Design tools for UHPC Pretensioned Bridge Girders

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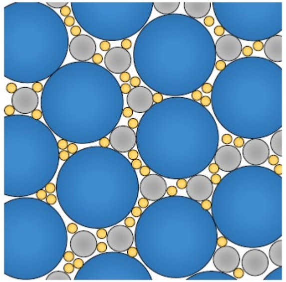
What is UHPC?

- Ultra-High-Performance Concrete
- Composite cementitious matrix (concrete)
- No coarse aggregates
- Steel fibers for tensile strength
- Low water/binder ratio
- Particle packing
- Self consolidating (superplasticizers)



What does UHPC offer?

- Durability
- High compressive strengths (17.5 – 36 ksi)
- Tensile strength (0.9 - 1.8 ksi)

- Primary use has been in connections and overlays
- Worldwide, main structural components from UHPC
- Longer spans, lighter weight, less reinforcement (no stirrups)
- Link slabs
- Piles

Why do we need Structural Design Guidance?

- Use of UHPC is increasing in US
- Early adopters need support and guidance for success
- Several states are looking at precast UHPC beam solutions (MN, NE, FL)
  - Iowa, Buchanan County, Pi Girders, ASPIRE Winter 2010
  - Michigan, St. Clair County, August 2023, ABC-UTC presentation

- Behavior of UHPC is different than conventional concrete
  - Strain is the limiting behavior
  - Can’t use higher UHPC f_c' in LRFD equations
  - LRFD BDS does not account for UHPC tension strength
  - UHPC failure modes not accounted for in LRFD BDS

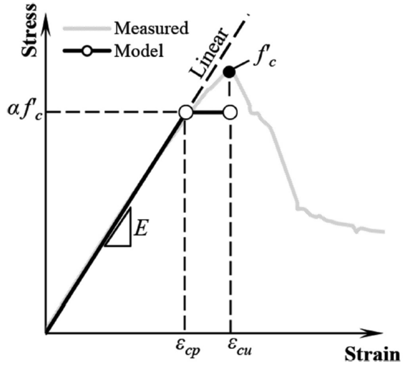
AASHTO UHPC Guide Specification

- Balloted and passed by AASHTO COBS, May 2023
- Adopts AASHTO LRFD BDS and replaces Section 5 (Concrete)

- Minimum UHPC Properties
  - $f_c' = 17.5\ ksi, f_{ci}' = 14\ ksi$
  - Cracking strength, $f_{t,cr} = 0.75\ ksi$
  - Crack localization strength, $f_{t,loc} \geq f_{t,cr}$ (Sustained post-cracking tension strength)
  - Crack localization strain, $e_{t,loc} = 0.0025$
- Fibers must be steel (secondary fibers of other types permitted)
- Tension properties characterized by direct tension test (AASHTO T 397)

