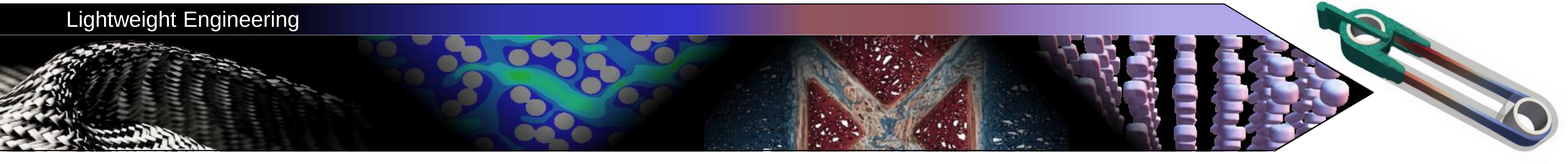
Overmolding of 3D Skeleton Winding Structures: Process effects and challenges for process modeling

Christina Dohmen[1], Nils Meyer[2], Jonathan Haas[3], Björn Beck[3], Florian Wittemann[1], Luise Kärger[1]

[1] Karlsruhe Institute of Technology (KIT), FAST Lightweight Engineering; [2] University of Augsburg; [3] Fraunhofer Institute for Chemical Technology



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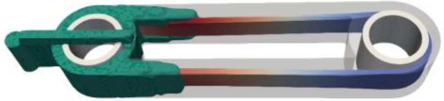
Nantes, France

Agenda

Overmolding of 3D Skeleton Winding Structures

Motivation → Process → Simulation approach → Conclusion



Motivation

3D Skeleton Winding technology (3DSW)

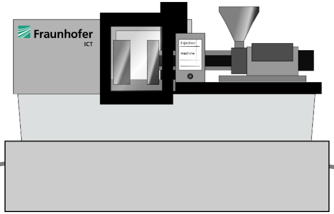
= robot-based filament winding process

- Local continuous fiber reinforcement
  - Flexible positioning of the fibers
  - resource-saving
  - load path optimized

→ high-performance structural components

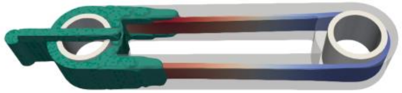
Beck et al. 2020
Minsch et al. 2019

Beck et al. 2024



Process modeling

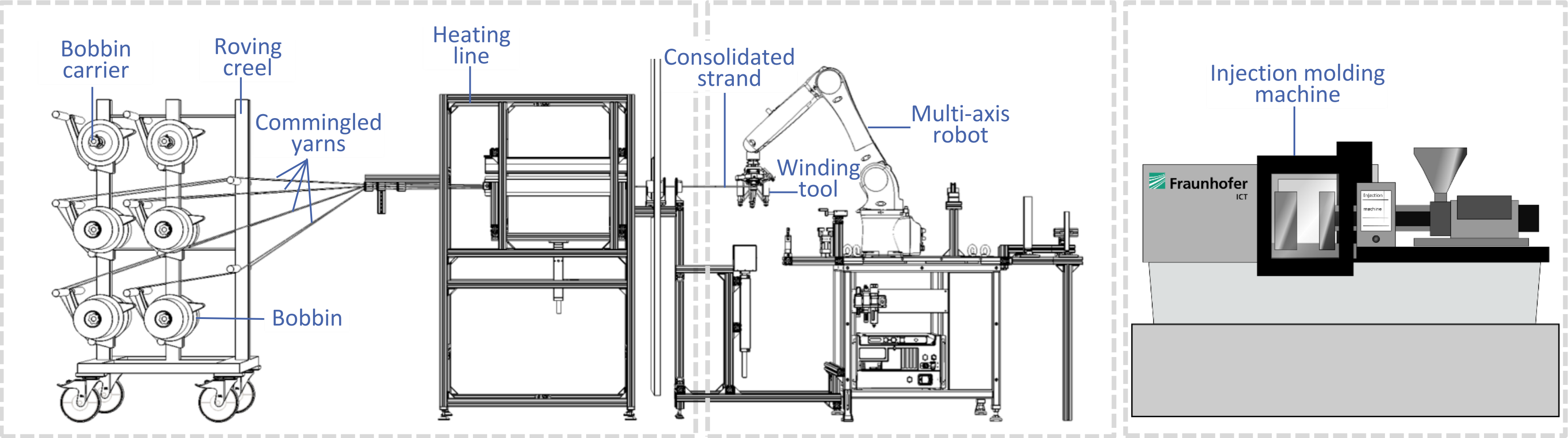
Fully coupled multi-physics simulation of overmolding



