MICROMECHANICAL FINITE ELEMENT MODELING OF LONG FIBER REINFORCED THERMOPLASTICS (LFT)

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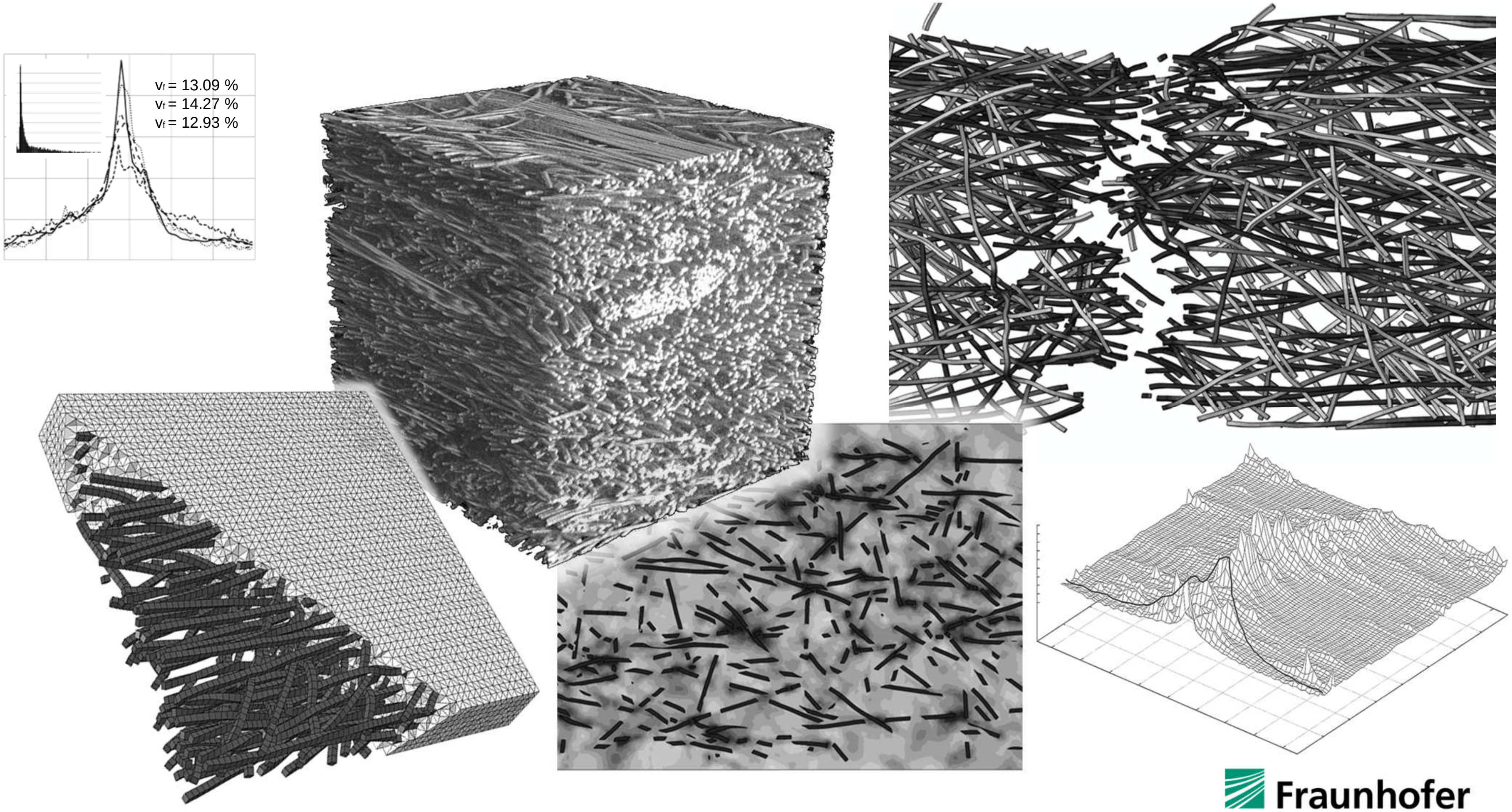

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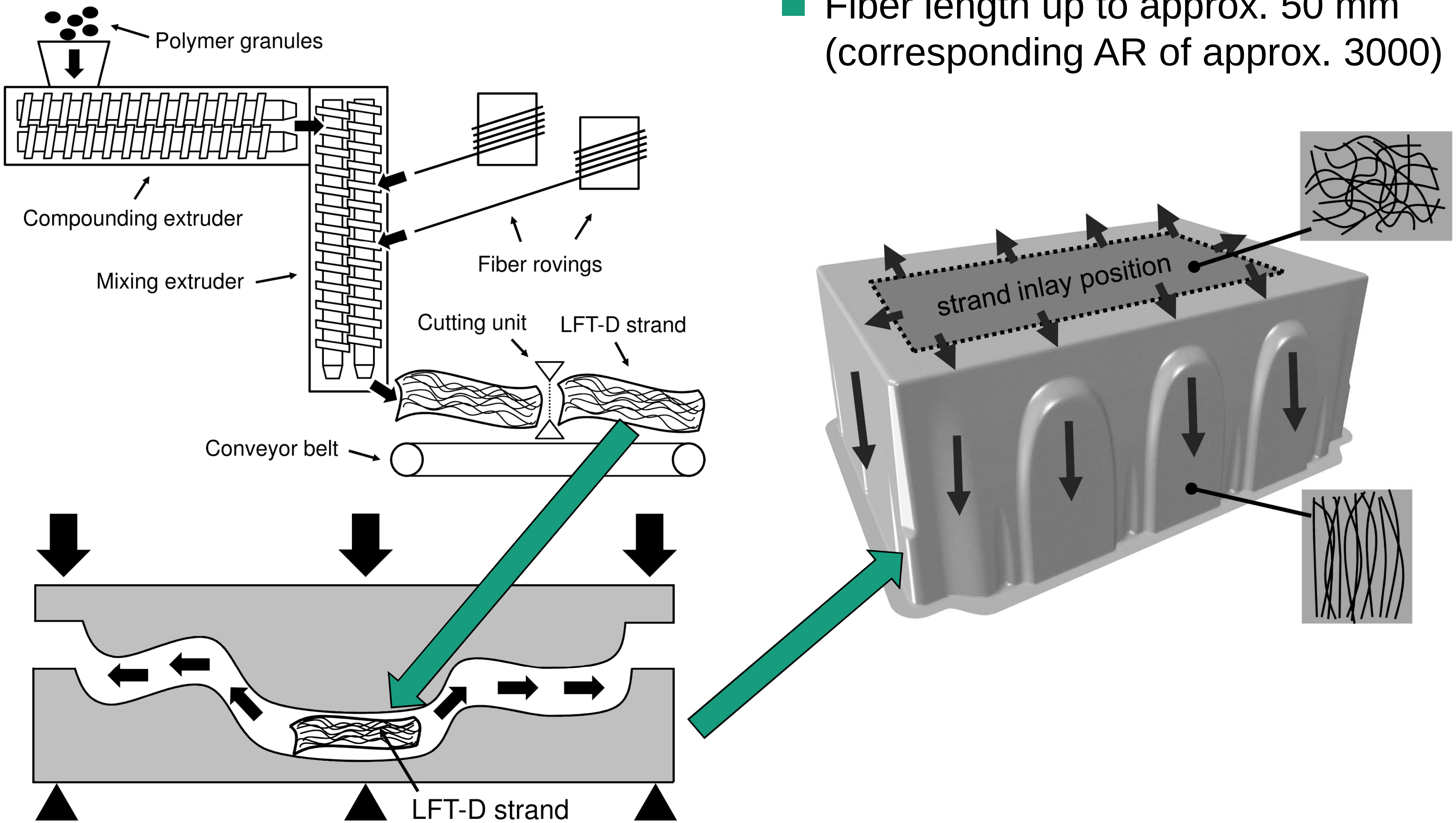
Outline

- Introduction
- LFT-D material
- **Microstructural model & generation**
- **Micromechanical simulations & experimental validation**
    - Elastic properties
    - Viscoelastic properties (creep)
    - Plasticity and damage
- **Outlook**
    - Probabilistic approach
    - Micro specimens and inverse modeling

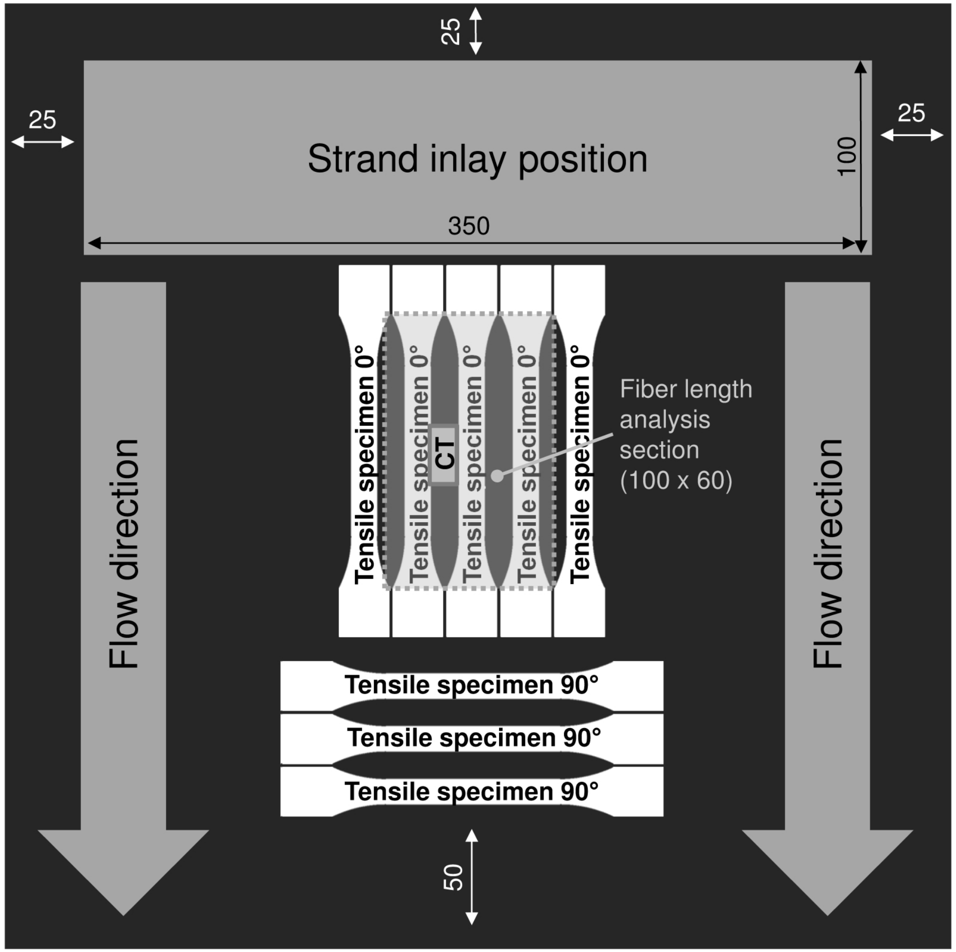
LFT-D material
Processing route*

- Fiber length up to approx. 50 mm (corresponding AR of approx. 3000)



*) Fraunhofer Institute for Chemical Technology (ICT), www.ict.fraunhofer.de

LFT-D material
Specimen plate



- Dimensions:

  400 x 400 x 3 mm³

- Three material variants with different fractions of glass fibers

  PPGF10 (3.8 vol-%)
  PPGF20 (8.2 vol-%)
  PPGF30 (13.2 vol-%)

- Neat matrix specimen plates (polypropylene) produced by injection compression molding

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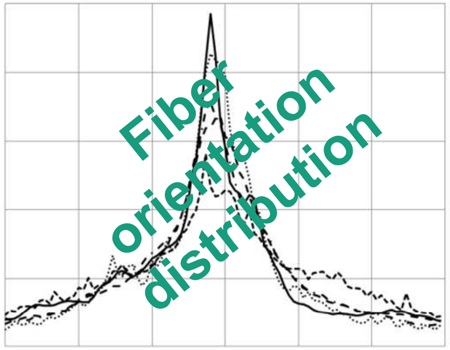
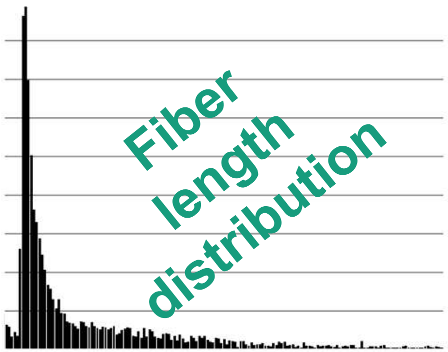
Microstructure generation*

