Effect of Fiber Reinforcement on the Tensile Behavior of Rebar Reinforced UHPC

Manish Roy (Asst. Professor in Residence)
Kay Wille (Associate Professor)

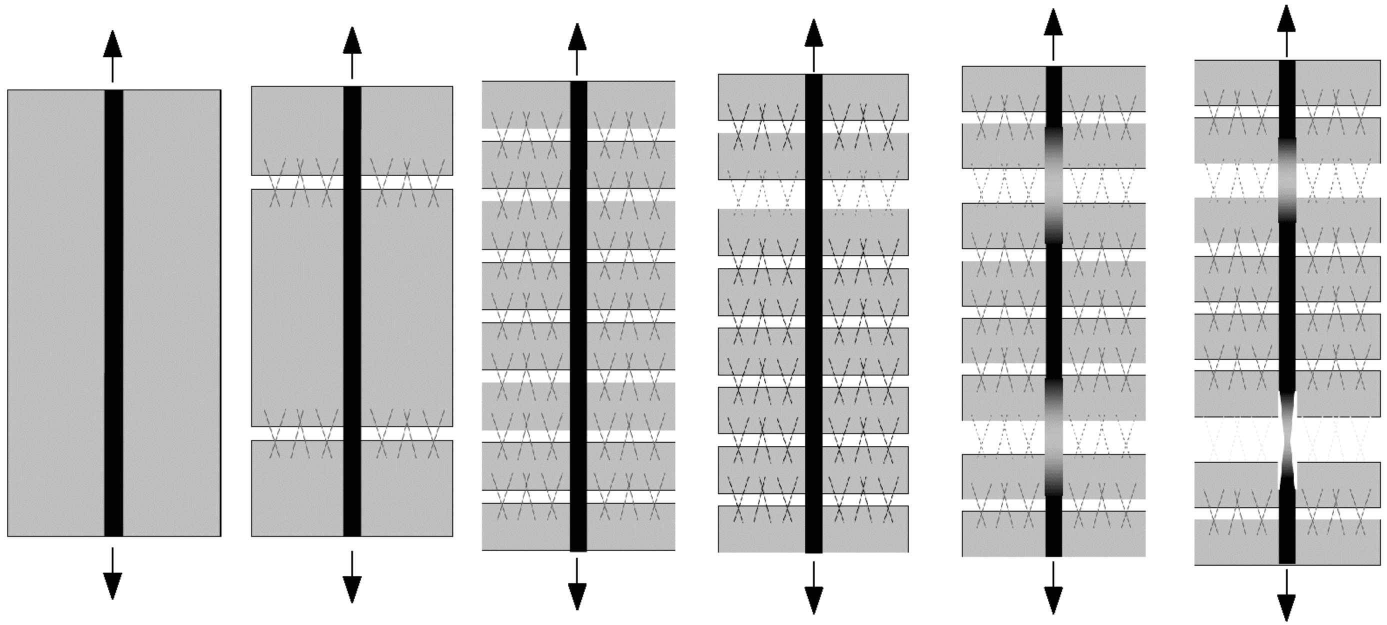
Advanced Cementitious Materials & Composites Laboratory
Civil & Environmental Engineering Department
School of Engineering
University of Connecticut
Storrs, CT, USA

ACI Fall 2019 The Concrete Convention and Exposition
American Concrete Institute
UHPC – Innovations and Changes in Structural Design, Part 3 of 3
October 20, 2019, Cincinnati, OH

Goal

To investigate the influence of fiber volume fraction and fiber orientation on the uniaxial tensile behavior of rebar-reinforced UHPC

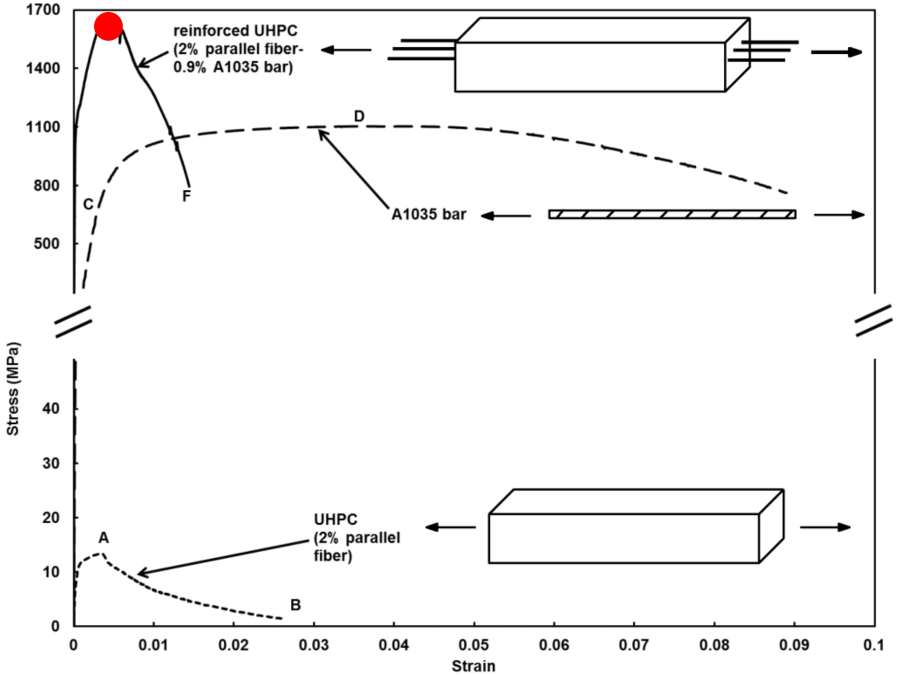
Mechanics of strain-hardening rebar-reinforced UHPC under tension

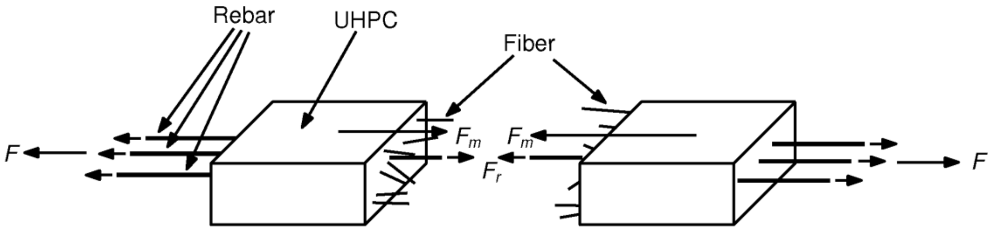


(from left to right)

- Uncracked
- Fiber bridging
- Multiple matrix cracking due to strain hardening
- Macro cracking due to matrix softening
- Multiple macro cracking due to rebar hardening
- Rebar failure/softening

Ductility criteria





F_m = Force in fiber-reinforced UHPC matrix, F_r = Force in rebar

From equilibrium, $F = F_m + F_r$

- Ductility – strain at peak stress

If $|\Delta F_m| < |\Delta F_r|$ → formation of multiple macro cracks → increase in ductility (1)

If $|\Delta F_m| > |\Delta F_r|$ → formation of one macro crack → loss of ductility (2)

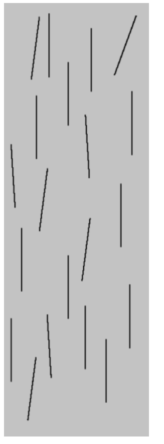
where,

$$\Delta F_m = \Delta\sigma_m \times A_m \quad (3)$$

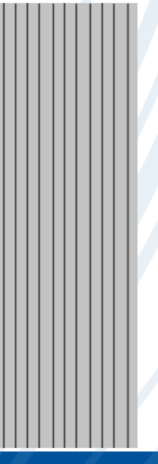
$$\Delta F_r = \Delta\sigma_r \times A_r \quad (4)$$

