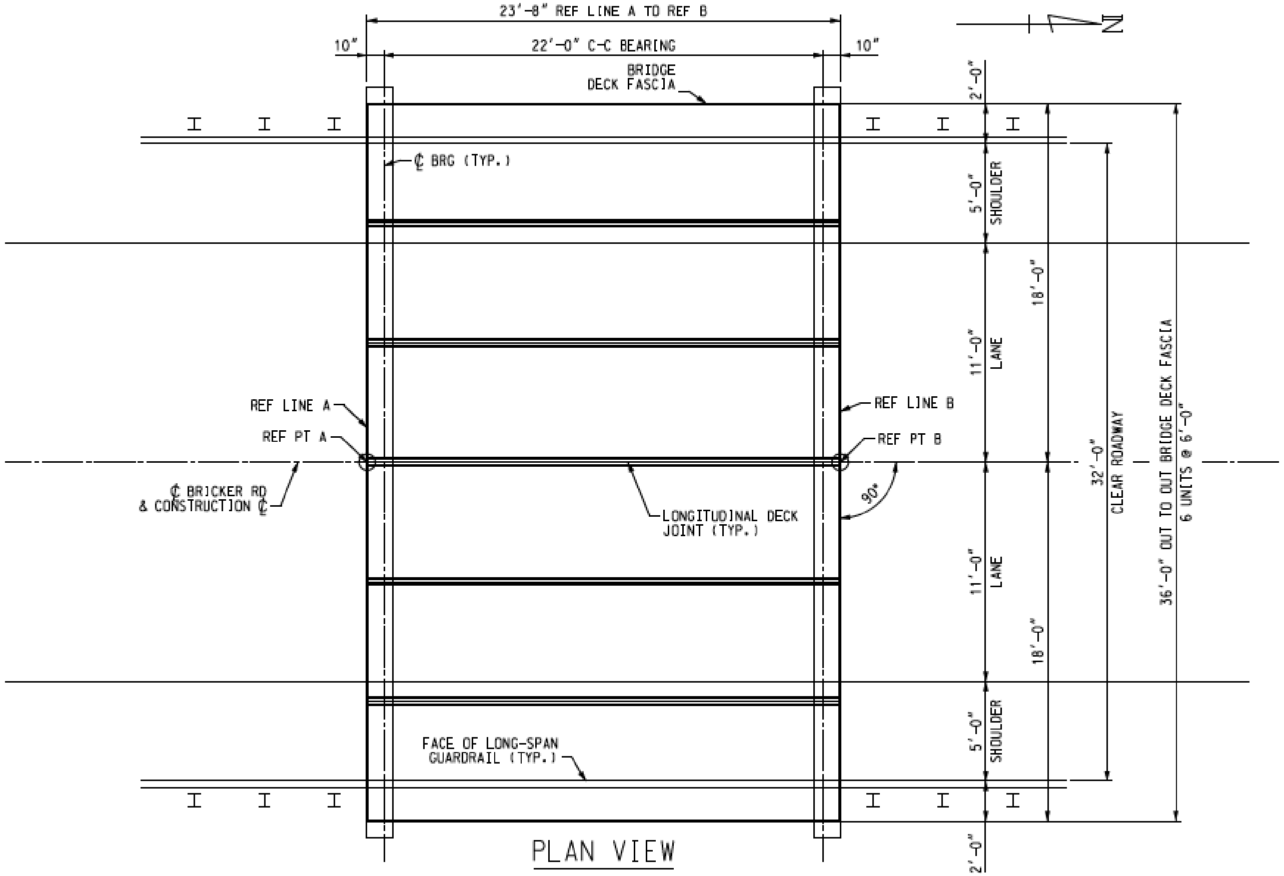
Example 3: Bricker Road bridge over the Quackenbush Drain