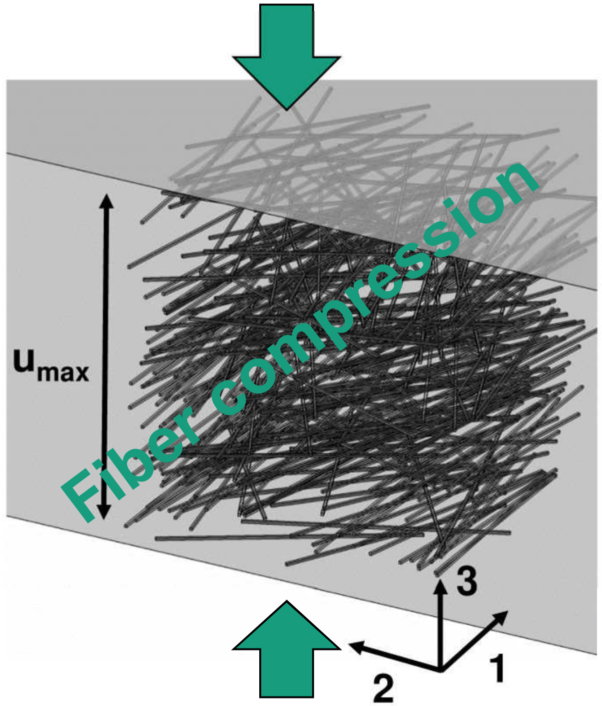
FiberGenerator





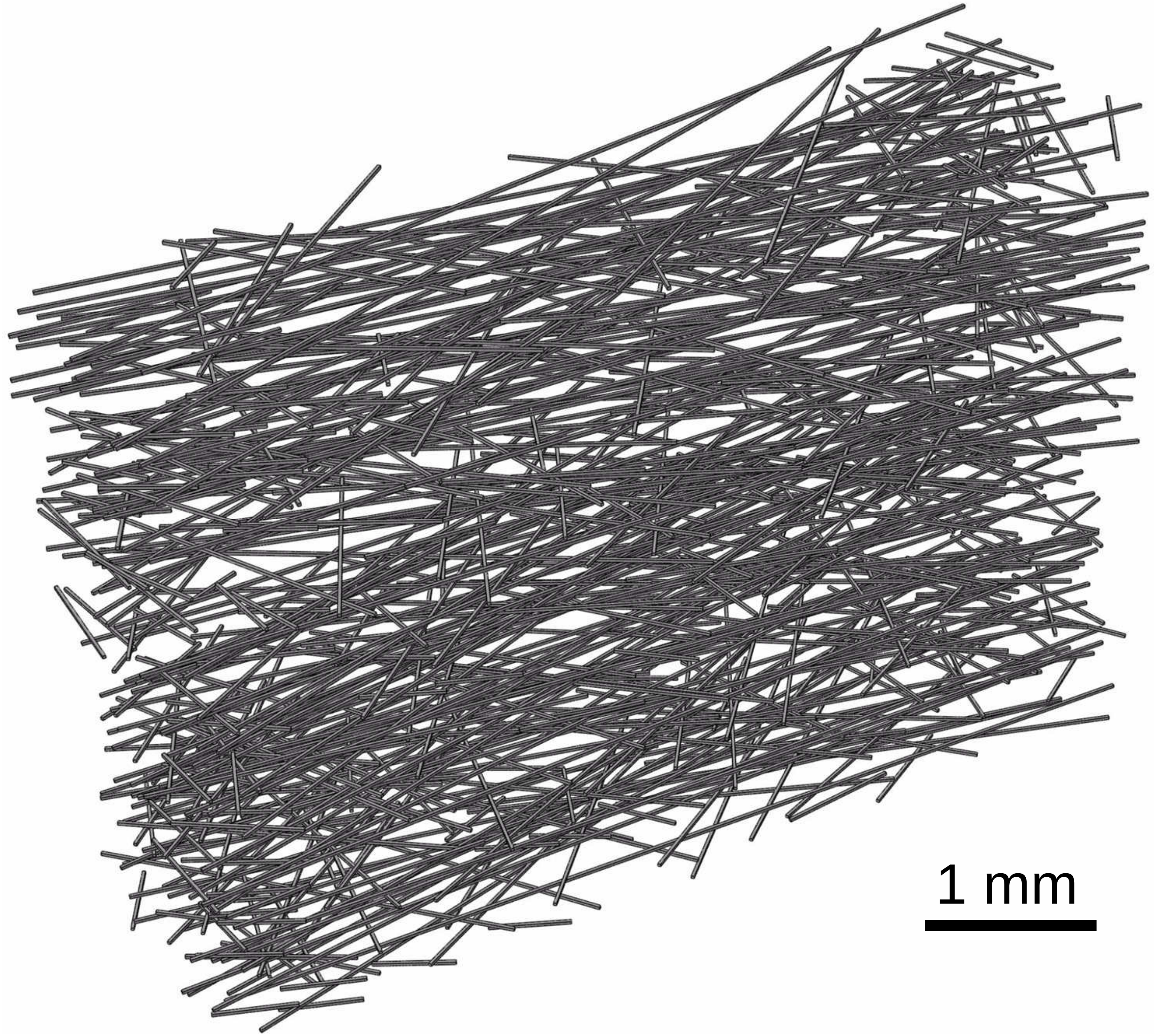
FiberGenerator

```
x11=temp_coord_x_start(m)+(1.5*element_length)
x12=temp_coord_x_end(m)+(1.5*element_length)
y11=temp_coord_y_start(m)+(1.5*element_length)
y12=temp_coord_y_end(m)+(1.5*element_length)

a1=y12-y11
a2=y22-y21
b1=x11-x12
b2=x21-x22
c1=x12*y11-x11*y12
c2=x22*y21-x21*y22

if ((a1*x21+b1*y21+c1)*(a1*x22+b1*y22+c1) .LE. 0.0) then
intersection=1
endif

if ((a2*x11+b2*y11+c2)*(a2*x12+b2*y12+c2) .LE. 0.0) then
intersection=1
endif
```

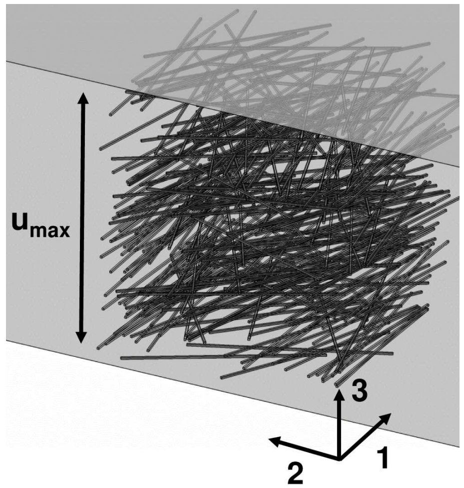


) Fliegener S, Luke M, Gumbsch P: 3D microstructure modeling of long fiber reinforced thermoplastics,* Comp. Sci. Tech. 104 (2014) 136-145

Microstructure generation
Fiber compression procedure - video phase A



- Compression phase A
- Plate displacement: 0 to 0.9 u_{max}
- Boundary conditions: u_1, u_2 = 0 u_3 = free
- BC regions: all nodes of each fiber
- Max. $v_f \approx 5 - 7.5$ %



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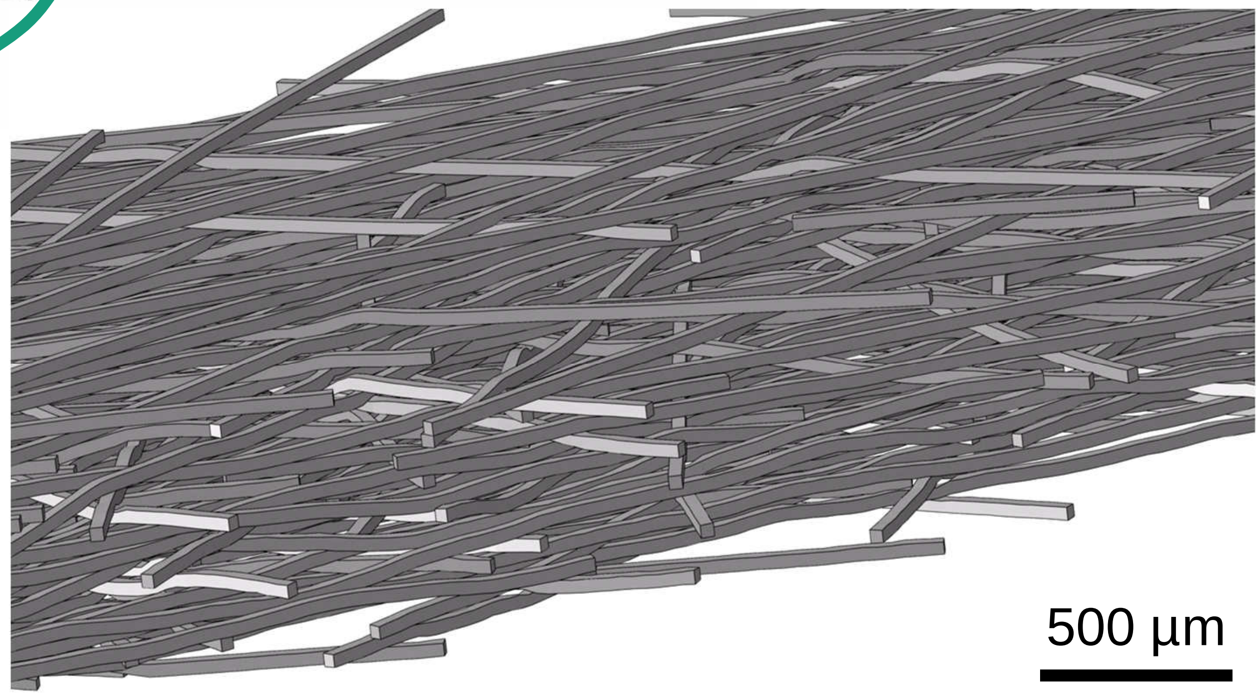
Microstructure generation

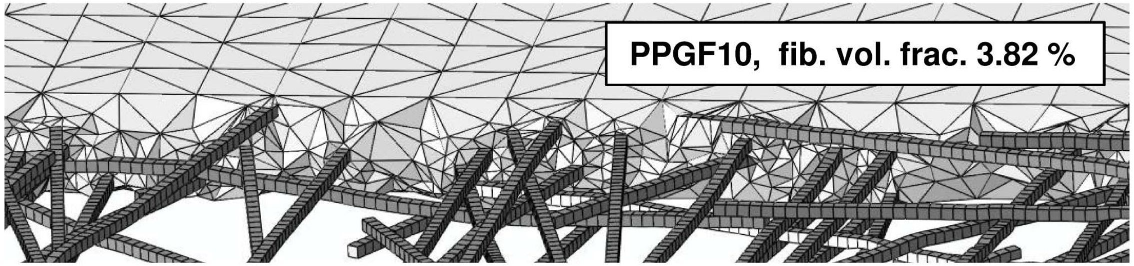
Fiber compression procedure - video phase B

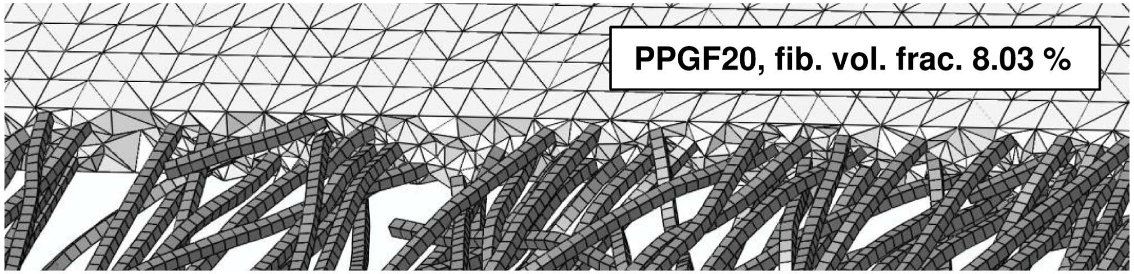


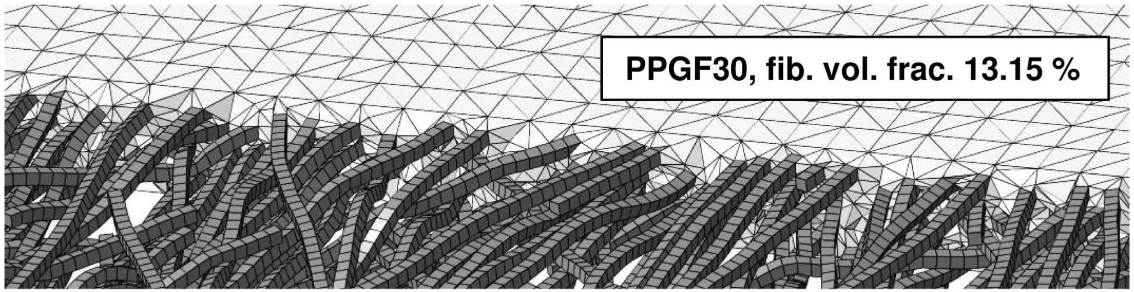
- Compression phase B
- Plate displacement: $0.9\ u_{max}$ to u_{max}
- BC regions: only nodes of first and last fiber element
- Contact accounting for friction
- Max. v_f up to ≈ 25 %

Microstructure generation
Mesh details

- **Different variants of representative volume elements (RVEs)**







100 µm

- **PPGF10 (3.82 vol-%)**
  RVE dim. 50 x 2.75 x 0.125 mm^3
  7.4 mio elements
  total fiber length 3056 mm
  mean weighted fib. len. 10.1 mm

- **PPGF20 (8.03 vol-%)**
  RVE dim. 50 x 2.75 x 0.099 mm^3
  8.7 mio elements
  total fiber length 5048 mm
  mean weighted fib. len. 9.4 mm

- **PPGF30 (13.15 vol-%)**
  RVE dim. 50 x 1.5 x 0.134 mm^3
  9.7 mio elements
  total fiber length 6067 mm
  mean weighted fib. len. 8.1 mm

