A CFD-DEM Approach to Model the Behavior of Fibers in Fresh UHPC

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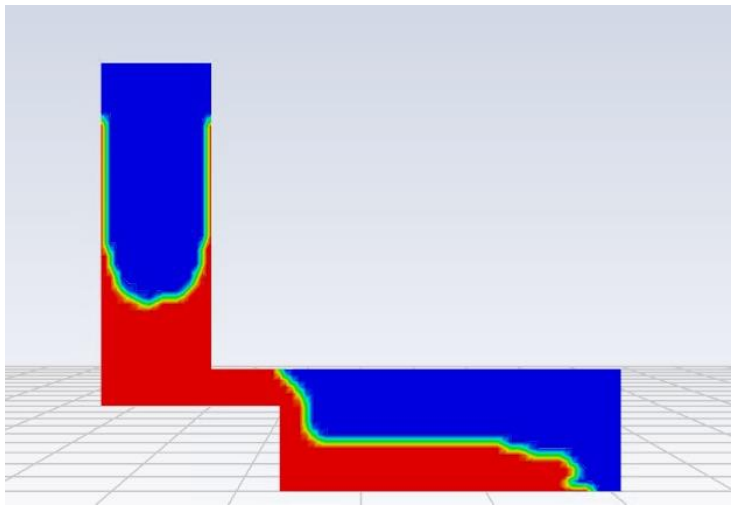
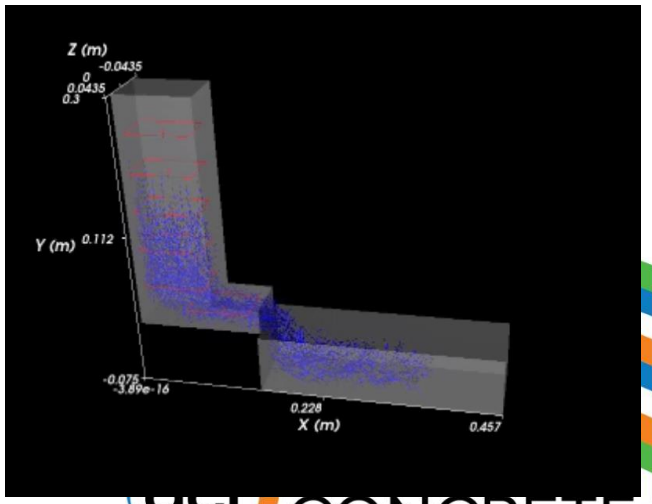
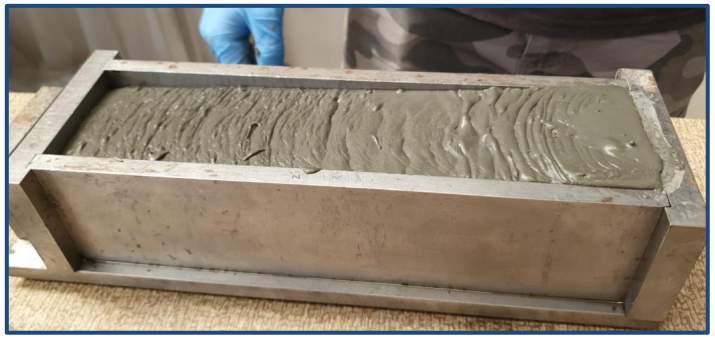




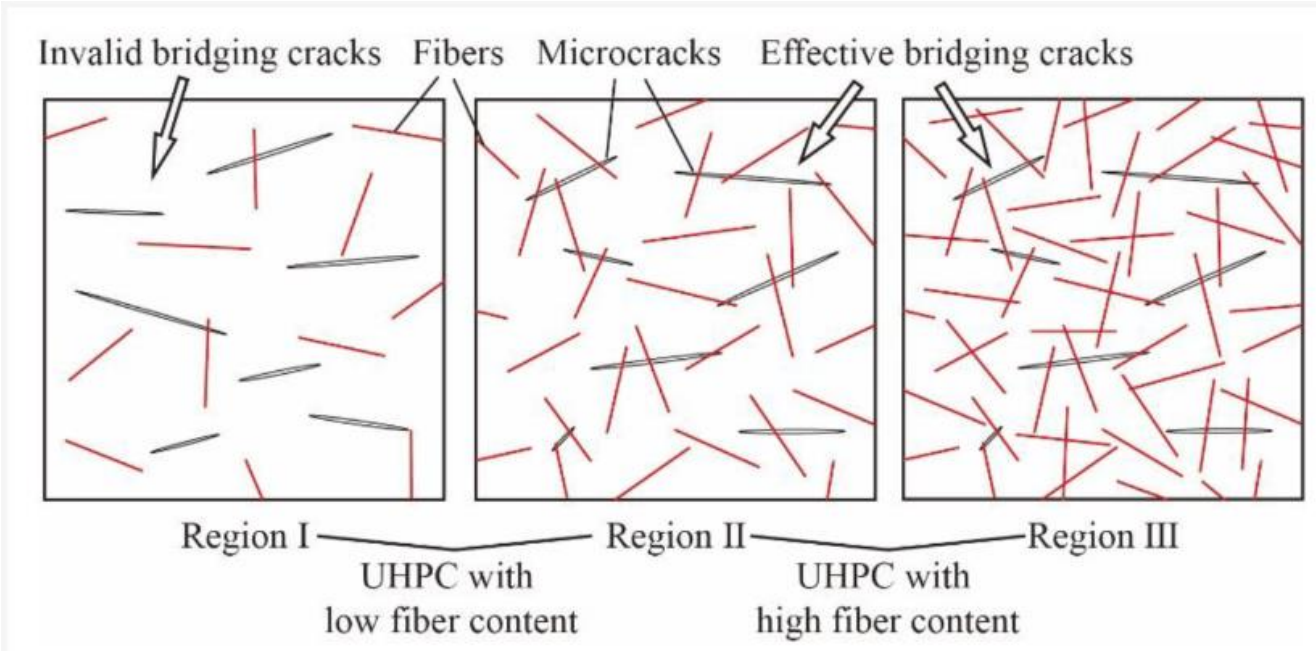
UHPC: Ultra-High Performance Concrete



- UHPC has exceptional strength and durability
- UHPC can extend the lifespan of infrastructure
- UHPC can reduce maintenance needs
- UHPC can increase structural resilience

UHPC: Fiber cracking bridging

- Post-cracking behavior is an important characteristic
- Cracking bridging effect of steel fibers
- There is a need to achieve uniform distribution and optimal alignment

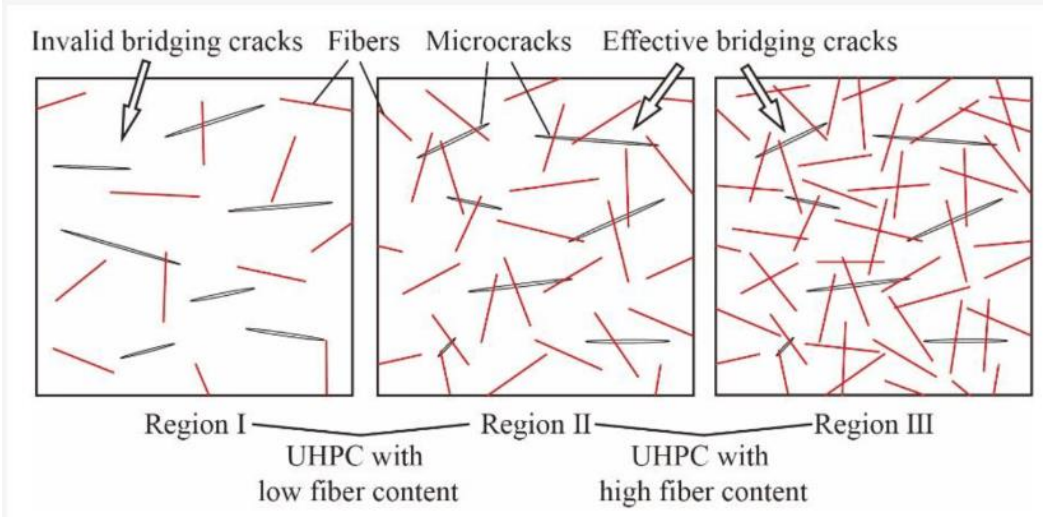


Source: Jiayuan et al. (2021)

