Linking Flow-Induced Fiber Orientation in Fresh UHPC and Hardened UHPC Tensile Characteristics: A Numerical Framework

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American Concrete Institute

Acknowledgement

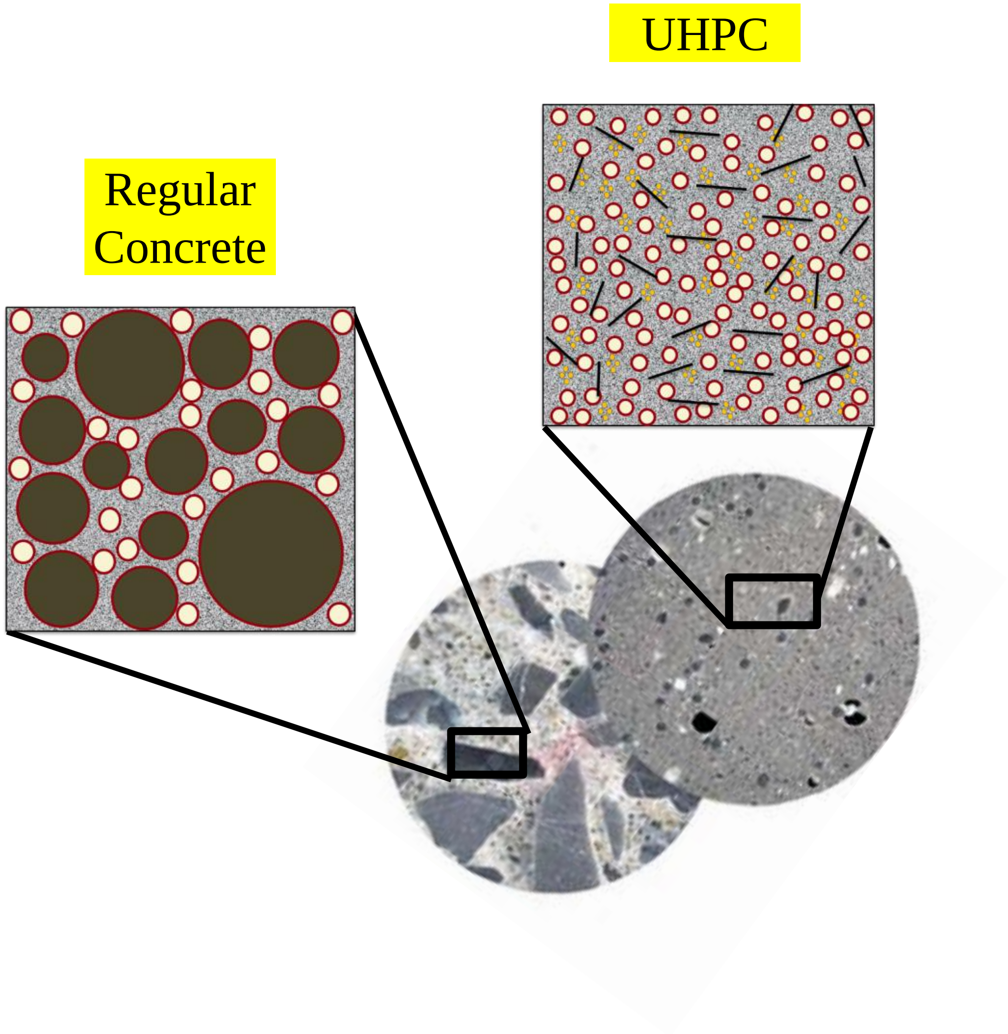
Colleagues:

- Dr. Mohammed Alnaggar, Senior Research Scientist, Oakridge National Laboratory

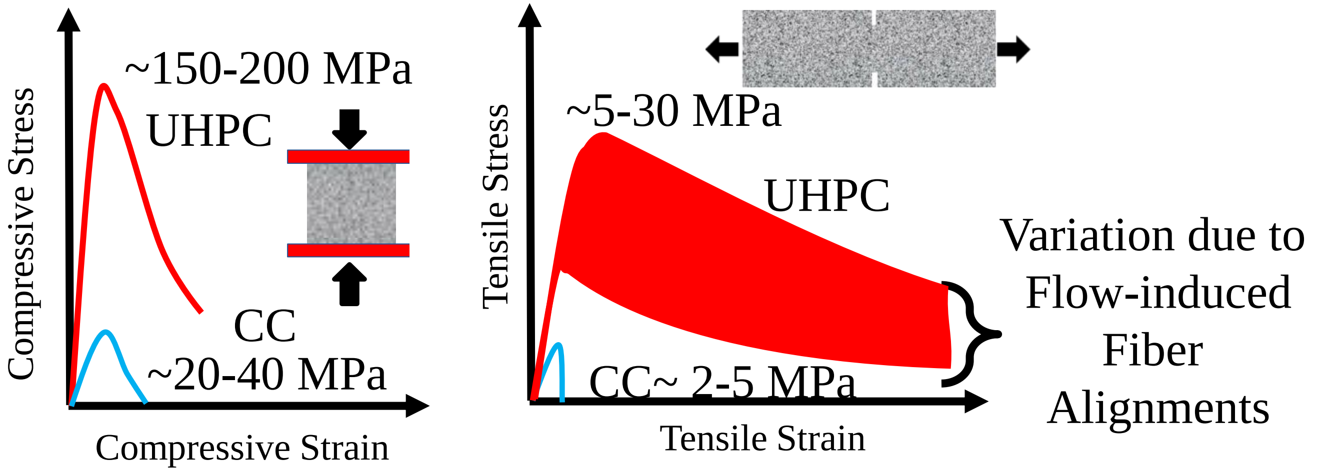
- Dr. Shady Gomma, Post-doc, Northwestern University

Center for Computational Innovations, RPI

Introduction

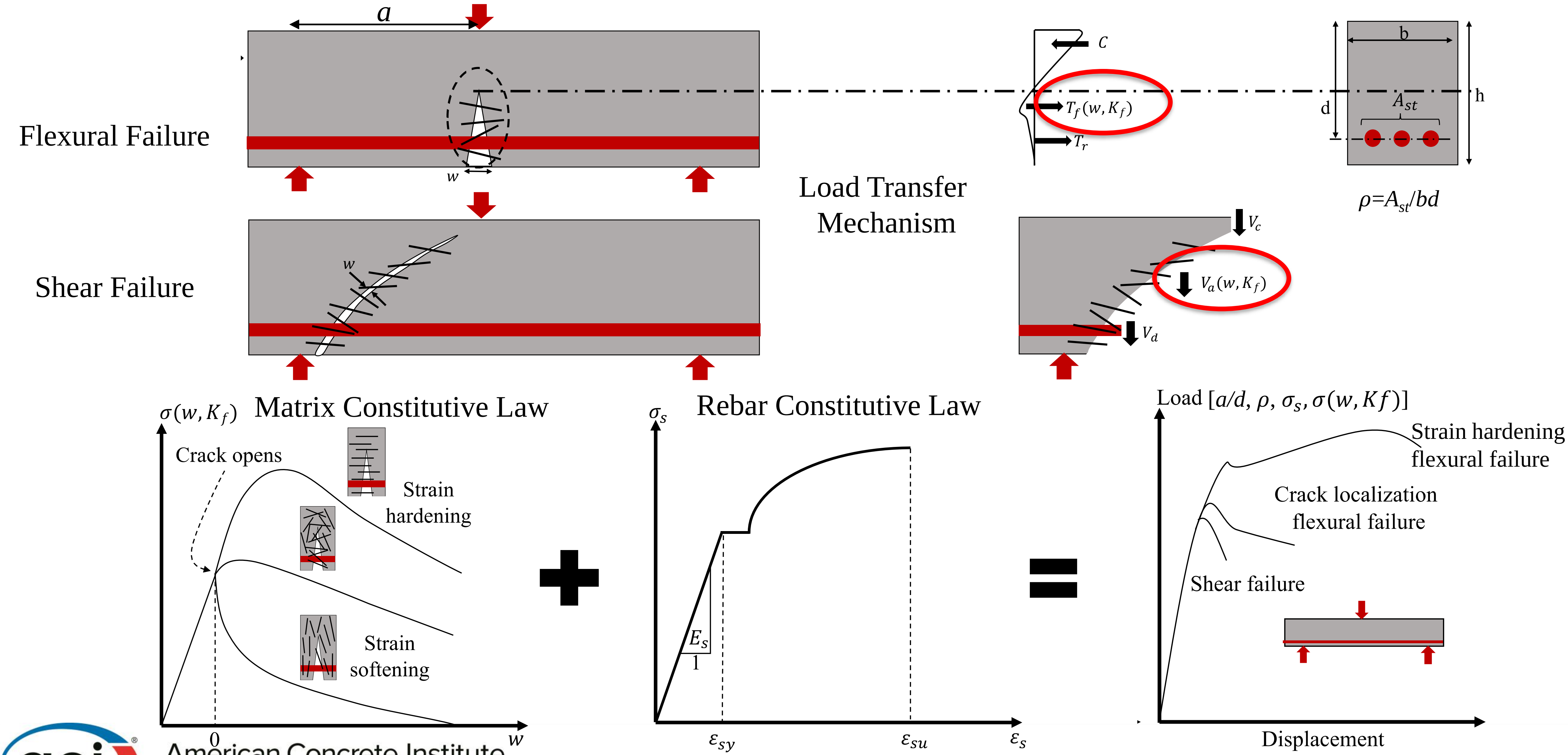


UHPC Material Properties



Ref: Ullah, Rahat, et al. "Ultra-high-performance concrete (UHPC): A state-of-the-art review." *Materials* 15.12 (2022): 4131.