3D Skeleton Winding technology

Schematic illustration of the 3D Skeleton Winding (3DSW) process chain

Heating and impregnation → Robot-based 3D winding → Overmolding of fiber skeleton structures



Commingled yarn (PP-GF)

Coreless-wound fiber skeleton

Continuous fiber-reinforced part

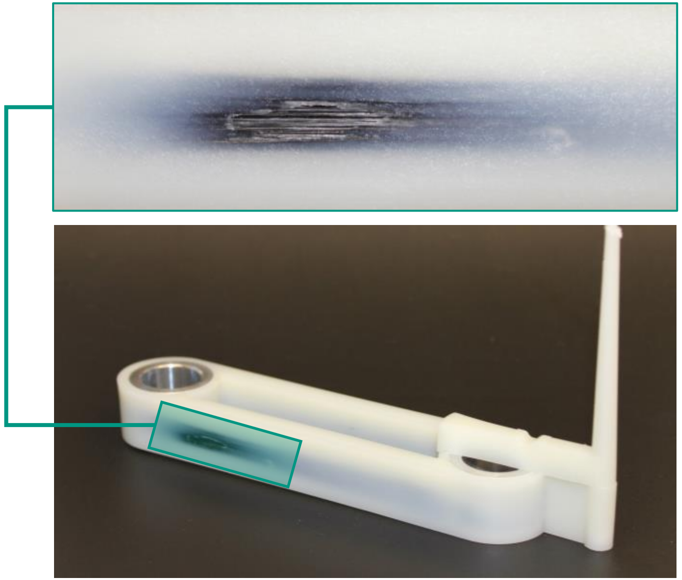
Beck 2023, Beck et al. 2024

Process effects during overmolding

Deformation of skeleton fiber structure

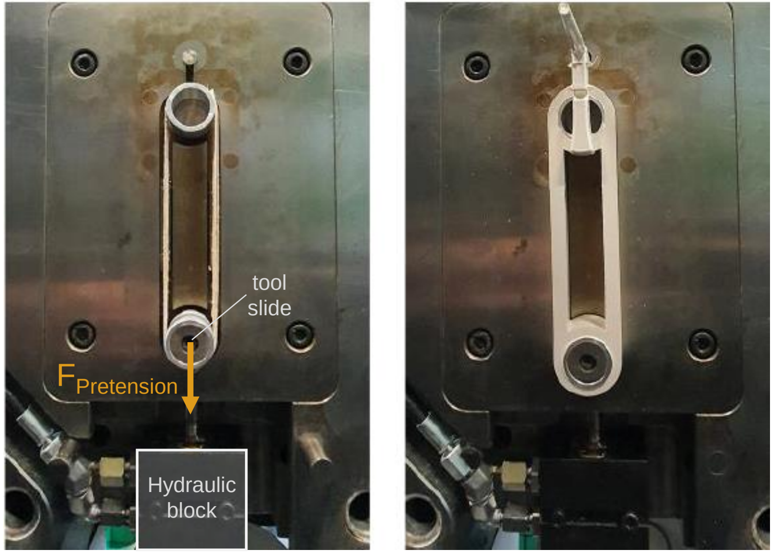
Fiber positioning due to filling

- Risk of visible fibers at the edge of the cavity



Specimen production

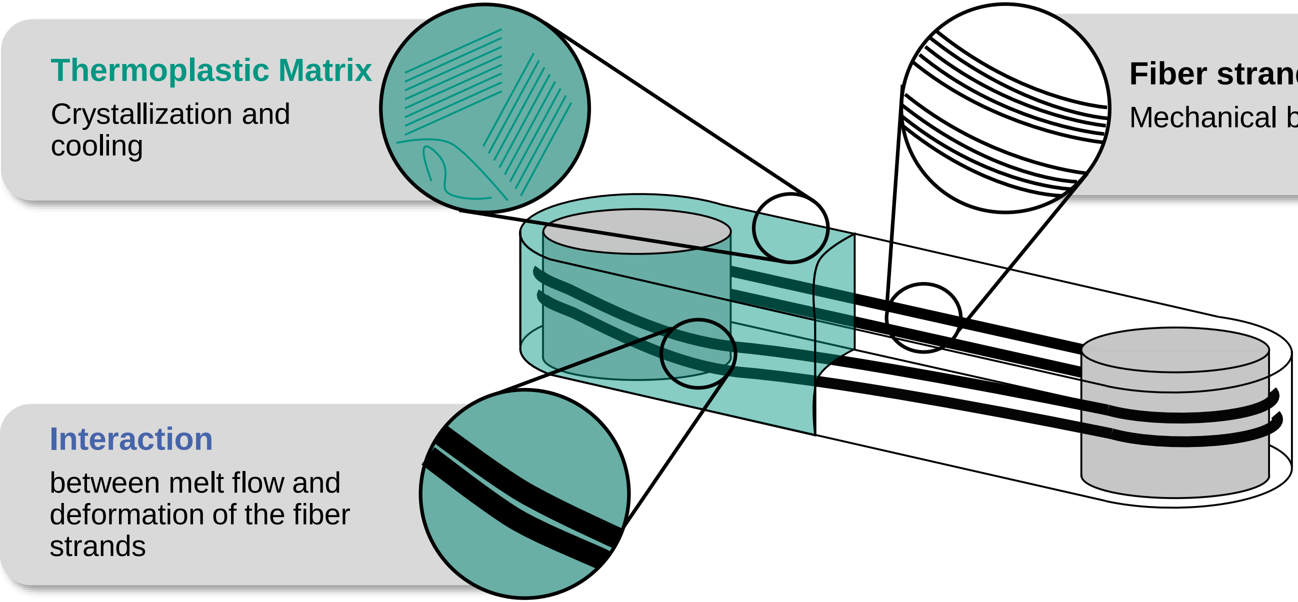
- Pretension during overmolding



Beck et al. 2024

Mechanisms during overmolding of fiber skeletons

Process behavior for modeling



Mechanisms during overmolding of fiber skeletons

Process behavior for modeling

Thermoplastic Matrix
Crystallization and cooling

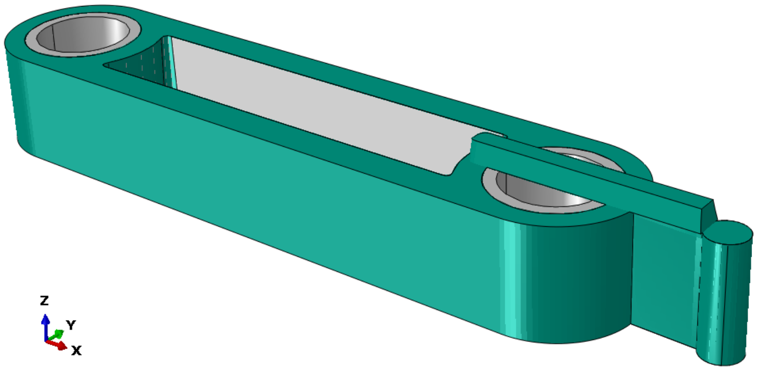