UHPC: Fiber dispersion and orientation

Fiber dispersion and orientation may be affected by:

- Rheological properties of UHPC
- Casting method
- Formwork due to wall effect
- Fiber aspect ratio (length: diameter)
- Rebar arrangement
- Fiber concentration



Source: Jiayuan et al. (2021)

- **A tool that predicts fiber orientation and dispersion is desired**
- **To understand fresh UHPC behavior at the fiber scale**
- **Improve UHPC behavior**

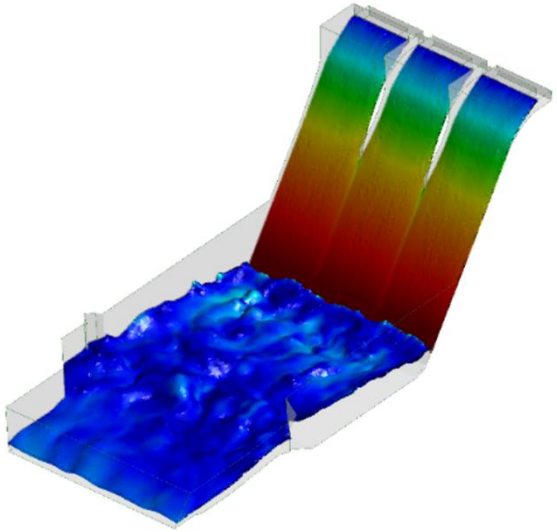
UHPC: fiber dispersion and orientation prediction

¿How?

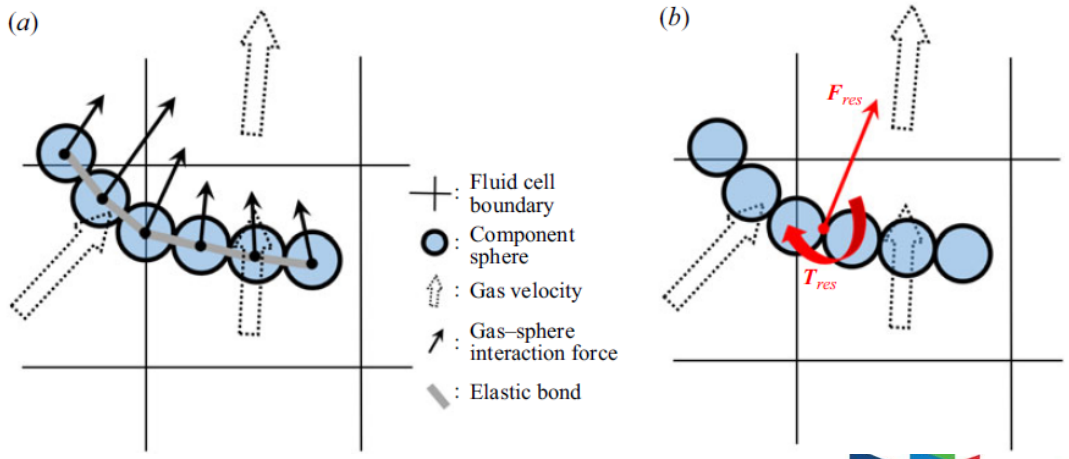
CFD + DEM

Computacional Fluid Dynamics

Discrete Element Method



Source: Salazar and San Mauro (2021)



Source: Jiang et al. (2021)

CFD – DEM tool

CFD – DEM model:

- Can predict fiber orientación and dispersión in UHPC
- Simulates fresh concrete as it flows and its interaction with fibers
- Enables the analysis under different scenarios:
  - UHPC rheological properties
  - Casting method
  - Formwork – different geometries of structural elements
  - Fiber aspect ratios
  - Rebar arrangement
  - Fiber concentrations

CFD – DEM tool: Characteristics

- CFD: solves the movement of fresh concrete using the NS equations

$$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \boldsymbol{f} \quad \text{Momentum}$$

$$\nabla \cdot \boldsymbol{v} = 0 \quad \text{Mass}$$

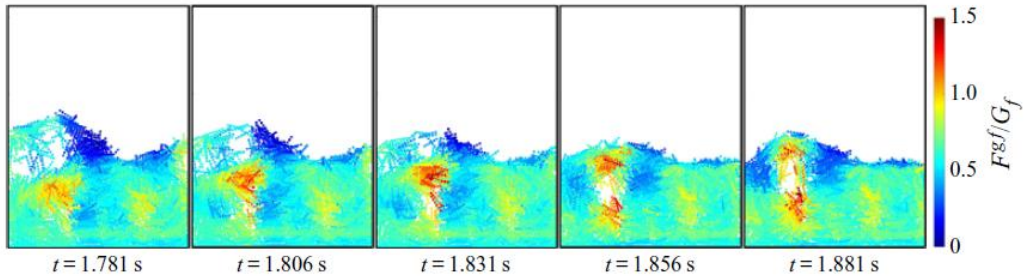
- DEM: solves particle dynamics, fluid-particle interaction

$$m_p \frac{d\boldsymbol{v}}{dt} = \sum \boldsymbol{F_p} \quad \text{Linear Momentum}$$

$$\boldsymbol{I} \frac{d\boldsymbol{\omega}}{dt} = \sum \frac{d_p}{2} \times \boldsymbol{F_p} \quad \text{Angular Momentum}$$

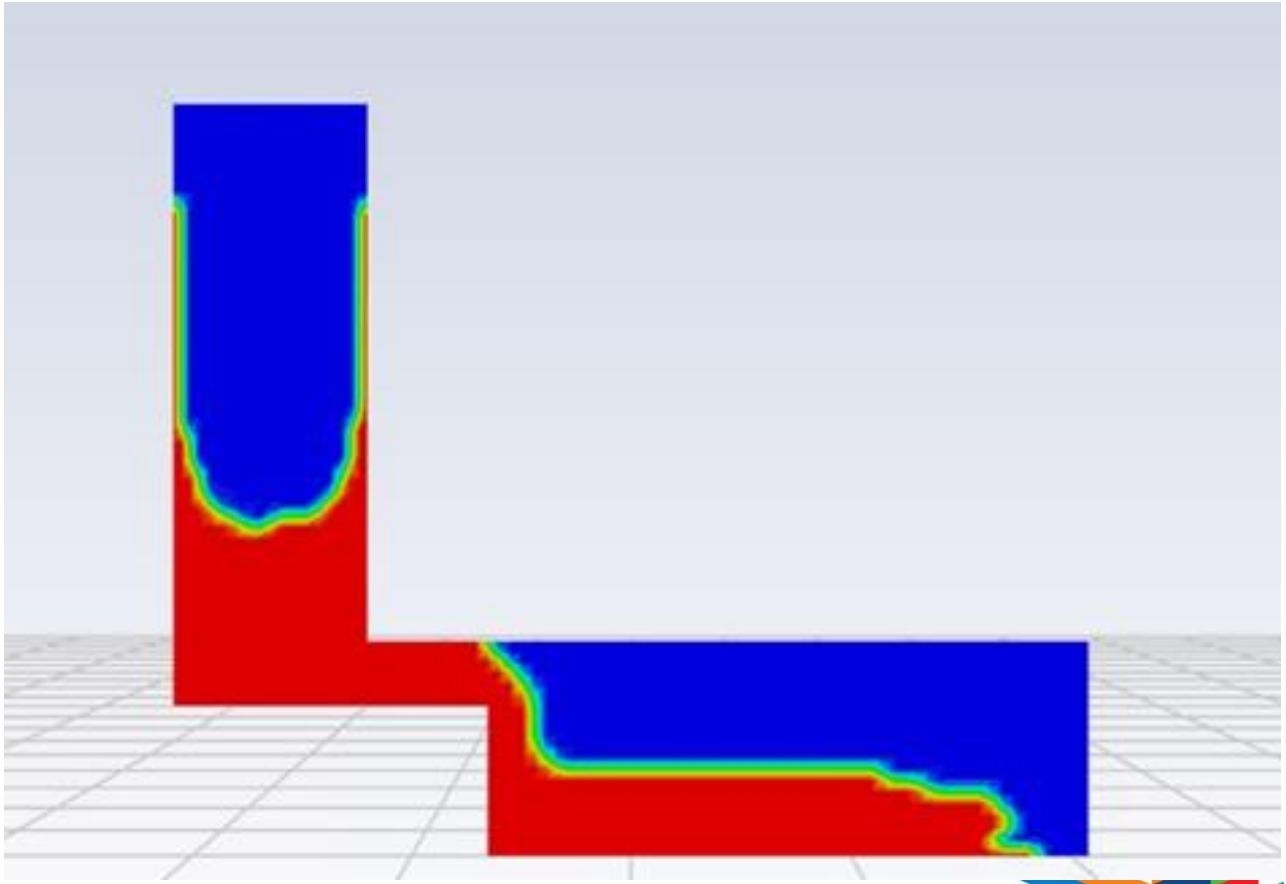
- CFD-DEM two-way coupling solves particle-flow interaction