Modeling approach – UHPC

- Discrete fiber model
  - Captures anisotropic behavior of UHPC
  - Time consuming
  - Lot of computational power



- Alternative modeling approach proposed
  - Fibers modeled as smeared reinforcement
  - Captures anisotropic behavior of UHPC
  - Computationally efficient



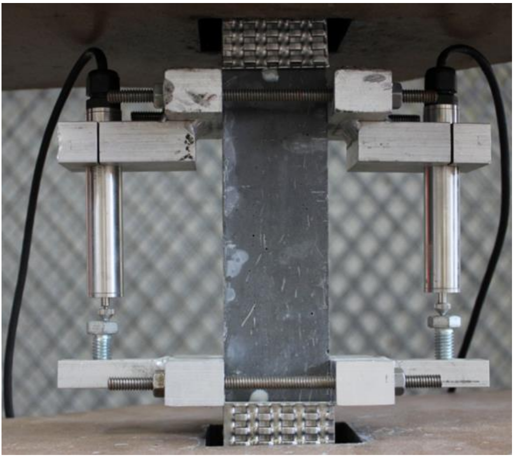
Smeared fiber reinforcement

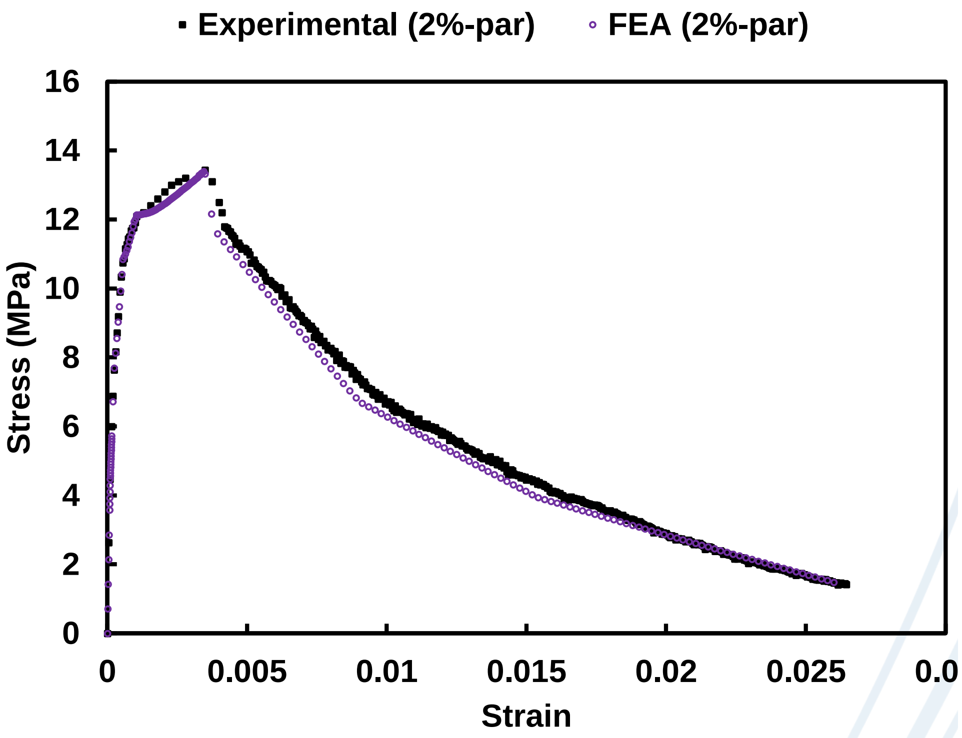
- FE program – ATENA (v. 5.6.1i)
  - 'Reinforced Concrete' material model
  - Concrete matrix – volume element
  - Fibers (smeared) – 1D element
  - Perfect bond between smeared reinforcement and concrete

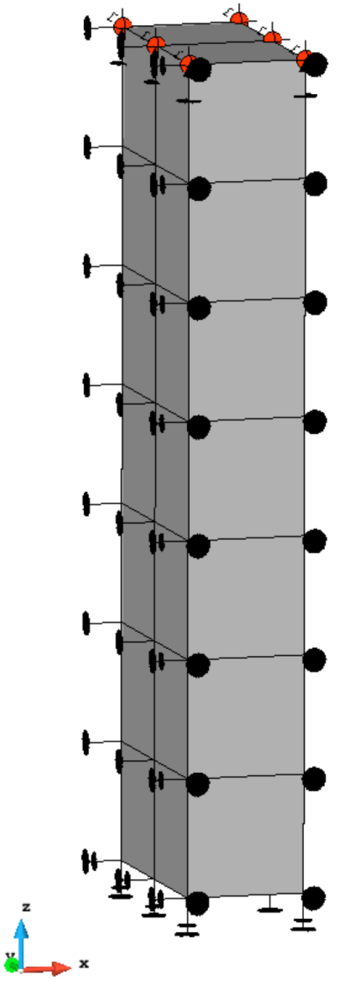
- $D = D_c + \sum_{i=1}^{n} D_{si}$

- σ-ε curve of fibers calibrated to correctly simulate the actual effect of discrete fibers

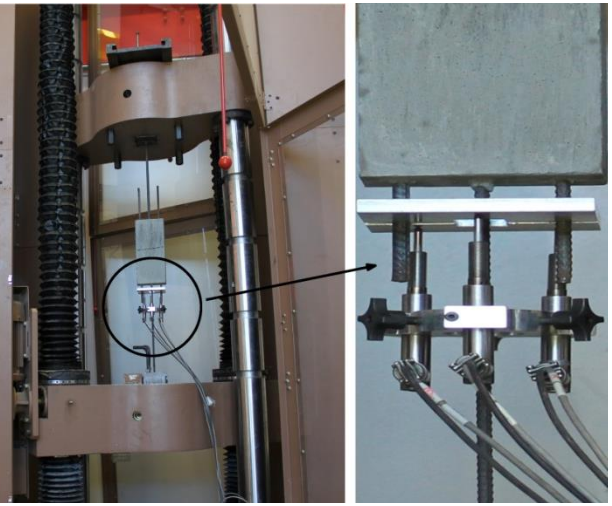
Fiber calibration – uniaxial tensile test