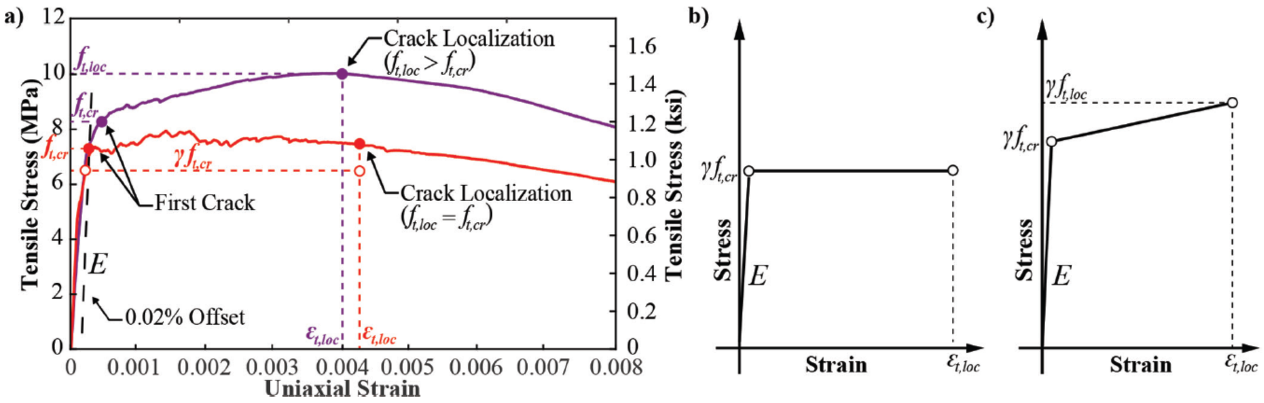
Material Models

- Compression



Source: El-Helou, et. al. ACI Materials Journal 2022

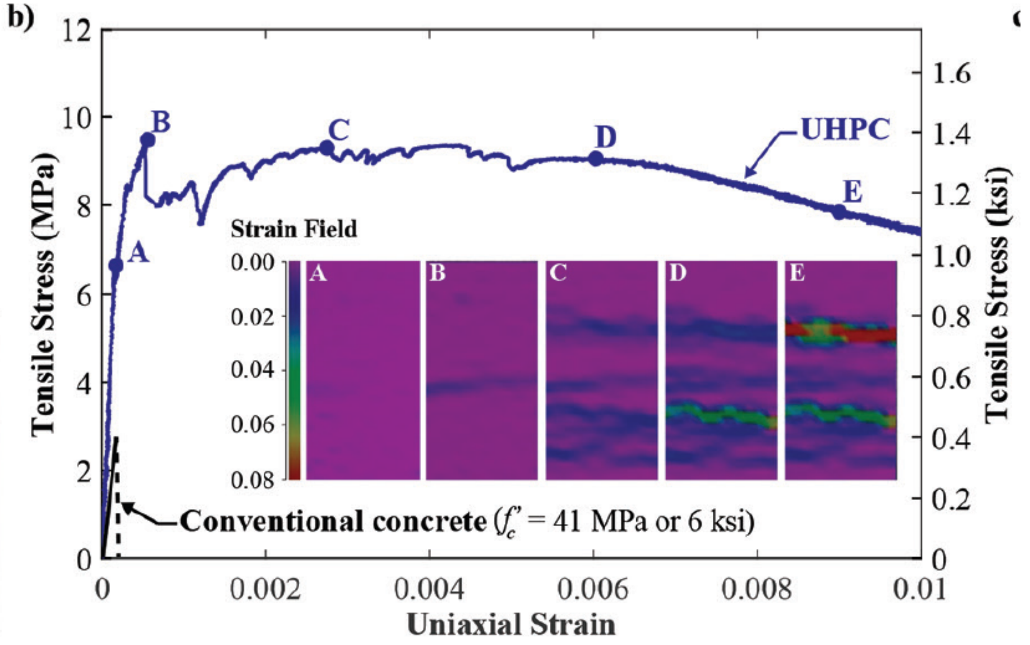
- Tension



Source: El-Helou, et. al. ACI Materials Journal 2022

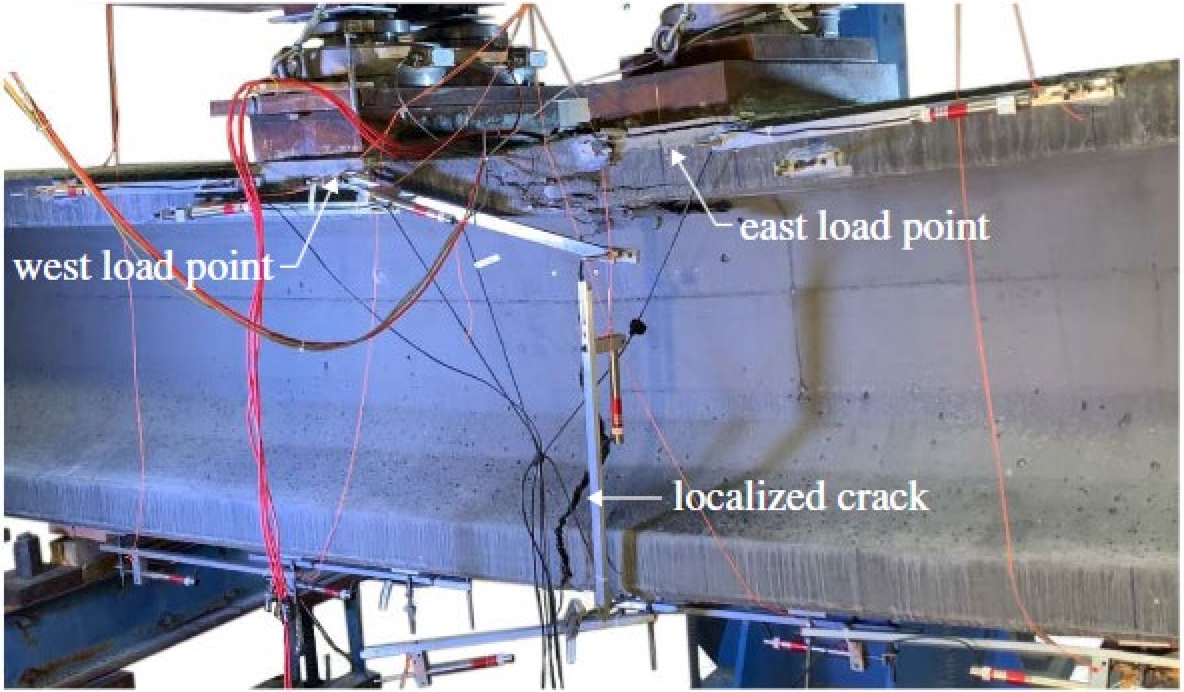
Crack Localization

- Unique failure mode
- Well distributed cracks coalesce into a single dominate crack
- Fibers are pulling out



