Achieving High Strength, Ductility, and Durability in Flexural Members Reinforced with Fiber-Reinforced Polymer Rebars by Using UHP-FRC

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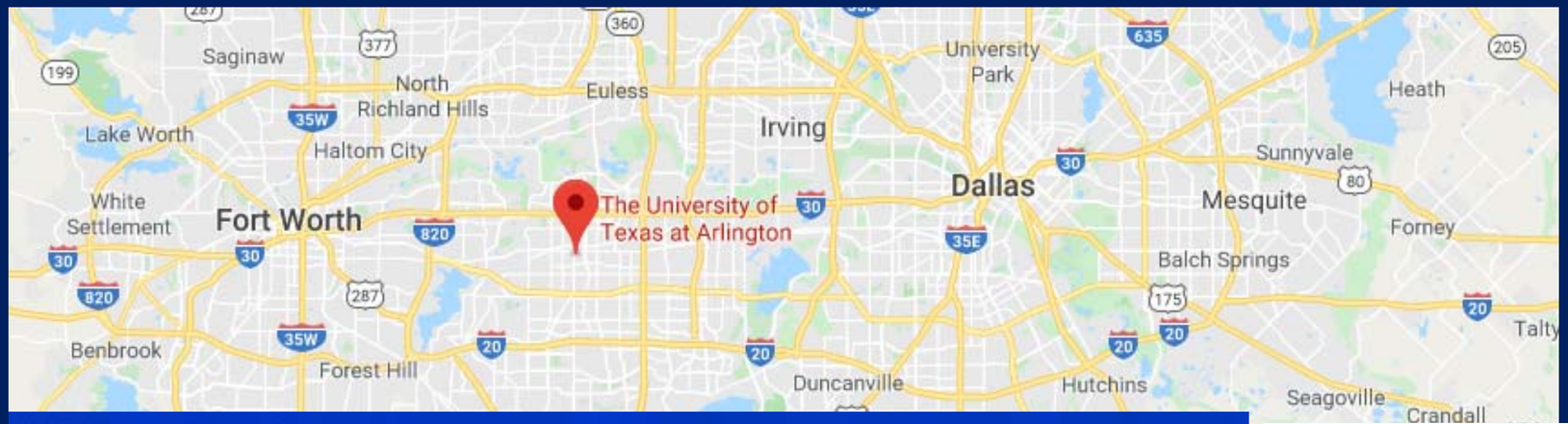
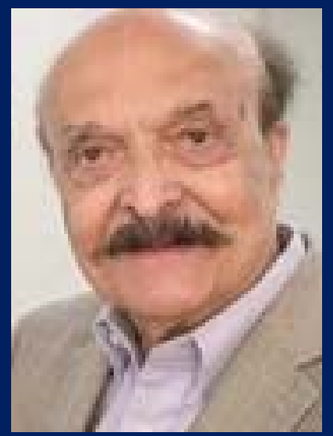


Department of Civil Engineering

Civil Engineering Laboratory Building



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Ultra-high-performance fiber-reinforced concrete (UHP-FRC)

- High compressive strength
- High compressive ductility
- High cracking resistance
- High shear strength

Fiber-reinforced polymer (FRP) rebars

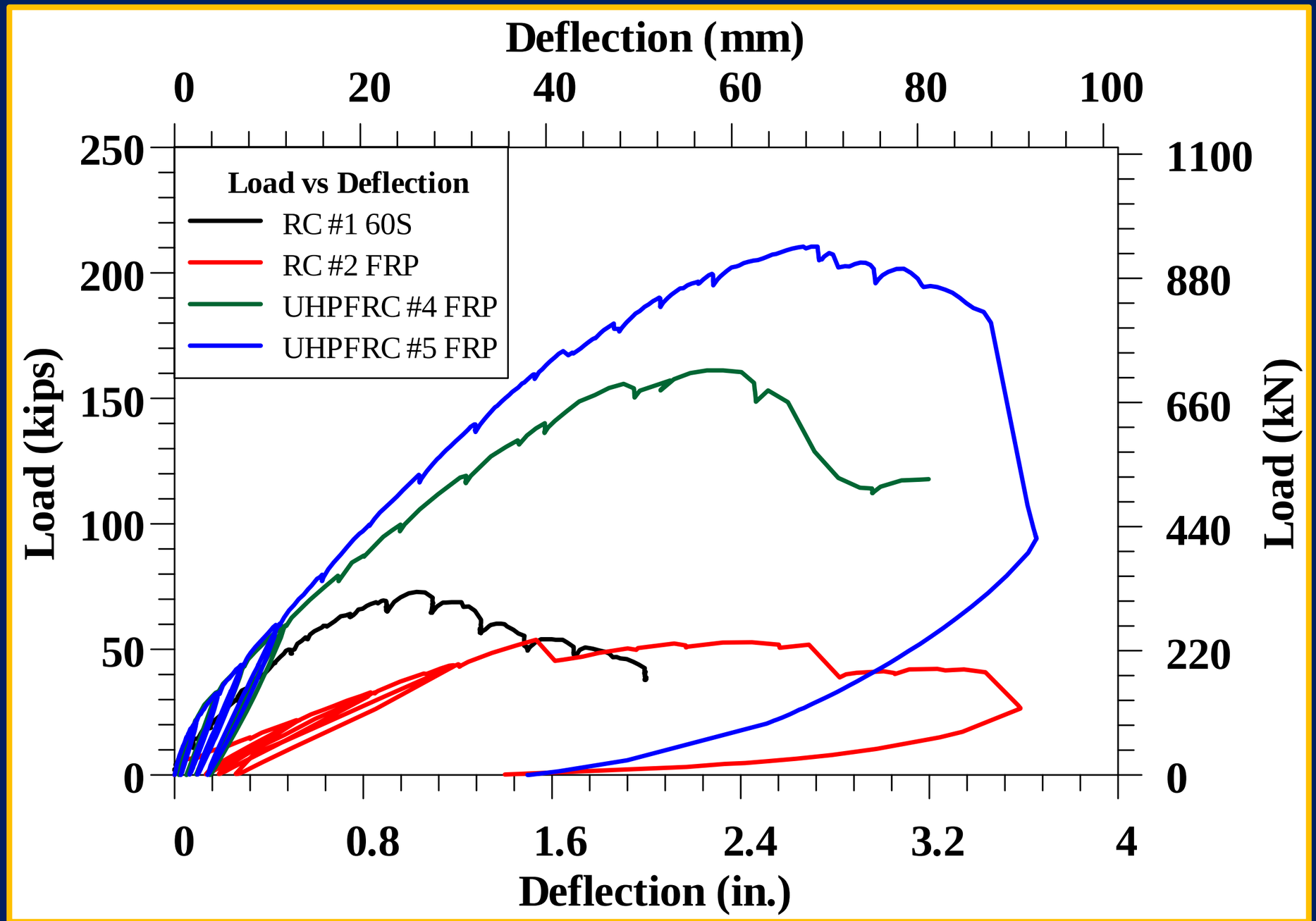
- High tensile strength
- Noncorrosive

Structural Members

- High durability (highly corrosion resistant)
- High flexural/shear strength
- High stiffness
- High ductility
- High resilience

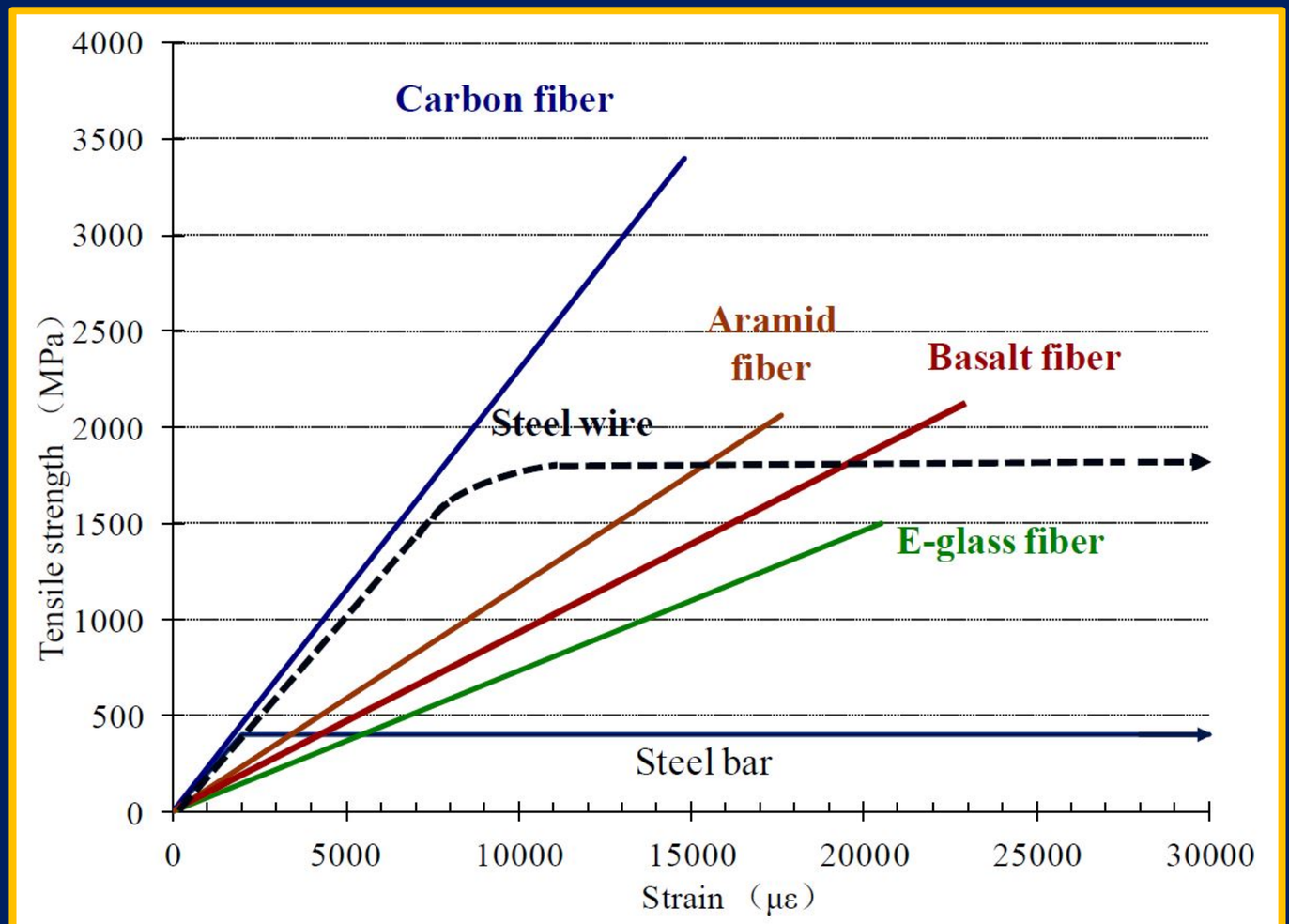
§ High strength, ductility, durability, and resilience cannot happen simultaneously in conventional RC members design by current design approach

Load vs Deflection behavior



Fiber-Reinforced Polymer (FRP) reinforcing bars

- ✓ High-strength FRP bars can reduce reinforcement congestion.
- ✓ Corrosion resistant – exposure to deicing salts, seawater
- ✓ Lighter than steel (~ 75% lighter).