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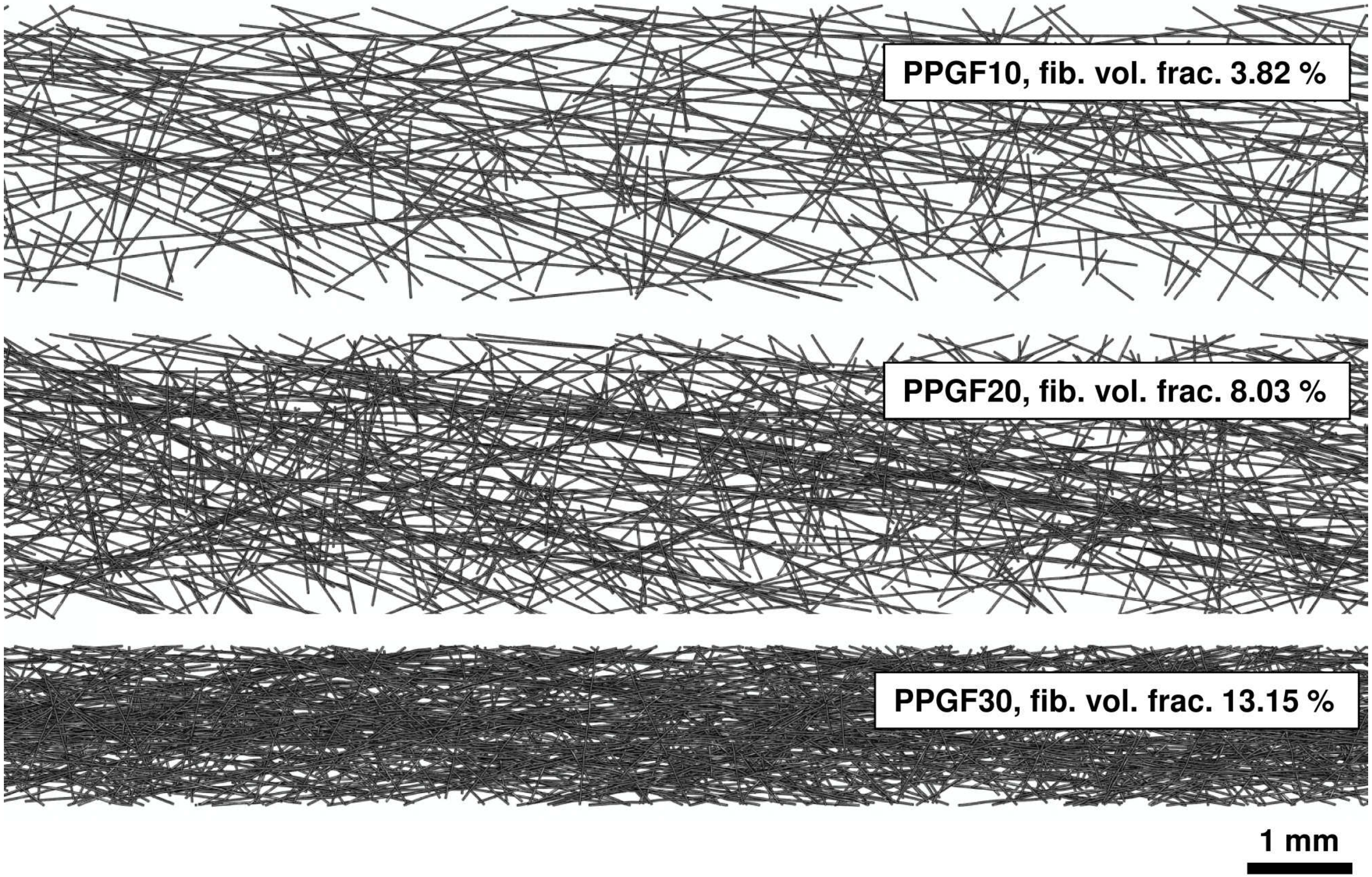
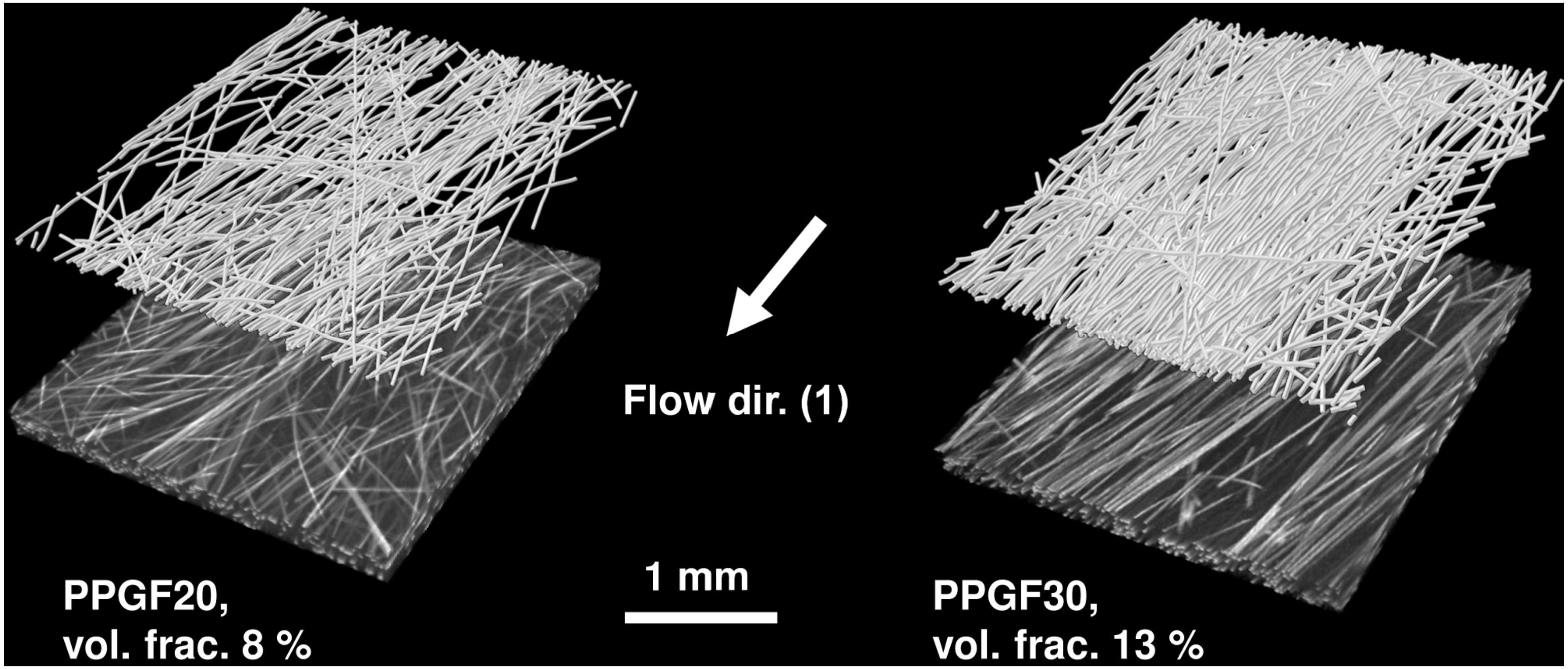
Microstructure generation
Fiber structure



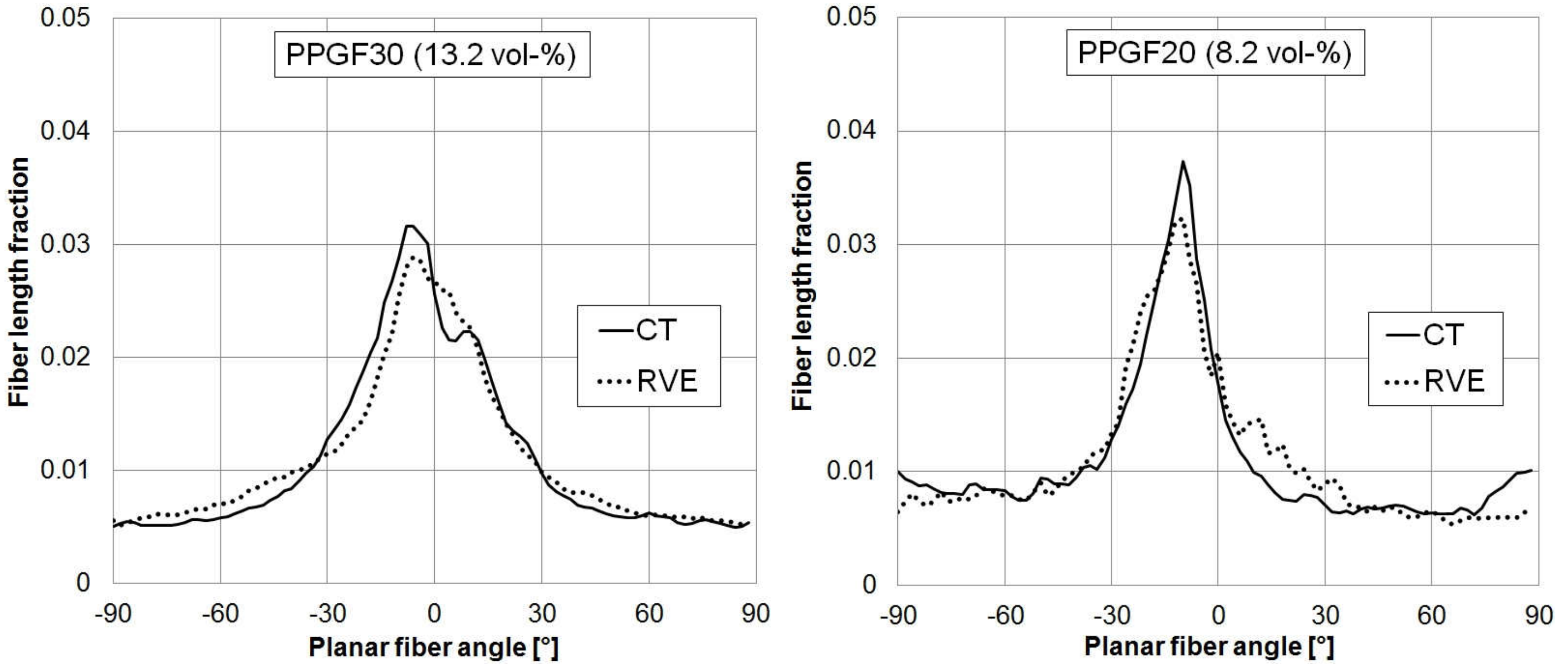
Microstructure generation
FE mesh vs. CT scan



Microstructure generation

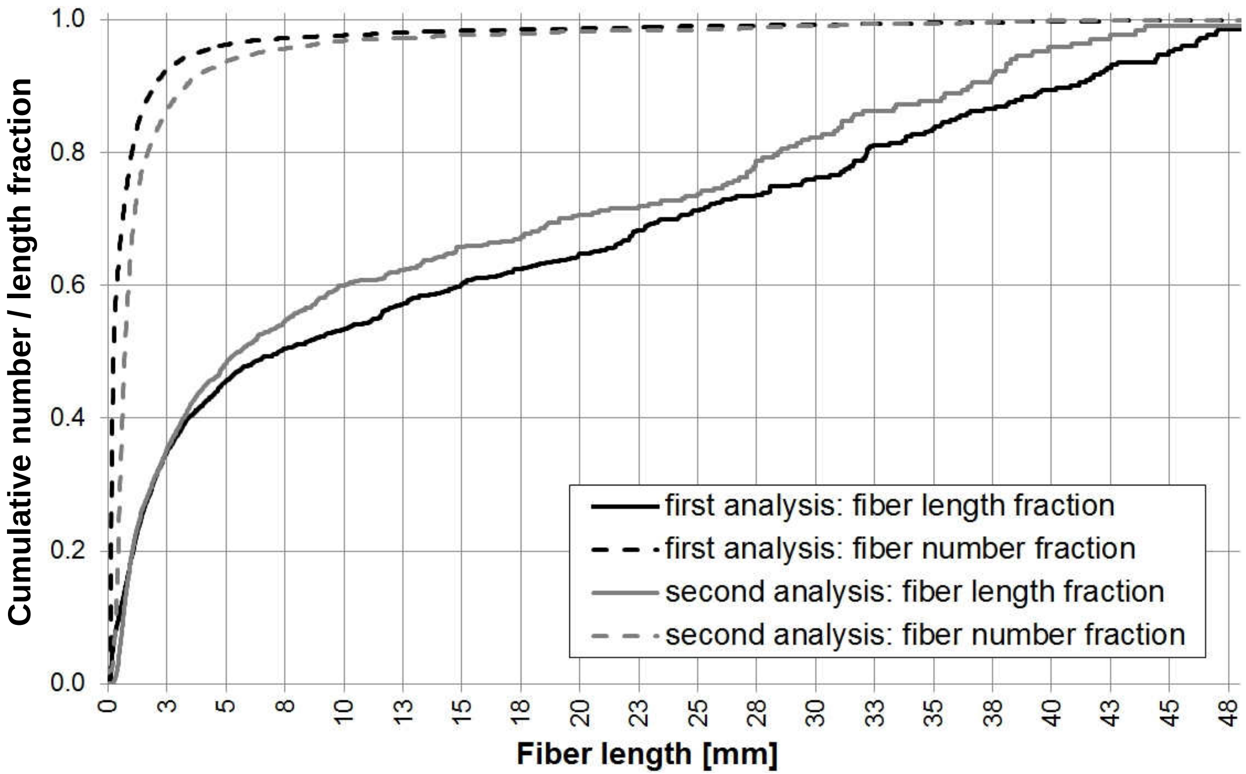
Fiber orientation distribution: RVE mesh vs. CT scan

- Image analysis procedure applied on RVE mesh
- 50 equidistant cuts over the RVE thickness
- In general, good agreement between CT analysis and RVE models



Microstructure generation
Fiber length distribution

- Analysis of an incinerated specimen (100 x 60 x 3 mm³) *
- Implementation: Bin size of 0.2 mm (0 < l < 2 mm) and 2 mm (2 ≤ l ≤ 48 mm)



- Number average

$$\bar{l}_\mathrm{n} = \frac{\sum_i n_i l_i}{\sum_i n_i} \approx 1.2 \text{ mm}$$

- Length / volume average

$$\bar{l}_\mathrm{w} = \frac{\sum_i n_i l_i^2}{\sum_i n_i l_i} \approx 15 \text{ mm}$$

*) FASEP®. *xyz high precision*. http://www.fasep.de

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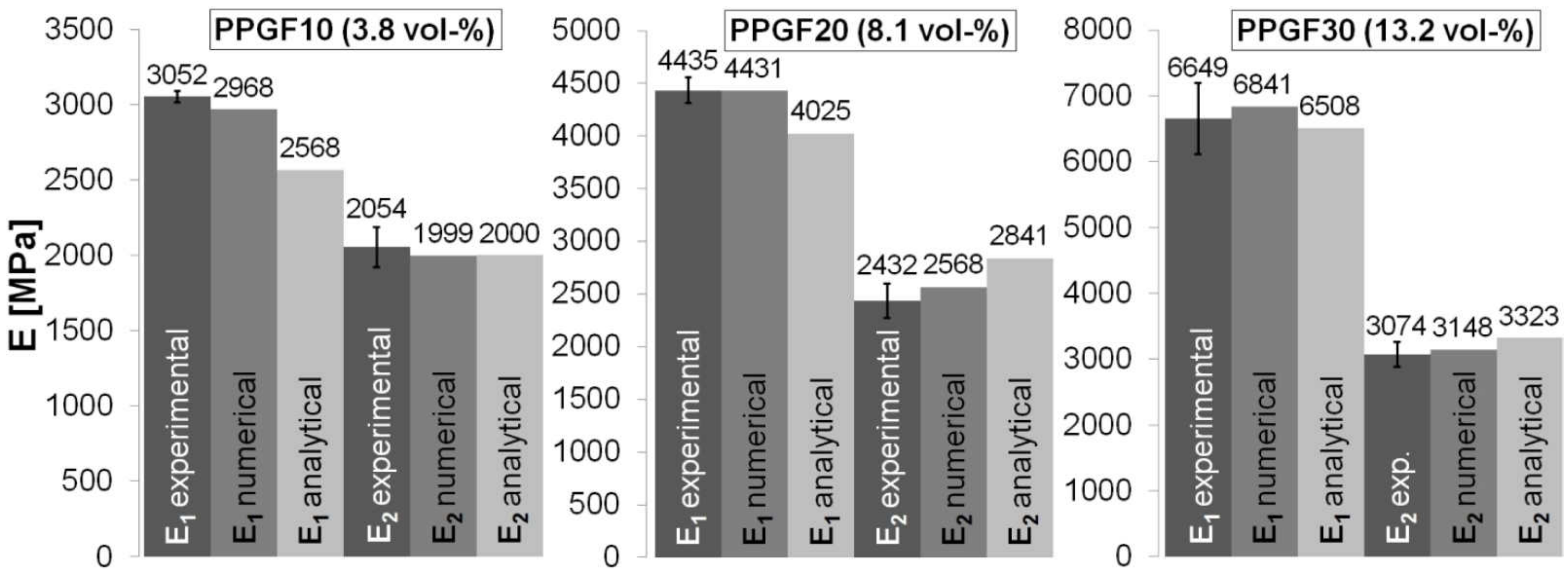
Application 1: Elasticity