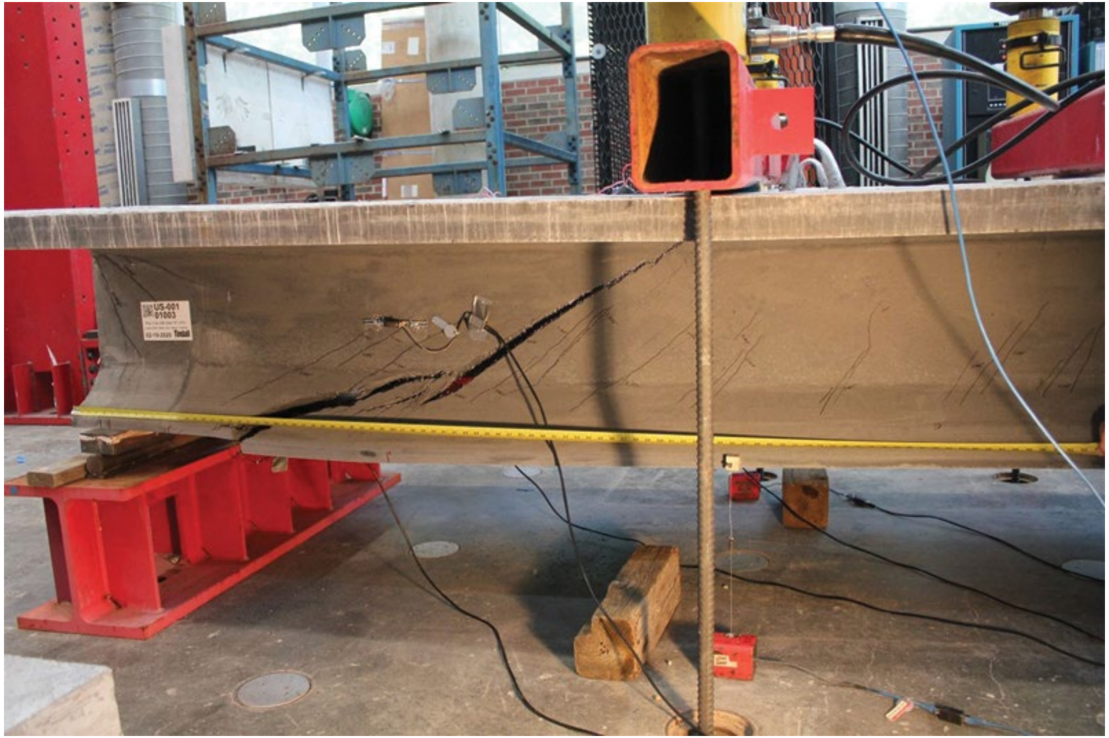
Source: El-Helou, et. al. ACI Materials Journal 2022

Crack Localization - Flexure



Source: El-Helou, et. al. ASCE J. Struct. Eng. 2022, 148(4)

Crack Localization - Shear



Service Limit State Design

- Generally, the same as for conventional concrete
- Modulus of elasticity $E_c = 2{,}500 K_1 {f'_c}^{0.33}$
- Creep and shrinkage use similar model to LRFD BDS
  - $\Psi(t, t_i) = 1.2 k_s k_{hc} k_f k_{td} k_\ell K_3$ $\varepsilon_{sh} = k_s k_{hs} k_f k_{td} K_4 0.6 \times 10^{-3}$
- Compression stress limits
  - Same as LRFD BDS
- Tension stress limits
  - Temporary, $\gamma_u f_{t,cri}$
  - Permanent, $\gamma_u f_{t,cr}$
  - Cyclic loading, $0.95 \gamma_u f_{t,cr}$ (fatigue of fibers is a concern – limited research)
  - Reinforcement fatigue checks apply

Transfer and Development

- Transfer length for prestress
  - $l_t = \xi 24 d_b, \xi = 0.75\ or\ 1.0$
- Development length for prestress
  - $l_d \geq l_t + 0.30\left(f_{ps} - f_{pe}\right)d_b$
- Development length for reinforcement
  - $l_d = \begin{cases} 10d_b\ f'_c < 75ksi \\ 12d_b\ 75ksi \leq f'_c \leq 100ksi \end{cases}$

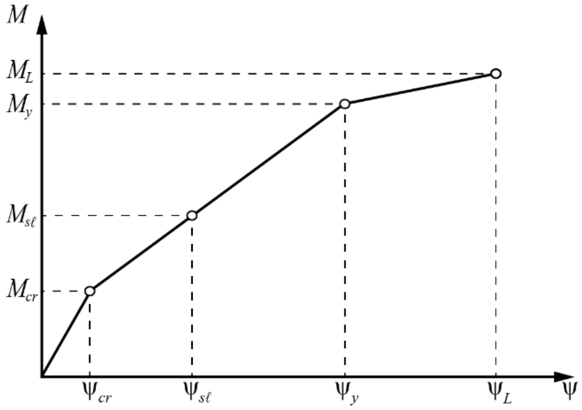
Strength Limit States

- UHPC tensile properties affect the strength limit state
- Crack localization strength typically governs strength of members

