STRUCTURAL MECHANICS

SPP 2020 EXPERIMENTAL-VIRTUAL-LAB

M. Sc. Vladislav Gudžulić
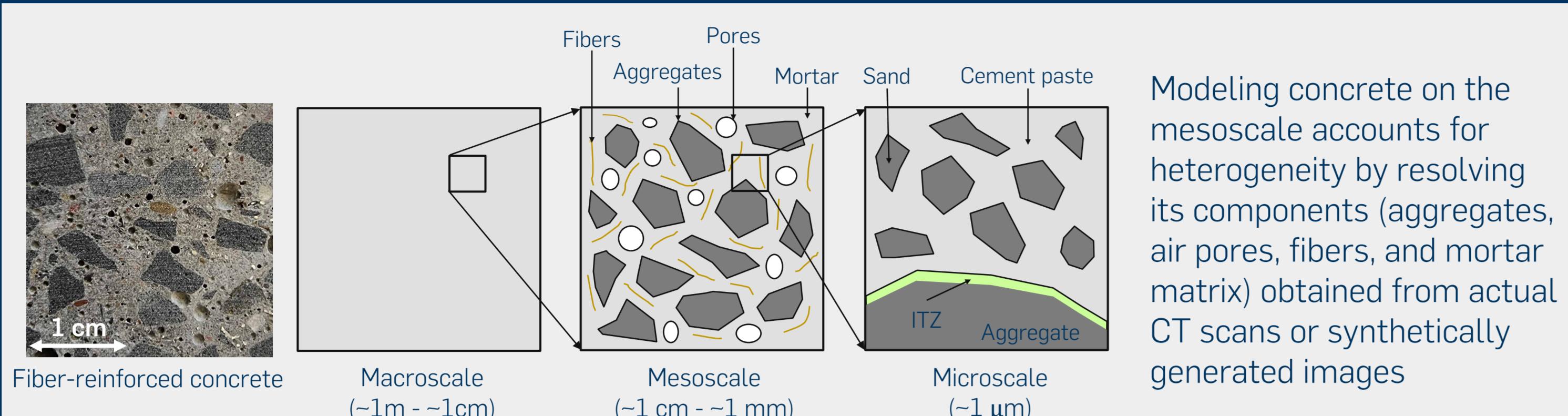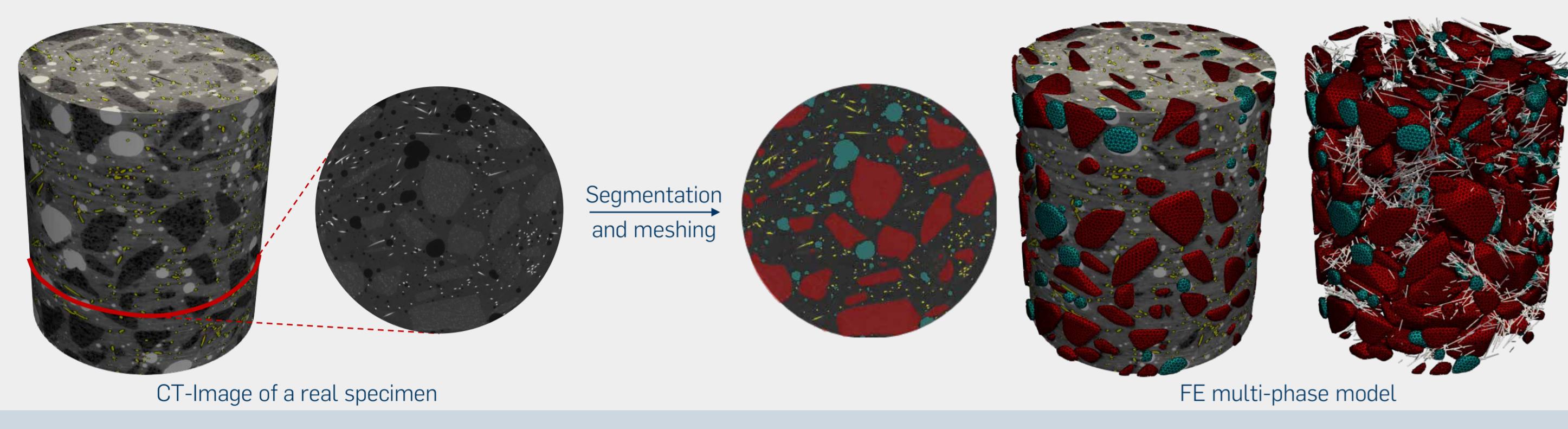M. Sc. Koussay Daadouch
Prof. Dr. Günther Meschke