- **Elasticity**
  - elastic matrix, elastic fibers, perfect interface
- **Viscoelasticity** (creep)
  - viscoelastic matrix, elastic fibers, perfect interface
- **Plasticity and damage**
  - plastic matrix, brittle fibers, interface damage

Micromechanical simulations and experimental validation
Elasticity - results



- Constituent properties: E_f = 72000 MPa, ν_f = 0.22, E_m = 1250 MPa, ν_m = 0.35
- Analytical homogenization: Orientation averaging acc. to Advani * / length averaging
- Experimental values: Tensile tests (three loading-unloading cycles in the elastic range)

*) Advani SG, Tucker CL: *The use of tensors to describe and predict fiber orientation in short fiber composites,* Journal of Rheology 31 (1987) 751-784

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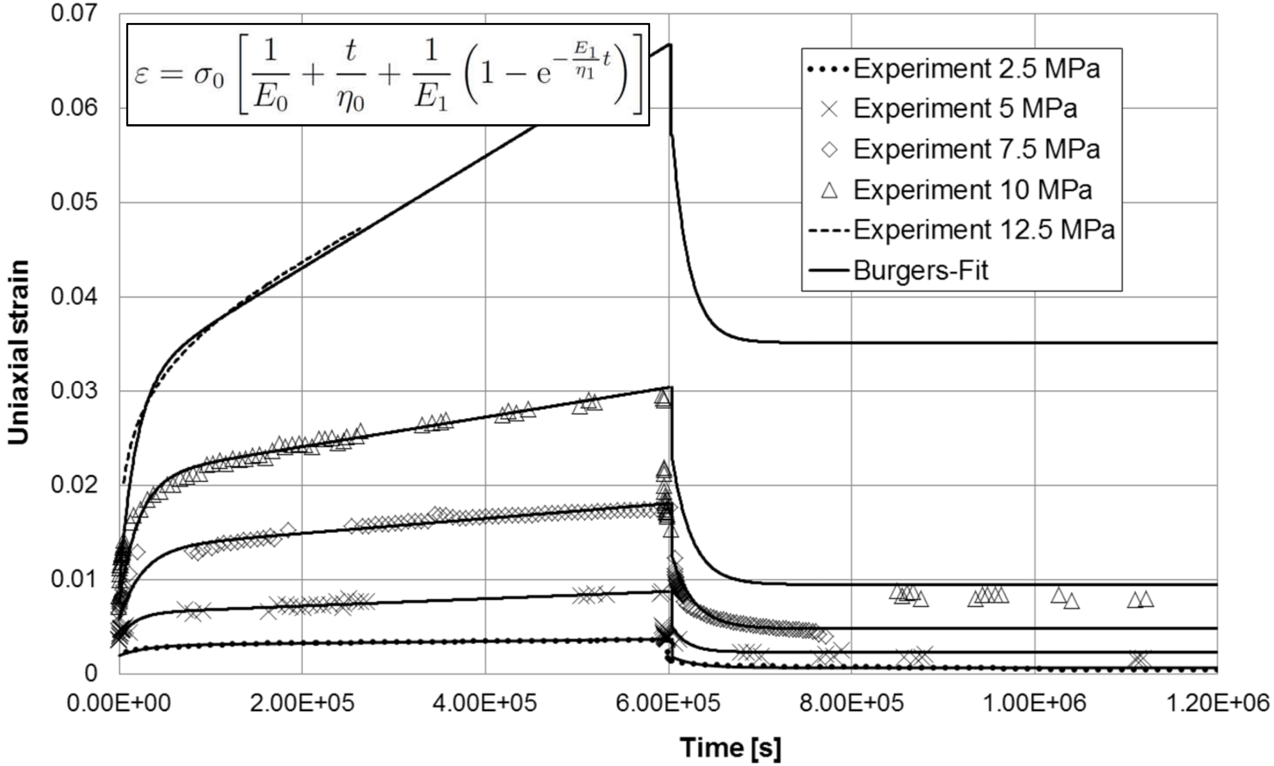
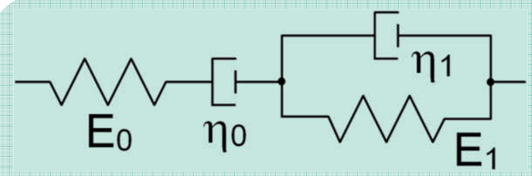
Application 2: Viscoelasticity (creep)

- **Elasticity**
  - elastic matrix, elastic fibers, perfect interface
- **Viscoelasticity** (creep)
  - viscoelastic matrix, elastic fibers, perfect interface
- **Plasticity and damage**
  - plastic matrix, brittle fibers, interface damage

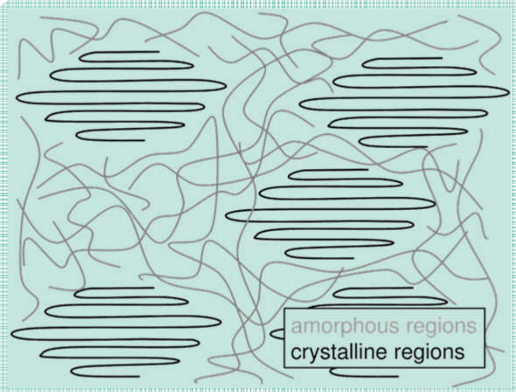
Micromechanical simulations and experimental validation

Viscoelasticity (creep) - matrix model





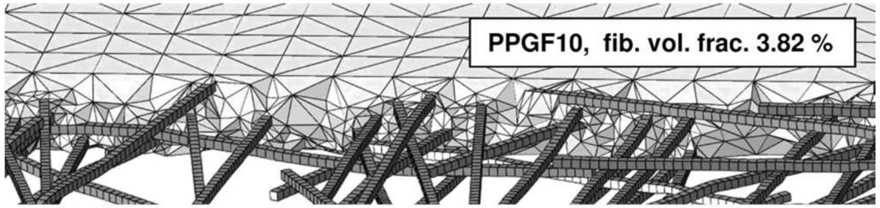
- Four parameter Burgers model

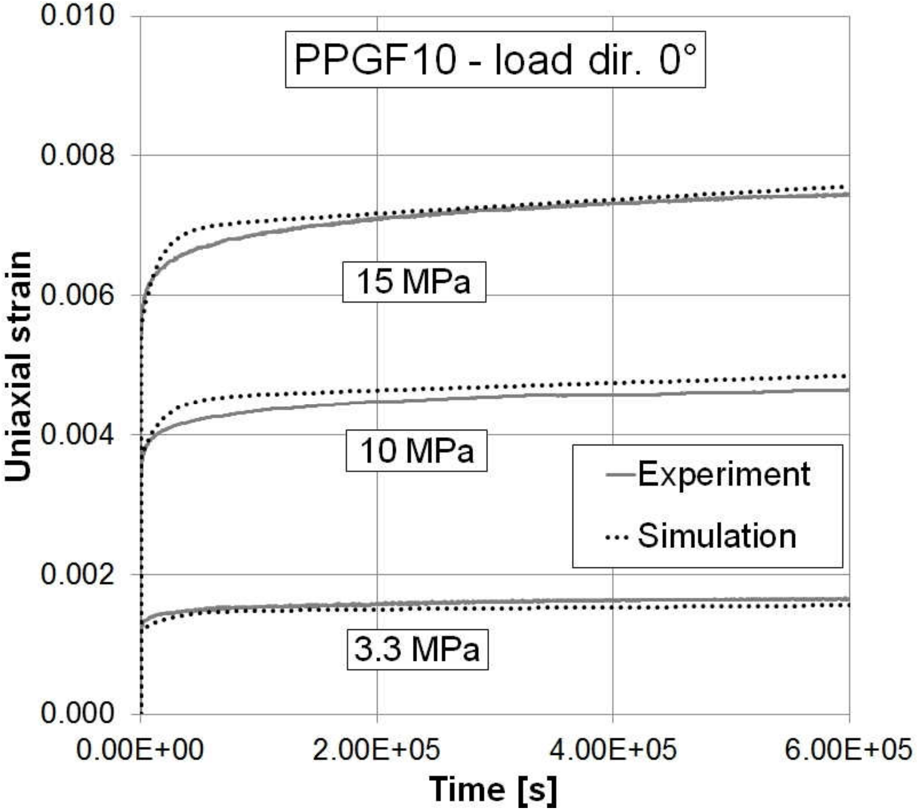


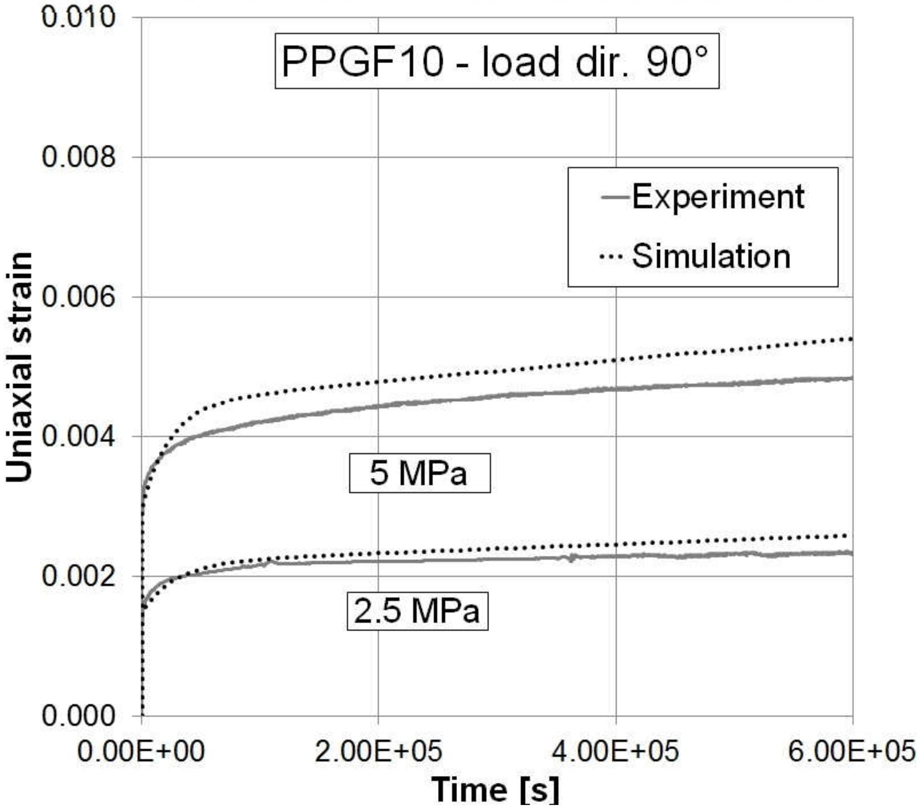
- The free dashpot η_0 corresponds to the continous sliding of the amorphous regions

- The Burgers model represents the experimental data very accurately with only four parameters
- The viscous behavior (constant creep rate of second period, irreversible recovery strain) is captured
- The model must be modified to account for the nonlinear viscoelastic range

Micromechanical simulations and experimental validation
Viscoelasticity (creep) - results PPGF10







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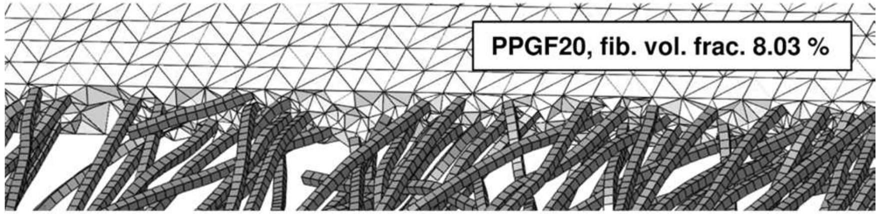
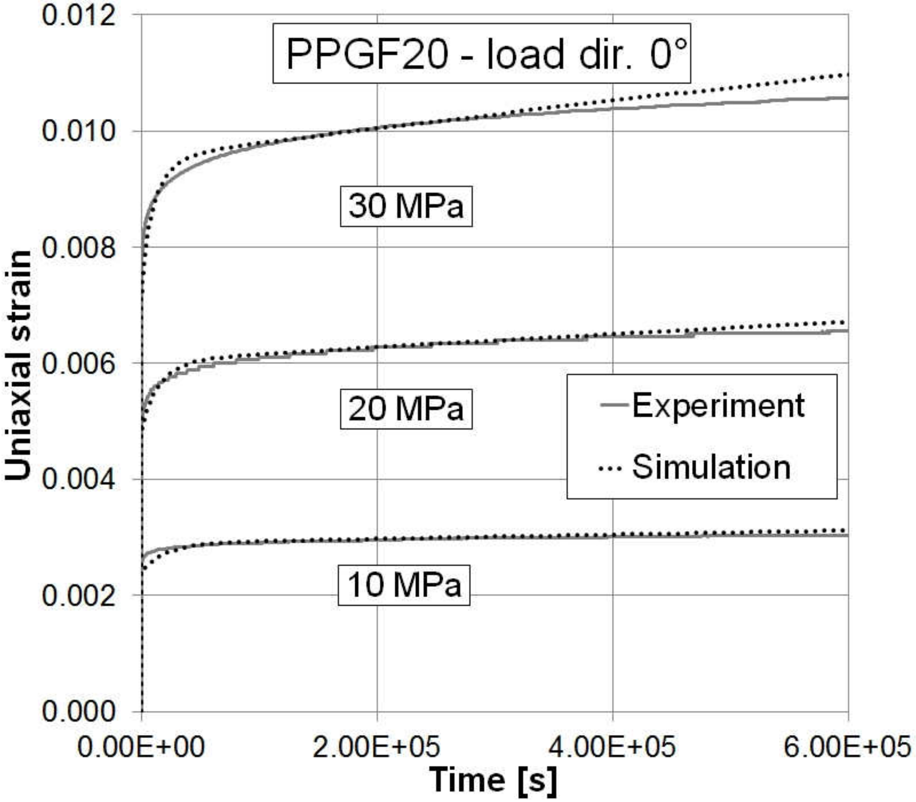
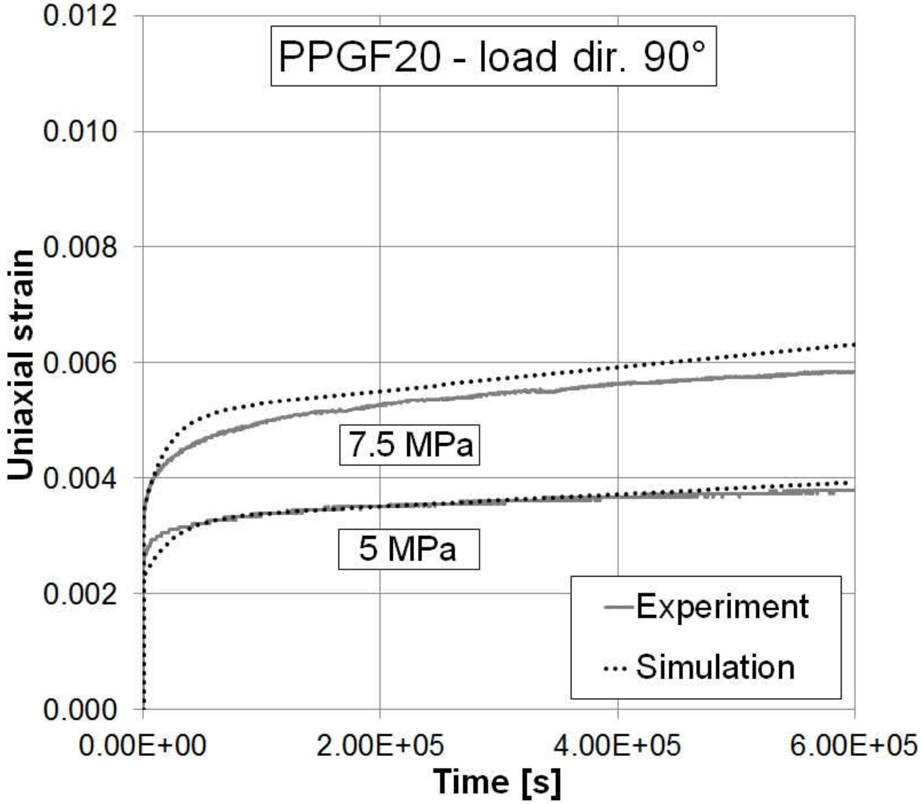
Micromechanical simulations and experimental validation