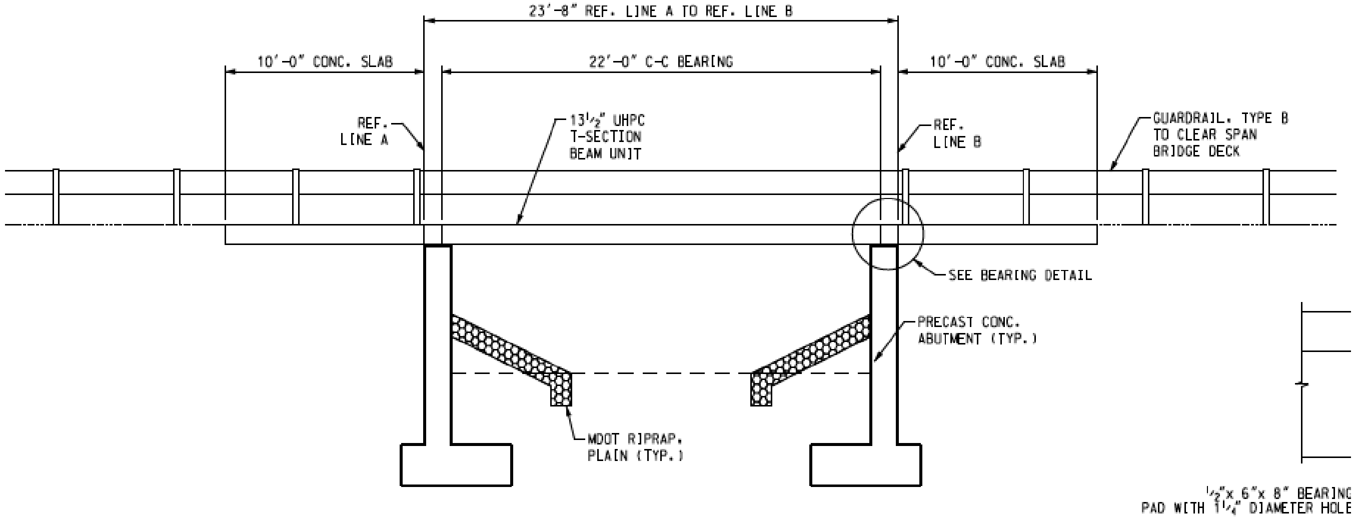
Example 3: Bricker Road bridge over the Quackenbush Drain

- Project was a total bridge replacement
- 23.7’ span by 36.0’ width
- New precast block abutments & wingwalls
- New road approaches
  - Concrete Paving
  - New Guardrail
- Triple Tee UHPC deck panels
  - Truck mixed open-design UHPC
  - Precast & Cured at ADL plant
  - Bridge assembled in field by County work force