Stress-strain relationship of various FRP bars, Wu et al. 2012

RC #2 beam (Plain Concrete + BFRP bar)

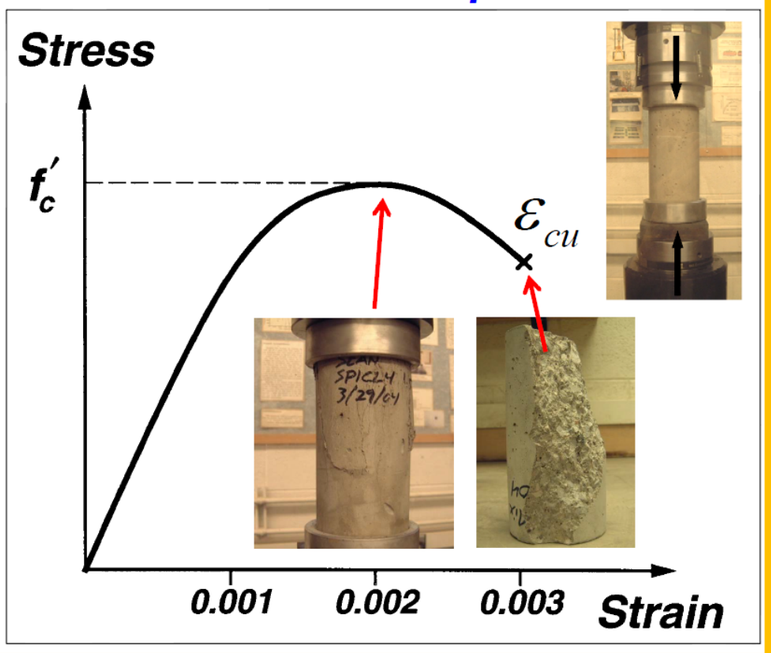
Low rebar axial stiffness → large crack width (lower flexural stiffness) and reduced shear resistance (due to reduced aggregate interlock, compression zone, and dowel strength)

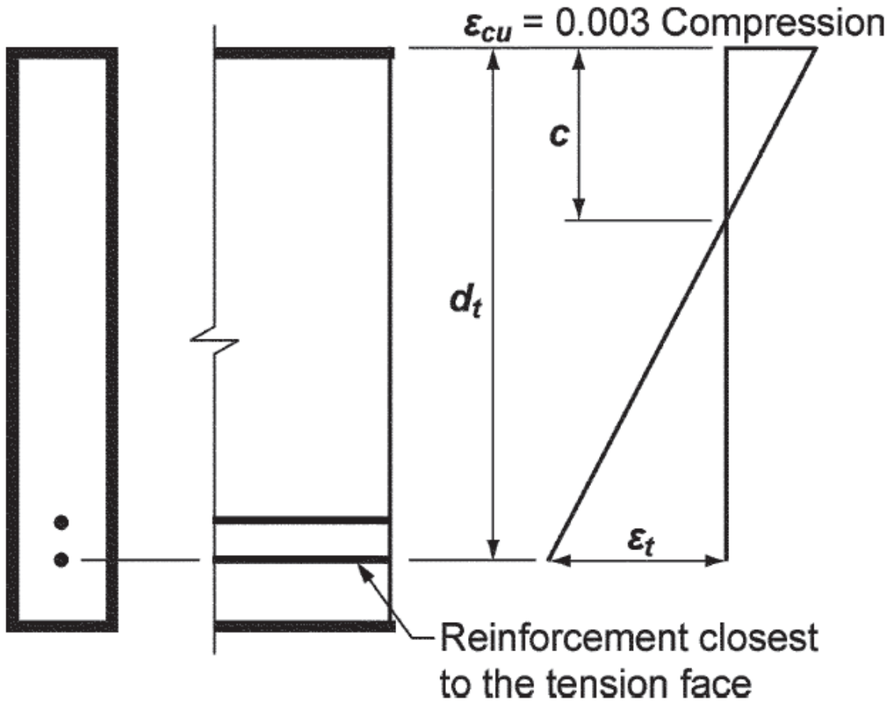
FRP rebars with conventional concrete

- The maximum usable compressive strain of plain concrete (at a post-peak stress of approximately 80% of the peak stress), ε_{cu}, is 0.003 (ACI 318-19 and 2017 AASHTO LRFD).

- ACI 440 (2015) uses a conservative design for concrete members reinforced with FRP bars because both concrete and FRP bars are brittle materials.

Typical Stress-Strain Curve for Concrete in Compression

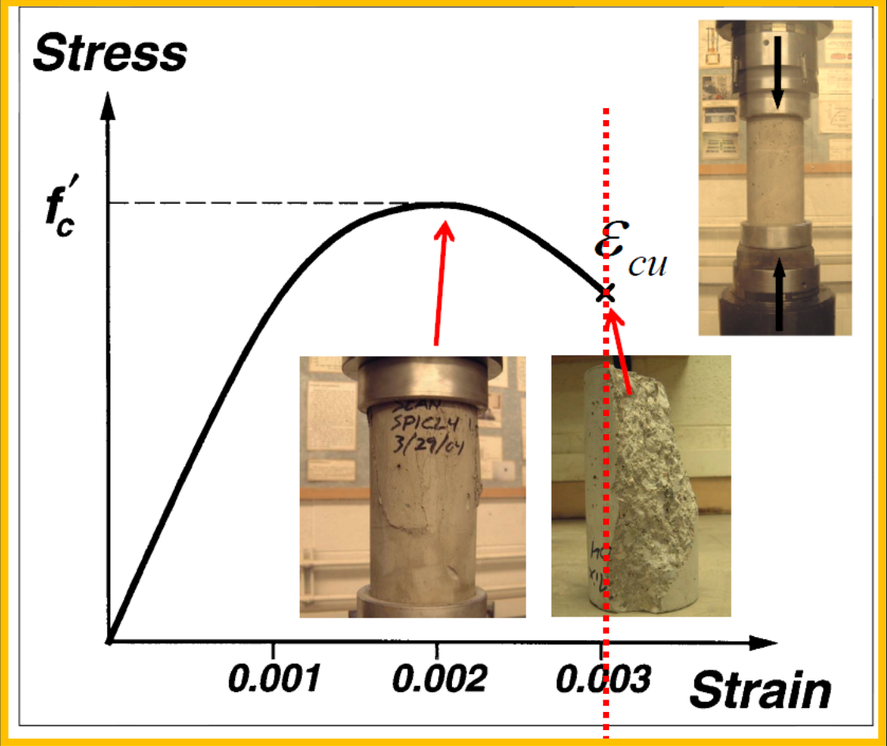


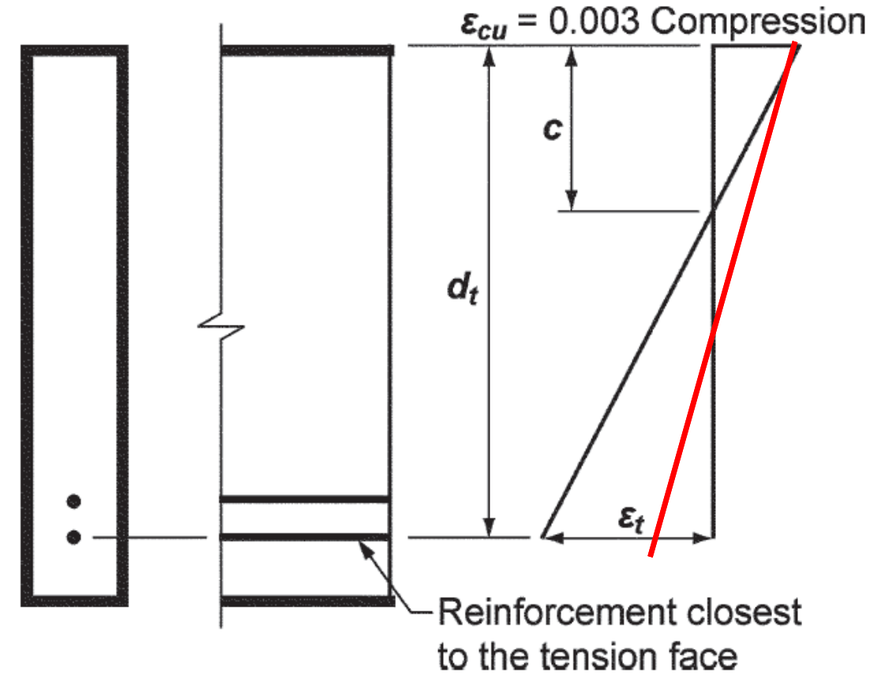


Comparison of typical conventional concrete and UHP-FRC

Properties of Concrete	Conventional Concrete	UHP-FRC
Ultimate Compressive Strength	< 8,000 psi (55 MPa)	18,000 to 30,000 psi (124 to 207 MPa)
Early (24-hour) compressive strength	< 3000 psi (21 MPa)	10,000 – 12,000 psi (69 to 83 MPa)
Flexural Strength	< 670 psi (4.6 MPa)	2,500 to 6,000 psi (17 to 41 MPa)
Shear strength	< 180 psi (1.2 MPa)	> 600 psi (4.1 MPa)
Direct Tension	< 350 psi (2.5 MPa)	up to 1,450 psi (10 MPa)
Rapid Chloride Penetration Test	2000-4000 Coulombs passed	Negligible (< 100 Coulombs passed)
Ductility	Negligible	High ductility
Ultimate Compressive Strain, ε_{cu}	0.003	0.015 to 0.03
Confining	Negligible	High confining capability

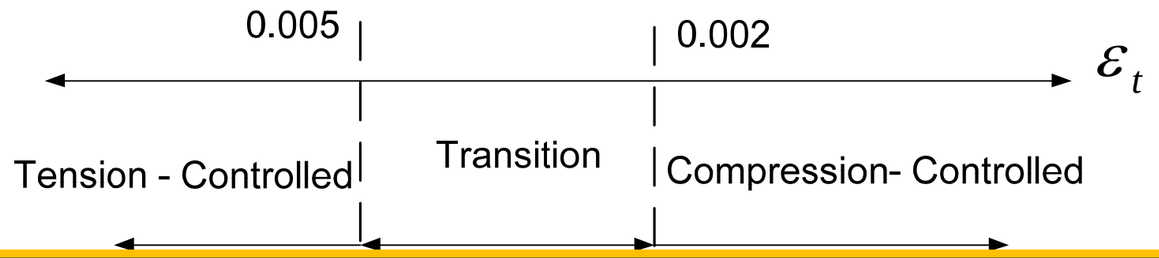
Traditional Design Concept for Reinforced Concrete



