Fiber length and orientation dependent flow modeling in macroscopic injection molding simulations

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FPCM 15

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Agenda

Karlsruhe Institute of Technology

Introduction

Methods

Results and Validation

Conclusion and Summary

Institute of Vehicle System Technology
Lightweight Design Division

Agenda

Karlsruhe Institute of Technology

Introduction

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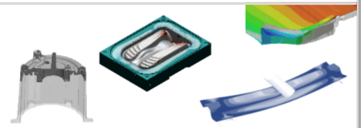
Introduction

House of Competence

Interdisciplinary lightweight solution

Methods

- Virtual process chains and mapping
- Process simulation
- Structural simulation
- Optimization & AI



FAST Institut für Fahrzeugsystemtechnik

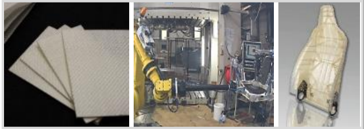
Materials

- Characterization
- Additive manufacturing
- Synthesis, formulation, modification
- Materials science
- CT scans
- Hybrids

IAM Institut für Angewandte Materialien

Processes

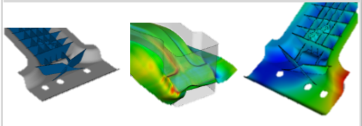
- Process development
- Plastics engineering
- Quality management
- Part development



Fraunhofer ICT

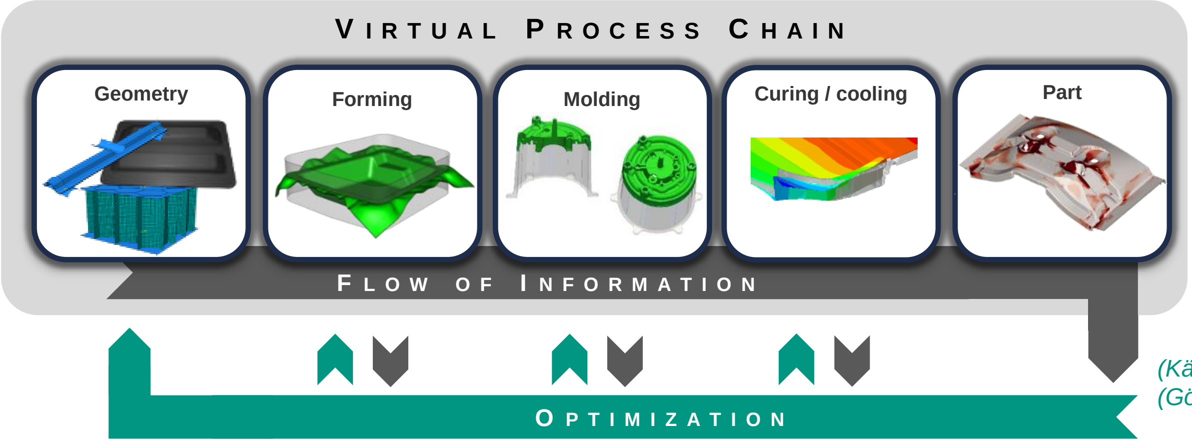
Business to industries

- Product development
- Method application
- Manufacturing assurance
- Engineering service provider



SIMUTENCE Virtual Composite Solutions

Integrated virtual process Chain



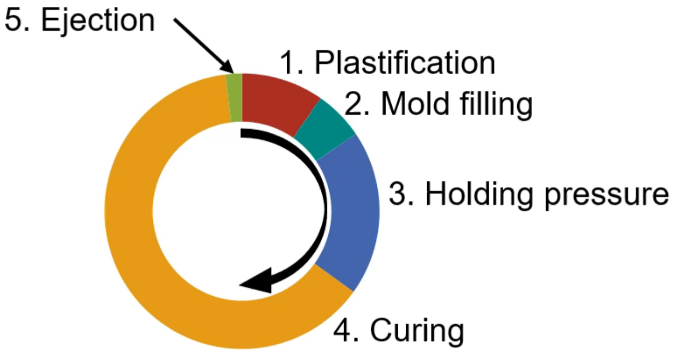
(Kärger et al. 2015)
(Görthofer et al. 2019)

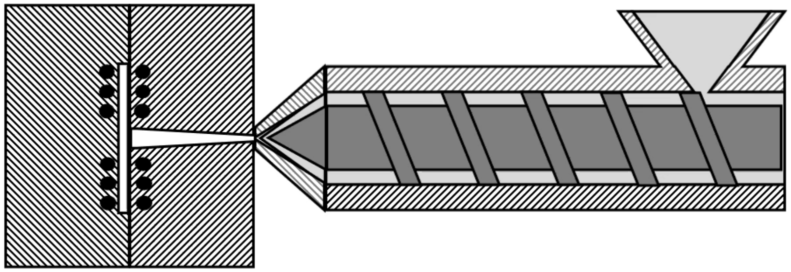
Benefits of a continuous CAE chain:

- Consideration of manufacturing effects and their influence on structural performance
- Initial verification of manufacturing
- Enabling iterative optimization over multiple simulation steps
  → Virtual design and process optimization
  → Accelerated design loops to reduce development time and resources

Injection molding process

1. Plastification
   - Temperature
   - Fiber length
2. Mold filling
   - Temperature
   - Voids
   - fiber orientation and length
3. Holding pressure
   - Voids
   - Shrinkage
4. Curing
   - Mechanical properties
   - Warpage
5. Ejection
   - Warpage
6. Cooling
   - Mechanical properties
   - Warpage





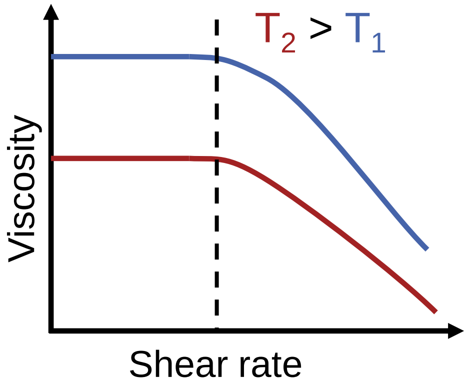
Introduction

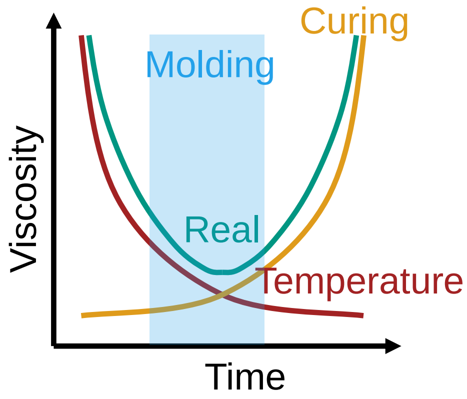
Material

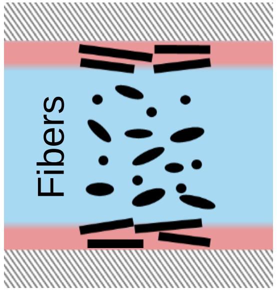
Eigenschaften

- Material is a suspension of matrix and fibers
- Raising temperature or shear rate lowers the viscosity
- Curing raises the viscosity
- Fiber orientation influences flow field ⟷ Flow field influences fiber orientation
- **Result: complex flow behavior**

