Bridging Classical FRC and AASHTO T-397:

A Consistent Path to Reporting the Effective Cracking and Localization Strengths for Strain-Hardening UHPC

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Yu-Hsin Cheng — Master Degree Student
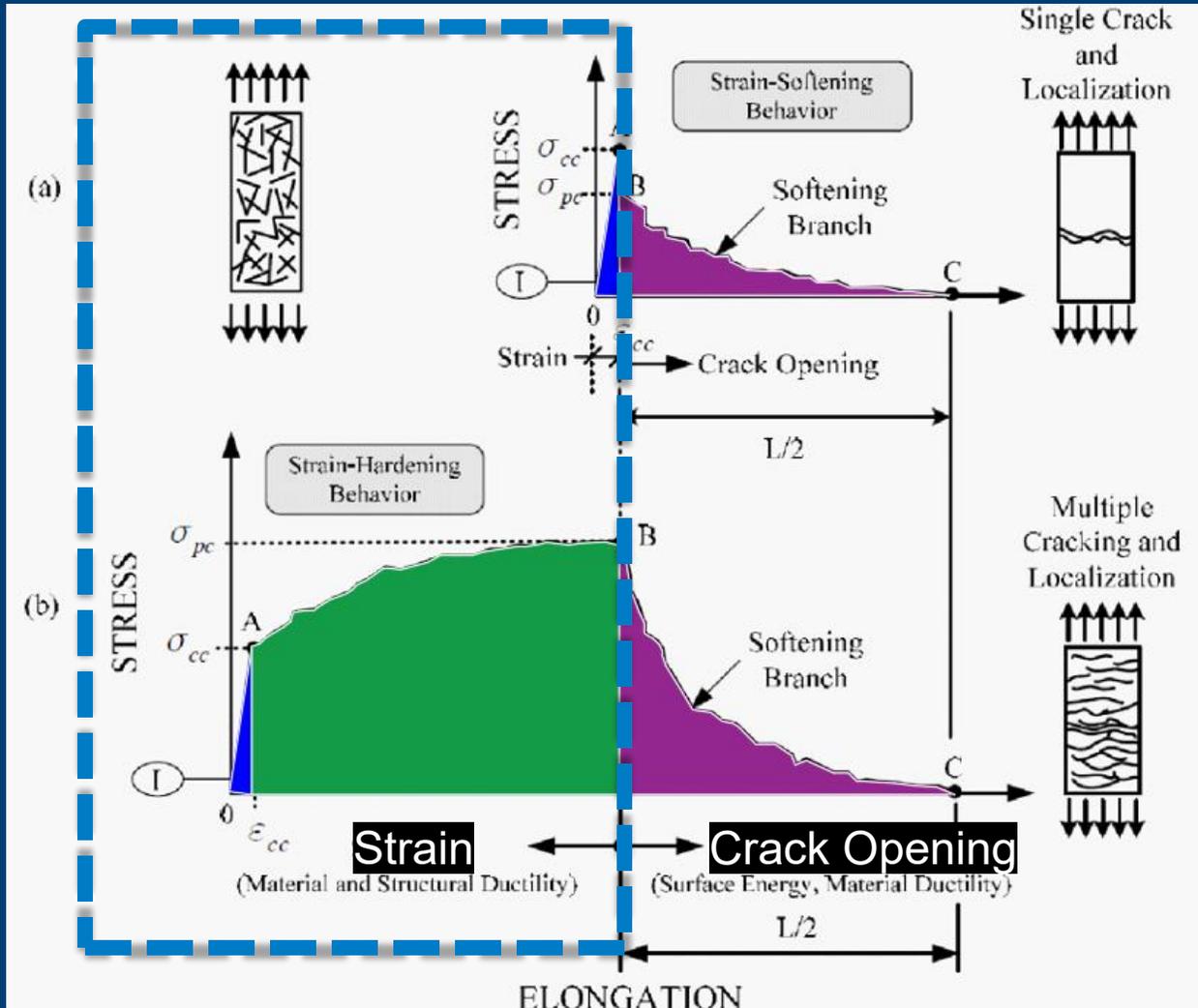Chung-Chan Hung — Distinguished Professor

National Cheng Kung University
1931

American Concrete Institute

Typical tensile strength and combined strain/crack opening curve

Naaman, A. E., & Reinhardt, H. W. (1996). Characterization of high performance fiber reinforced cement composites—HPFRCC.
In High performance fiber reinforced cement composites (Vol. 2, pp. 1-24).

Strain-softening response
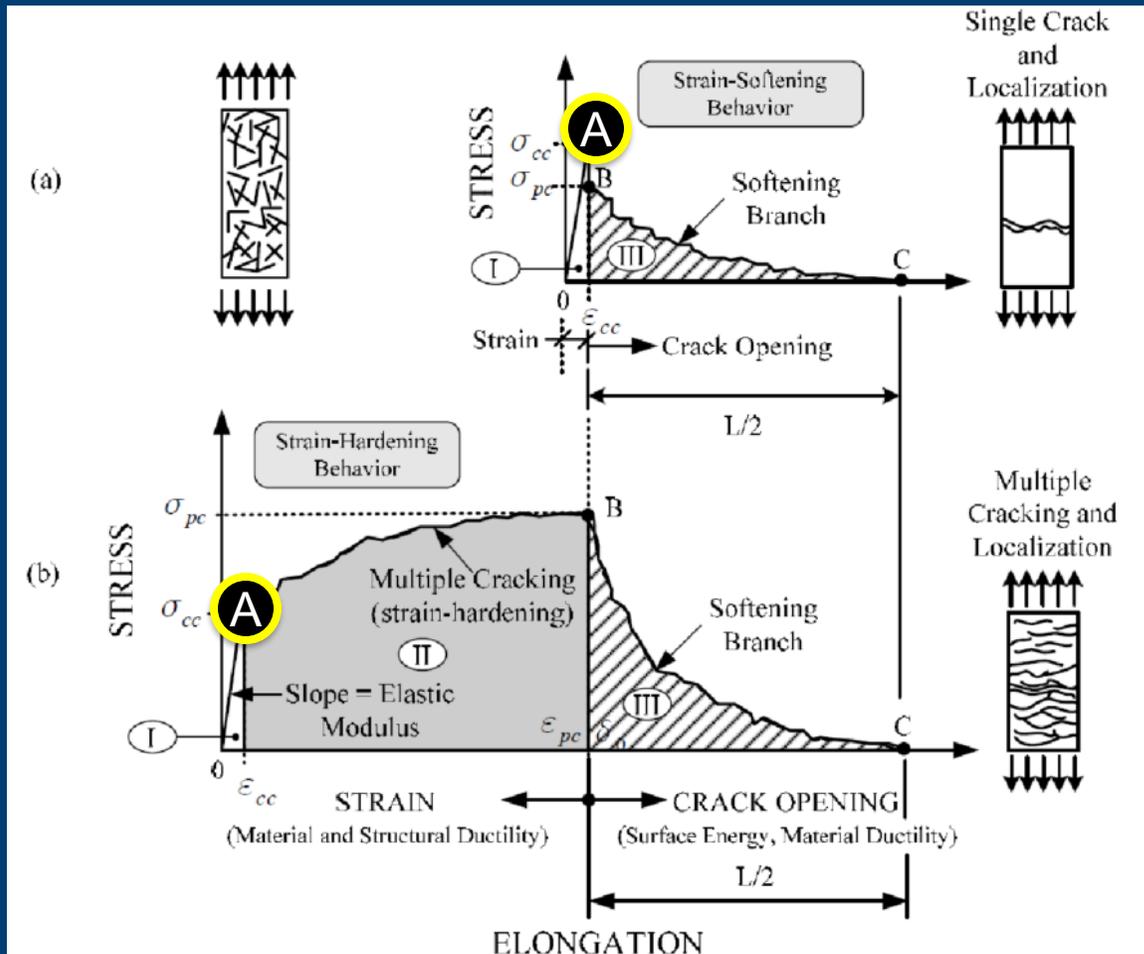*Two key regions*
1. Elastic region
2. Softening region
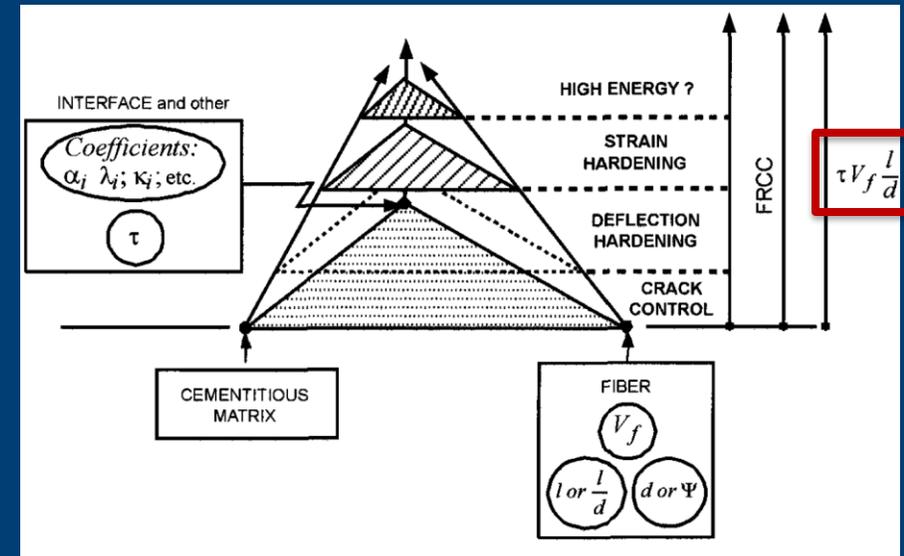
Strain-hardening response
Three key regions
1. Elastic Region
2. Strain-Hardening Region (Multiple microcracks)
3. Softening Region