Understanding UHPC Structural Behavior



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Overarching Goal

Flow-induced Fiber Orientation

Quantitative Identification of Fiber Orientation

Constitutive Behavior at Meso-scale

+

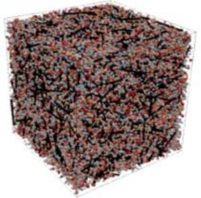
Reinforcement Constitutive Modelling

+

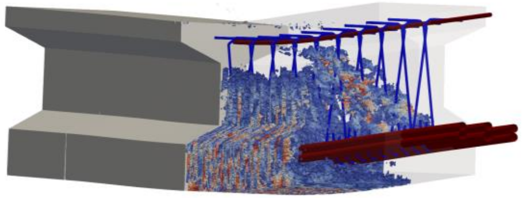
Fiber-matrix Interaction

Mechanics of Interplay for Fiber and Rebar

Multi-scale Linking



Mesoscale

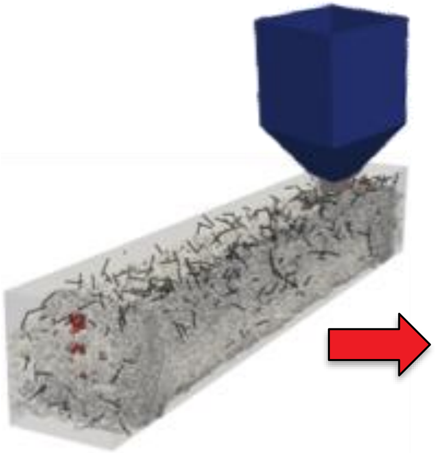


Structural scale

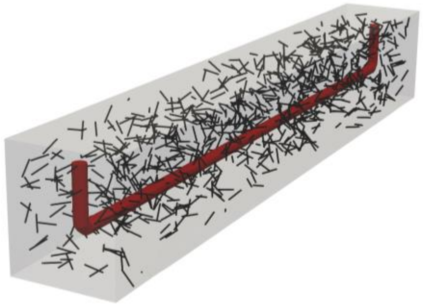
Energy based Coarse-Graining

Computationally Efficient Modelling at Structural Scale

Multi-state Linking



Fluid/Fresh State

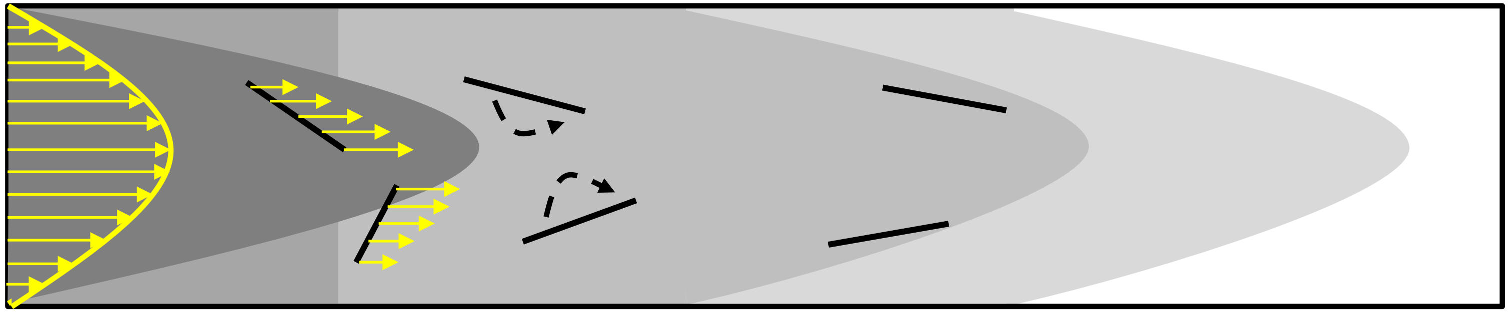


Solid/Hardened State

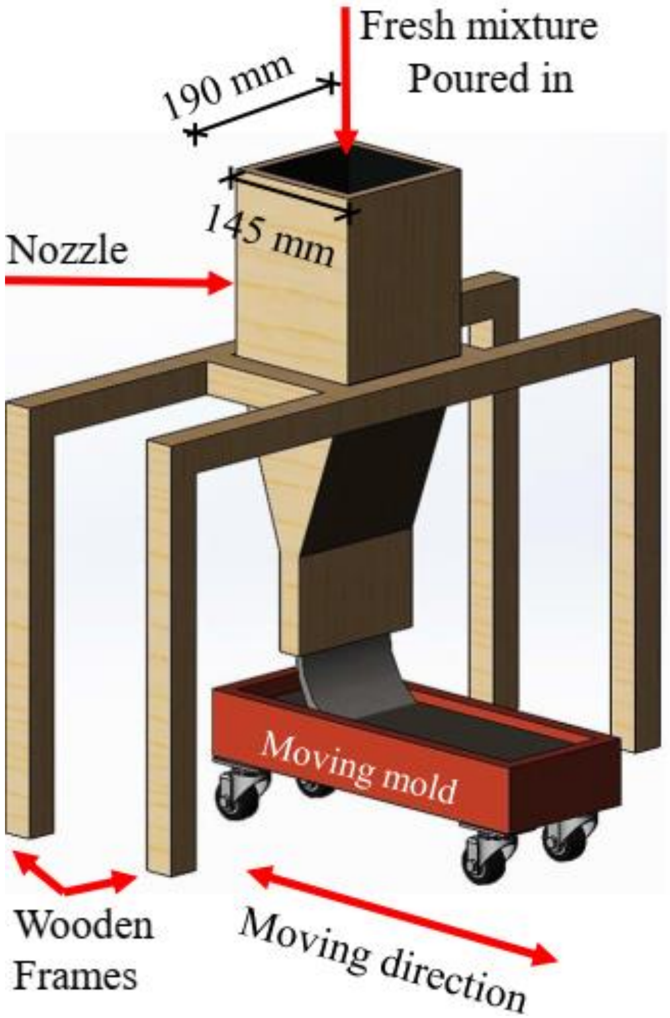
Questions Addressed in Current Study

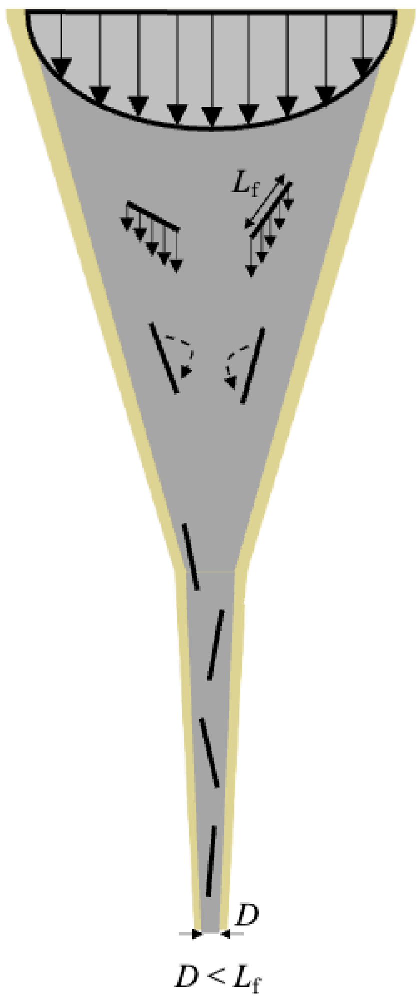
- Can we numerically predict fiber orientation coupled with UHPC flow?
- Can we use that description to quantitatively measure fiber orientation as an input for solid model from fresh UHPC flow behavior?
- Can we predict behavior of hardened UHPC from predicted fiber orientations by coupling the flow model to solid model?