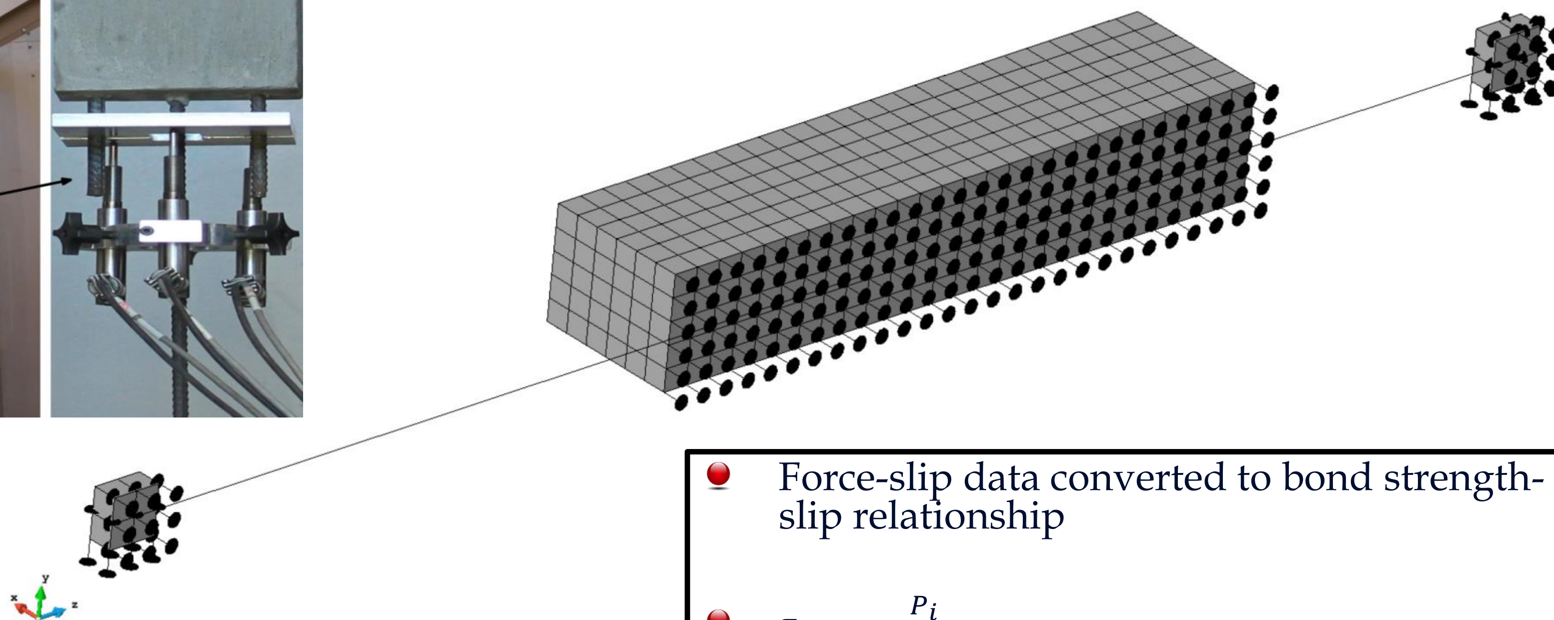






Pullout test – bond-slip calibration

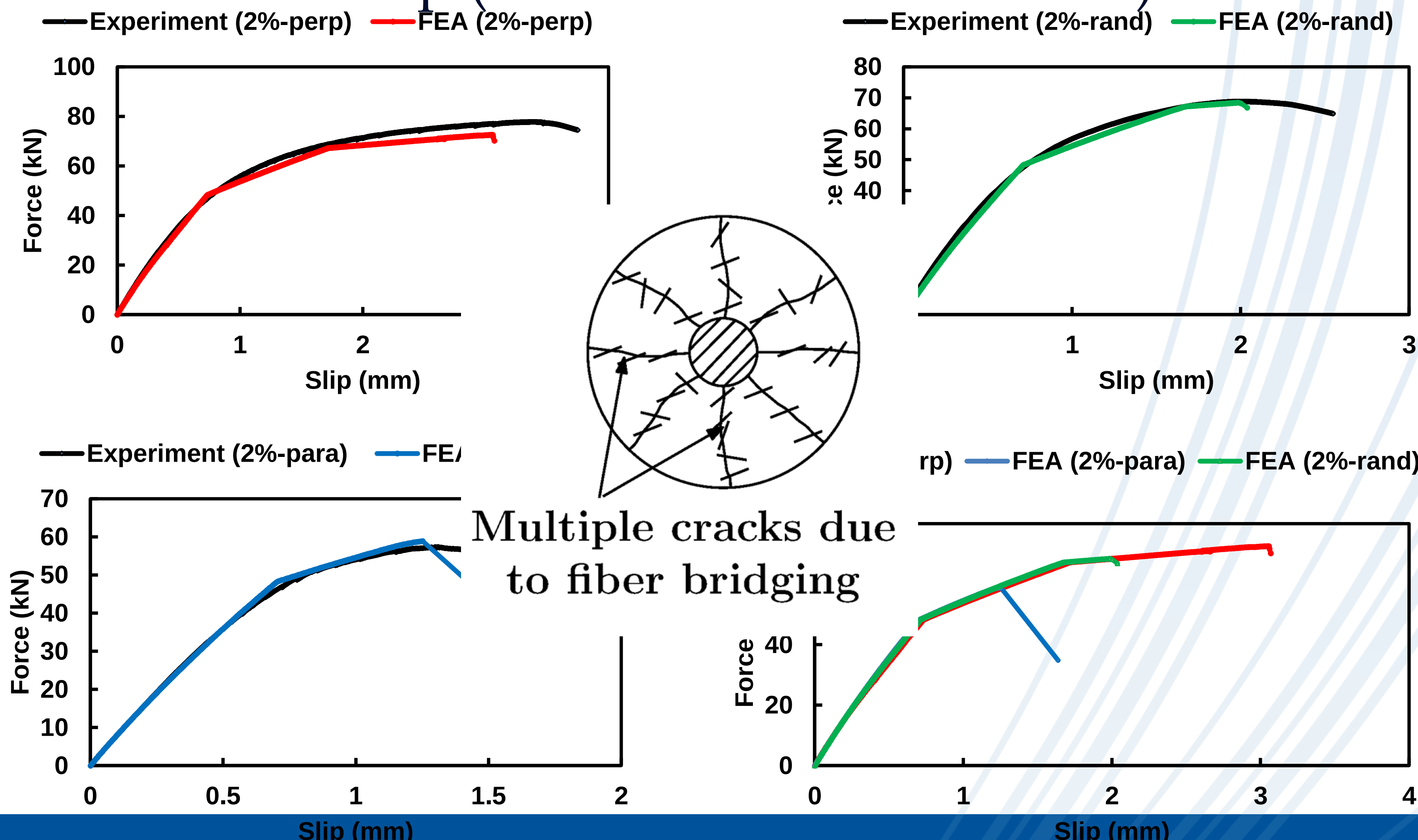




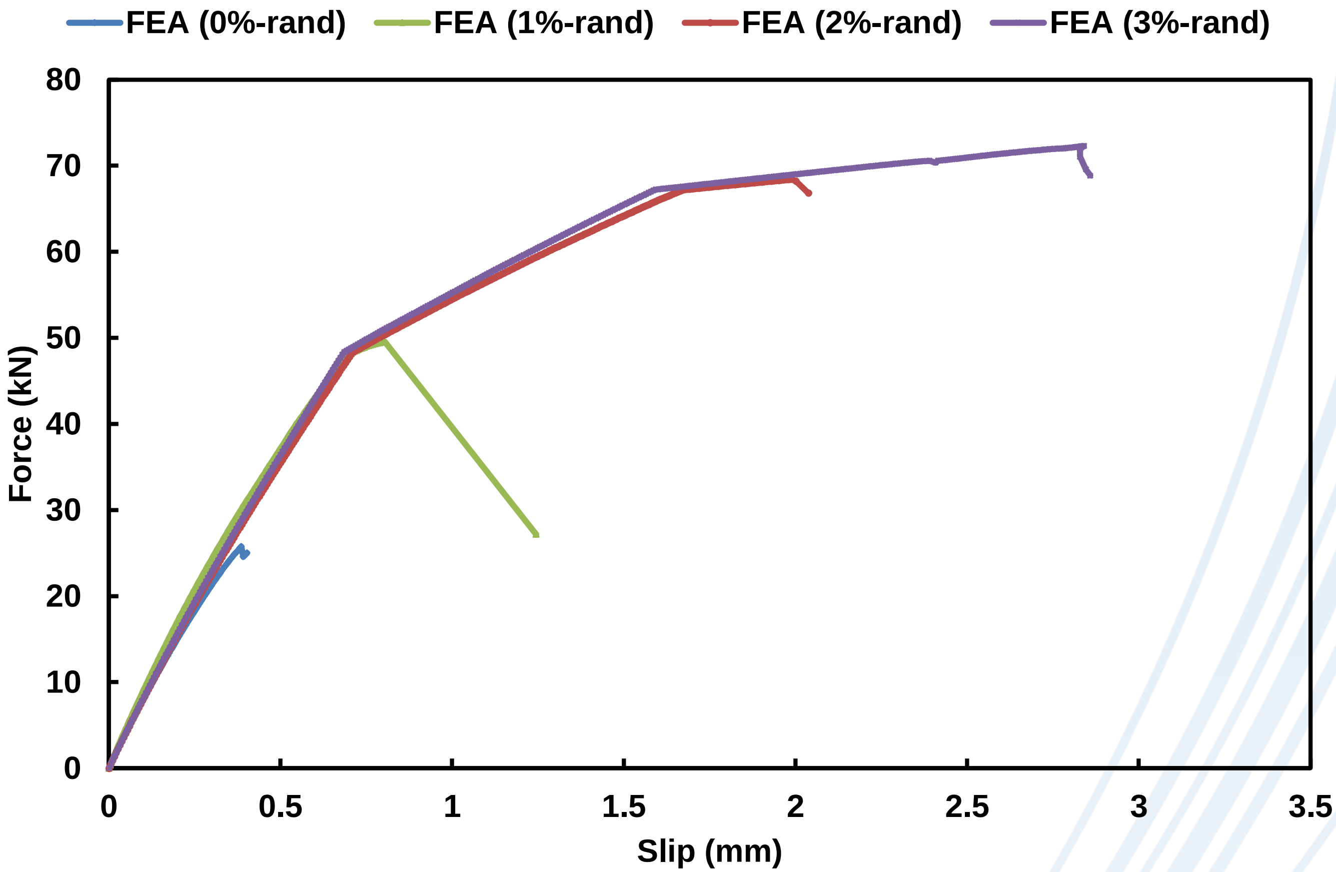
Data from	A1035 bars		
	E_r (GPa)	f_y (MPa)	f_{ult} (MPa)
Roy et al. 2017	222	700	1102

- Force-slip data converted to bond strength-slip relationship