Fließverhalten







Introduction

Process phases

1. Plastification
   - Temperature
   - Fiber length
2. Mold filling
   - Temperature
   - Voids
   - fiber orientation and length
3. Holding pressure
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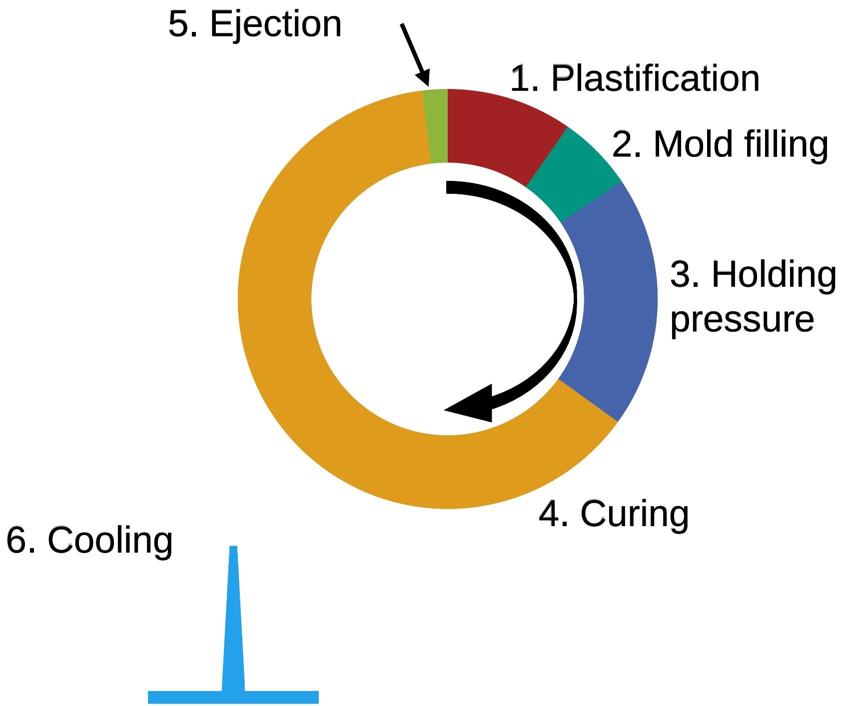


Introduction

Mold filling simulation

State of the art

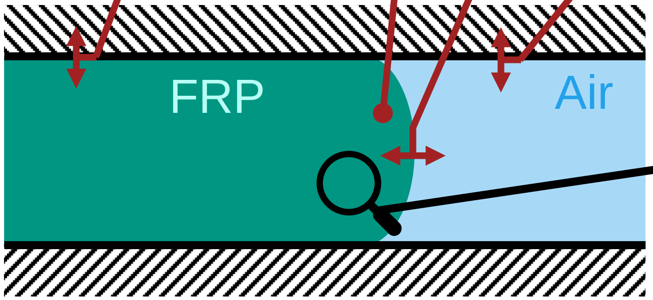
- Simulation model
  - Non-isothermal
  - Non-Newtonian
  - Isotropic
  - Results: p, T, FO
- Boundary conditions for FRP

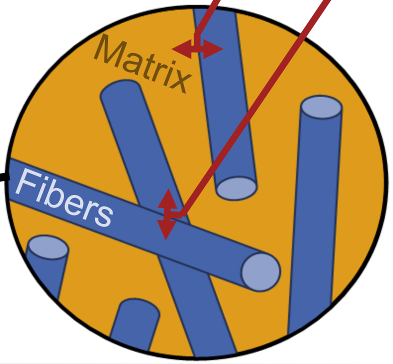
Multiphase approach

- Air as second phase
  - Volume-of-Fluid approach
- Interpolation in partially filled cells
- Additional boundary conditions

Material internal Aspects

- Interaction between matrix and fibers
  - Anisotropic viscosity
  - Hydrodynamic forces
  - Fiber breakage
- Fiber-fiber-interaction
  - Contact forces at contact points





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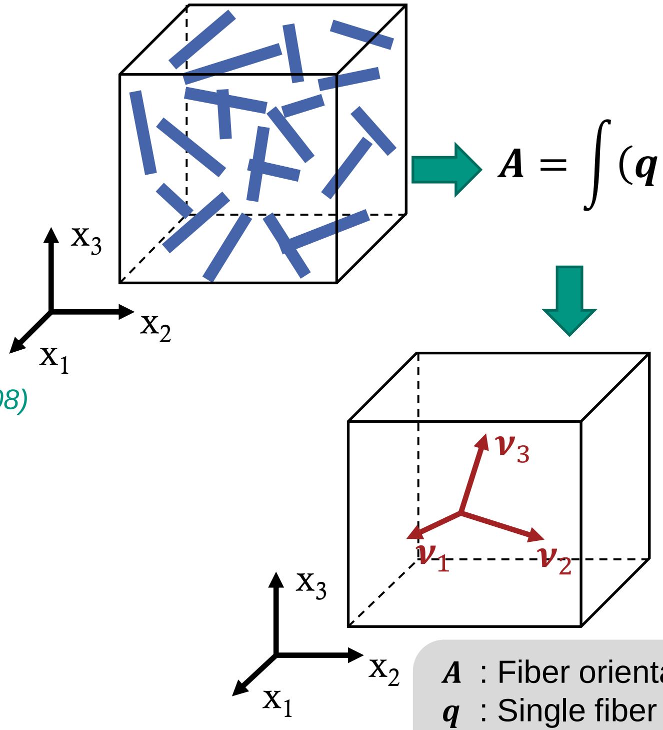
Methods