Fiber Orientation Prediction in fresh state of UHPC → Validate with hardened UHPC mechanical behavior



Experimental Program: Nozzle-based Casting Process of UHPC

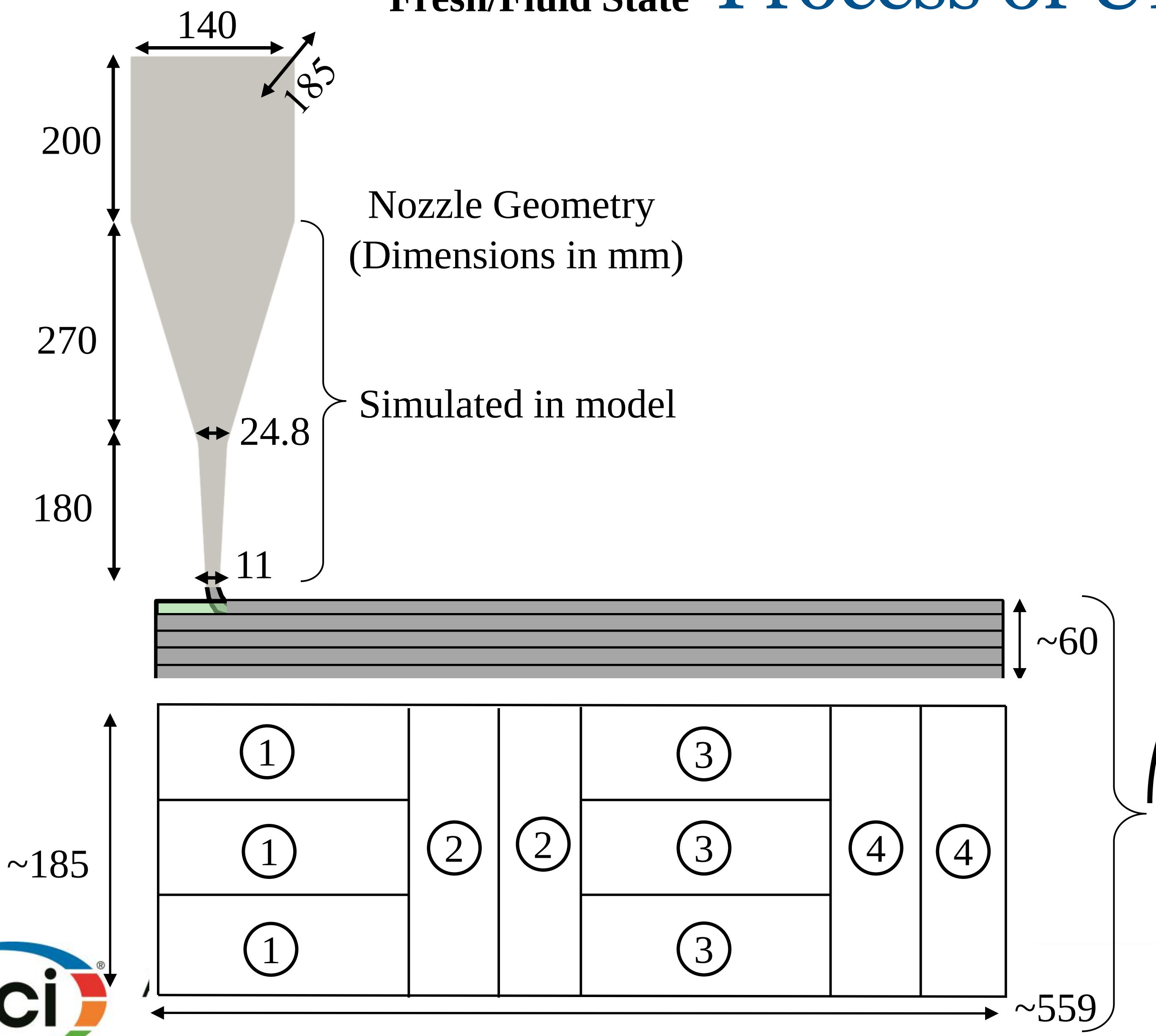




Ref: Gomaa, Shady. Corrosion of Steel Plate Girder Bridges and Rehabilitation Using UHPC. Diss. Rensselaer Polytechnic Institute, 2020.

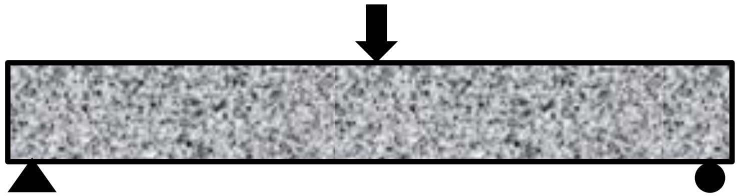
Experimental Program: Nozzle-based Casting Process of UHPC

Fresh/Fluid State

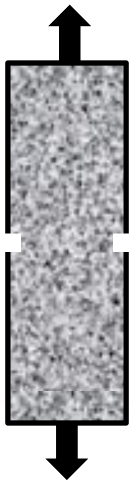


Hardened/Solid State

Flexural Test on
Cast Slab



Direct Tension Test on
Notched Prisms

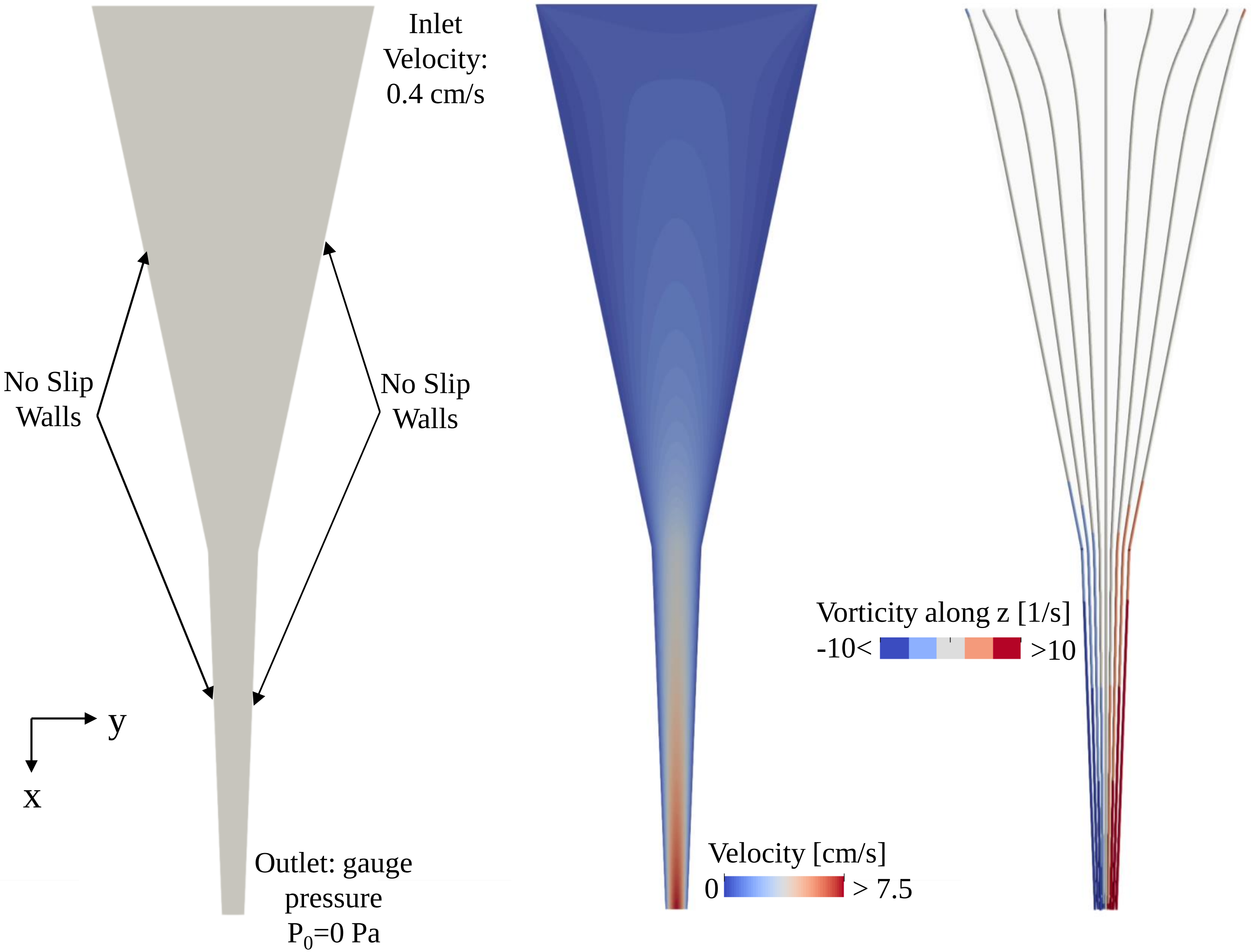


Modeling Fresh UHPC Flow

Single phase fluid motion with Navier-Stokes Equation

$$\rho\left[\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v}\cdot\nabla\boldsymbol{v}\right] = \nabla\cdot\boldsymbol{\sigma} + \boldsymbol{f} \quad \text{and}$$

$$\nabla\cdot\boldsymbol{v} = 0$$



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Predicting Fiber Orientation

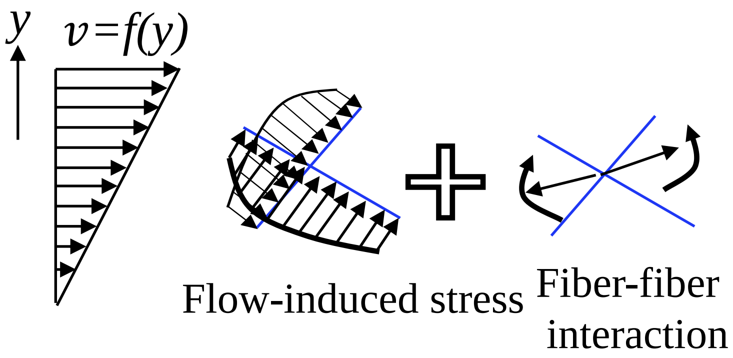
Jeffery's equations

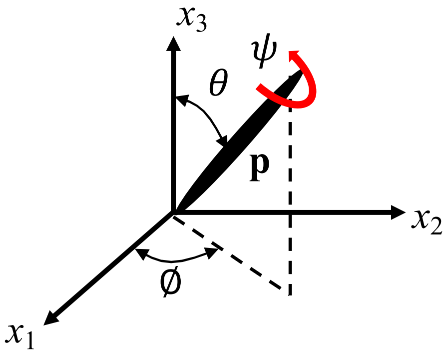
$$\frac{d\psi}{dt} = -\nabla_s . (\psi\dot{\mathbf{p}})$$