→ **Coupled-Eulerian-Lagrangian**

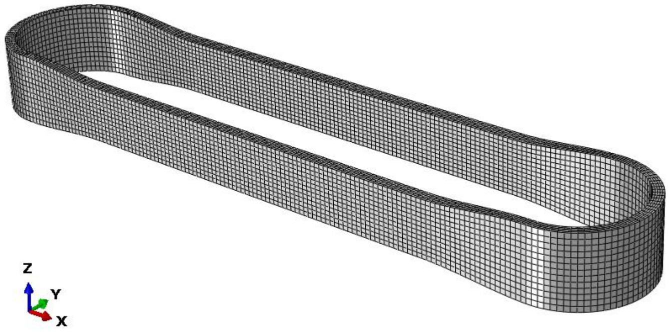
Interaction
between melt flow and deformation of the fiber strands

→ **Contact**

Fiber strands
Mechanical behavior

→ **Lagrangian**



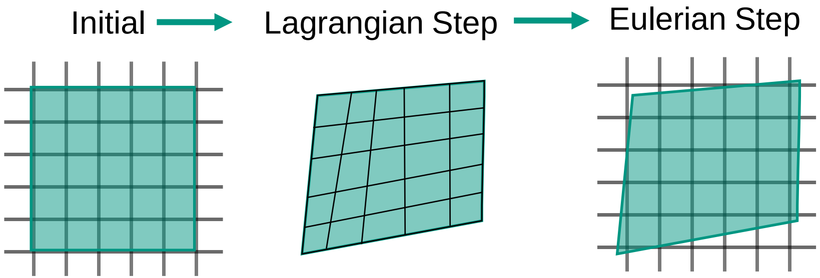


Coupled-Eulerian-Lagrangian (CEL) analysis

Eulerian time integration algorithm - Operator split

- $\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \boldsymbol{v}) = 0$ *mass*
- $\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \operatorname{div}\big((\rho \boldsymbol{v}) \otimes \boldsymbol{v}\big) = \operatorname{div}(\boldsymbol{\sigma})$ *momentum*
- $\frac{\partial (\rho c_{\mathrm{p}} T)}{\partial t} + \operatorname{div}\Big(\big(\rho c_{\mathrm{p}} T\big) \cdot \boldsymbol{v}\Big) = -\operatorname{div}(\boldsymbol{d}) + \boldsymbol{\sigma} : \boldsymbol{D}$ *energy*