RUB

Virtual Concrete Lab
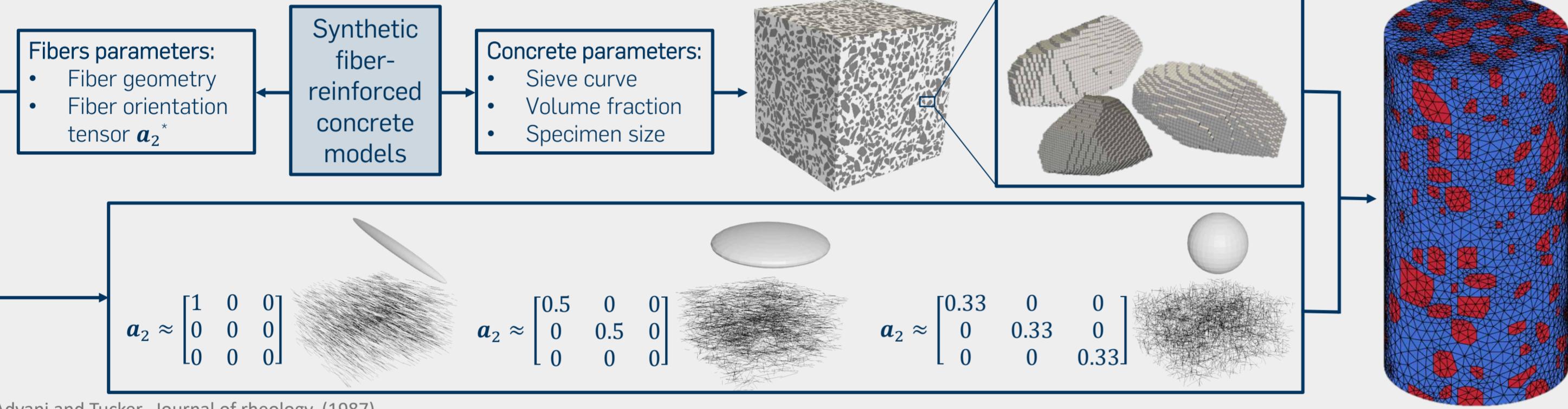## Simulating Damage Processes in Concrete with Steel Reinforcement

Generation of Mesoscale Finite Element Models

Fibers
Pores
Aggregates
Mortar
Sand
Cement paste

Fiber-reinforced concrete
1 cm
Macroscale (~1m – ~1cm)
Mesoscale (~1 cm – ~1 mm)
ITZ
Aggregate
Microscale (~1 µm)

Modeling concrete on the mesoscale accounts for heterogeneity by resolving its components (aggregates, air pores, fibers, and mortar matrix) obtained from actual CT scans or synthetically generated images

Generating models from CT images of the real specimens

CT-Image of a real specimen
Segmentation and meshing
FE multi-phase model

Generating synthetic models

Fibers parameters:
• Fiber geometry
• Fiber orientation tensor a_2*

Synthetic fiber-reinforced concrete models

Concrete parameters:
• Sieve curve
• Volume fraction
• Specimen size

$a_2 \approx \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$
$a_2 \approx \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0 \end{bmatrix}$
$a_2 \approx \begin{bmatrix} 0.33 & 0 & 0 \\ 0 & 0.33 & 0 \\ 0 & 0 & 0.33 \end{bmatrix}$

*Advani and Tucker. Journal of rheology. (1987)
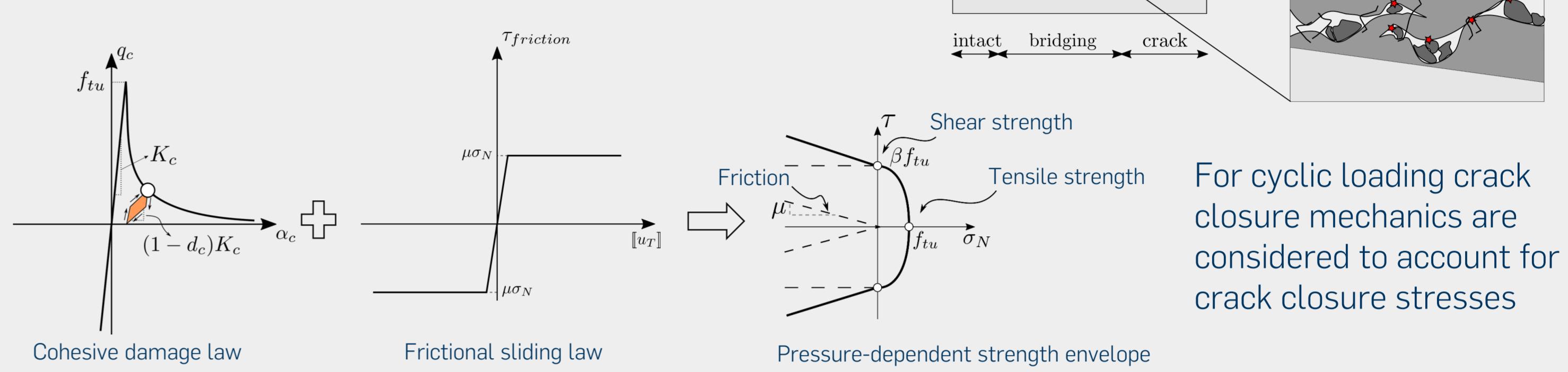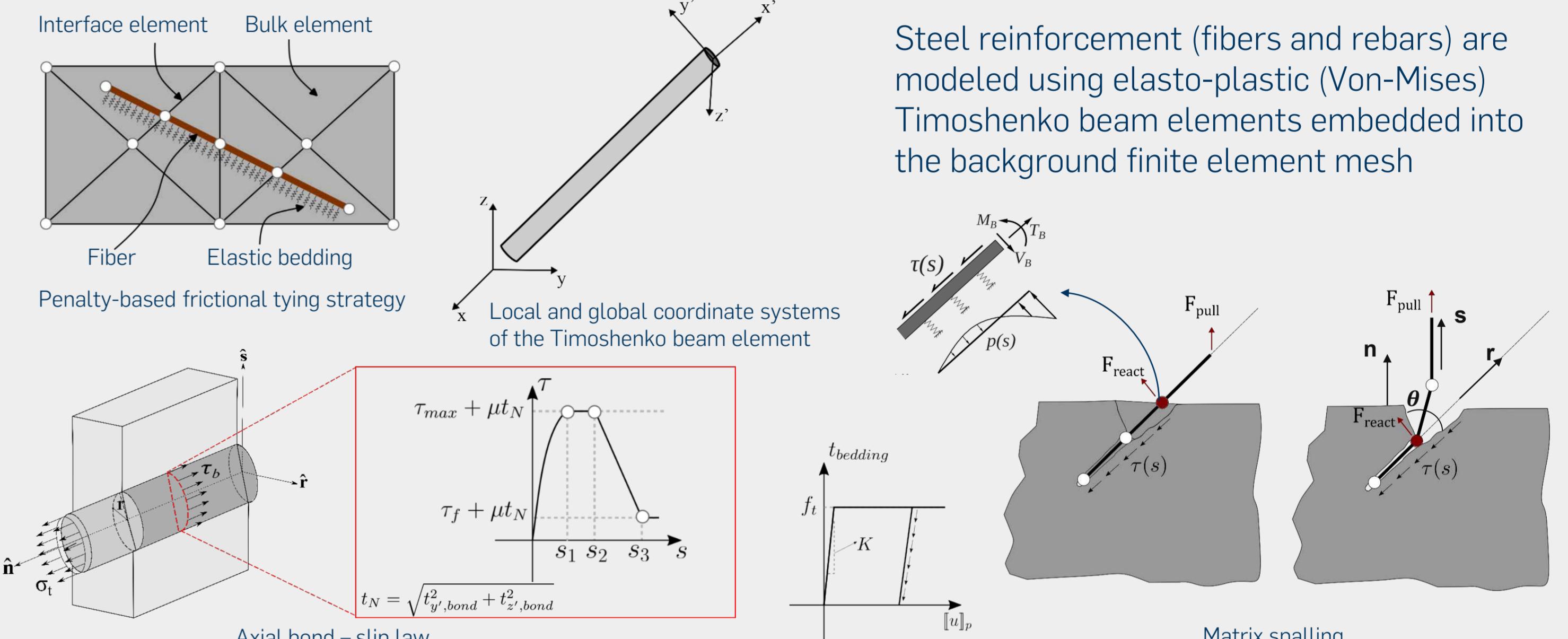
Structural Analysis Technology