Folgar-Tucker Modifications

$$\frac{d\psi}{dt} = -\nabla_s \cdot \left(\psi\left(\underbrace{-\mathbf{W}\cdot\mathbf{p} + \lambda(\mathbf{D}\cdot\mathbf{p}}_{\text{Flow-induced stress}} - \underbrace{\mathbf{D}:\mathbf{ppp})}_{\text{Internal stress}}\right) - \underbrace{C_I\dot{\gamma}\nabla_s\psi}_{\text{Fiber-fiber interaction}}\right)$$

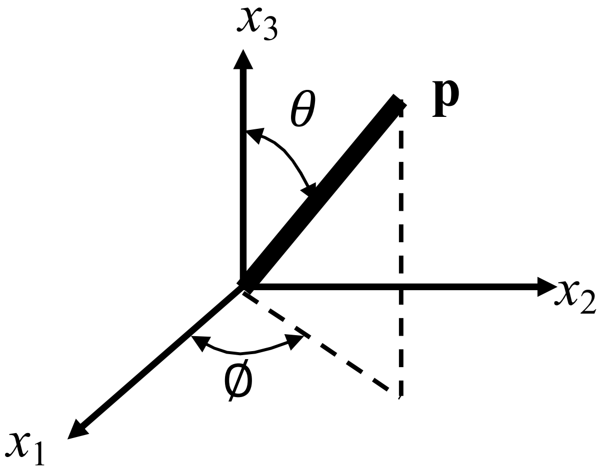
Ellipsoid Based Formulation

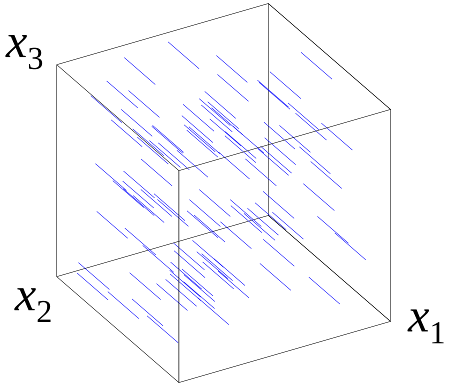




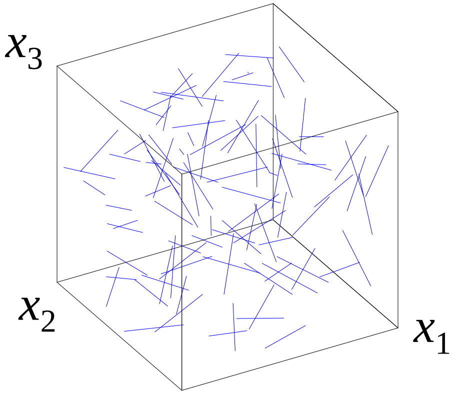
Advani-Tucker Modifications (1987)

$$\frac{d\mathbf{A}_2}{dt} = -(\mathbf{W}\cdot\mathbf{A}_2 - \mathbf{A}_2\cdot\mathbf{W}) + \lambda(\mathbf{D}\cdot\mathbf{A}_2 + \mathbf{A}_2\cdot\mathbf{D} - 2\mathbf{A}_4:\mathbf{D}) + 2C_I\dot{\gamma}(\mathbf{I} - 3\mathbf{A}_2)$$





$$\mathbf{A}_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



$$\mathbf{A}_2 = \begin{bmatrix} 1/3 & 0 & 0 \\ 0 & 1/3 & 0 \\ 0 & 0 & 1/3 \end{bmatrix}$$

$$\mathbf{A_i} = \oint_{\Omega} \psi(\mathbf{p})\mathbf{pppp}\cdots(i\ \ times)d\theta d\phi$$

$$\mathbf{W} = \frac{1}{2}(\nabla^T\mathbf{v} - \nabla\mathbf{v}) \quad \mathbf{D} = \frac{1}{2}(\nabla\mathbf{v} + \nabla^T\mathbf{v})$$

Predicting Fiber Orientation

Invariant-based optimal fitting closure approximation (Chung and Kwon, 2002)

$$\mathbf{A}_4 = f(\mathbf{A}_2) = f(I_2, I_3)$$

$$A_{ijkl} = \beta_1 S(\delta_{ij}\delta_{kl}) + \beta_2 S(\delta_{ij}A_{kl}) + \beta_3 S(A_{ij}A_{kl}) + \beta_4 S(\delta_{ij}A_{km}A_{ml}) + \beta_5 S(A_{ij}A_{km}A_{ml}) + \beta_6 S(A_{im}A_{mj}A_{kn}A_{nl})$$

$$S(T_{a_1a_2a_3....a_n}) = \frac{1}{n!}\sum_{\text{permutations}} T_{a_1a_2...a_n} \qquad \beta_i = f(I_2, I_3)$$

Evolution of Orientation Tensor with time

$$\frac{d\mathbf{A}_2}{dt} = -(\mathbf{W}\cdot\mathbf{A}_2 - \mathbf{A}_2\cdot\mathbf{W}) + \lambda(\mathbf{D}\cdot\mathbf{A}_2 + \mathbf{A}_2\cdot\mathbf{D} - 2\mathbf{A}_4\!:\!\mathbf{D}) + 2C_I\dot{\gamma}(\mathbf{I} - 3\mathbf{A}_2)$$

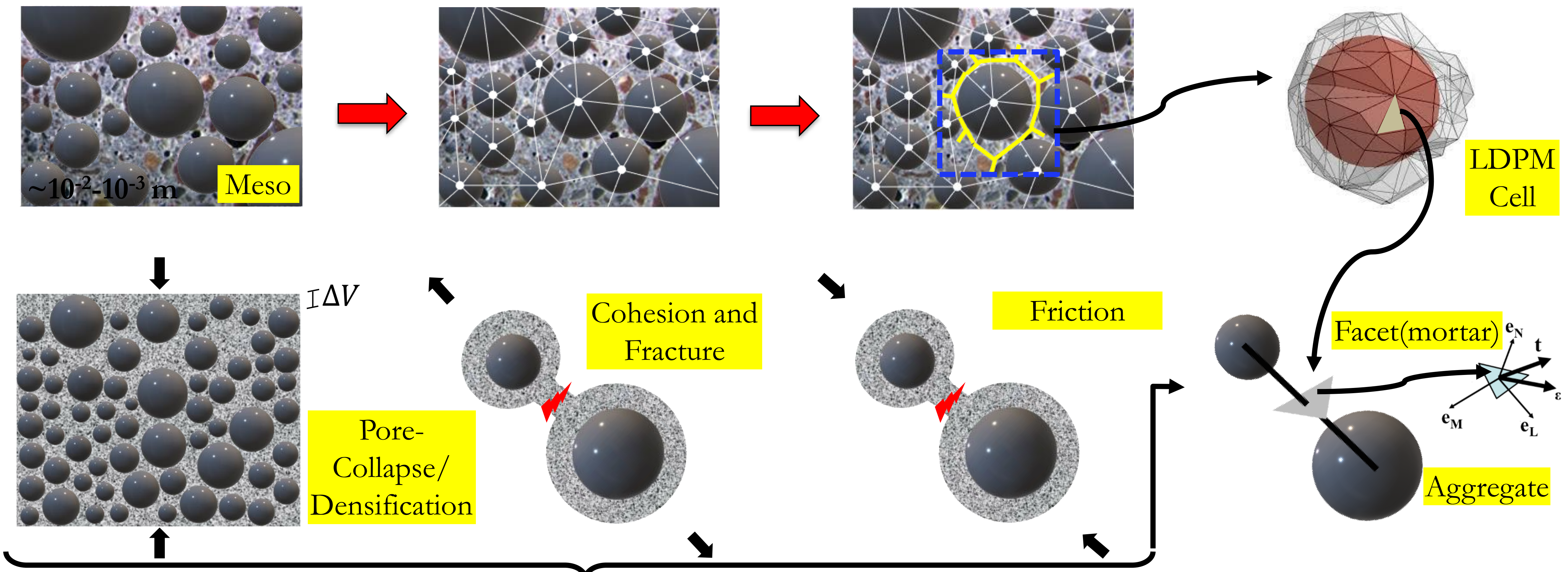
Single phase fluid motion with Navier-Stokes Equation

$$\rho\left[\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v}\cdot\nabla\boldsymbol{v}\right] = \nabla\cdot\boldsymbol{\sigma} + \boldsymbol{f} \quad \text{and} \quad \nabla\cdot\boldsymbol{v} = 0$$