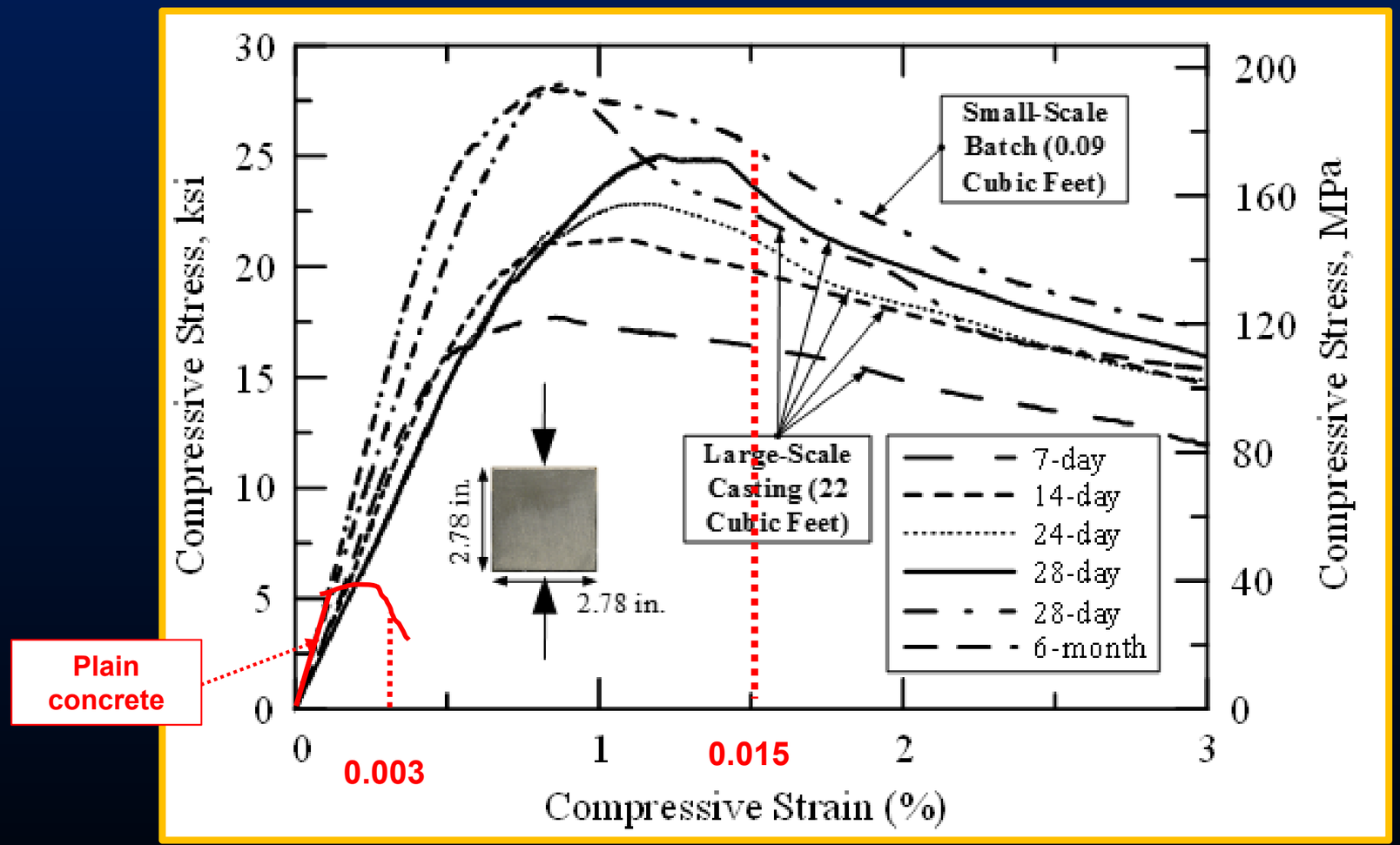


$$\frac{c}{d_t} = \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_t}$$

Value of Ultimate Compressive Strain in concrete (ε_{cu}) = 0.003



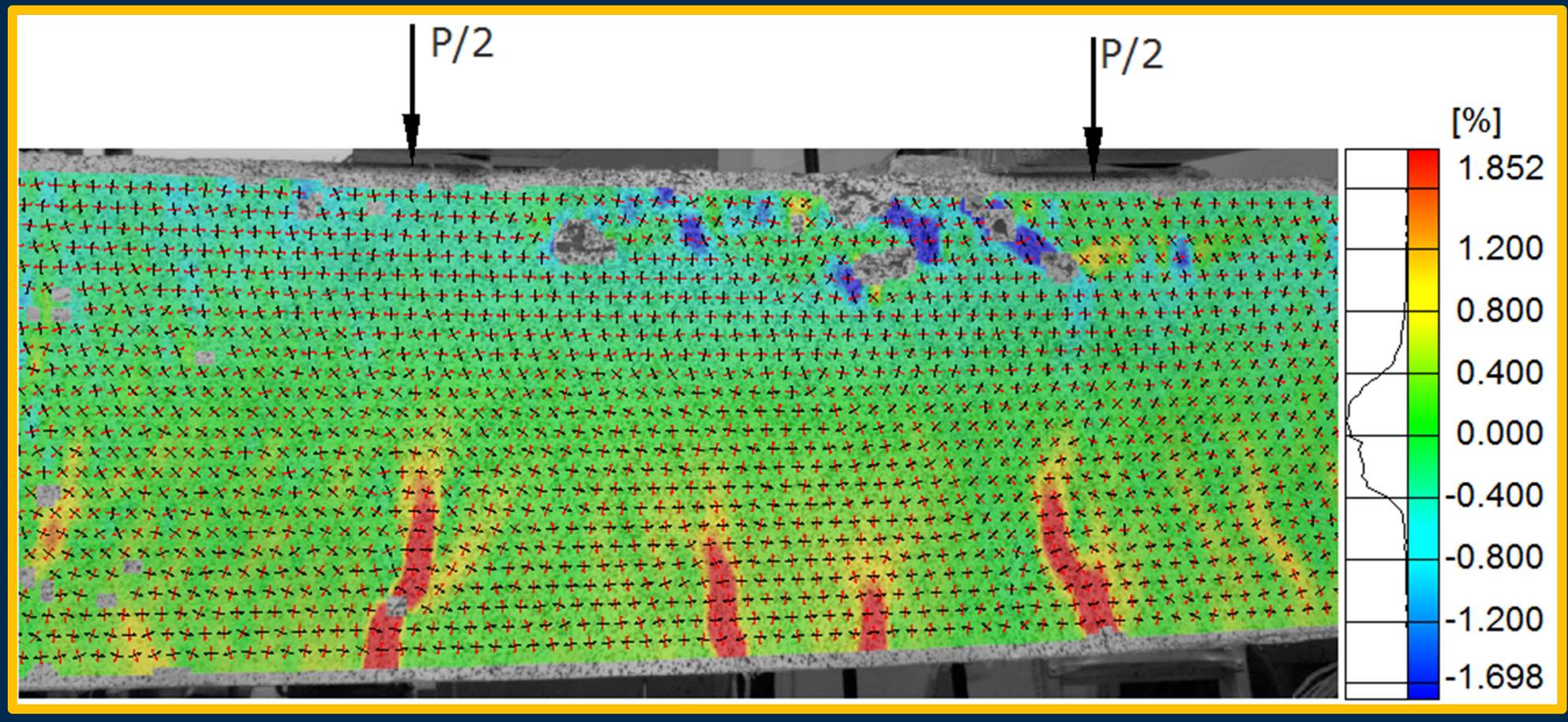
Compressive Ductility of UHP-FRC



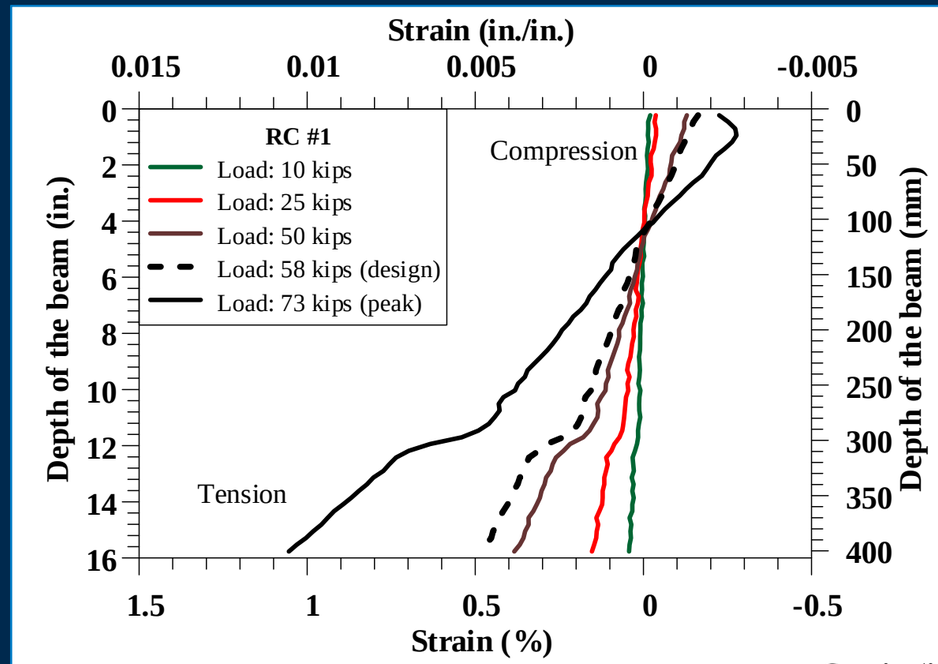
Aghdasi, P., Heid A. E., and Chao, S.-H. (2016). “Developing Ultra-High-Performance Fiber-Reinforced Concrete for Large-Scale Structural Applications,” *ACI Materials Journal*, V. 113, No. 5, September-October 2016, pp. 559-570.

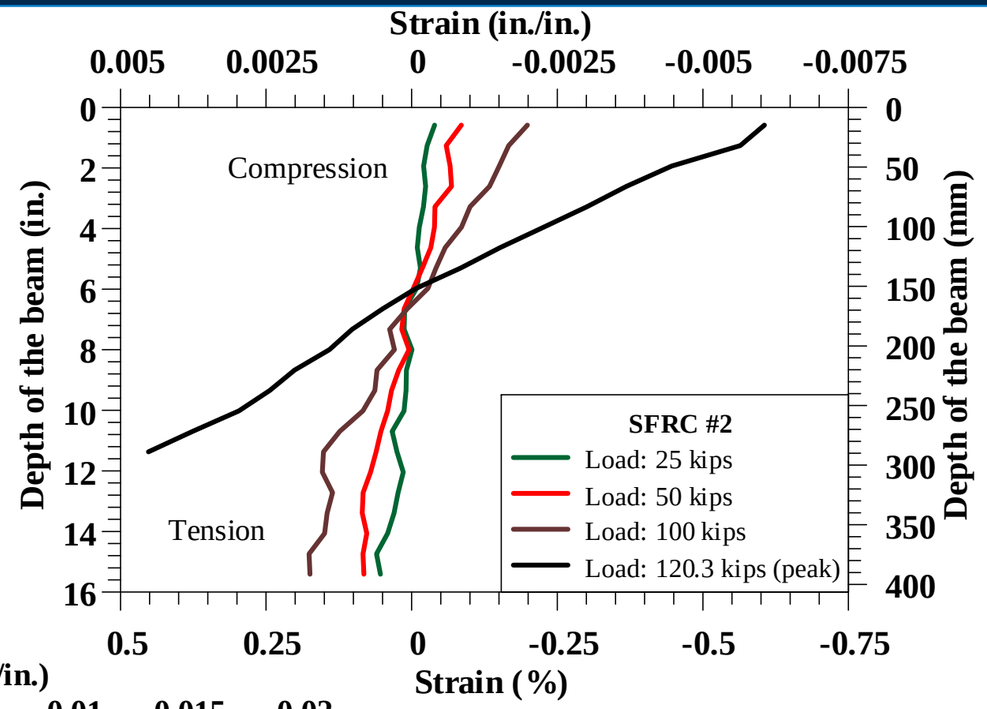
Strains of UHP-FRC beam measured by high resolution digital image correlation (DIC) technology

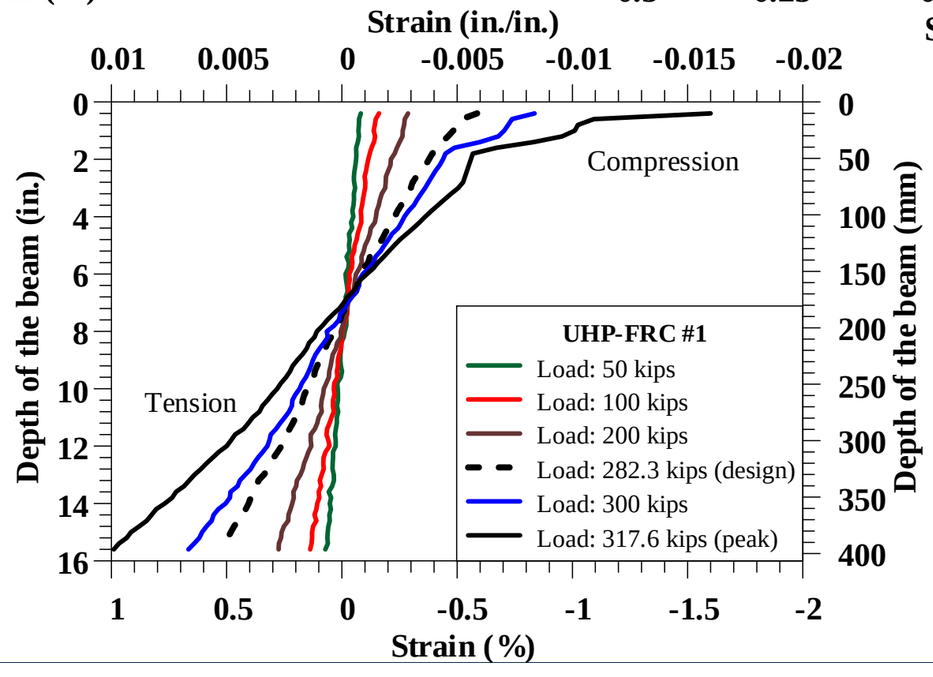
Full-field concrete longitudinal strain (ε_x) along moment region for UHP-FRC#1 at an applied load of 317.7 kips (peak load)