Viscoelasticity (creep) - results PPGF20







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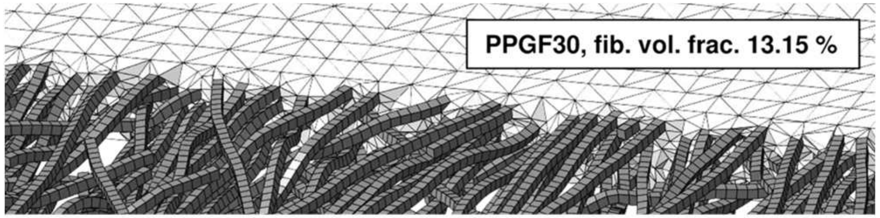
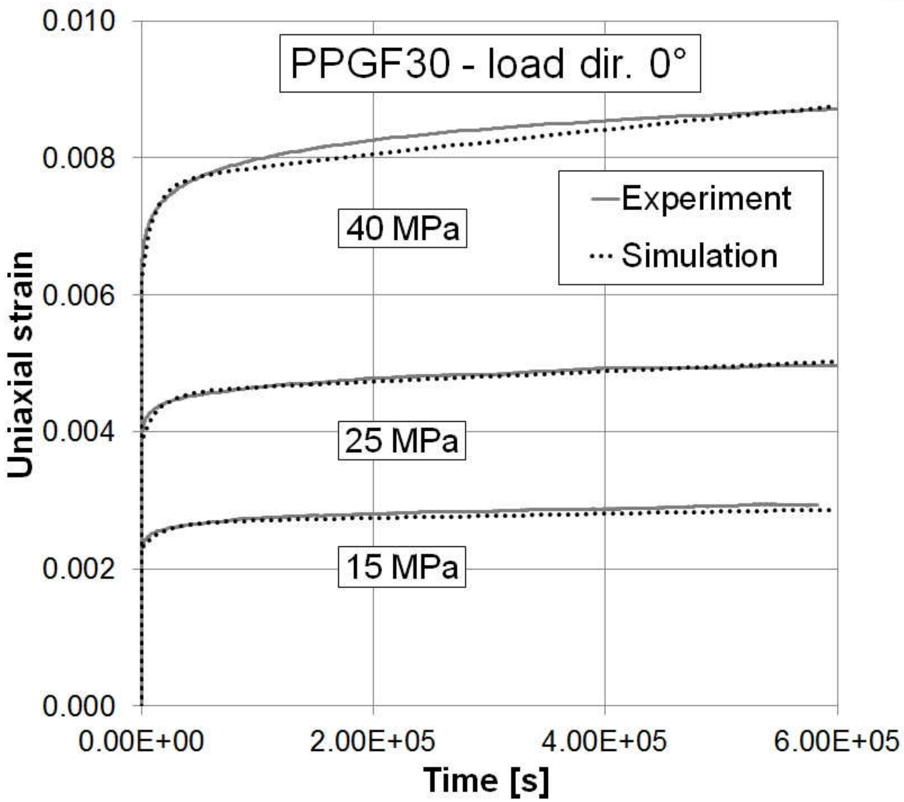
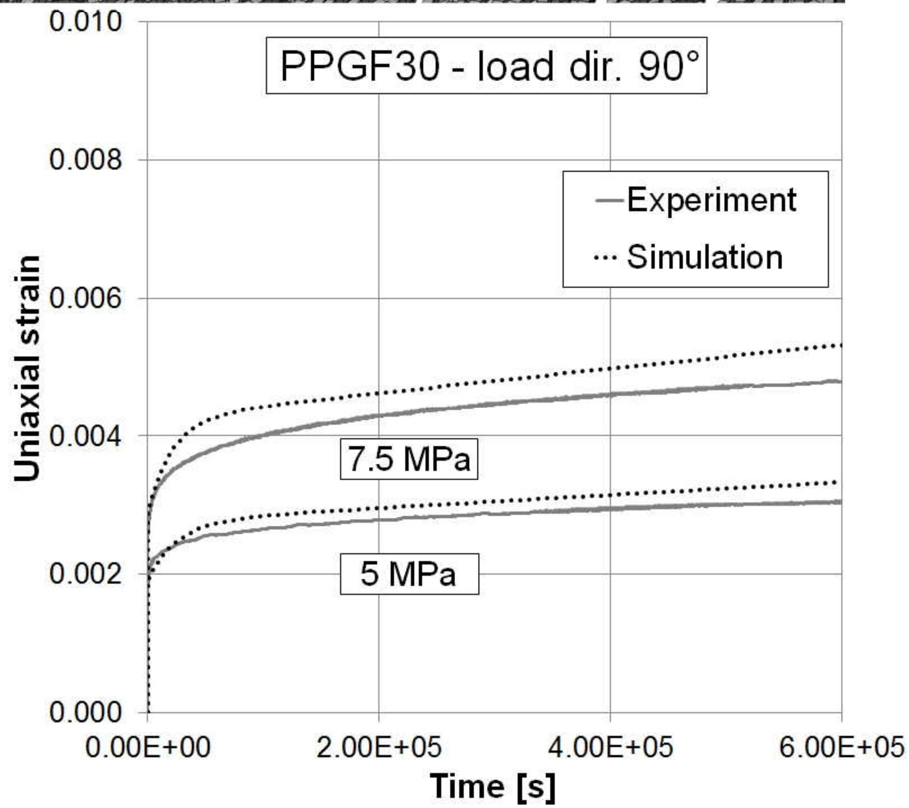
Micromechanical simulations and experimental validation

Viscoelasticity (creep) - results PPGF30





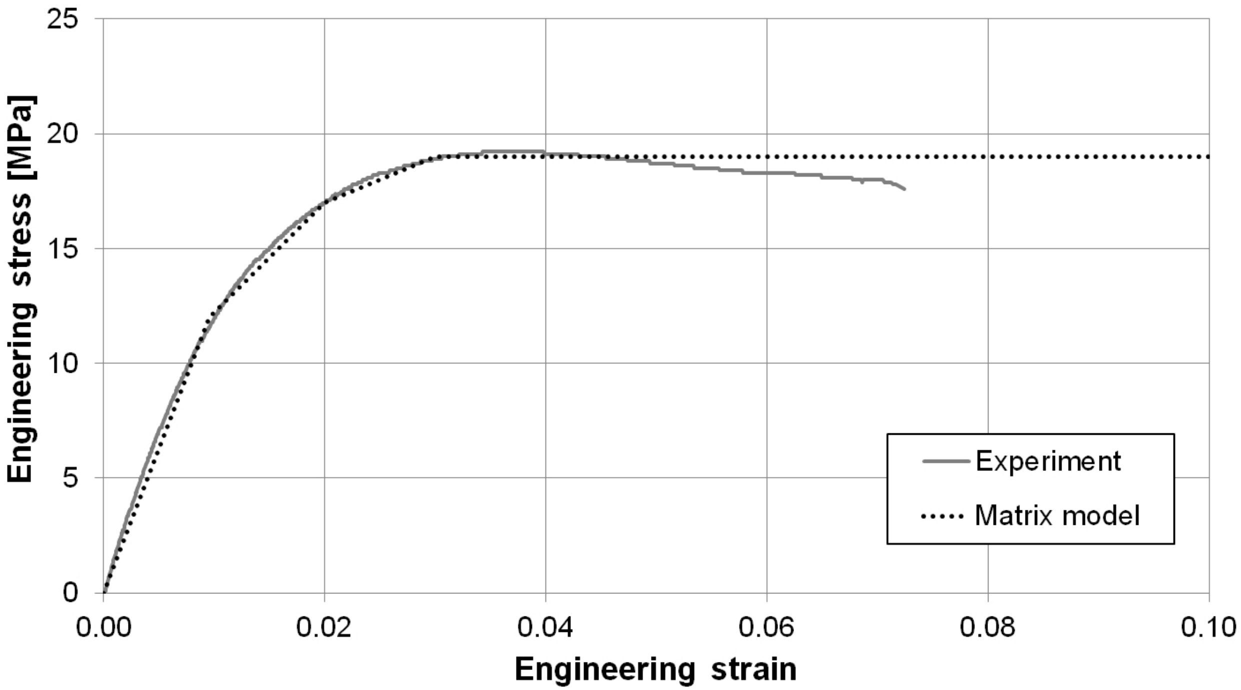


Application 3: Plasticity and damage

- **Elasticity**
  - elastic matrix, elastic fibers, perfect interface
- **Viscoelasticity** (creep)
  - viscoelastic matrix, elastic fibers, perfect interface
- **Plasticity and damage**
  - plastic matrix, brittle fibers, interface damage

Micromechanical simulations and experimental validation
Plasticity & damage - matrix model

- Classical von Mises plasticity model
- Calibration with quasi static tensile tests on matrix substance specimen (containing the same additives and stabilizers as used for the LFT compounding procedure)
- No damage considered due to variation of the element size and shape



$$\sigma_{\mathrm{Y}} = \sqrt{\frac{3}{2}\sigma'_{ij}\sigma'_{ij}}$$

Equivalent (yield) stress

$$\dot{\varepsilon}_{\mathrm{p}} = \sqrt{\frac{2}{3}\dot{\varepsilon}^{\mathrm{p}}_{ij}\dot{\varepsilon}^{\mathrm{p}}_{ij}}$$

Equivalent plastic strain rate

$$\varepsilon_{\mathrm{p}} = \int_0^t \dot{\varepsilon}_{\mathrm{p}}\,\mathrm{d}t$$

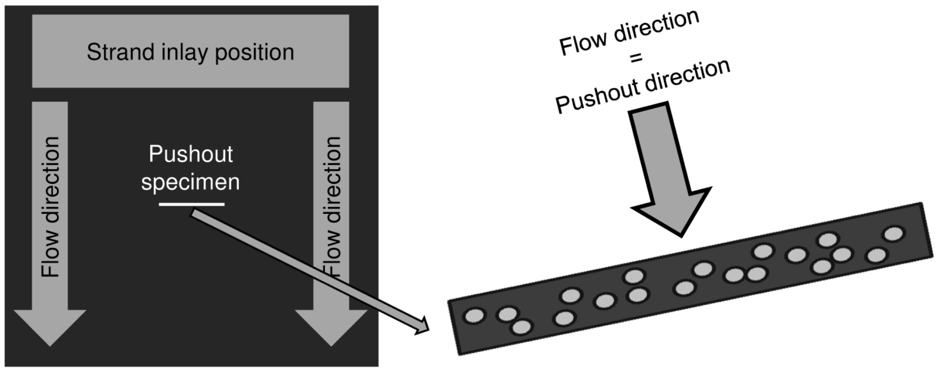
Equivalent plastic strain

Isotropic, multilinear hardening:
Value pairs of $[\sigma_{\mathrm{Y}}|\varepsilon_{\mathrm{p}}]$

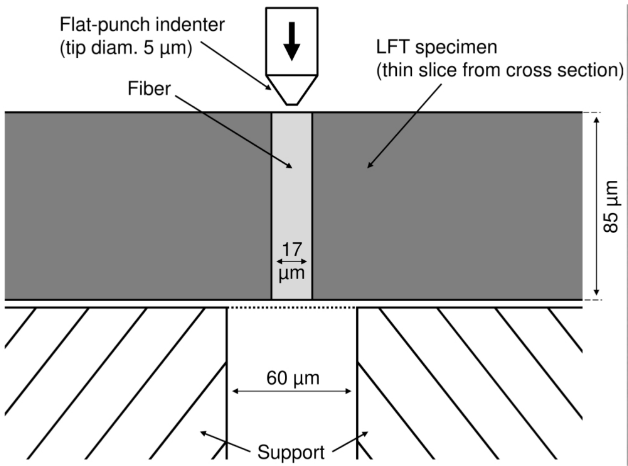
Micromechanical simulations and experimental validation

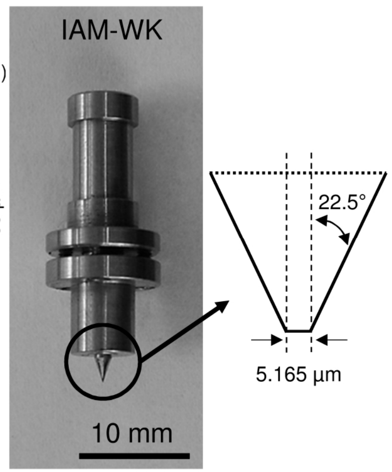
Plasticity & damage - fiber pushout experiments*

