U.S. Department of Transportation
Federal Highway Administration

Turner-Fairbank
Highway Research Center

Structural Design Guidance for UHPC

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U.S. Department of Transportation
Federal Highway Administration

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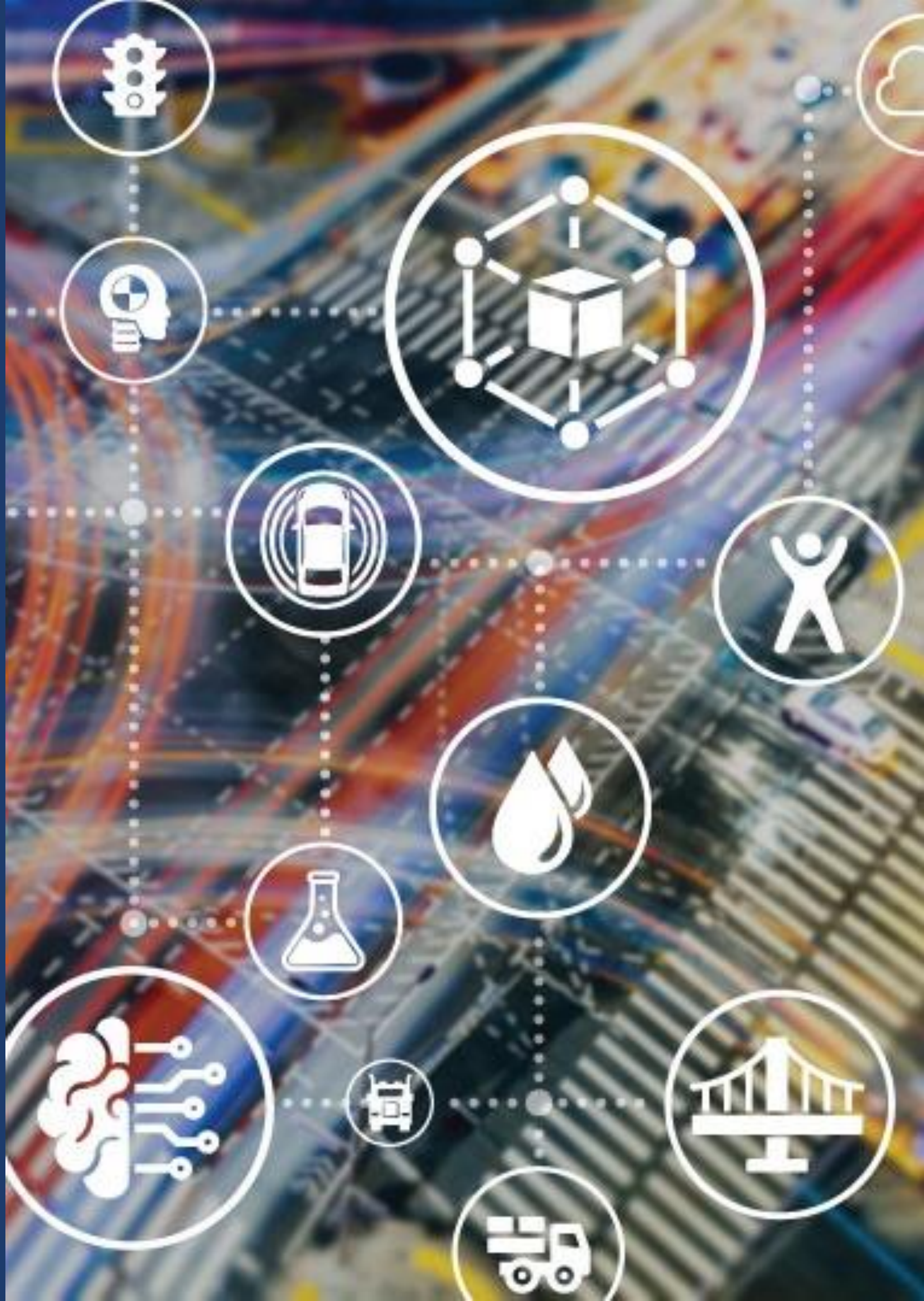

