Effect of Tensile Strain Capacity of UHPC on the Bond with Steel Reinforcement

ACI Convention- Fall 2021

THE WORLD'S GATHERING PLACE FOR ADVANCING CONCRETE

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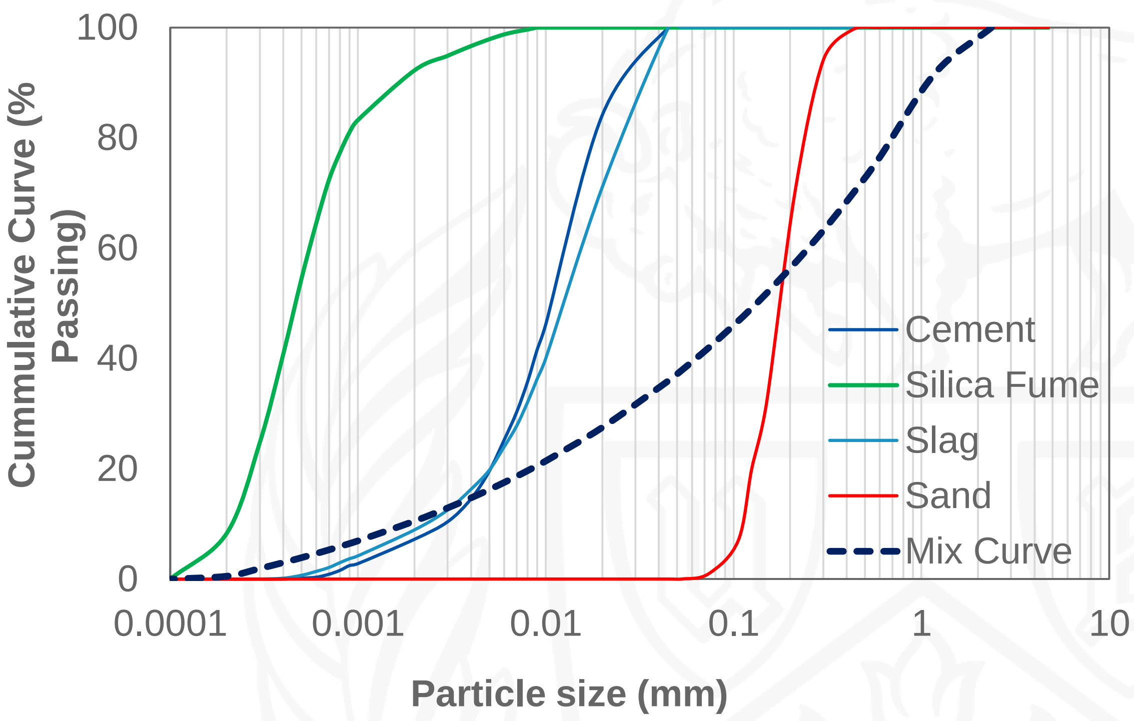
Ultra-High Performance Concrete

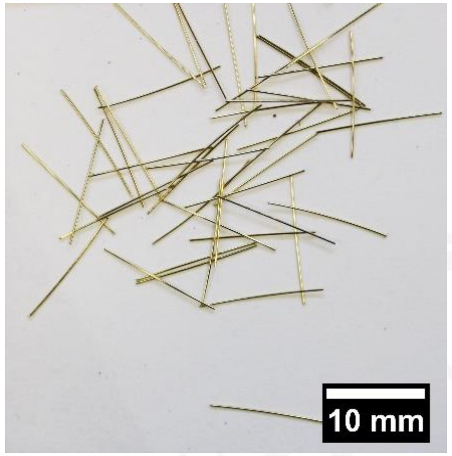
- Compressive strength of at least 150 MPa (22 ksi) (ACI 239)
  - w/c = 0.15 - 0.25
  - Dense particle packing
  - High durability
- Steel or polymer fibers are typically used
- High tensile strength of at least 6 MPa (ACI 239), and high flexural toughness

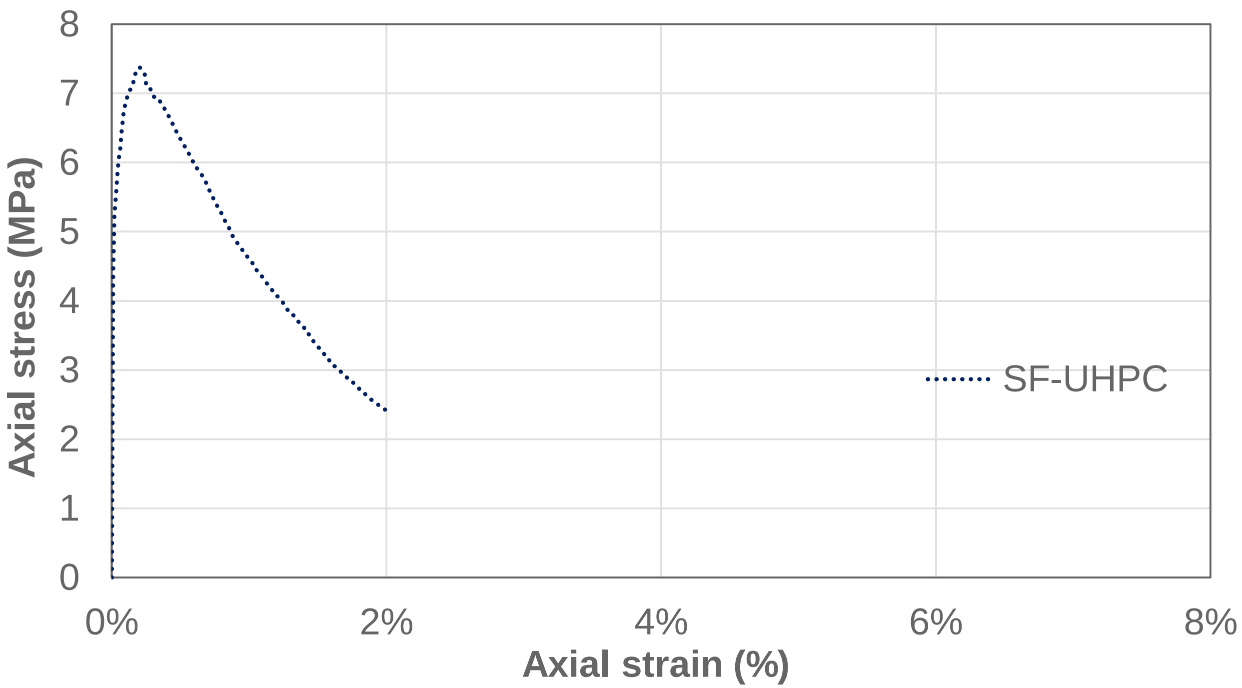


Ultra-High Performance Concrete

Two types of UHPC are used:

- UHPC with smooth straight steel fibers (SF-UHPC)