Modelling fracture

Cracks are discretely modelled using interface elements equipped with a cohesive- frictional law which are inserted between solid finite elements

Bulk
Interface
open crack
partially closed crack
intact   bridging   crack

Cohesive damage law
f_{tu}, q_c, $-K_c$, $(1-d_c)K_c$, $[u_T]$

Frictional sliding law
$\tau_{friction}$, $\mu\sigma_N$

Pressure-dependent strength envelope
τ, Shear strength, Friction, μ, βf_{tu}, Tensile strength, f_{tu}, σ_N

For cyclic loading crack closure mechanics are considered to account for crack closure stresses

### Modelling steel reinforcement (fibers and conventional rebars)

Interface element
Bulk element
Fiber
Elastic bedding
Penalty-based frictional tying strategy

Local and global coordinate systems of the Timoshenko beam element

Steel reinforcement (fibers and rebars) are modeled using elasto-plastic (Von-Mises) Timoshenko beam elements embedded into the background finite element mesh

F_{pull}, F_{react}, $\tau(s)$, $p(s)$

Axial bond – slip law
$\tau_{max} + \mu t_N$, $\tau_f + \mu t_N$, s_1 s_2 s_3, $t_N = \sqrt{t_{y,bond}^2 + t_{z,bond}^2}$