- $\tau_i = \frac{P_i}{\pi \times db \times l_e}$
- No slip considered for side bar and support bar
- No slip in pullout bar inside elastic volume

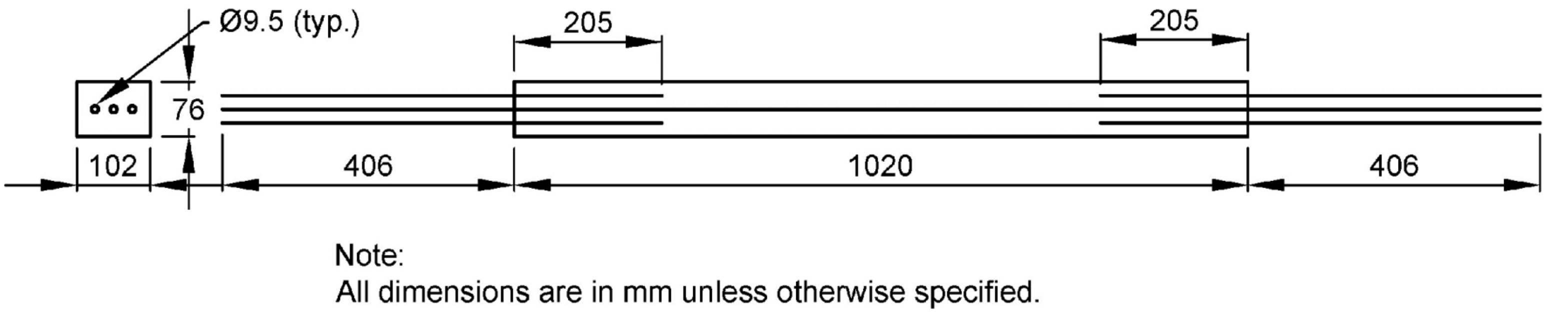
Bond-slip (effect of fiber orientation)

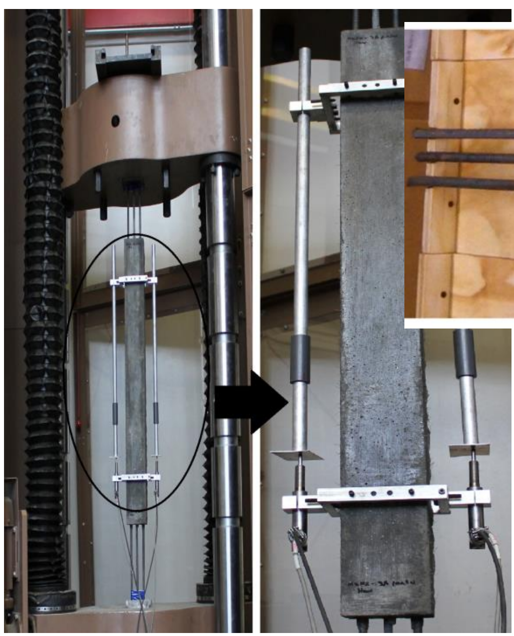


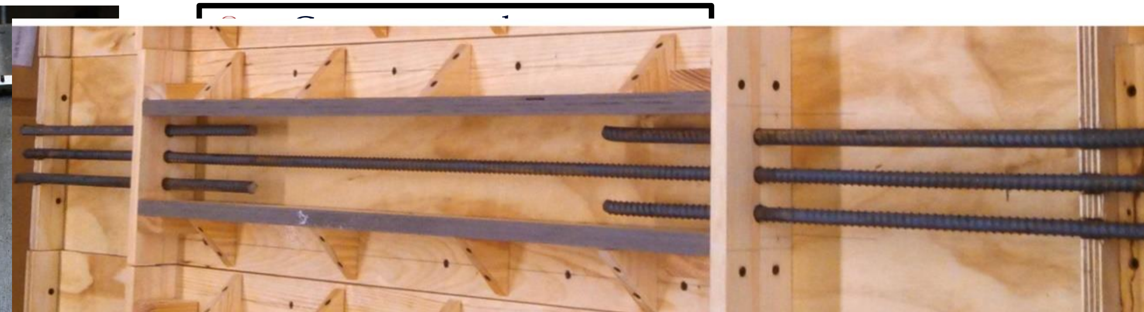
Bond-slip (effect of fiber volume fraction)