- **Specimen preparation**

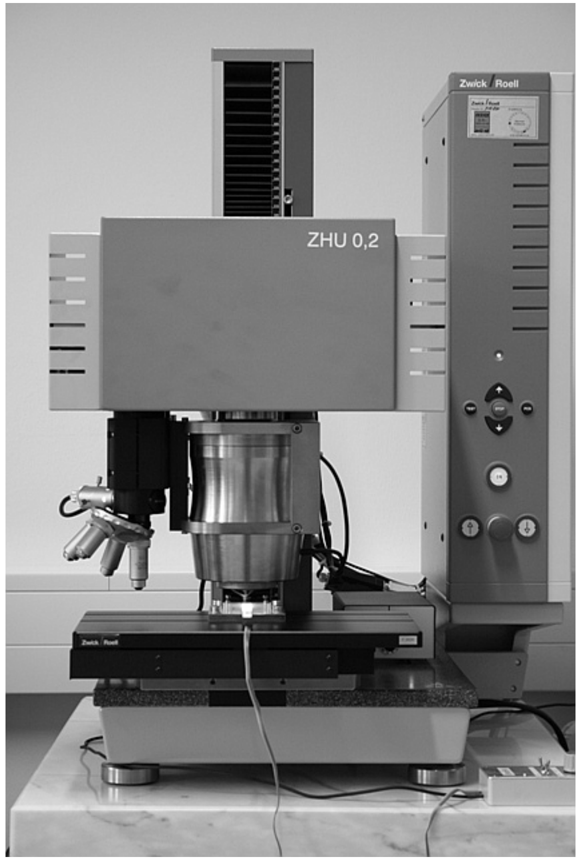


- **Push-out setup / indenter**





- **Modified hardness testing machine (Zwick ZHU 0,2)**



*) *Institute for Applied Materials IAM-WK,* Karlsruhe Institute of Technology (KIT), http://www.iam.kit.edu/wk/

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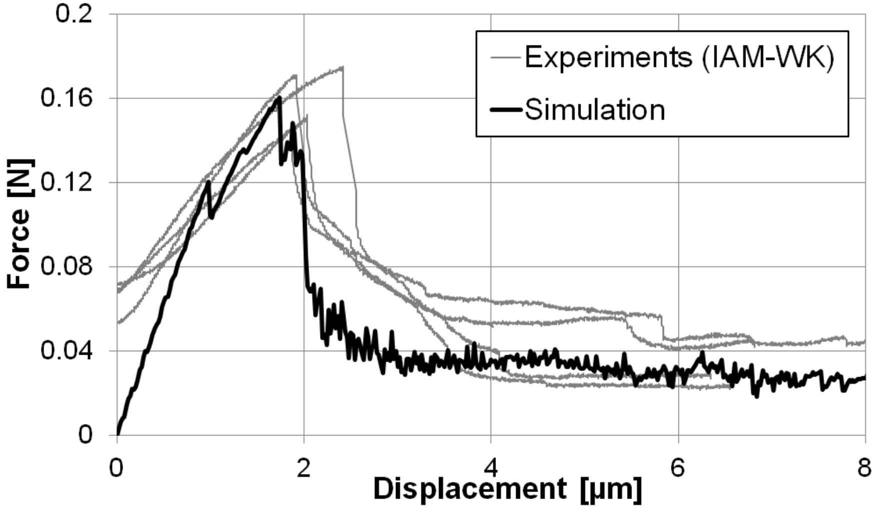
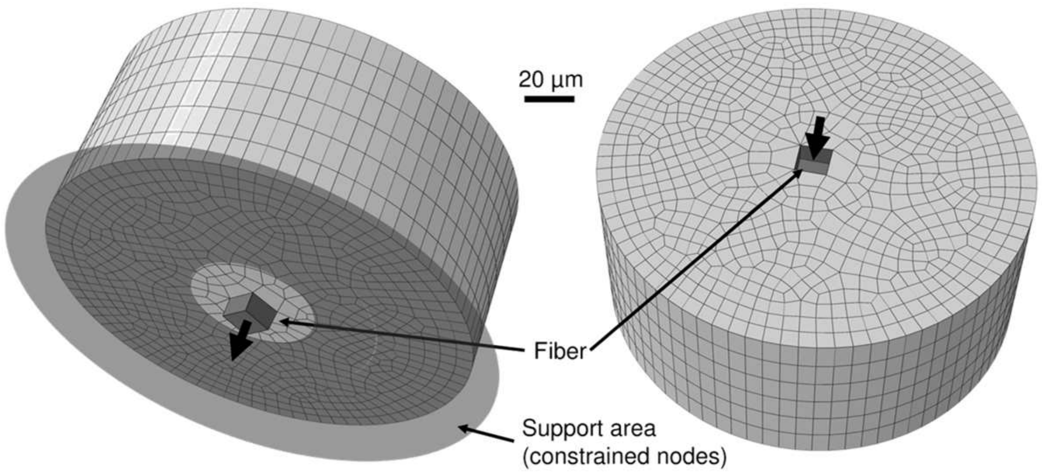
Micromechanical simulations and experimental validation

Plasticity & damage - fiber pushout simulation





- **Inverse modeling** for parameter identification of the traction-separation law assigned to cohesive elements beetween fiber and matrix and contact accounting for friction
- **Fit parameters:**
  - Failure energy (traction-separation law)
  - coeffient of friction (contact)

$$\begin{pmatrix} t_\mathrm{n} \\ t_\mathrm{s} \\ t_\mathrm{t} \end{pmatrix} = \begin{bmatrix} K_\mathrm{n} & & \\ & K_\mathrm{s} & \\ & & K_\mathrm{t} \end{bmatrix} \begin{pmatrix} \varepsilon_\mathrm{n} \\ \varepsilon_\mathrm{s} \\ \varepsilon_\mathrm{t} \end{pmatrix}$$

Traction-separation law (with $\boldsymbol{\varepsilon} = \boldsymbol{\delta}/h$)

$$\left(\frac{\langle \varepsilon_\mathrm{n} \rangle}{\varepsilon_\mathrm{n}^0}\right)^2 + \left(\frac{\varepsilon_\mathrm{s}}{\varepsilon_\mathrm{s}^0}\right)^2 + \left(\frac{\varepsilon_\mathrm{t}}{\varepsilon_\mathrm{t}^0}\right)^2 = 1$$

Quadratic damage initiation criterion

$$t_\mathrm{n,s,t} = (1-D)\bar{t}_\mathrm{n,s,t}$$

Damage evolution with damage variable D

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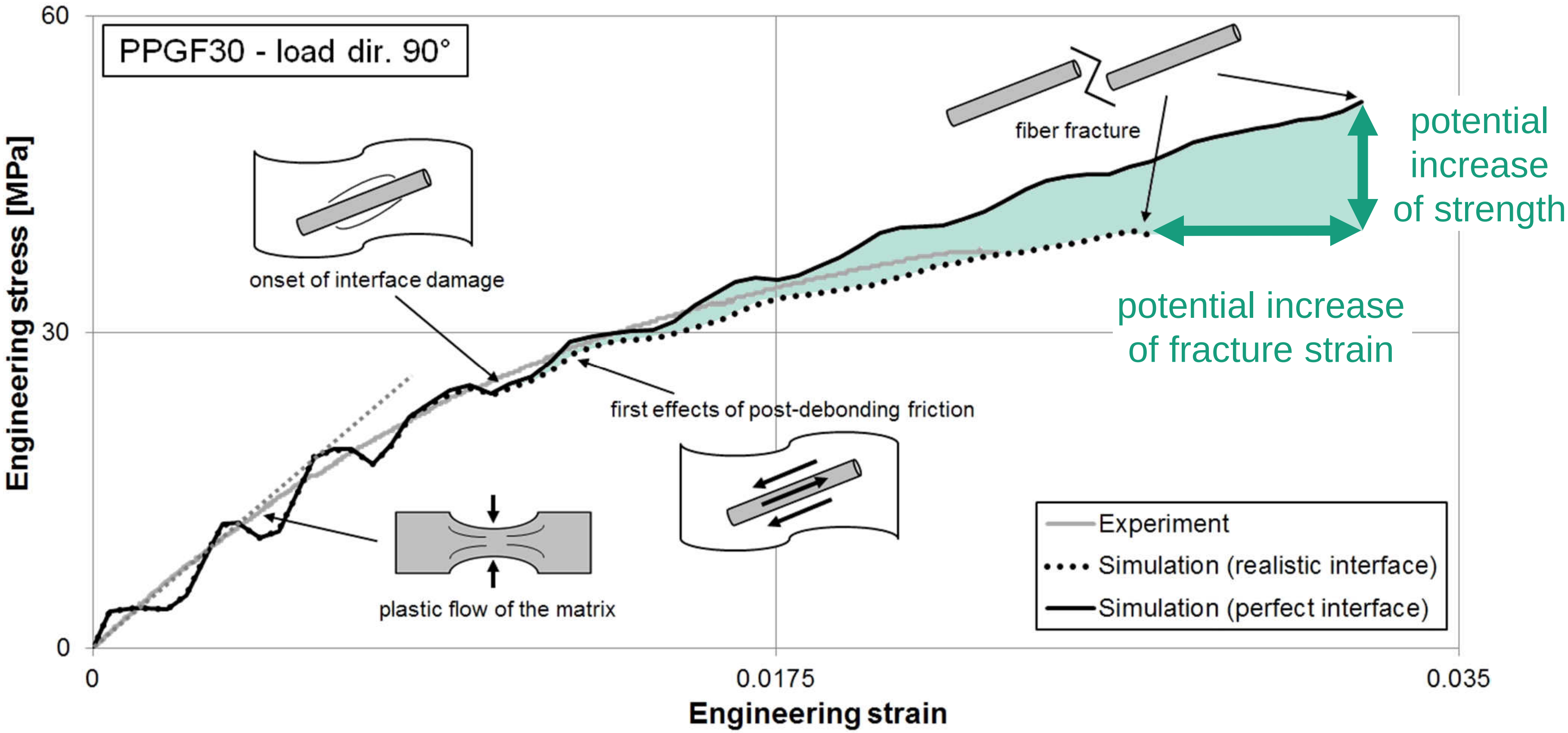
Micromechanical simulations and experimental validation
Plasticity & damage - results



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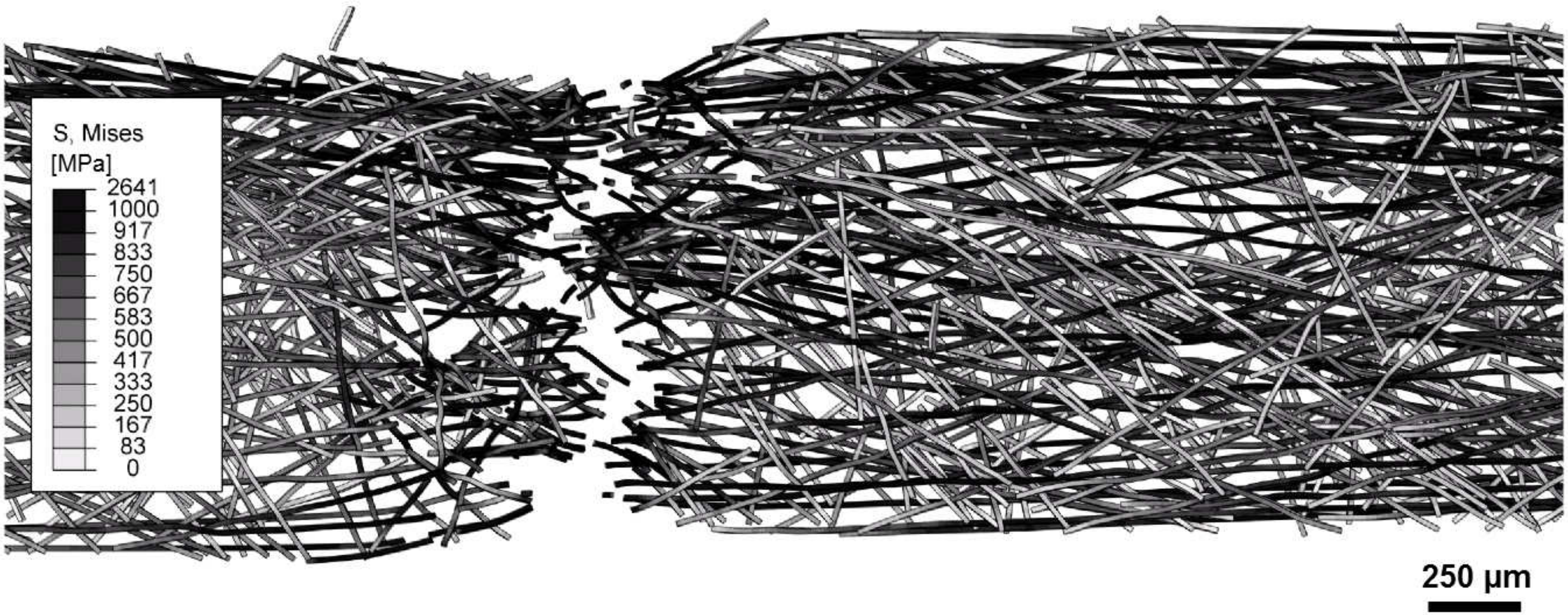
Micromechanical simulations and experimental validation
Plasticity & damage - video

- Simulation accounting for matrix plasticity, debonding, friction and fiber failure
- PPGF30, 0° load direction
- Only fibers shown