ε_{cu} of Plain Concrete, FRC, and UHP-FRC

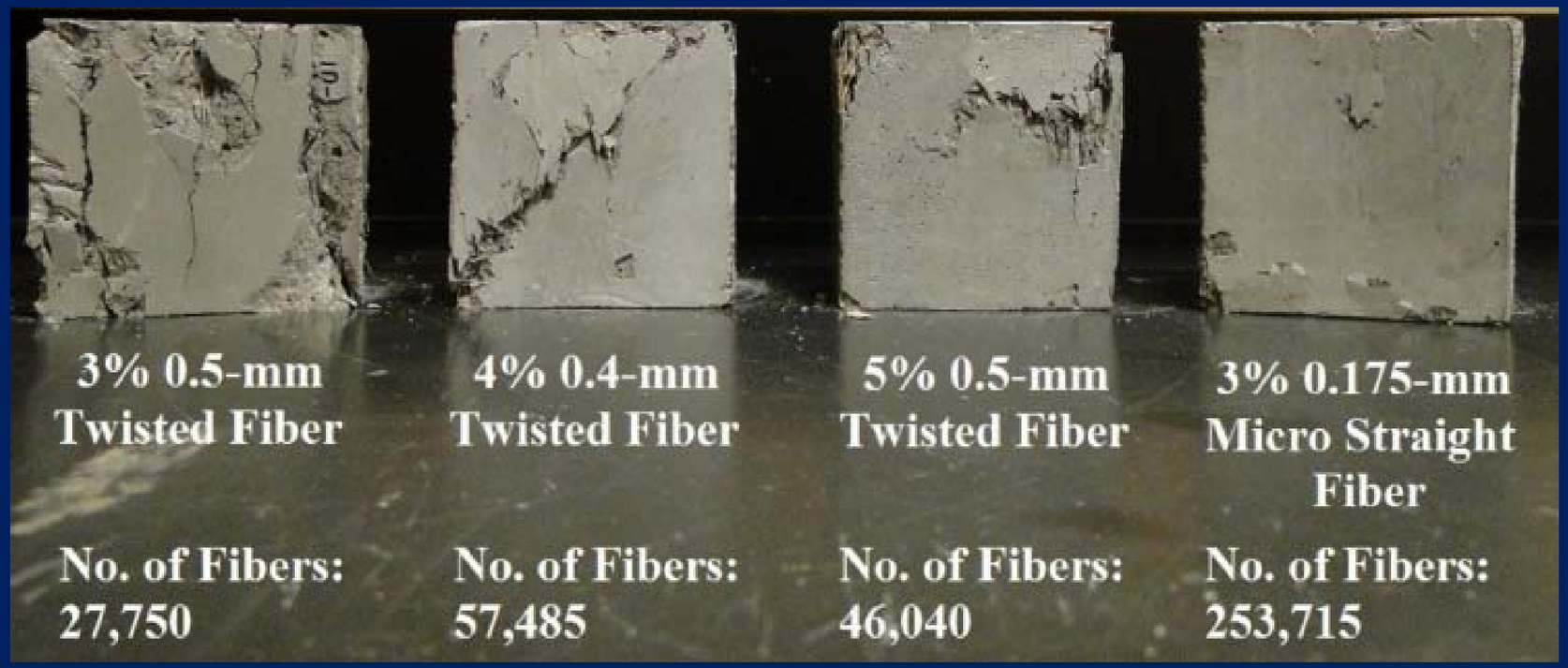






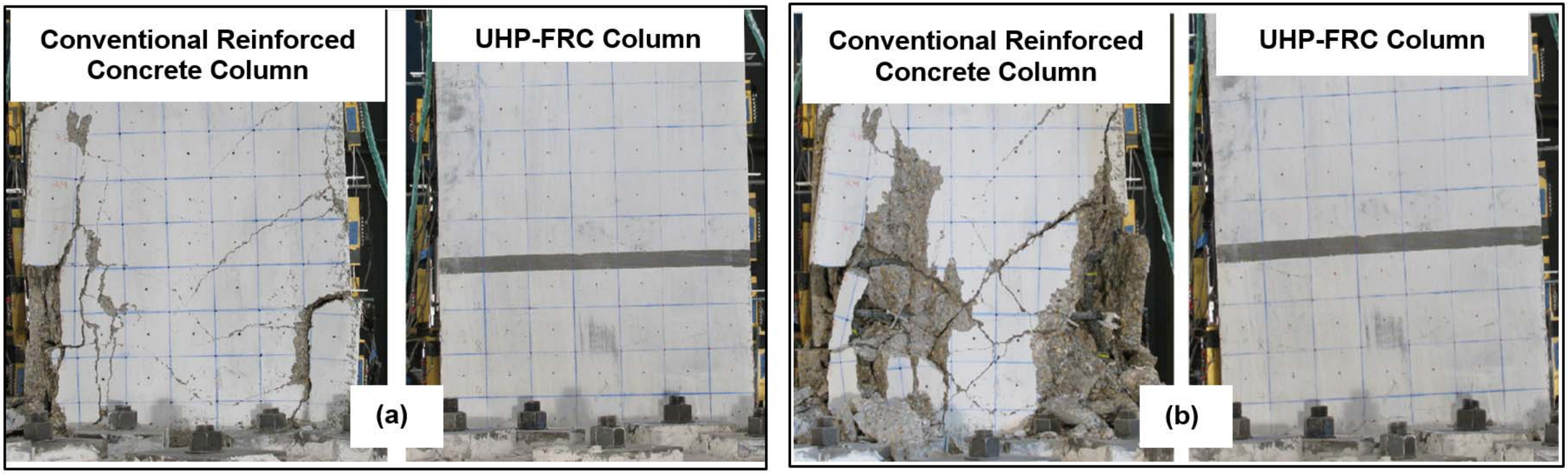
Ultra-High-Performance Fiber-Reinforced Concrete (UHP-FRC): High Compressive Strength & Ductility

Plain concrete



UHP-FRC

Full-scale Column Experimental Results (NSF Award No. 1041633)

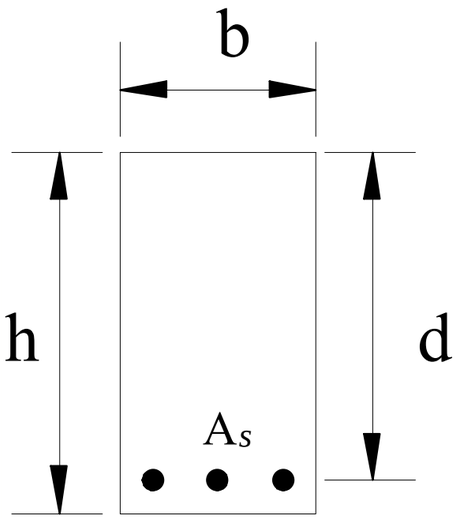


Experimental test results (a) at 2.75% drift ratio and (b) at 5.25% drift ratio (Palacios et al., 2017)

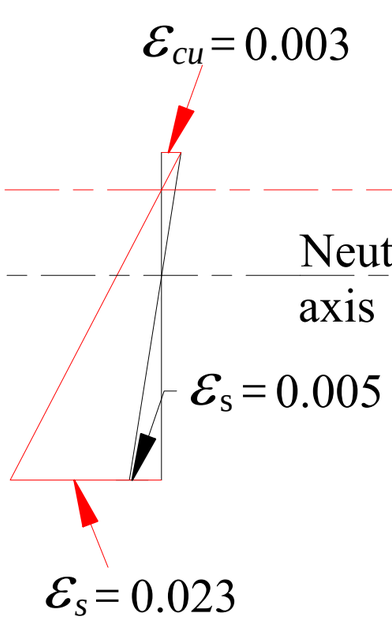
Note: The conventional RC column was designed based on ACI 318-14's seismic provisions.

Effect of UHP-FRC's High Compressive Strain and Strength on A Flexural Member's Curvature Ductility

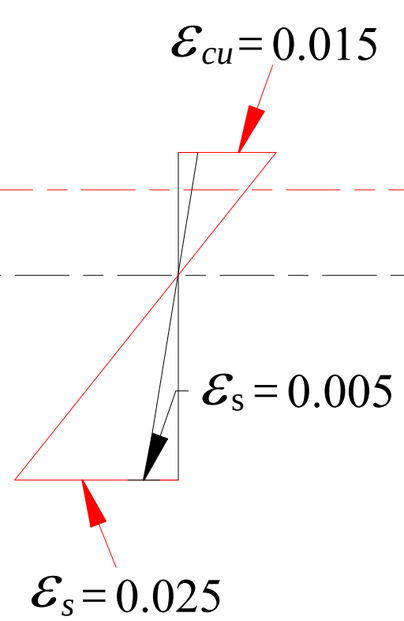
ε_{cu} is approximately 0.015, five times of plain concrete's ε_{cu}



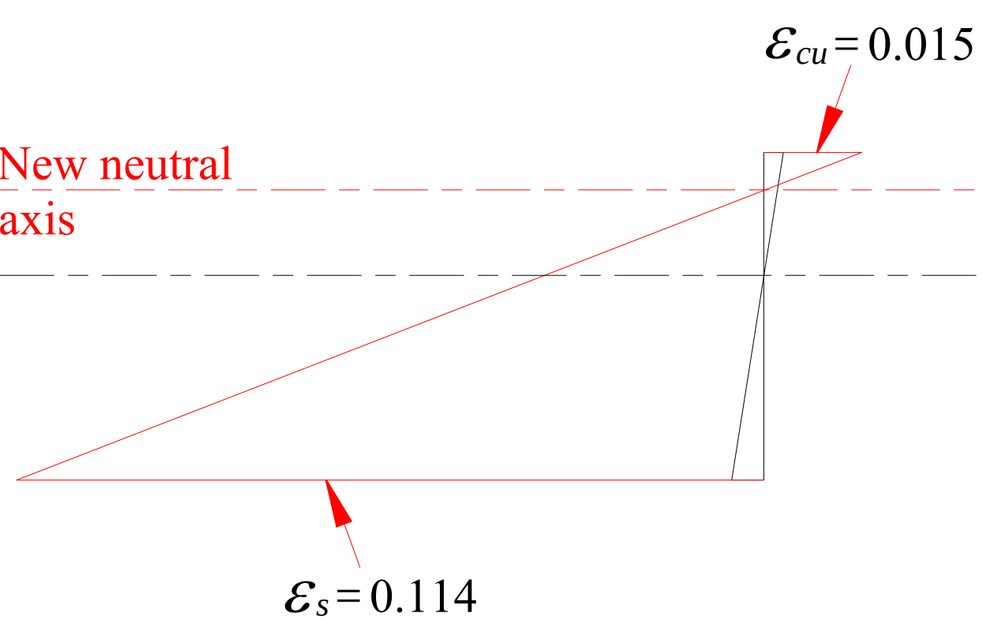
Singly reinforced section



Strain distribution for increased compressive strength



Strain distribution for increased compressive strain



Strain distribution for combined increased compressive strength and strain

New Design Concept : Ductile-Concrete Strong-Reinforcement concept (DCSR design concept)

UHP-FRC (ductile element) + FRP bars (elastic element)

Opposite to conventional RC members

Steel bars (yielding element) + concrete (brittle element, crushed)

Ductile-Concrete Strong-Reinforcement concept (Summary)

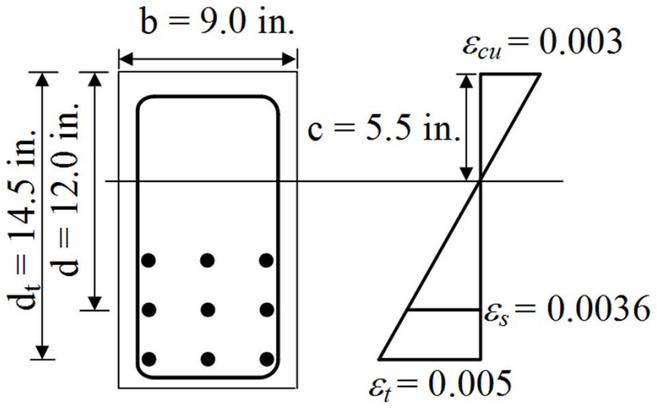
- Using high reinforcement ratio of high-strength FRP bars can achieve high structural efficiency (i.e., high flexural strength with a relatively smaller cross-section).

- Keeping rebars elastic can minimize deterioration of bond strength, limit the crack width (thereby maintaining the shear strength and stiffness), and provide restoring force for reducing residual deformation (i.e., self-centering capability).

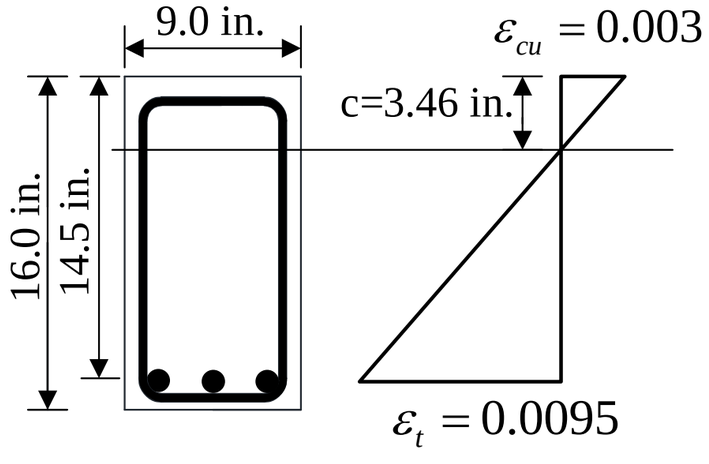
- The high shear strength of UHP-FRC allows partial or total elimination of shear reinforcement.

- FRP bars + UHP-FRC → a highly durable structural member.

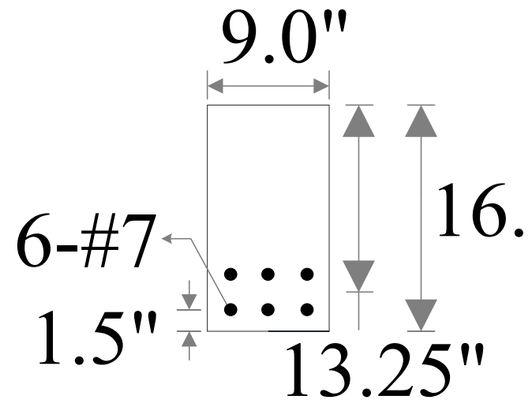
Strain profile and Design Sections



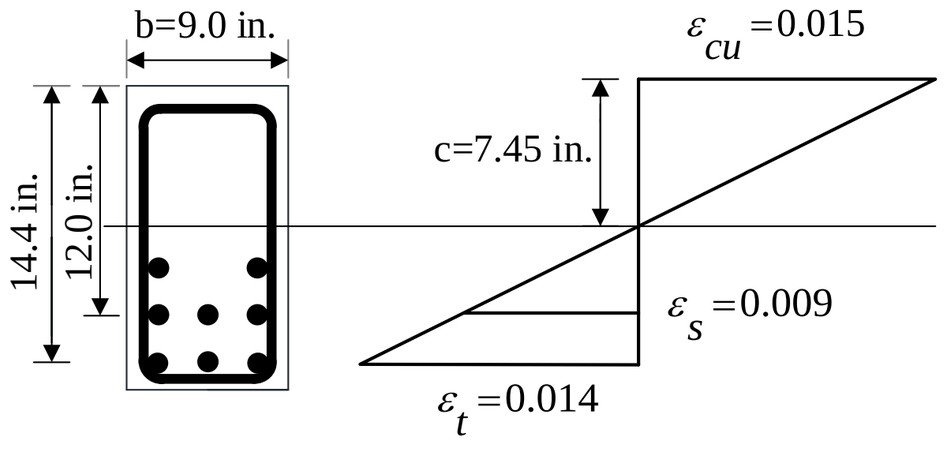
RC #1 (9-#5 Gr. 60 mild steel rebars)



RC #2 (3-#7 BFRP bars)



UHP-FRC #4 (6-#7 BFRP bars; no shear reinforcement)