- Then, we can computer fiber particle location, dispersion, orientation, interaction, etc., at every time step

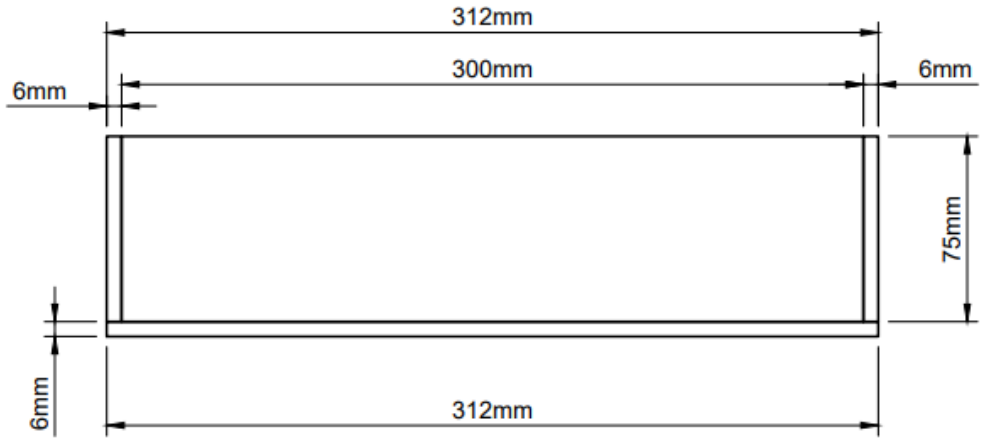


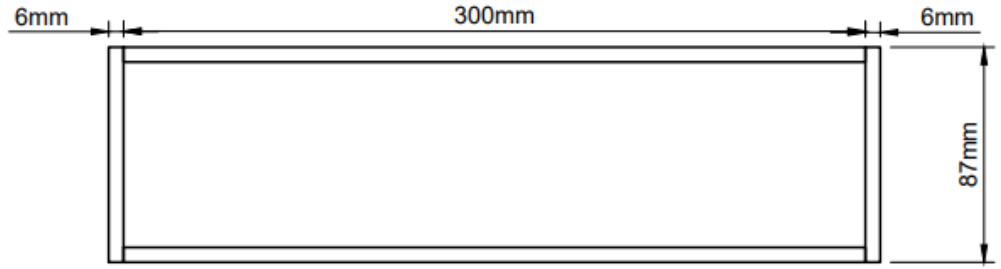
Source: Jiang et al. (2021)