Restrictions and Approximations

- Approaches for macroscopic level
  - Fiber orientation tensors *(Advani and Tucker 1987)*
  - Homogenized material model
- Use of standard models
  - Matrix viscosity *(Castro and Macosko 1982)*
  - Fiber orientation *(Folgar and Tucker 1984, Wang et al. 2008)*
  - Curing *(Kamal and Sourour 1973)*
- Eigenvectors of the orientation tensors represent reference fibers *(Wittemann et al. 2021)*
  - Three fibers per cell
  - Eigenvalue is orientation probability
  - Reference fibers are perpendicular



$$\boldsymbol{A} = \int (\boldsymbol{q} \otimes \boldsymbol{q}) \psi(\boldsymbol{q}) \mathrm{d}\boldsymbol{q}$$

$\boldsymbol{A}$: Fiber orientation tensor
$\boldsymbol{q}$: Single fiber vector
$\boldsymbol{v}_n$: n-th eigenvector

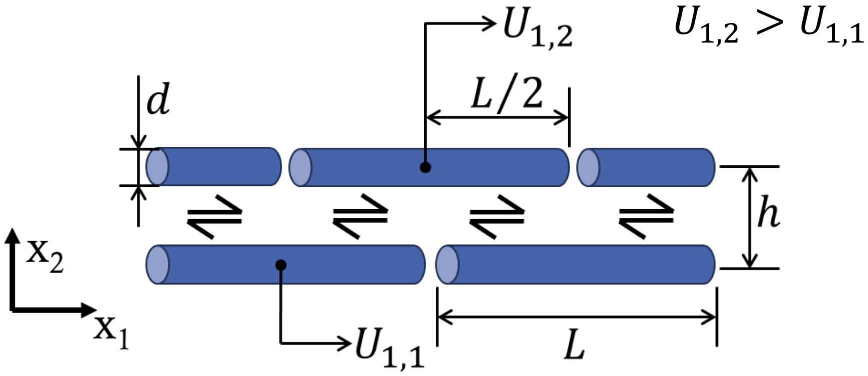
Methods

Anisotropic viscosity

Assumptions (Gibson 1989, Pipes et al. 1991)

- Fibers full orientated (transverse isotropic)
- Incompressible
- Fiber geometries are identical
- Variation of velocity for different direction viscosities
- Calculation of η_{11}, η_{12} and η_{23} based on microscopic model

Model visualization (Pipes et al. 1991)



d : Fiber diameter
L : Fiber length
h : Fiber distance
U_1 : Velocity in x_1

η_{11} : Strain viscosity
η_{12} : Axial shear viscosity
η_{23} : transverse shear viscosity

Methods

Anisotropic viscosity

Scheme

- Formulation of transverse isotropic fluidity tensor (Pipes et al. 1991)
- Building a pseudo inverse viscosity tensors (Loredo and Klöcker 1997)
- Orientation averaging (Advani and Tucker 1987)
- Fourth order viscosity tensor as function of fiber orientation, length and volume fraction (Sommer et al. 2018, Wittemann et al. 2019)

Final Formulation

$$\begin{aligned}\boldsymbol{\eta}^{\mathrm{IV}} = {} & (\eta_{11} - 4\eta_{12} + \eta_{23})\mathbb{A} \\ & + \left(\frac{\eta_{11}}{3} + \eta_{23}\right)(\boldsymbol{A} \otimes \boldsymbol{I} + \boldsymbol{I} \otimes \boldsymbol{A}) \\ & + (\eta_{12} - \eta_{23})(\boldsymbol{A} \square \boldsymbol{I} + \boldsymbol{I} \square \boldsymbol{A}) \\ & + (\eta_{12} - \eta_{23})\left((\boldsymbol{A} \square \boldsymbol{I})^{\mathrm{T_R}} + (\boldsymbol{I} \square \boldsymbol{A})^{\mathrm{T_R}}\right) \\ & + \left(\frac{\eta_{11}}{9} - \eta_{23}\right)(\boldsymbol{I} \otimes \boldsymbol{I}) \\ & + \eta_{23}\left(\boldsymbol{I} \square \boldsymbol{I} + (\boldsymbol{I} \square \boldsymbol{I})^{\mathrm{T_R}}\right)\end{aligned}$$

$\mathbb{A}$: Fourth order orientation tensor
$\boldsymbol{A}$: Second order orientation tensor
$\boldsymbol{I}$: Unity tensor
$\boldsymbol{\eta}^{\mathrm{IV}}$: Viscosity tensor
η_{11} : Strain viscosity
η_{12} : Axial shear viscosity
η_{23} : transverse shear viscosity

Methods

Hydrodynamic forces

Force approximation

- Stokes Flow for drag force:

$$\boldsymbol{F}_{\mathrm{D}}^{\mathrm{sphere}} = 3\pi\eta_{\mathrm{M}} d\boldsymbol{U}$$

- Approximation for fibers *(Meyer et al. 2020)*

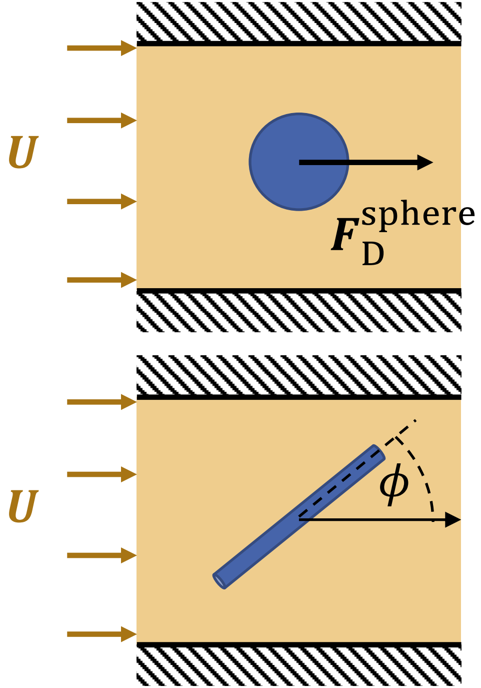
$$\boldsymbol{F}_{\mathrm{D}}^{\mathrm{fiber}} = 3\pi\eta_{\mathrm{M}} d k_{\mathrm{D}}\boldsymbol{U} \text{ mit } k_{\mathrm{D}} = f(\phi, r, \alpha, \beta)$$

- Lift force similar *(Meyer et al. 2020)*

$$\boldsymbol{F}_{\mathrm{Li}}^{\mathrm{fiber}} = 3\pi\eta_{\mathrm{M}} d k_{\mathrm{Li}}\boldsymbol{U} \text{ mit } k_{\mathrm{Li}} = f(\phi, r, \alpha)$$