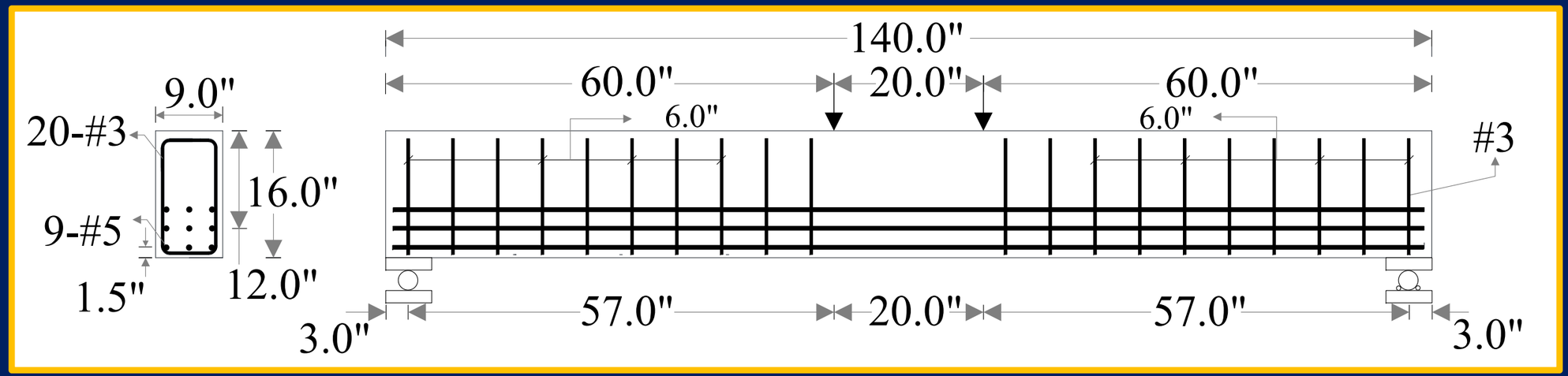


UHP-FRC #5 (8-#8 BFRP bars)

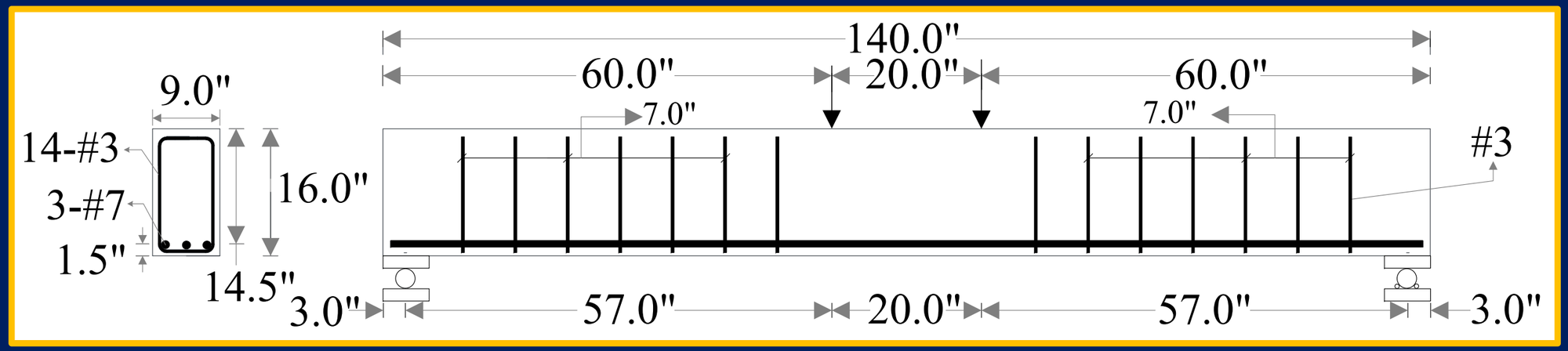
The BFRP (baslt) bars had an ultimate tensile strength of approximately 125 ~ 150 ksi and an ultimate tensile strain of 0.017 to 0.025.

Previous test results : Monotonic Loading

Geometry and reinforcement details



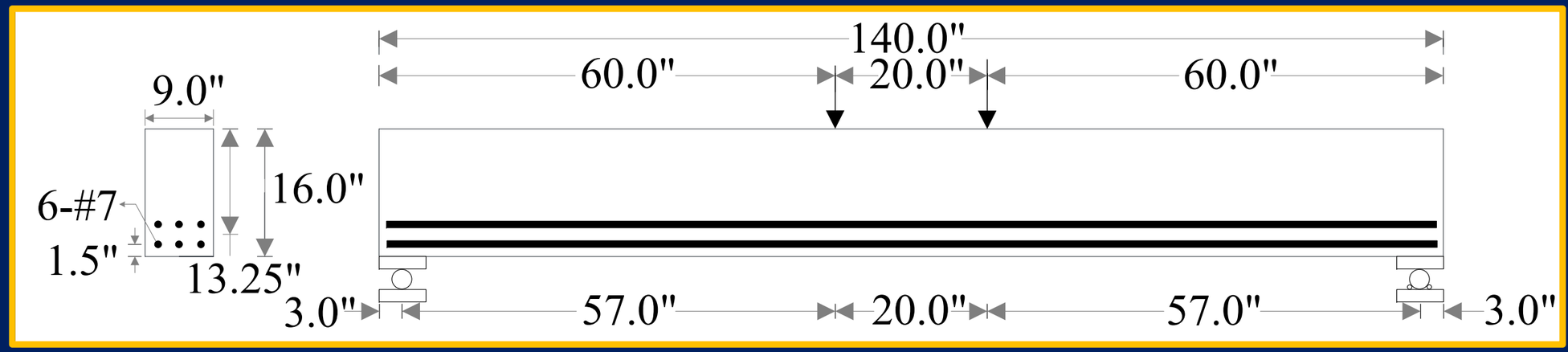
Beam RC #1 (plain concrete +Grade 60 longitudinal rebar)



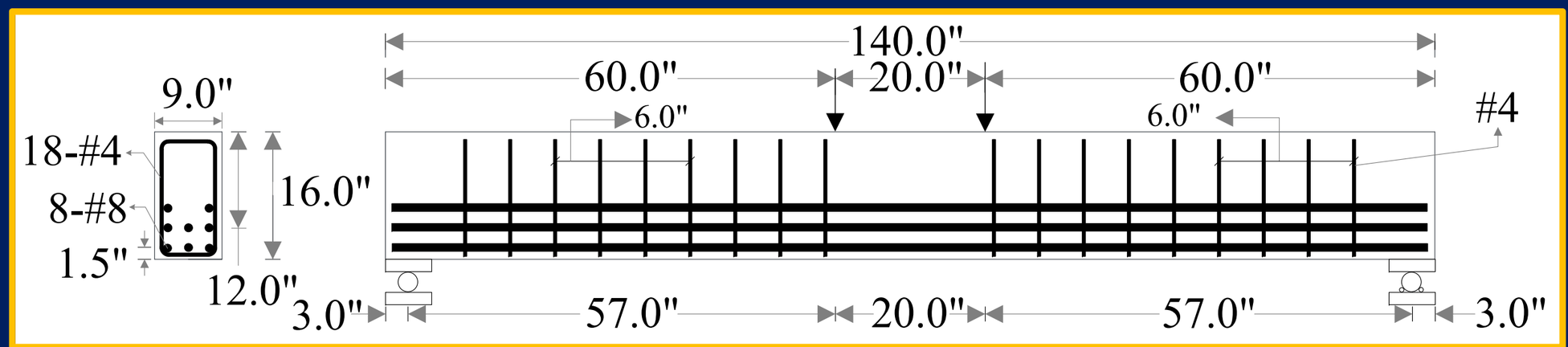
Beam RC #2 (plain concrete + BFRP longitudinal rebar)

Previous test results : Monotonic Loading

Geometry and reinforcement details

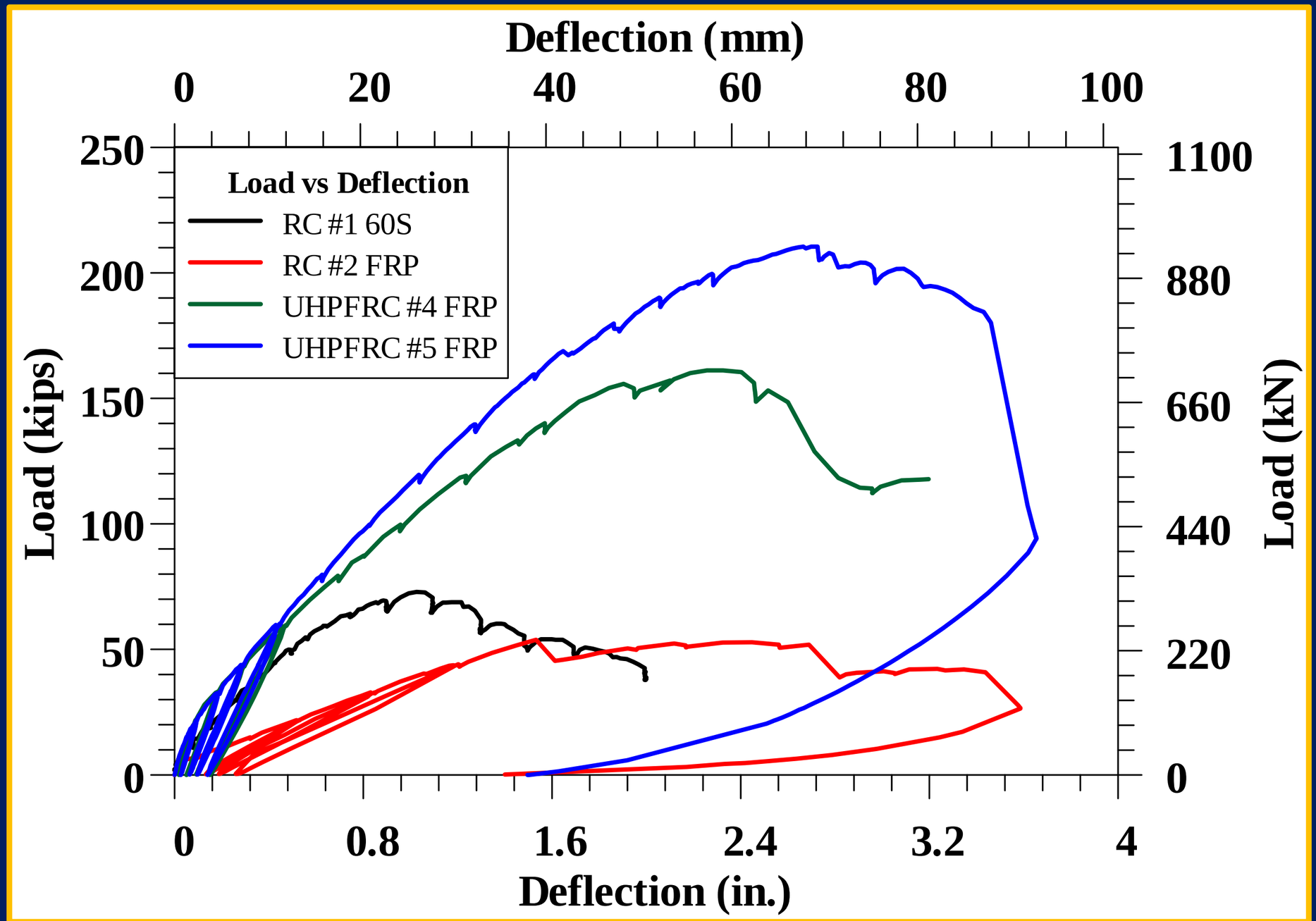


Beam UHP-FRC #4 (BFRP longitudinal rebar)



Beam UHP-FRC #5 (BFRP longitudinal rebar)

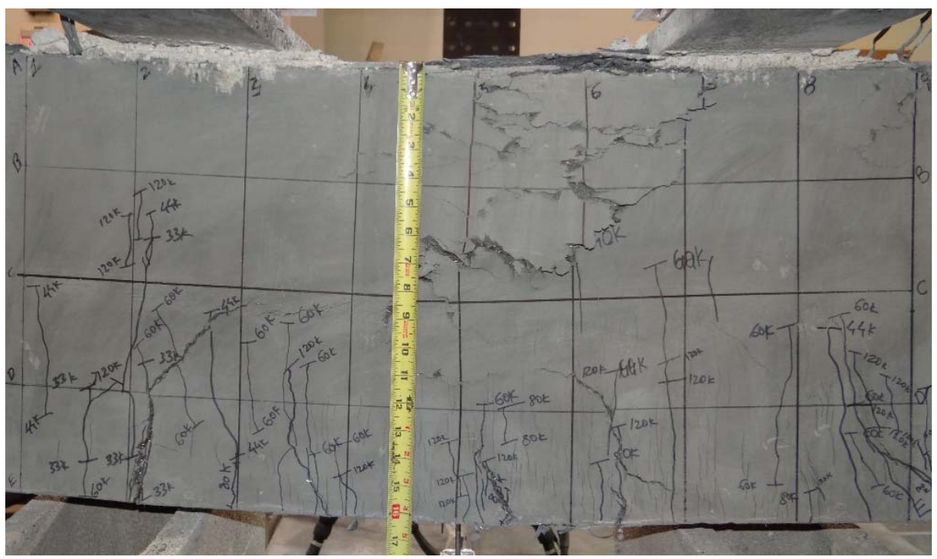
Load vs Deflection behavior



Cracking patterns at the end of test

RC #2 beam (Plain Concrete + BFRP bar)