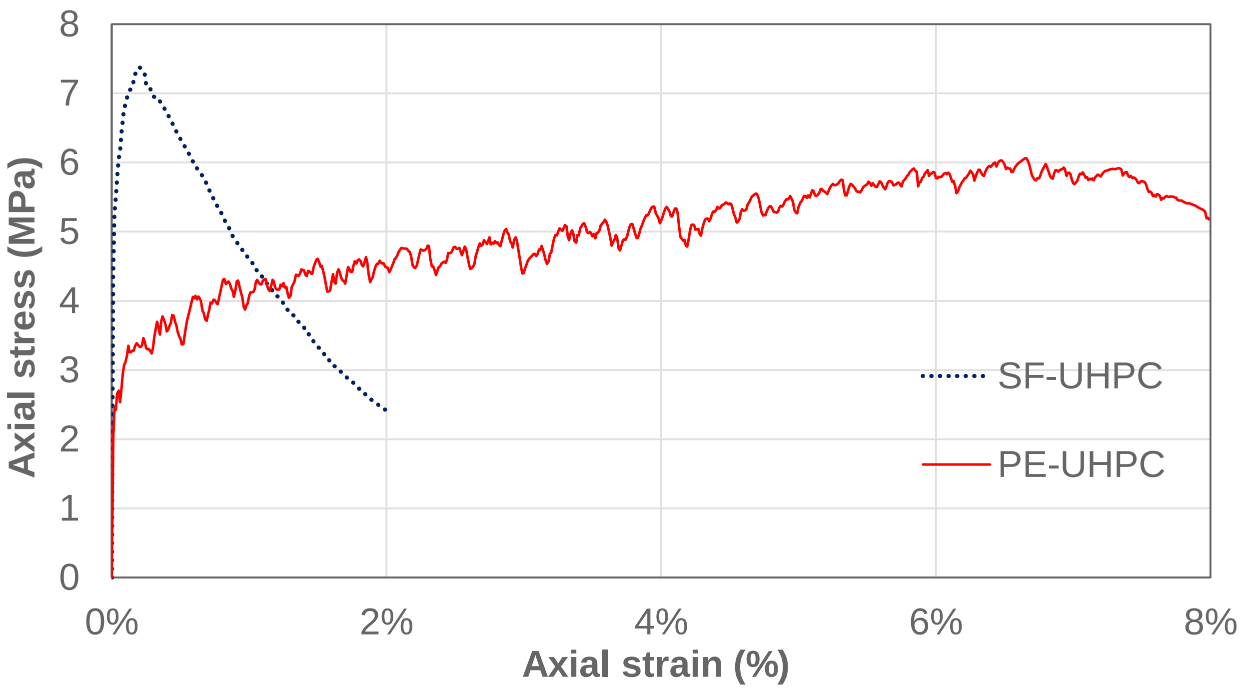


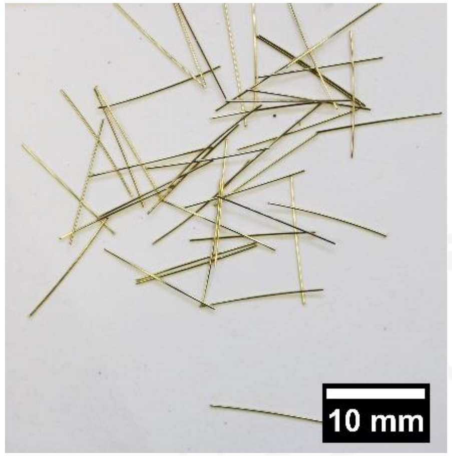


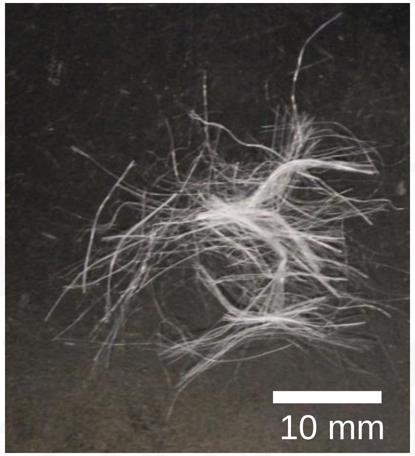
Ultra-High Performance Concrete

Two types of UHPC are used:

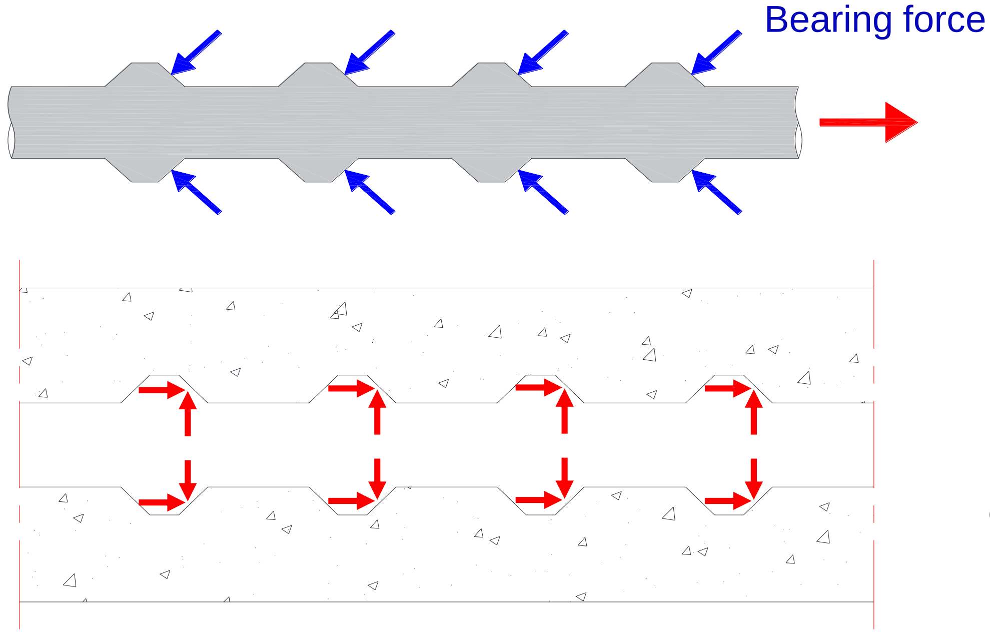
- UHPC with smooth straight steel fibers (SF-UHPC)
- UHPC with polyethylene fibers (PE-UHPC)

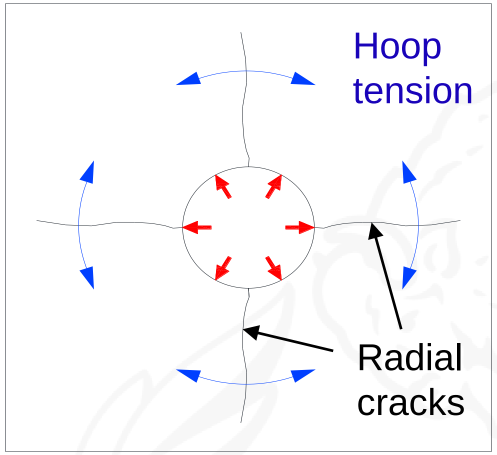


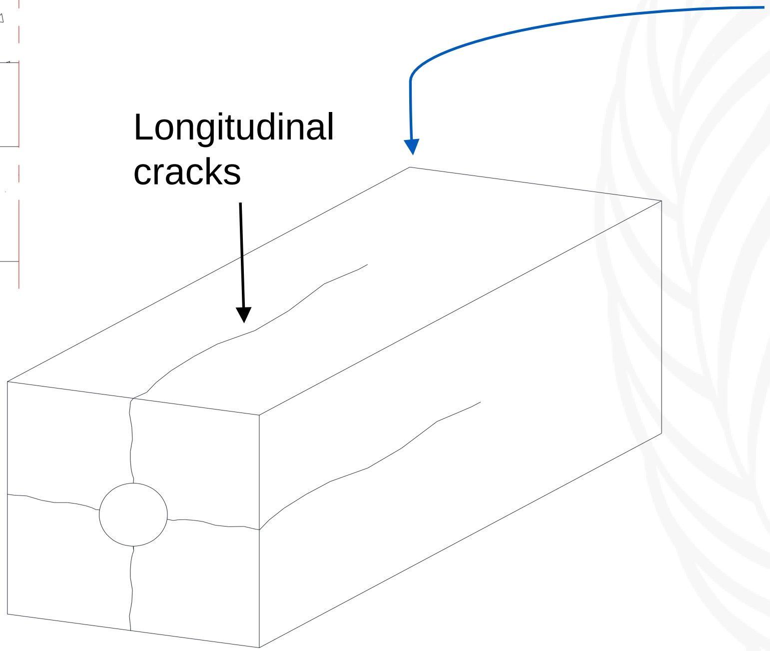




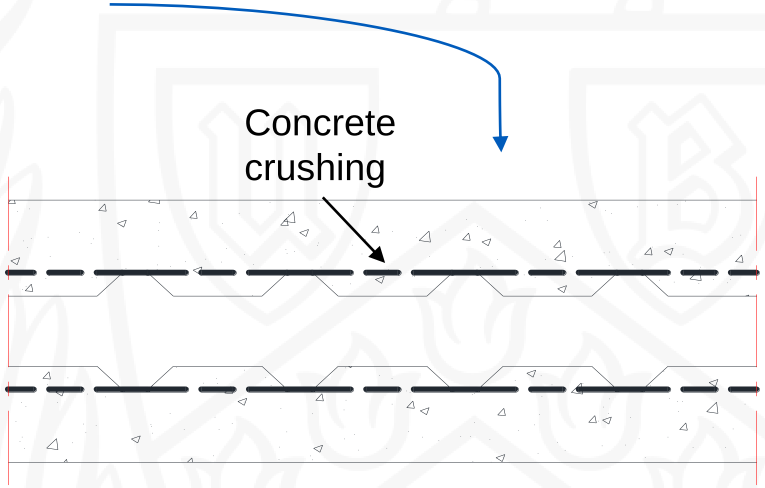
Bond transfer mechanism







Splitting crack failure



Pullout failure

Factors controlling bond failure

Splitting crack failure

- Tensile strength and fracture toughness of concrete
- Confinement by cover thickness and transverse reinforcement
- Bonded length

Pullout failure (Concrete crushing)

- Compressive strength of concrete
- Steel rebar rib dimensions
- Bonded length

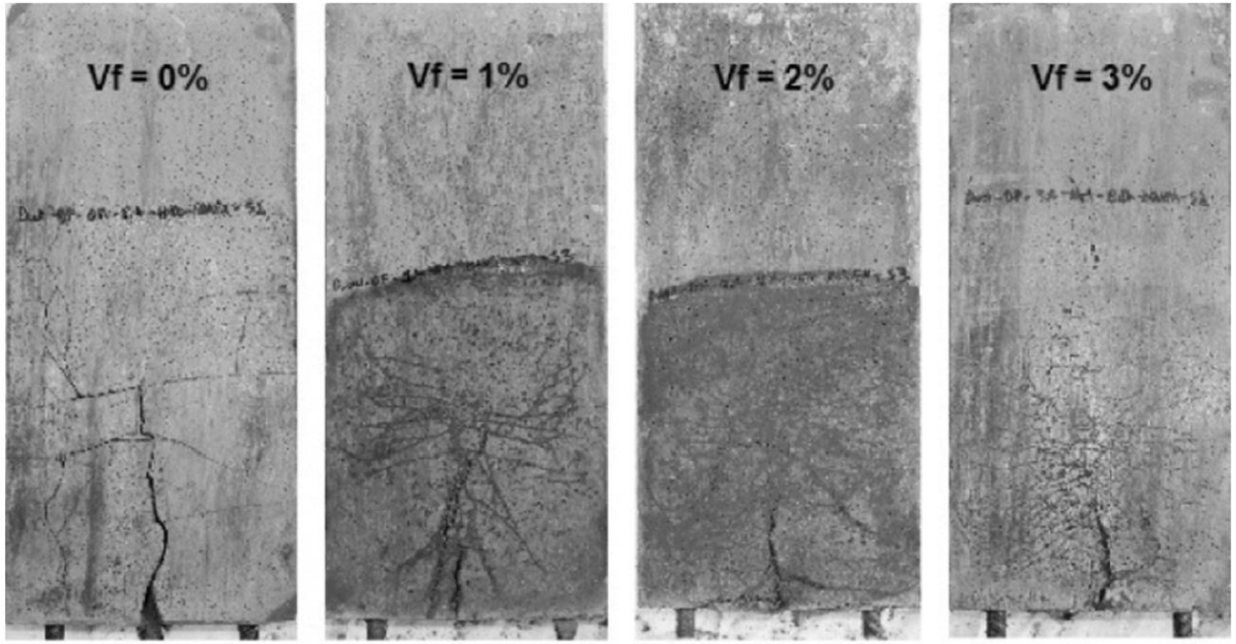
Steel reinforcement bond with conventional concrete usually fails by splitting cracks