$l_{bedding}$, f_t, $-K$, $[u]_n$

Matrix spalling
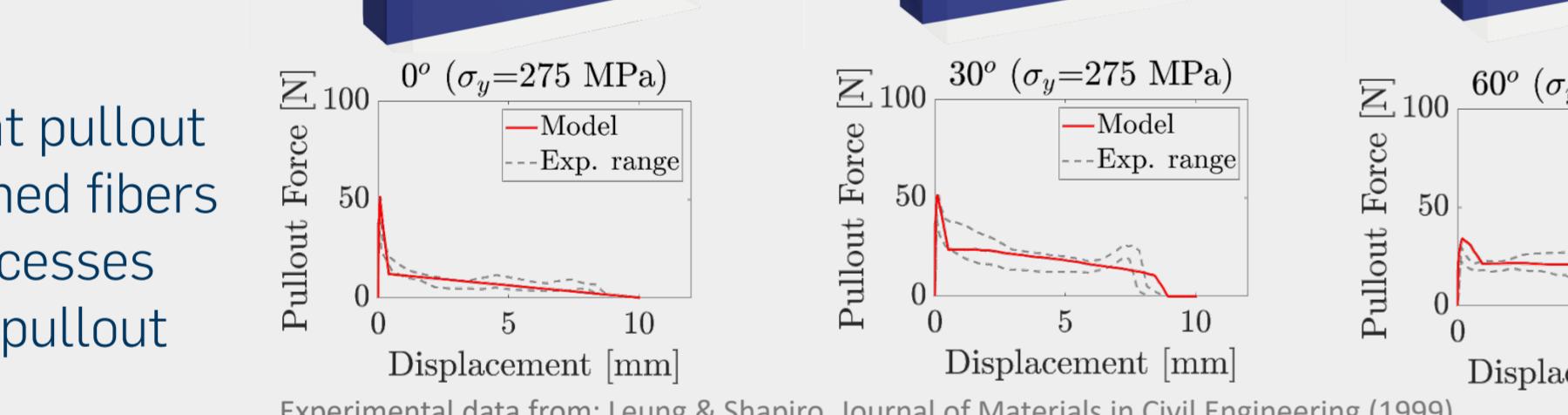
Model Validation

Crack bridging action of fibers

Straight and inclined single fiber pullout tests
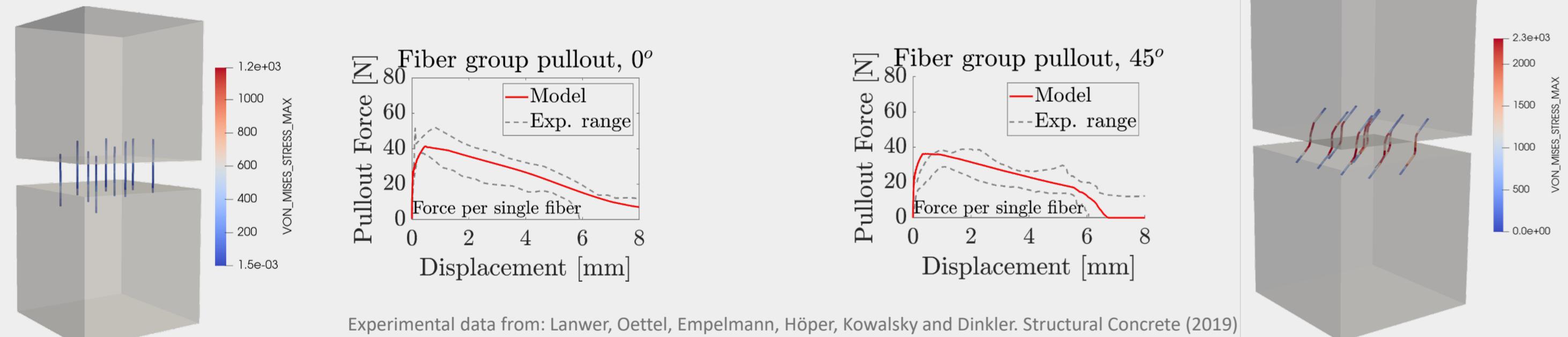
Damage processes during fiber pullout:
• Plastic hinge formation