ST. CLAIR COUNTY ROAD COMMISSION
BRICKER ROAD OVER WHACKENBUSH DRAIN
03/09/22 UHPC SUPERSTRUCTURE DETAILS



PLAN VIEW



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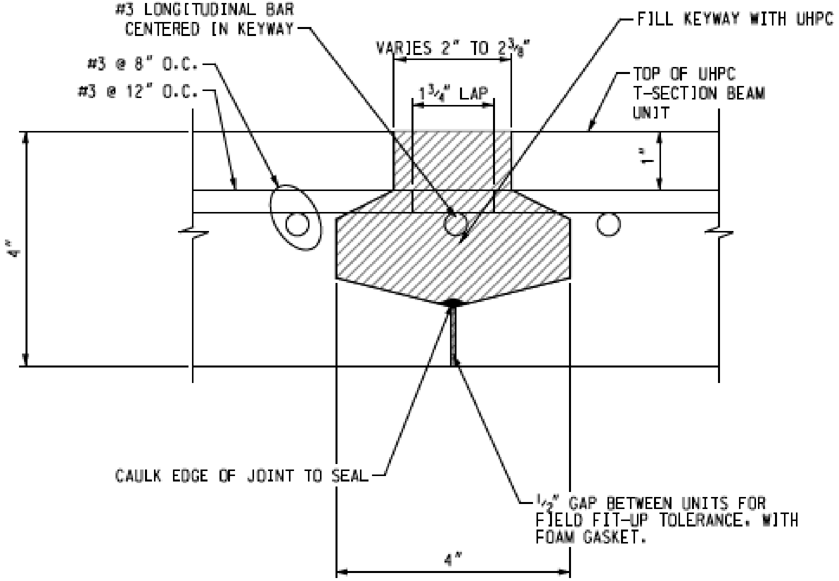
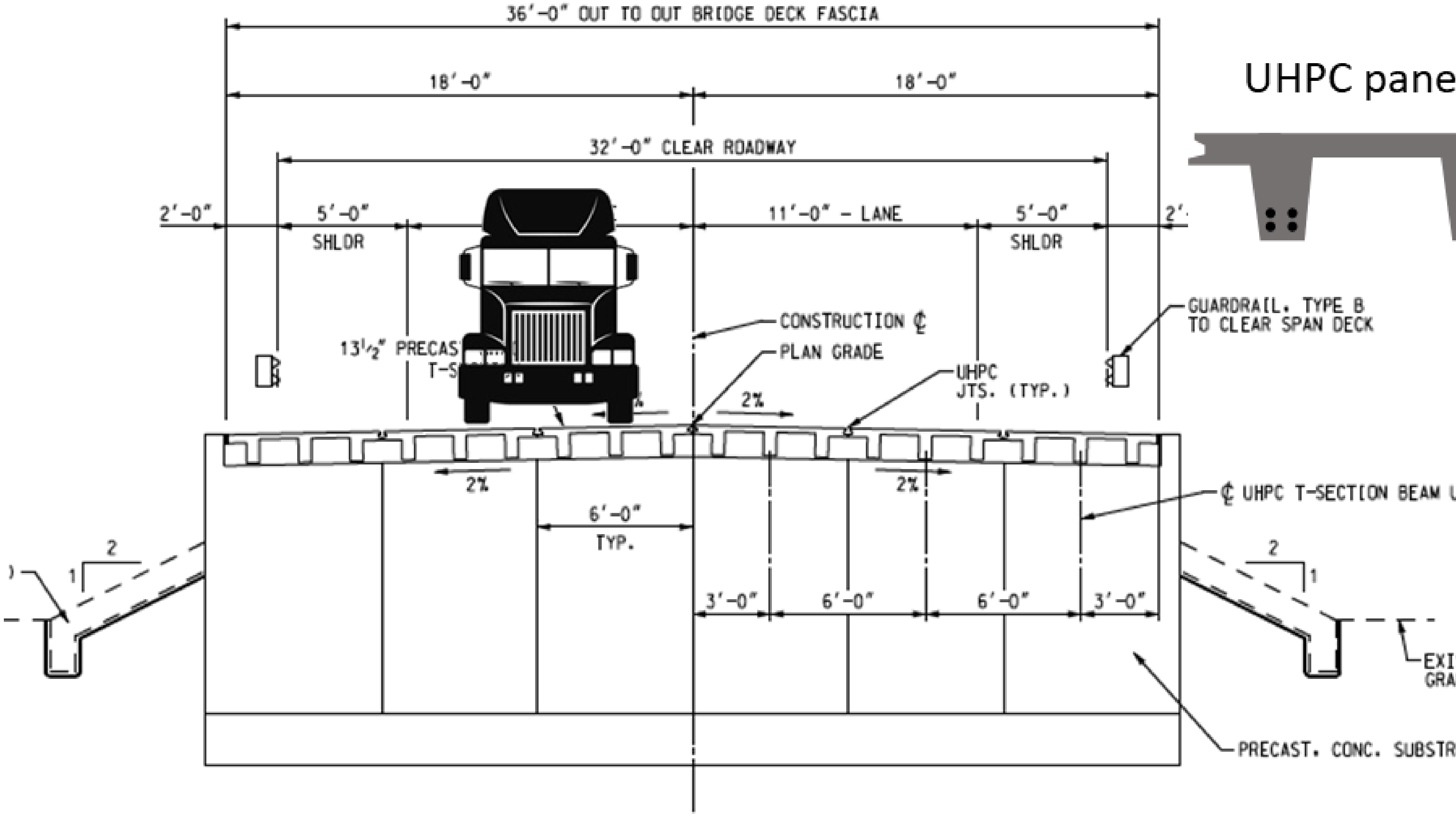


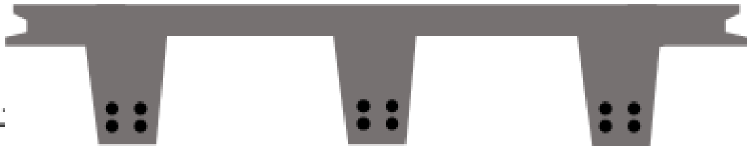
LONGITUDINAL DECK JOINT DETAIL

(THROUGH ℄ OF BRIDGE DECK JOINT TYP.)