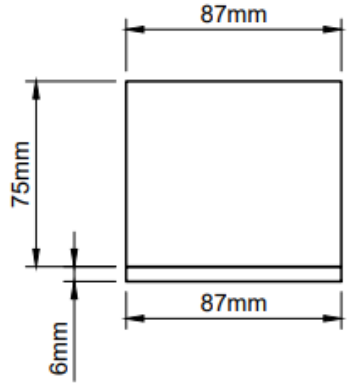
CFD Simulation

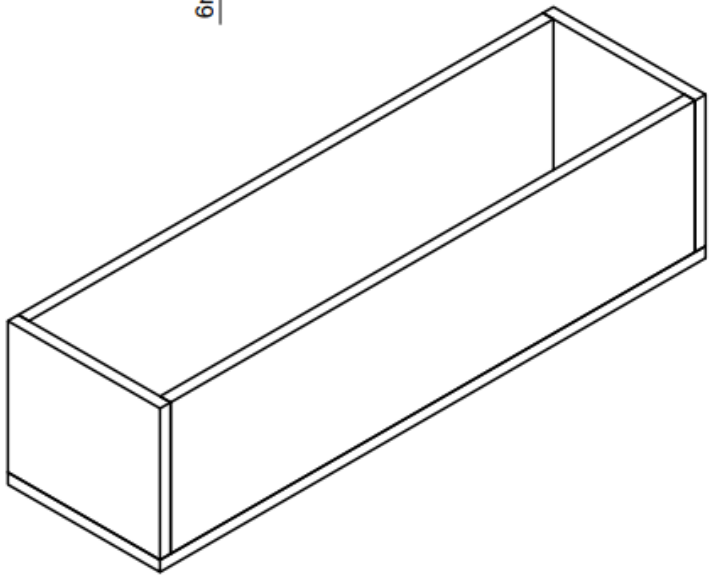


Computational domain: Beam dimensions

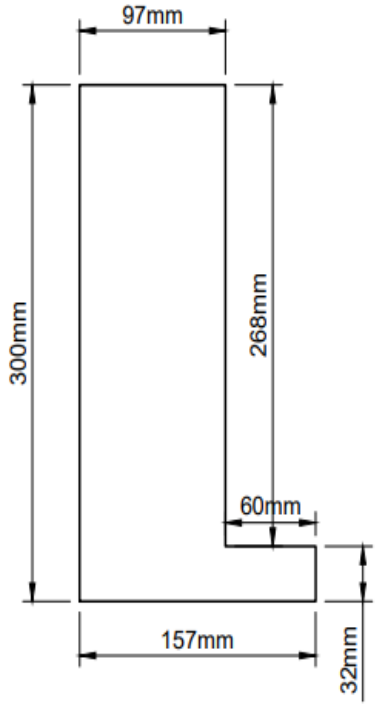


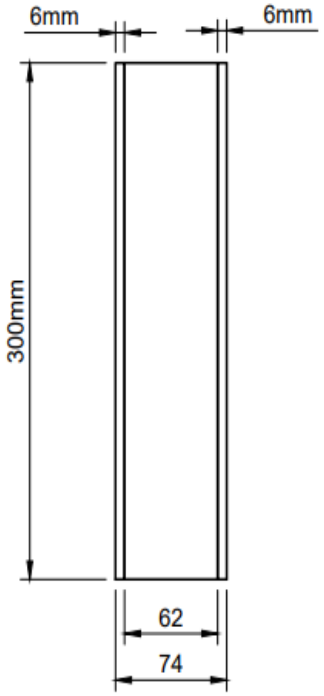


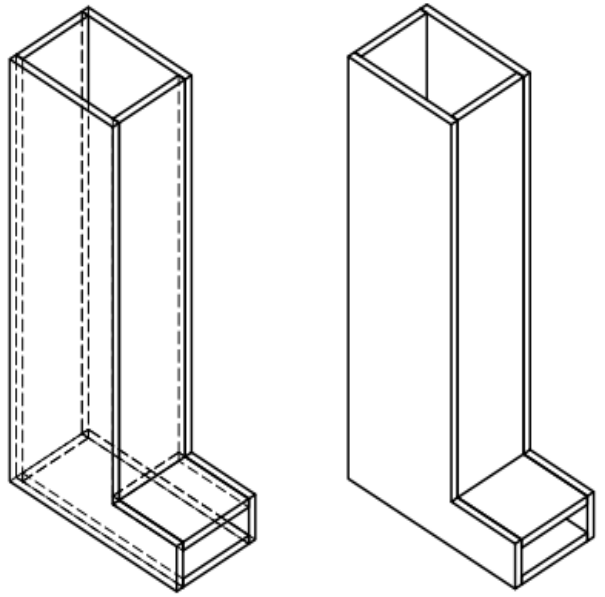


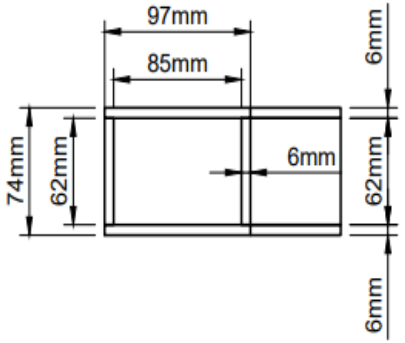


Computational domain: L-shape casting device dimensions





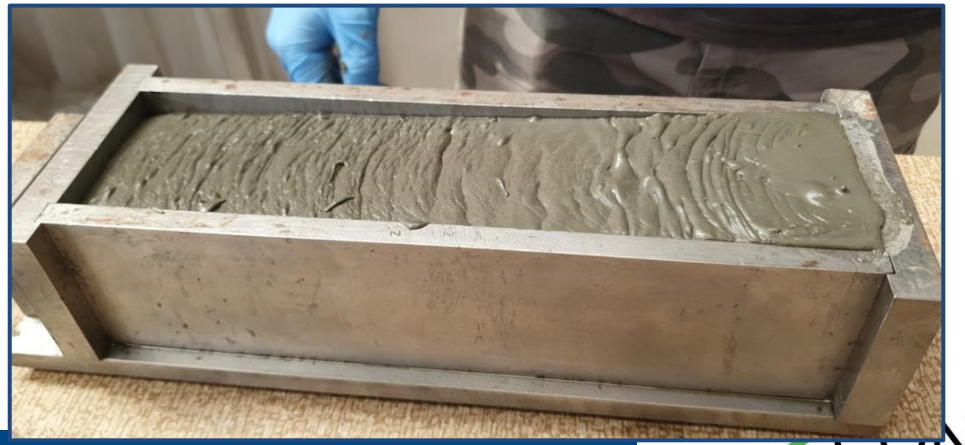




Total UHPC volume: 1.75 L

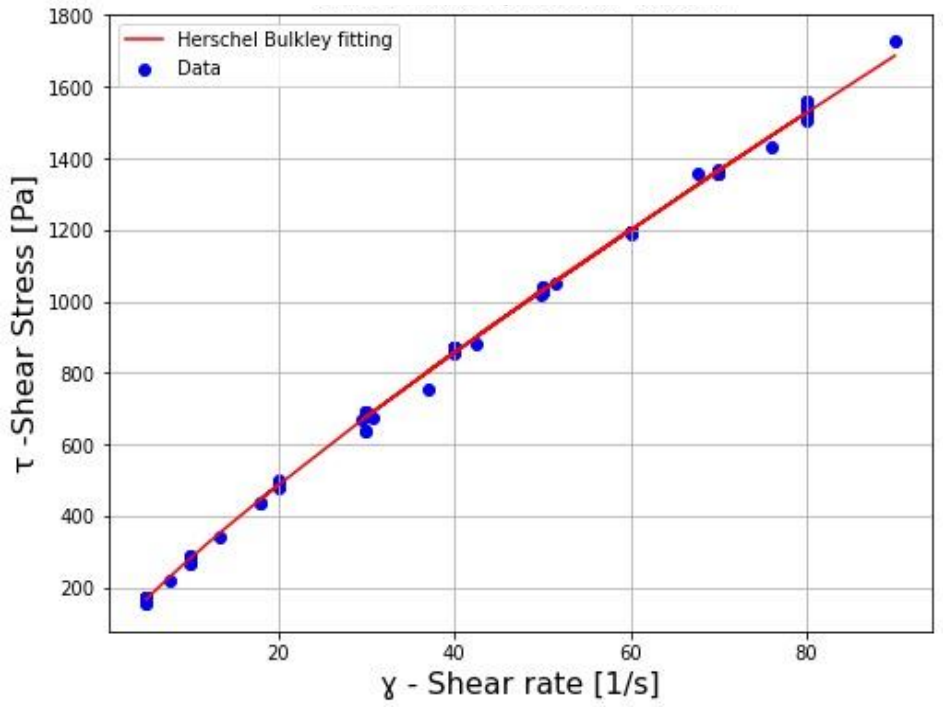
Beam with UHPC mixture

UHPC mixtures with 0.7% of concentration by volume of fibers
Casting with an L-shaped devise



UHPC Rheology: Non-Newtonian fluid

TA Instruments Discovery HR 2



Non-Newtonian fluid: Herschel- Bulkley

$$\tau = \begin{cases} 0 & if \ \ \tau < \tau_0 \\ \tau = \tau_0 + k\dot{\gamma}^n & if \ \ \tau \geq \tau_0 \end{cases}$$

τ: fluid shear stress $[Pa]$

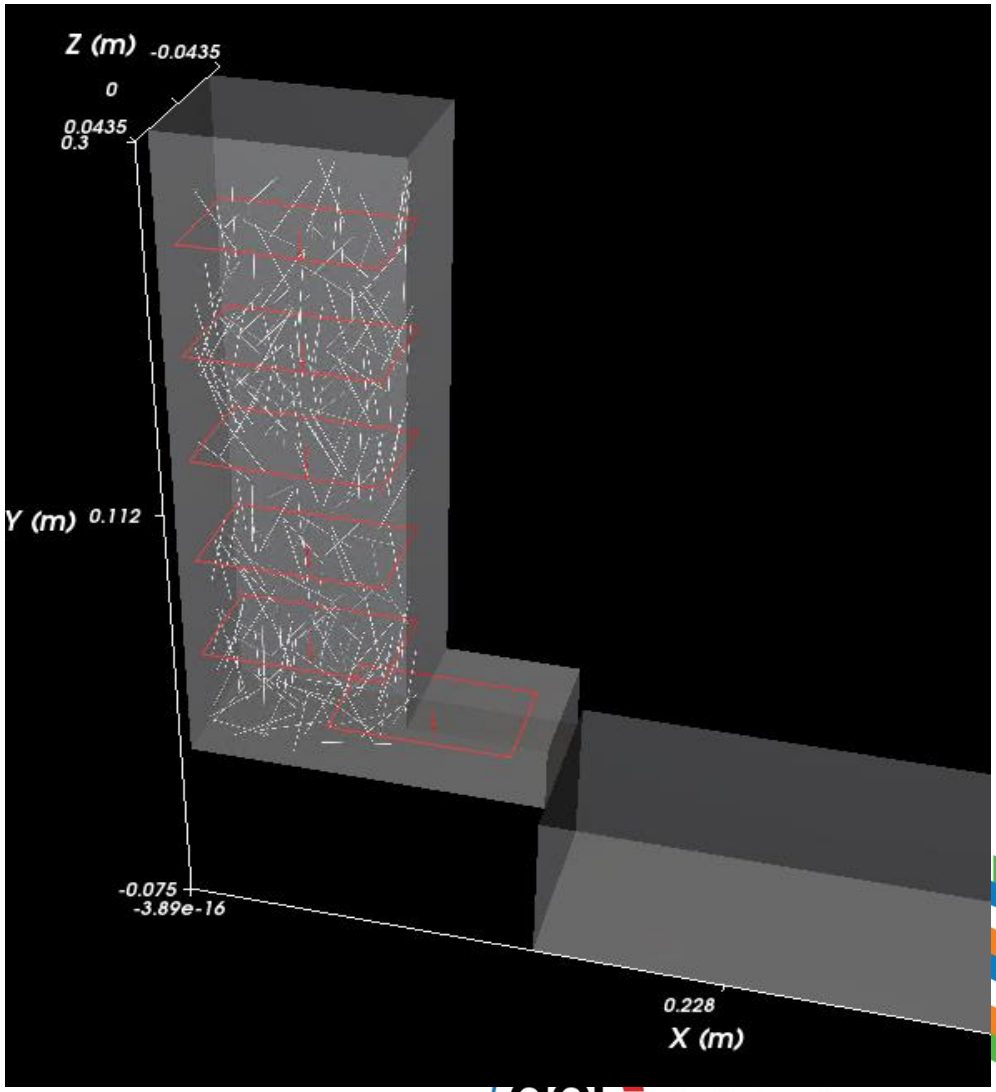
τ_0: yield stress $\langle \mathbf{23.62} \rangle$ $[Pa]$