$\boldsymbol{F}_{\mathrm{D}}$	: Drag force	d	: Fiber diameter
$\boldsymbol{F}_{\mathrm{Li}}$	: Lift force	ϕ	: Angle btw. fiber and $\boldsymbol{U}$
$\boldsymbol{U}$	: Velocity	r	: Fiber aspect ratio
η_M	: Matrix viscosity	α, β	: Fitting factors

Model illustration



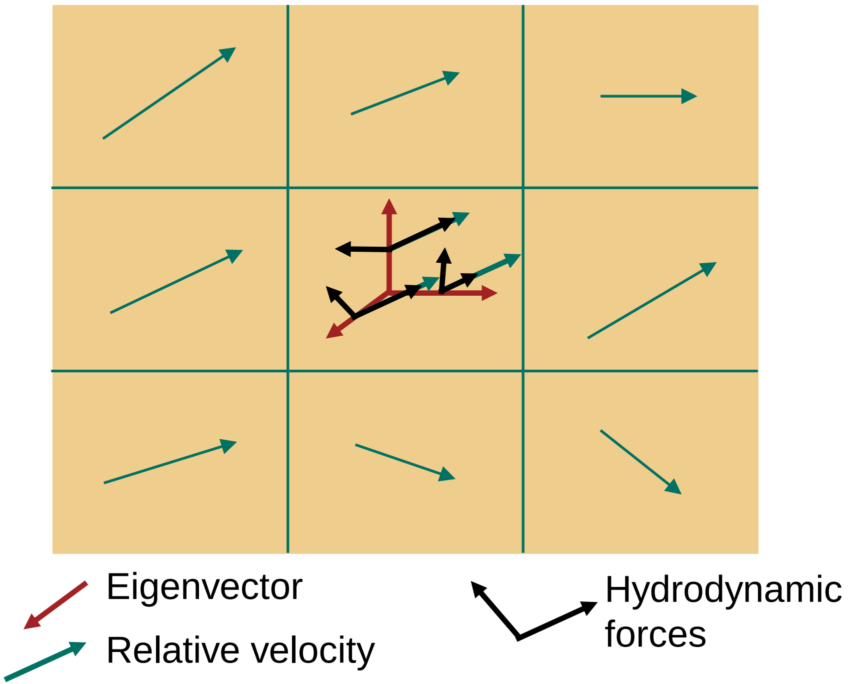
Methods

Hydrodynamic forces

Application on macro scale *(Wittemann et al. 2021)*

- Fibers move with the velocity of the cell
- Calculation of relative velocity with neighbor cells
  → Number depends on fiber length
- 3 eigenvectors = 3 reference fibers
  →Individual angle for every eigenvector
  →Individual forces for every eigenvector

Model illustration



Methods

Fiber breakage

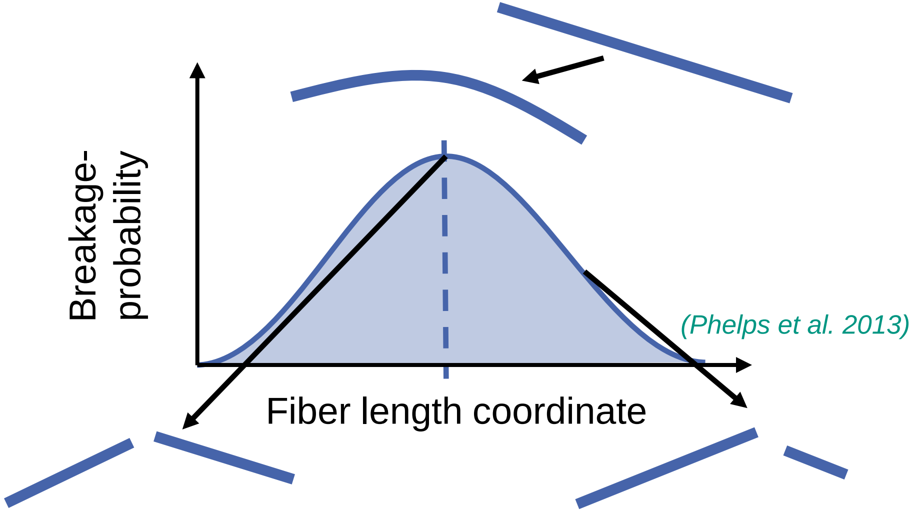
Model

- Buckling is breakage mechanism
  (Hernandez et al. 2004, Durin et al. 2013, Phelps et al. 2013)
- Breaking point and equation by Phelps
  (Phelps et al. 2013)

$$\frac{\partial N_n^{\mathrm{f}}}{\partial t} = -P_n^{\mathrm{br}} N_n^{\mathrm{f}} + \sum_m R_{nm}^{\mathrm{br}} N_m^{\mathrm{f}}$$

- Force calculation with hydrodynamic forces *(Wittemann et al. 2022)*
- Orientation dependent forces and reduction of model parameters

Breaking by buckling



N_n^{f}: Number of fibers with length L_n
P_n^{br}: Breakage probability of fibers with length L_n
R_{nm}^{br}: Probability of creating fibers fibers with length L_n by fibers of length L_m

Methods

Fiber-fiber contact points

Theory

- Contact points according to Toll *(Toll 1998)*
- Invariants f and g need single fiber orientations
- Eigenvectors as reference fibers *(Wittemann et al. 2021)*
- Polynomial approach as function of eigenvalues *(Wittemann et al. 2021)*

N_{fc} : Contact points
f, g : Invariants
Φ : Fiber volume fraction
$\boldsymbol{q}$: Single fiber vector
$\boldsymbol{\nu}$: Eigenvector
λ : Eigenvalue
M : Coefficient matrix

Equations

$$N_{\mathrm{fc}} = {}^{8}/_{\pi}\,\Phi r f + 4\Phi(g+1)$$

$$f = \int\int |\boldsymbol{q}_n \times \boldsymbol{q}_m| \psi(\boldsymbol{q}_n)\psi(\boldsymbol{q}_m)\mathrm{d}\boldsymbol{q}_n\mathrm{d}\boldsymbol{q}_m$$

$$g = \int\int |\boldsymbol{q}_n \cdot \boldsymbol{q}_m| \psi(\boldsymbol{q}_n)\psi(\boldsymbol{q}_m)\mathrm{d}\boldsymbol{q}_n\mathrm{d}\boldsymbol{q}_m$$

$$f = \sum_{n,m=1}^{3} |\boldsymbol{\nu}_n \times \boldsymbol{\nu}_m| \lambda_n \lambda_m = (2\lambda_1\lambda_2 + 2\lambda_1\lambda_3 + 2\lambda_2\lambda_3)$$