• Matrix spalling
• Debonding
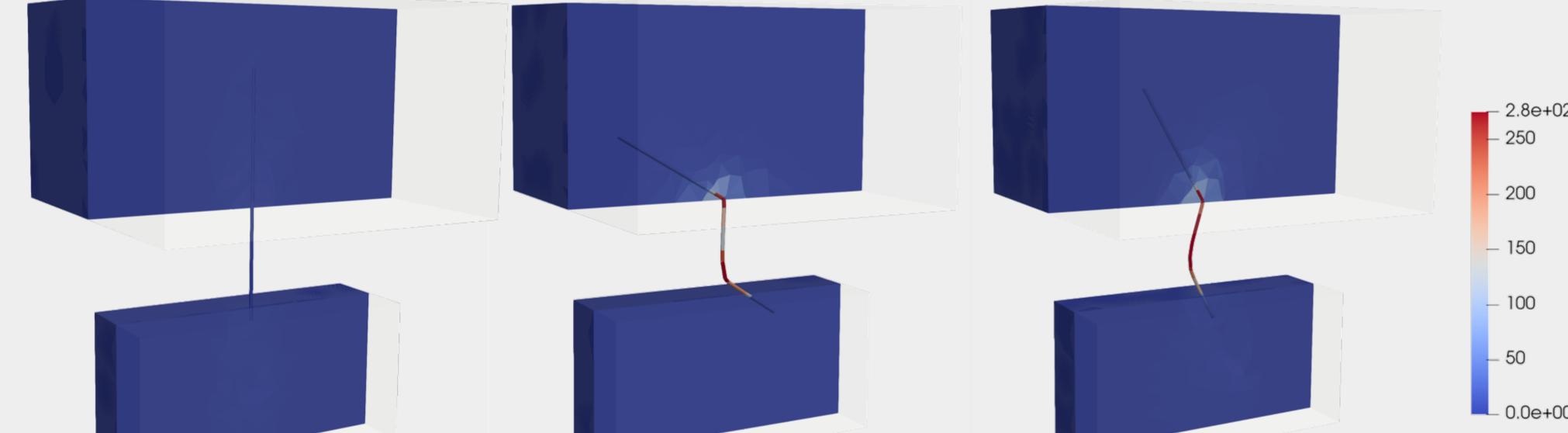
Qualitatively different pullout response of the inclined fibers due to additional processes occurring during the pullout
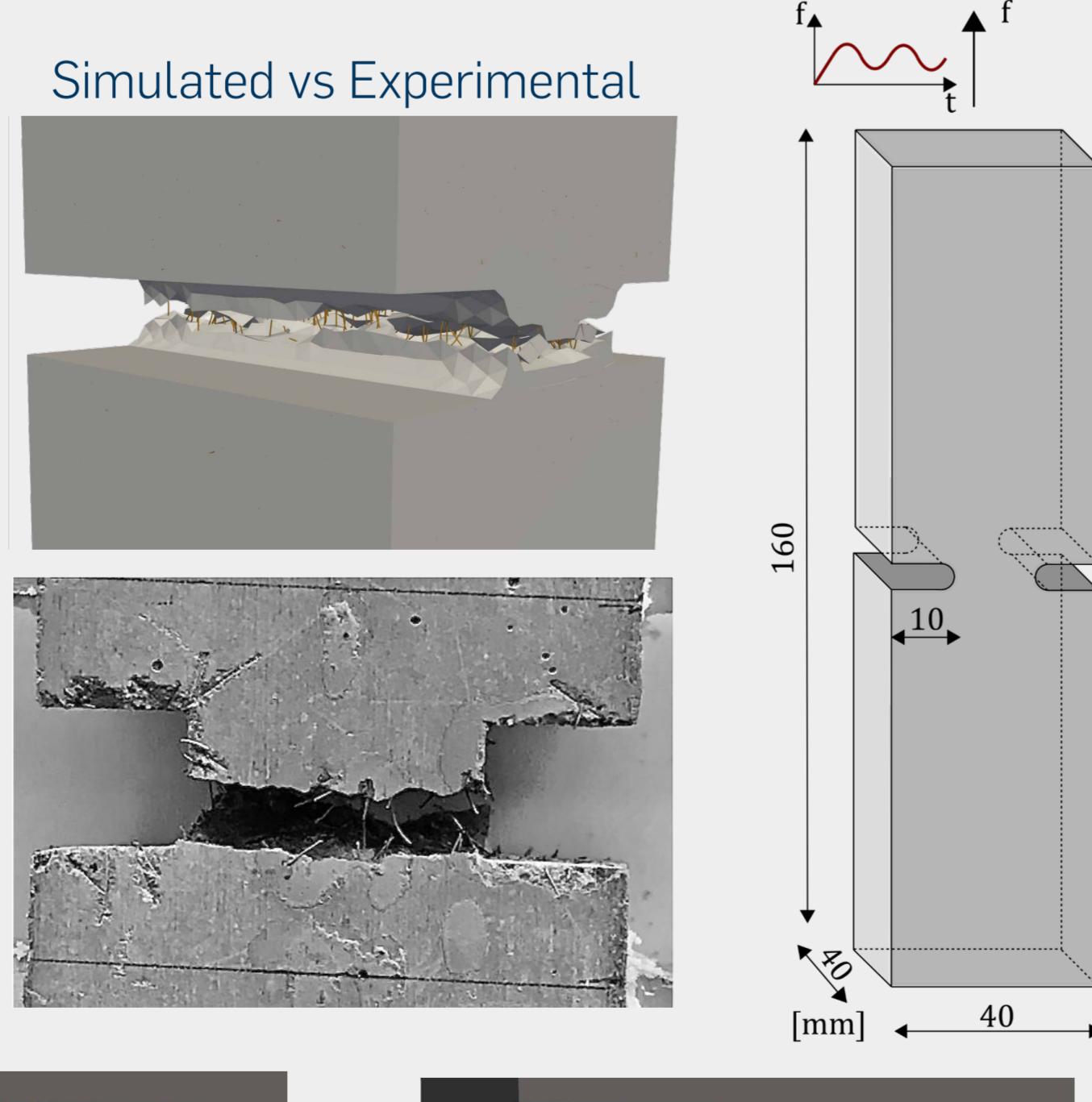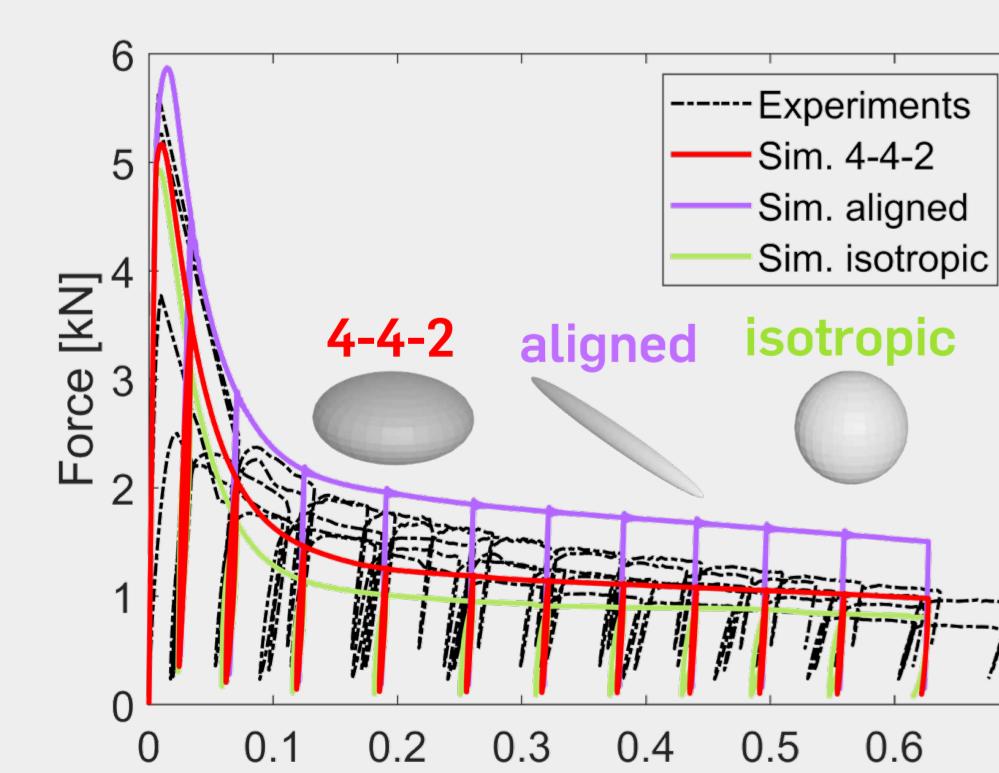
VON_MISES_STRESS_MAX 2.8e+02 ... 0.0e+00