From Strain-Softening to Strain-Hardening: Key UHPC Parameters

Post-cracking slope (after point A) of the UHPC stress–strain response depends on three key parameters:

- Fiber volume fraction (V_f)
- Aspect ratio (L_f/D_f)
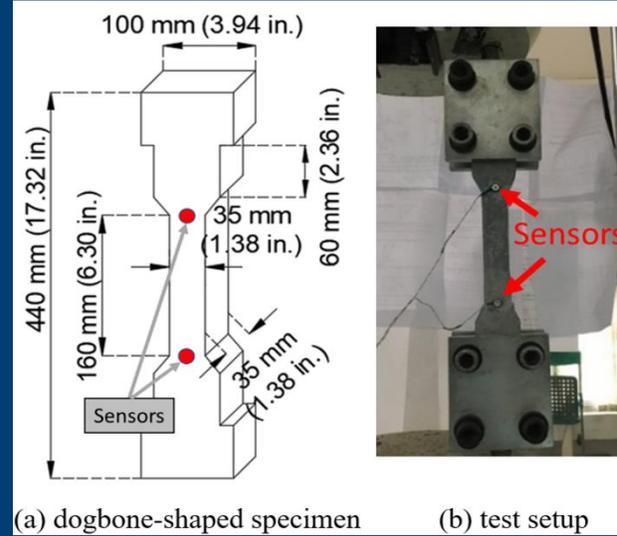- Fiber–matrix interface bond strength (τ)

*These parameters **collectively** control the fiber-bridging efficiency, which governs whether the material exhibits strain-hardening or strain-softening behavior.*

Naaman, A. E., & Reinhardt, H. W. (1996). Characterization of high performance fiber reinforced cement composites—HPFRCC.
In High performance fiber reinforced cement composites (Vol. 2, pp. 1-24).

Test setups for quantifying tensile strength for UHPC materials

Direct methods

Direct tensile test (dogbone)

Wille, K., El-Tawil, S., & Naaman, A. E. (2014). Properties of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) under direct tensile loading. *Cement and Concrete Composites*, *48*, 53-66.`

For UHPC → AASHTO UHPC Guide /

AASHTO T-397

Indirect methods
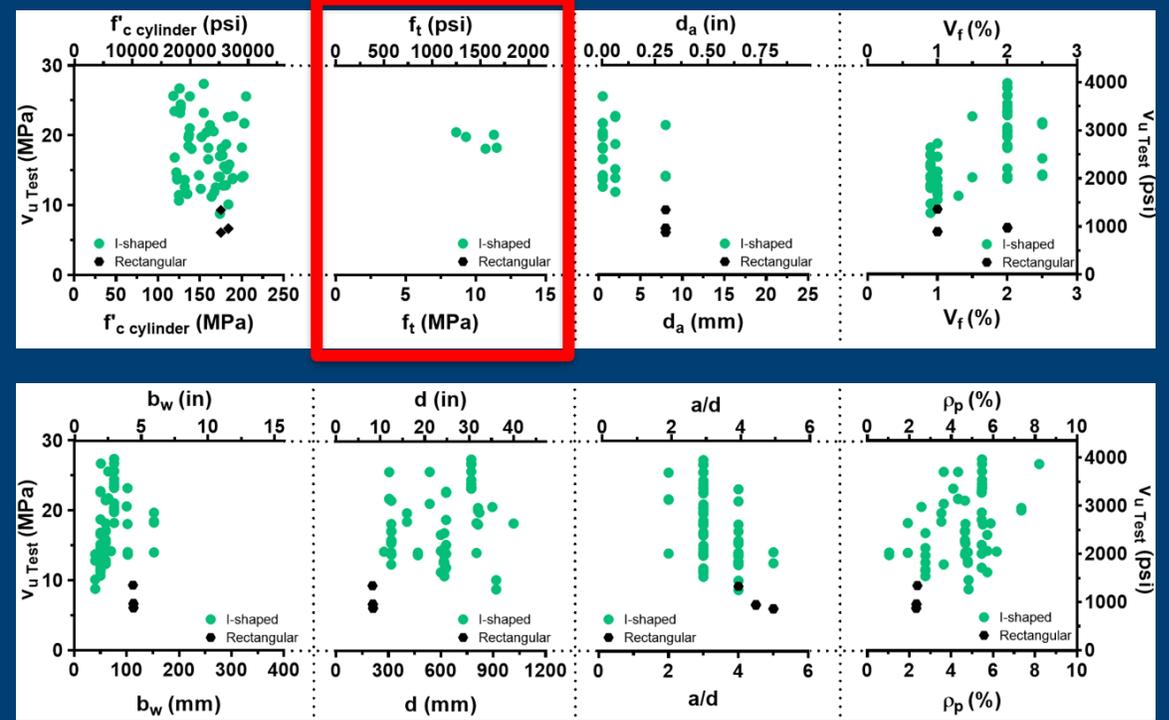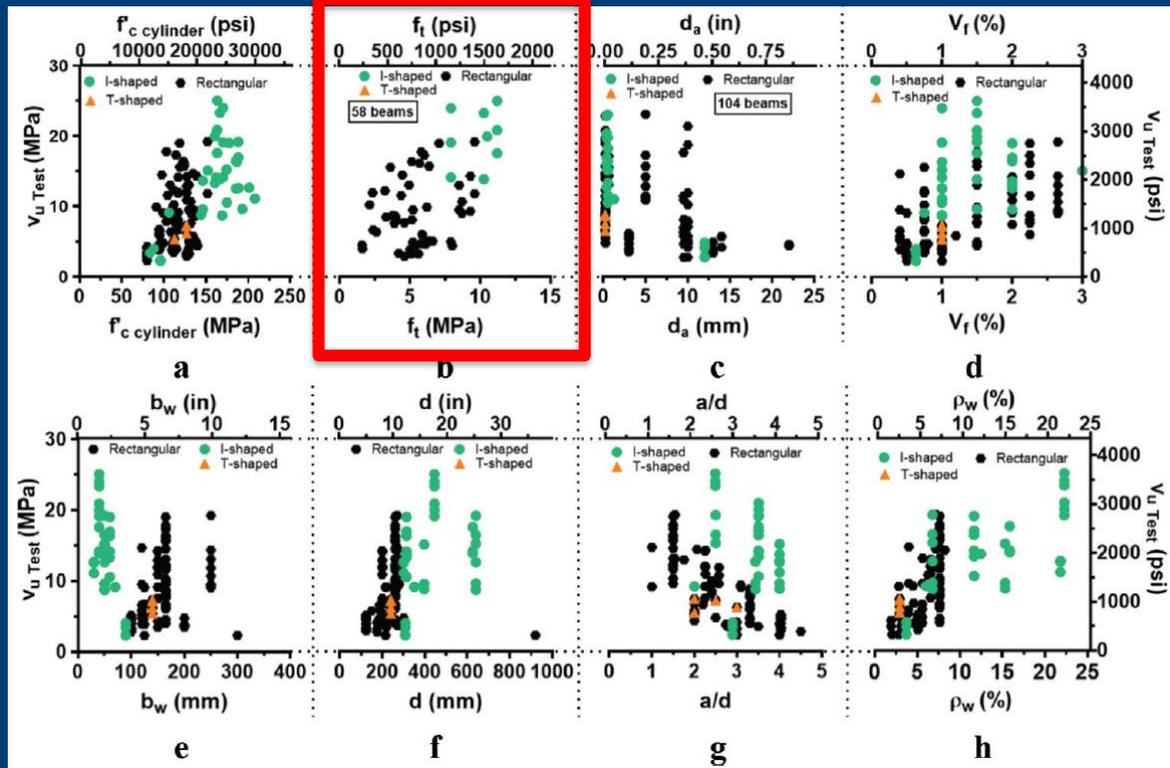