$$g = \sum_{n,m=1}^{3} |\boldsymbol{\nu}_n \cdot \boldsymbol{\nu}_m| \lambda_n \lambda_m = \lambda_1\lambda_1 + \lambda_2\lambda_2 + \lambda_3\lambda_3$$

$$f, g = \sum_{n,m=1}^{3} M_{nm}\tilde{\lambda}_n\tilde{\lambda}_m$$

Methods

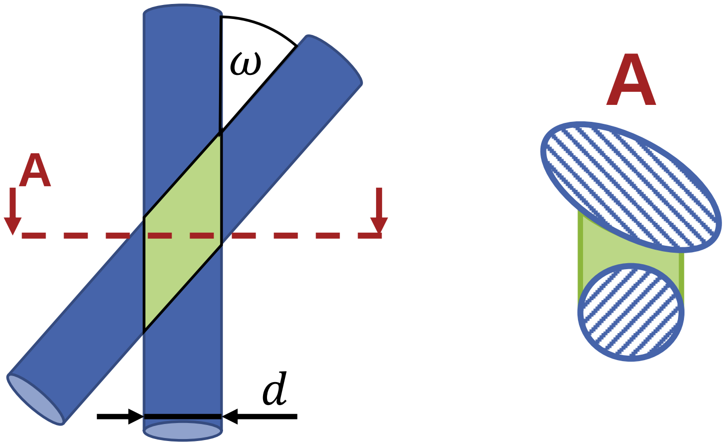
Contact forces

Lubrication force

- Before and after fiber contact
- Proportional to matrix viscosity, relative velocity, fiber distance and overlap
- Approximation of overlap by average fiber angle
  (Wittemann et al. 2021)

$$\boldsymbol{F}_{\mathrm{L}} = \frac{k_{\mathrm{S}}\eta_{\mathrm{M}}\boldsymbol{U}_{\mathrm{ff}}}{\|\boldsymbol{h}\|}A_{\mathrm{ff}} = \frac{k_{\mathrm{S}}\eta_{\mathrm{M}}\boldsymbol{U}_{\mathrm{ff}}}{\|\boldsymbol{h}\|}\frac{d^2}{\sin(\omega)}$$

Model



$\boldsymbol{F}_{\mathrm{L}}$	: Lubrication force	d	: Fiber diameter
$\boldsymbol{U}_{\mathrm{ff}}$	: Relative velocity	ω	: Fiber angle
A_{ff}	: Overlap	k_{S}	: Lubrication coefficient
$\boldsymbol{h}$	: Fiber-fiber distance	η_{M}	: Matrix viscosity

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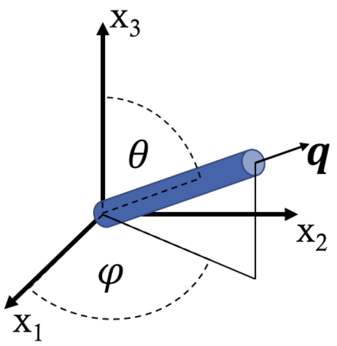
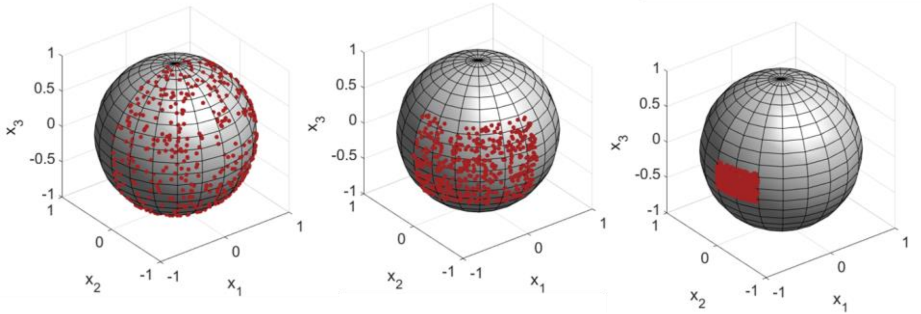
Numerical verification

Single fibers as reference case

- Forces and contact points are verified by reference cases, built up with 500 individual fibers
- 22 different orientation states are considered
- Orientation tensors are directly calculated with the single fiber orientations

Examples



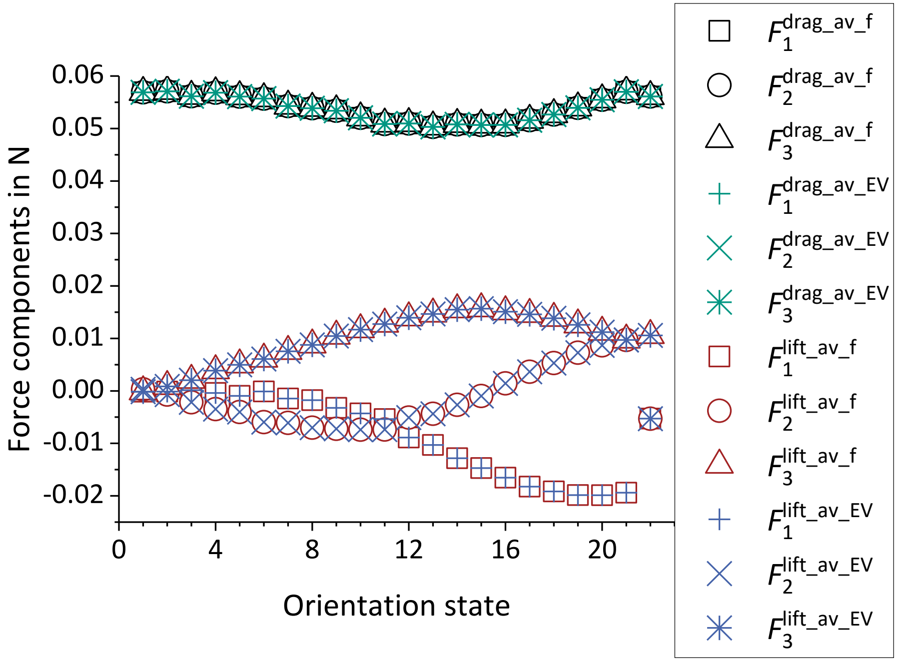


Hydrodynamic forces

Summary

- Comparison of averaged force on single fibers (f) and eigenvectors (EV)
- $\boldsymbol{U} = {}^{1}/_{\sqrt{3}}\,(1 \quad 1 \quad 1)$ m/s
- Fit perfectly *(Wittemann et al. 2021)*
- Force values contribute to the relation of orientation and velocity