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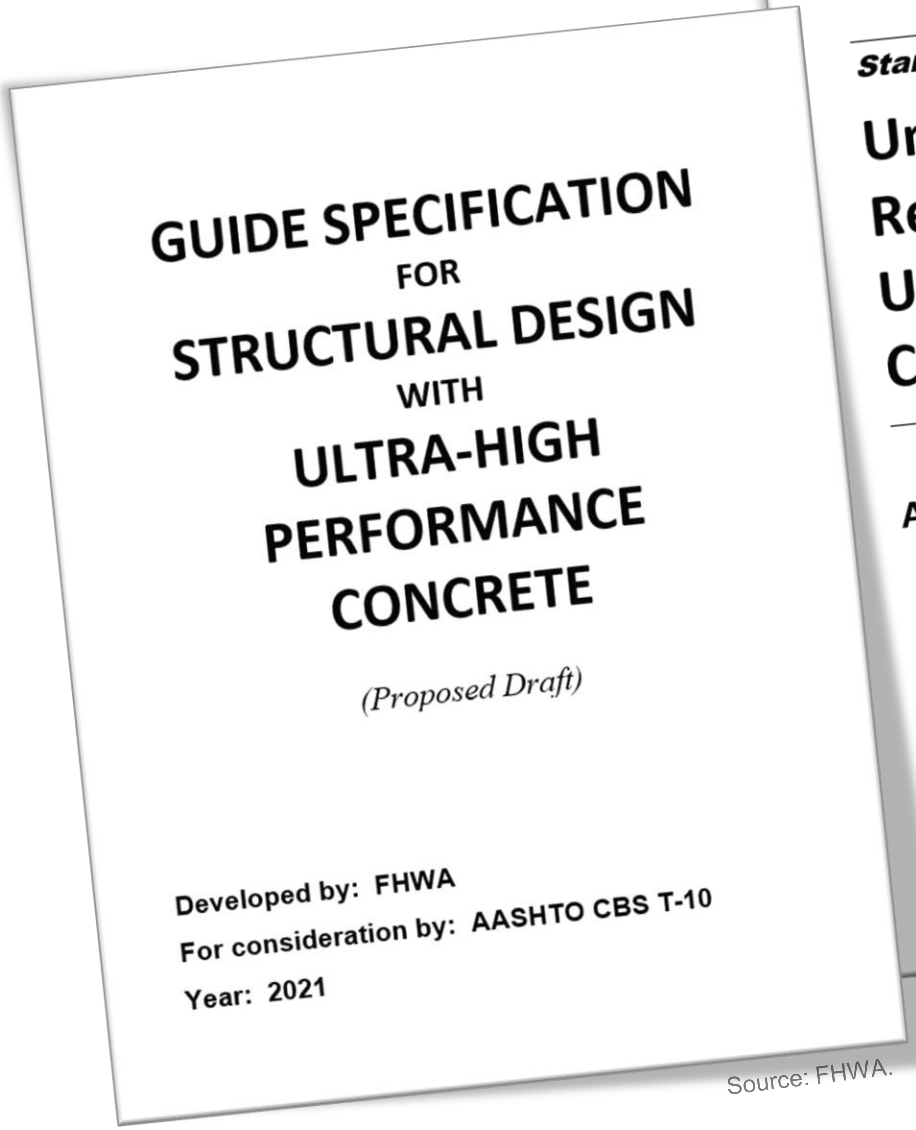
A Path Forward


GUIDE SPECIFICATION
FOR
STRUCTURAL DESIGN
WITH
ULTRA-HIGH
PERFORMANCE
CONCRETE

(Proposed Draft)

Developed by: FHWA
For consideration by: AASHTO CBS T-10
Year: 2021

Source: FHWA.


Standard Method of Test for

Uniaxial Tensile Response of Ultra-High Performance Concrete

AASHTO T 397-22

Developed by: FHWA
Handled by: AASHTO COMP TS3c (Hardened Concrete)

Source: FHWA.

Ultra-High Performance Concrete

Source: FHWA.

What is the GOAL?

UHPC Prestressed Girders

- Engineering benefits:
  - Increased span length.
  - Decreased dead load.
  - Enhanced durability.
- General benefits:
  - Accelerated construction.
  - Lessened constriction at waterway crossings.
  - Reduced local environmental footprint.
  - Lessened maintenance and disruption.

Source: FHWA.

What is the GOAL?

What is the GOAL?

How do we ACHIEVE IT?

Expertise

Expertise

Collaboration

Perspective

UHPC Structural Design Guidance

- Concept: UHPC is a structural material that provides advantages in design and construction.
- Needs:
  - Knowledge of UHPC behavior at the material level.
  - Knowledge of UHPC behavior at the structural level.
  - Applicable models to translate UHPC material and structural behaviors into structural design/construction.
- The BIG Questions:
  - Can we assume that UHPC is conventional concrete with extra benefits?
  - Can we use the same assumptions and the same conventional concrete models with a tweak here or there?

Assumptions

Conventional Concrete:

- Engineering mechanics is fundamental.
- Postcracking tensile resistance can be 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.

Assumptions

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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.