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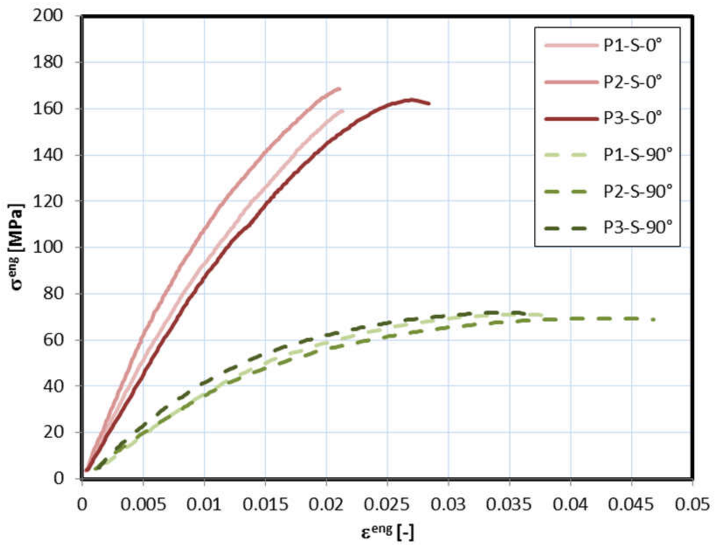
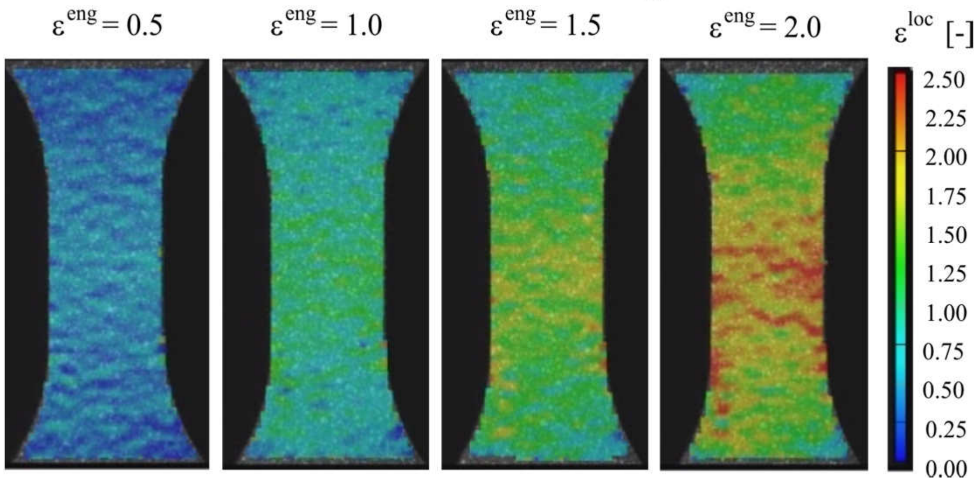
Outlook
Probabilistic approach*

- material: PA6.6 GF40 (compression molded)
- stress-strain response
  - overall
    - tensile tests within and perpendicular to flow direction
    - section 10 mm x 3 mm
    - overall scatter
  - local
    - grey scale correlation system (ARAMIS)
    - distinct scatter on length scales below 10 mm

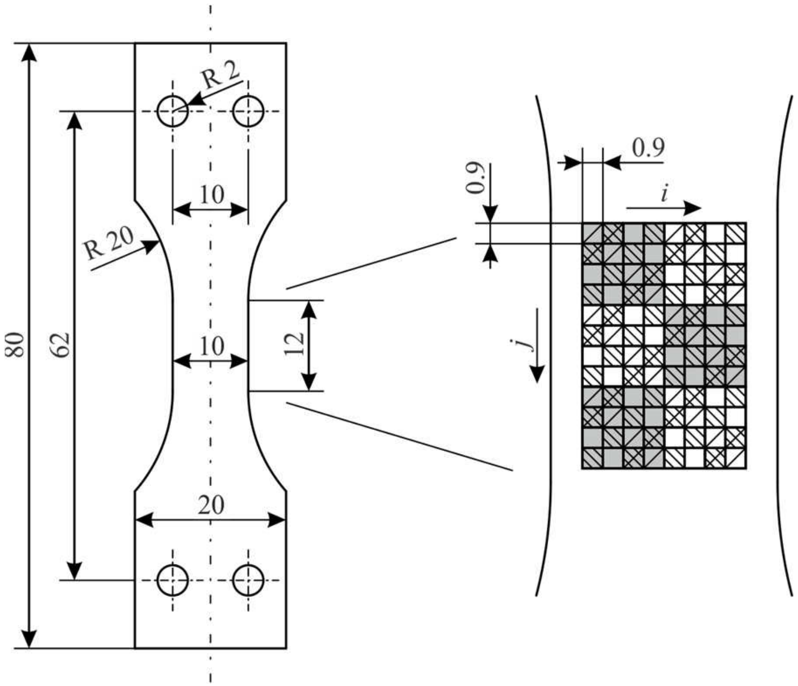




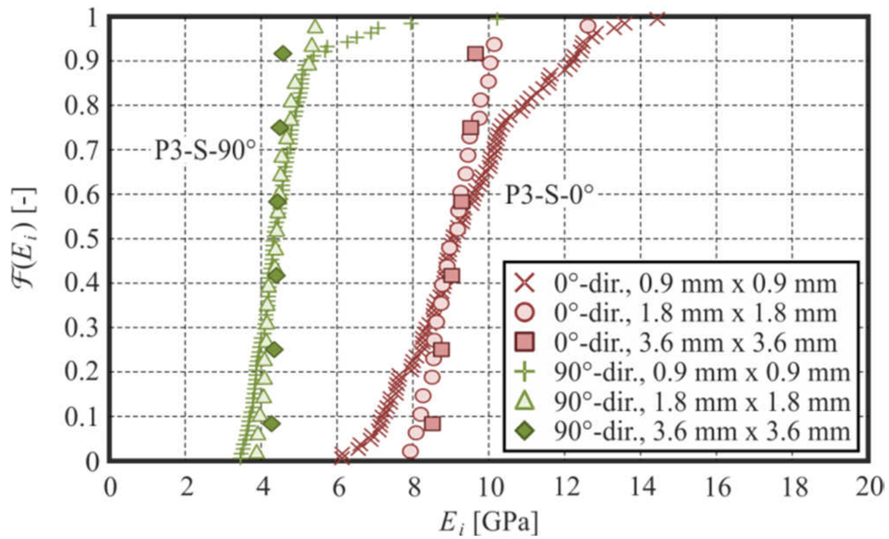
*) Hohe J et al.: *Modeling of uncertainties in long fiber reinforced thermoplastics,* Materials and Design 66 (2015) 390–399

Outlook
Probabilistic approach

- local elastic response evaluated by ARAMIS (image correlation)



longitudinal and transverse Young's moduli



→ non-negligible uncertainty in elastic constants
→ dependent on size of evaluation area

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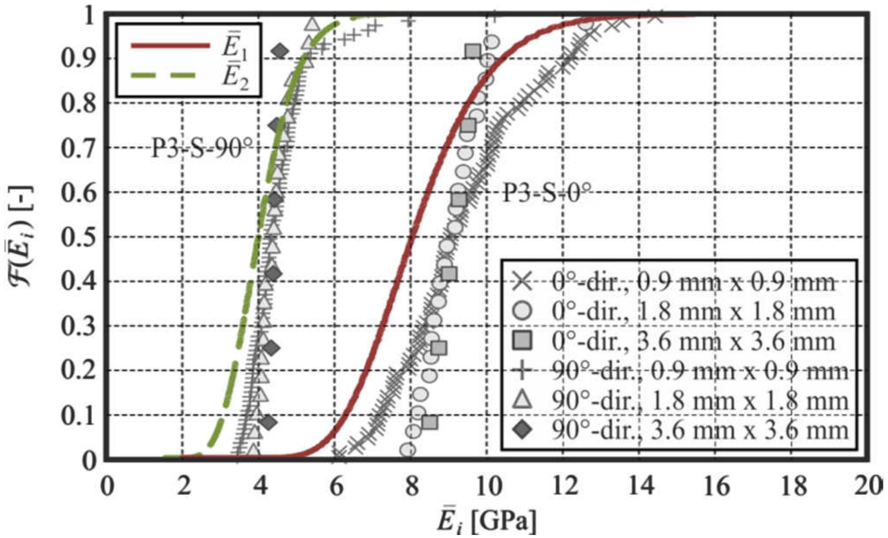
Outlook
Probabilistic approach

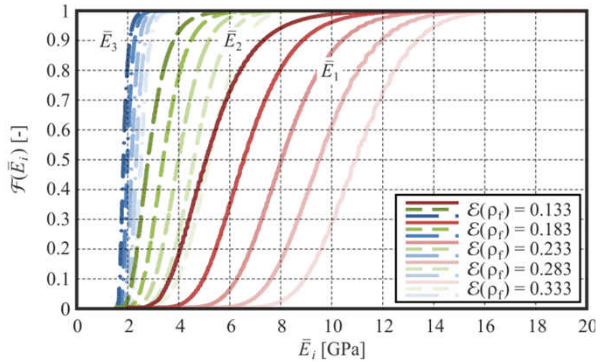
- comparison of experimental observation and numerical prediction

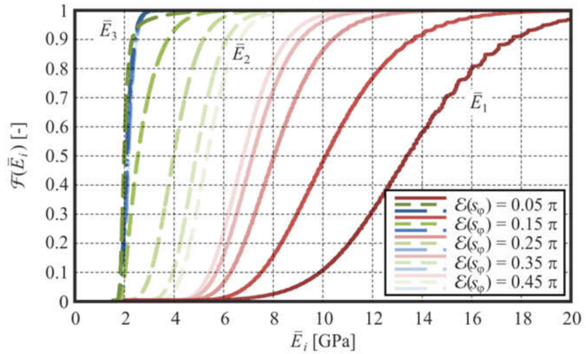


→ good agreement of experimental and numerical results

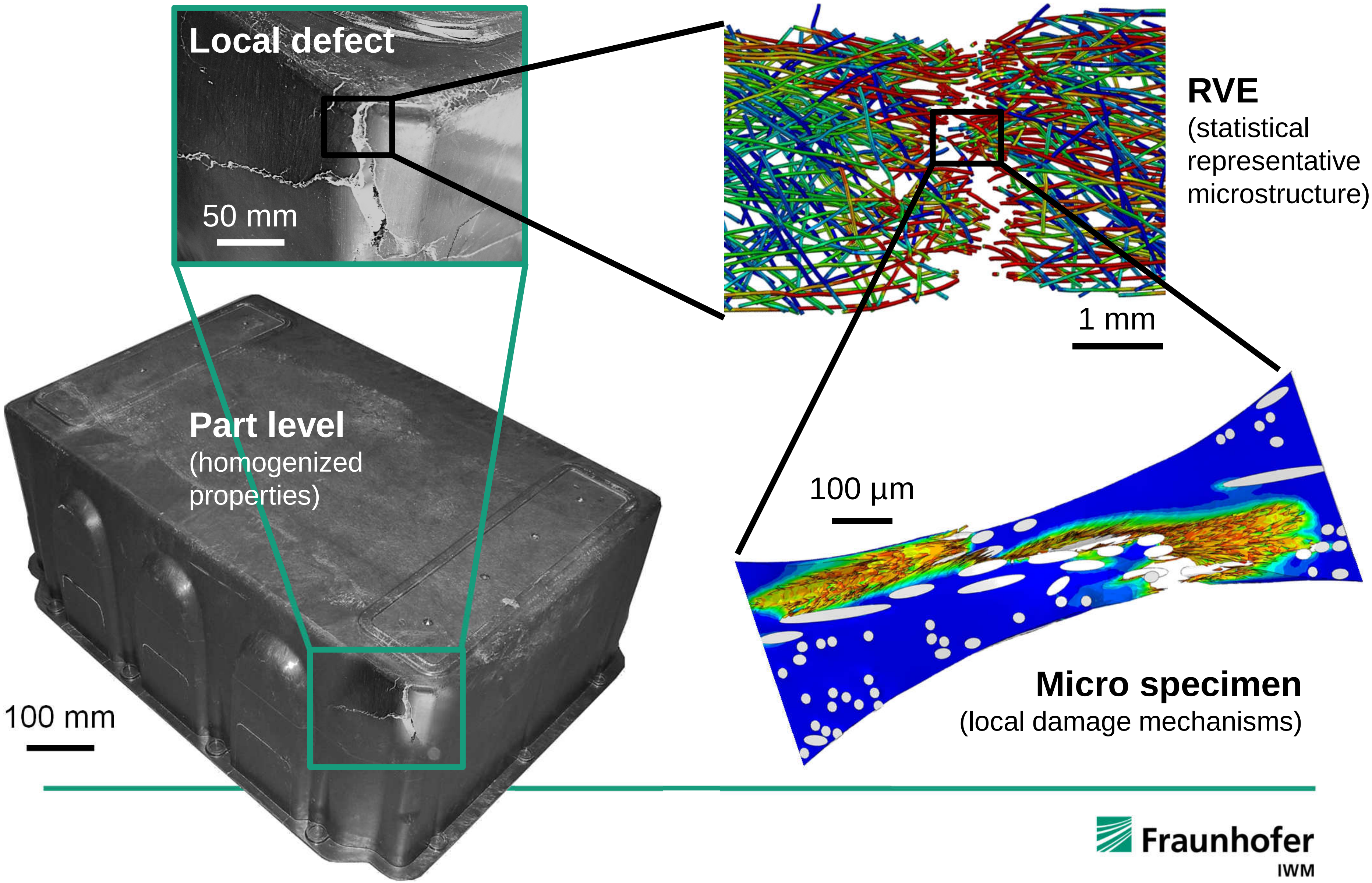
→ differences in E_1 might be caused by variation in ρ_f

- parametric study:
  influence of fiber density (top)
  and fiber angle (bottom)
  on elastic moduli





Outlook
Micro specimens and inverse modeling



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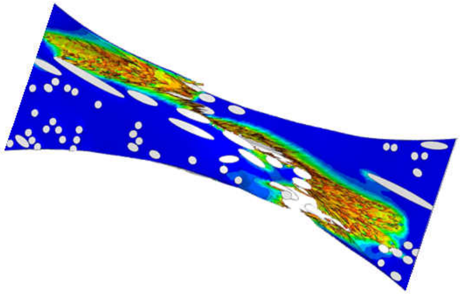
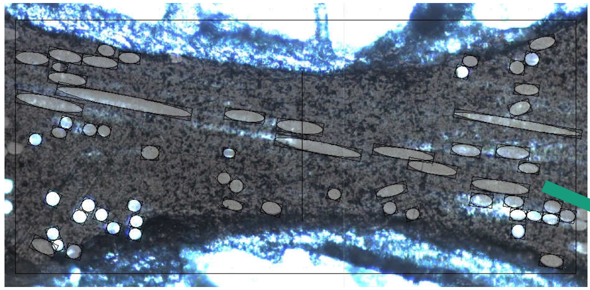
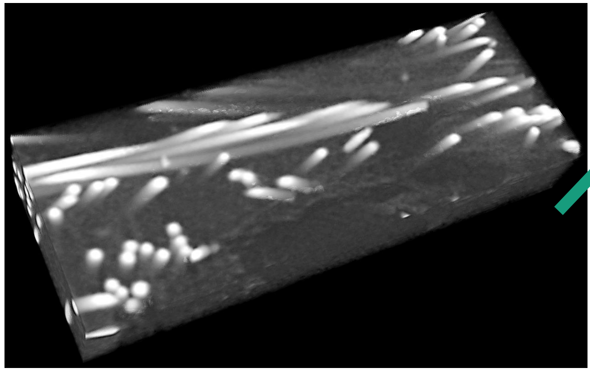
Outlook