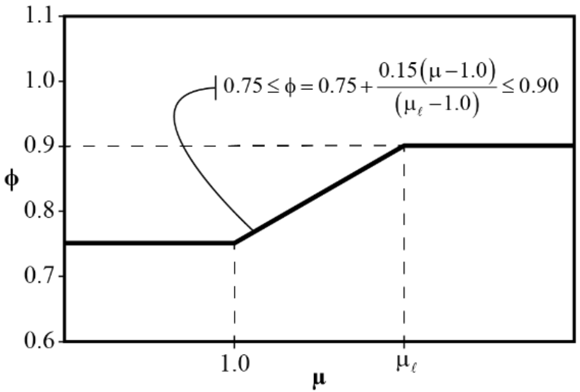
- Flexure and shear capacity analysis is considerably different than LRFD BDS
  - Whitney stress block is not valid
  - Concrete crushing strain may not be the limiting value

Flexural Capacity

- Moment curvature response computed using strain compatibility
- Governing failure mode can be
  - Composite concrete crushing (deck)
  - UHPC crushing
  - Reinforcement rupture
  - UHPC crack localization
- Resistance factor accounts for ductility in terms of curvature prior to failure limit, $\mu = \Psi_L / \Psi_{sl}$
  - 0.75 when localization controls
  - 0.90 otherwise ($\mu_l = 3$)



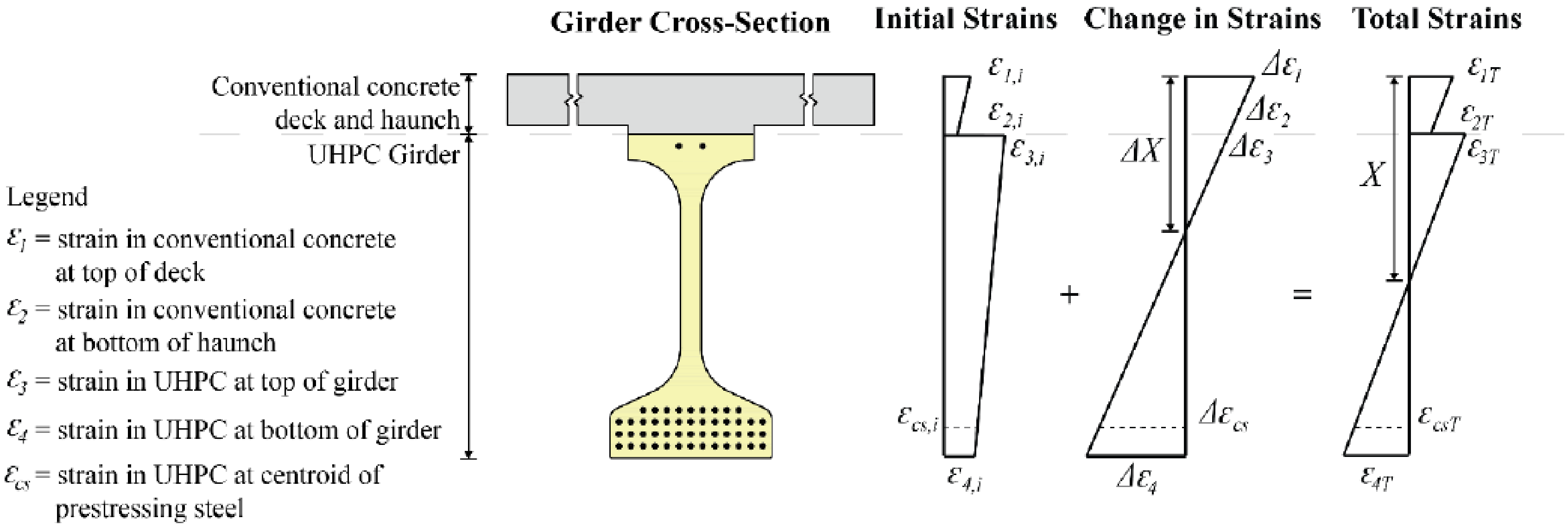
Moment curvature



Resistance factor

Strain Compatibility

- Must account for initial strains (generally ignored for conventional concrete)



Shear Capacity

- Capacity based on MCFT
- $V_n = V_{UHPC} + V_s + V_p$
- $V_{UHPC} = \gamma_u f_{t,loc} b_v d_v \cot\theta$
- $V_s = \frac{A_v f_{v,\alpha} d_v \cot\theta}{s}$
- $f_{v,\alpha}$ = stress in reinforcement at crack localization (may be less than f_y)
- Reduction factor, $\phi = 0.9$ (Same as LRFD BDS)