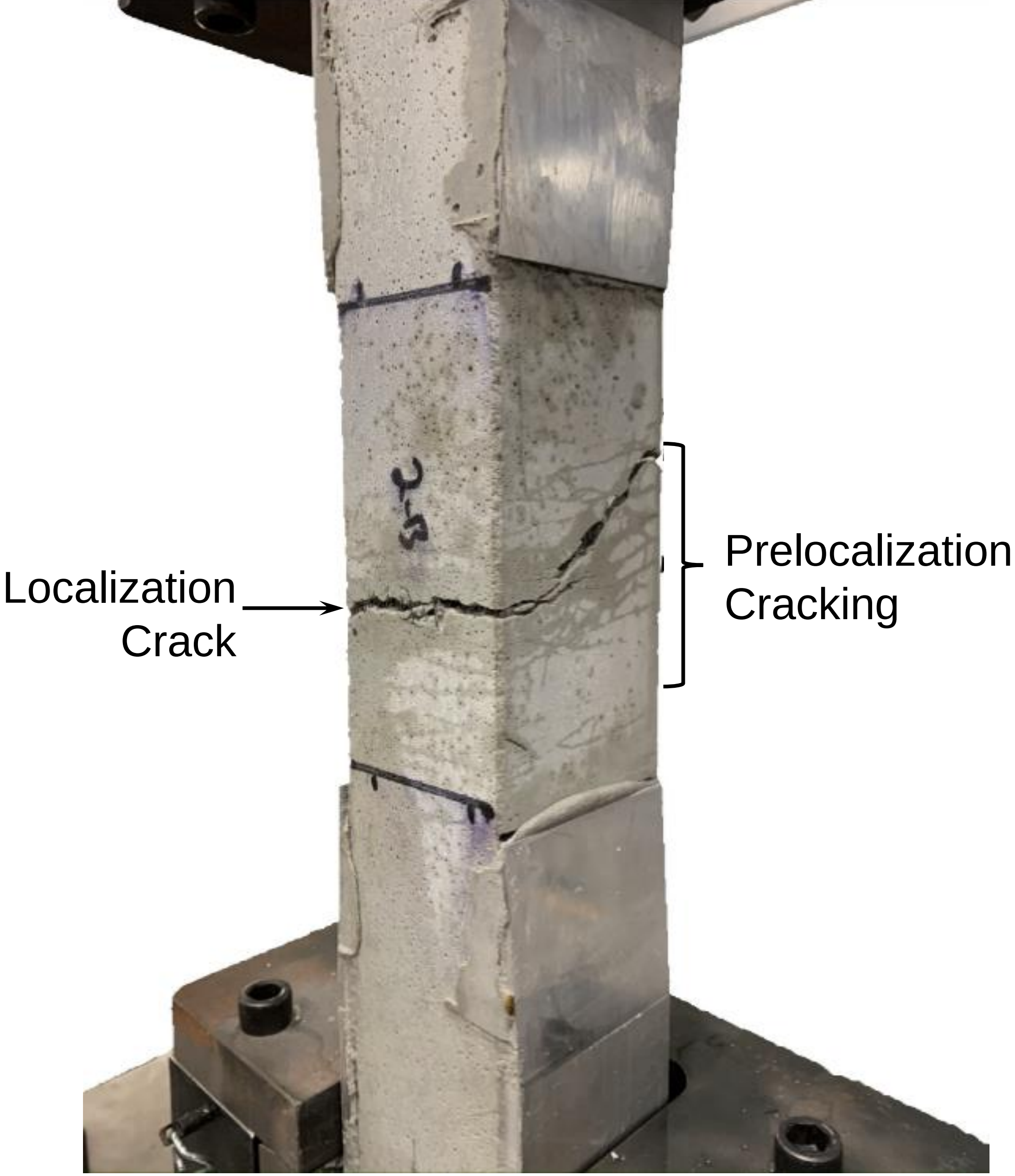
Ultra-High Performance Concrete

Source: FHWA.

Tensile Response of UHPC

Source: FHWA.

Source: FHWA.