RC #1 beam (Grade 60 steel)



UHP-FRC #5 beam (UHP-FRC+ BFRP bar)

Ductile-Concrete Strong-Reinforcement concept – Cyclic Testing

Design Summary

Specimen	Effective depth (d), in. (mm)	Width of compression face (b), in. (mm)	ρ (%)	Reinforcement type	Fiber type	Effective span, in. (mm)
UHP-FRC #1	4.311 (109)	6 (152)	15.5	MMFX	Steel	49.5 (1257)
UHP-FRC #2	6.375 (162)	6 (152)	13.9	GFRP	Steel	49.5 (1257)
UHP-FRC #3	5.35 (136)	8 (203)	14.8	BFRP	UHMW-PE	34 (864)
UHP-FRC #4	5.35 (136)	8 (203)	14.8	BFRP	Steel	34 (864)

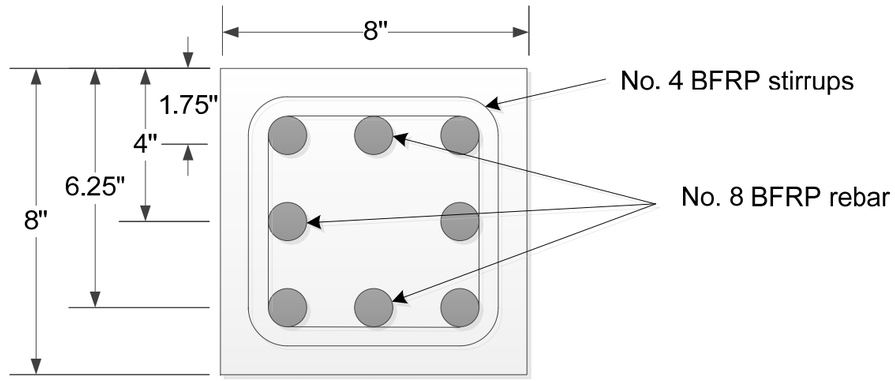
Reinforcement Details

Reinforcement type	Diameter in. (mm)	Tensile strength ksi (MPa)
MMFX (Micro Composite Steel) Grade 100 (ASTM 1035)	1.125 (29)	100 (690)
GFRP (Glass Fiber-Reinforced Polymer)	0.75 (19)	90 (620)
BFRP (Basalt Fiber-Reinforced Polymer)	1.00 (25)	147 (1014)

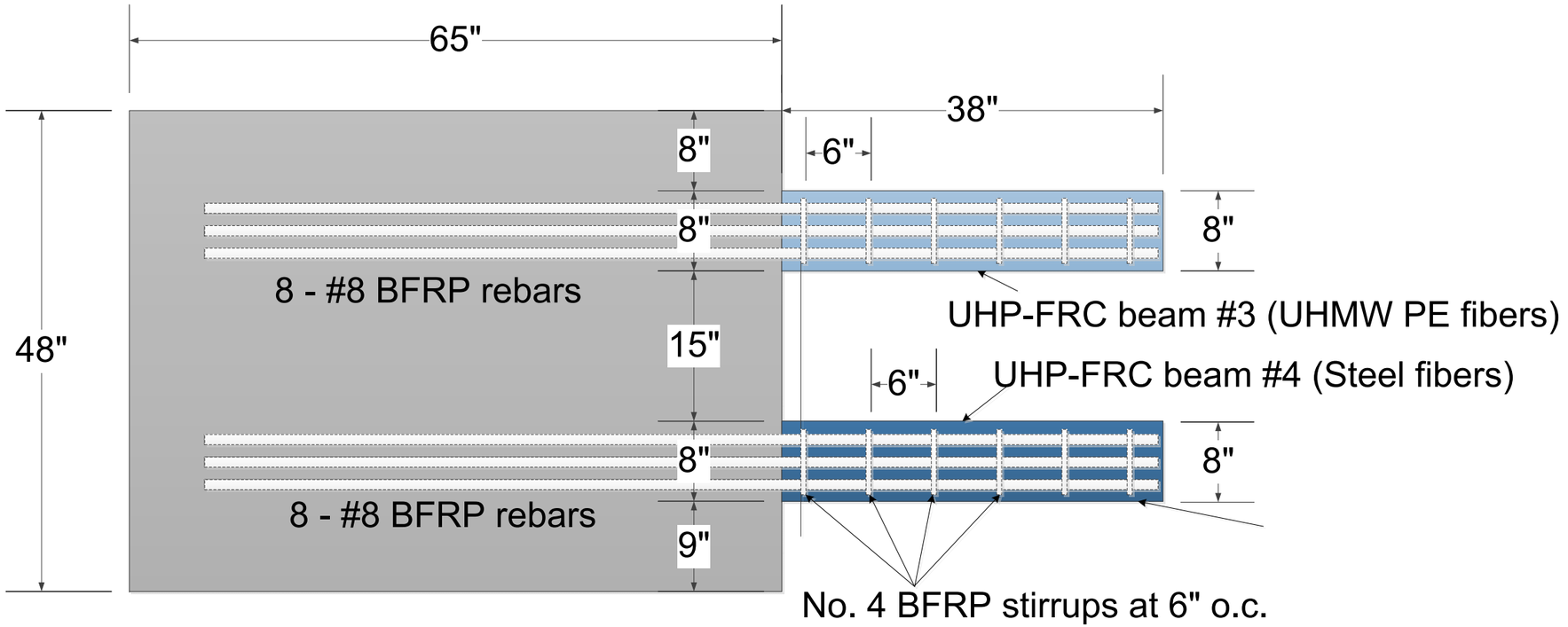
Ductile-Concrete Strong-Reinforcement concept – Cyclic Testing : Fibers used

	Length (mm)	Diameter (mm)	Tensile Strength (ksi)
Micro Steel Fibers	13	0.12	313
UHMW Polyethylene Fibers	13	0.0015	375

UHP-FRC Beam #3 and #4

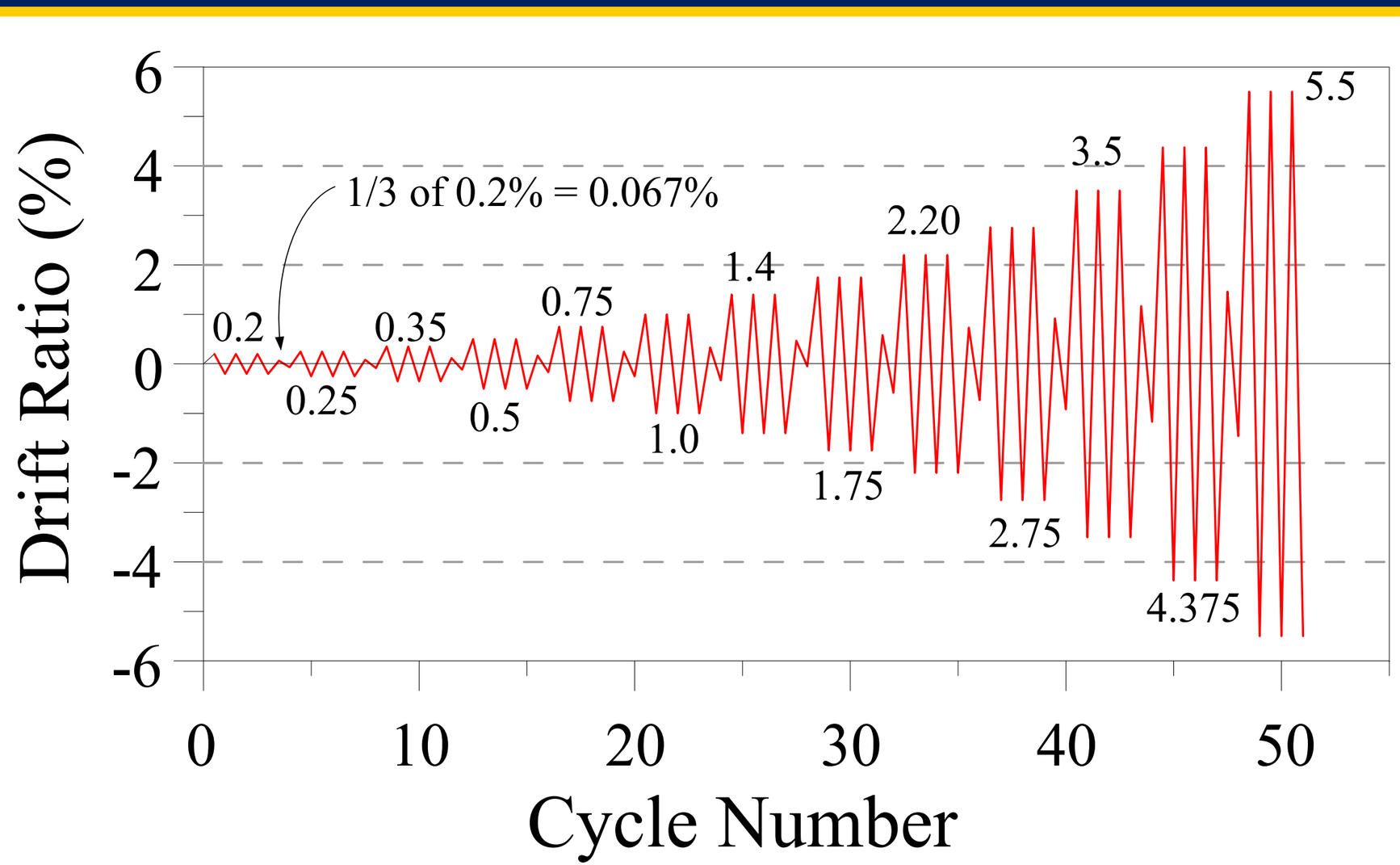


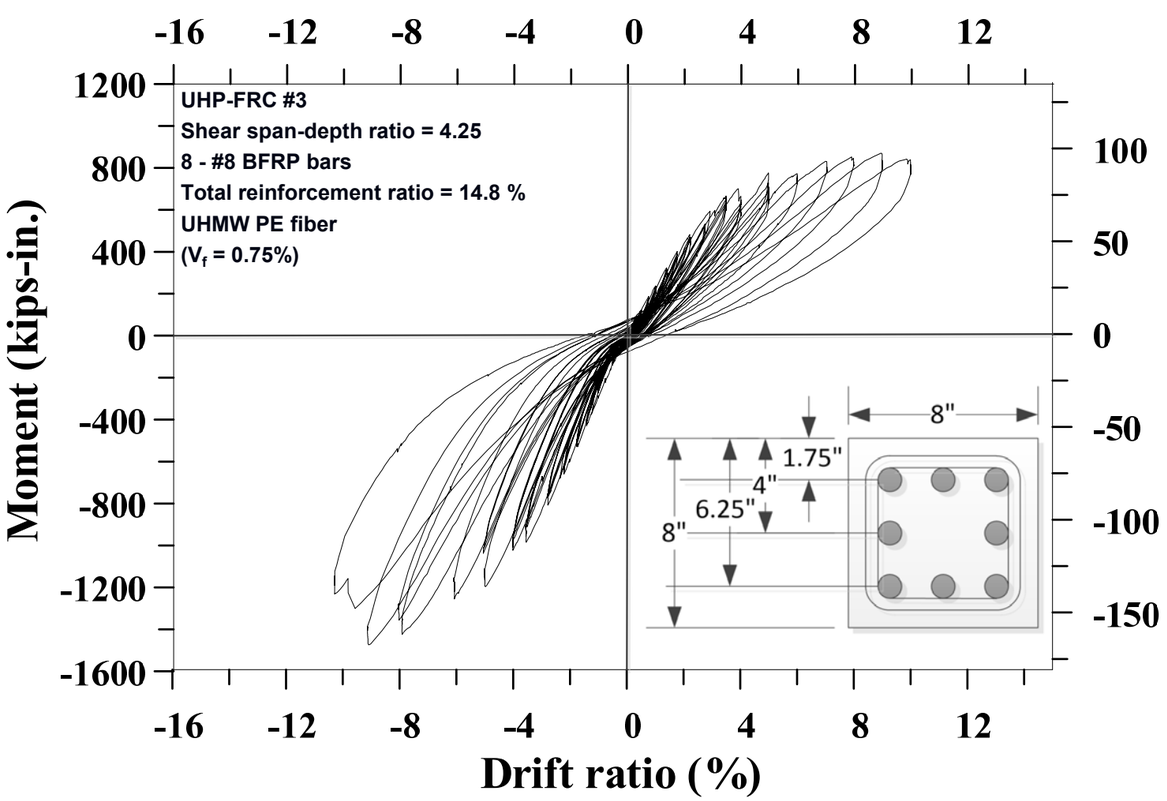
Cross section of beam UHP-FRC #3 and UHP-FRC #4 (BFRP)