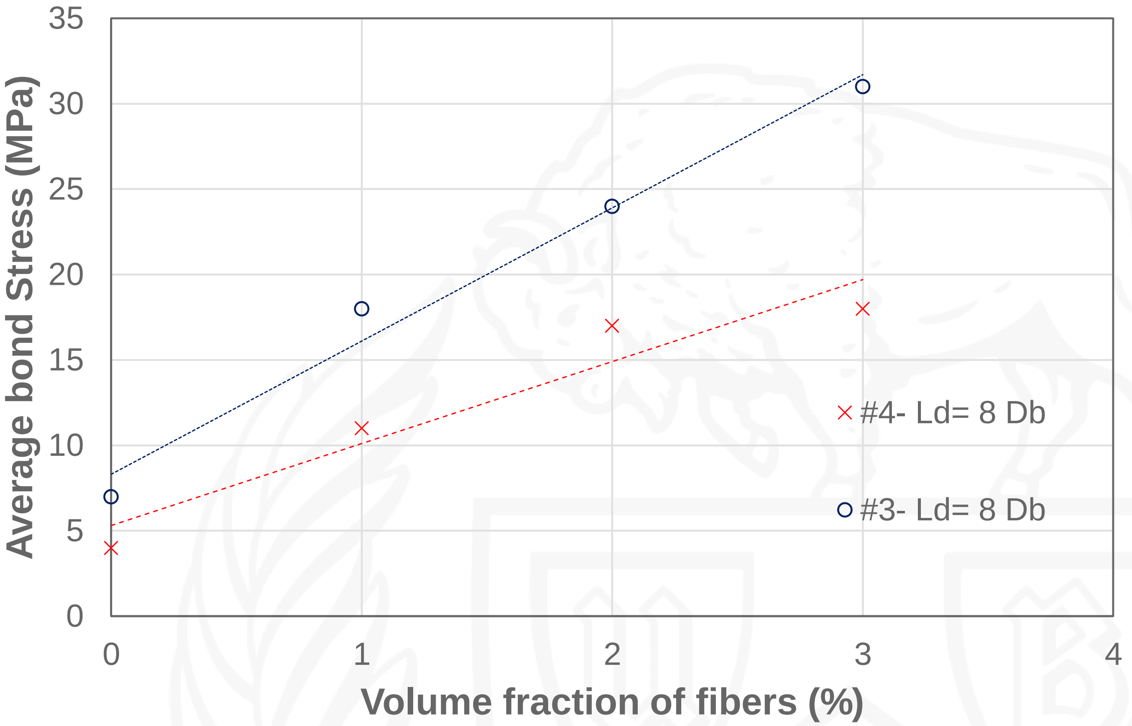
Steel reinforcement bond in fiber reinforced composites depend on Compressive/Tensile strength ratio

Effect of fibers contribution in UHPC

- Lagier et al 2015, Roy et al 2017, and Elkaysi and Eltawil 2017 found that an increase in fiber content leads to linear increase in the bond strength.

- Roy et al 2017 found that the number of cracks increases due to fiber bridging as the fiber volume fraction increases.

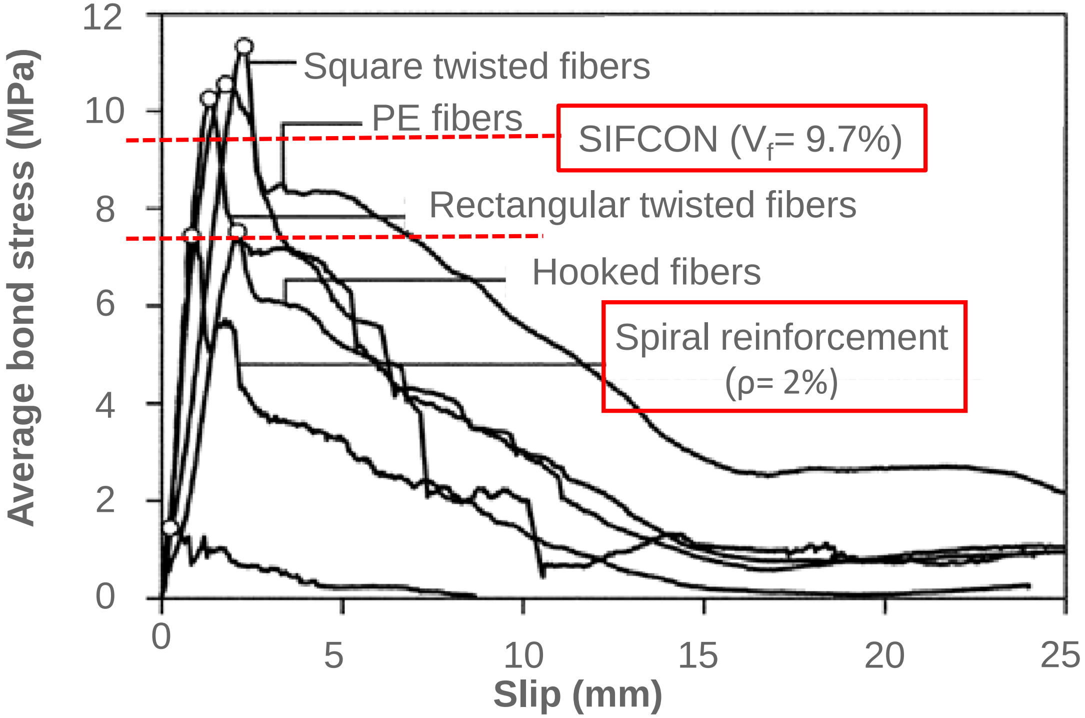


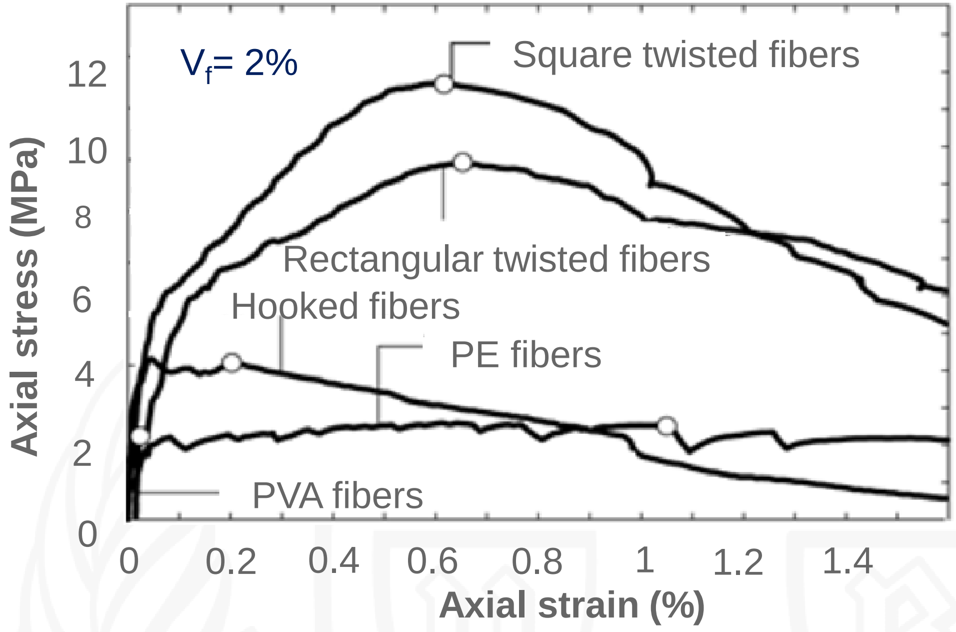


Ref: Roy et al 2017

Effect of tensile Properties of FRC

- Chao et al 2009: The use of tensile strain-hardening FRC composites led to better bar bond performance.
- The use of strain hardening composites with only 2% fibers led to higher bond strength compared to SIFCON with 9.7% fibers.