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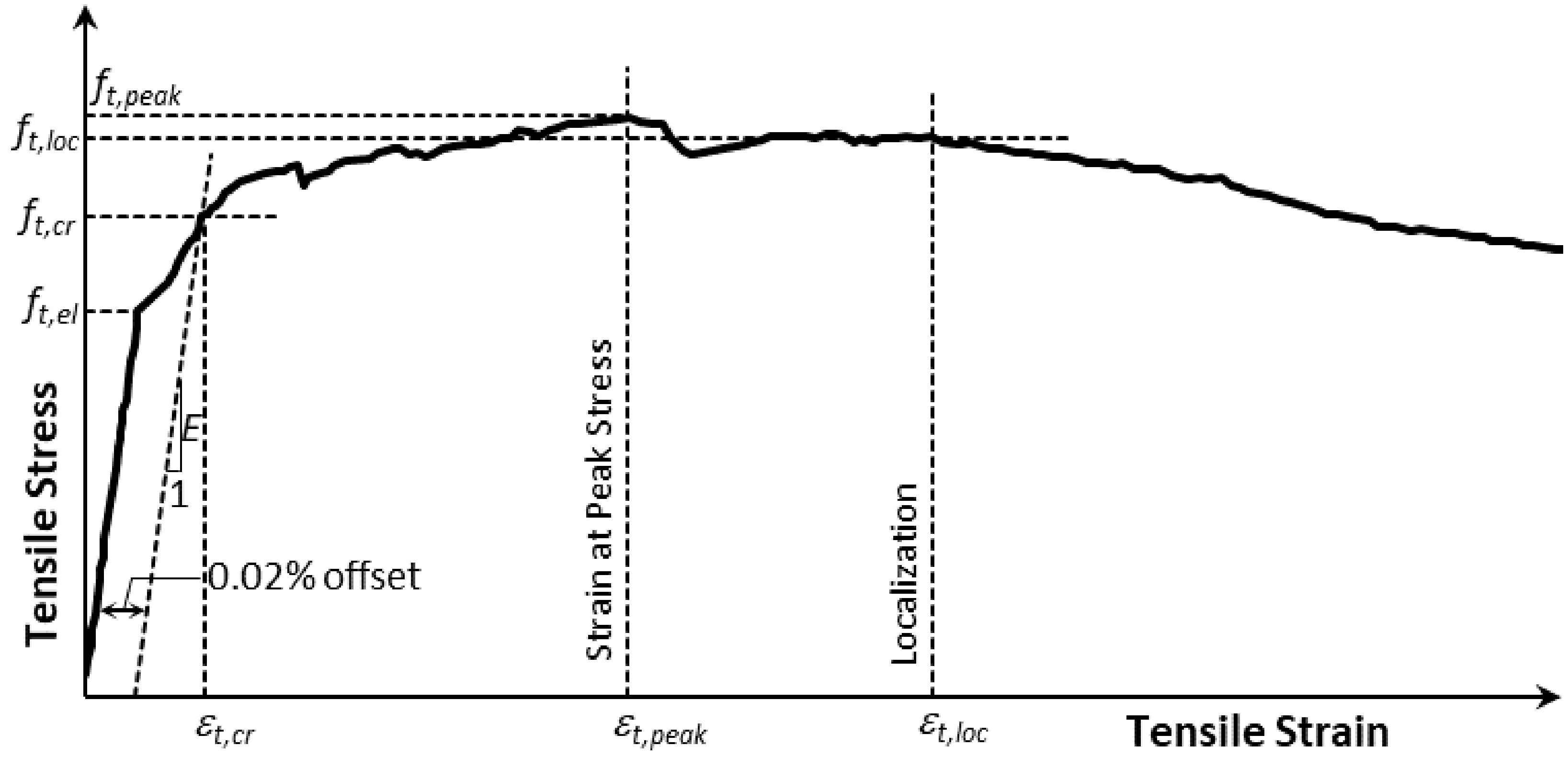
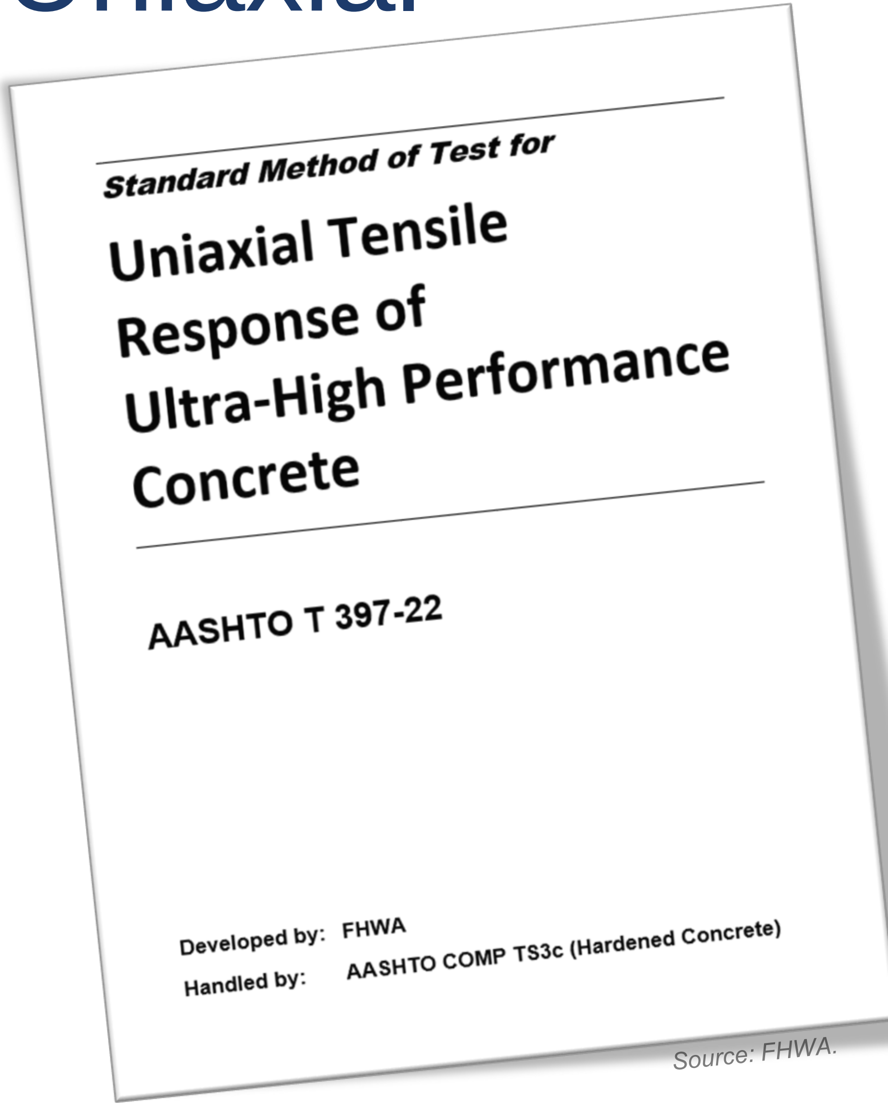
Tensile Response of UHPC



Source: FHWA.

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.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UHPC Design Guide Specification (Draft)

- FHWA developed the document in consultation with, and for consideration by, AASHTO CBS T-10.
- AASHTO CBS T-10 is considering the next steps, which will potentially lead to the balloting of an AASHTO guide specification document.