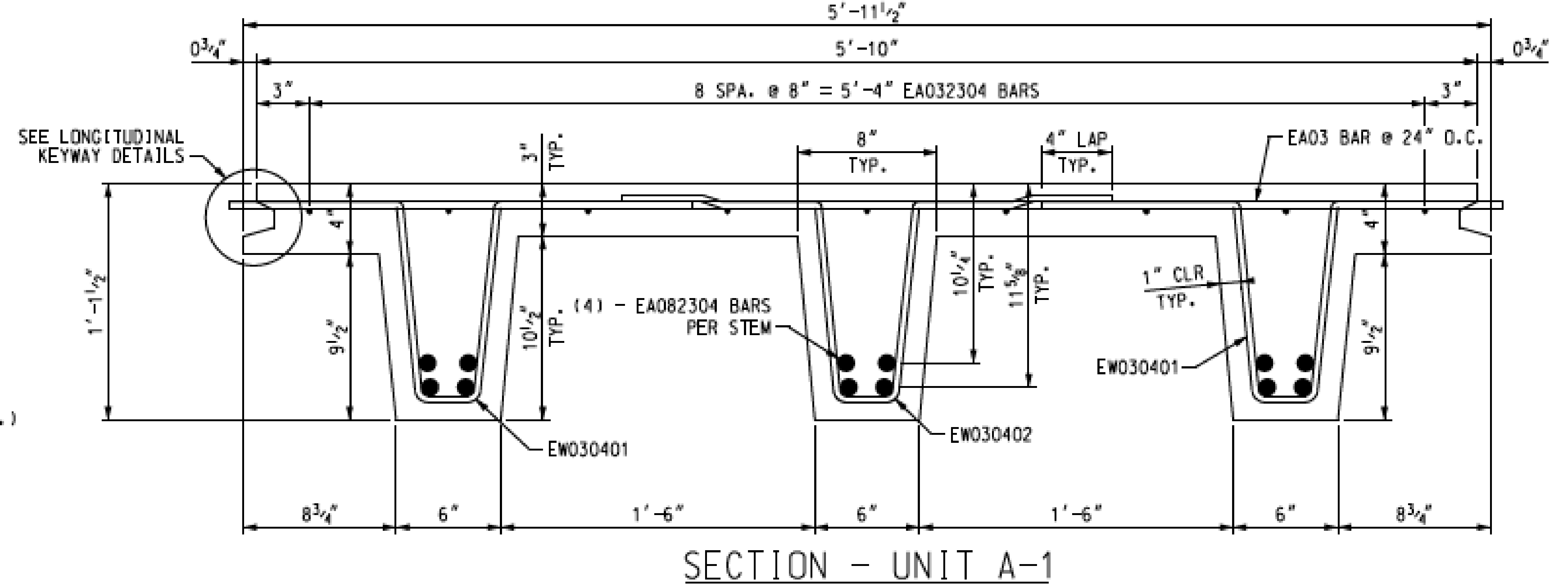
Bricker Road bridge over the Quackenbush Drain