Micro specimens and inverse modeling

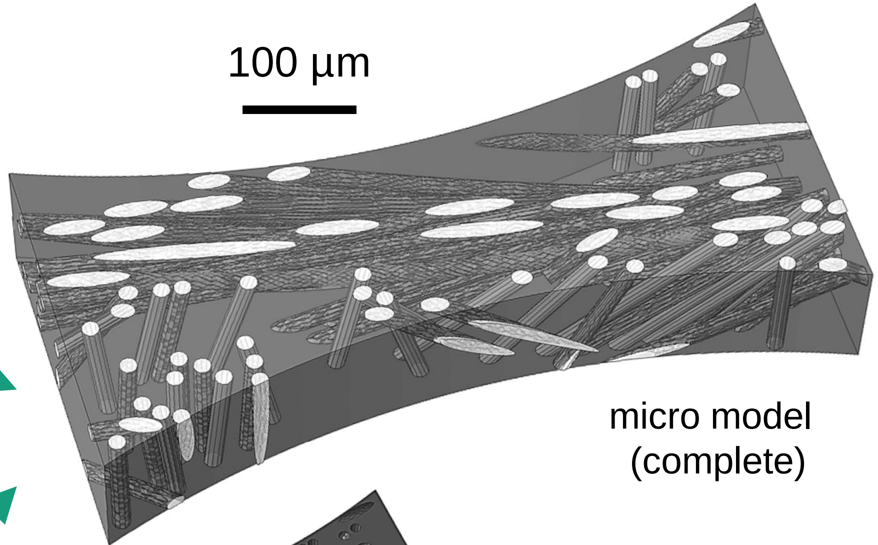




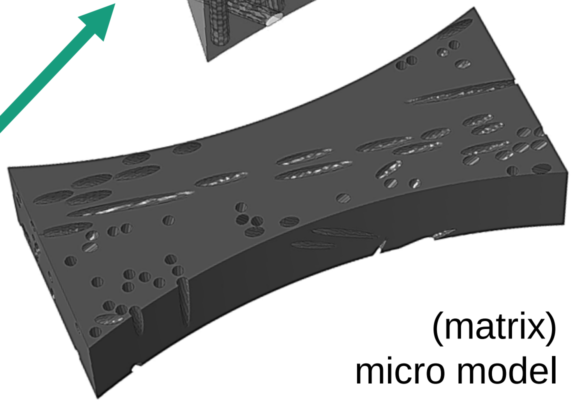
microscope image



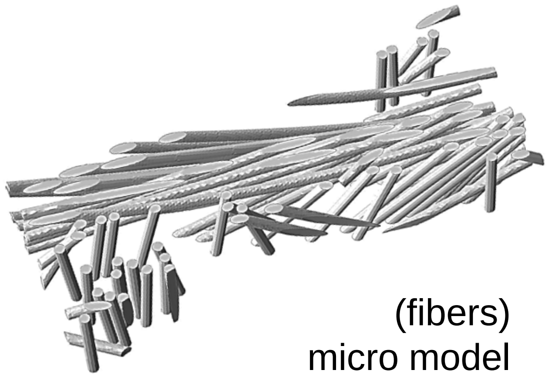
CT scan



micro model
(complete)

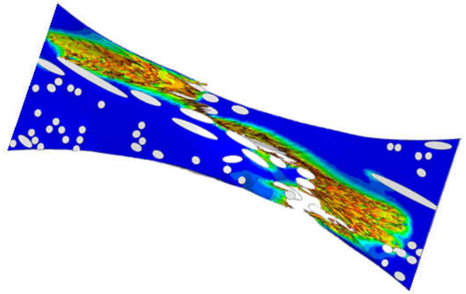


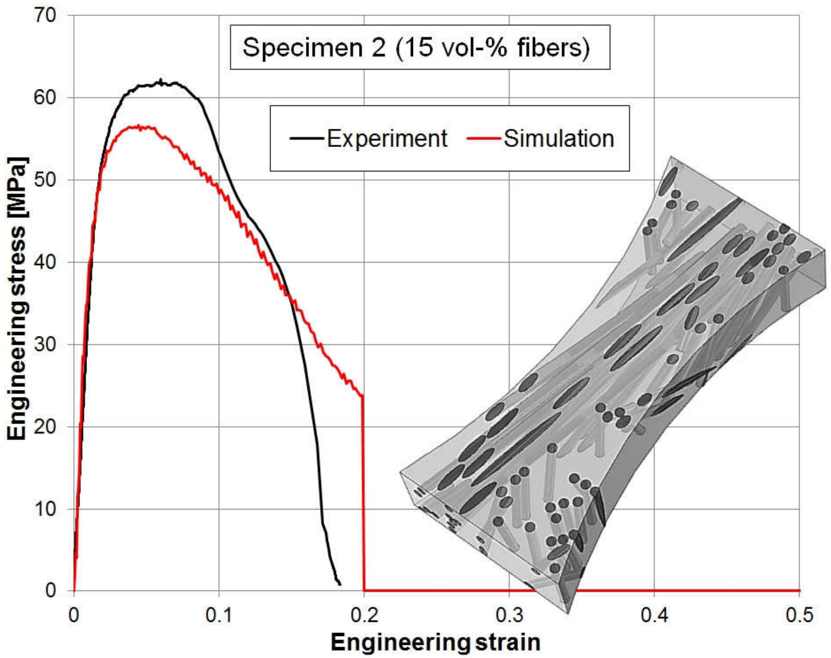
(matrix)
micro model

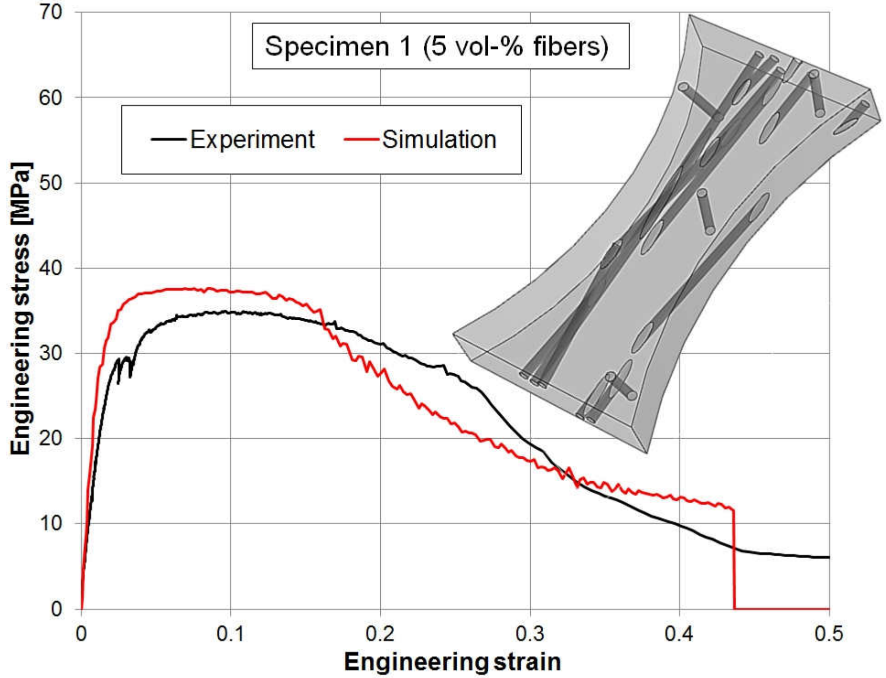


(fibers)
micro model

Outlook
Micro specimens and inverse modeling







- All simulations are performed with **identical material parameters** (damage energy of matrix/interface)
- **Different damage modes** (shear/normal)
- **200% difference** in ultimate stress/strain between both specimens

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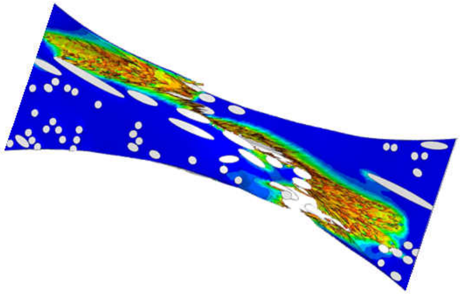
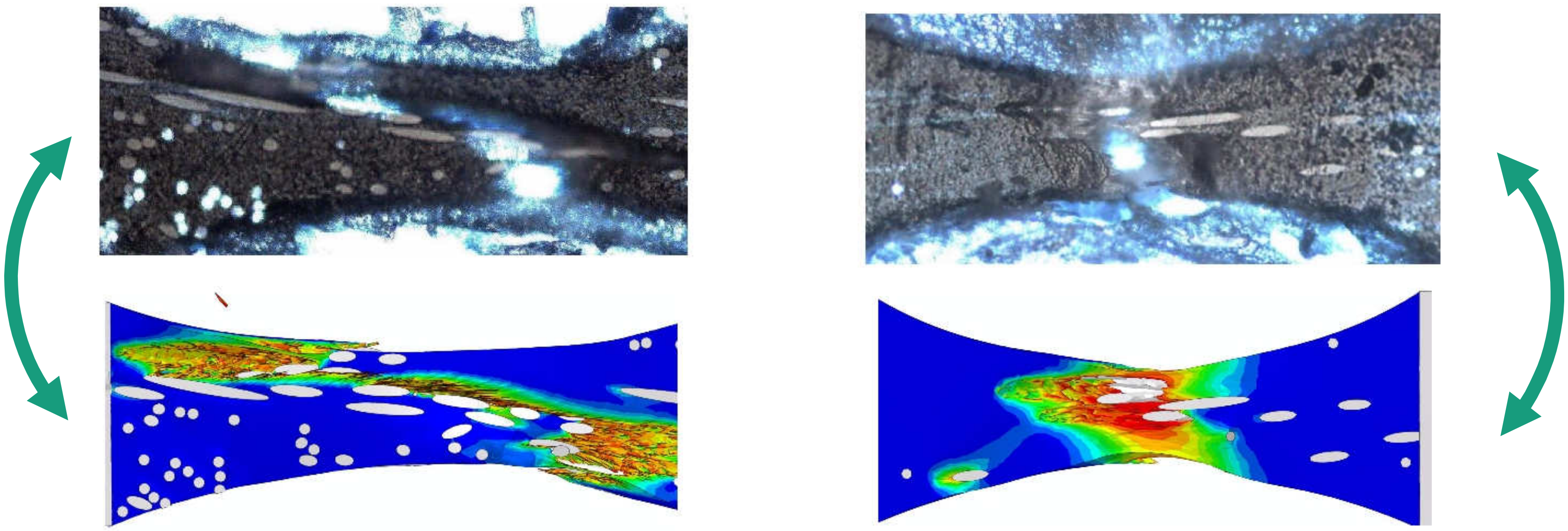
Outlook
Micro specimens and inverse modeling





100 µm

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THANK YOU !

Contact:

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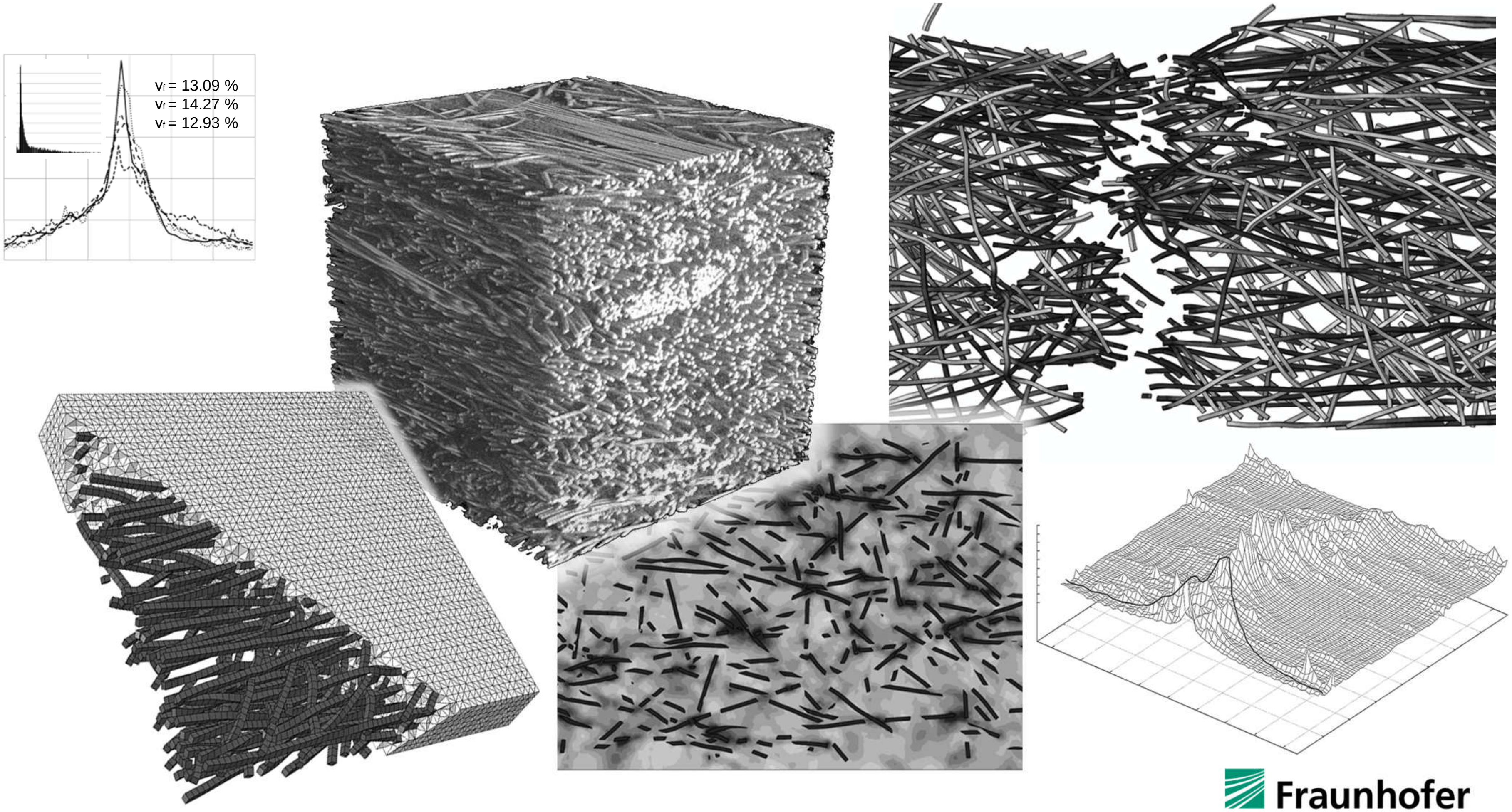

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