Flexural tensile test on an unnotched beam (ASTM C1609)

fib Model code 2020
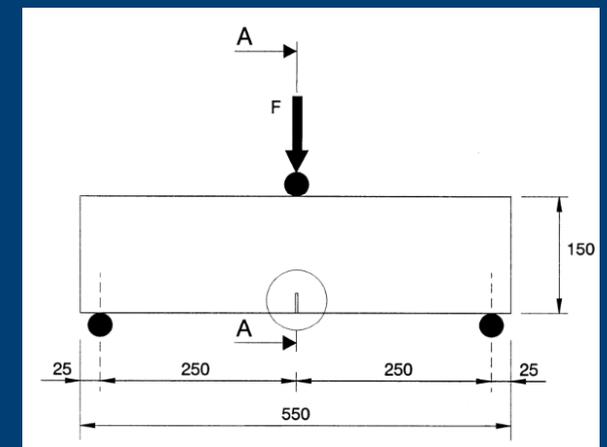
Flexural tensile test on a notched beam (EN 14651)

Material properties reported in UHPC beam shear databases

Shear database of non-prestressed beams (118 beams) [1992-2022]

Shear database in prestressed beams (64 beams) [2003-2022]

- None reported tensile cracking strength.
- No tests followed AASHTO T-397; all used dog-bone specimens.
- 58 beams (50% of the database) reported direct tensile strength.

- 5 beams (8% of the database) reported tensile properties in accordance with AASHTO T-397.

Bermudez M, Hung C-C, "Shear Strength Database for Nonprestressed High-Strength High-Performance Fiber-Reinforced Cementitious Composites and Ultra-High-Performance Concrete Beams without Stirrups," ACI Structural Journal, V. 122, No. 4. 2025.

Foster, S. J., & Bentz, E. (2024). Design of UHPC prestressed girders for shear. Structural Concrete, 25(2), 780-795.

Tensile behavior requirements in design guidelines for structural concrete

Direct tensile test method

1.1. SCOPE

1.1.1. General

The provisions in Section 1 of this Appendix 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 and Section 2 of this Appendix:

- A minimum compressive strength, f'_c, of 17.5 ksi,
- A minimum effective cracking strength, $f_{t,cr}$, of 0.75 ksi,
- A minimum crack localization strength, $f_{t,loc}$, greater than or equal to the effective cracking strength, $f_{t,cr}$,
- A minimum crack localization strain, $\varepsilon_{t,loc}$, of 0.0025, and
- A minimum durability performance as defined in Article 2.6.5 of this Appendix or as specified by the owner.

AASHTO, "Guide Specifications for Structural Design with Ultra-High Performance Concrete," first edition, American Association of State Highway and Transportation Officials, Washington, DC, 2024, 97 pp.

Graybeal, B. A., & El-Helou, R. (2023). Structural design with ultra-high performance concrete (No. FHWA-HRT-23-077). United States. Department of Transportation. Federal Highway Administration. Office of Infrastructure Research and Development.

Indirect tensile test method

Chapter 18 fib Model Code 2020

In the case of softening behaviour (a) the deformations localise in one crack. In the case of hardening behaviour (b) multiple cracking occurs before reaching the peak value.

The relation between strain softening and strain hardening behaviour is shown in Figure 18.1-1. A FRC with softening behaviour in tension can develop hardening behaviour in bending. A FRC with softening behaviour in bending can exhibit a monotonically increasing load in the structure (Figure 18.1-2).
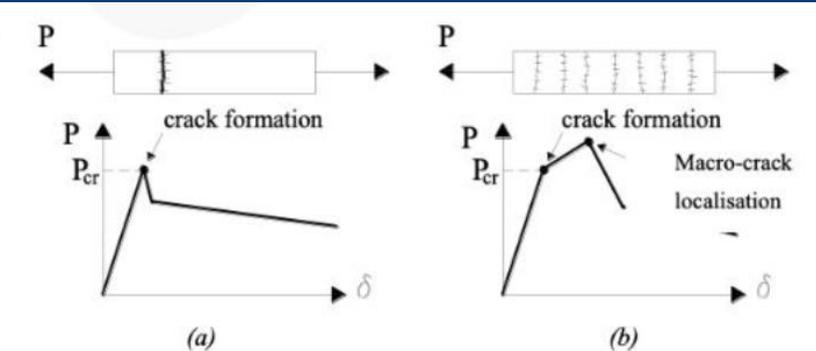

Figure 18.1-1: Softening (a) and hardening (b) behaviour in axial tension

18.2.2 Behaviour in tension

With regard to the characterisation of the tensile behaviour, which is the most important aspect of FRC, various test methods are possible.

In general, uniaxial tensile testing is not advised for standard testing of new mixtures since these tests are difficult to carry out and interpret. Uniaxial tensile tests are especially suitable for determining the strain hardening behaviour.

fib-federation internationale du beton. (2023). fib Model Code for Concrete Structures 2020. John Wiley & Sons.

Tensile properties required for flexural and shear design in the AASHTO UHPC guide

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

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$f_{t,cr}$ = effective cracking strength
$f_{t,loc}$ = crack localization strength

Contribution of UHPC tensile properties for structural design

1.6.3.2. Flexural Resistance

1.6.3.2.1. Factored Flexural Resistance

The factored flexural resistance, M_r, shall be taken as:

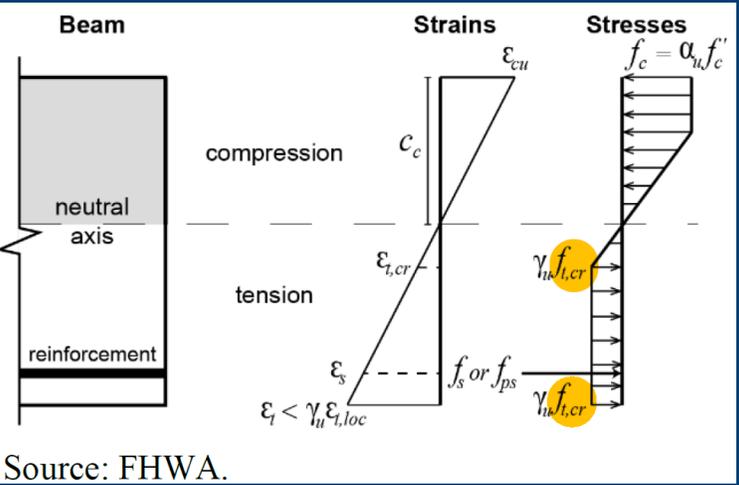$$M_r = \phi M_n \qquad (1.6.3.2.1\text{-}1)$$

1.7.3.3. Nominal Shear Resistance

The nominal shear resistance, V_n, shall be determined as the lesser of both of the following:

$$V_n = V_{UHPC} + V_s + V_p \qquad (1.7.3.3\text{-}1)$$

$$V_n = 0.25 f'_c \, b_v \, d_v + V_p \qquad (1.7.3.3\text{-}2)$$

in which:

$$V_{UHPC} = \gamma_u f_{t,loc} \, b_v \, d_v \cot\theta \qquad (1.7.3.3\text{-}3)$$

$$V_s = \frac{A_v f_{v,\alpha} d_v (\cot\theta + \cot\alpha)\sin\alpha}{s} \qquad (1.7.3.3\text{-}4)$$


Source: FHWA.