$\boldsymbol{v}$: Velocity, ρ: Density, $\boldsymbol{\sigma}$: Cauchy stress, c_{p}: Specific heat capacity, $\boldsymbol{d}$: Heat flux, T: Temperature, $\boldsymbol{D}$: Strain rate tensor



based on Benson & Okazawa 2004

Lagrangian Step

- $\left.\frac{\partial \rho}{\partial t}\right|_L = 0$
- $\left.\frac{\partial (\rho \boldsymbol{v})}{\partial t}\right|_L = \operatorname{div}(\boldsymbol{\sigma})$
- $\left.\frac{\partial (\rho c_{\mathrm{p}} T)}{\partial t}\right|_L = -\operatorname{div}(\boldsymbol{d}) + \boldsymbol{\sigma} : \boldsymbol{D}$

Eulerian Step

- $\left.\frac{\partial \rho}{\partial t}\right|_E + \operatorname{div}(\rho \boldsymbol{v}) = 0$
- $\left.\frac{\partial (\rho \boldsymbol{v})}{\partial t}\right|_E + \operatorname{div}(\rho \boldsymbol{v} \otimes \boldsymbol{v}) = \boldsymbol{0}$
- $\left.\frac{\partial (\rho c_{\mathrm{p}} T)}{\partial t}\right|_E + \operatorname{div}\Big(\big(\rho c_{\mathrm{p}} T\big) \cdot \boldsymbol{v}\Big) = 0$