Results – comparison to single fibers

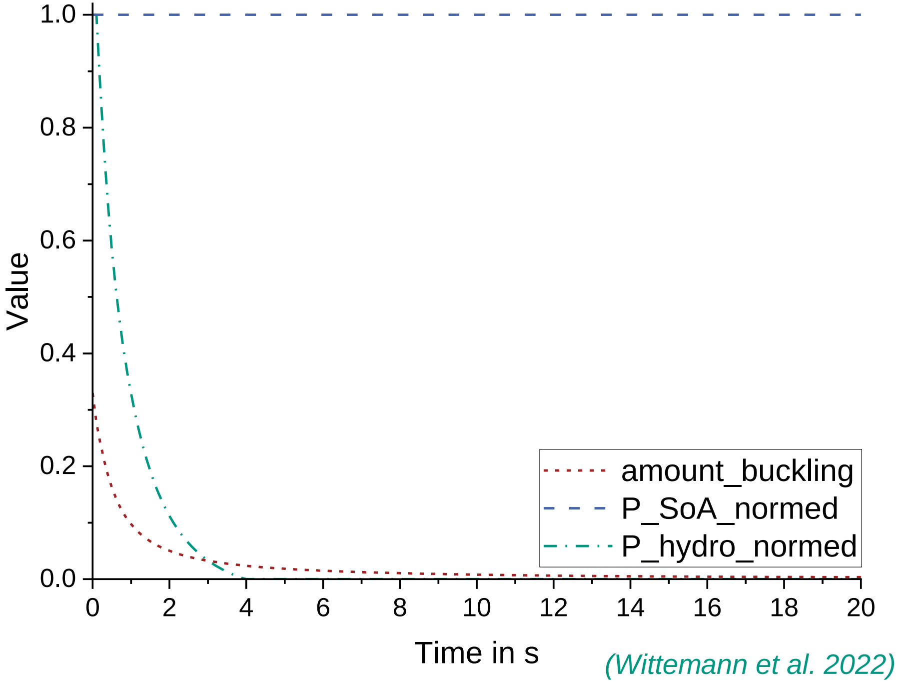


Fiber breakage model

Summary

- Fibers under simple shear
  → reorientation due to shearing
- Number of buckling fibers decreases due to orientation
- Constant breakage probability for SoA
- Decreasing breakage probability of novel approach due to buckling amount and force calculation

Results – comparison to SoA



(Wittemann et al. 2022)

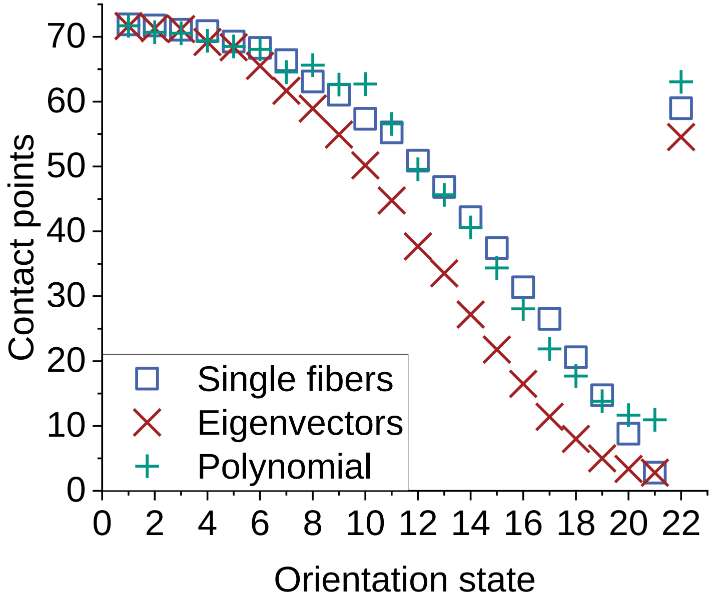
Results and Validation

Fiber-fiber contact points

Summary

- Results for aspect ratio 100
- Eigenvector approach fitted with factor $3\pi/8$ *(Férec et al. 2009, Wittemann et al. 2021)*
- Eigenvector approach predicts too low
- Polynomial approach creates best results

Comparison to single fibers



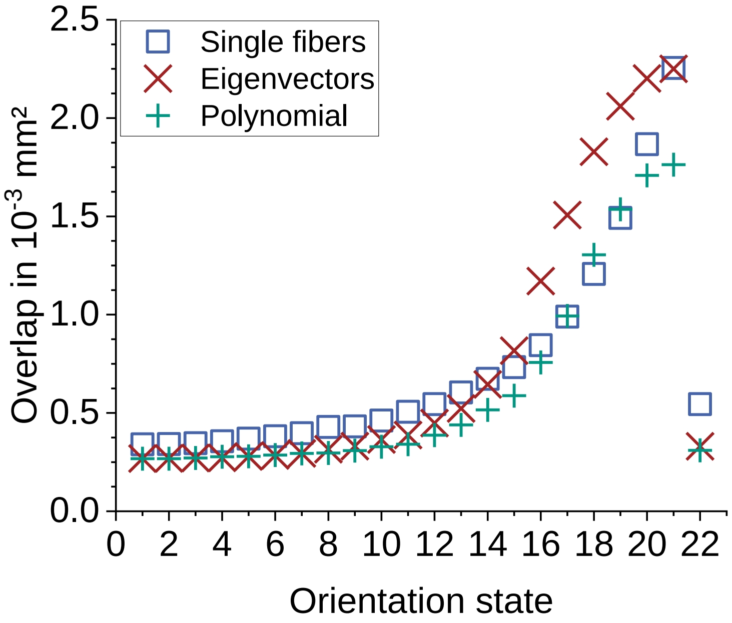
Results and Validation

Fiber-fiber overlap

Summary

- Results for aspect ratio10
- Individual overlap and averaging for single fibers
- Average angle approximated with
  $\omega = 4/\pi\, f$ *(Wittemann et al. 2021)*
- Average overlap with average angle
- Polynomial approach creates best results