Ref: Chao et al 2009

Experimental parameters

Material properties

- SF-UHPC

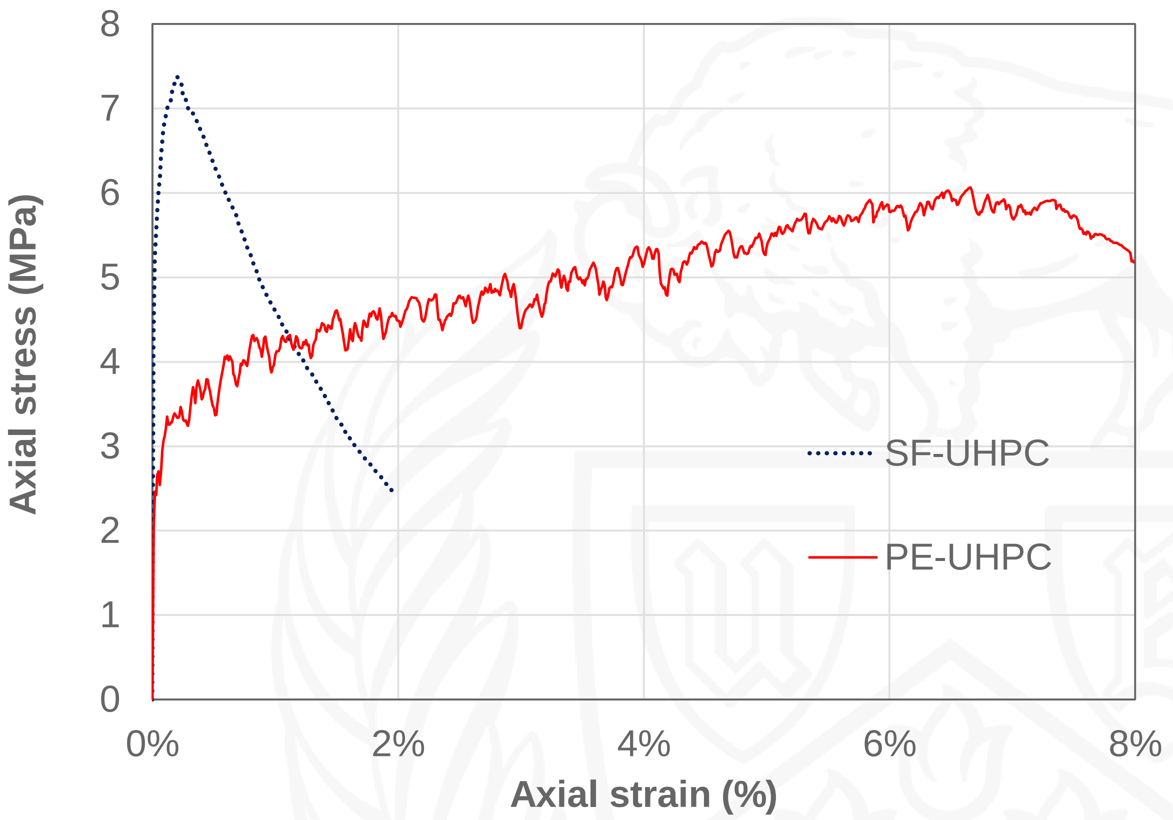
f_c'= 151 MPa f_t= 7.4 Mpa ε_u= 0.2%

- PE-UHPC

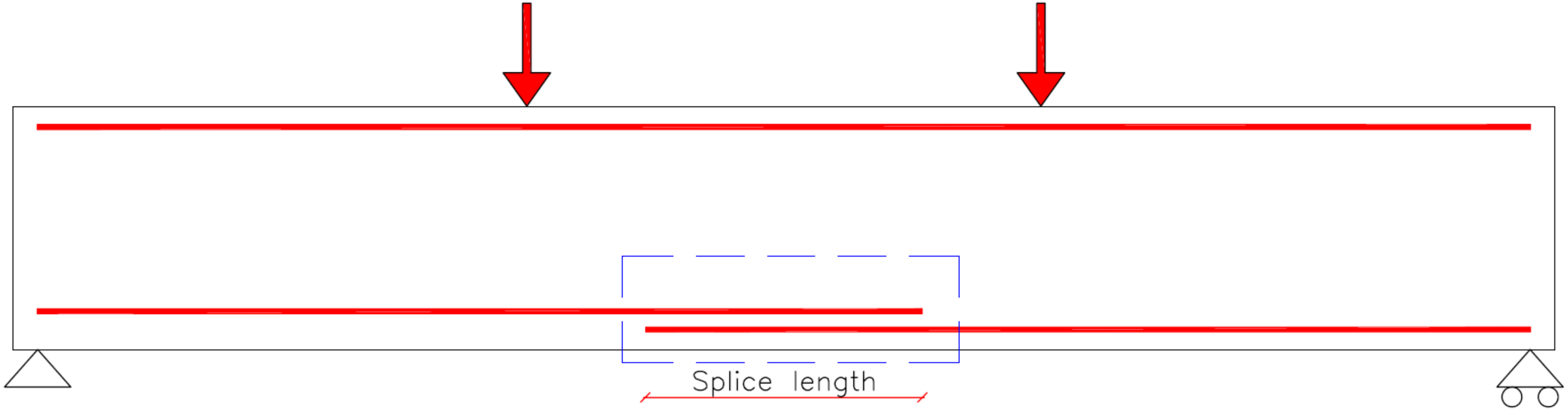
f_c'= 119 MPa f_t= 6.1 Mpa ε_u= 6.6%

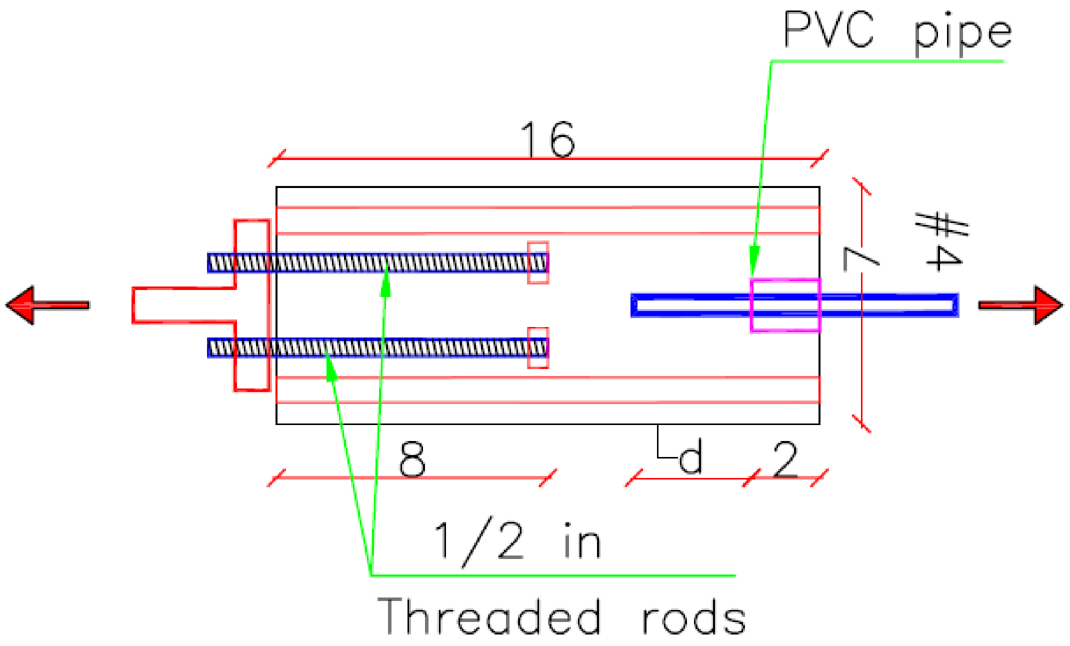
Test matrix

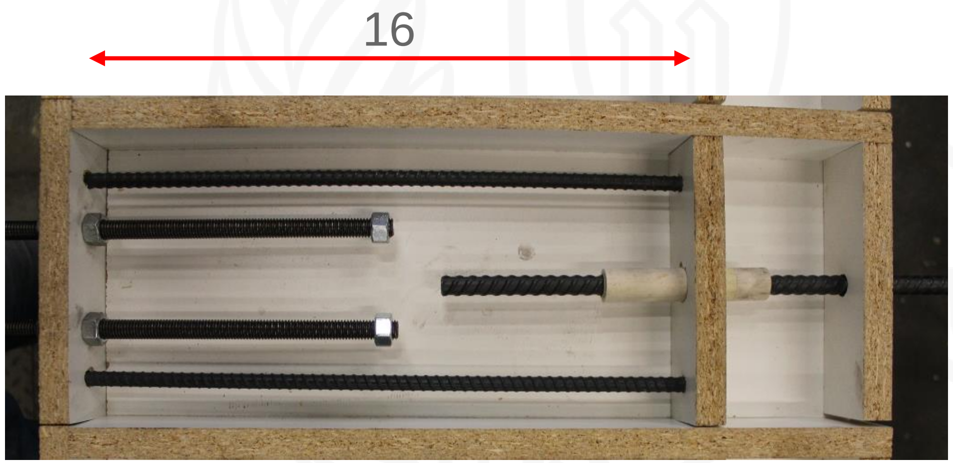
Cover	Embedment length
1.5 d_b	3 d_b
	4 d_b
	6 d_b
	8 d_b
2.5 d_b	2 d_b
	3 d_b
	4 d_b
	6 d_b