- Graybeal, B. A., & El-Helou, R. (2023). Structural design with ultra-high performance concrete (No. FHWA-HRT-23-077). United States. Department of Transportation. Federal Highway Administration. Office of Infrastructure Research and Development.
- AASHTO, "Guide Specifications for Structural Design with Ultra-High Performance Concrete," first edition, American Association of State Highway and Transportation Officials, Washington, DC, 2024, 97 pp.
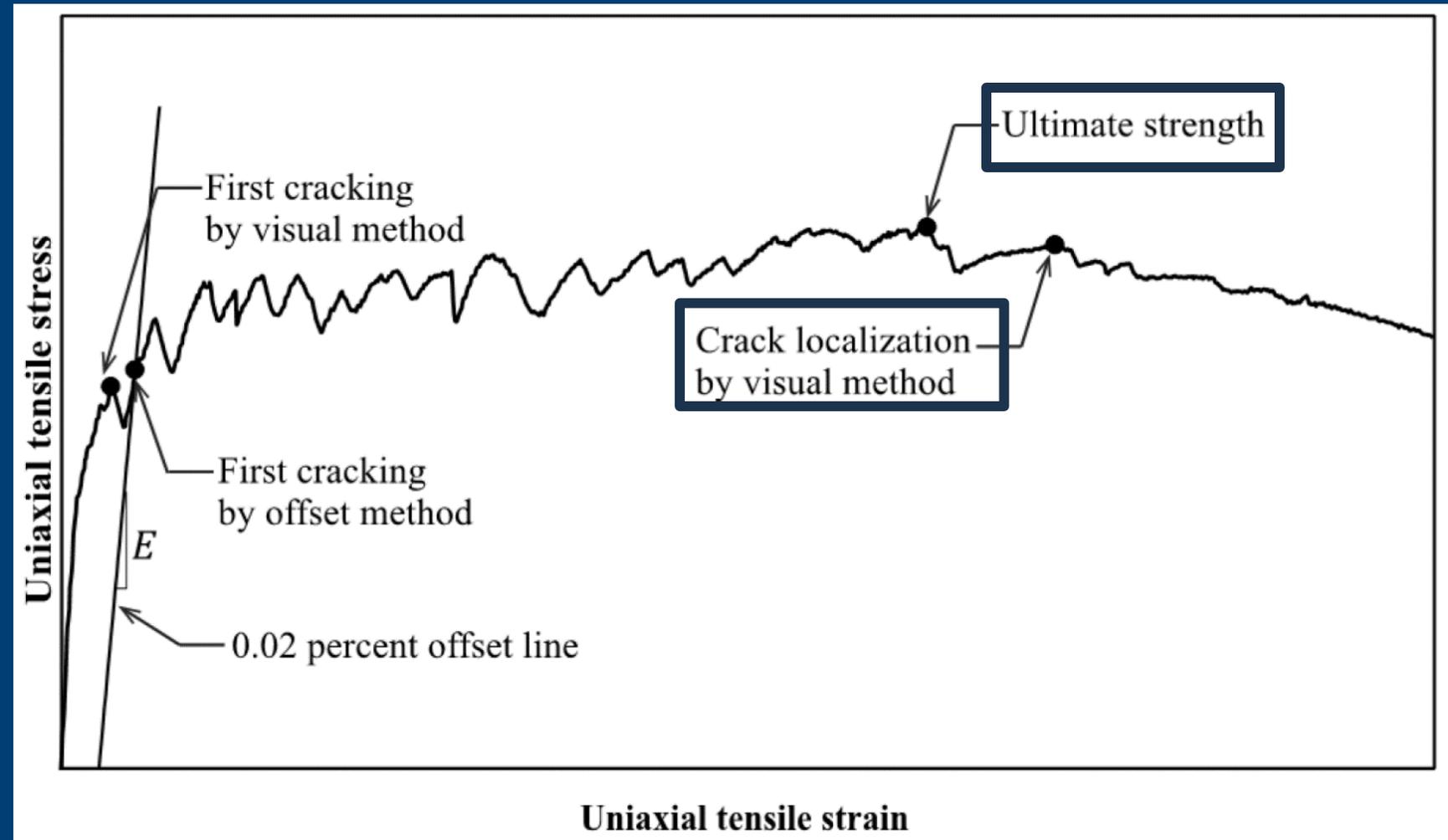
Toward Consistent Reporting of Tensile Properties in Strain-Hardening UHPC:
Key Difficulties in Test Interpretation

Three Characteristic Tensile Responses in the Strain-Hardening Region
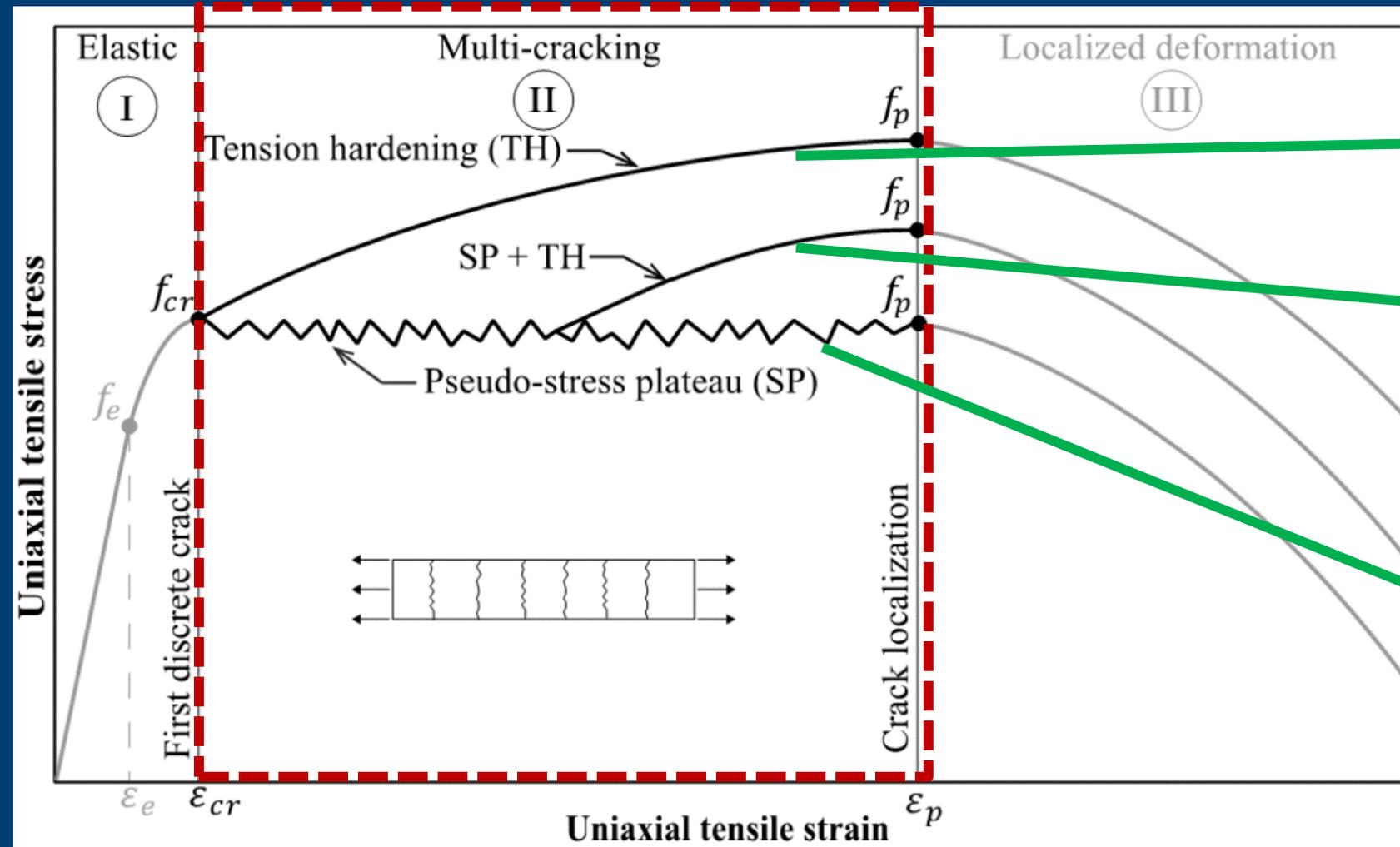
- **TH**: bilinear tension-hardening response $f_p > f_{cr}$

- **SP+TH**: combined behavior showing partial plateau and moderate hardening $f_p > f_{cr}$

- **SP**: pseudo-stress plateau (elastic–perfectly plastic response) $f_p \approx f_{cr}$

Haber, Z. B., De la Varga, I., Graybeal, B. A., Nakashoji, B., & El-Helou, R. (2018). Properties and behavior of UHPC-class materials (No. FHWA-HRT-18-036; HRDI-40/3-18 (WEB) EHIF). United States. Department of Transportation. Federal Highway Administration. Office of Infrastructure Research and Development.