UHPC panel cross-section



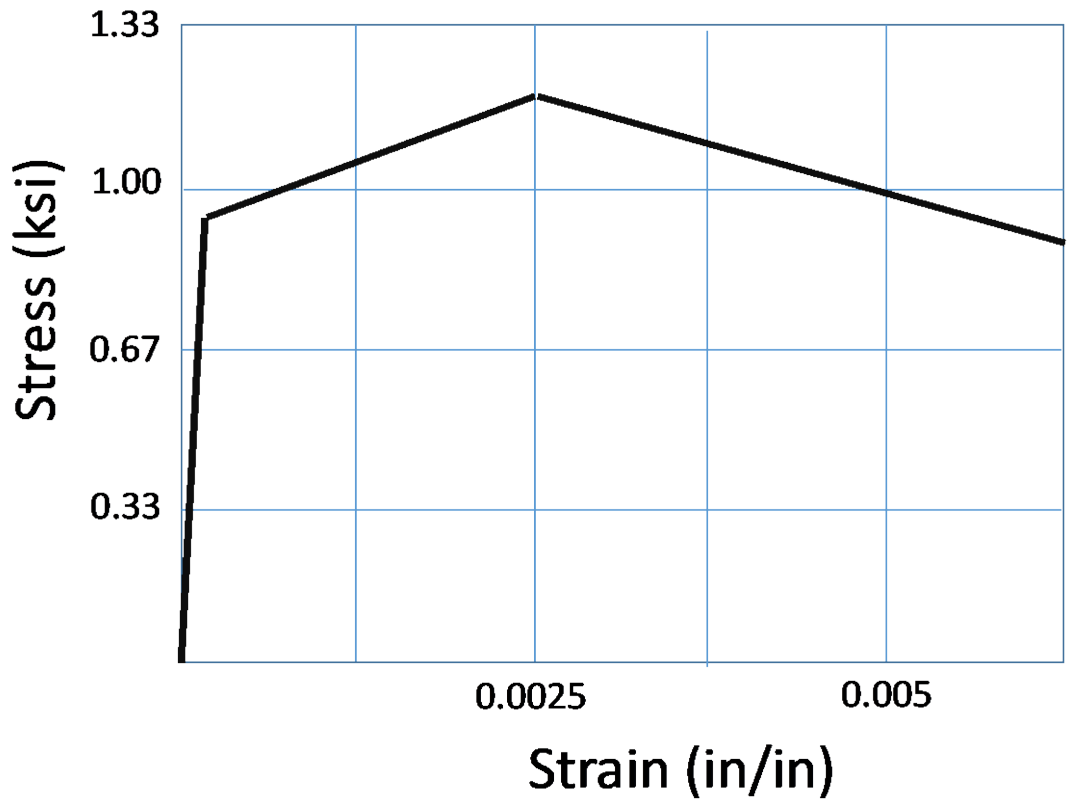
Novel Ribbed Deck Profile

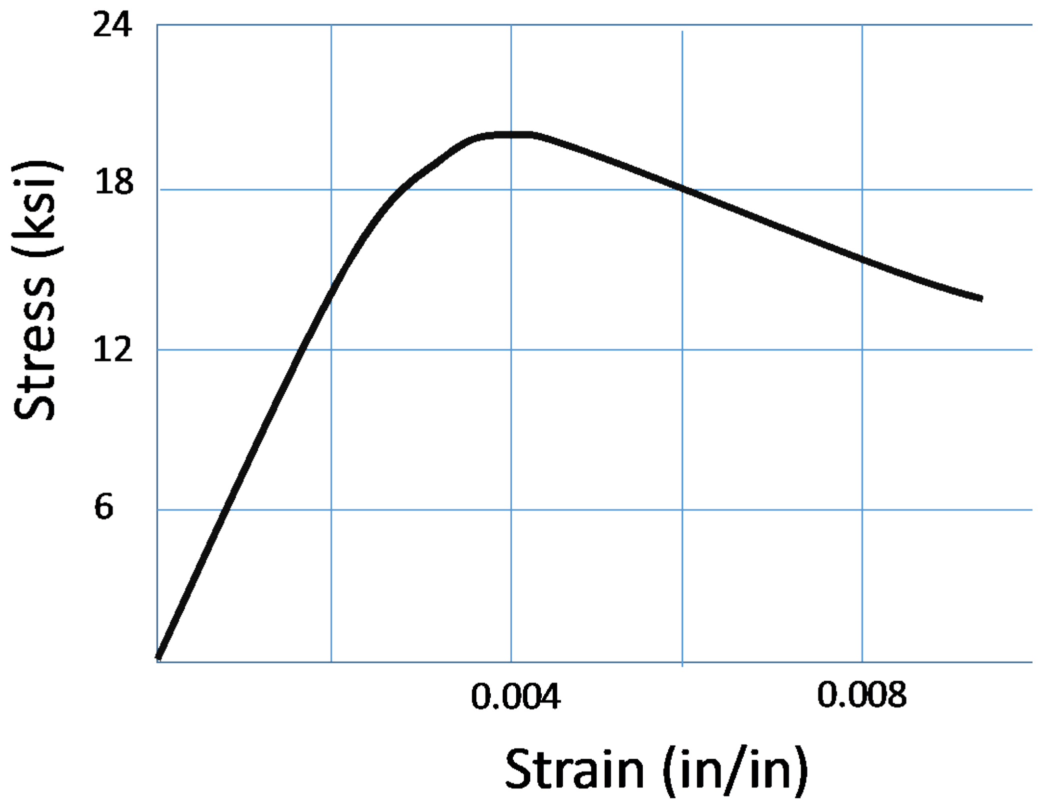


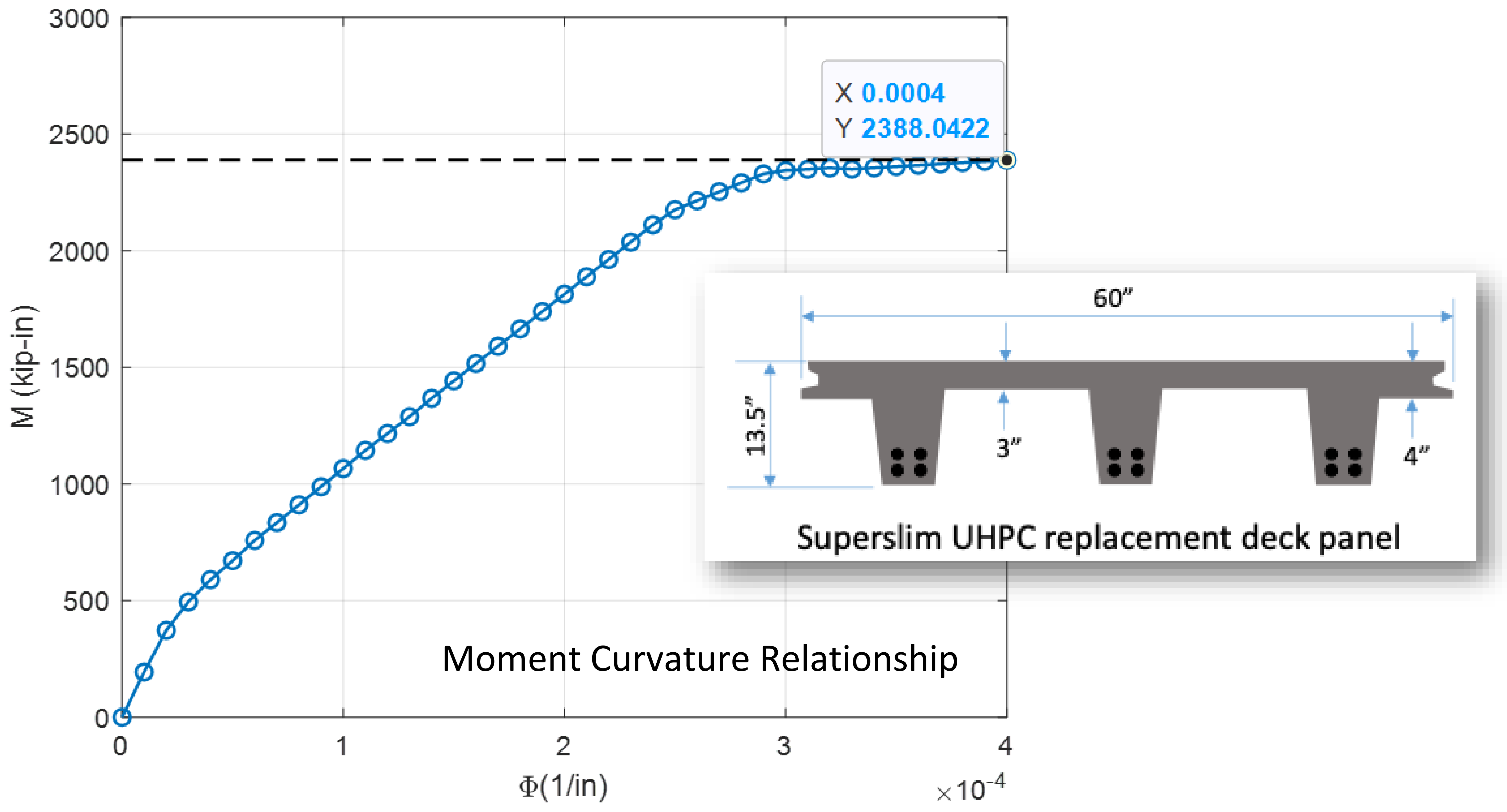
Design vs. Measured Parameters

Design Parameters	Actual Parameters From Test Data
f_c'=21.5 ksi	f_c'=23.9 ksi
ε_{cu}=0.004	ε_{cu}=0.005
E=7500 ksi	E=8750 ksi
f_t=1.15 ksi	f_t=1.42 ksi
$\varepsilon_{t,loc}$=0.0025	$\varepsilon_{t,loc}$=0.005
f_y=60ksi	f_y=60ksi