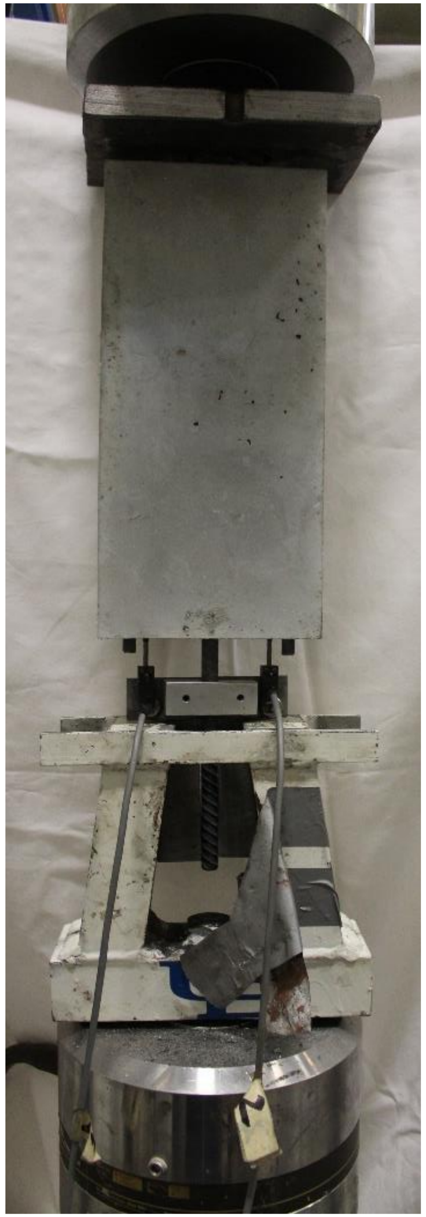
Test setup

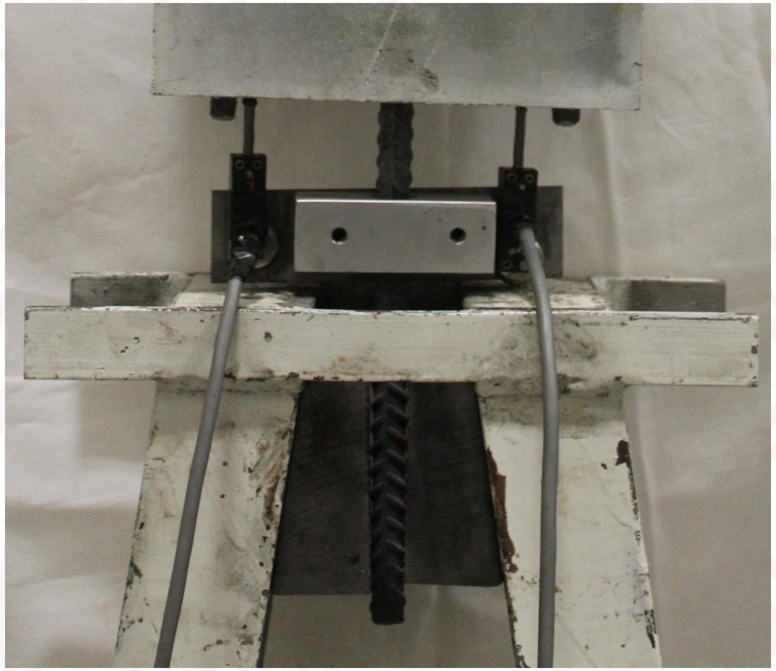






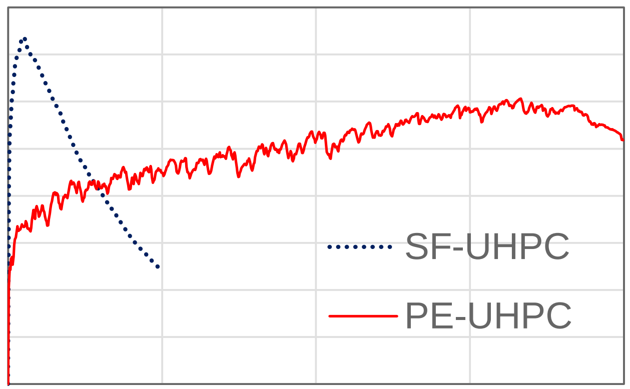
Rebar pullout test setup



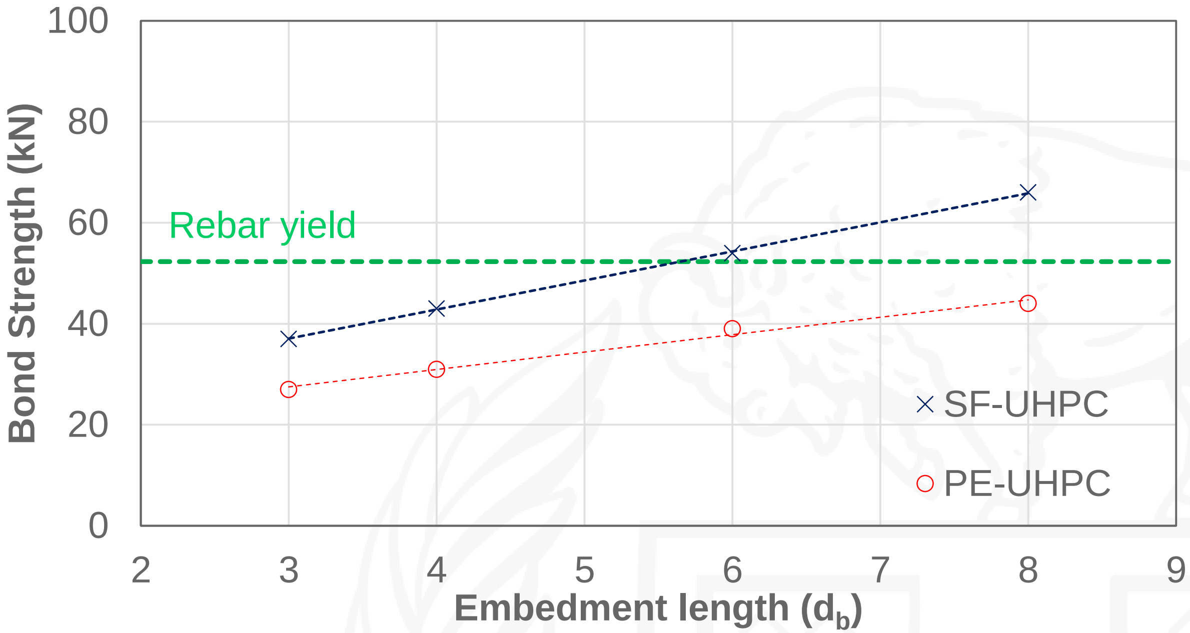


Results: Bond strength variation with cover depth and embedment length

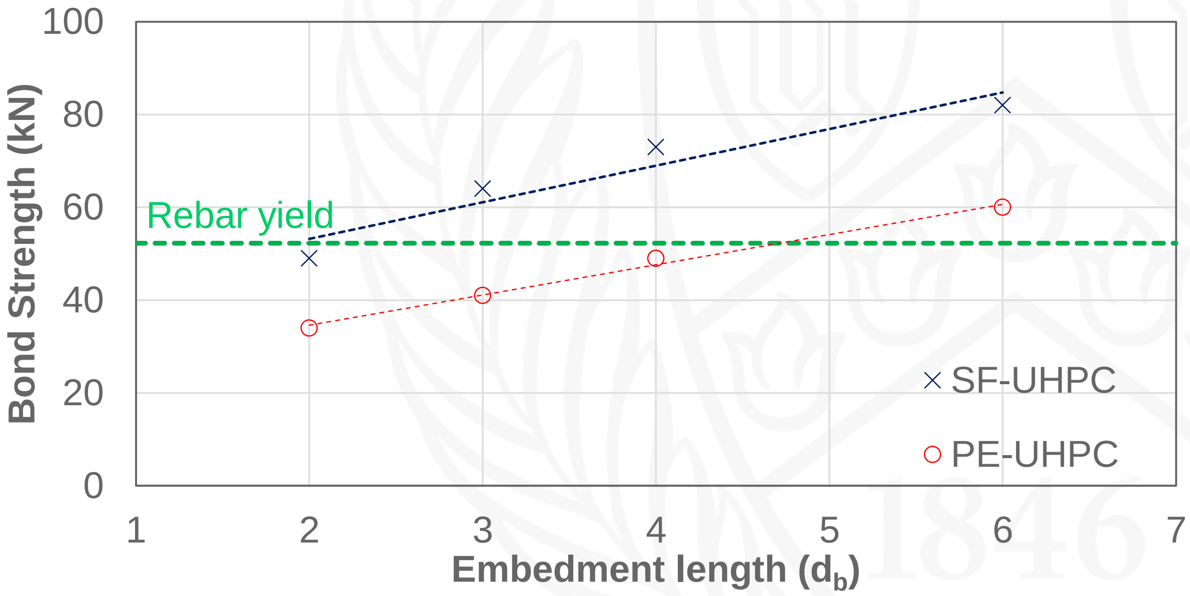
- Bond strength increases linearly with increase in development length, with average R^2 value of 0.95.
- Bond strength in PE-UHPC is on average 30% lower than the bond strength in SF-UHPC