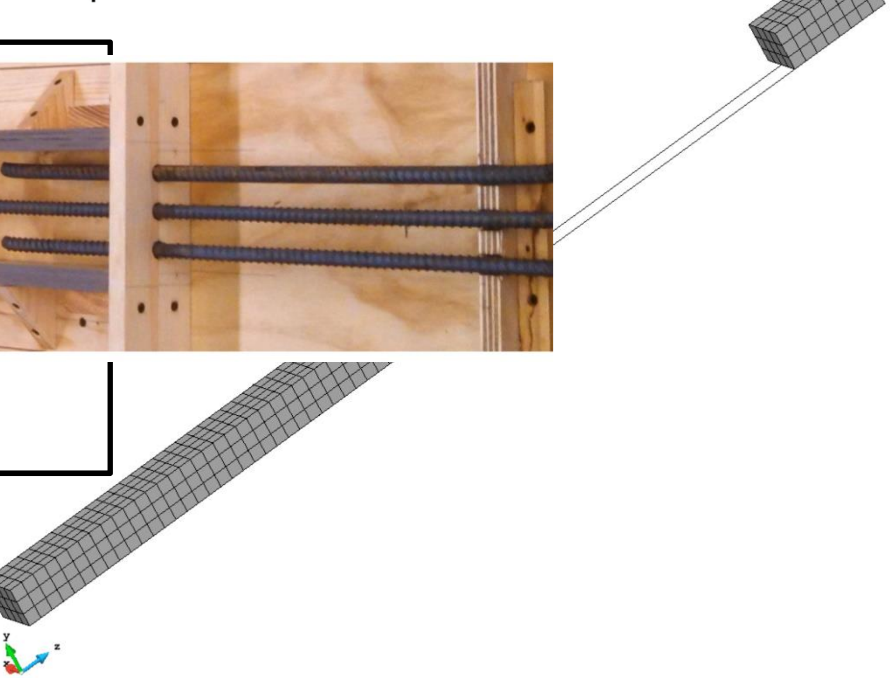
Uniaxial test simulation



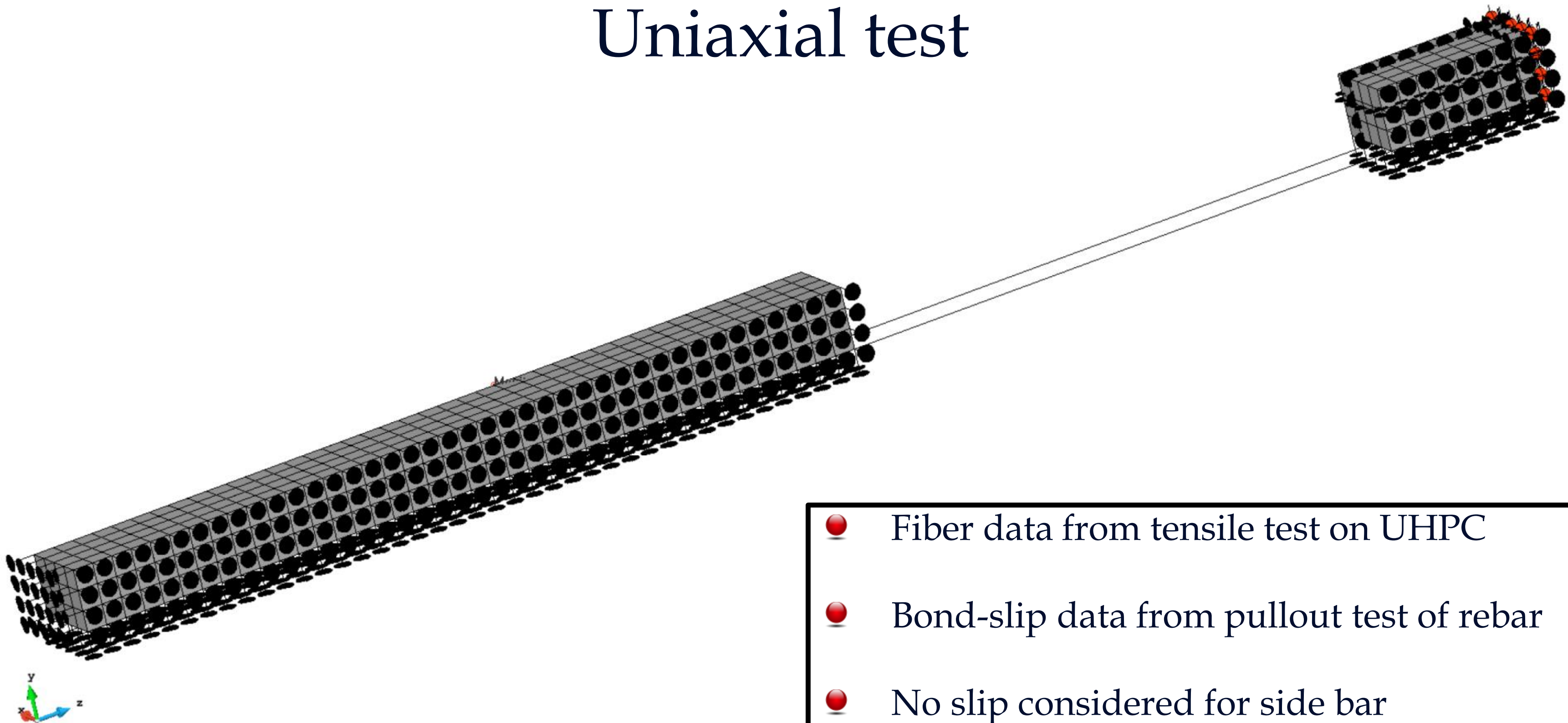




- ¼ model due to symmetry



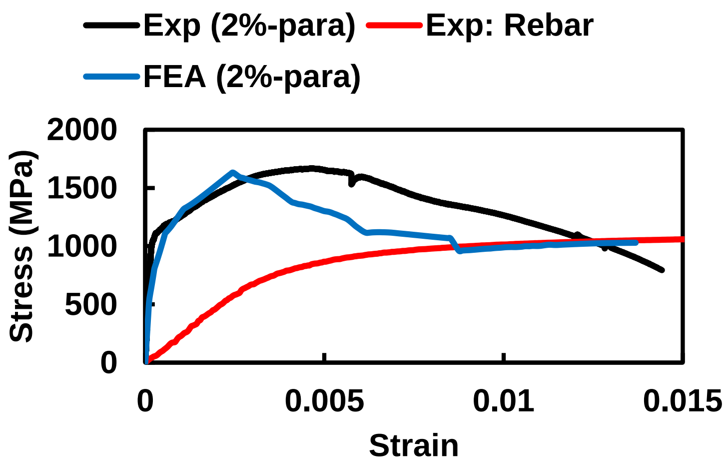
Uniaxial test

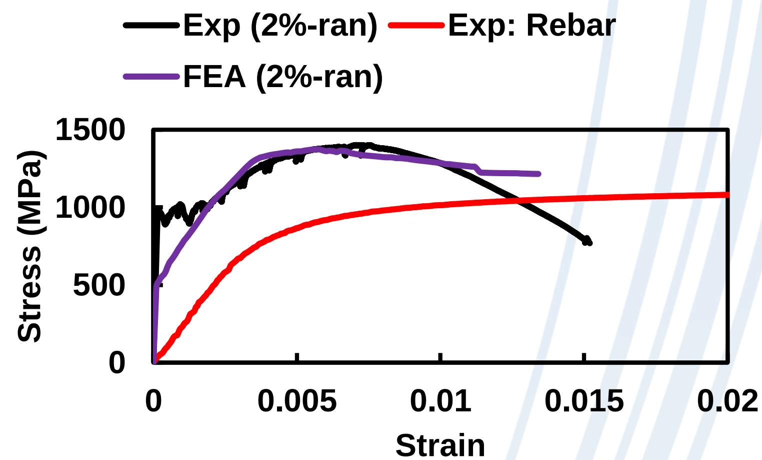


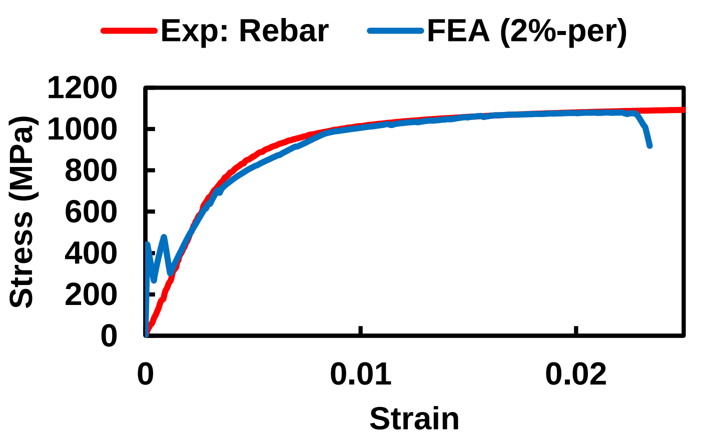
Data from	A1035 bars		
	E_r (GPa)	f_y (MPa)	f_{ult} (MPa)
Roy et al. 2017	222	700	1102

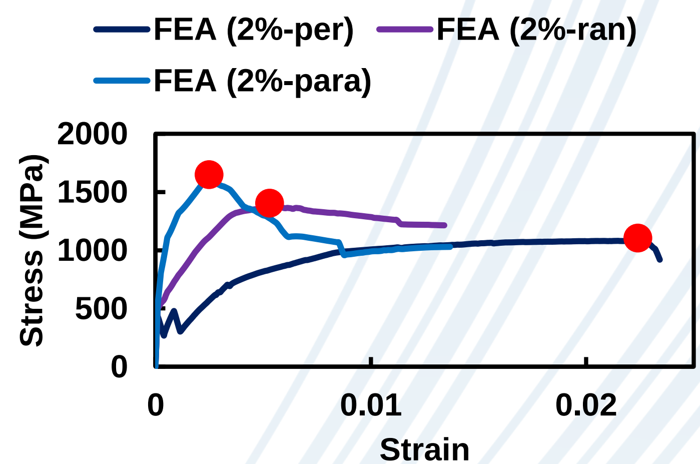
- Fiber data from tensile test on UHPC
- Bond-slip data from pullout test of rebar
- No slip considered for side bar
- $\sigma_{comp} = \frac{F_{peak}}{\pi {r_b}^2}$
- No slip in rebar inside elastic volume

Tensile test (effect of fiber orientation)