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UHPC Design Guide Specification (Draft)

- Is a stand-alone document.
- Parallels section 5 of the AASHTO *LRFD Bridge Specifications*: “Concrete Structures.”*
- Contains 1 section, 11 articles, and 3 appendices for a total of 70 pages.
- Uses two-column format with commentary paralleling the guidance text.
- Covers key aspects of structural design with UHPC.

Guide Specification for Structural Design with Ultra-High Performance Concrete

(Proposed Draft)

Source: FHWA.

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

Article 1.1—Scope

Source: FHWA.

1.1.1—General

The provisions in this document apply to the design of bridge and ancillary structures constructed of ultra-high performance concrete (UHPC). UHPC shall be a Portland cement composite with a discontinuous pore structure and reinforced with steel fiber reinforcement.

The provisions are based on UHPC materials exhibiting a strain-hardening behavior and having the following minimum property values for use in design determined according to Article 1.4:

- A minimum compressive strength, f'_c, of 18.0 ksi,
- A minimum effective cracking strength, $f_{t,cr}$, of 0.75 ksi,
- A minimum localization stress, $f_{t,loc}$, greater or equal to the effective cracking strength, $f_{t,cr}$,
- A minimum localization strain, $\varepsilon_{t,loc}$, of 0.0025, and
- Minimum durability criteria as specified in Appendix C1.

C1.1.1

UHPC is a class of concrete that has emerged as a compelling material for use in the design, construction, and preservation of structures. It is a versatile material that can be used in primary structural components, field-cast conn... repair a... UHPC i... which, admixtu... from a ... material.

The... concrete... requirem... high con... near or g... common... materials... coarse ag...

Source: FHWA.

1.1.4—Limitations

The provisions in this Guidance shall not apply to:

- the non-UHPC portion of composite structural members,
- the design of post-tensioned components,
- the specific structure components and types discussed in Article 5.12 of AASHTO LRFD (2020), and
- the design of components in Seismic Zones 2, 3, or 4 as defined within AASHTO LRFD (2020).

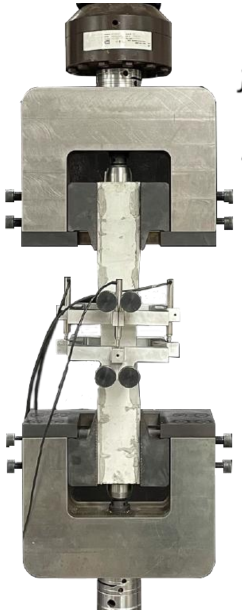
The document does not provide guidance regarding the design of conventional concrete or structural steel portions of a member partially composed of UHPC. The Design Professional is referred to Section 5.0 and Section 6.0 of AASHTO LRFD (2020) for provisions applicable to these structural materials.

Post-tensioned structure design includes special considerations and detailing. Provisions specific to post-tensioned structures have not yet been developed.

Although many of the concepts contained in these provisions may be applicable to capacity calculations in Seismic Zones 2, 3, and 4, the provisions were not developed for application in these seismic zones.

Source: FHWA.

Tension Design Models*



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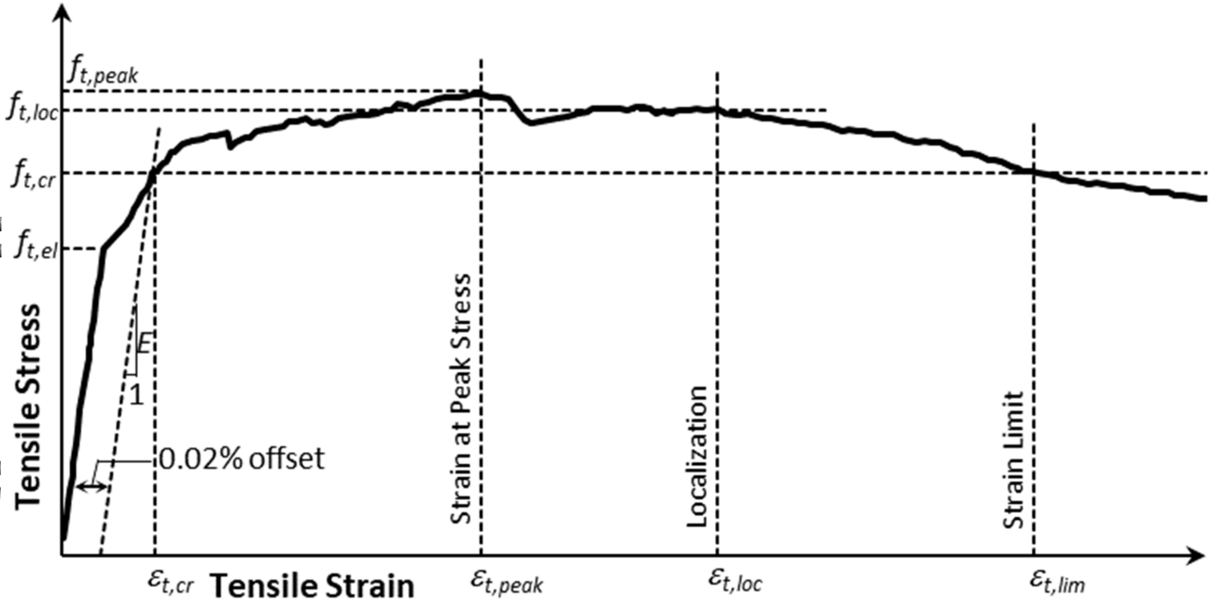