k : consistency index $\langle \mathbf{36.16} \rangle$ $[Pa \cdot s^n]$

$\dot{\gamma}$: shear rate $[s^{-1}]$

n : flow index $\langle \mathbf{0.85} \rangle$ [ ]

DEM Simulation



DEM: Steel fibers (Lagrangian approach)

- Spheres glued together (rigid, no flexibility)
- Diameter and length
- Random within 45° from vertical axis
- How many particles 1342 fibers
- Hydrodynamic forces: F_D, F_L, F_{VM}
- Body forces: F_{Bu}
- Collision forces: F_{col}

Real Fiber Element

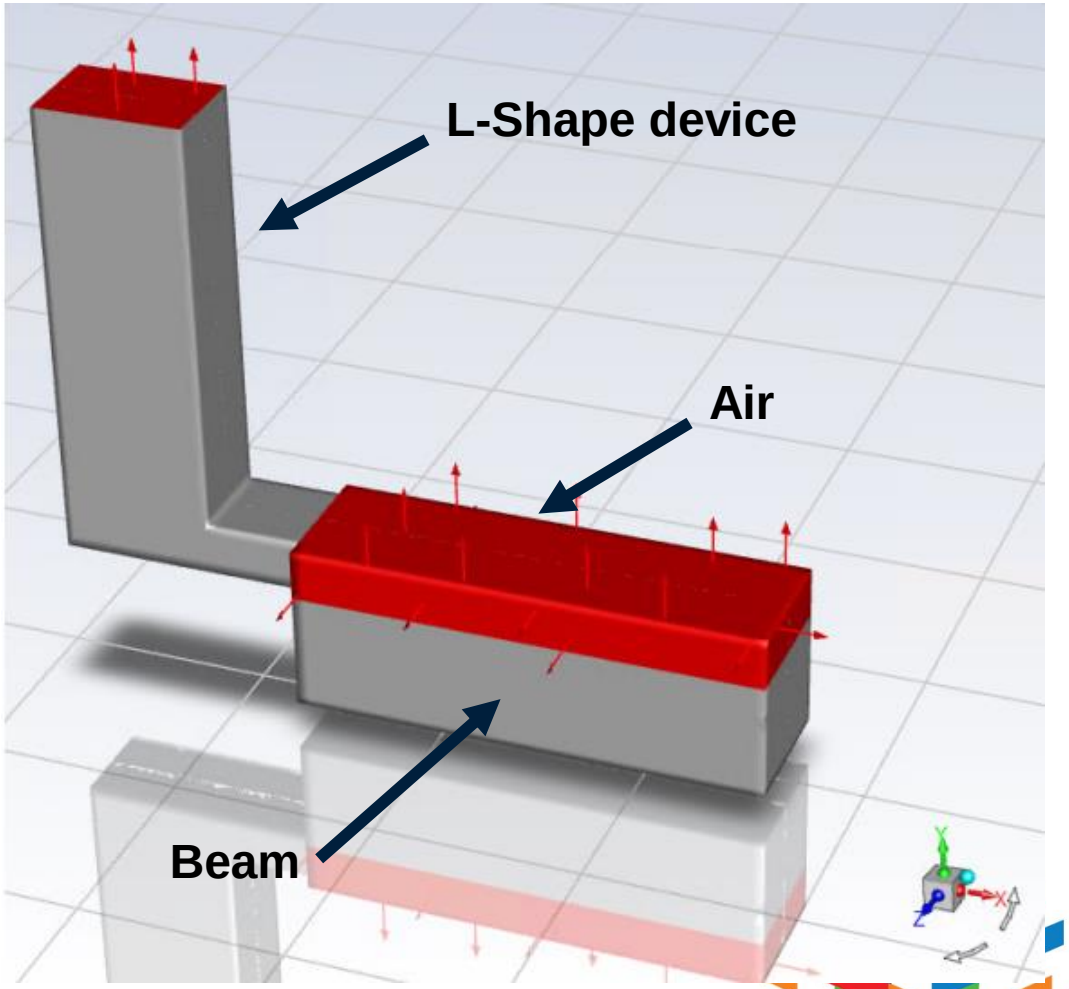
Length : 20.8 mm
Diameter : 0.38 mm
Aspect ratio: ~ 55

DEM Element

Diameter : 0.38 mm
N° of spheres: 55

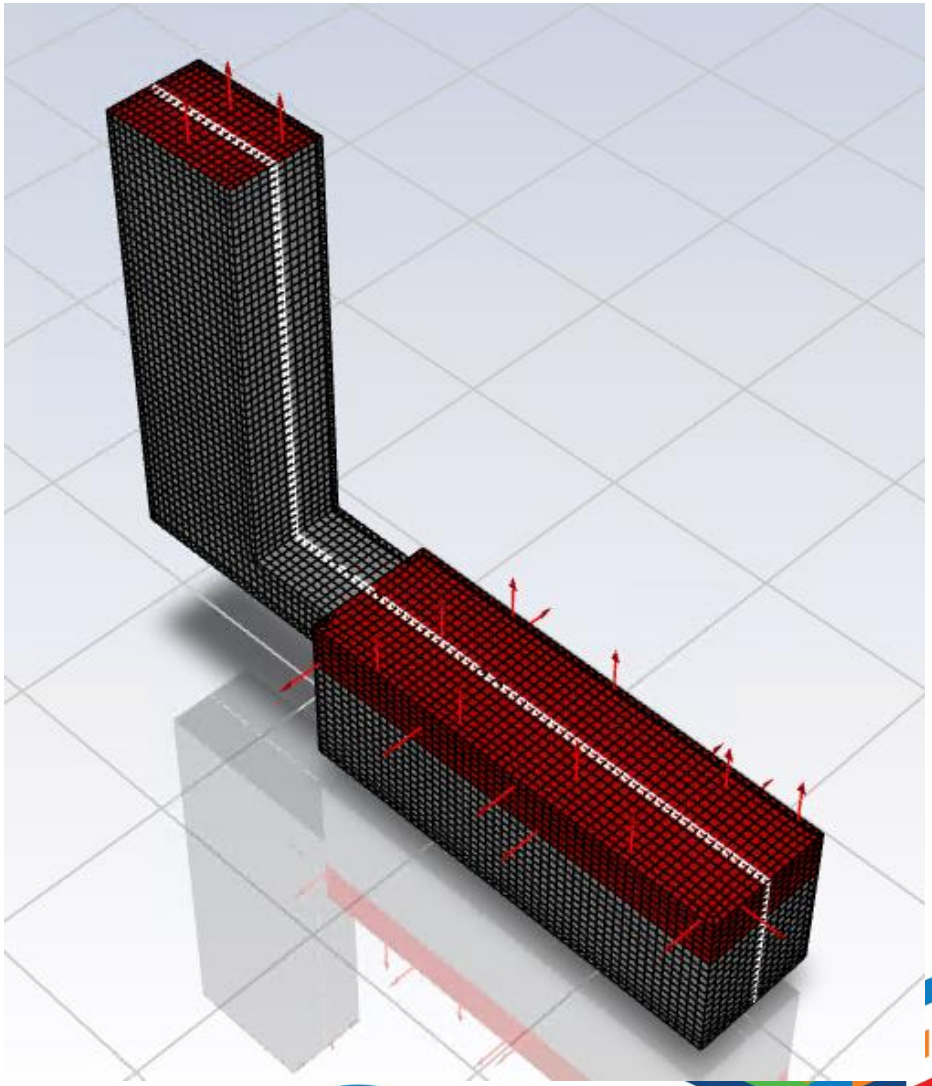
Numerical Experiment Setup

- Computational domain
- Multiphase flow (three phases)
- UHPC is initialized in the L-shape device