Cover= 1.5 d_b

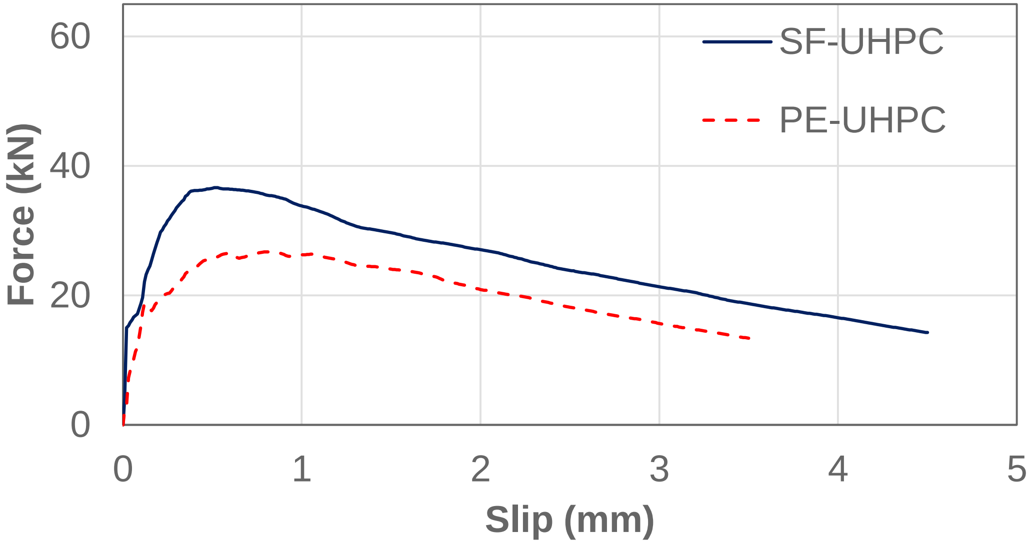


Cover= 2.5 d_b

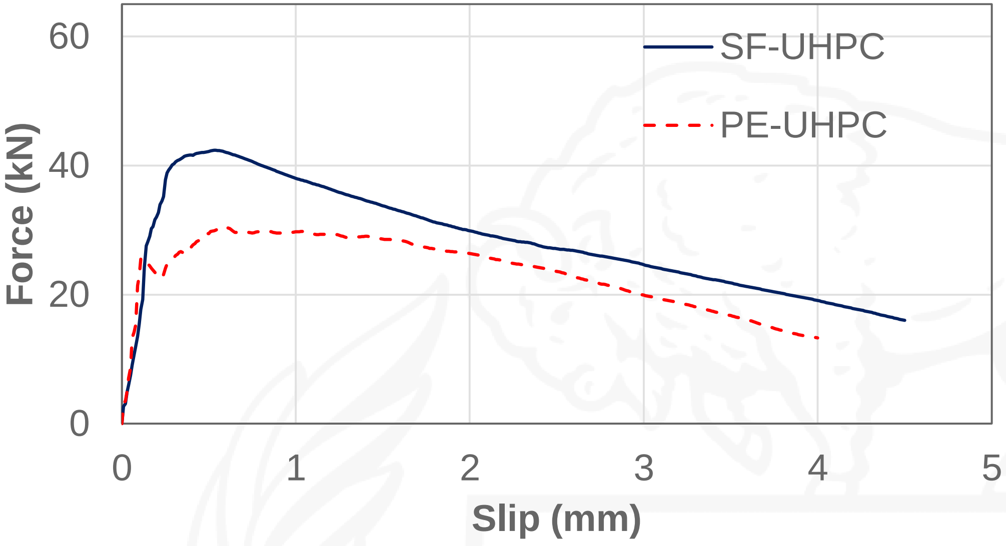


Results: Rebar pullout curves (Cover = 1.5 d_b)

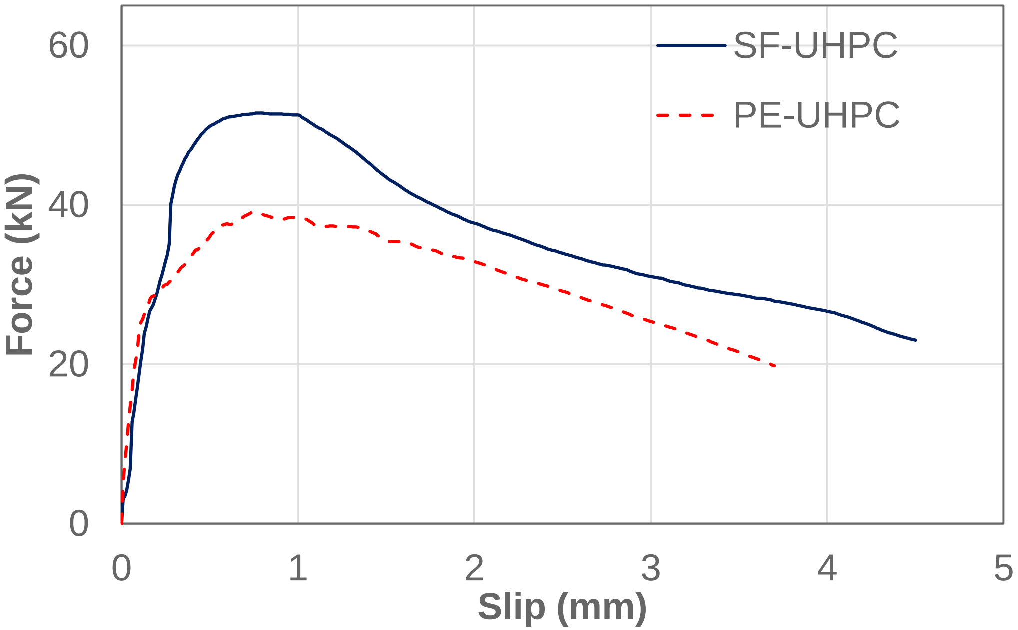
L_d= 3 d_b



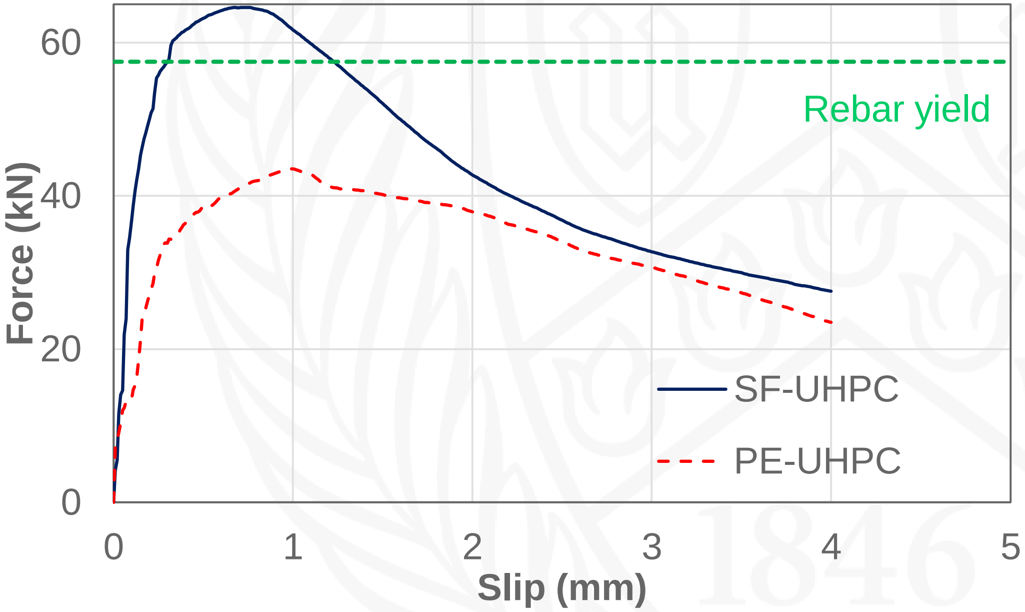
L_d= 4 d_b



L_d= 6 d_b

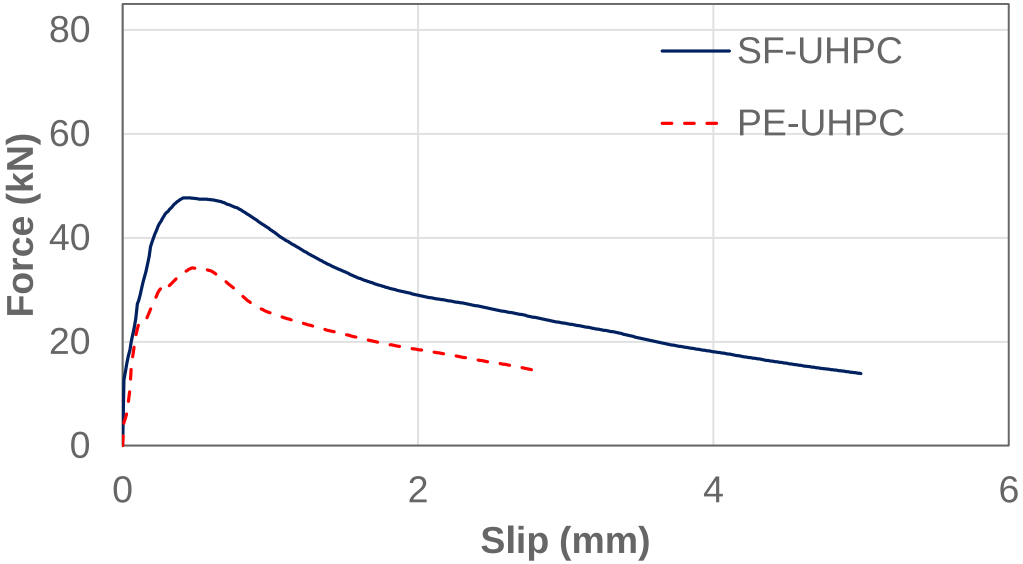


L_d= 8 d_b

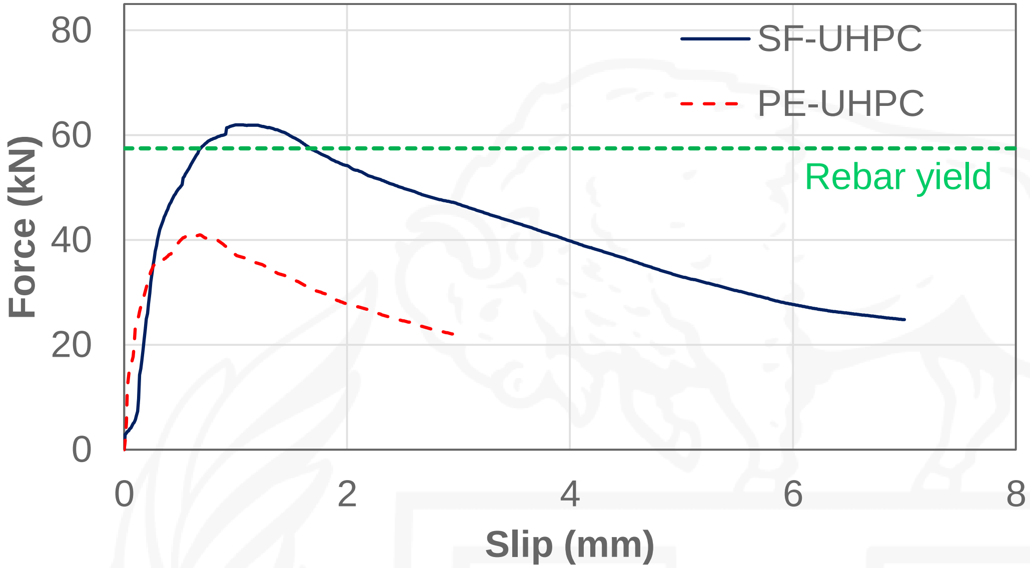


Results: Rebar pullout curves (Cover = 2.5 d_b)