Shear Parameters, $f_{v,\alpha}$ and θ

- Iterate design equations to determining $f_{v,\alpha}$ and θ
- Guess $f_{v,\alpha} = f_y$, solve for θ
- Compute ε_2, ε_v, and $f_{v,\alpha}$
- Repeat until convergence
- Simplified method using tables in appendix

- $f_{v,\alpha}$ = stress in reinforcement
- θ = inclination of shear crack

$$\gamma_u \varepsilon_{t,loc} = \frac{\varepsilon_s}{2}(1+\cot^2\theta) + \frac{2f_{t,loc}}{E_c}\cot^4\theta + \frac{2\rho_{v,\alpha}f_{v,\alpha}}{E_c}\cot^2\theta\,(1+\cot^2\theta)$$

$$\varepsilon_2 = -\frac{2f_{t,loc}}{E_c}\cot^2\theta - \frac{2\rho_{v,\alpha}f_{v,\alpha}}{E_c}(1+\cot^2\theta)$$

$$\varepsilon_v = \gamma_u\varepsilon_{t,loc} - 0.5\varepsilon_s + \varepsilon_2$$

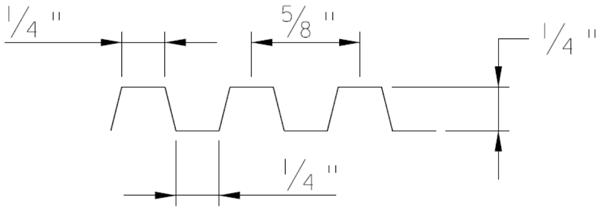
$$f_{v,\alpha} = \frac{E_s\varepsilon_v}{\sin\alpha} \le f_y \qquad \rho_{v,\alpha} = \frac{A_v}{b_v s}\left(1 + \frac{\cot\alpha}{\cot\theta}\right)\sin\alpha$$

Table B1.3-1. Values of θ (degrees) and upper limit of $f_{v,\alpha}$ (ksi) for sections with transverse reinforcement with $\rho_{v,\alpha} \le$ 1.0 percent.

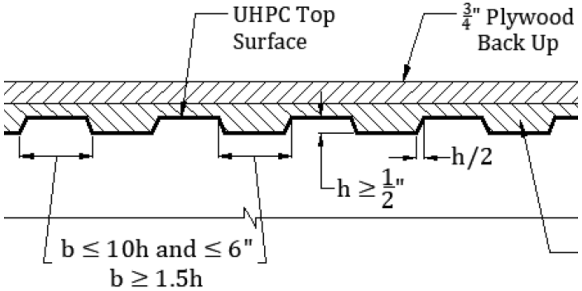
ε_s × 1,000	Parameter	$\gamma_u\varepsilon_{t,loc}$ × 1,000											
		≥2.5	≥3.0	≥3.5	≥4.0	≥4.5	≥5.0	≥5.5	≥6.0	≥6.5	≥7.0	≥7.5	≥8.0
≤ −1.0	θ (deg.)	32.7	32.3	31.9	31.6	31.3	30.8	30.2	29.8	29.3	28.9	28.6	28.2
	$f_{v,\alpha}$ (ksi)	≤36.7	≤46.6	≤56.5	≤66.5	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤ −0.5	θ (deg.)	34.3	33.7	33.2	32.8	32.4	31.8	31.2	30.7	30.2	29.8	29.4	29.0
	$f_{v,\alpha}$ (ksi)	≤35.3	≤45.1	≤54.9	≤64.8	≤74.8	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0
≤0.0	θ (deg.)	36.2	35.3	34.6	34.1	33.6	32.9	32.3	31.7	31.2	30.7	30.2	29.8
	$f_{v,\alpha}$ (ksi)	≤33.8	≤43.4	≤53.1	≤63.0	≤72.9	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0	≤75.0

Horizontal Interface Shear

- Similar to conventional concrete, friction and cohesion factors
- UHPC is self consolidating, so surface tends to be smooth
- Roughening of UHPC surface is difficult
- Options for forming flutes or shear keys



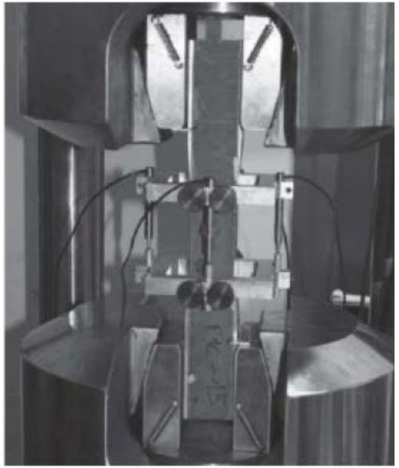
Formed Flutes



Formed Shear Keys

Material Testing and Qualification

- Material conformance guidance is being developed (AASHTO ballot 2024)
- PCI has done significant work in material testing
- Tension properties of UHPC is important for structural behavior
- Test Methods – Flexural Prism, Direct Tension
- T-10 intends for direct tension for mix qualification with flexural prism as datum for QC testing