Benson 1992, 2002, 2004; Meyer 2021

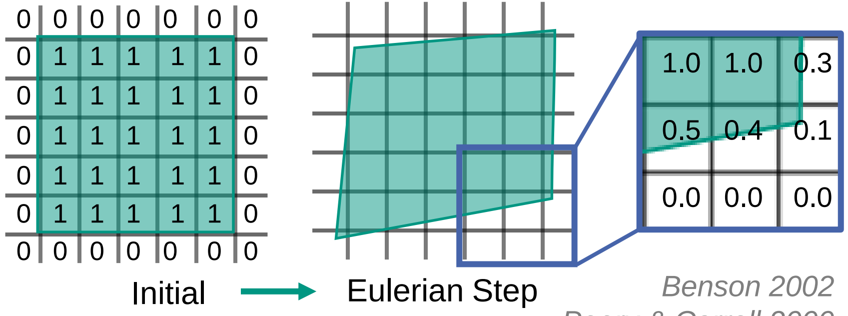
Coupled-Eulerian-Lagrangian (CEL) analysis

Karlsruhe Institute of Technology

Interface reconstruction method

- **Volume of fluid (VoF)**
  - Based on the volume fractions of the material in an element and its neighboring elements the material interfaces are reconstructed
  - $EVF \begin{cases} = 0, \text{ void} \\ > 0 \cap < 1, \text{ partially filled} \\ = 1, \text{ filled} \end{cases}$

EVF: Eulerian Volume Fraction



Benson 2002
Peery & Carroll 2000

Interaction through Eulerian-Lagrangian-Contact

- Based on an enhanced immersed boundary method
- Lagrangian structure occupies void regions inside the Eulerian mesh
- Contact algorithm computes and tracks the interface between the Lagrangian structure and the Eulerian material

  → guarantees that two materials never occupy the same physical domain

Abaqus 2024

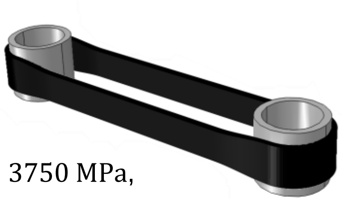
Simple loop structure

Model

KIT – Karlsruhe Institute of Technology

Material

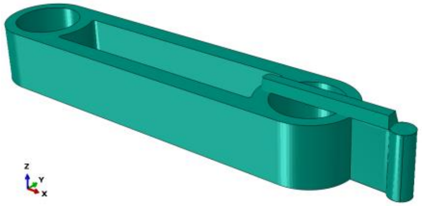
- Fiber strands: PP-GF
  - Density $10000\,\frac{\mathrm{kg}}{\mathrm{m}^3}$
  - Engineering Constants
    - $E_1 = 23963\ \mathrm{MPa},\ E_2 = E_3 = 3750\ \mathrm{MPa},$
    - $\nu_{12} = \nu_{23} = 0.32, \nu_{13} = 0.59$
    - $G_{12} = G_{23} = 1225\ \mathrm{MPa}, G_{13} = 1125\ \mathrm{MPa}$



Haas et al. 2021, 2022

- Matrix: PP
  - Density $10000\,\frac{\mathrm{kg}}{\mathrm{m}^3}$
  - Viscosity $1000\ \mathrm{Pas}$
  - Equation of state
    - Mie-Grüneisen

$$C_0 = 1000\,\frac{\mathrm{m}}{\mathrm{s}}, s = 0, \mathrm{T}_0 = 0$$



Boundary Conditions

- Inlet
  - Constant volumetric flow $75\,\frac{\mathrm{cm}^3}{\mathrm{s}}$
  - Inlet velocity $v_0 = 2\,\frac{\mathrm{m}}{\mathrm{s}}$
- Walls
  - No slip $v_1 = v_2 = v_3 = 0\,\frac{\mathrm{m}}{\mathrm{s}}$