Toward a Unified Definition of Tensile Strength: Linking FRC and UHPC
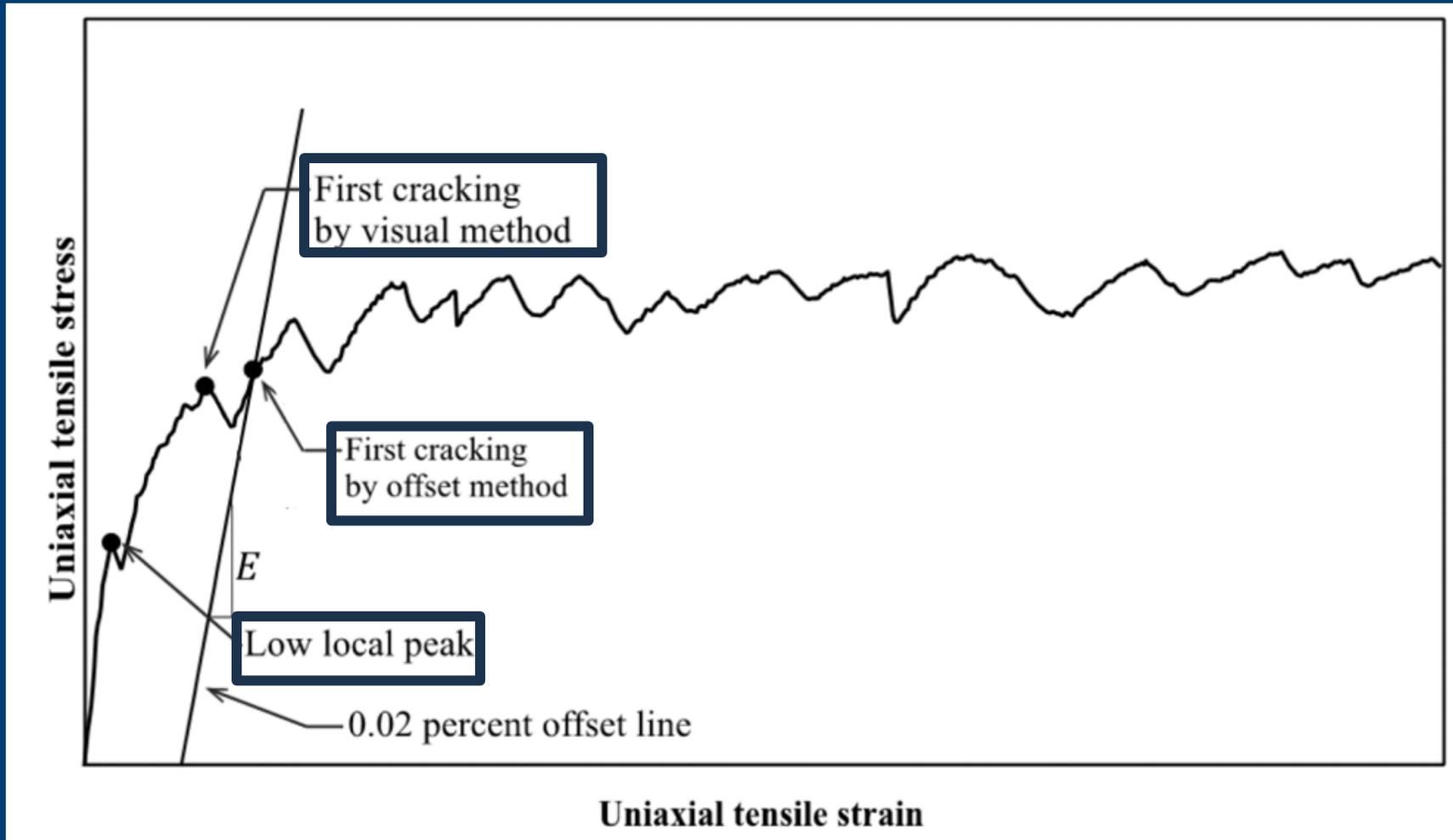

FRC
The post-cracking strength (σ_{pc}) is typically reported as the maximum or ultimate tensile strength.

AASHTO T-397 approach
Defines the crack localization strength $(f_{t,loc})$ as the first strength value where strength continuously decreases with increasing strain.

$f_{t,loc}$ → **Easier to identify, less subjective, and more reproducible.**

Haber, Z. B., De la Varga, I., Graybeal, B. A., Nakashoji, B., & El-Helou, R. (2018). Properties and behavior of UHPC-class materials (No. FHWA-HRT-18-036; HRDI-40/3-18 (WEB) EHIF). United States. Department of Transportation. Federal Highway Administration. Office of Infrastructure Research and Development.

First cracking by visual method

First cracking by offset method

Low local peak

E

0.02 percent offset line

Uniaxial tensile stress
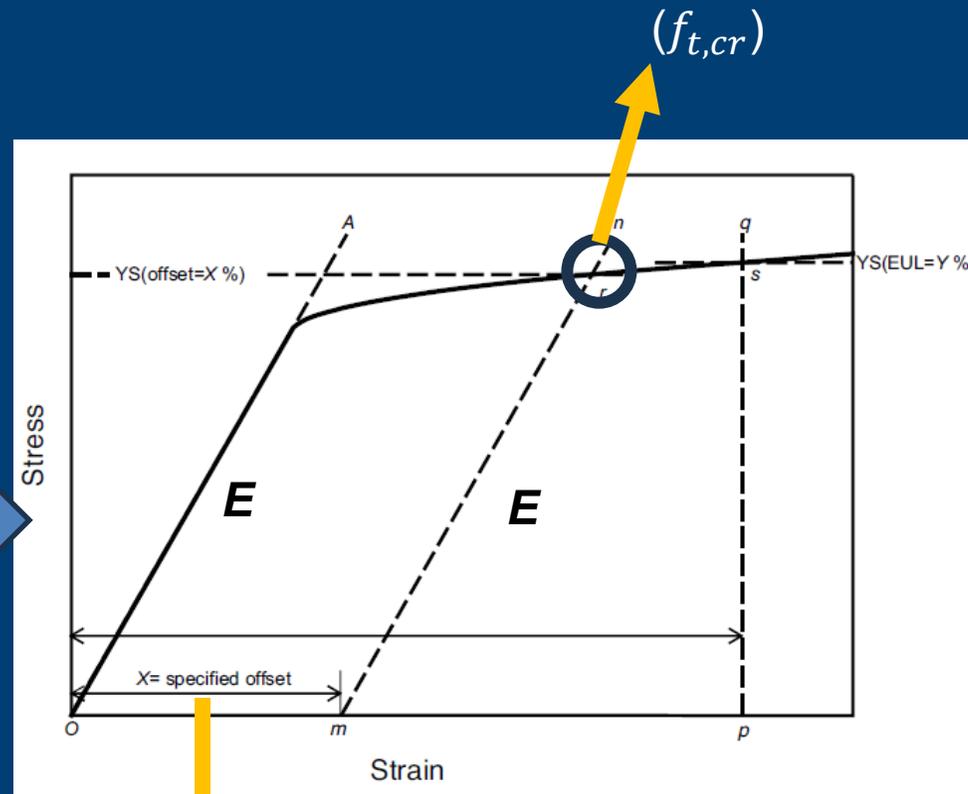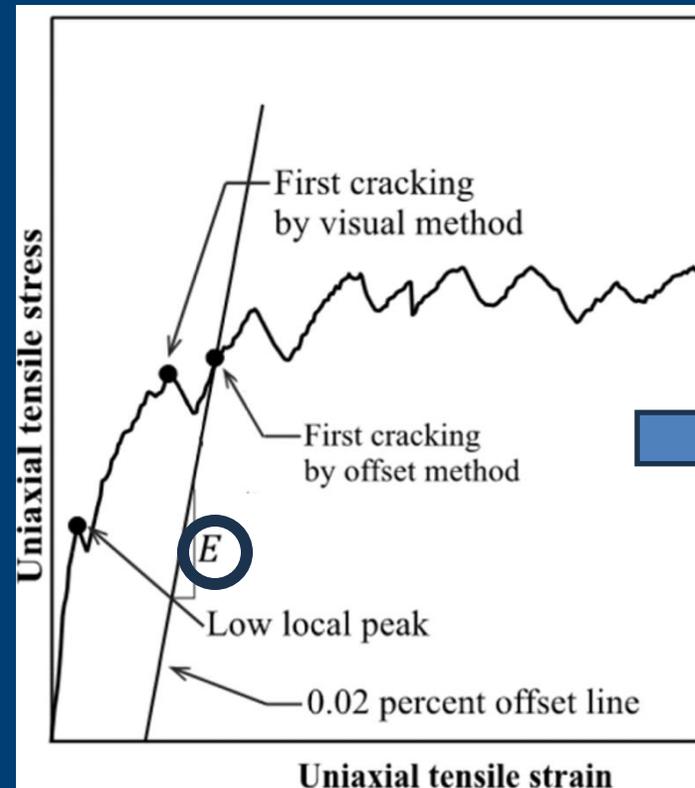
Uniaxial tensile strain