$0°$ (σ_y=275 MPa) — Model, Exp. range — Pullout Force [N], Displacement [mm]
$30°$ (σ_y=275 MPa) — Model, Exp. range
$60°$ (σ_y=275 MPa) — Model, Exp. range

Experimental data from: Leung & Shapiro. Journal of Materials in Civil Engineering (1999)

Pullout of a group of fibers (0° and 45° inclination)

Fiber group pullout, 0° — Model, Exp. range, Force per single fiber — Pullout Force [N], Displacement [mm]
Fiber group pullout, 45° — Model, Exp. range, Force per single fiber

Experimental data from: Lanwer, Oettel, Empelmann, Höper, Kowalsky and Dinkler. Structural Concrete (2019)

Predicting the correct failure mode

Reinforced beams subjected to 4-point bending test

Small depth (h = 230 mm) — Exp., Sim., $\sim P_{max}$ — Force [kN], Displacement [mm]

1180 540 1180
230 2700 250 50 180 50 [mm] 2RØ20

Failure due to reinforcement yielding: comparison with the exp. crack pattern

Large depth (h = 410 mm) — Exp., Sim., $\sim P_{max}$ — Force [kN], Displacement [mm]

1180 540 1180
410 2700 360 250 [mm] 4RØ20

Failure due to formation of dominant shear crack: comparison with the exp. crack pattern

Experimental data from: Suchorzewski, Korol, Tejchman and Mroz. Engineering Structures (2018)

Effect of fiber orientation

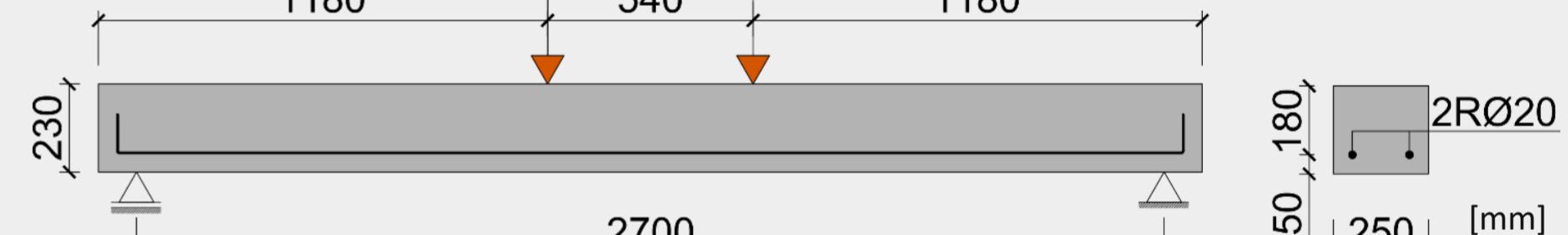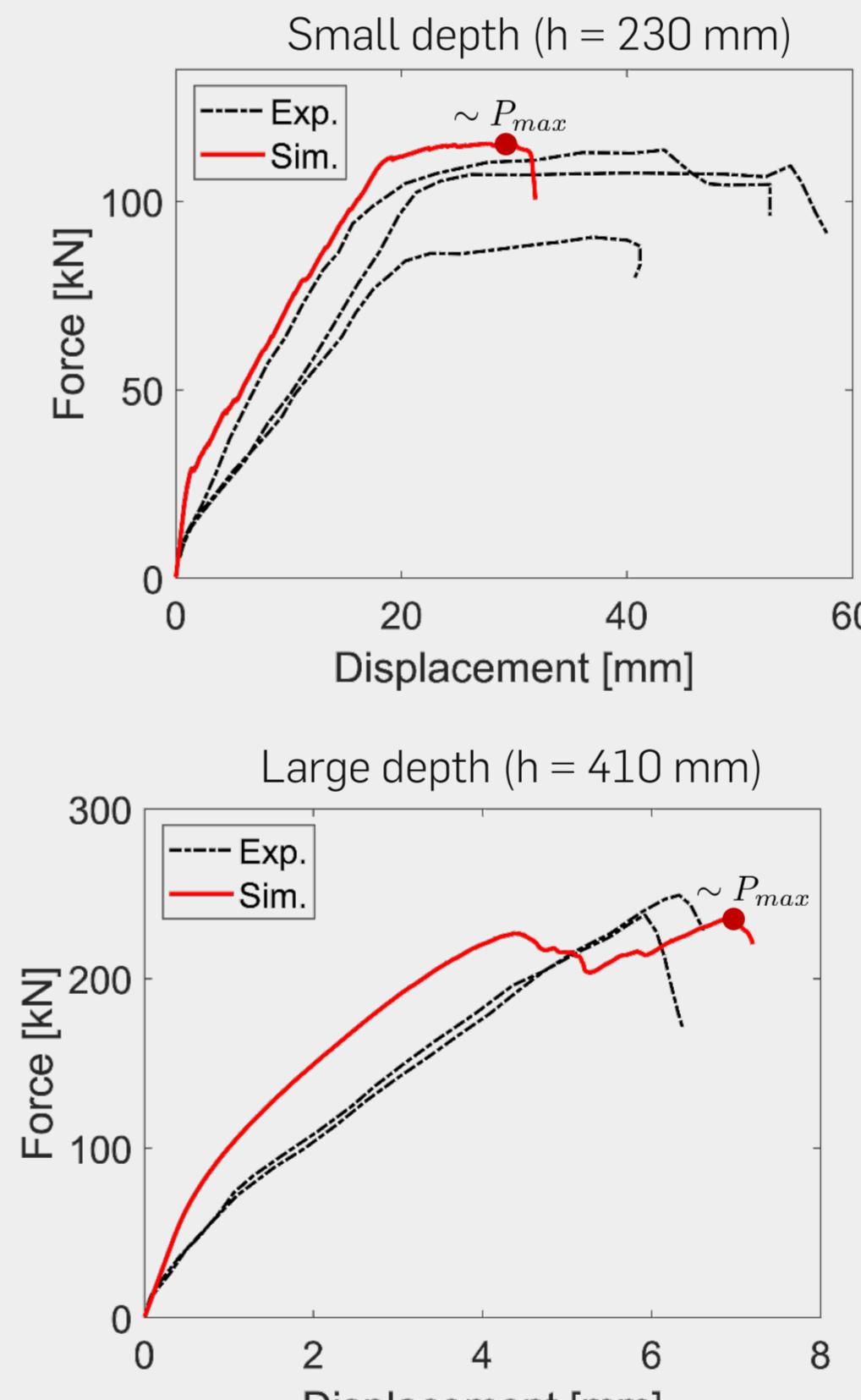#### Notched HPSFRC prism under cyclic uniaxial tension