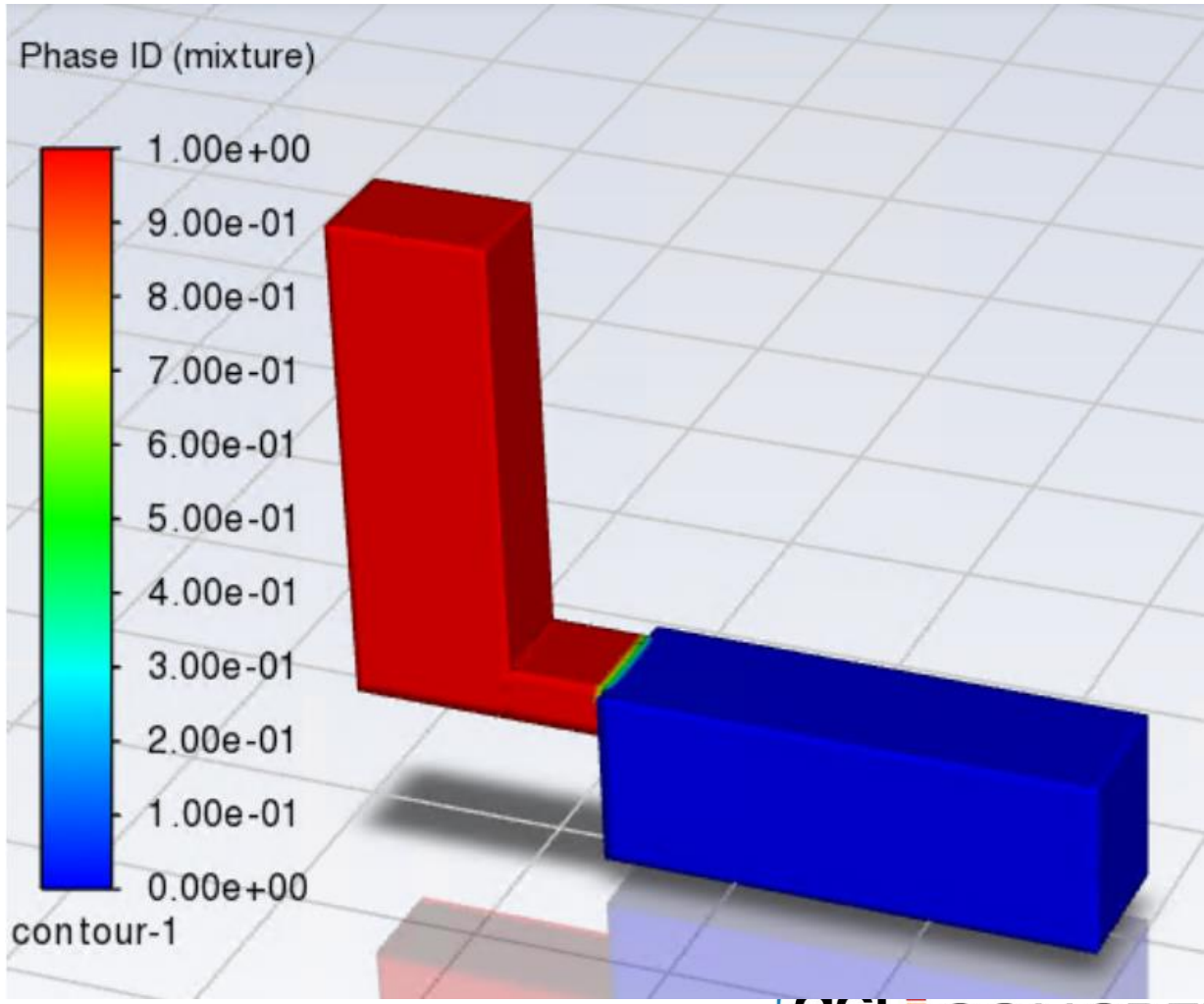
Numerical Experiment Setup

- Fixed mesh
- Cells are hexahedrons
- **~ 31.000** cells
- Laminar flow ($\boldsymbol{R_e = 0.23}$)