FRC (σ_{cc})
- *First visible crack*: based on visual detection

- *Deviation from linearity*: first nonlinearity in the stress–strain curve

- *Low local peaks*: may appear early and cause misinterpretation

AASHTO T-397 approach
Effective cracking strength ($f_{t,cr}$) determined using the 0.02% offset method

$f_{t,cr}$ → **Easier to identify, less subjective, and more reproducible.**
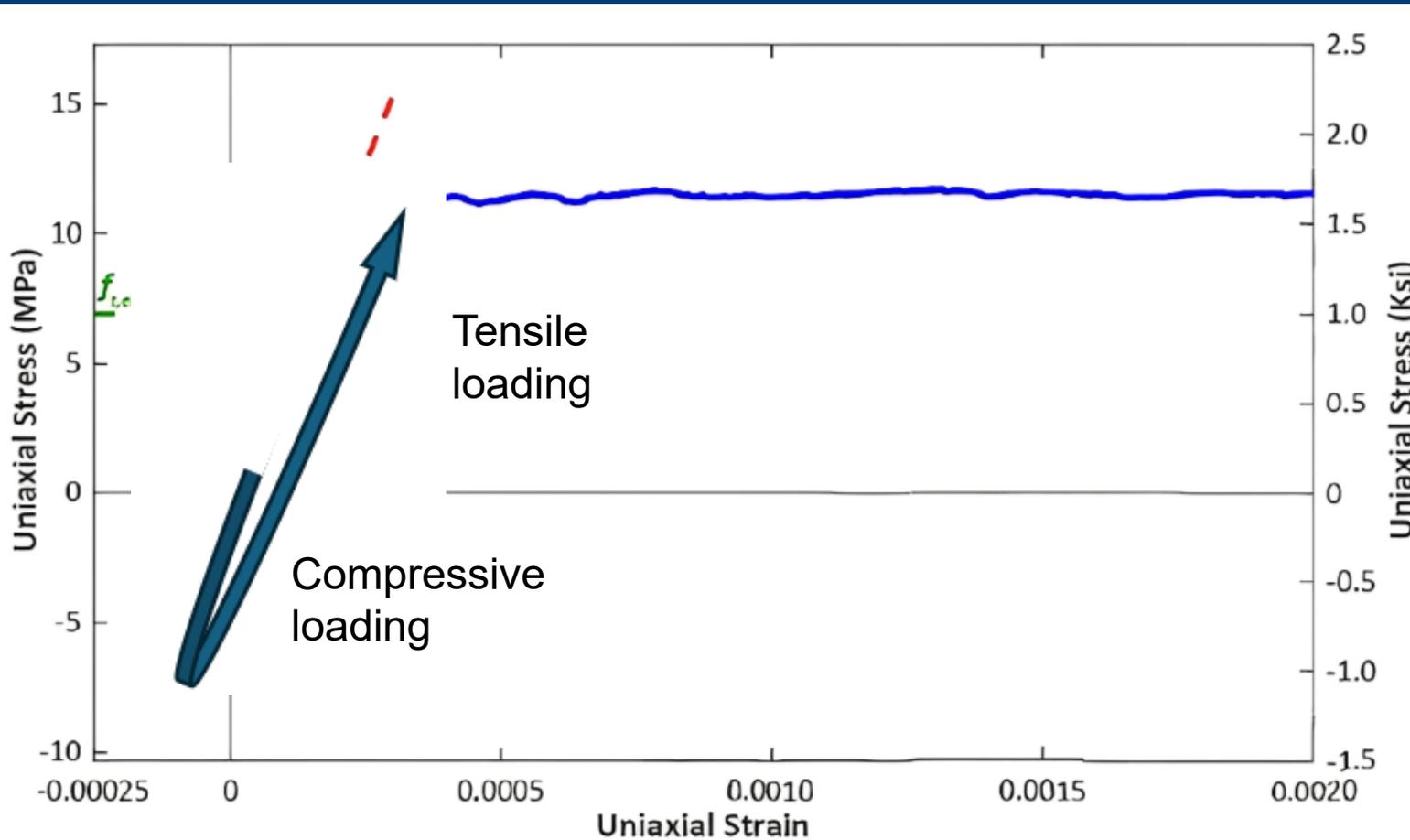
Haber, Z. B., De la Varga, I., Graybeal, B. A., Nakashoji, B., & El-Helou, R. (2018). Properties and behavior of UHPC-class materials (No. FHWA-HRT-18-036; HRDI-40/3-18 (WEB) EHIF). United States. Department of Transportation. Federal Highway Administration. Office of Infrastructure Research and Development.

0.02% Offset Method for Effective Cracking Strength

$(f_{t,cr})$

Specified offset = 0.02%

- Originates from ASTM E8 for metallic materials.

- The offset is set at 0.02% of the elastic modulus (E).

- The point where the offset line intersects the tensile stress–strain curve defines $f_{t,cr}$.

- Provides an objective and reproducible means to identify the cracking strength.

- ASTM E8/E8M-22. (2022). Standard Test Methods for Tension Testing of Metallic Materials. ASTM International, West Conshohocken, PA, 31 pp.
- Haber, Z. B., De la Varga, I., Graybeal, B. A., Nakashoji, B., & El-Helou, R. (2018). Properties and behavior of UHPC-class materials (No. FHWA-HRT-18-036; HRDI-40/3-18 (WEB) EHIF). United States. Department of Transportation. Federal Highway Administration. Office of Infrastructure Research and Development.

Determining Effective Cracking Strength: The Role of Elastic Modulus (E)

- AASHTO T-397: E should be obtained directly from the uniaxial tensile test.

- In practice, many test setups cannot apply a compressive preload of 3.5–7.0 MPa (0.5–1.0 ksi) before switching to tension.

    Alternative approaches
- Determine E from cylinder tests following ASTM C1856, with a loading rate of 145 $\pm$ 7 psi/s.

- If no measured data, $E = 2500k_1 {f'_c}^{0.33}$, where f'_c in ksi and k_1 is 1 unless determined by physical test.