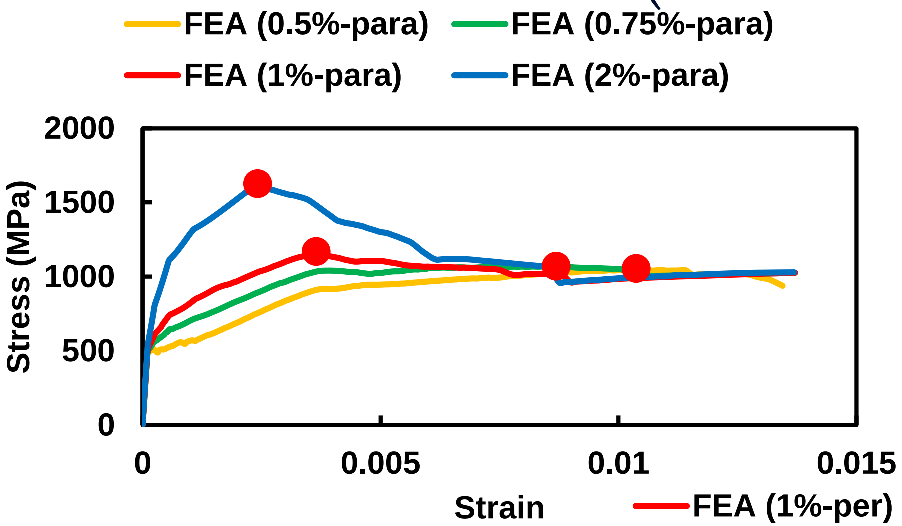


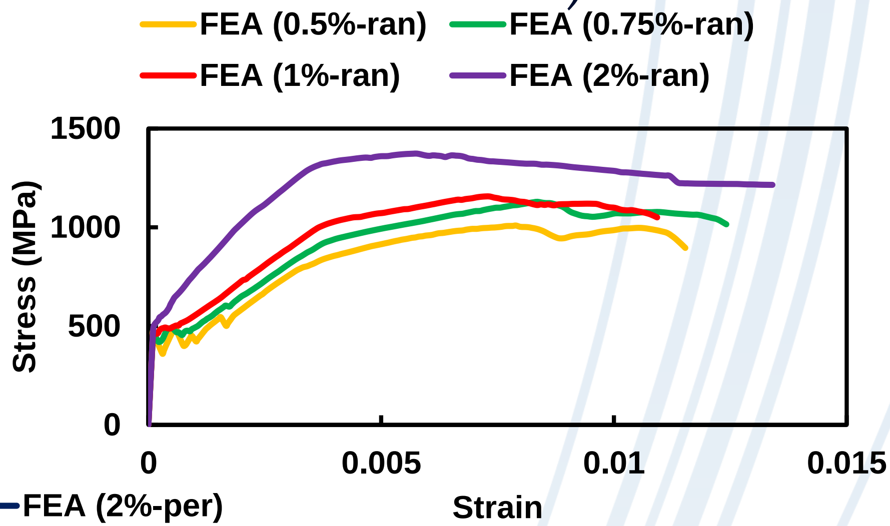


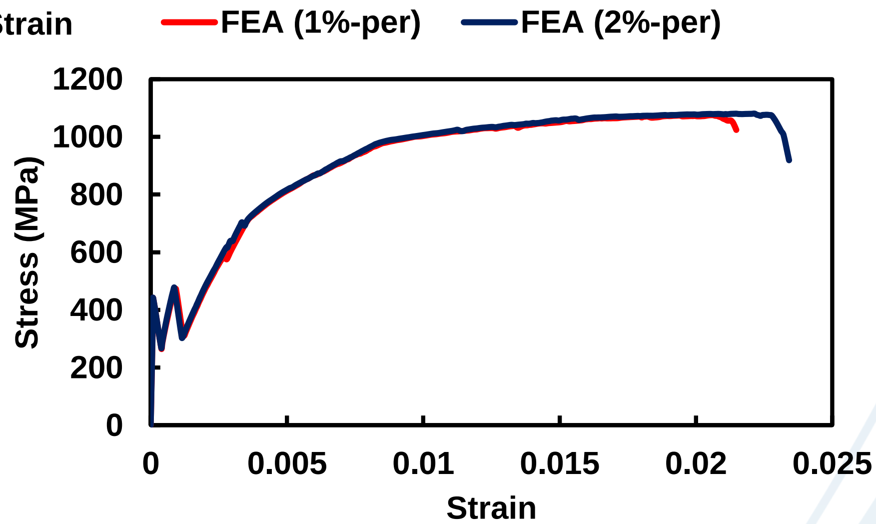




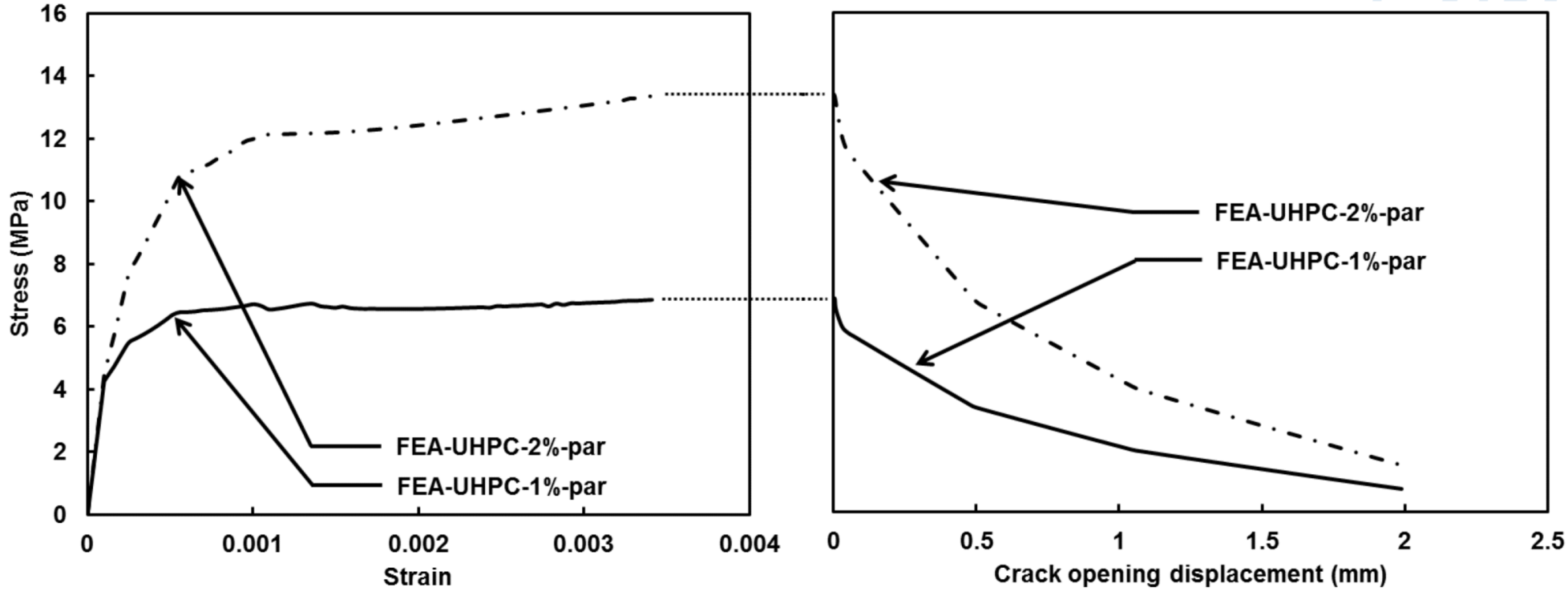
Tensile test (effect of fiber volume fraction)

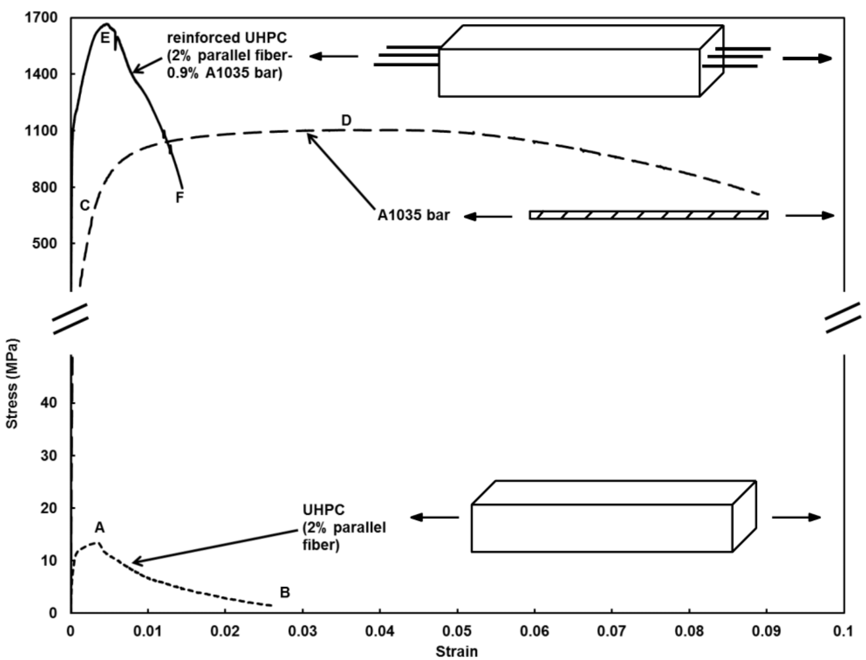


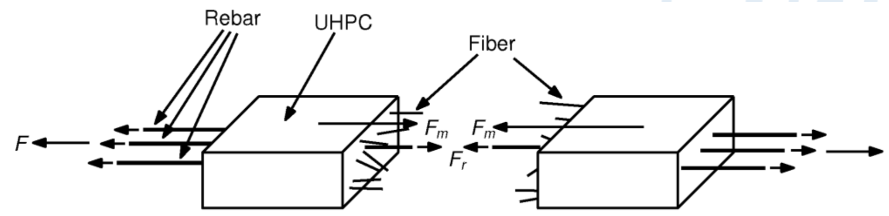




Discussion - ductility







F_m = Force in fiber-reinforced UHPC matrix, F_r = Force in rebar