One-way coupling

Modeling of Hardened UHPC

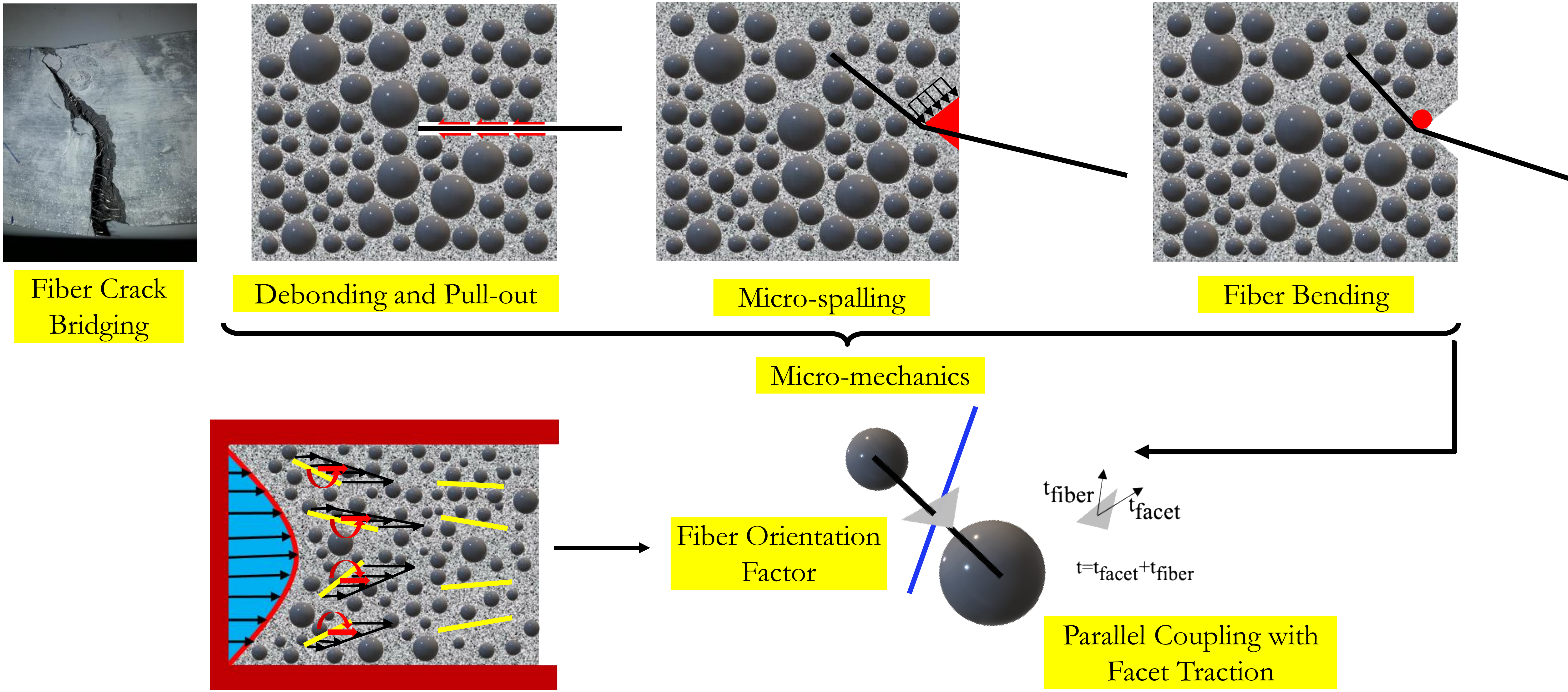
Lattice Discrete Particle Modeling (LDPM)



Ref: Cusatis, Gianluca, Daniele Pelessone, and Andrea Mencarelli. "Lattice discrete particle model (LDPM) for failure behavior of concrete. I: Theory." Cement and Concrete Composites 33.9 (2011): 881-890.

Modeling of Hardened UHPC

Lattice Discrete Particle Modeling for Fiber-reinforced Concrete (LDPM-F)



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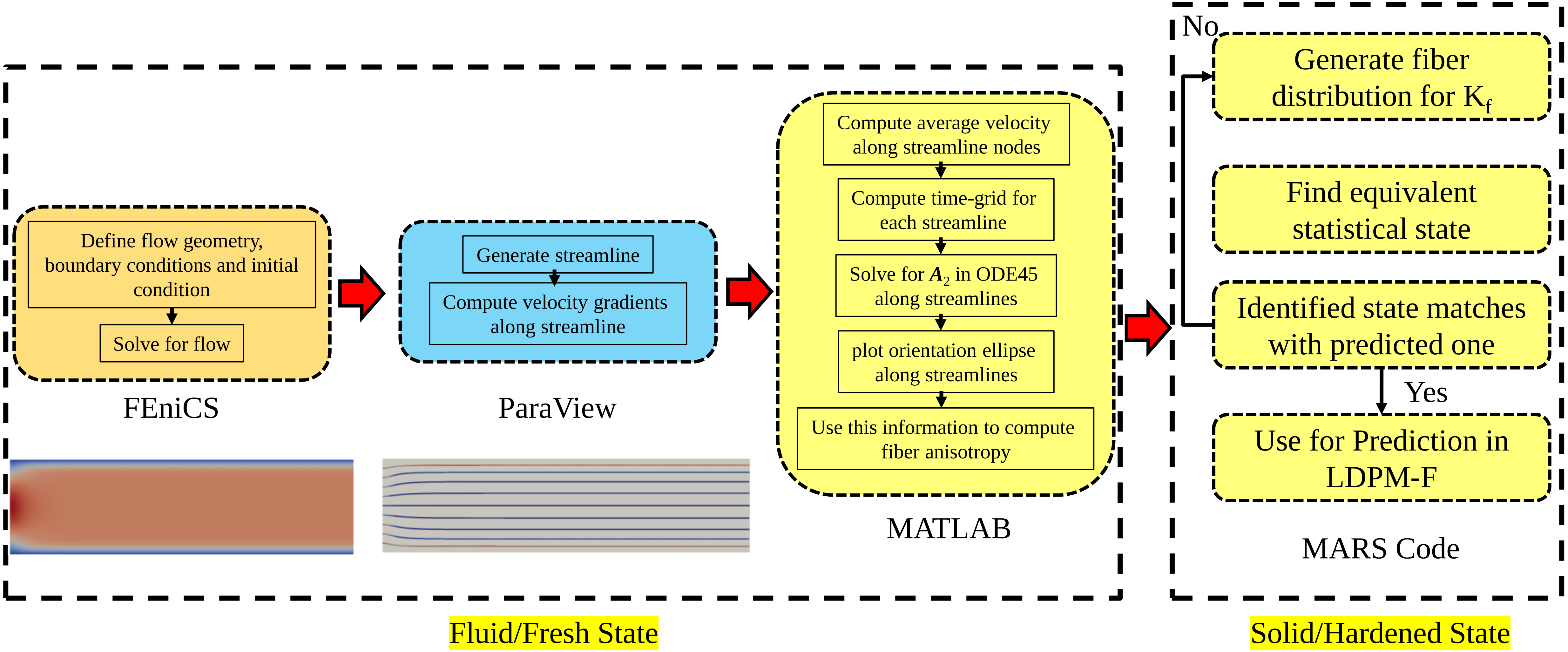
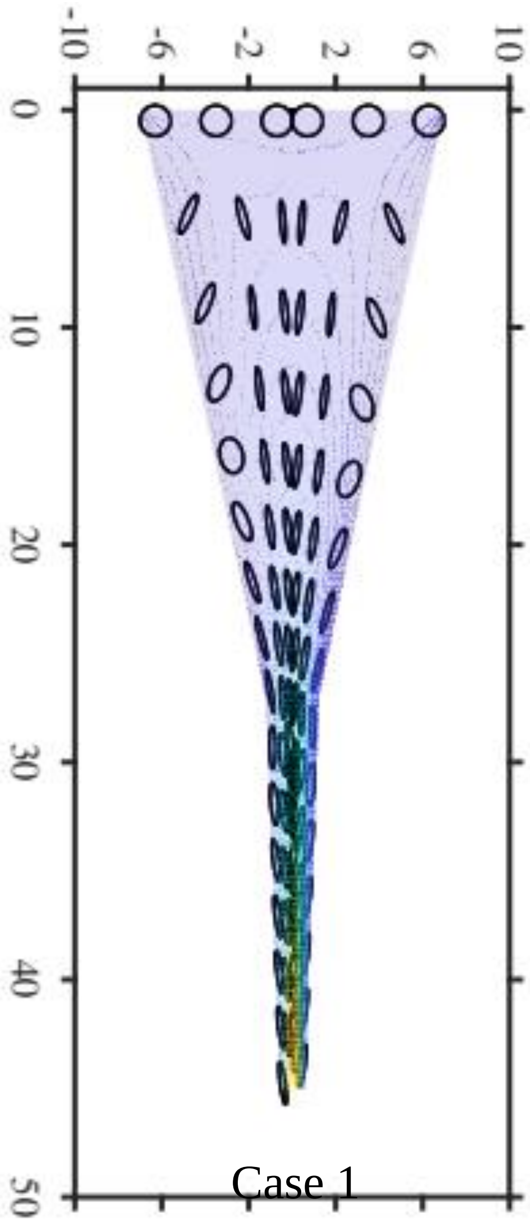
Ref: Schauffert, Edward A., and Gianluca Cusatis. "Lattice discrete particle model for fiber-reinforced concrete. I: Theory." *Journal of Engineering Mechanics* 138.7 (2012): 826-833.33.9 (2011): 881-890.