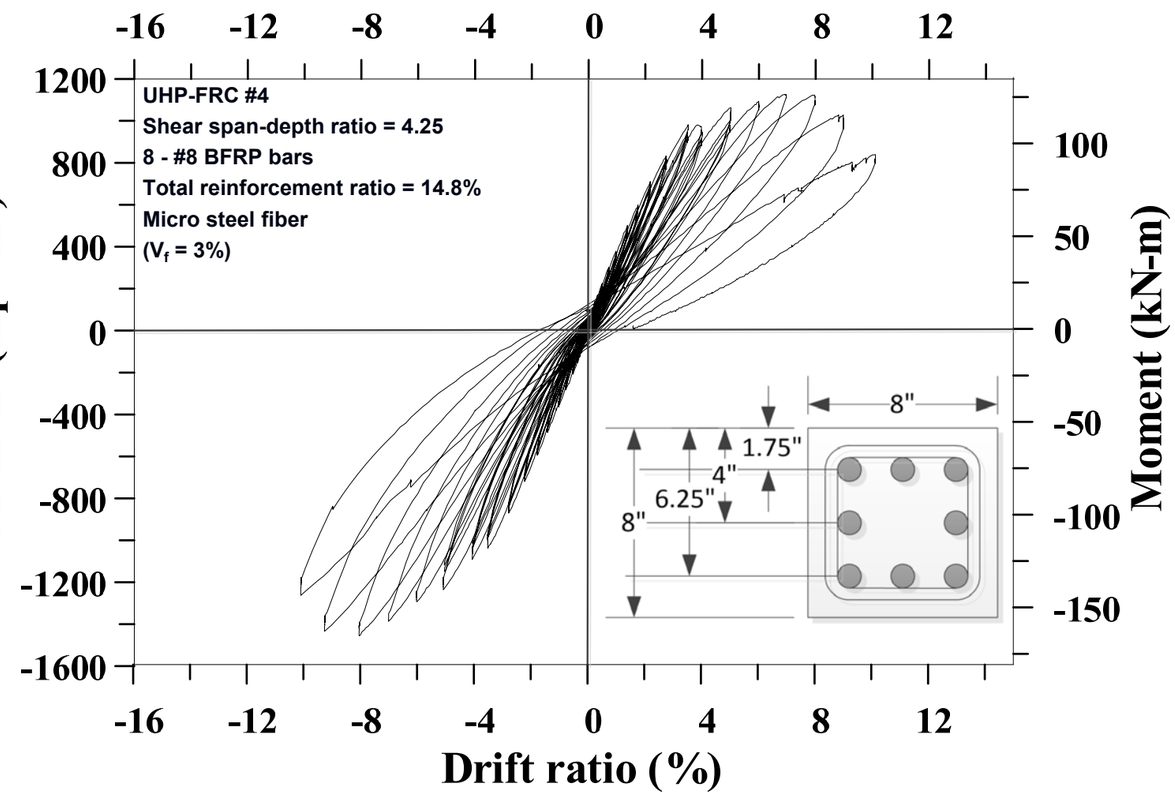
Detailed side view of the specimen showing specimens UHP-FRC #3 and UHP-FRC #4

Loading Protocol

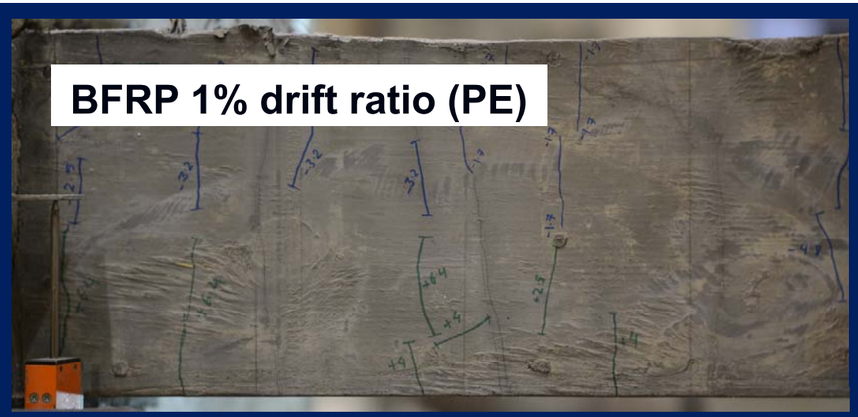


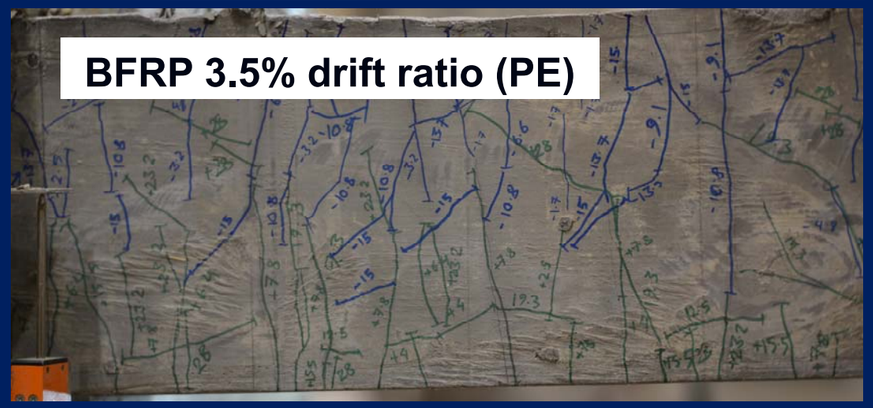


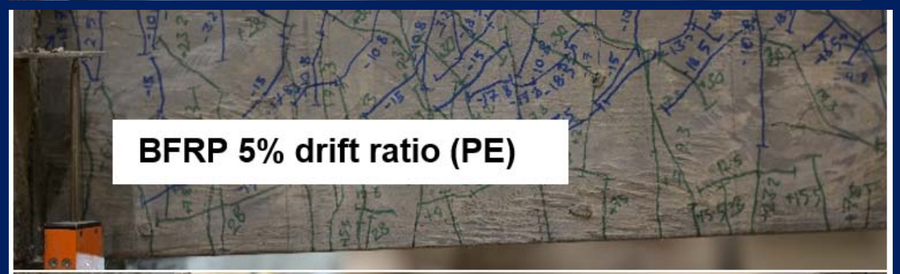
Moment vs Drift ratio for UHP-FRC #3 with UHMW PE fibers (BFRP)

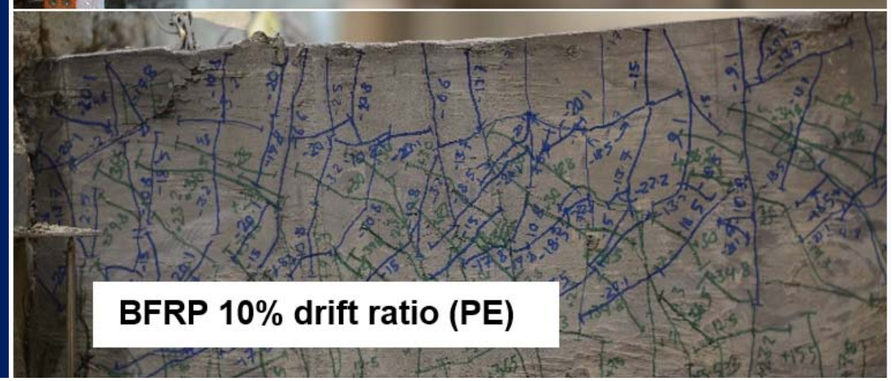


Moment vs Drift ratio for UHP-FRC #4 with steel fibers (BFRP)

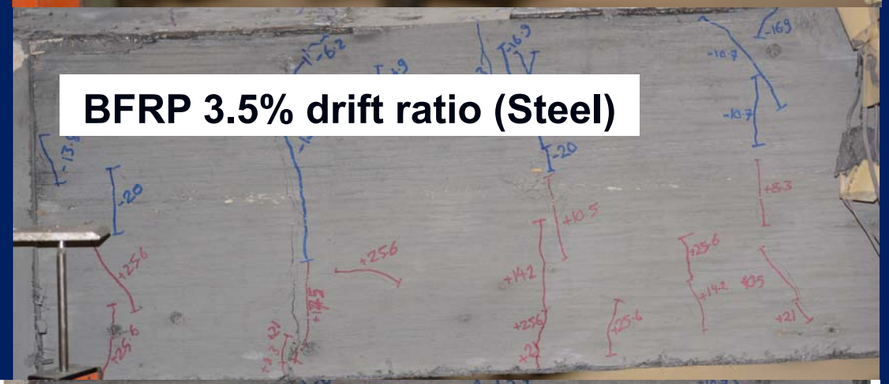

BFRP 1% drift ratio (PE)

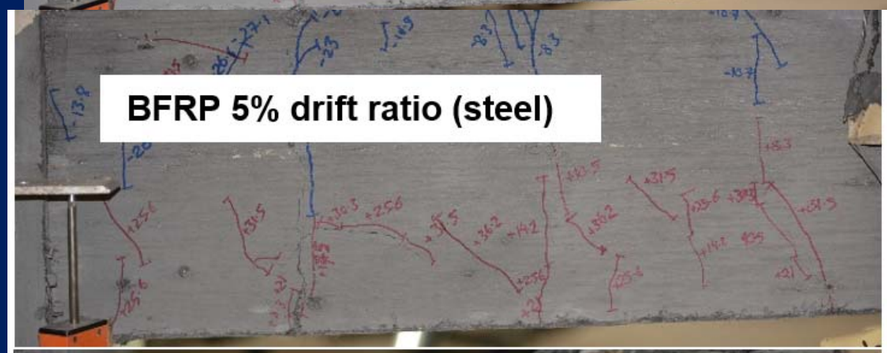

BFRP 3.5% drift ratio (PE)

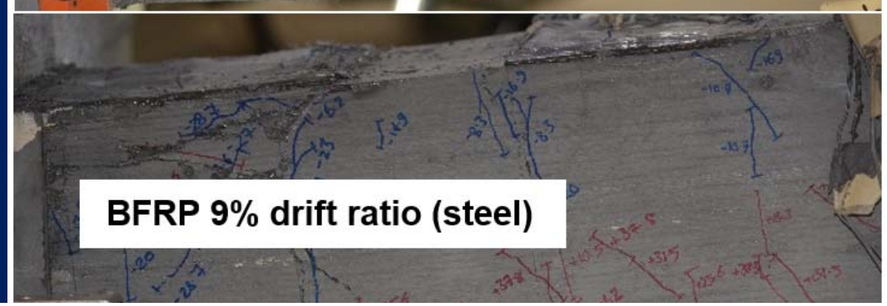

BFRP 5% drift ratio (PE)


BFRP 10% drift ratio (PE)


BFRP 1% drift ratio (Steel)


BFRP 3.5% drift ratio (Steel)


BFRP 5% drift ratio (steel)


BFRP 9% drift ratio (steel)