From equilibrium, $F = F_m + F_r$

If $|\Delta F_m| < |\Delta F_r|$ → formation of multiple macro cracks → increase in ductility (1)

If $|\Delta F_m| > |\Delta F_r|$ → formation of one macro crack → loss of ductility (2)

where,

$$\Delta F_m = \Delta\sigma_m \times A_m \quad (3)$$

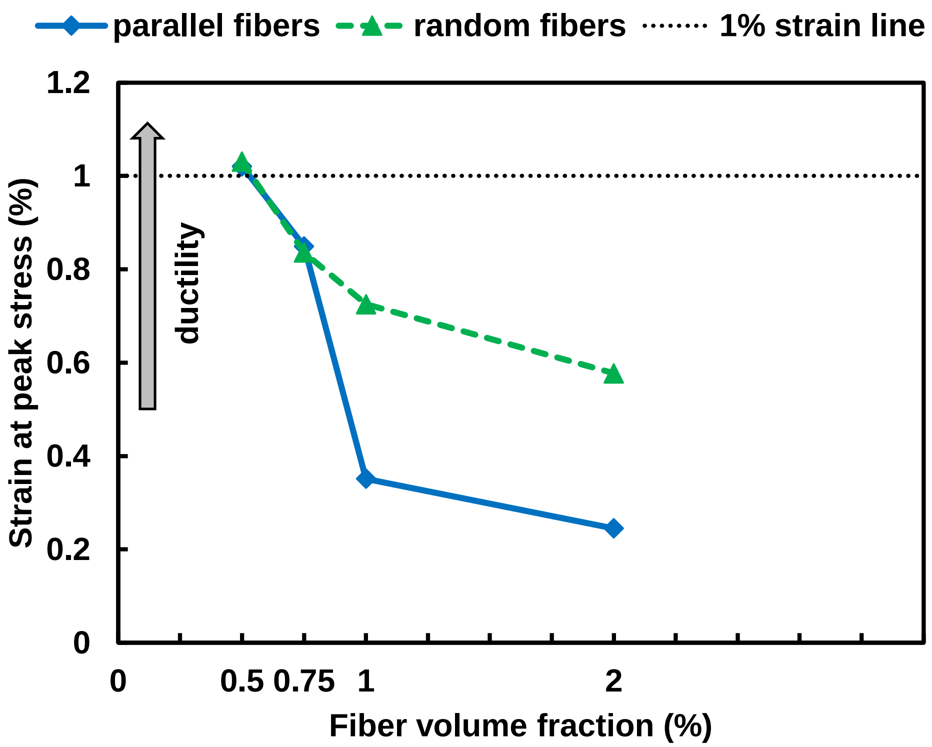
$$\Delta F_r = \Delta\sigma_r \times A_r \quad (4)$$