• High-performance fiber-reinforced concrete
• 1% vol. fraction (~78.5kg/m^3) of fibers
• Utilizing virtually generated random fiber distributions to analyze the impact of casting on fiber orientation and structural performance
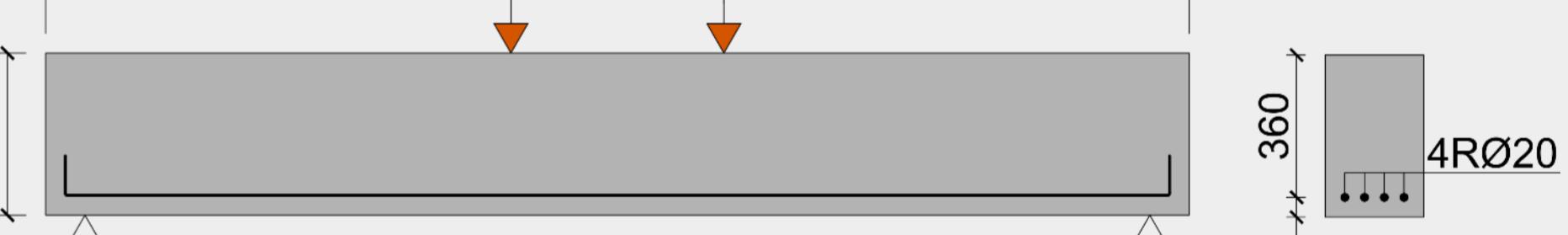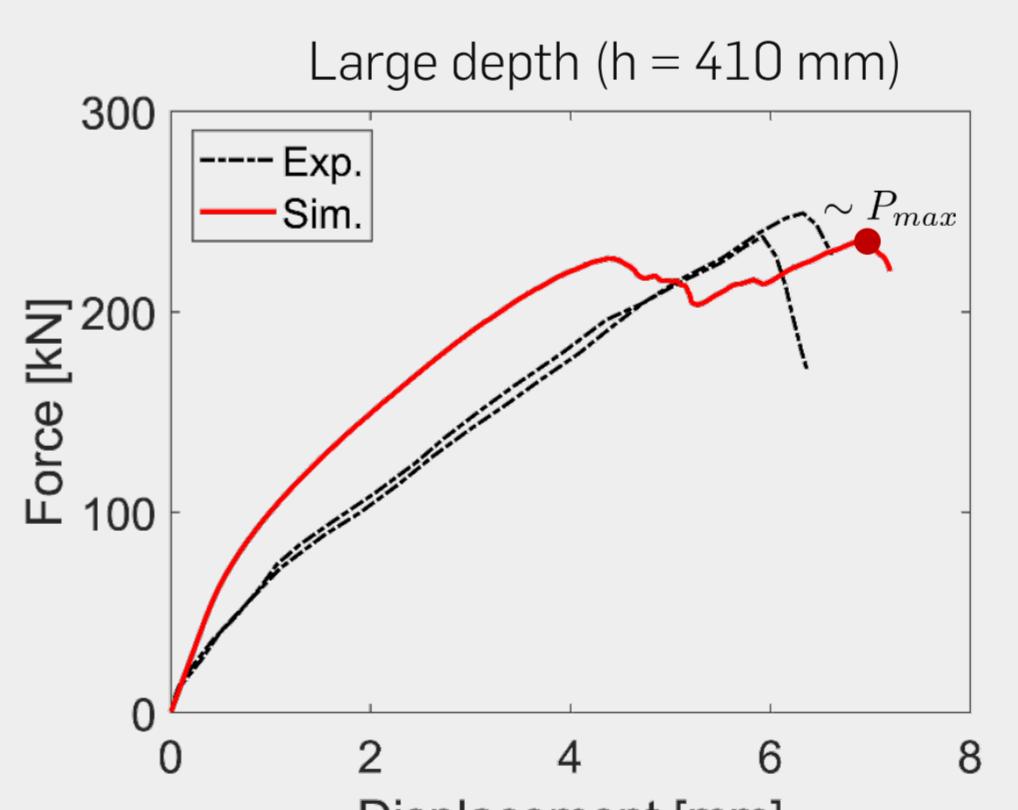
Simulated vs Experimental