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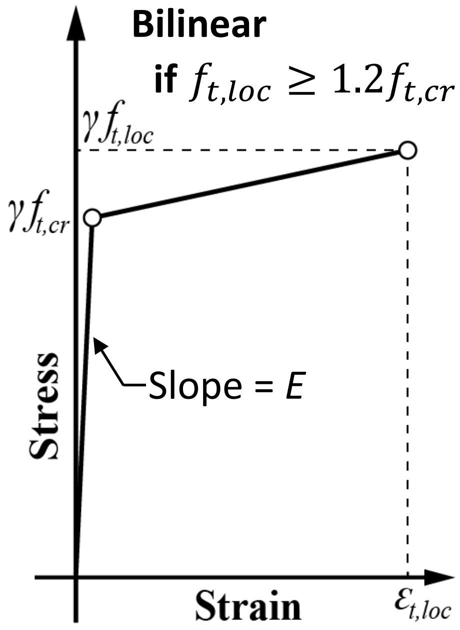

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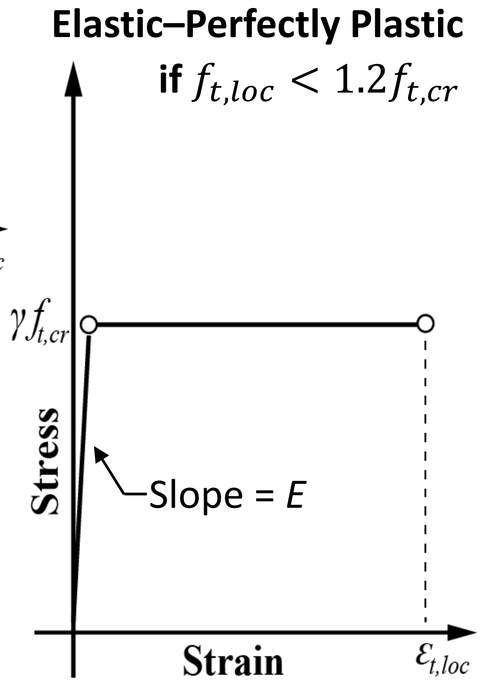


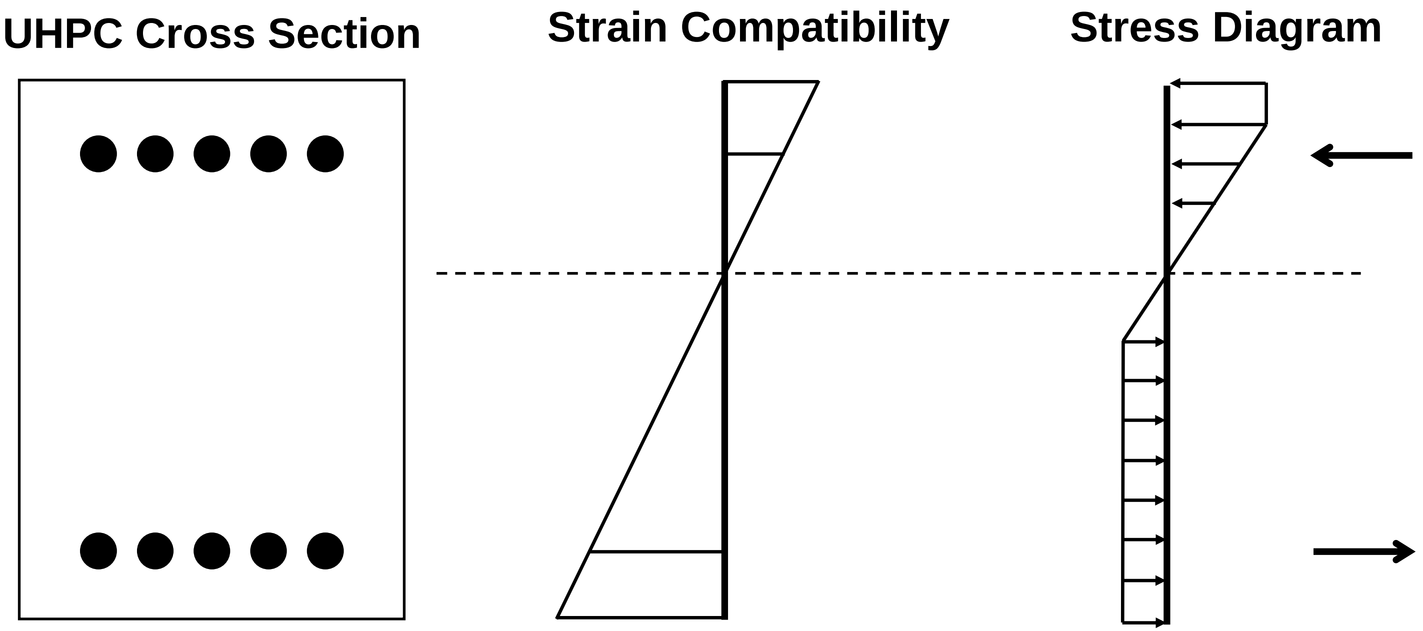
Source: FHWA.