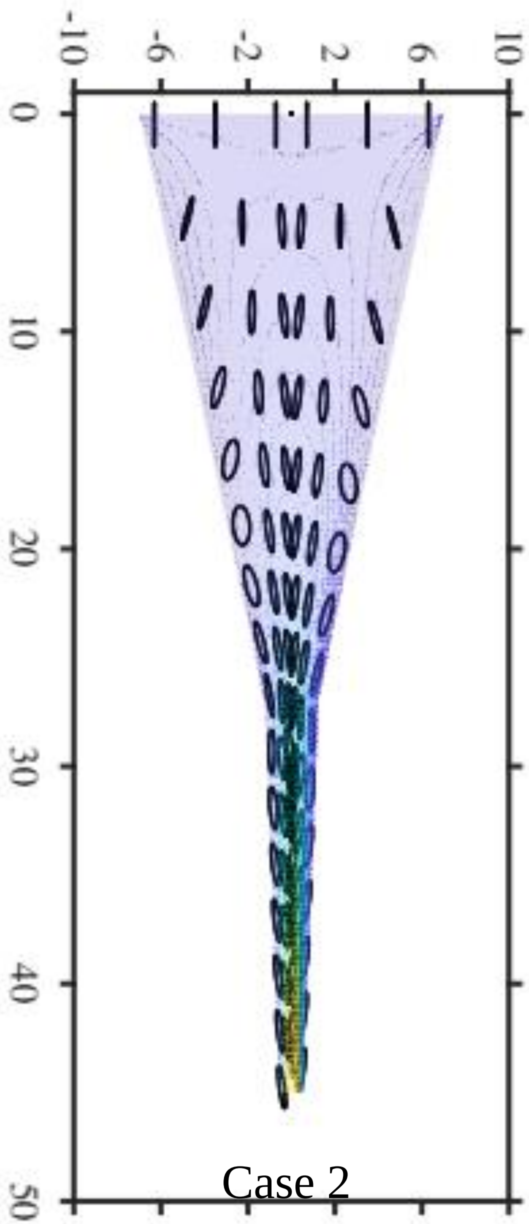
Linking Computational Models



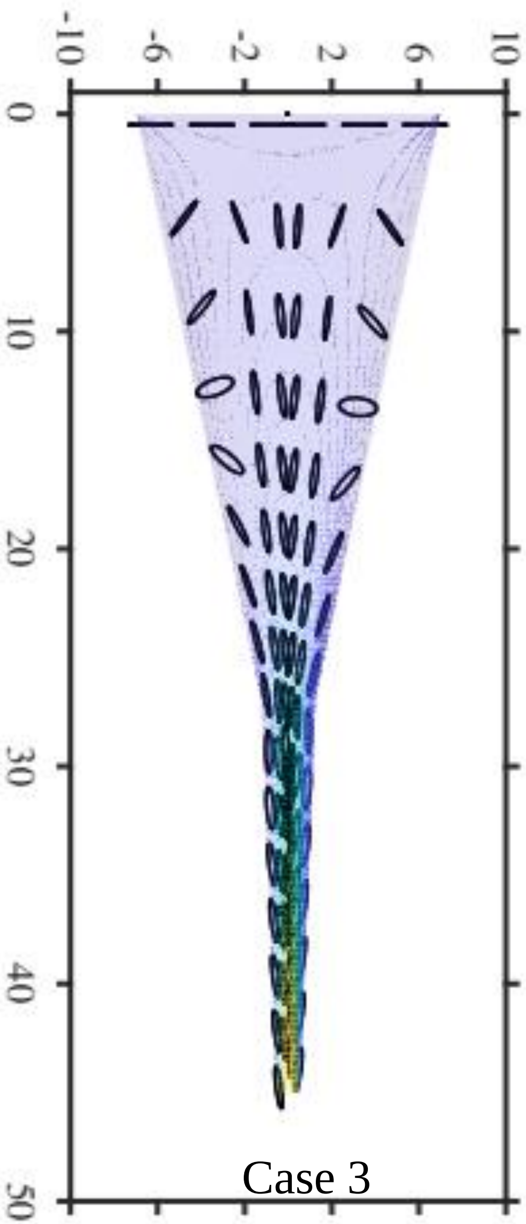
Predicted Fiber Orientation



Case 1

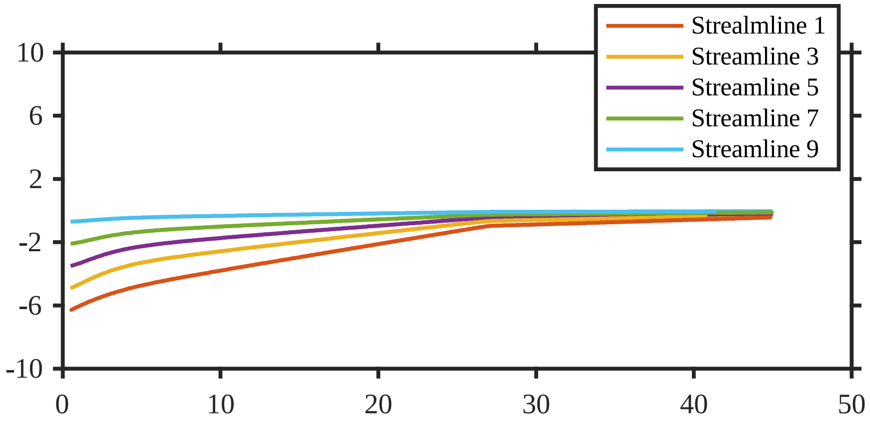


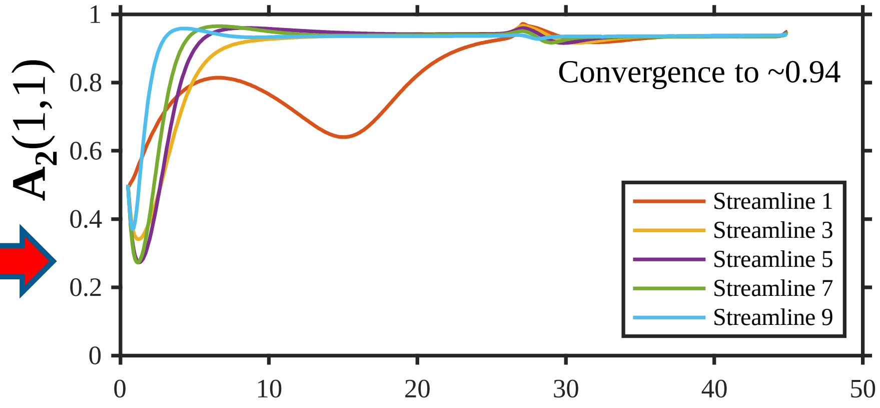
Case 2



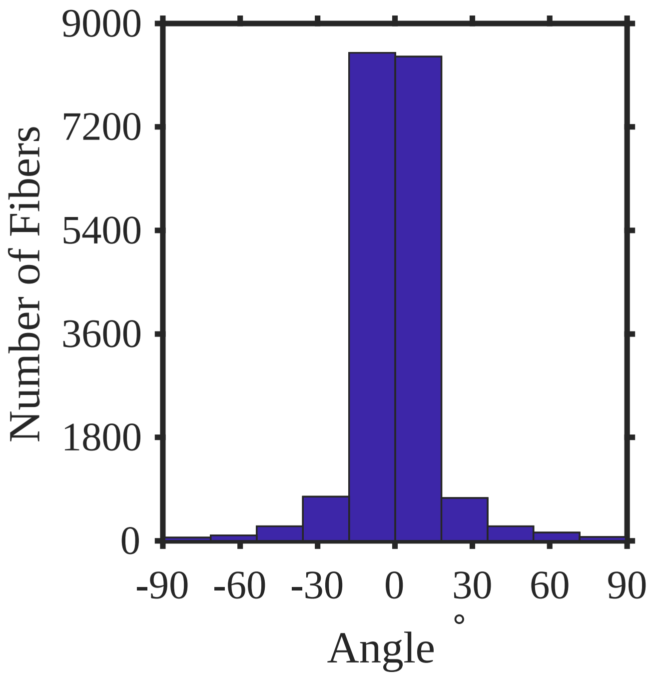
Case 3

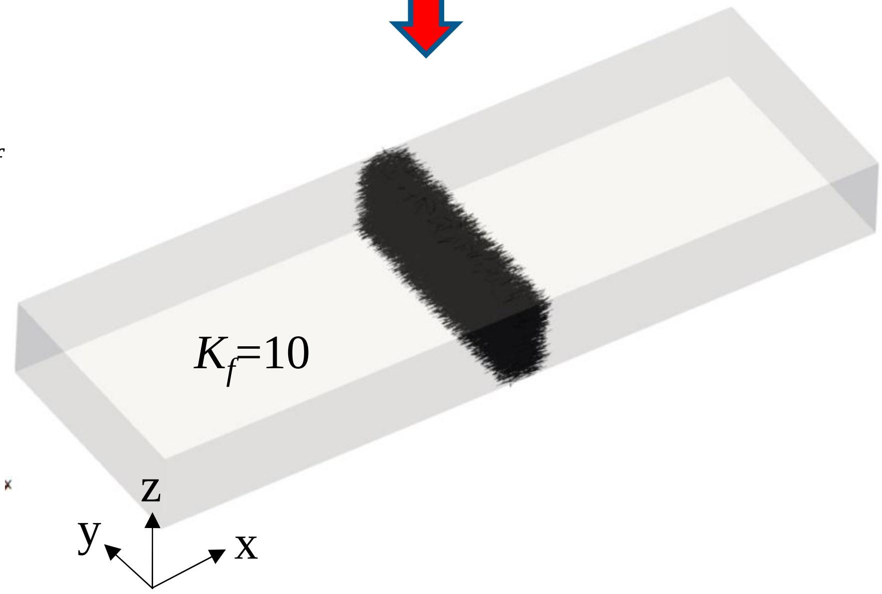
Calibration of Fiber Orientation Factor for LDPM-F