160 10 40 [mm]

Experiments — Sim. 4-4-2, Sim. aligned, Sim. isotropic — Force [kN], CMOD [mm]
4-4-2   aligned   isotropic

4-4-2   aligned   isotropic

Experimental data from Schäfer, Gudžulić, Breitenbücher, and Meschke. Materials (2021)

Full mesoscale model reconstructed from the CT Image

HPSFRC cylinder under uniaxial compression

• High-performance fiber-reinforced concrete
• 1% vol. fraction (~78.5kg/m^3) of fibers
• The full mesoscopic analysis provides insight into failure mechanisms occurring in real specimens, identifying the effectiveness of the added reinforcement and allowing for the optimization of concrete composition

Stress - displacement curve — 5ou Experiment, 5ou Simulation, Linear elastic — Nominal stress [MPa], Displacement [µm]

39.56 35.42 [mm]
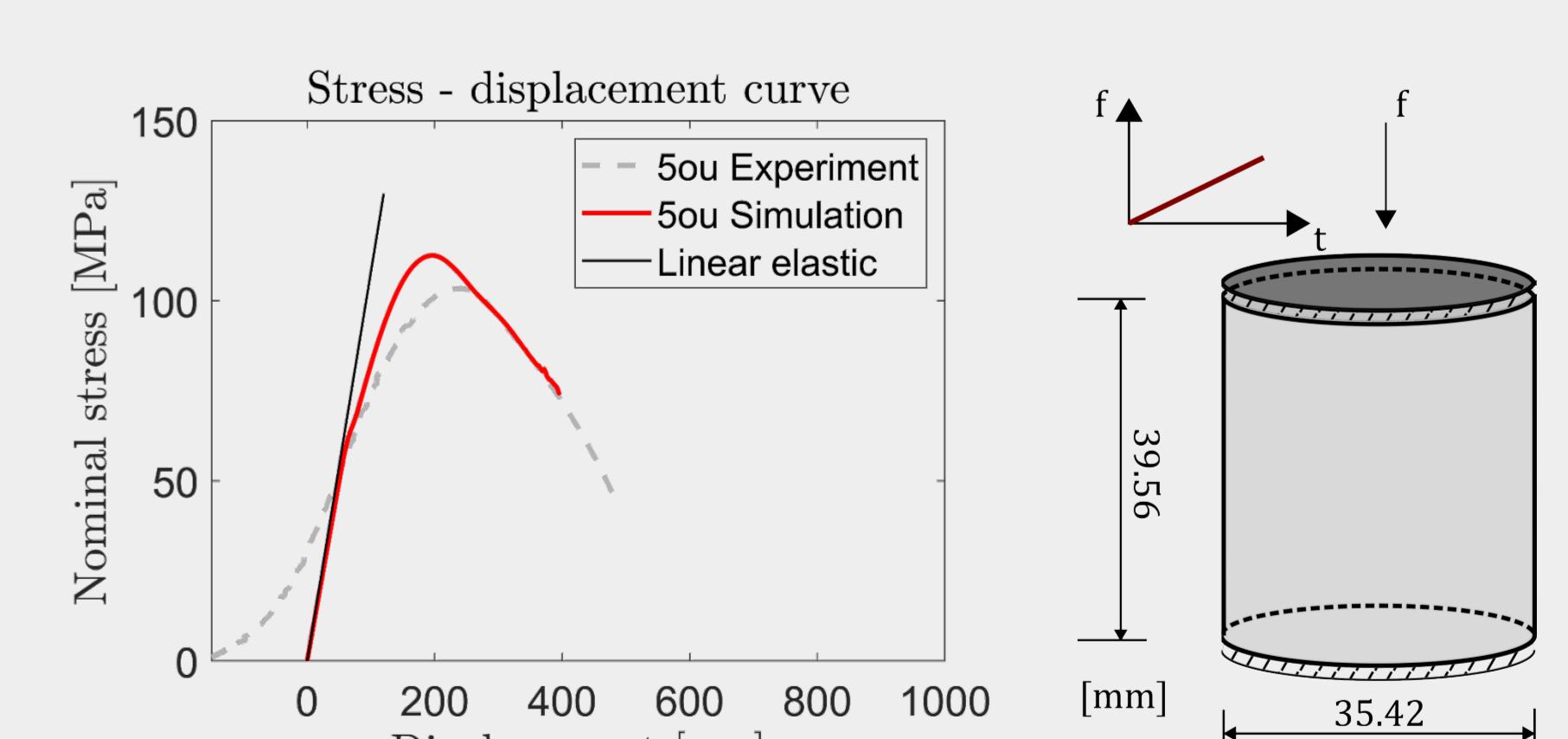
Simulated vs Experimental Crack Pattern

Experiments performed by M. Sc. Niklas Schäfer, Ruhr University Bochum