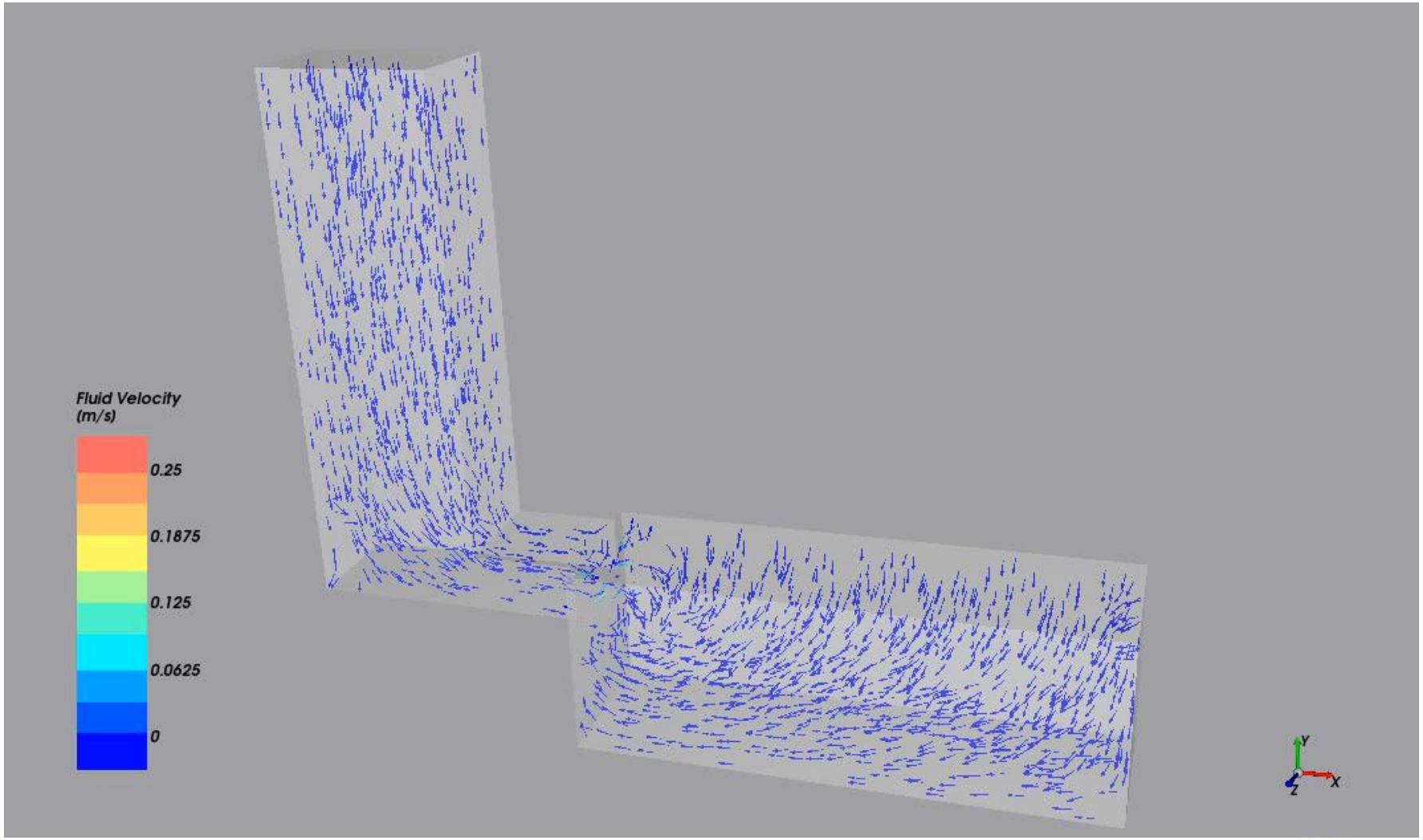


Initial Conditions

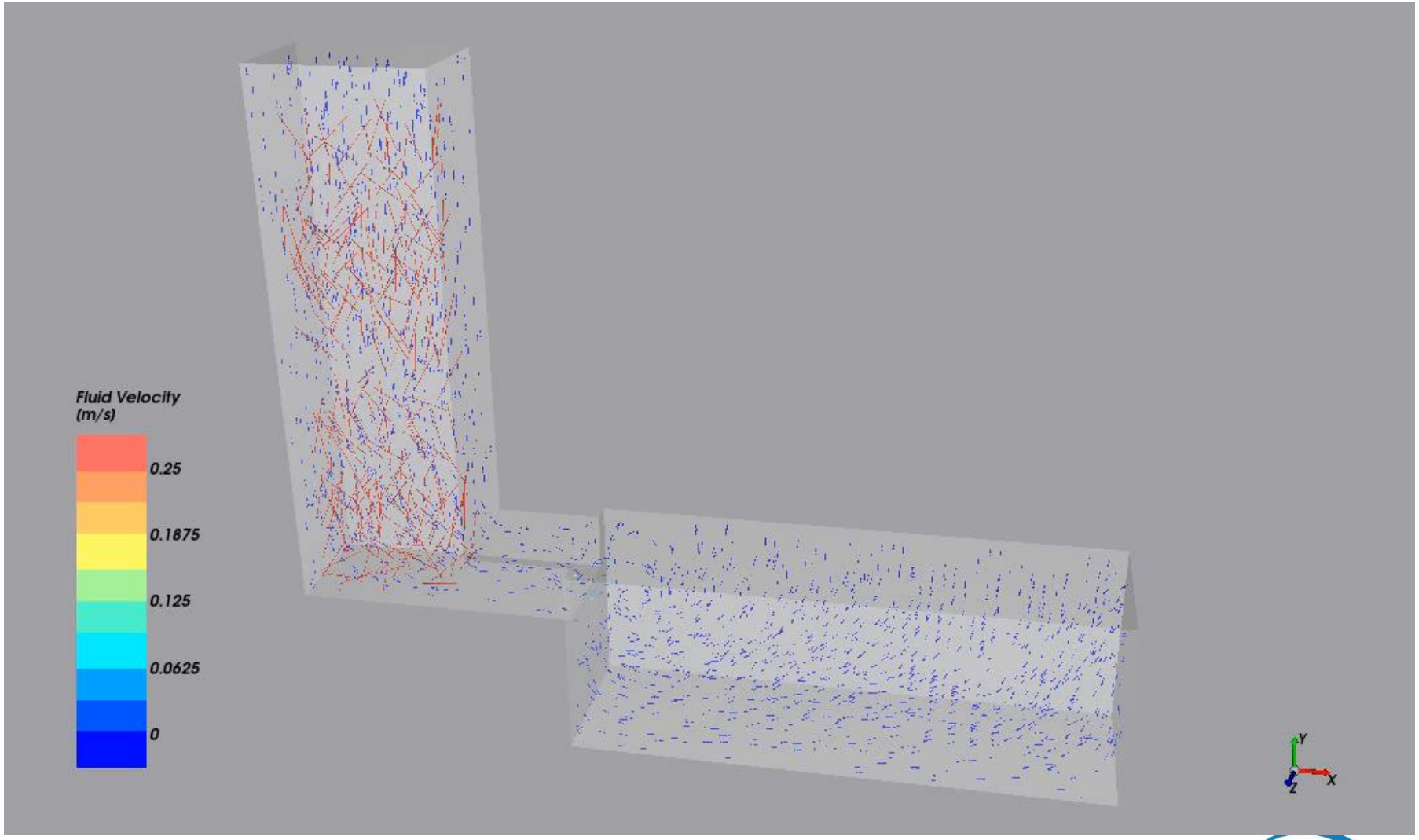
- **1.75 L** of UHPC (red)
- Blue means air phase
- Fiber volume fraction **0.7%**



First simulation results: Flow vectors



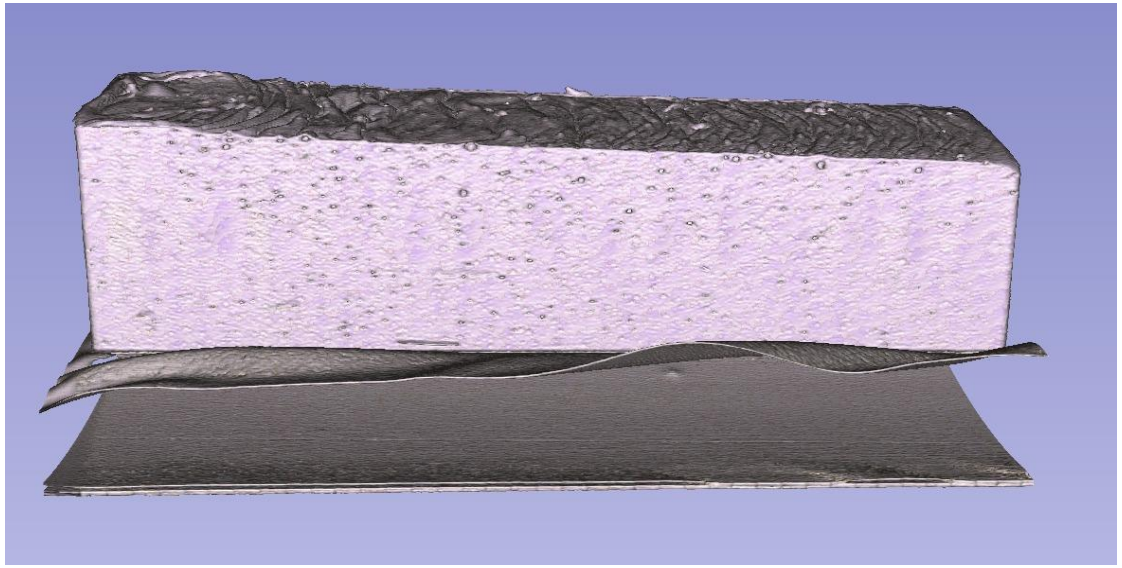
First simulation results: Fibers



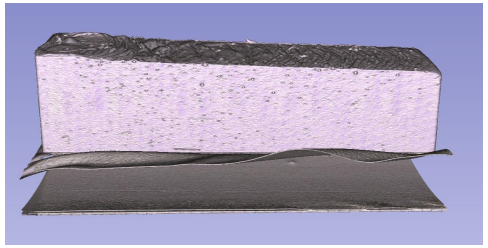
Model advantages and validation

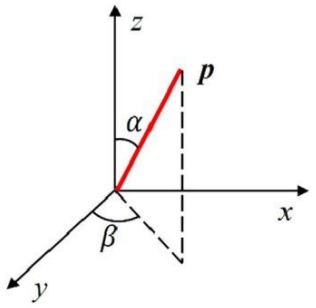
- Study different casting configurations
- Different fiber geometries and aspect ratios
- Study different fiber concentrations
- Study different UHPC rheology
- Include rebar
- Different structural elements