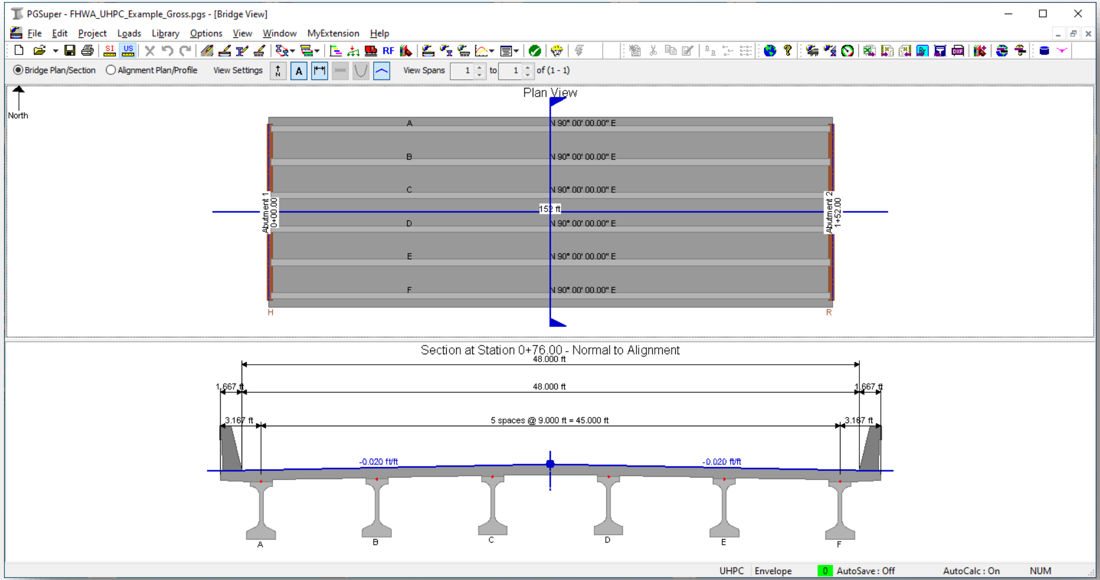


Direct Tension
AASHTO T 397

Flexural Prism
ASTM C 1609

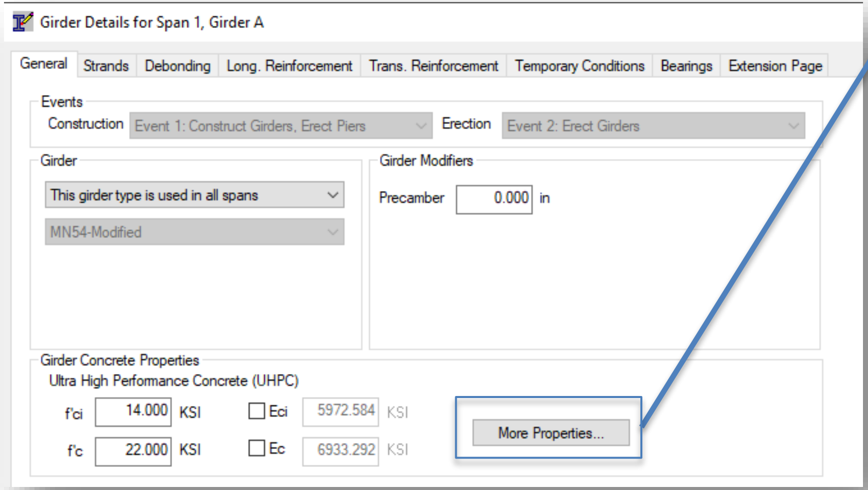
UHPC Design with PGSuper

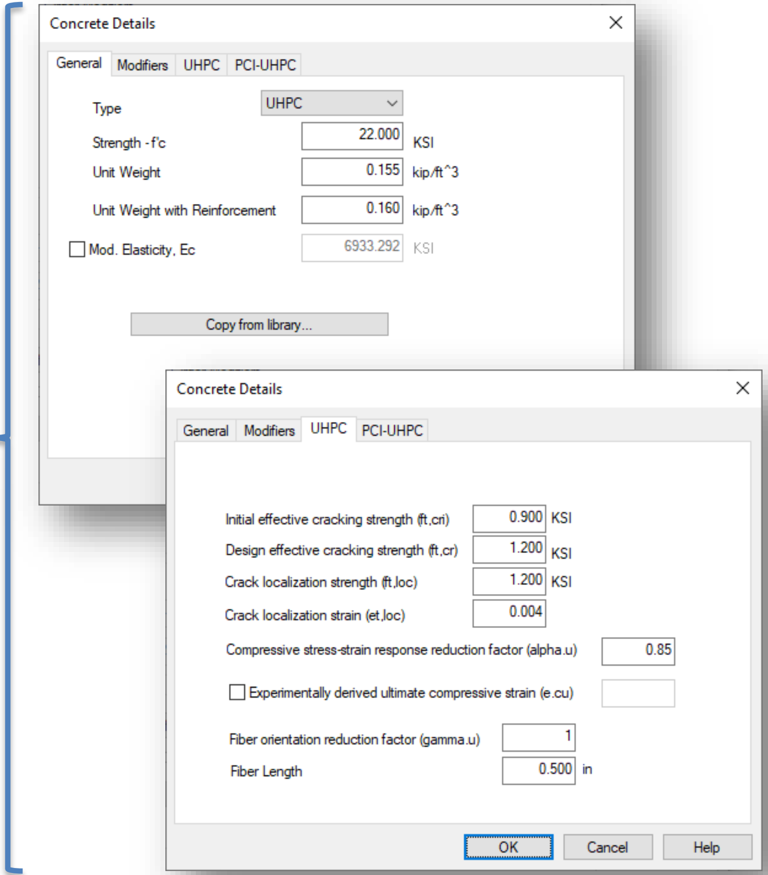
- PGSuper 8.0 Beta
- Support for UHPC class materials in prestress components
- Evaluates service, fatigue, and strength limit states
- Performs flexural analysis with strain compatibility & moment curvature
- Shear capacity using general method



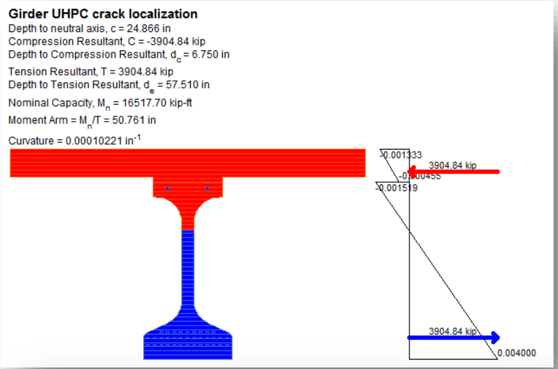