- ASTM C1856/C1856M-17. (2017). Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete," ASTM International, West Conshohocken, PA. 4 pp.
- AASHTO T-397. (2022). Standard method of test for uniaxial tensile response of ultra-high performance concrete. American Association of State Highway and Transportation Officials. DC. 49pp.
- Graybeal, B. A., and El-Helou, R.. (2023). Structural Design with Ultra-High Performance Concrete. Report No. FHWA-HRT-23-077, Federal Highway Administration, McLean, VA, 2023, 294 pp.
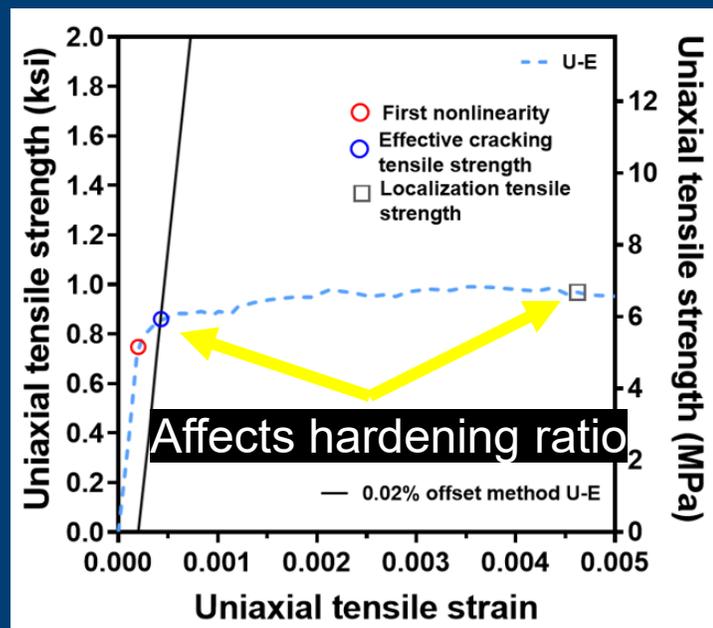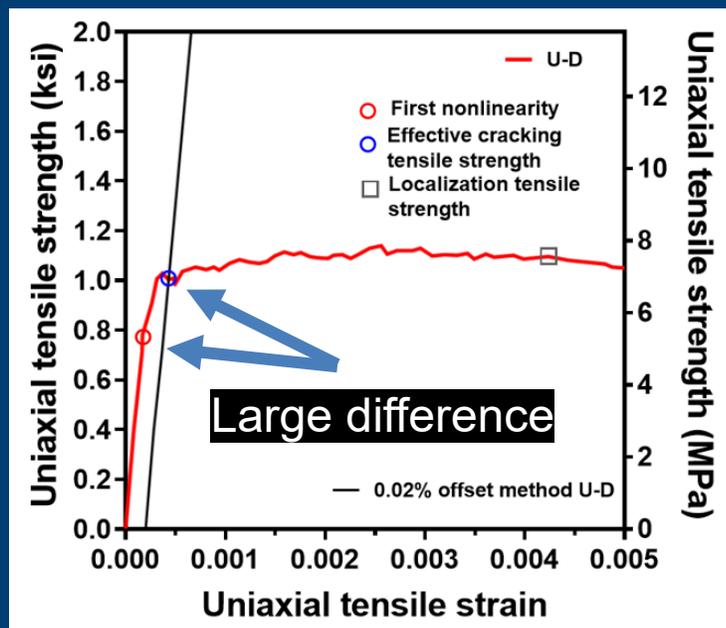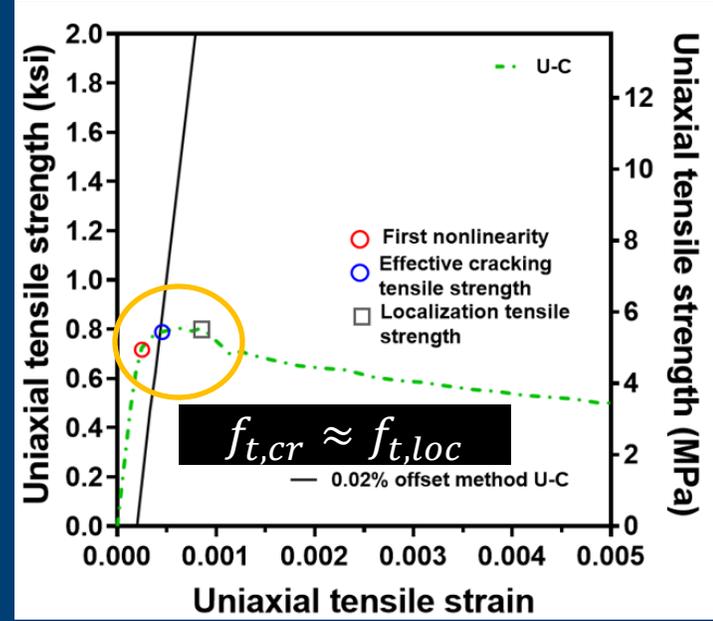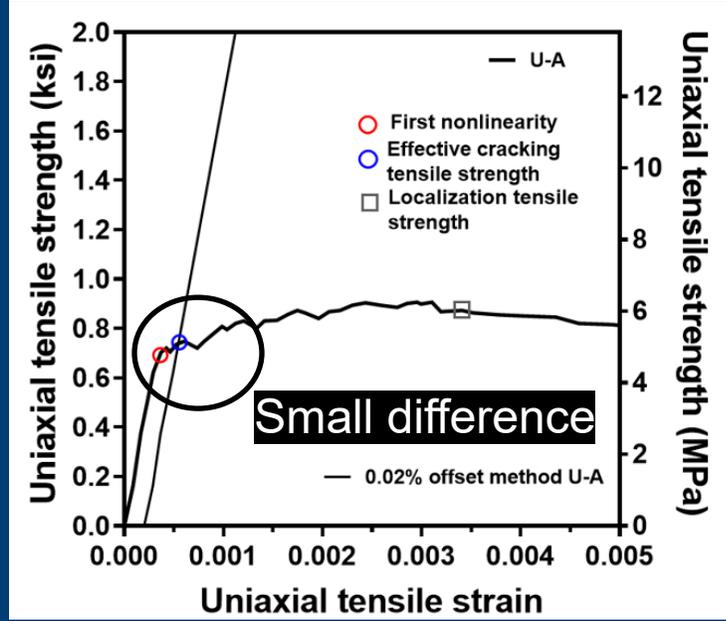
Demonstration of Consistent Reporting of Effective Cracking and Localization Strengths for Strain-Hardening UHPC
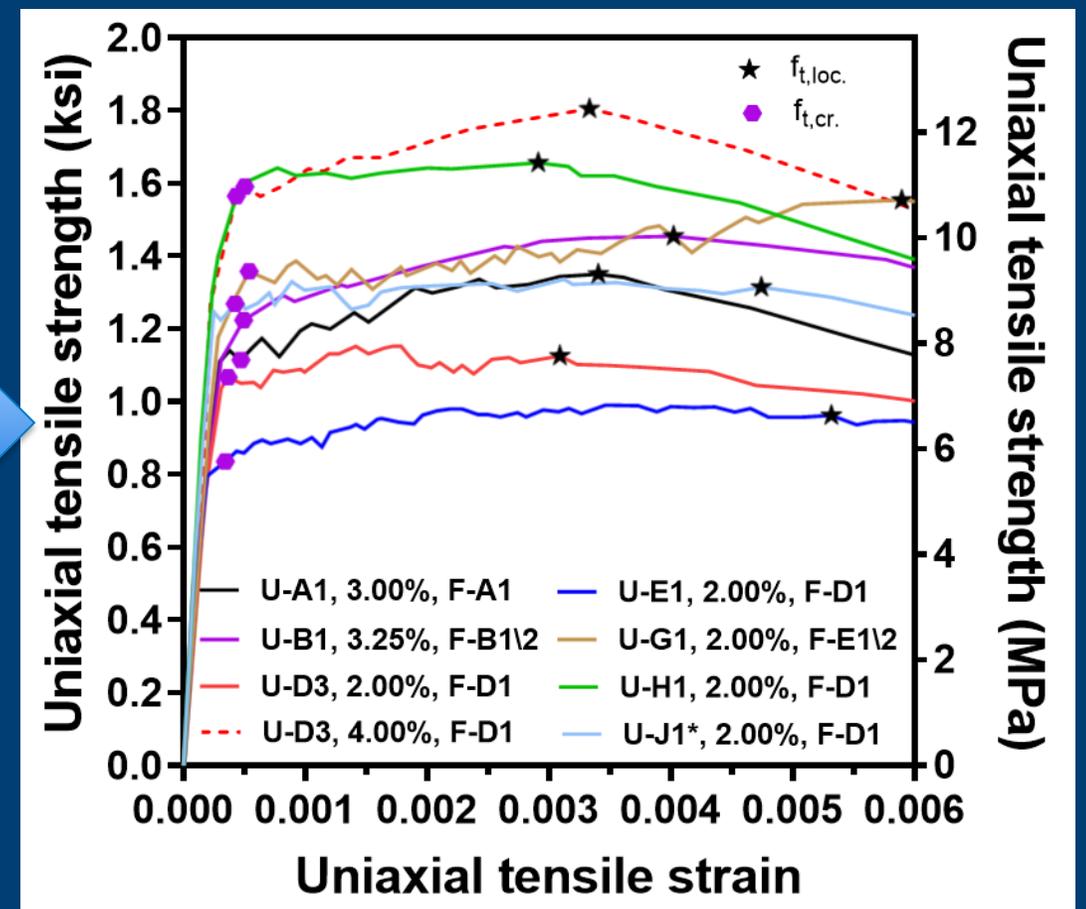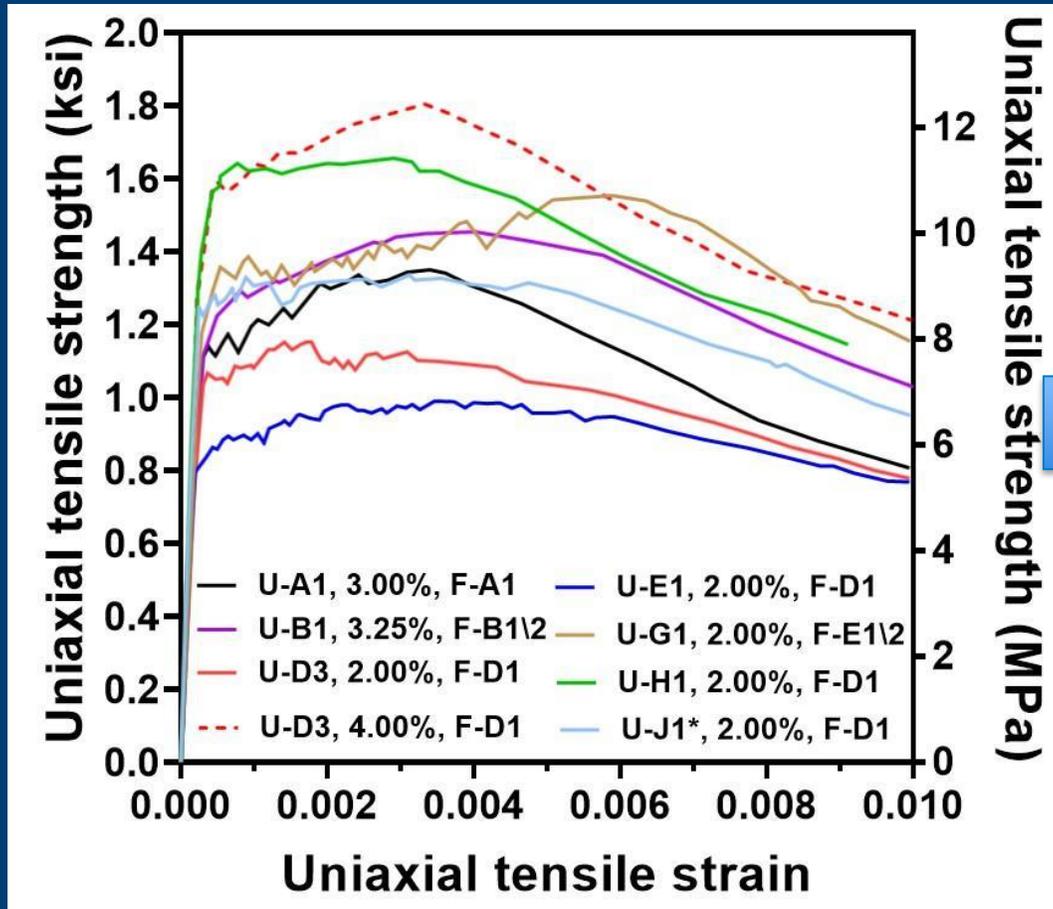
Impact of $f_{t,cr}$ on Tensile Strength-Strain Curves ($V_f = 2.0\%$)
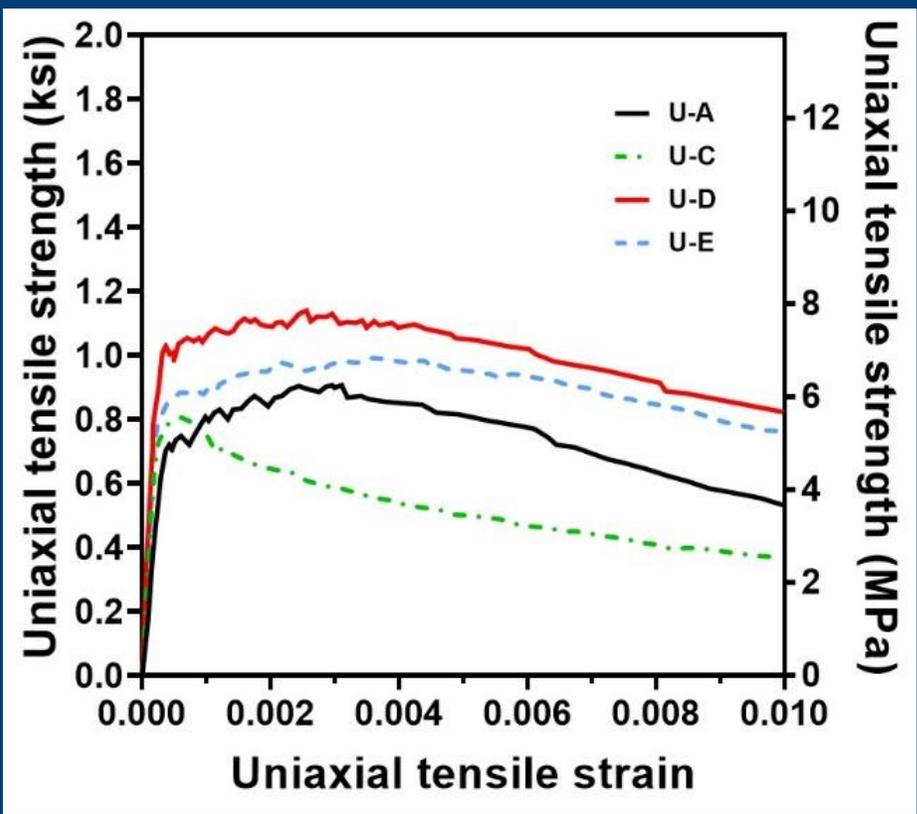
Modified from Haber et al. (2018), FHWA-HRT-18-036

Key Points in the Tensile Strength–Strain Curves for UHPC Mixes (V_f varies)

Modified from El-Helou et al. (2022), ACI Materials Journal

✓ $f_{t,cr}$ determined using the 0.02% offset method
✓ $f_{t,loc}$ identified according to AASHTO T-397

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From FRC to UHPC: Toward Consistent Tensile Strength Reporting

Classical FRC

1. $f_{t,cr}$: Multiple methods$\rightarrow$ subjectivity

2. $f_{t,max}$: highest peak strength$\rightarrow$ subjectivity

3. Lacks a standardized approach for identifying key tensile parameters.

UHPC

1. $f_{t,cr}$: Effective cracking strength$\rightarrow$ 0.02% offset method (AASHTO T-397)

2. $f_{t,loc}$: stress at which strain increases while strength continuously decreases$\rightarrow$ easier to identify.

*$f_{t,cr}$ is not trivial; it is fundamental for characterizing **strain-hardening behavior in UHPC**.*

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Thank you!

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