UHP-FRC #3

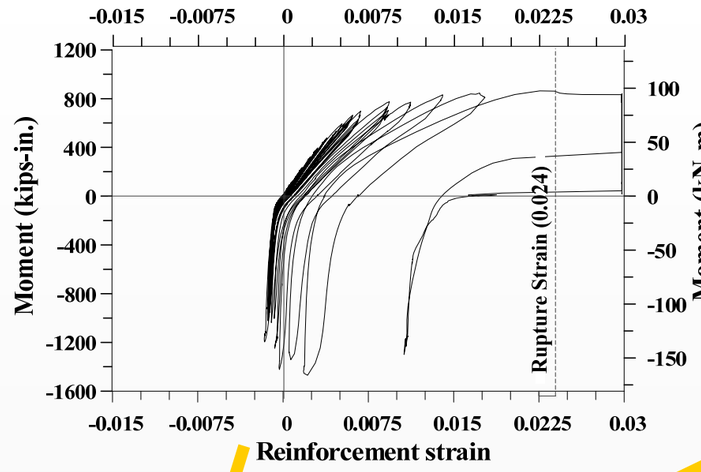
Shear span-depth ratio = 4.25

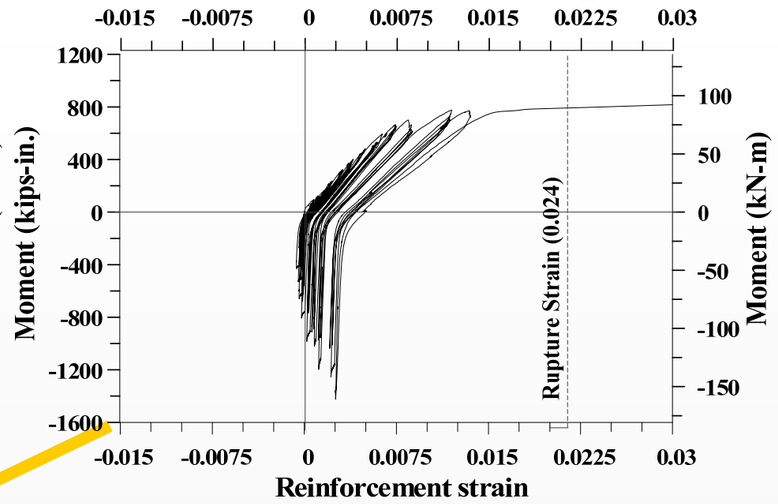
8 - #8 BFRP bars

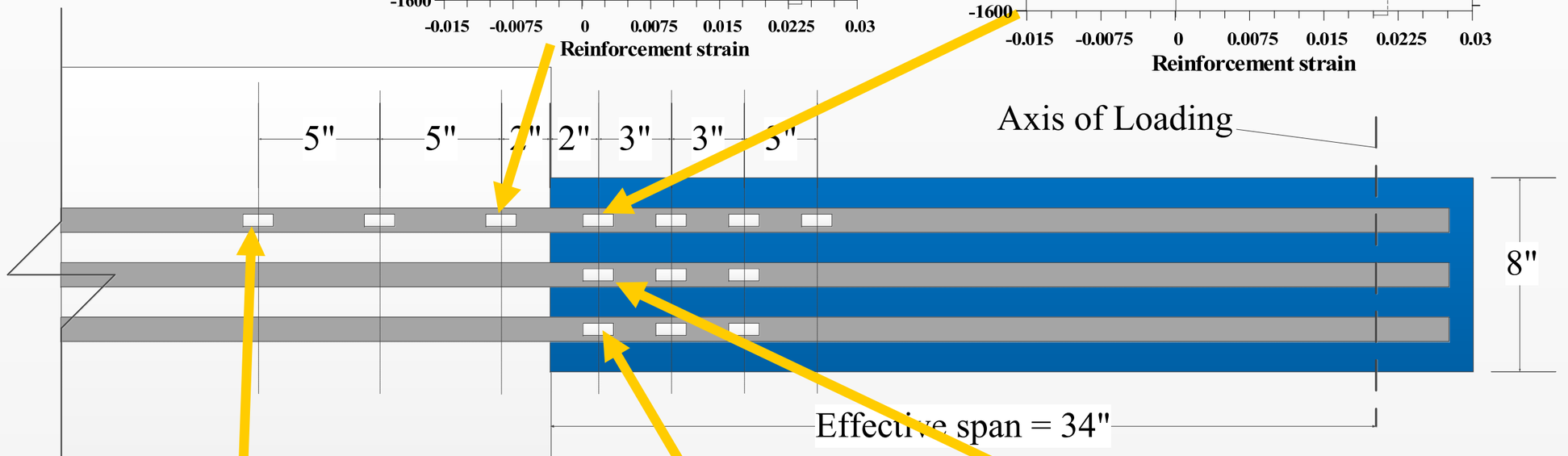
Total reinforcement ratio = 14.8 %

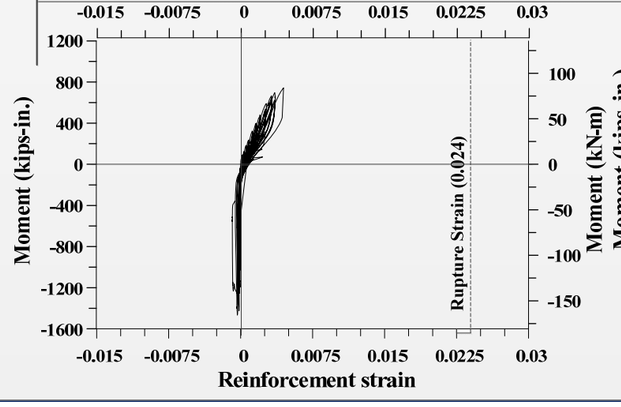
UHMW PE fiber

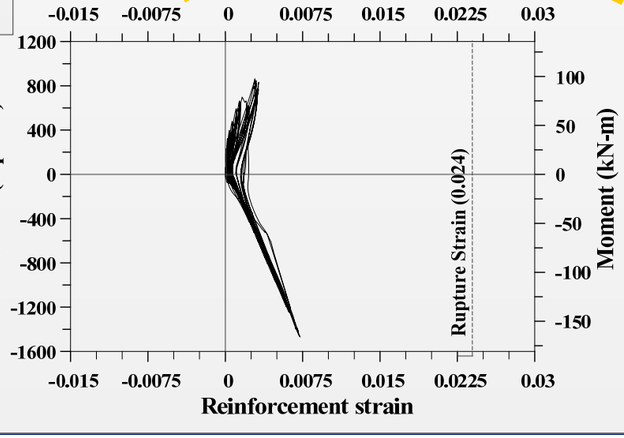
(V_f = 0.75%)

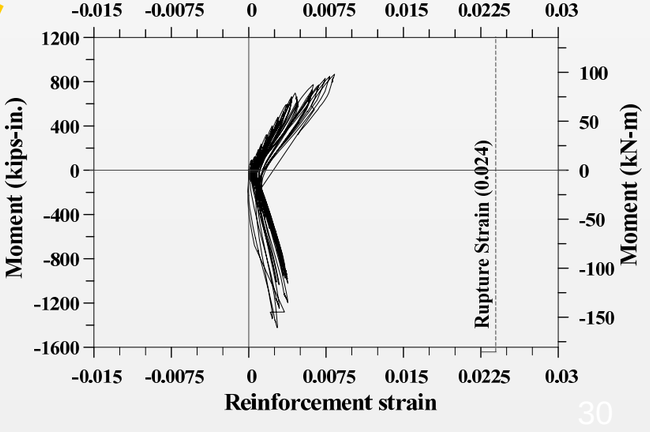












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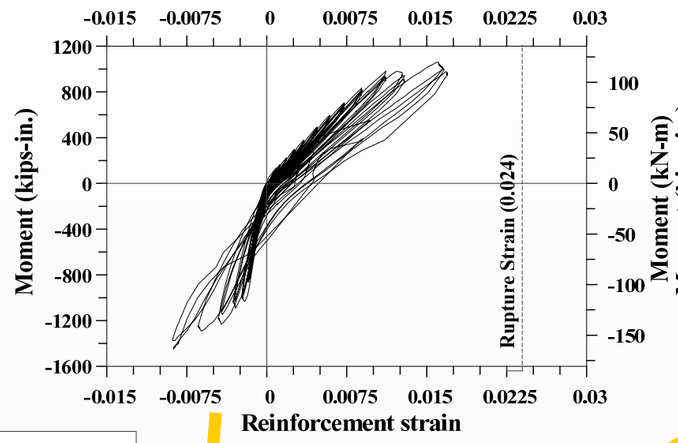
UHP-FRC #4

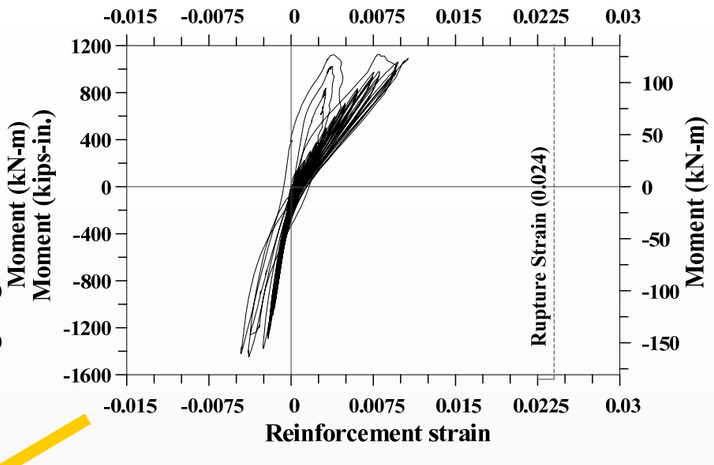
Shear span-depth ratio = 4.25

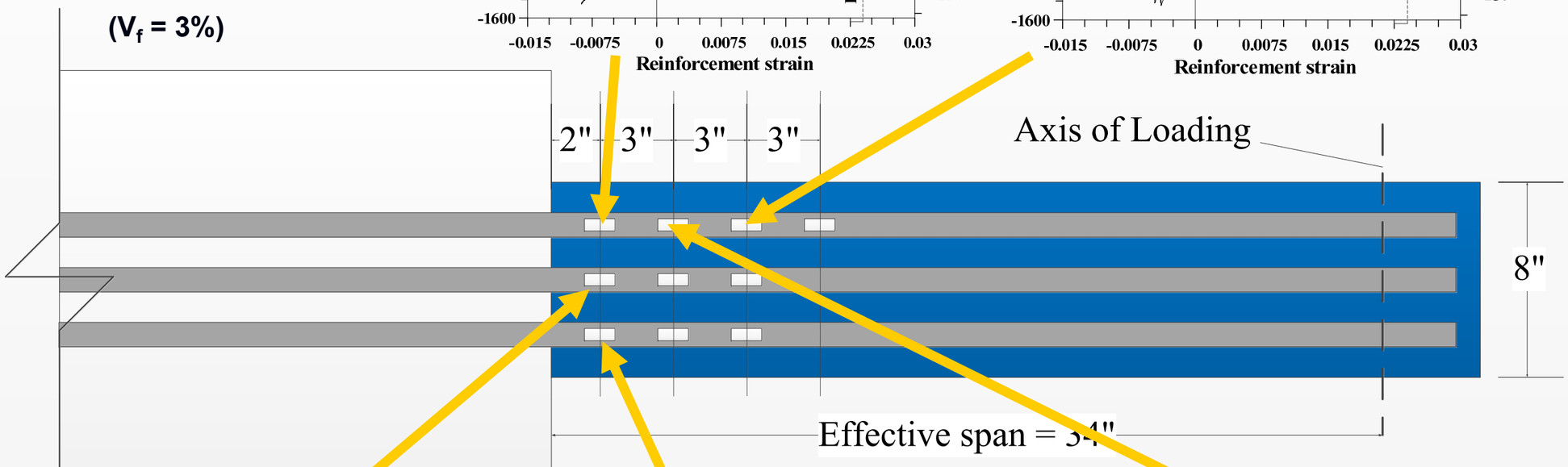
8 - #8 BFRP bars

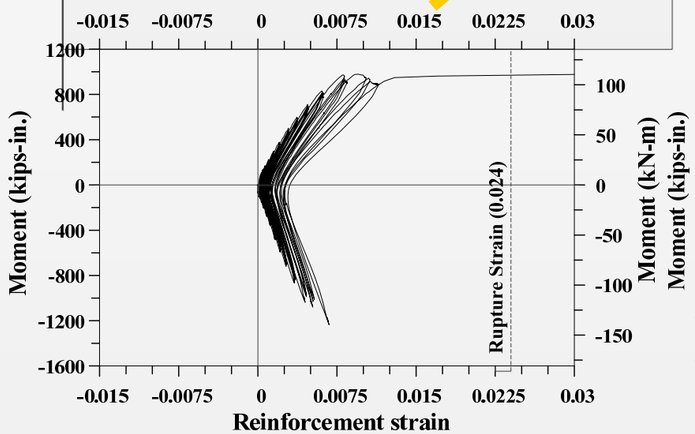
Total reinforcement ratio = 14.8 %

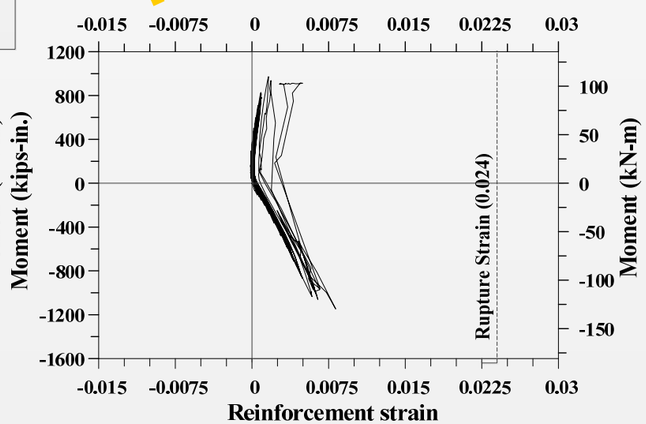
Micro steel fiber (V_f = 3%)

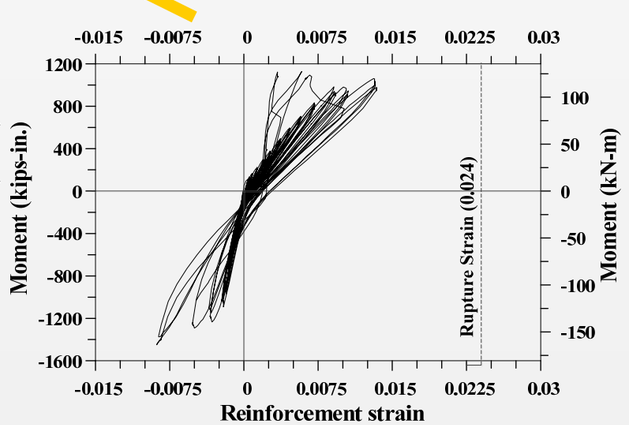












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Ultra-high-performance fiber-reinforced concrete (UHP-FRC)

- High compressive strength
- High compressive ductility
- High crack resistance
- High shear strength

Fiber-reinforced polymer (FRP) rebars

- High tensile strength
- Noncorrosive

Structural Members can Simultaneously Achieve All Functions:

- High durability (highly corrosion resistant) → material properties of FRP and UHP-FRC
- High flexural/shear strength → through DCSR design
- High stiffness/→ through DCSR design
- High ductility → through DCSR design (reminder: FRP is a brittle material)
- High resilience (small residual deformation) → through DCSR design