Modeling UHPC

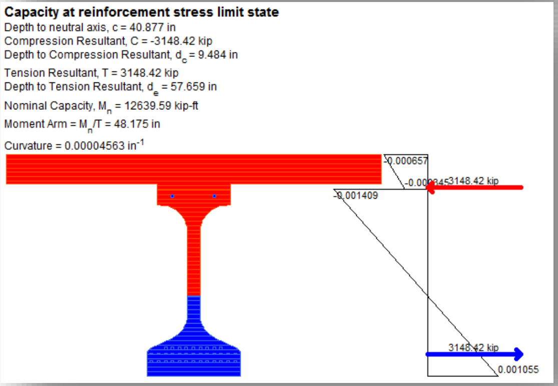
- Edit Girder
- Press [More Properties…]
- Select concrete UHPC
- Define UHPC parameters

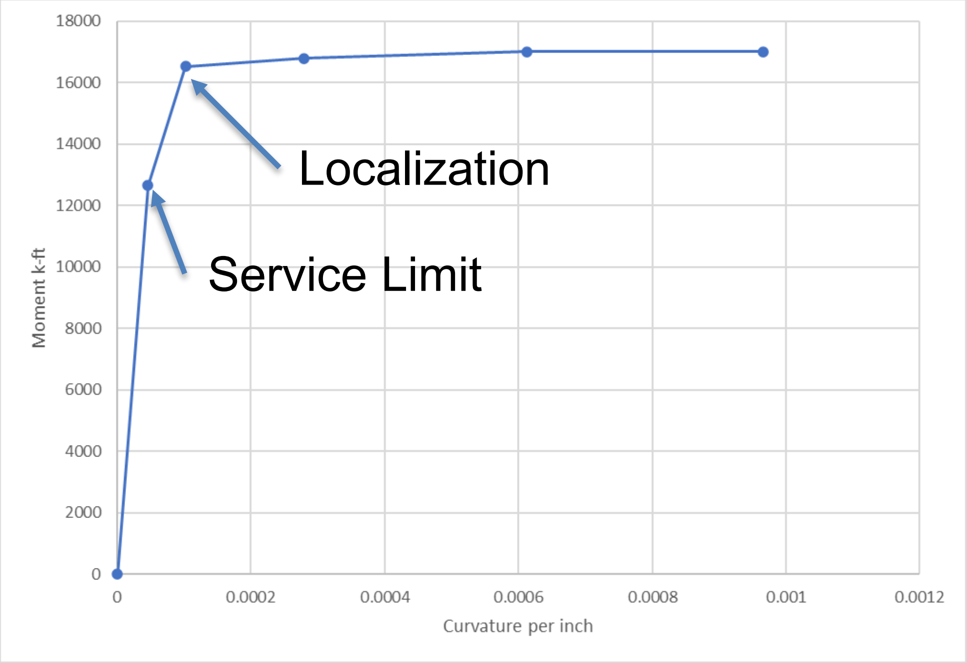




Flexural Strength Analysis







Shear Resistance Parameters

Shear Resistance Parameter - Strength I - GS 1.7.3.4

$$\gamma_u \varepsilon_{t,loc} = \frac{\varepsilon_s}{2}(1+\cot^2\theta) + \frac{2f_{t,loc}}{E_c}\cot^4\theta + \frac{2\rho_{v,\alpha}f_{v,\alpha}}{E_c}\cot^2\theta\,(1+\cot^2\theta)$$