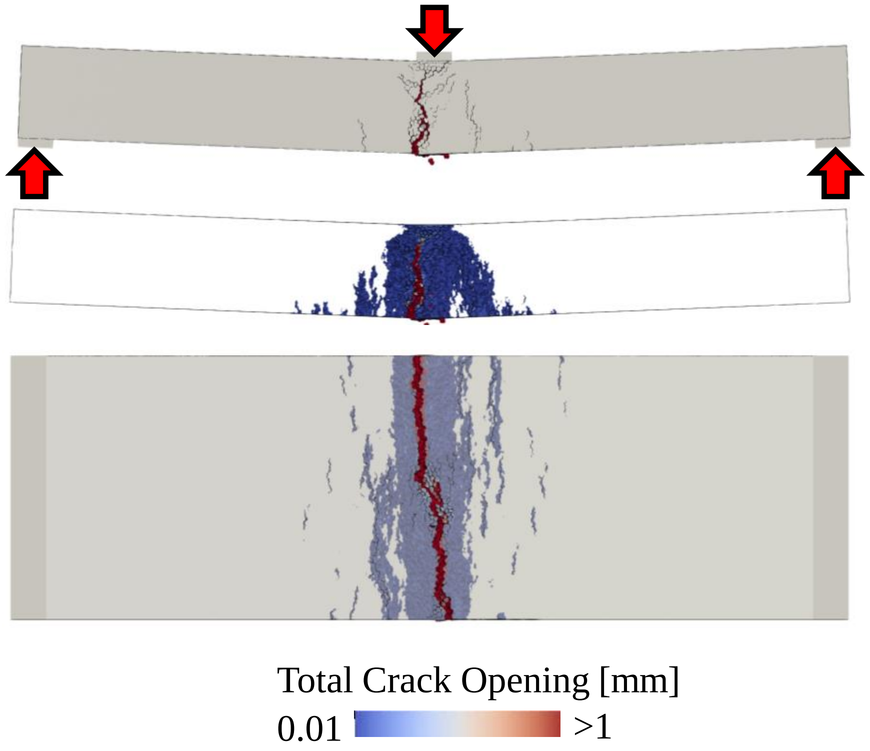
Calibrate K_f

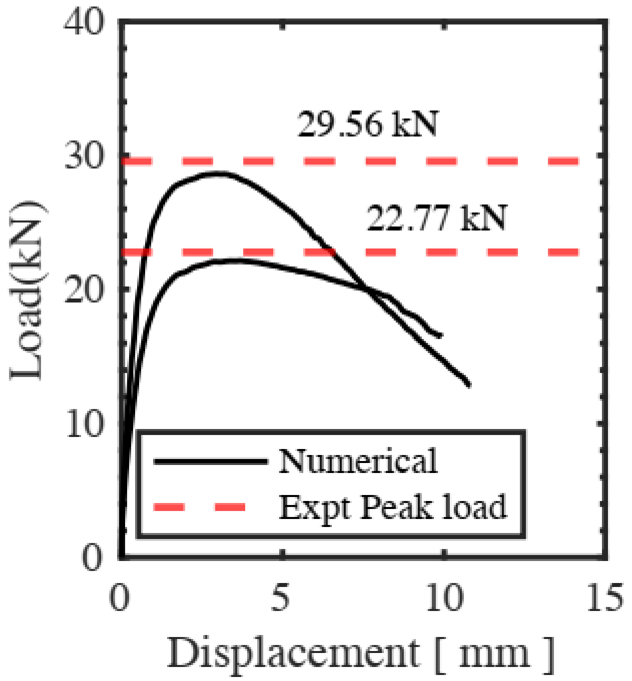




Numerical Validation of Experimental Predictions

Three Point Flexural Test for Slabs





Numerical Validation of Experimental Predictions

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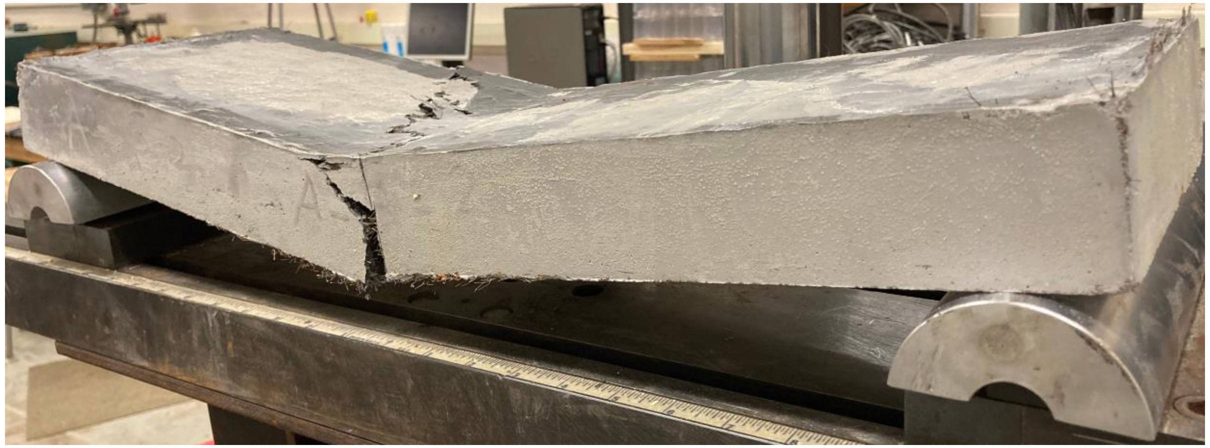
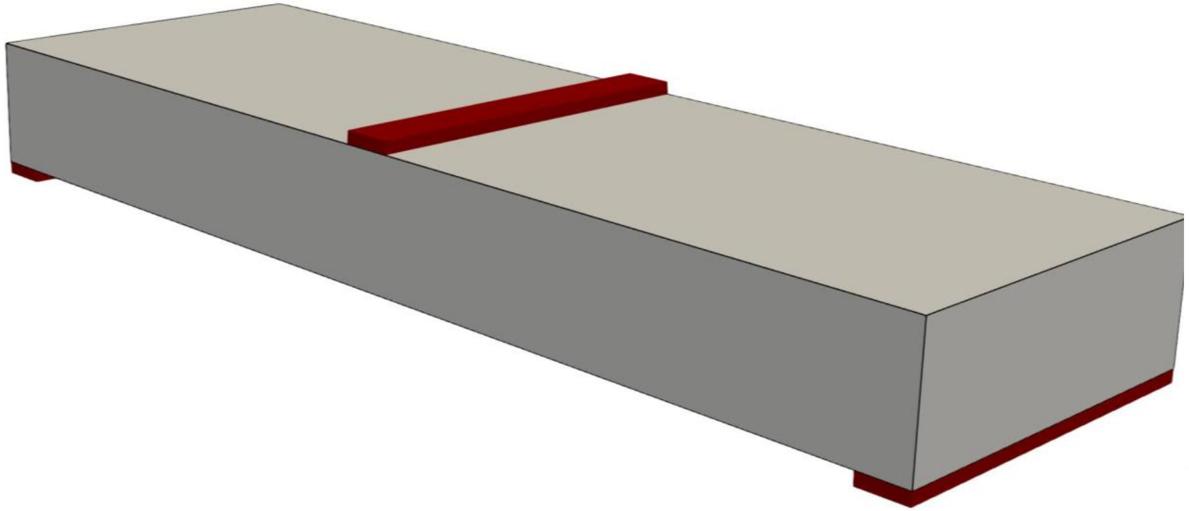
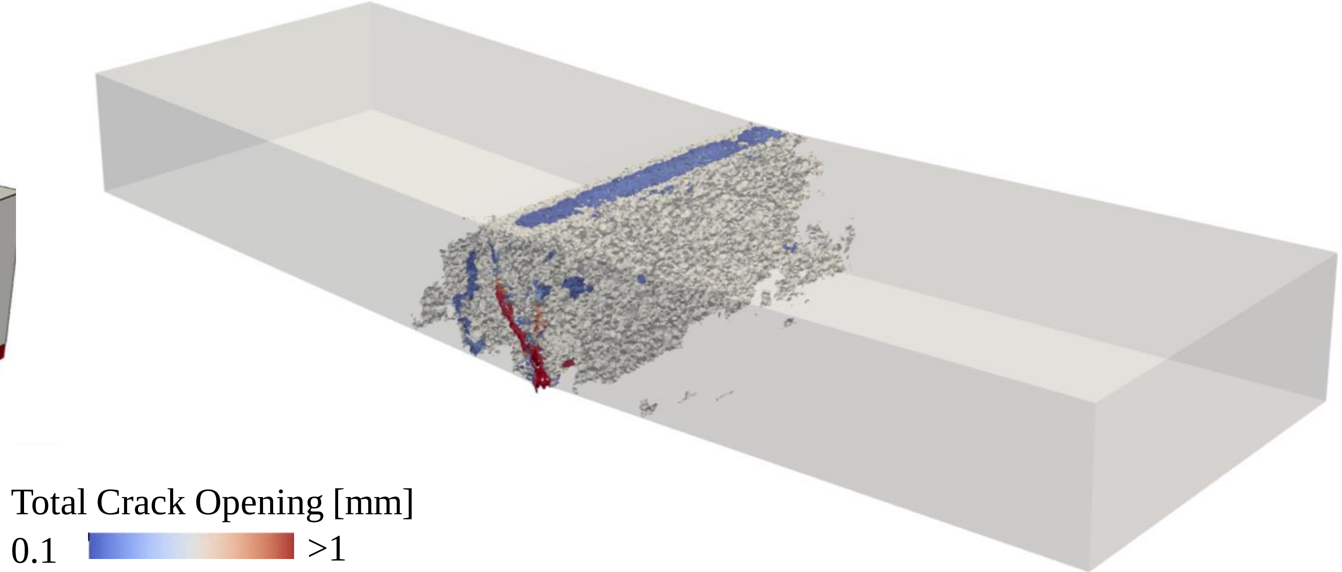
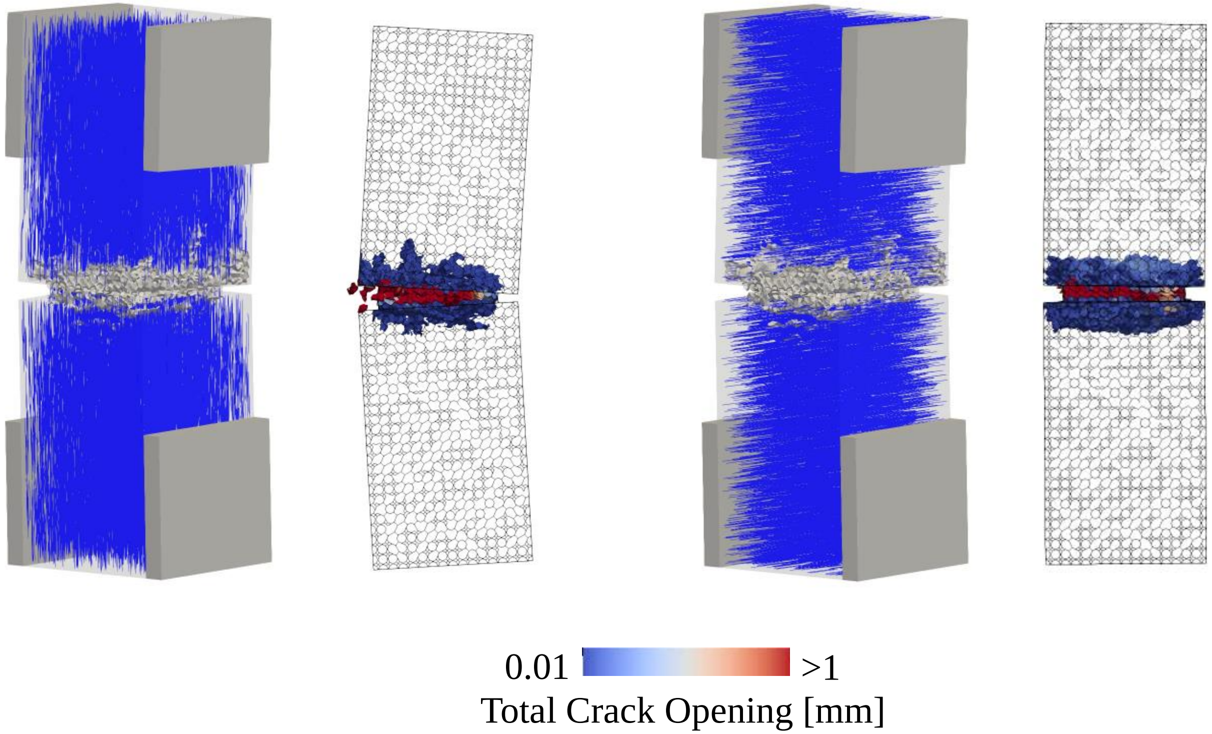