Comparison to single fibers

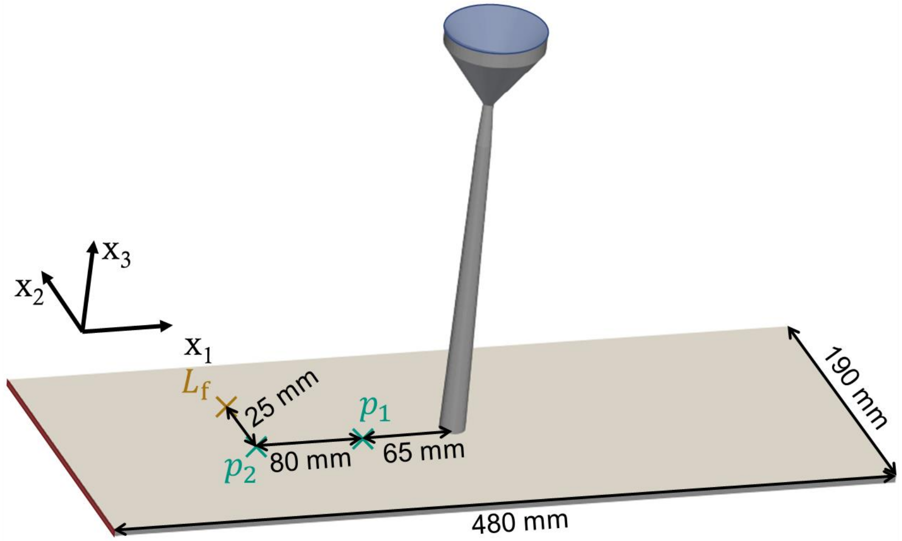


Experimental validation

Material and Process parameters

- Material
  - 55 %-weight glass fiber filled phenolic
  - Modeling non-Newtonian, anisotropic
- Process
  - Filling rate 150 cm³/s
  - Tool temperature 185 °C
- Recorded data
  - Two pressure sensors in mold (p_1 and p_2)
  - Fiber length measured at L_f
- Experiments by Maertens *(Maertens et al. 2021)*

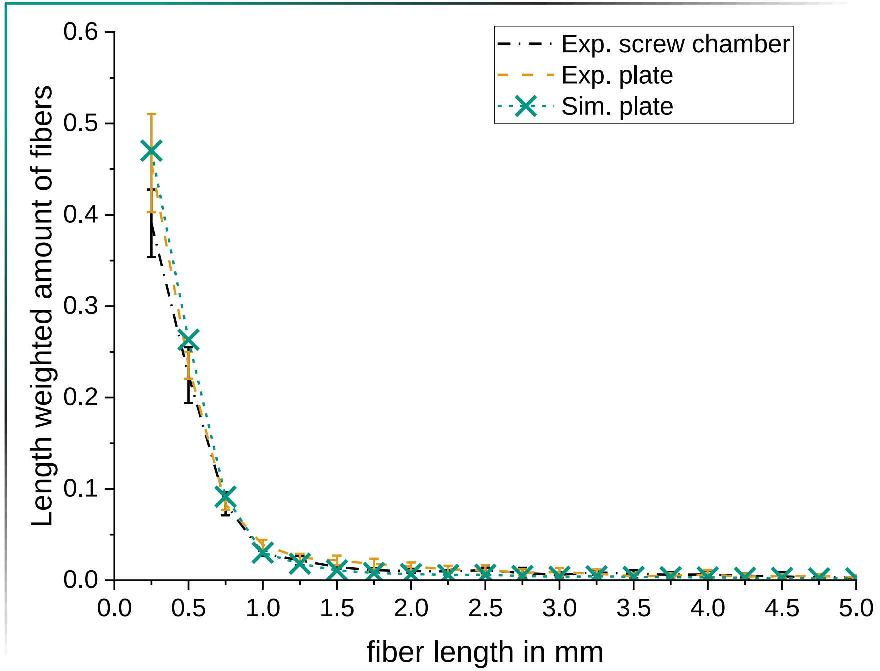
Model



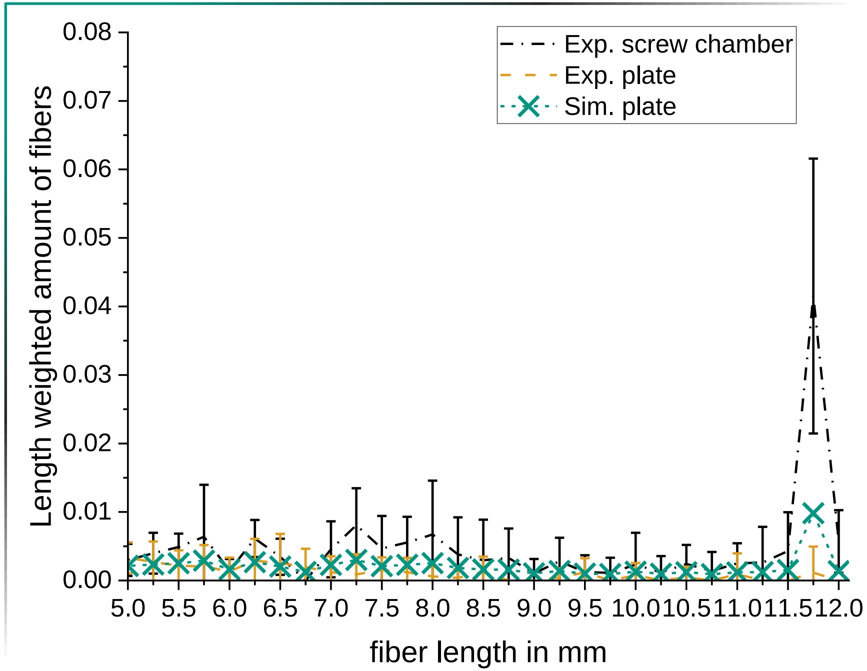
Results and Validation

Experimental validation

Fiber length distribution 1 – 5 mm



Fiber length distribution 5 – 12 mm



(Wittemann et al. 2022)