*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).

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.



Source: FHWA.

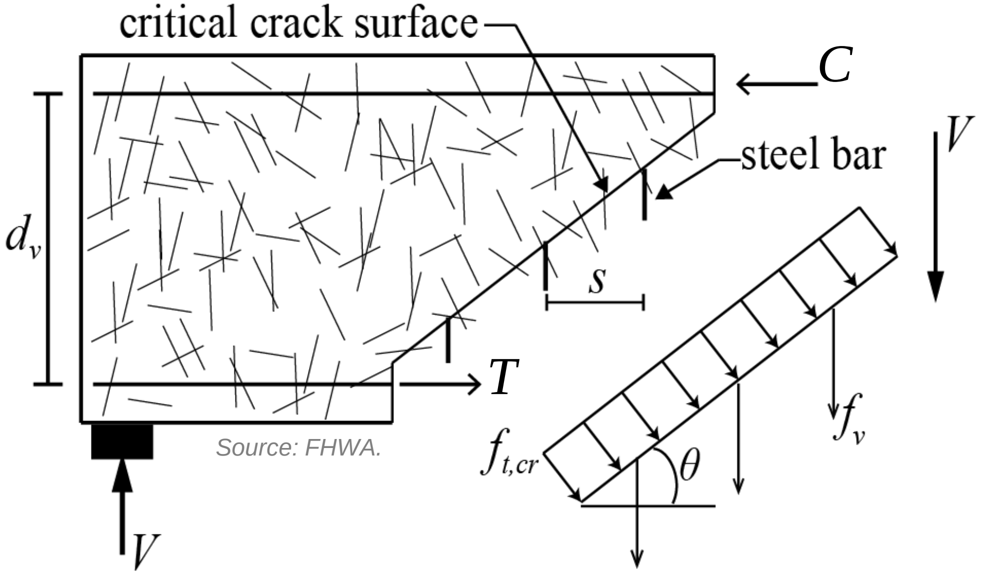
Failure modes:

- 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).

Shear Design Model*

Article 1.7.3.3



Source: FHWA.

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

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

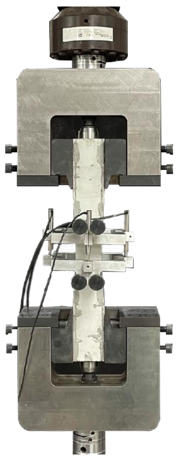
$$V_s = \frac{A_v f_v}{s} d_v \cot\theta$$

Localization Stress, $f_{t,loc}$

Inclination angle, θ

Steel stress at failure, f_v

Direct Tension Test



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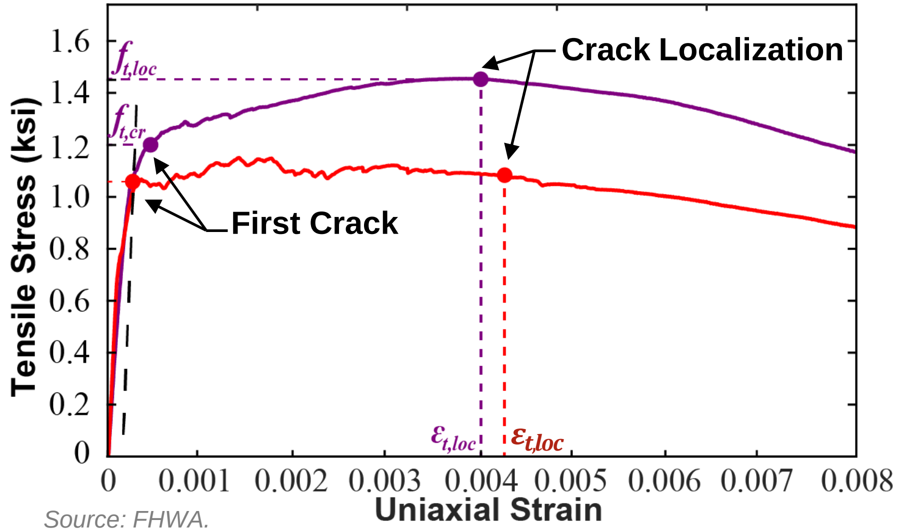

Source: FHWA.

*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.*

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.
- Is being considered by AASHTO CBS T-10, and, if published, may be entitled *Guide Specification for Structural Design with Ultra-High Performance Concrete*.