$$\varepsilon_2 = -\frac{2f_{t,loc}}{E_c}\cot^2\theta - \frac{2\rho_{v,\alpha}f_{v,\alpha}}{E_c}(1+\cot^2\theta)$$

$$\varepsilon_v = \gamma_u\varepsilon_{t,loc} - 0.5\varepsilon_s + \varepsilon_2$$

$$f_{v,\alpha} = \frac{E_s\varepsilon_v}{\sin\alpha} \le f_y$$

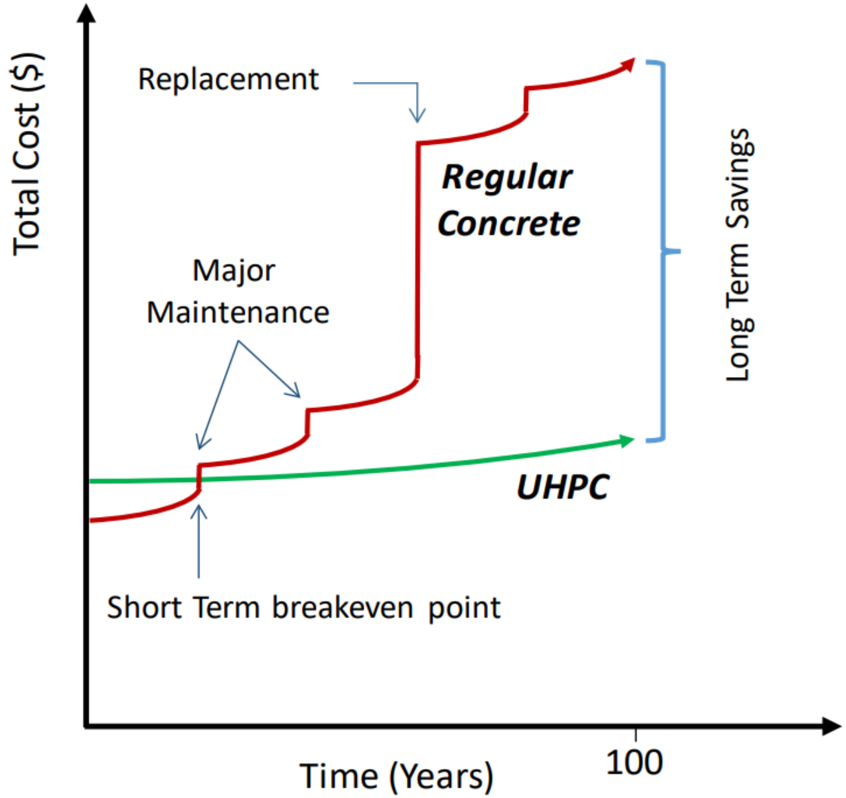
$$\rho_{v,\alpha} = \frac{A_v}{b_v s}\left(1+\frac{\cot\alpha}{\cot\theta}\right)\sin\alpha$$

Location from Left Support (ft)	ε_s x 1000	$\gamma_u\varepsilon_{t,loc}$ x 1000	$f_{t,loc}$ (KSI)	E_c (KSI)	α (deg)	$\rho_{v,\alpha}$	ε_2 x 1000	ε_v x 1000	θ (deg)	$f_{v,\alpha}$ (KSI)
(CS) 4.939	-0.398	4	1.200	6933.292	90.00	0.00952	-1.65	2.55	30.42	60.000
(H) 5.000	-0.402	4	1.200	6933.292	90.00	0.00952	-1.65	2.55	30.41	60.000
(PSXFR) 5.550	-0.436	4	1.200	6933.292	90.00	0.00952	-1.66	2.56	30.31	60.000
(1.5H) 7.250	-0.471	4	1.200	6933.292	90.00	0.00952	-1.67	2.56	30.21	60.000
(Debond) 9.500	-0.444	4	1.200	6933.292	90.00	0.00952	-1.66	2.56	30.29	60.000
(PSXFR) 10.550	-0.451	4	1.200	6933.292	90.00	0.00952	-1.67	2.56	30.27	60.000
14.500	-0.416	4	1.200	6933.292	90.00	0.00952	-1.65	2.56	30.37	60.000

Questions?

Download BridgeLink
https://wsdot.wa.gov/eesc/bridge/software

Real Opportunity for Cost Savings



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