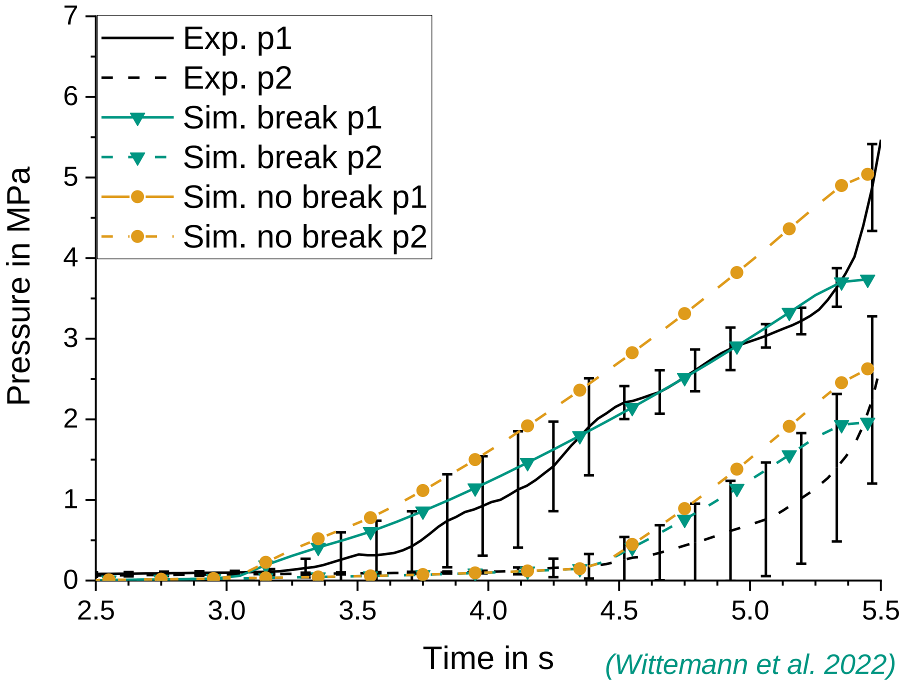
Results and Validation

Experimental validation

Summary

- Good results for fiber length distribution
- Good prognostication of pressure at p_1
- Simulated pressure too high at p_2
- Fiber breakage influences pressure results
  → fiber length is parameter of the anisotropic viscosity tensor

In-mold pressure



(Wittemann et al. 2022)

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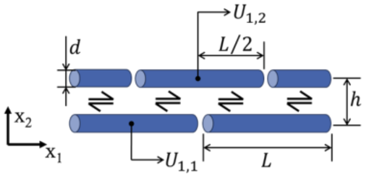
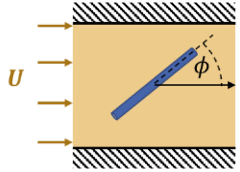
Conclusion and Summary

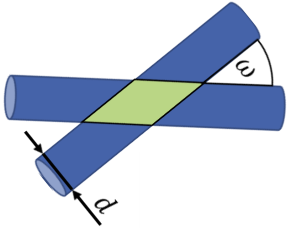
Summary

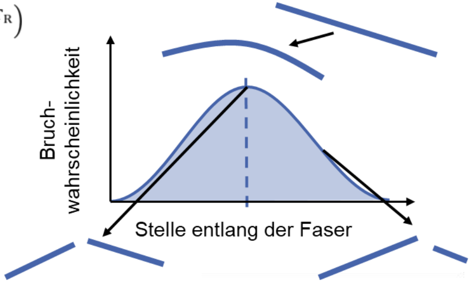
- Novel simulation approaches for more detailed mold filling simulations
  - Anisotropic viscosity tensor
  - Calculation of hydrodynamic forces and fiber breakage
  - Calculation of fiber-fiber contact points and forces
- Application on macroscopic scale
- Good agreement of simulation results and experimental data

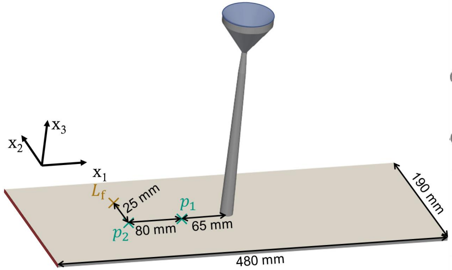


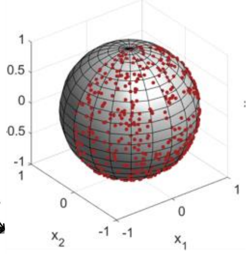
$$
\begin{aligned}
\boldsymbol{\eta}^{\mathrm{IV}} = {} & (\eta_{11} - 4\eta_{12} + \eta_{23})\mathbb{A} \\
& + \left(\frac{\eta_{11}}{3} + \eta_{23}\right)(\boldsymbol{A} \otimes \boldsymbol{I} + \boldsymbol{I} \otimes \boldsymbol{A}) \\
& + (\eta_{12} - \eta_{23})(\boldsymbol{A} \square \boldsymbol{I} + \boldsymbol{I} \square \boldsymbol{A}) \\
& + (\eta_{12} - \eta_{23})\left((\boldsymbol{A} \square \boldsymbol{I})^{\mathrm{TR}} + (\boldsymbol{I} \square \boldsymbol{A})^{\mathrm{TR}}\right) \\
& + \left(\frac{\eta_{11}}{9} - \eta_{23}\right)(\boldsymbol{I} \otimes \boldsymbol{I}) \\
& + \eta_{23}\left(\boldsymbol{I} \square \boldsymbol{I} + (\boldsymbol{I} \square \boldsymbol{I})^{\mathrm{TR}}\right)
\end{aligned}
$$







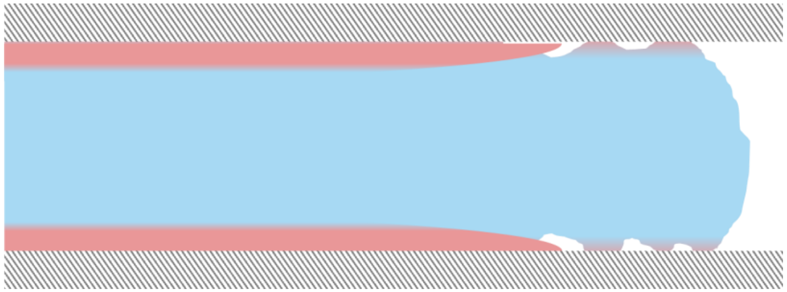


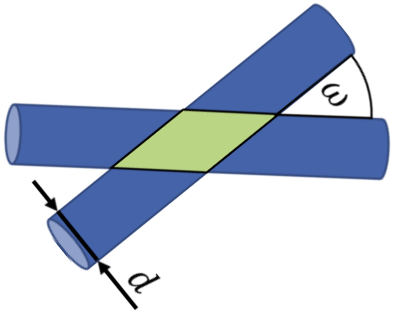


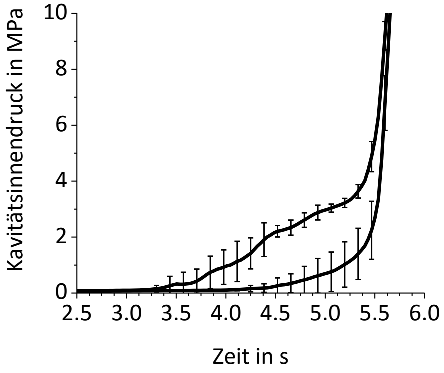
Conclusion and Summary

Next steps

- Wall slip
- Better formulation for temperature boundary conditions
- Usage of information about fiber-fiber contact points, forces and length distribution
- Probabilistic approaches to model process uncertainties







Conclusion and Summary

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Thank you for your attention.

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