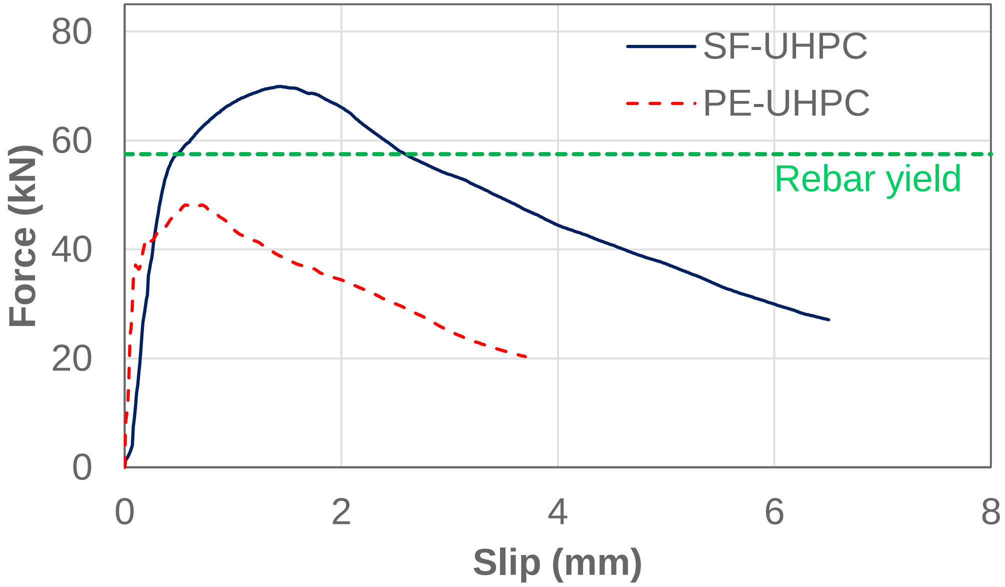
$L_d = 2\ d_b$



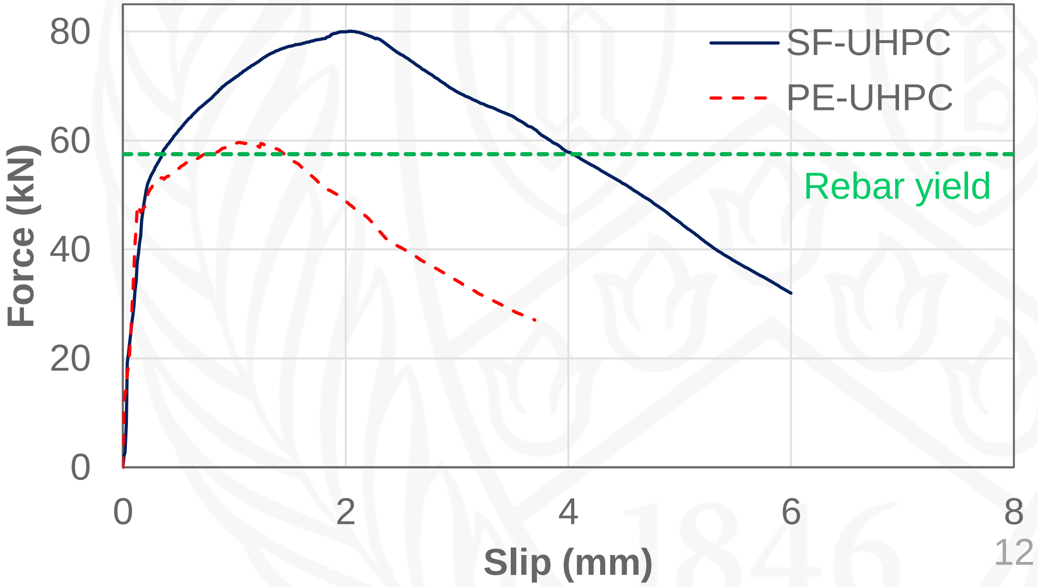
$L_d = 3\ d_b$



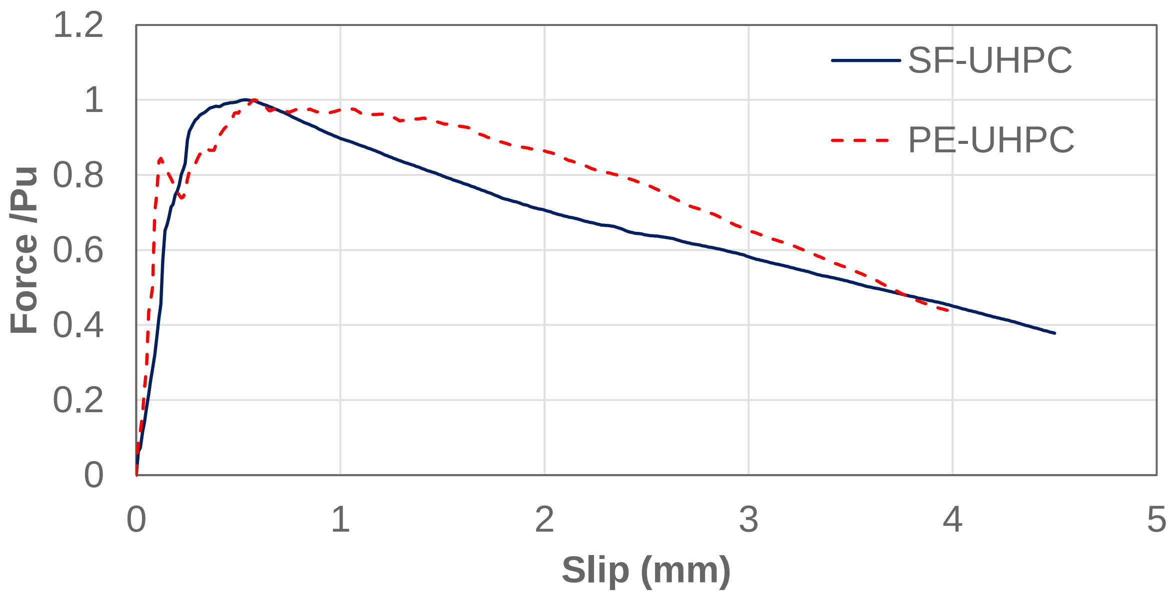
$L_d = 4\ d_b$

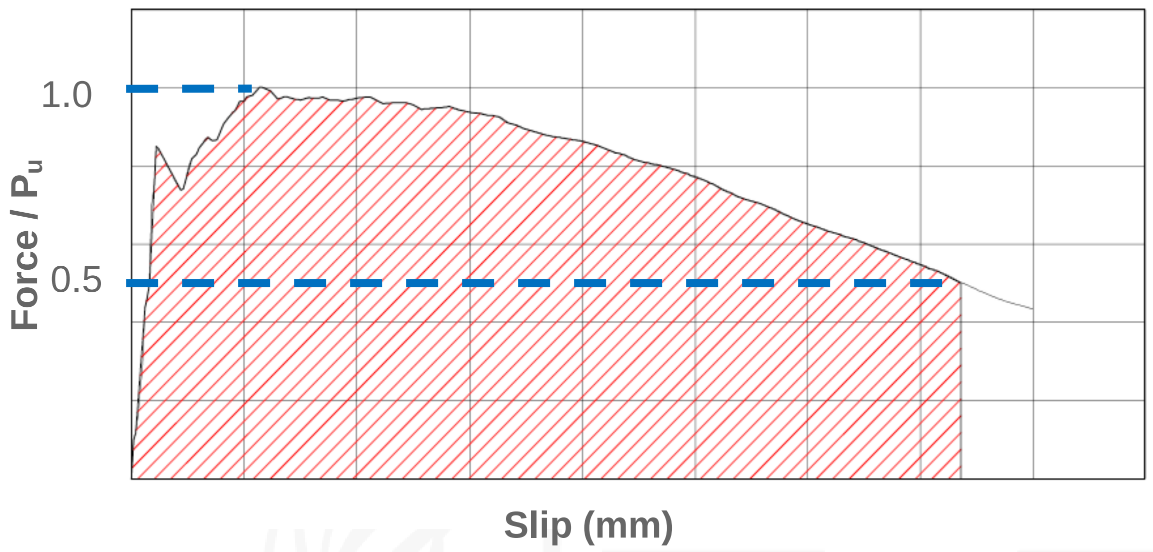


$L_d = 6\ d_b$



Results: Energy dissipation





- PE-UHPC dissipates on average 17% higher energy than SF-UHPC for specimens with cover= 1.5 d_b
- SF-UHPC dissipates higher energy in specimens with cover= 2.5 d_b due to rebar yielding