Specimen	ΔF_r (kN) [a]	ΔF_m (kN) [b]	Crack Width (mm)	
1%-par-A1035	28.5	12.5	0.15 [c]	$\lvert\Delta F_m\rvert < \lvert\Delta F_r\rvert$ (Equation (1))
1%-par-A1035	28.5	22.9	0.4 [d]	$\lvert\Delta F_m\rvert < \lvert\Delta F_r\rvert$ (Equation (1))
2%-par-A1035	28.5	21.9	0.15 [c]	$\lvert\Delta F_m\rvert < \lvert\Delta F_r\rvert$ (Equation (1))
2%-par-A1035	28.5	42.9	0.4 [d]	$\lvert\Delta F_m\rvert > \lvert\Delta F_r\rvert$ (Equation (2))

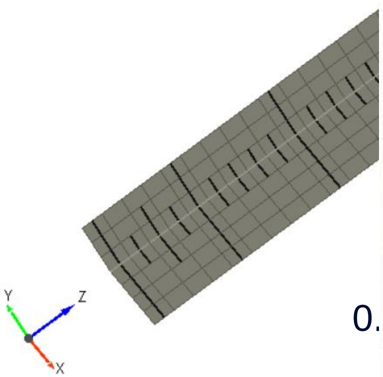
[a] $\Delta F_r = (f_t - f_y)A_r$. [b] $\Delta F_m = (f_t' - \sigma_w)A_m$; σ_w is the stress in UHPC at a specific crack width (w). [c] seawater; wetting and drying, [d] Dry air or protective membrane (Exposure data from ACI 224R-01).

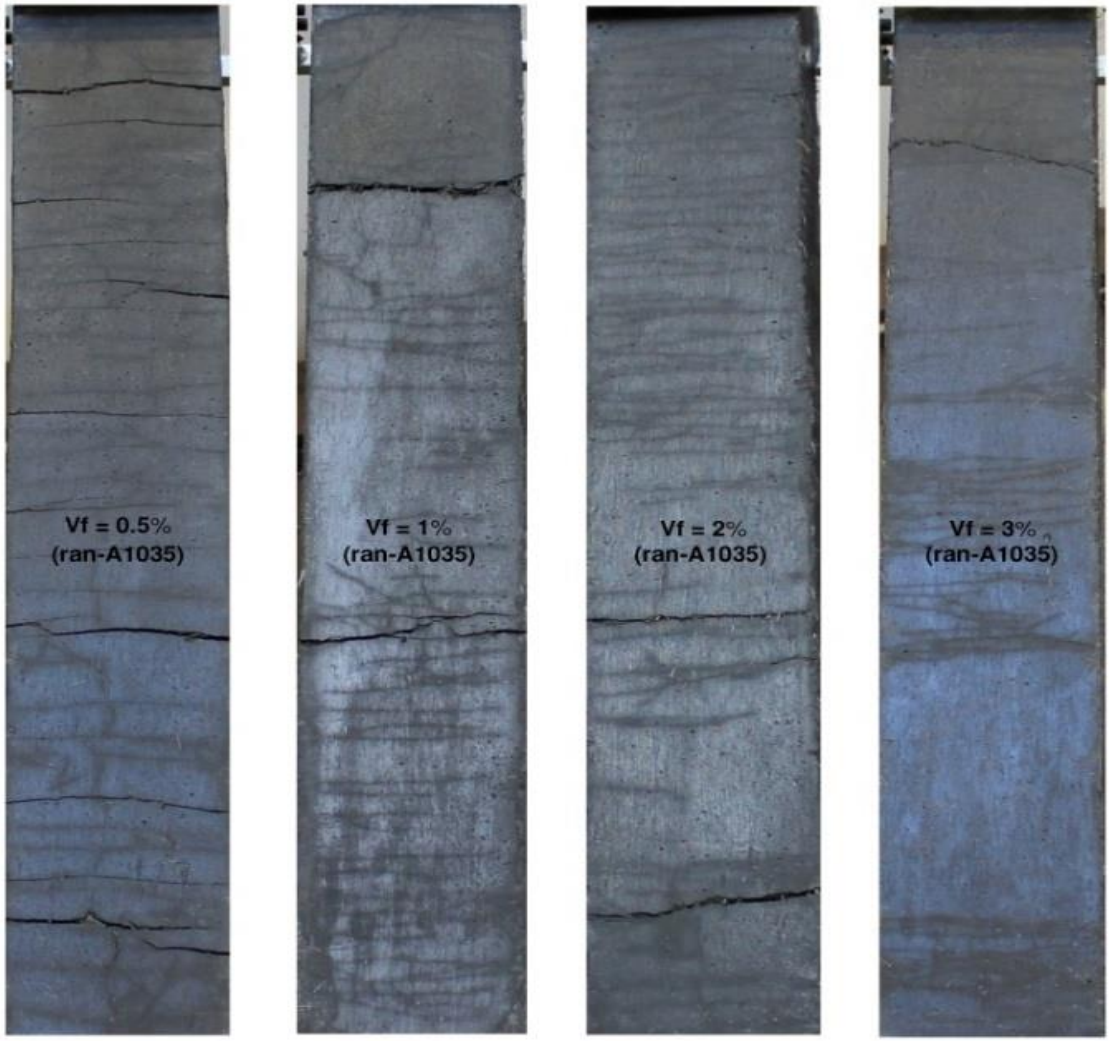
Recommendation for ductility

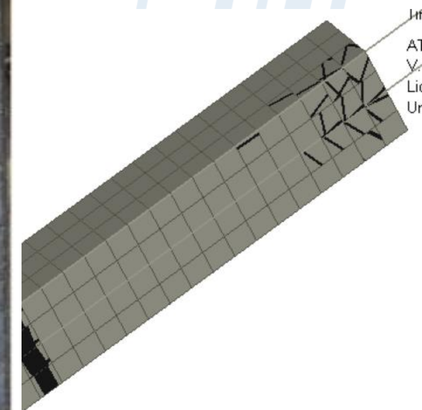
- RC design – min. 0.5% strain for rebar (tension controlled)
- Reinforced UHPC – 1% strain



- 0.5% fibers recommended for ductility







0.

bers

Conclusions

- A computationally efficient method of modeling UHPC proposed
- Fiber modeled as smeared reinforcement
- Bond between UHPC and rebar investigated
- Effect of fiber volume fraction and fiber orientation on uniaxial tensile behavior of reinforced UHPC investigated
- Recommendation on fiber volume fraction made based on ductility criteria

Acknowledgments

Department of Homeland Security (DHS), USA

Department of Civil and Environmental Engineering, UConn

Fellowships: NorthEast Transportation Technician Certification Program (NETTCP); Graduate School at UConn

Cervenka Consulting