Software

SIMULIA ABAQUS

2023.HF4

Explicit

Simulia

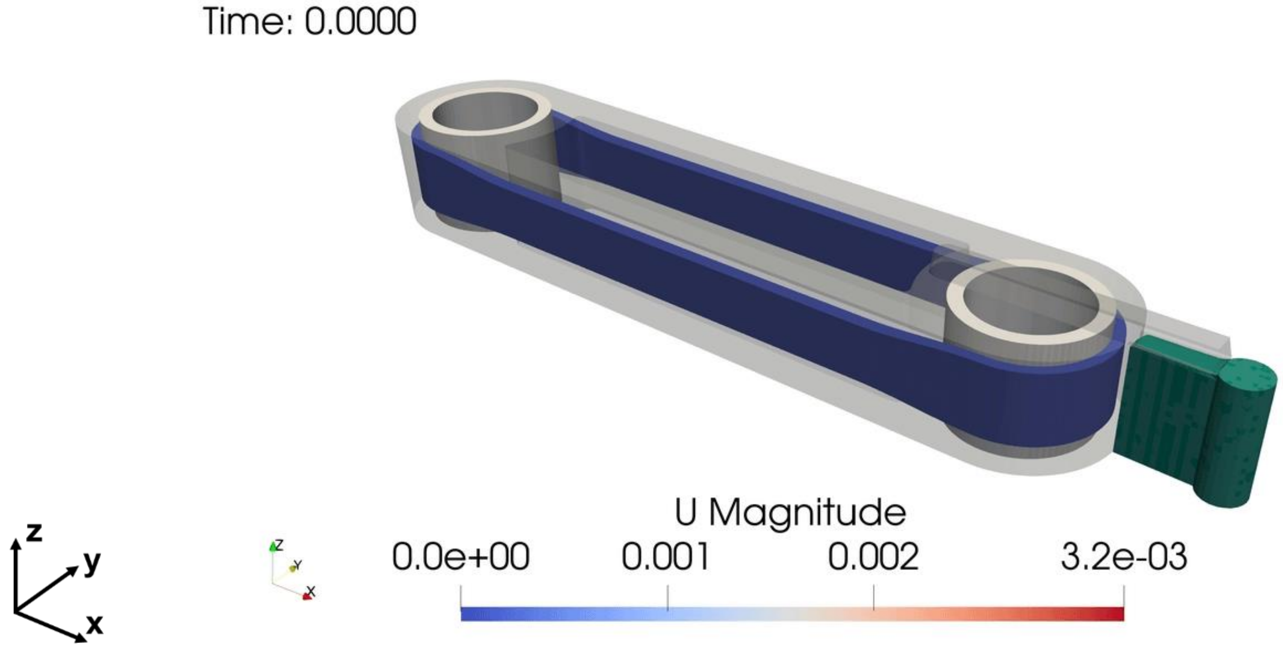
Interaction: General contact

- Contact between Matrix and Walls
  - Tangential Behavior: Rough
  - Normal Behavior: “Hard” contact
- Contact between Fiber strands and Matrix
  - Tangential Behavior: Frictionless
  - Normal Behavior: “Hard” contact