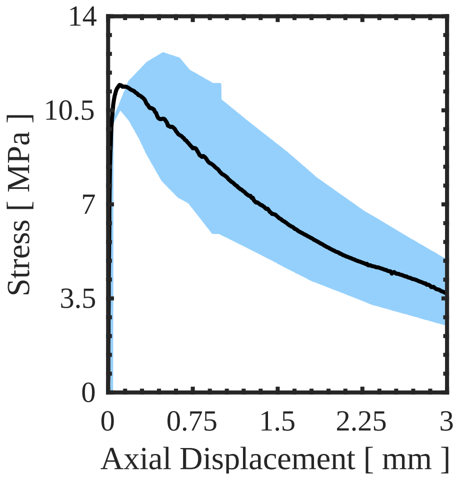


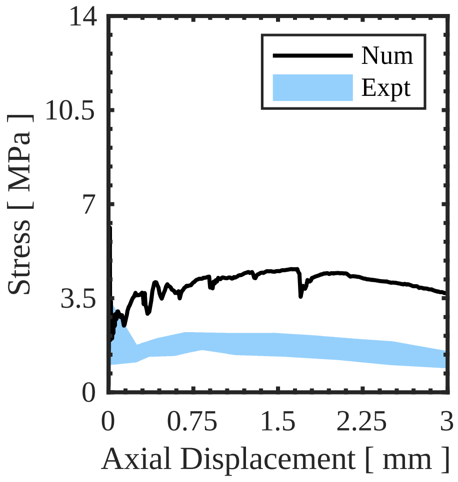


Numerical Validation of Experimental Predictions

Direct Tension Test







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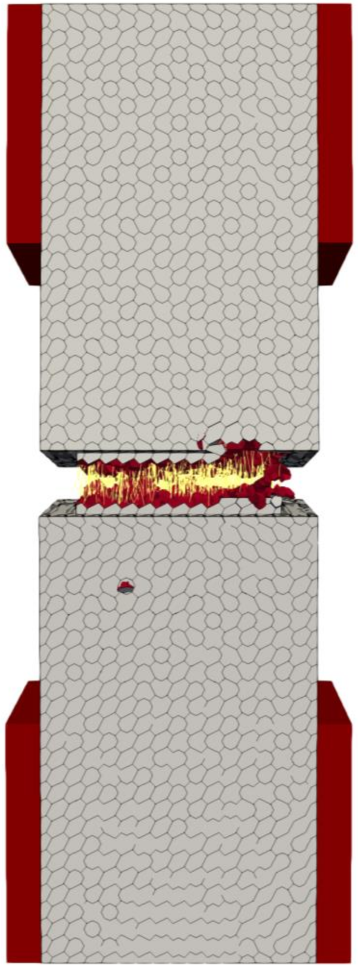

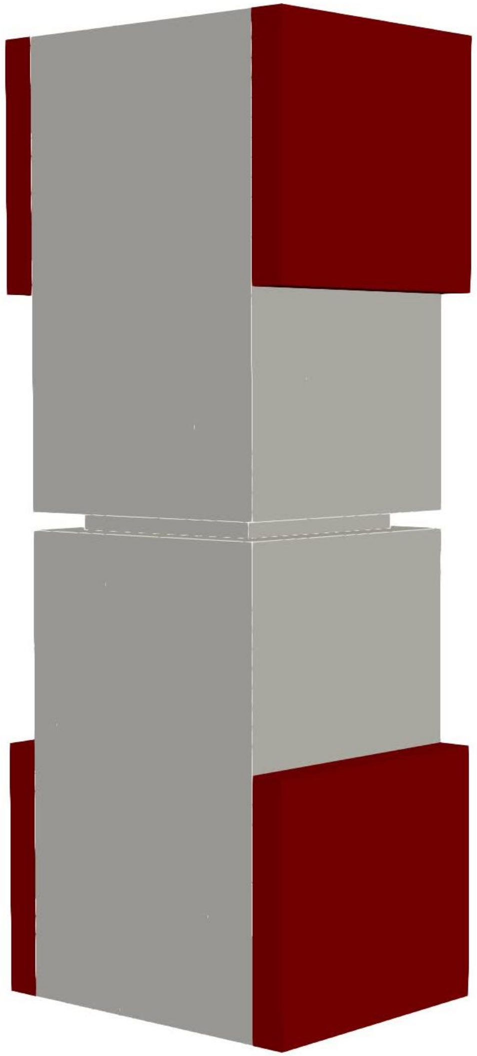

Total Crack Opening [mm]

0.1 >1

Conclusions

- ✓ Modeling fiber orientation with the presented computational approach shows promise in prediction of hardened UHPC behavior from fresh state.

- ✓ **Simulations for fiber orientation model** show that given the significantly small volume and mass of fiber relative to its high aspect ratio and stiffness, it is reasonable to assume **that fibers can be aligned by flow** neglecting the contribution of fibers to the system momentum, i.e., the coupling term is negligible and thus, **one-way coupling is reasonable.**

- ✓ To better understand effect of fiber-fiber interactions as well as fiber-formwork interaction, explicit fiber flow model needs to be considered which is challenging!

Thank You for Listening!

Questions?