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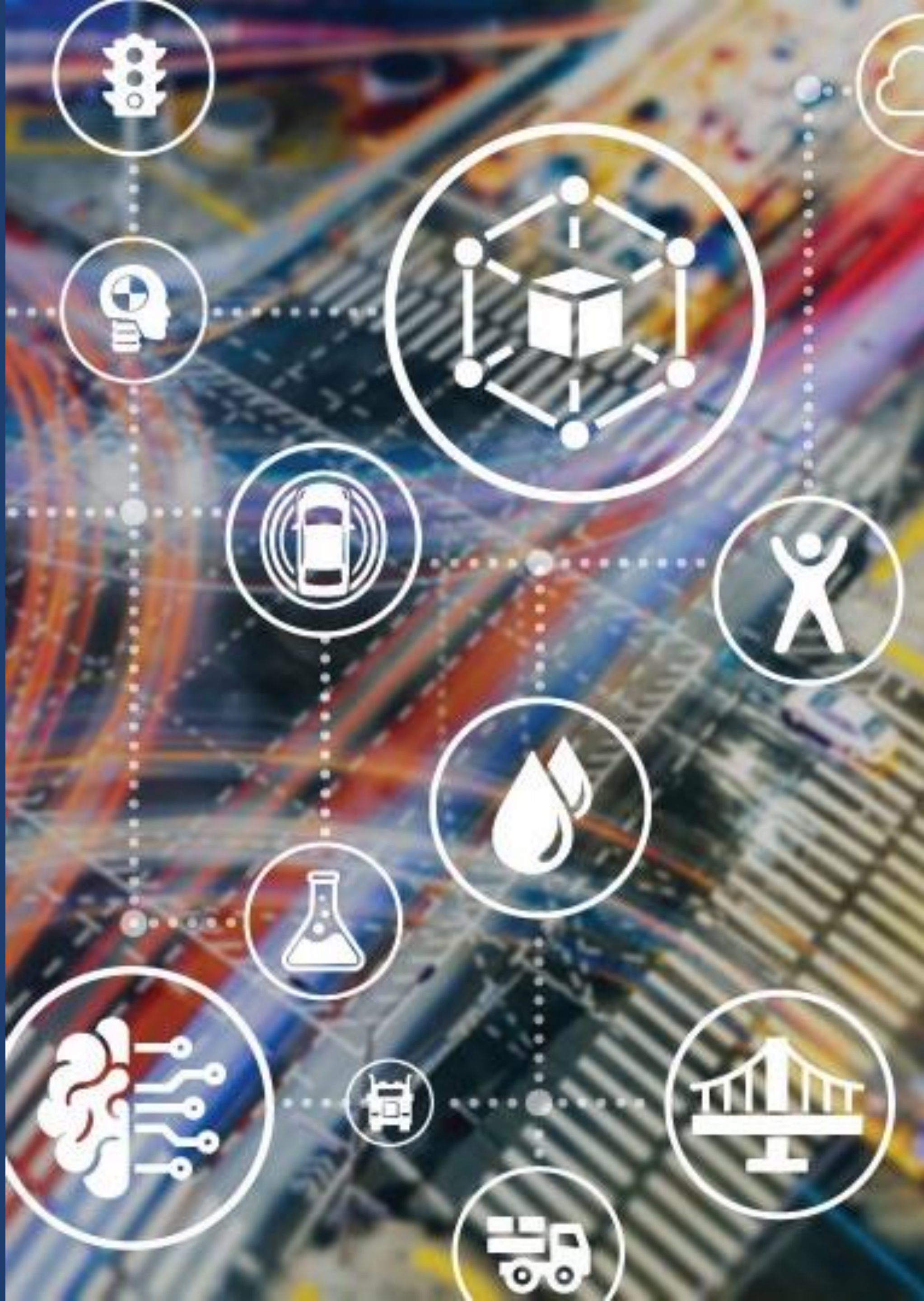

Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
CBS T-10	Committee on Bridges and Structures T-10—Structural Concrete Design
COMP	Committee on Materials and Pavements
FHWA	Federal Highway Administration
ksi	kip per square inch
LRFD	Load and resistance factor design
TS-3c	Technical Subcommittee 3c—Hardened Concrete
UHPC	Ultra-high performance concrete

Variables

A_v	=	area of transverse reinforcement within a distance s
b_v	=	minimum thickness of the girder's web
C	=	compression force in compression flexural side of member
d_v	=	effective shear depth of member
E	=	modulus of elasticity of UHPC
f_c'	=	compressive strength of UHPC
$f_{t,cr}$	=	effective cracking stress of UHPC
$f_{t,el}$	=	tensile elastic limit of UHPC
$f_{t,loc}$	=	localization stress of UHPC
$f_{t,peak}$	=	maximum tensile stress that can be sustained
f_v	=	stress in the transverse reinforcement at shear failure

Variables (Continued)

s	=	longitudinal spacing of transverse reinforcement
T	=	tensile force in tension flexural side of member
V	=	total shear force at failure
V_n	=	total shear resistance
V_s	=	shear resistance provided by transverse reinforcement at failure
V_{UHPC}	=	shear resistance provided by UHPC at failure
γ	=	reduction factor applied on tensile stress parameters ($f_{t,cr}$ and $f_{t,loc}$) to account for variability in material testing results
$\varepsilon_{t,cr}$	=	strain at effective cracking stress of UHPC
$\varepsilon_{t,lim}$	=	tensile strain limit of UHPC
$\varepsilon_{t,loc}$	=	average localization strain of UHPC
$\varepsilon_{t,peak}$	=	strain that corresponds to peak tensile strength
θ	=	angle of inclination of diagonal compressive stress

Contact

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