Results Simulation Approach

Simple Loop structure

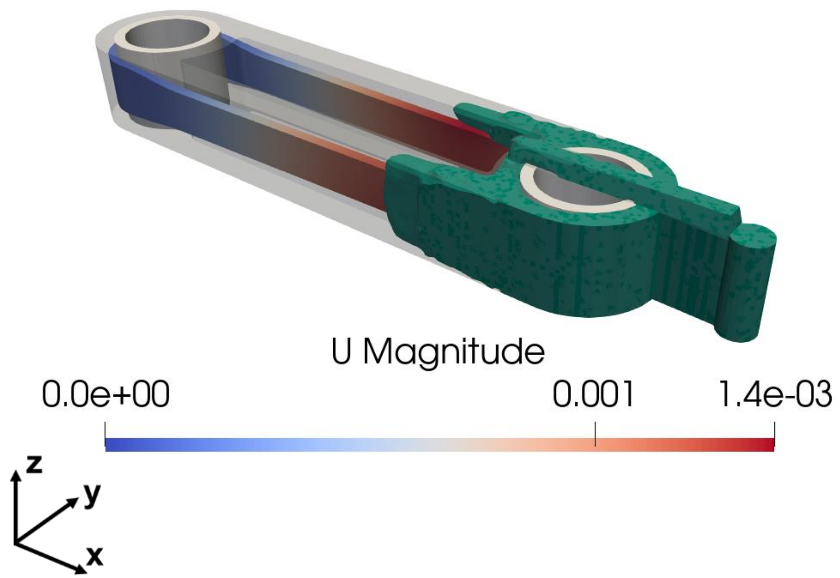
Overmolding



Results Simulation Approach

Simple Loop structure

Overmolding



Numerical Challenges

- Explicit analysis
  - Explicit procedure integrates through time by using many small time increments
    - Stable time increment scales with the smallest element size

$$\Delta t \approx \frac{L_{\min}}{c_d}$$

$L_{\min}$: smallest element dimension
c_d: dilatational wave speed

    - Number of increments required scales by simulated time period

$$n = \frac{T}{\Delta t}$$

→ High computational cost
  - Use mass scaling for Lagrangian parts
- Contact algorithm

Abaqus 2024

Conclusion and outlook

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Overmolding of 3D Skeleton Winding Structures

It was motivated that …

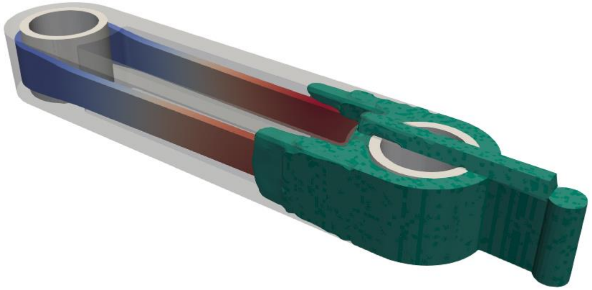
- 3DSW allows to reinforce complex structural components
- Process modeling requires a fully coupled thermomechanical analysis for the fluid flow and the deformation of the fiber bundles

It was show that …

- Coupled-Eulerian-Lagrangian (CEL) approach is suitable to capture the fluid-structure-interaction
  - Fluid phase is modeled as Eulerian elements while fiber strands are described by Lagrangian solid elements
  - Numerical difficulties

Outlook

- Extend the considered material behavior to a more realistic material model
- Extend the simulation approach with temperature dependencies
- Validation of the simulation approach to experimental results



Thank you for your attention.

Karlsruhe Institute of Technology

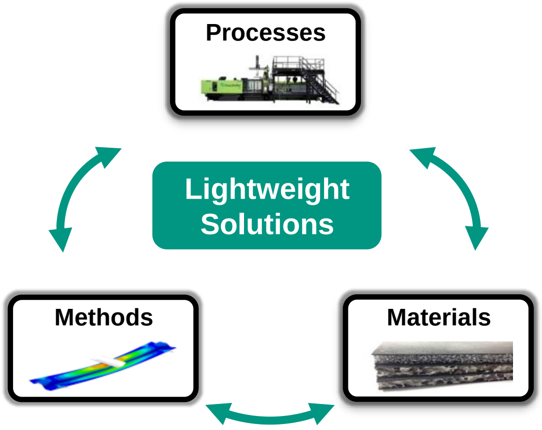
Karlsruhe Institute of Technology (KIT)
FAST Institute of Vehicle System Technology
LB Lightweight Engineering

Prof. Dr.-Ing. Luise Kärger, Professor of Digitization in Lightweight Design
Prof. Dr.-Ing. Frank Henning, Professor of Lightweight Technology

Rintheimer Querallee 2, 76131 Karlsruhe, Germany
www.fast.kit.edu | LinkedIn: Lightweight Engineering at FAST, KIT

Christina Dohmen
Research Associate
christina.dohmen@kit.edu
phone +49 721 608 45409

Lightweight Design Network



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IAM Institut für Angewandte Materialien · FAST · ITM · ICT Polymeric Materials · Versuchsanstalt · IKFT · IPEK · wbk · IHM · Fraunhofer ICT

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