Normalized energy dissipation (kN.mm/kN)

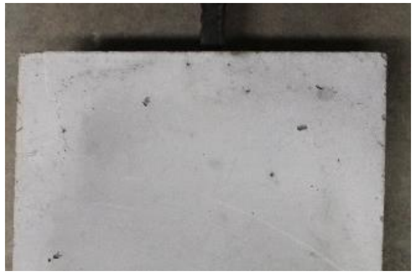
Cover	Embedment length	SF-UHPC	PE-UHPC
1.5 d_b	3 d_b	2.71	2.65
	4 d_b	2.56	2.91
	6 d_b	2.71	2.92
	8 d_b	2.17	3.26
2.5 d_b	2 d_b	2.17	1.56
	3 d_b	3.77	2.41
	4 d_b	3.8	2.27
	6 d_b	4.11	2.63

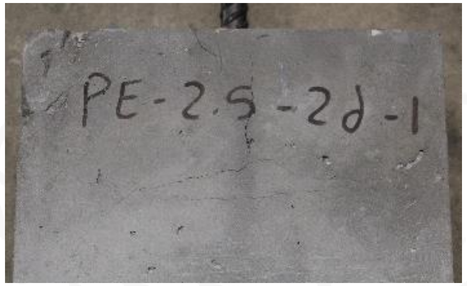
Failure mode (Cover= 2.5 d_b)

SF-UHPC

PE-UHPC

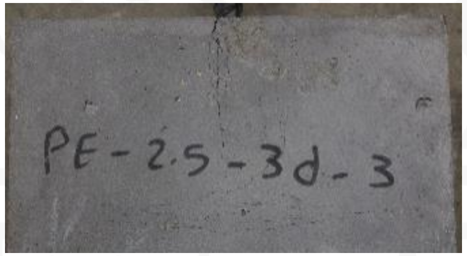
L_d= 2 d_b



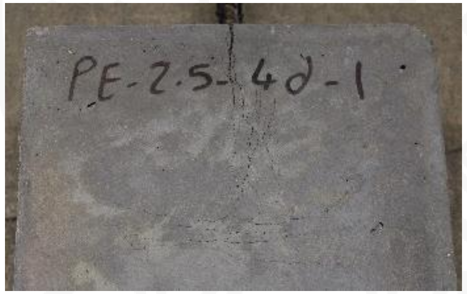
L_d= 3 d_b



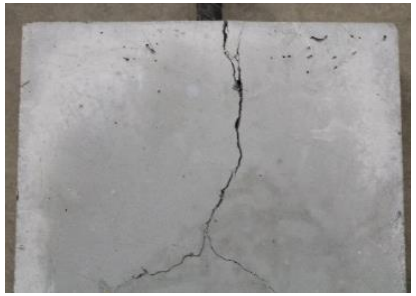



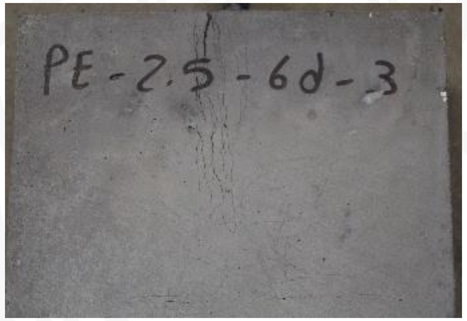
L_d= 4 d_b



L_d= 6 d_b

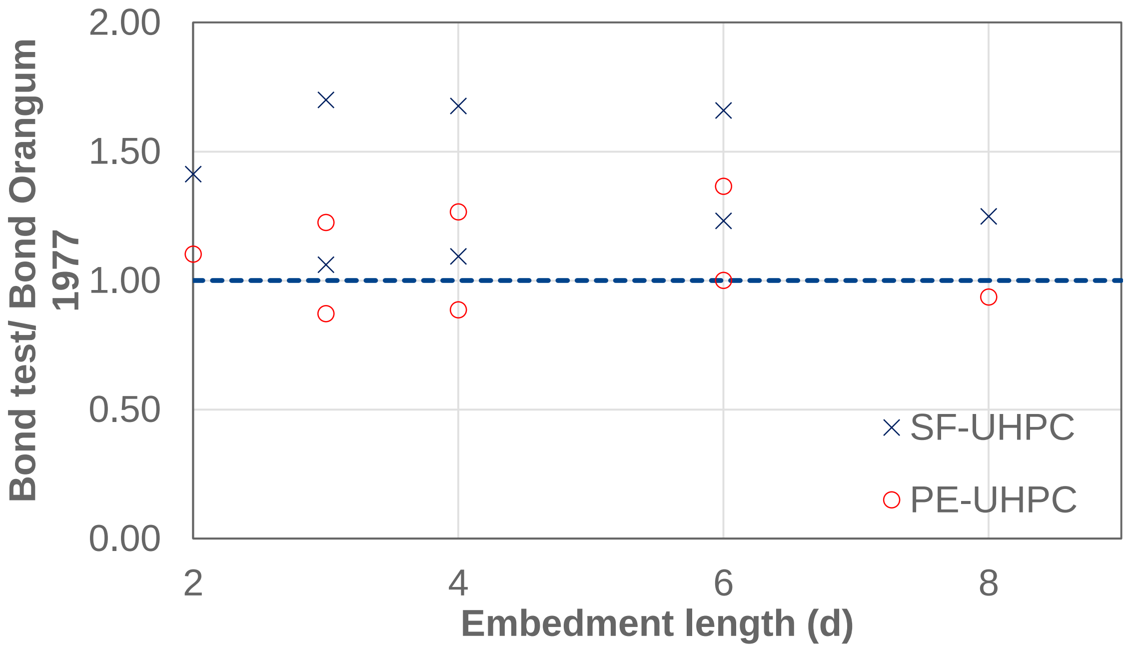





Predicted bond strength

- Orangum et al 1977 (ACI 318)

$$U_c = \left(1.2 + 3 * \frac{C}{d_b} + 50 * \frac{d_b}{l_d}\right) * \sqrt{f'_c}$$

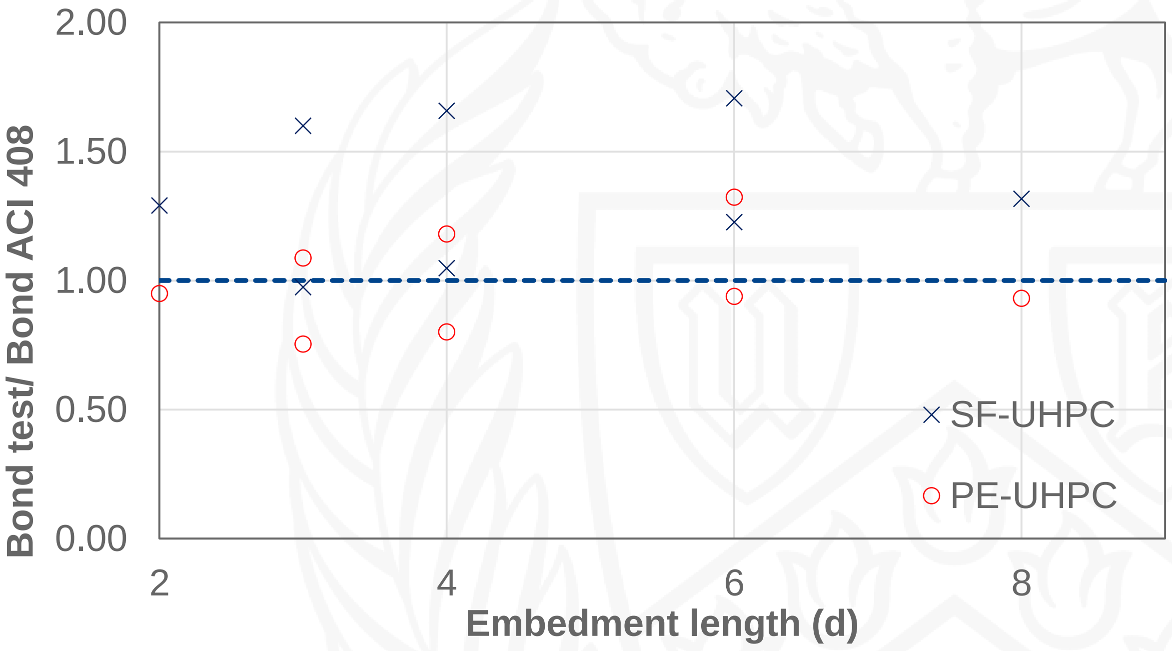


$(T_{test}/T_{Orangum})_{SF\text{-}UHPC} = 1.39$

$(T_{test}/T_{Orangum})_{PE\text{-}UHPC} = 1.08$

- ACI 408-03

$$T_c = (59.9 * l_d * (C + 0.5 * d_b) + 2400 * A_b) * 1.25 * f'^{1/4}_c$$



$(T_{test}/T_{ACI\ 408})_{SF\text{-}UHPC} = 1.35$

$(T_{test}/T_{ACI\ 408})_{PE\text{-}UHPC} = 1.00$

Conclusions

- The reinforcement-UHPC bond strength increases linearly with increase in the embedment length.
- The bond strength increases by increasing cover thickness, and the failure mode changes from splitting cracks to rebar pullout in the specimens with high tensile strength and short embedment length.
- PE-UHPC showed higher energy dissipation and hardening behavior due to the formation of multiple cracking.
- Despite the high strain capacity of PE-UHPC, it showed on average 30% lower bond strength than SF-UHPC.
- The bond strength calculated following ACI 408 showed better prediction than ACI 318 compared to test results.

Thank you!

Questions?