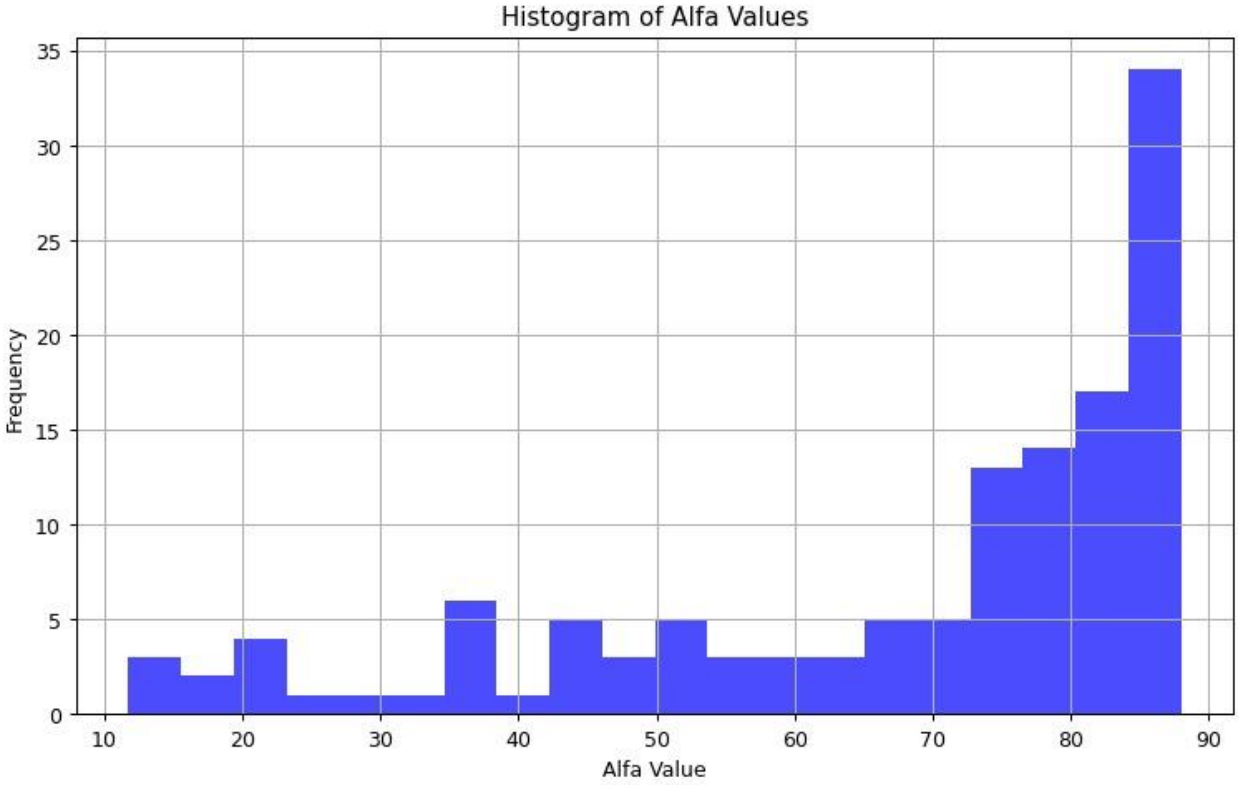
Use CT to validate

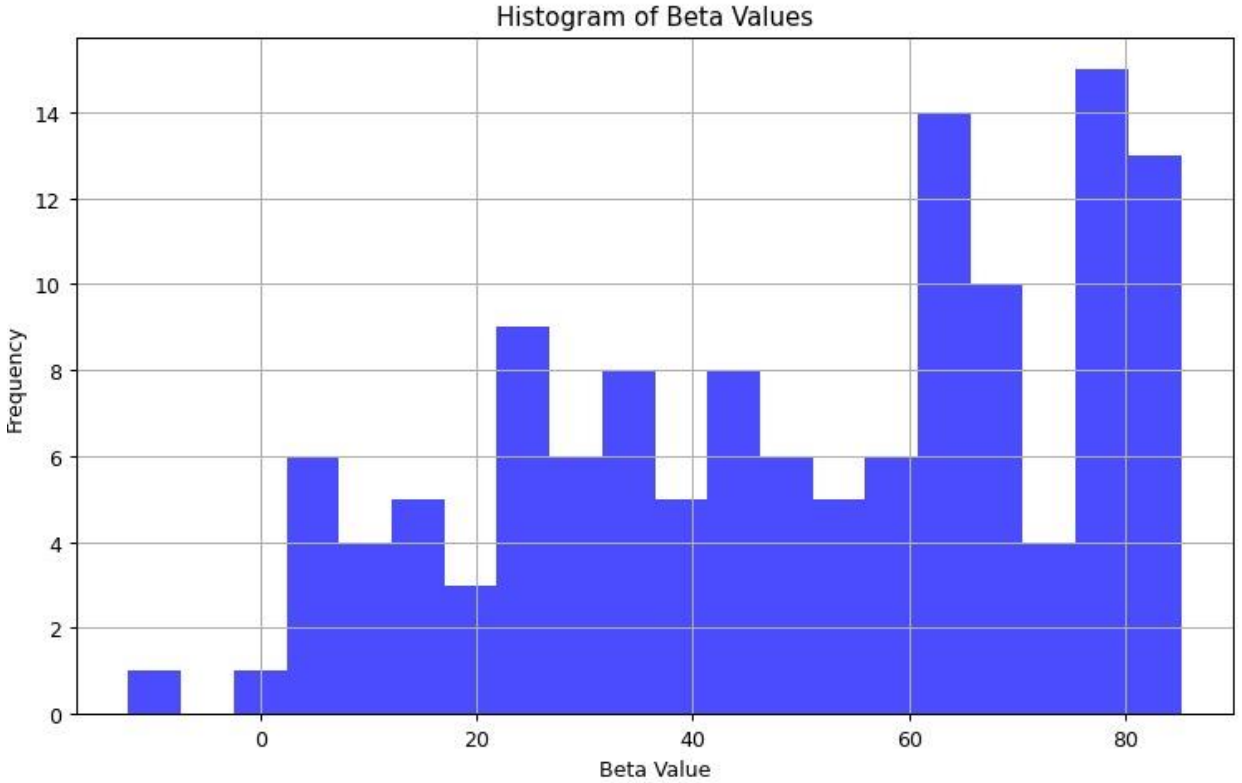


Fiber orientation from CT









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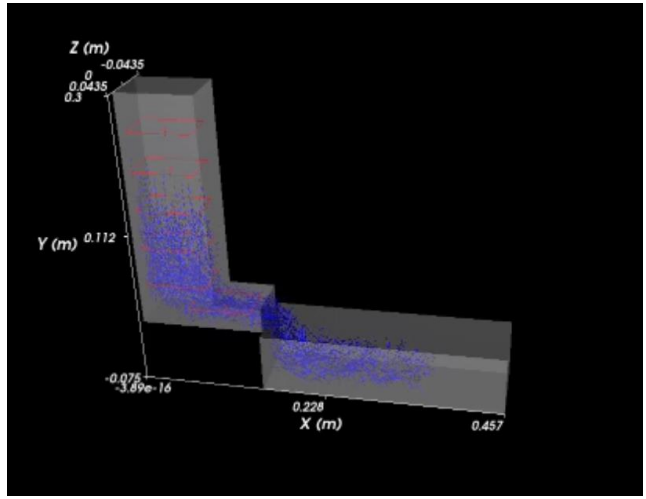

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