Properties used in Design







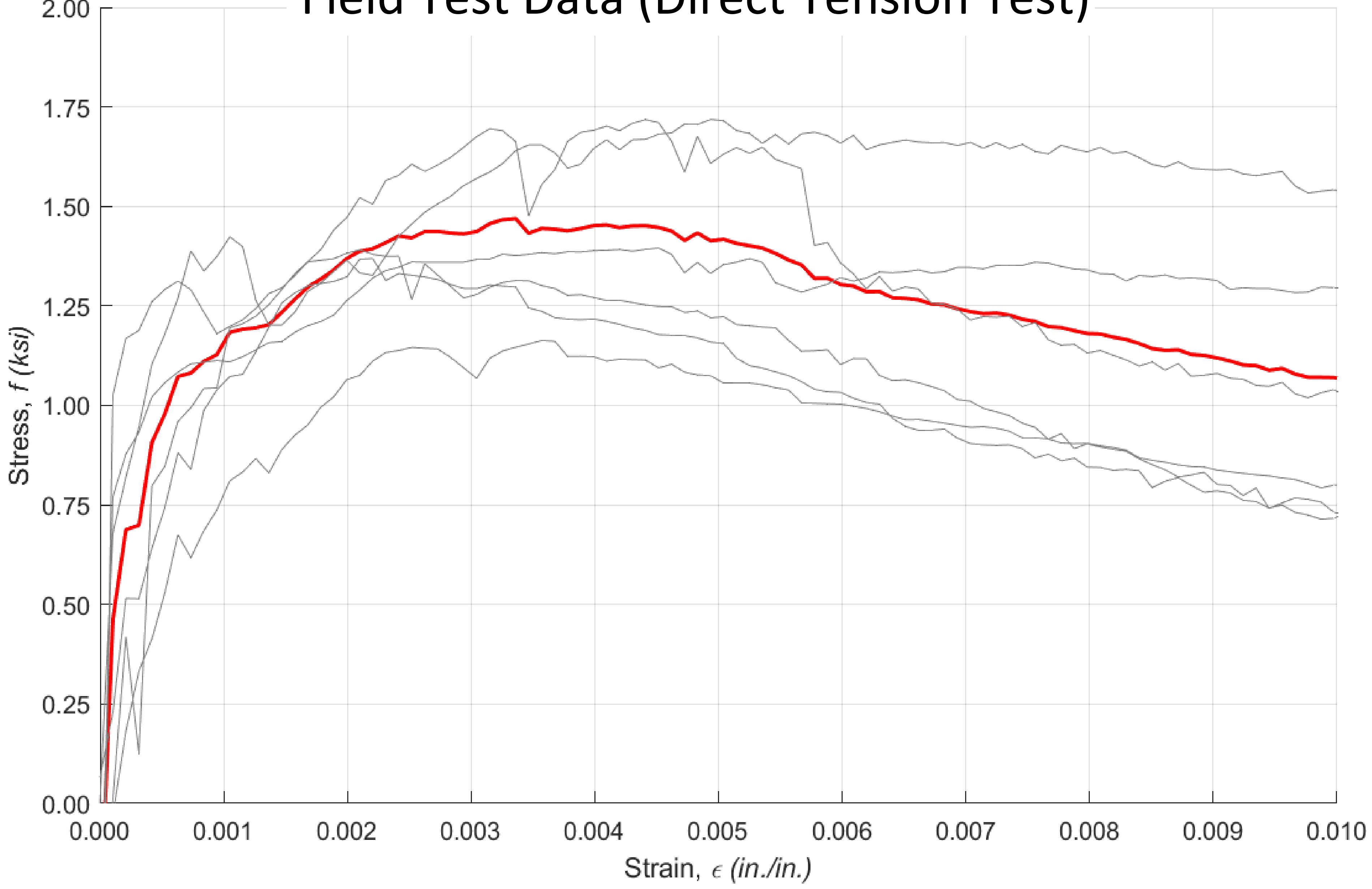
X 0.0004
Y 2388.0422
M (kip-in)
Φ(1/in)
×10^-4
60″
13.5″
3″
4″
Superslim UHPC replacement deck panel
Moment Curvature Relationship

Measured Strength Data

Pour Date	Curing Time (days)							
	3	4	5	7	10	11	14	28
12-Jul	15.1			20.2				25.0
14-Jul			16.7	20.6				23.4
15-Jul		17.6			20.7			23.5
18-Jul						19.1	20.2	24.1
19-Jul					18.9		22.4	23.7
Average	15.1	17.6	16.7	20.4	19.8	19.1	21.3	23.9

Mix Date: July 15th July 18th July 19th

Field Test Data (Direct Tension Test)



a) Forms ready for casting

b) Loading of sand into ready-mix truck

c) Loading of water and water reducer

d) Loading steel fibers

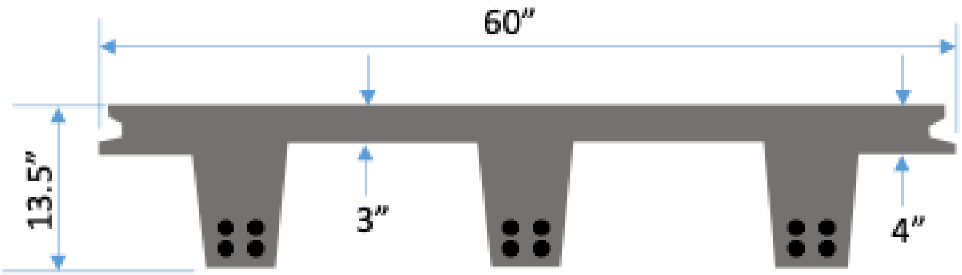
a) Casting of UHPC materials in form

b) Casting of UHPC materials in form

c) Finished panel

d) Wrapped and curing panel

a) Closure pours



Superslim UHPC replacement deck panel

Ultra slim, ultra durable bridge
Weight savings about 2/3 (67%)

St. Clair County (Bill Hazelton)
First bridge with 100% UHPC deck

St. Clair County (Bill Hazelton)
First bridge with 100% UHPC deck

Substantial Short Term Savings

- Reported by County (Michael Clark and Bill Hazelton)
- MDOT 2022 Scoping Estimate Worksheet: $560,000
- St. Claire County cost: $379,000
  - Includes road work, new abutments & UHPC panels plus county labor & equipment
- Short Term Savings: $181,000 (32.3%)
- Long Term Savings: Discussed Later

Prestressed Concrete Girders — Increase in Total Cost

Y \ Z	0.2	0.3	0.4	0.5	0.6	0.7
0.4	23	14	5	-4	-13	-21
0.5	14	5	-4	-13	-21	-30
0.6	5	-4	-13	-21	-30	-39
0.7	-4	-13	-21	-30	-39	-48

Pavement Concrete — Increase in Total Cost

Y \ Z	0.2	0.3	0.4	0.5	0.6	0.7
0.4	65	58	50	43	35	28
0.5	48	40	33	25	18	10
0.6	30	23	15	8	0	-8
0.7	13	5	-2	-10	-18	-25

Y: reduction in volume due to the use of UHPC

Z: reduction in ‘other’ costs for the replaced product

UHPC Overlay: Delaware Memorial Bridge
Largest UHPC Deployment in the US

https://www.delawareonline.com/story/news/2019/04/30/dont-forget-tolls-go-up-delaware-memorial-bridge-tomorrow/3625235002/

Federal Highway Administration
63,962 followers
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The Delaware River and Bay Authority estimates it will save $65M by using an ultra-high performance concrete (UHPC) overlay instead of replacing a bridge deck. Agencies are also using UHPC for bridge beam or girder ends an ...see more

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The Delaware River and Bay Authority estimates it will save $65M by using an ultra-high performance concrete (UHPC) overlay instead of replacing a bridge deck. Agencies are also using UHPC for bridge beam or girder ends an ...see more


Upcoming overlay construction
Commodore Barry Truss Bridge


Upcoming overlay construction
Claiborne Pell Newport Suspension Bridge

Theodore Roosevelt Bridge is slated for renovation with UHPC by 2026.

Ohio-Kentucky Bridge is slated for renovation with UHPC by 2027

Final Thoughts: Cost Considerations

- UHPC provides cost savings along two fronts
  - Long term savings due to extreme durability
    - Minimal maintenance (reduced citizen annoyance)
    - Extremely durable deck (projected ~150 year life)
    - Significantly lower replacement costs
  - Short term savings due to lighter superstructure
    - Cheaper transportation cost
    - Easier and cheaper handling (needs smaller cranes on construction site)
    - Smaller substructure system

UHPC Presents a Compelling Case

- UHPC is going mainstream
  - There is a lot of practical experience across the US
- UHPC can be cheaper in both the short run (32% savings in shown examples) and long run (substantially so)
- Certainly, there are problems, as is true with any new technology.
  - Problems are surmountable and many States have forged ahead
- You will reap rewards if you experiment with open recipe UHPC

Menti

UHPC presentation

Choose a slide to present

Instructions

Why is UHPC so Durable?

The ductility of UHPC beams is limited because:

Fiber clumping is a sign of: