TECHNISCHE UNIVERSITÄT DRESDEN

Karlsruhe Institute of Technology

DRESDEN concept

Fakultät Maschinenwesen, Fakultät Verkehrswissenschaften „Friedrich List“

Experimental Description of Draping Effects and their Influence on the Structural Behavior of Fiber Reinforced Composites

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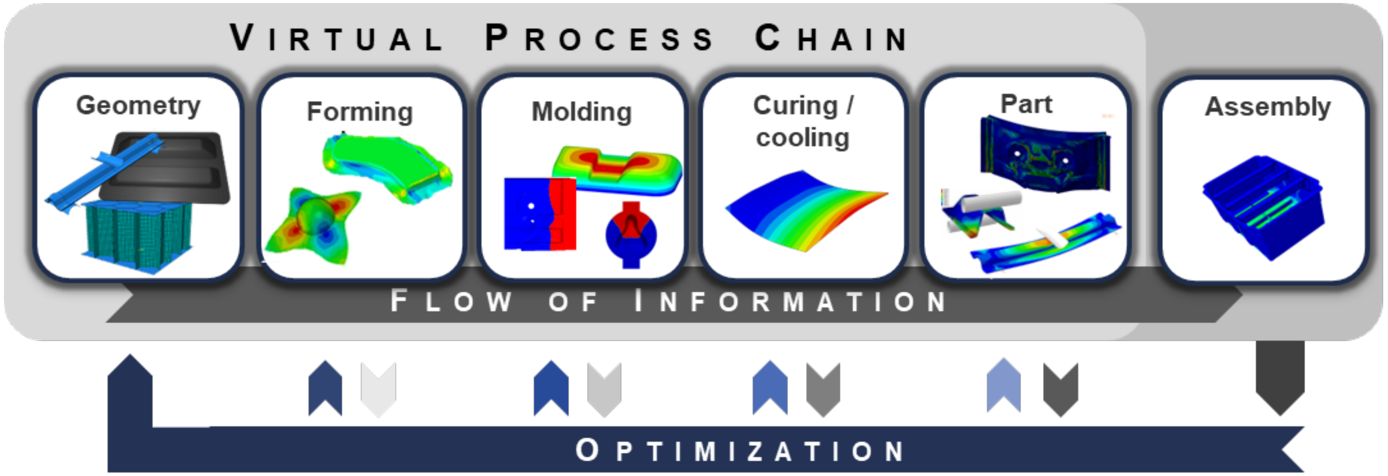
Outline

- Motivation
- Draping Effects and Methodology
- Experimental approach
- Simulation approach
- Results

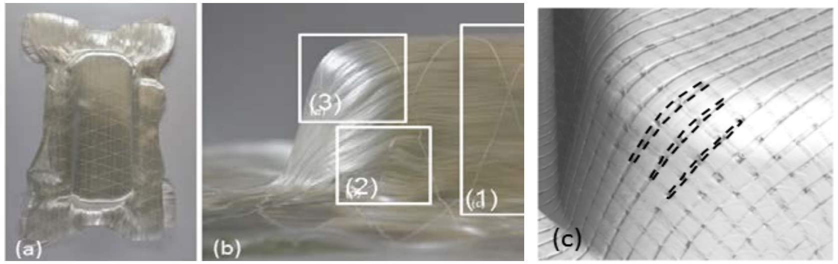
Motivation

Inclusion of processing effects into structural simulation



[1]

Draping effects

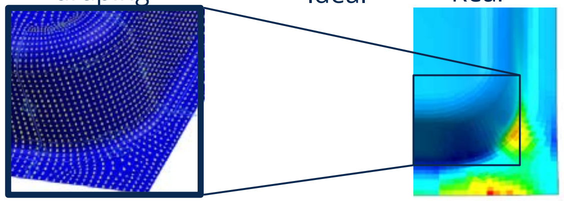


(a) formed UD-fabric
(b) fiber waviness (2)
(c) Fiber gapping

Description of structural behavior

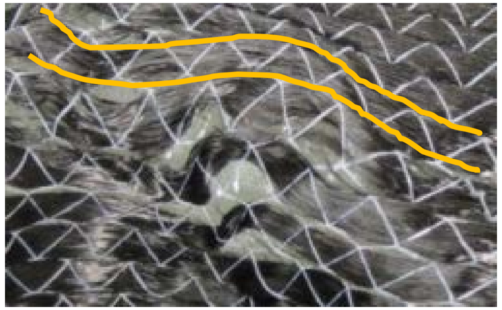
e.g. draping effect dependent fiber volume content

Numeric process – structure - interaction

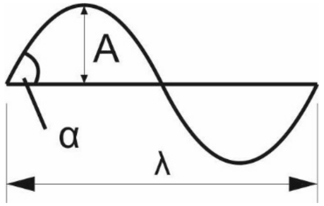


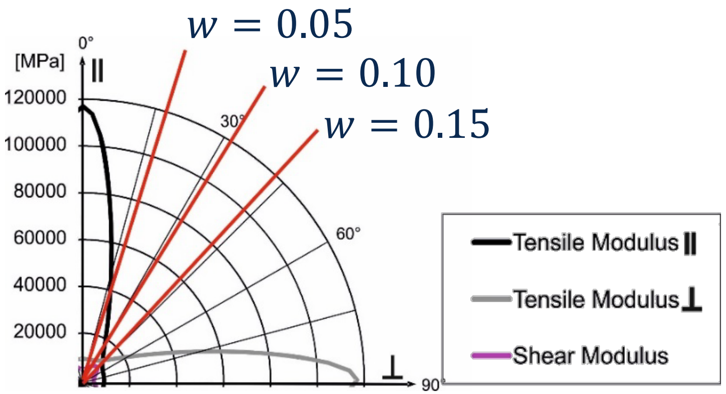
Draping effects - definition

1. Fiber waviness
(due to compression)

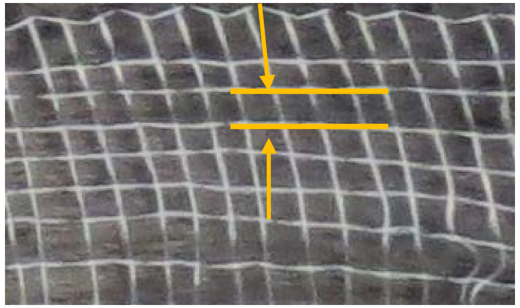


$$w = \frac{A}{\lambda}$$

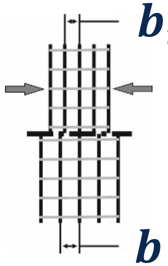




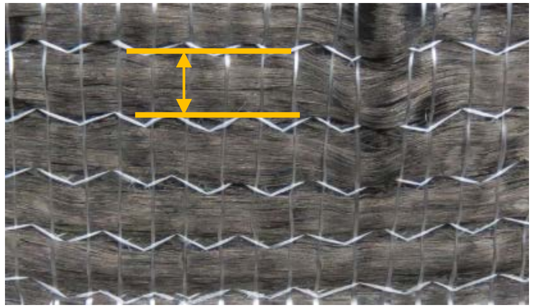
2. Transverse compression
(due to compression or shear)



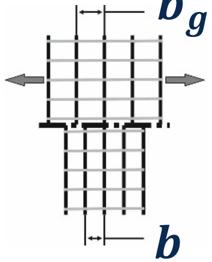
$$tc = \frac{b_{tc}}{b} < 1$$



3. Gapping
(due to transverse tension)



$$g = \frac{b_g}{b} > 1$$



$$\varphi = \frac{n\, m_A * \frac{b_{g/tc}}{b}}{\rho\, t} = \varphi_{initial} * \frac{b_{g/tc}}{b}$$

m_A – areal weight
n – number of layers
ρ – density of fiber
t – thickness
φ – fiber volume content

Methodical approach

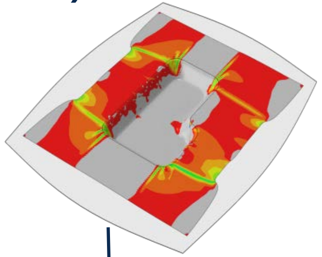
UD non-crimp fabric

Zoltek PX 35 (50K)

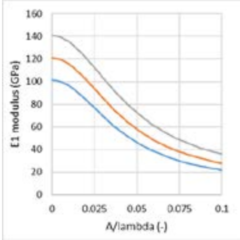
- 338 g/m²
- 5 mm roving width
- Pre-applied non-reactive powder binder

Draping effects

Change in fiber volume content (FVC) and orientation



Influence on mechanical properties



Experiment

Analysis of draping effects
On structural level

Reproducing draping effects
On coupon level

Reproducible Manufacturing

Mechanical Testing
On coupon and structural level

validation of models

Simulation

Draping
Macro-scale
Fiber orientation
Draping effects
FVC change

Modelling draping effects
Micro-scale
Meso-scale
Macro-scale
Stiffness and strength

Structural
Macro-scale
Influence of draping effects on structural performance

homogenized geometry and material information

Experimental approach

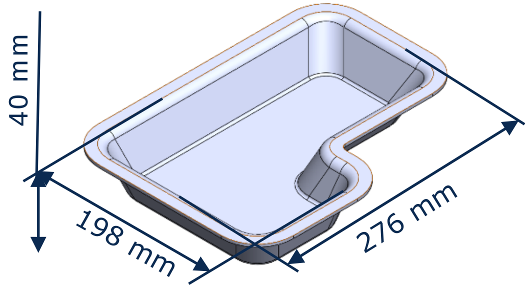
Material forming on structural level and reproducing effects on coupon level

Analysis of draping effects → Reproducing identified effects → Consolidation → Mechanical Testing

Analysis of draping effects

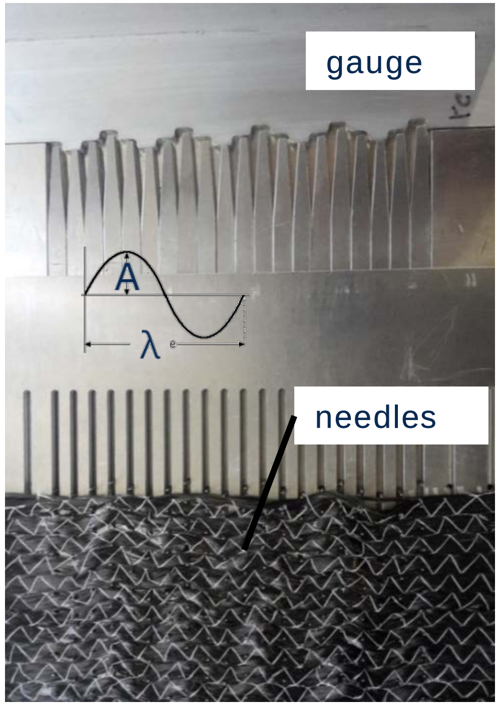
- Gapping
- Waviness
- Transverse compression

- Practice-oriented L-shaped geometry



Reproducing identified effects

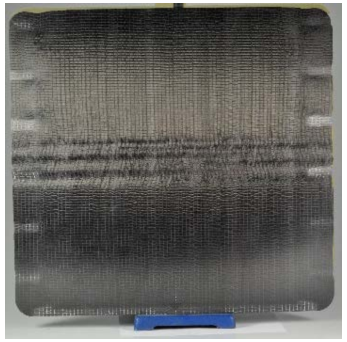
- Dedicated to tools with sliding mechanism
- Realigning fibers
- Changing FVC



Reproducing waviness

Consolidation

- High-pressure resin transfer molding
- Epoxy resin Sika CR 170/CH150-3



395 x 414 mm plate with waviness W=0.10

L-shaped part

Mechanical Testing

- Reference/without and with draping effects
- Tensile, compression, shear and bending tests
- In and perpendicular to fiber direction
- Properties and failure behavior (GOM ARAMIS)

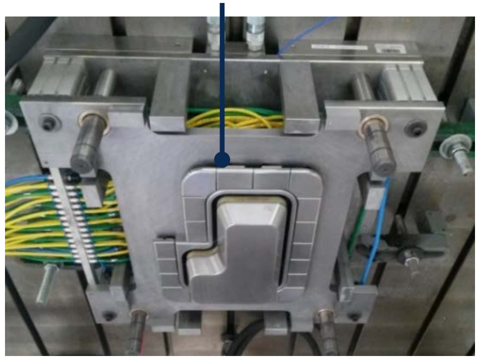
Specimen with waviness

Analysis of draping effects on structural level

Quantification and investigation of the effect limits

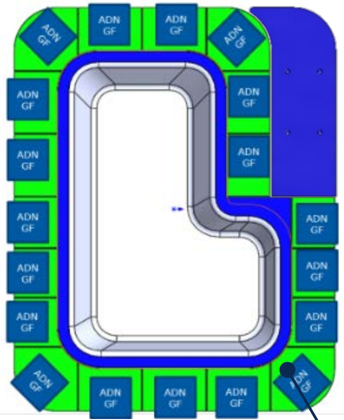
Forming tool

Draping unit



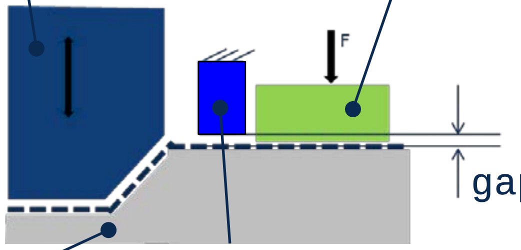
mold

Forming principle [2]



punch

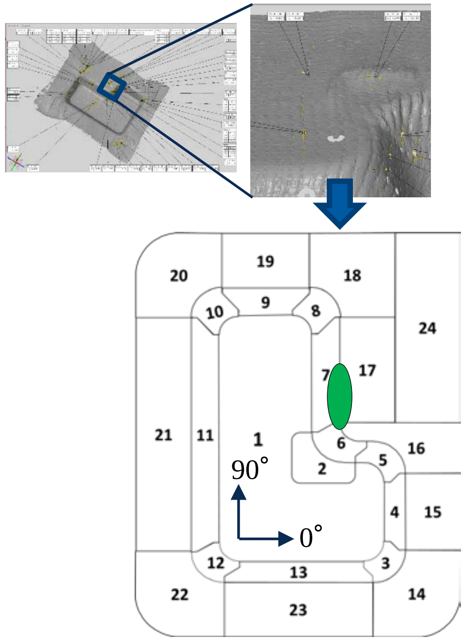
19 adjustable segmented blank holders 0..250 N



gap

global blank holder

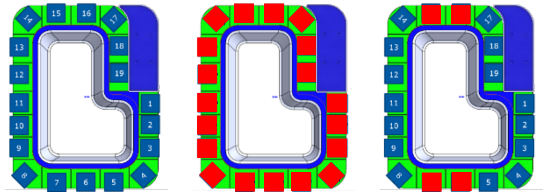
Quantification and representation on map with areas of interest



- optical 3D-measurement with ATOS (GOM)
- Measurement of distances on the polygonised virtual image
- Visualization through colored regions
  (Shape ≙ spatial extension,
  Color ≙ Maximum measured)

Tested configurations

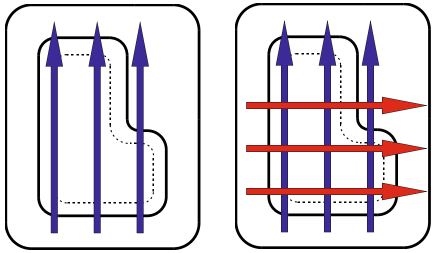
- 3 blank holder configurations



BH 1 BH 2 BH 3

(red ≙ active, blue ≙ inactive)

- 2 ply lay ups
  a) Unidirectional 90° (2 plies)
  b) Bidirectional 0°/90° (2 plies)



a) b)

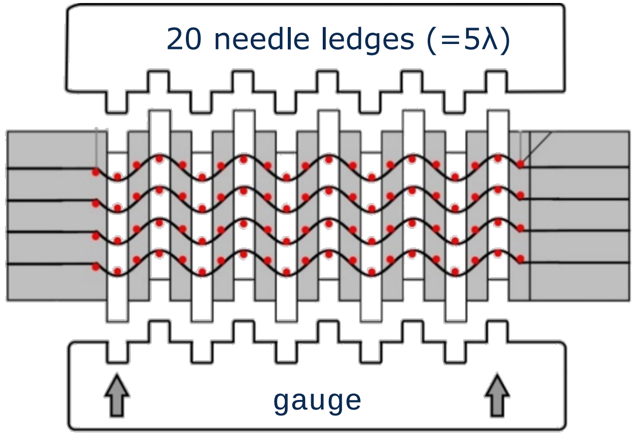
Forming on coupon level

Reproducing draping effects for mechanical testing

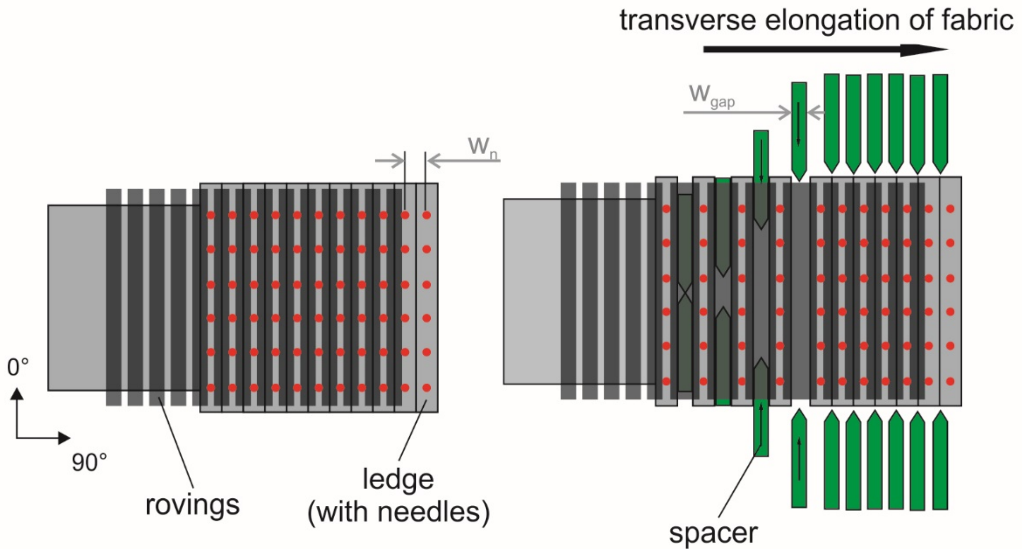
- Fabric samples with predefined deformation states
- One tool for each draping effect
  - **Sliding mechanism for waviness and gaps**
  - **Shear frame for transverse compression**
- Single fabric layers with draping effects
  - Local fixation of draping effects with binder
- Stacking of single layers
- Optical analysis of single layers and Computer tomography of the final stack
- Inferences on the fiber volume content φ are made from measured areal weight of fabric [3]

$$\varphi = \frac{n}{\rho \cdot t} \frac{m_{f,\mathrm{i}}}{A_0}$$

φ −fiber volume content
$m_{f,\mathrm{i}}$: fabric weight per area A_0
$m_{f,0}$: undeformed
$m_{f,\mathrm{w}}$: with waviness
$m_{f,\mathrm{g}}$: with gapping
$m_{f,\mathrm{tc}}$: with transverse compression



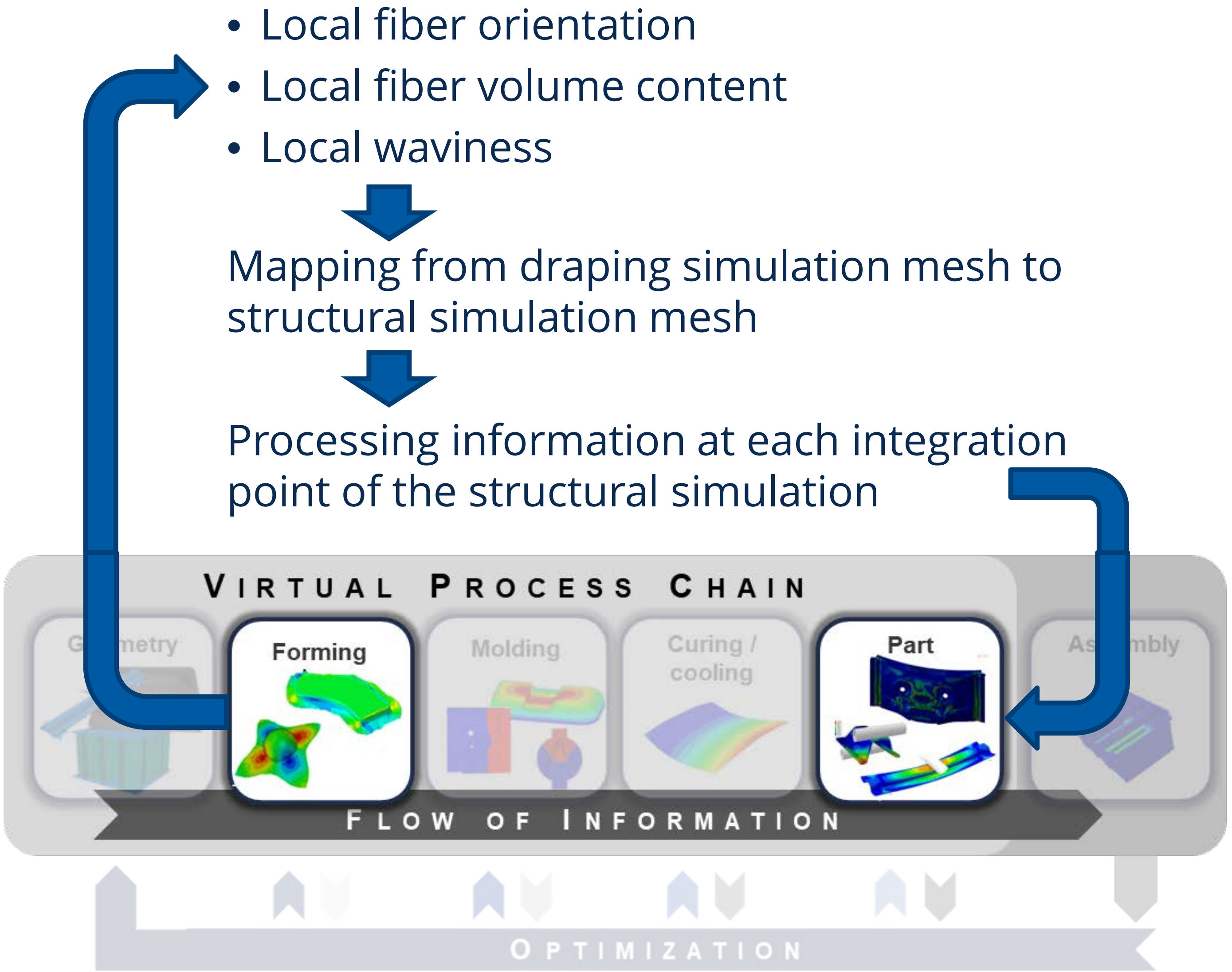
Schematic: sliding mechanism for waviness [3]



Schematic: sliding mechanism for gaps [3]

Simulation approach
A continuous virtual process chain

- Continuous virtual process chain: information from each simulation step is transferred to the next simulation step
- Macroscopic draping simulation model: prediction of material behavior and non-linear deformation of the UD non-crimp fabric [4]
- Based on the deformation of each mesh element, draping effects like local fiber orientation and varying fiber volume content are processed and exported to a neutral file format for the mapping step [5]
- After mapping the draping information is available to a macroscopic damage model for UD composites



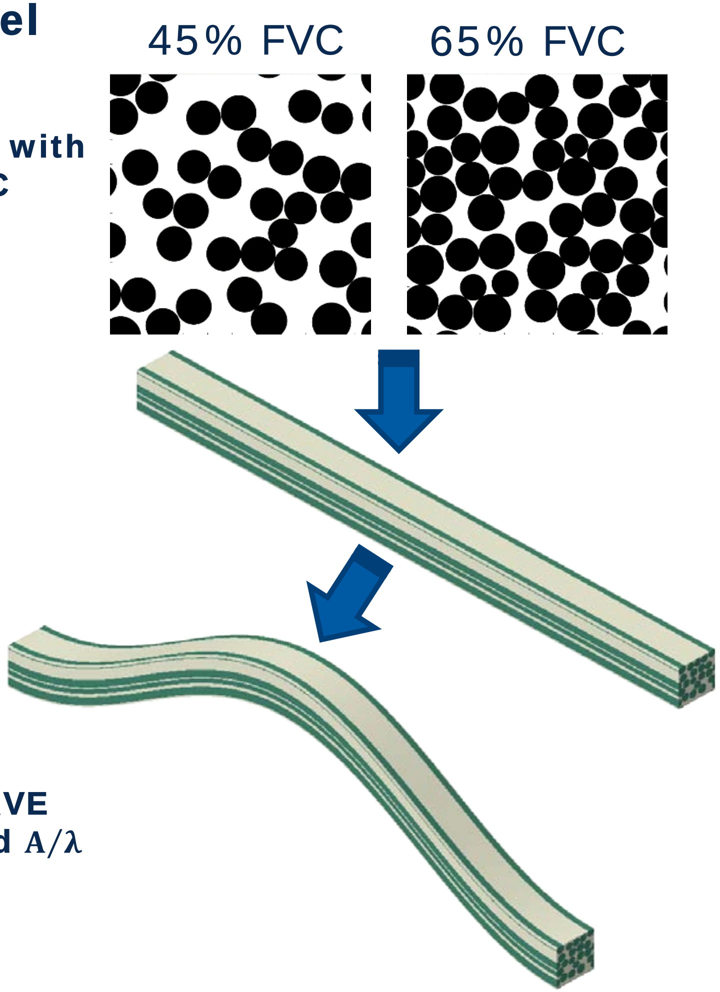
Modelling on micro, meso and macro scale

Multiscale evaluation of draping effect

- Multiscale approach for evaluation of draping effects on the structural performance
- Variation of fiber volume content (FVC) and amplitude to wavelength ratio A/λ on different length scales
- Analysis of failure initiation and damage progression for varying fiber volume content at undulated and non-undulated areas
- Comparison of simulation results at different length scales with experimental results

Micro model

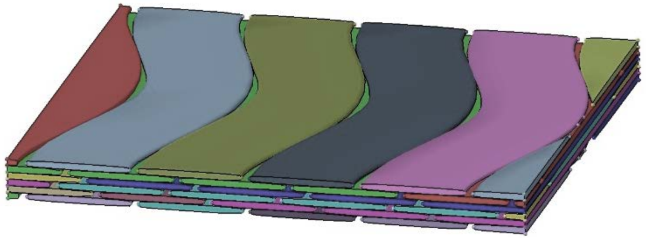
Generated micro structure with varying FVC (2D SRVE)



non-undulated SRVE

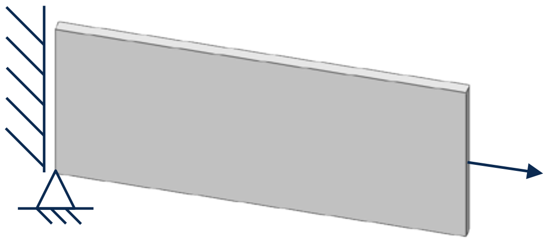
undulated SRVE with predefined A/λ ratio

Meso model



Embedded cell meso model with given waviness W (A/λ)

Macro model



Boundary conditions

Material model

Constitutive law - Fiber

- Fibers under shear load undergo large rigid body rotations
  → hypo-elastic damage material model is implemented as UMAT
- Rotation tensor l_{ij} is computed via deformation gradient F_{ij}:

$$l_{ij} = (\hat{e}_i)_m \cdot (\hat{e}_j)_p \qquad \text{with} \qquad (\hat{e}_i)_m = \frac{F_{ij}(\hat{e}_j)_p}{\|F_{ij}(\hat{e}_j)_p\|}$$

with p ≙ co-rotational Abaqus CSYS and m ≙ Material CSYS

- Strains are rotated to the material coordinate system

$$\left(\varepsilon_{ij}^{(t+\Delta t)}\right)_m = \left(\varepsilon_{ij}^{(t)}\right)_m + l_{ik} l_{jl} (\Delta\varepsilon_{kl})_p$$

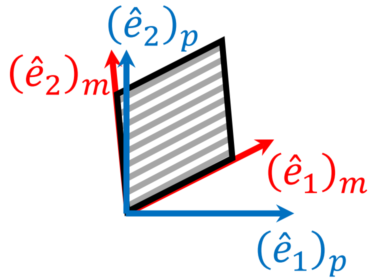
- The calculated material stresses are rotated back to the co-rotational frame

$$(\sigma_{kl})_p = l_{ki} l_{lj} (\sigma_{ij})_m$$

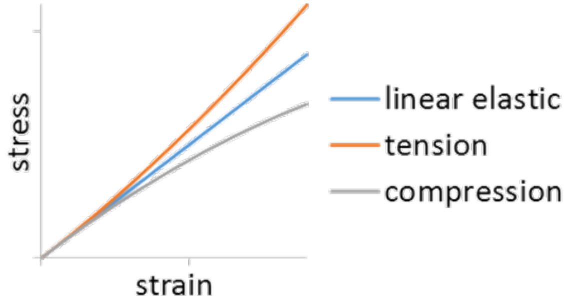
- Fibers are considered non-Hookean linear elastic and transverse-isotropic, with the stiffness tensor defined in the local material coordinate system m:

$$C_{ijkl} = \lambda \delta_{ij}\delta_{kl} + 2\mu_T I_{ijkl}^{(s)} + \alpha(\delta_{ij} n_k n_l + n_i n_j \delta_{kl}) + 2(\mu_L - \mu_T) I_{ijkl}^A + \beta n_i n_j n_k n_l$$

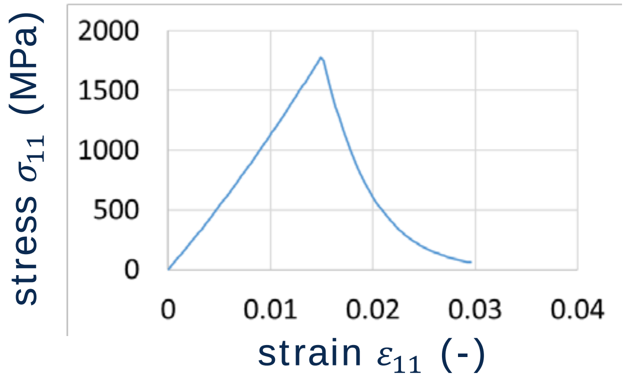
where $n = (1,0,0)^T$ and $I_{ijkl}^A = \frac{1}{2}(\delta_{ik} n_j n_l + \delta_{il} n_j n_k + \delta_{jl} n_i n_k + \delta_{jk} n_i n_l)$



Material axis rotation



non-Hookean linear elastic material behavior



Material model
Constitutive law - Matrix

- Matrix material modelled with hypo-viscoplastic approach with isotropic damage

Viscoplasticity

- Yield surface proposed by [Tschoegel 1971] or [Raghava et al. 1973]

$$\Phi_{\mathrm{pl}} = 6J_2 + 2(\sigma_c - \sigma_t)I_1 - 2\sigma_c\sigma_t = 0$$

- Plastic flow rule (in incremental form)

$$\Delta\varepsilon^{\mathrm{pl}} = \Delta\gamma \frac{\partial g}{\partial \sigma}$$

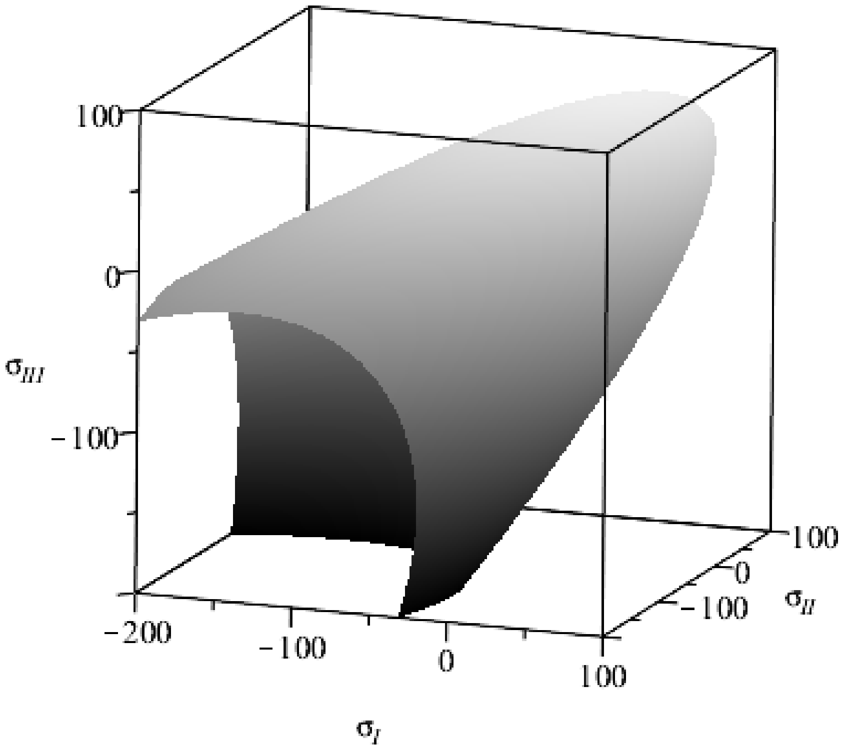
- Plastic multiplier $\Delta\gamma$ according to [Perzyna 1966]

$$\Delta\gamma = \begin{cases} \frac{1}{\mu}\left[F\left(\Phi_{\mathrm{pl}}\right)\right]^{1/h}, & \Phi_{\mathrm{pl}} = 0 \\ 0, & \Phi_{\mathrm{pl}} < 0 \end{cases}$$

- Plastic potential of a non-associative flow rule

$$g = \sqrt{\sigma_{\mathrm{vm}}^2 + \alpha p^2}$$

where α controls the volumetric component of the flow [Melro et al. 2013]



Yield surface proposed by Tschoegel or Raghava

Material model

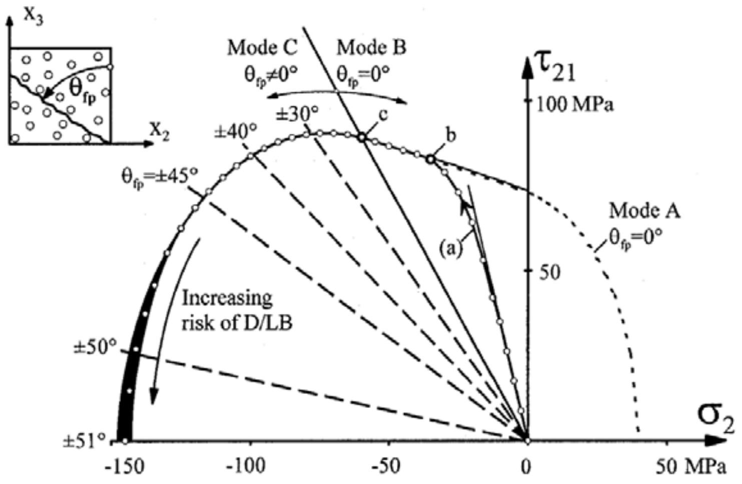
Constitutive law – macroscopic UD composite

- Hypo-elastic anisotropic damage material model is implemented as UMAT
- Similar to the fiber model the stress in fiber direction is non-Hookean linear elastic until fiber failure (FF)
- Non-linear stresses σ pre inter fiber failure (IFF) are determined from effective stresses $\bar{\sigma}$: $\sigma = f(\bar{\sigma})$
- Failure initiation is modeled using Puck's failure theory [6] where the IFF is divided into three distinct modes (Mode A, B and C)

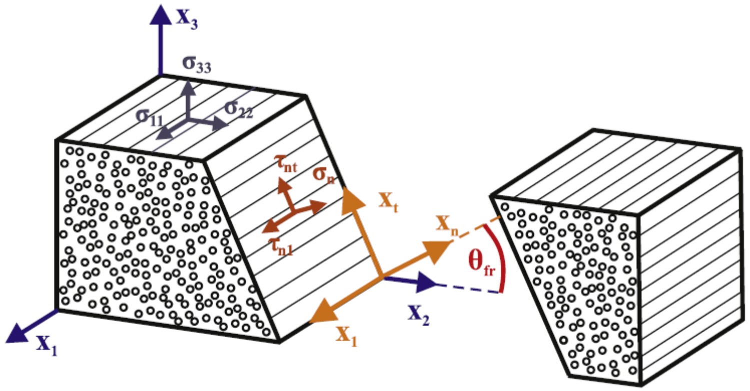
$$\sigma_n \geqslant 0 : f_E = \sqrt{\left(\frac{1}{R_{\perp}^{(+)}} - \frac{p_{\perp\psi}^{(+)}}{R_{\perp\psi}^{A}}\right)^2 \cdot \sigma_n^2(\theta) + \left(\frac{\tau_{nt}(\theta)}{R_{\perp\perp}^{A}}\right)^2 + \left(\frac{\tau_{n1}(\theta)}{R_{\perp\parallel}}\right)^2} + \frac{p_{\perp\psi}^{(+)}}{R_{\perp\psi}^{A}} \cdot \sigma_n(\theta)$$

$$= \sqrt{\left(\frac{\tau_{nt}(\theta)}{R_{\perp\perp}^{A}}\right)^2 + \left(\frac{\tau_{n1}(\theta)}{R_{\perp\parallel}}\right)^2 + \left(\frac{p_{\perp\psi}^{(-)}}{R_{\perp\psi}^{A}} \cdot \sigma_n(\theta)\right)^2} + \frac{p_{\perp\psi}^{(-)}}{R_{\perp\psi}^{A}} \cdot \sigma_n(\theta)$$

- The fracture angle according to Puck's failure theory is computed using selective range golden section search algorithm [7]
- Using the fracture angle the damage in different axes directions is predicted



Failure envelope according to Puck in the τ_{12} vs σ_{22} plane [6]



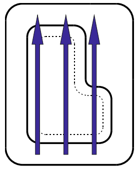
Efficient and reliable fracture angle search algorithm [7]

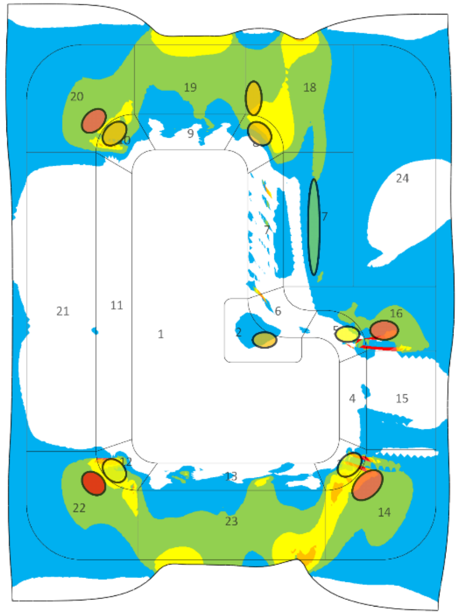
Numerical and experimental quantification of draping effects

Evaluation of the draping effect transverse compression

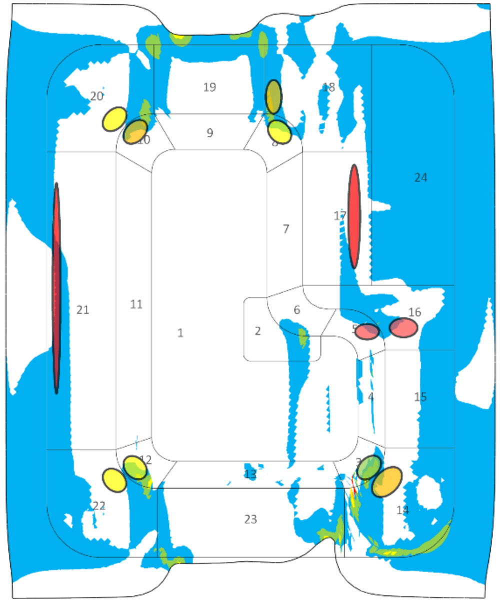
Superposition of numerically (contour plot) and experimentally generated draping maps

Lay up a)
UD 90° (2 plies)

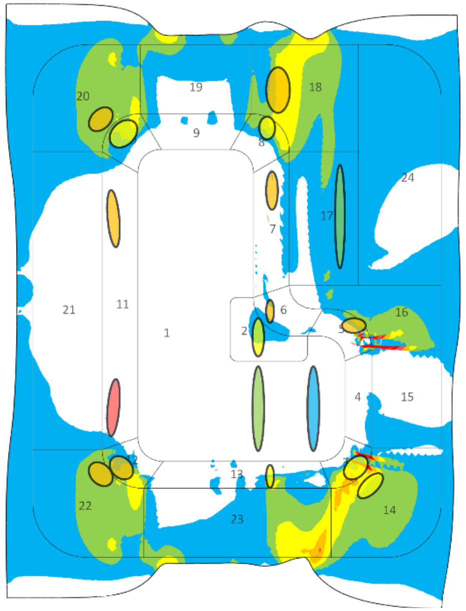


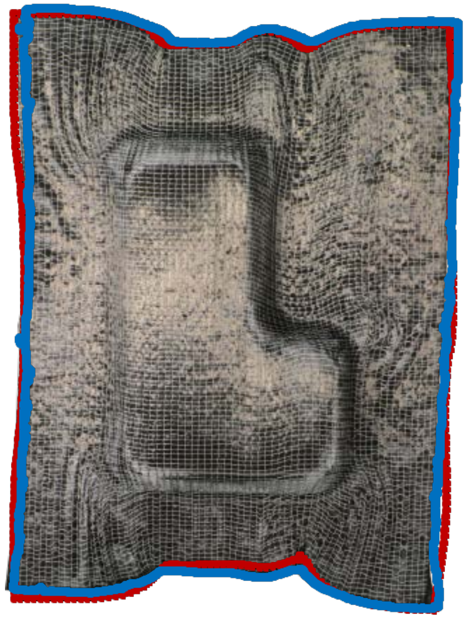


BH 1 (free forming)



BH 2 (250 N @ all BHs)





BH 3 (250 N @ sel. BHs)

Color legend

transverse compression $t_c = \frac{b_{tc}}{b_r}$	ΔFVC (%)
$= 0$	$= 0$
> 0.9	< 11
> 0.8	< 25
> 0.7	< 43
> 0.6	< 67
> 0.5	< 100
< 0.5	> 100 wrinkles

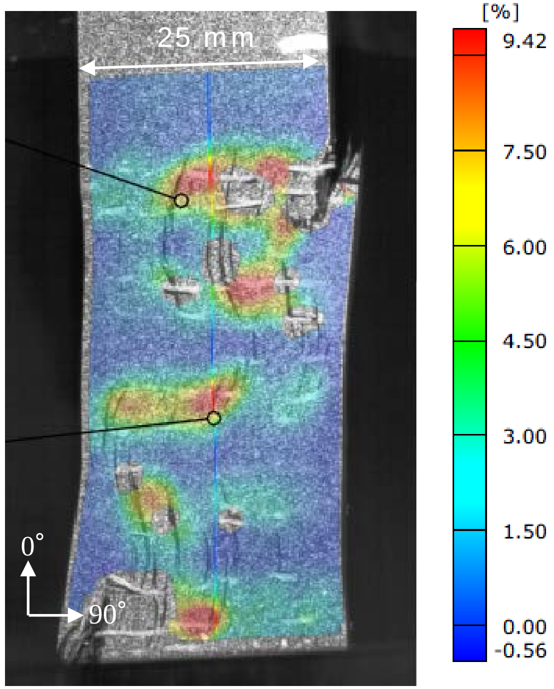
Outer contour
- Simulation
- Experiment

- Outer contours correspond to each other
- Results match well in the corners areas with high shearing
- Deviations in the bottom area of the mold
- Results underneath or in front of blank holders do not match – transverse compression found in front of the blank holders (red ellipses in BH2) were not seen in simulation → different friction behavior between experiment and simulation
- Influencing of draping effects through different BH configurations possible

Mechanical properties

Tensile properties of specimen with waviness

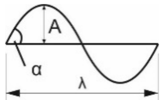
Experimental Results

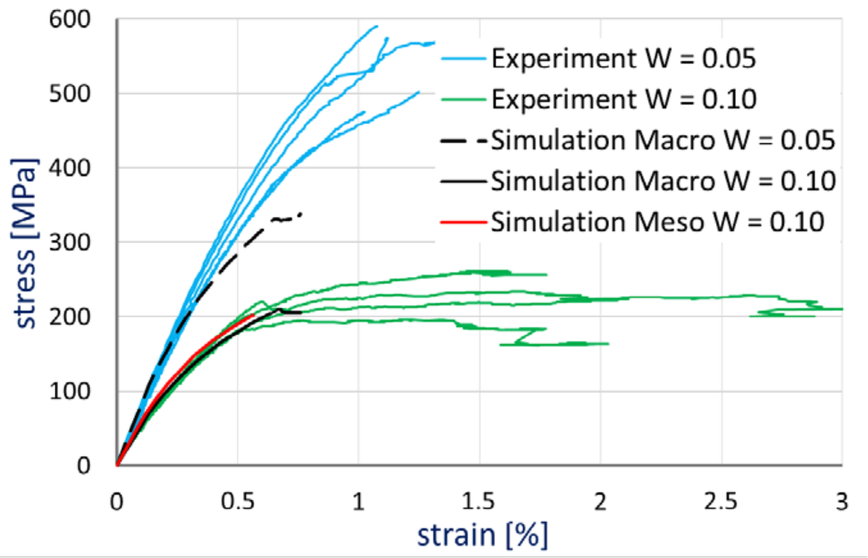


W=0.10 - strain in 0°-direction

(sample D-03_04, $\lambda = 20\,mm,\ A = 2\,mm$)

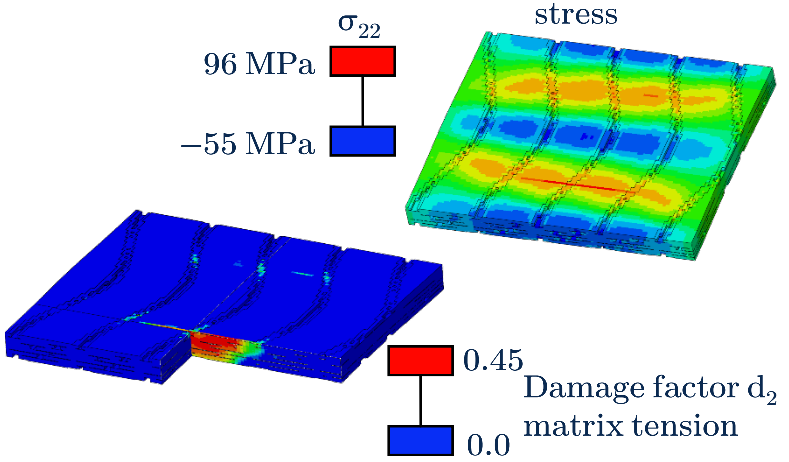
- Initial failure at edge of specimens
- Realignment of rovings under load
- Transverse tensile strength determines crack growth

Mean ± standard deviation	Young's Modulus (GPa)		
	Exp.	**Macro model**	**Meso model**
Reference	105.00±6.40	105	/
W = 0.05	73.15±6.27	69.7	/
W = 0.10	43.80±2.54	42.8	46.0
 $W = \frac{A}{\lambda}$	Initial failure (MPa)		
	Exp.	**Macro model**	**Meso model**
Reference	1503±127	1500	/
W = 0.05	421±37	331	/
W = 0.10	205±16	210	202

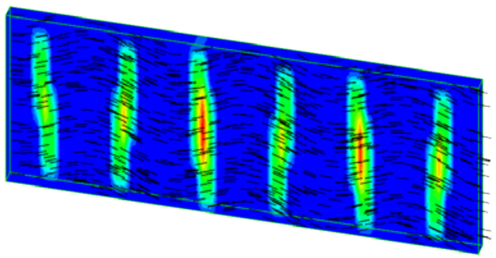


Experiment vs. simulation: σ-ε-curve

Meso model



Macro model

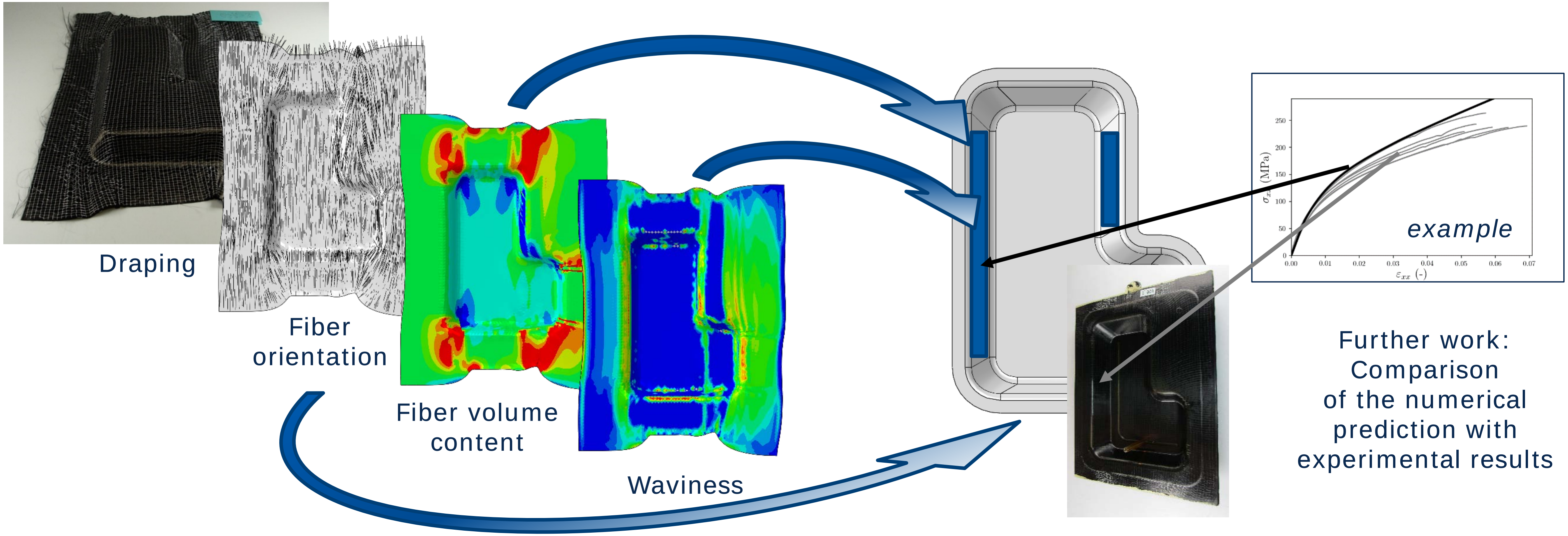


- Prediction of Young's Modulus and Initial Failure
- Initial failure at inflection point of wave
- Good agreement with experiment

Transferring results to structural simulation

Closed process chain and further works

Main goal: prediction of a more realistic structural performance of a composite part



Further work:
Comparison
of the numerical
prediction with
experimental results

Draping simulation and experiment → **Information mapping** → **Structural simulation and testing**

Conclusions

- Draping effects such as change of the fiber orientation, varying fiber volume content or waviness occur during the draping process
- Structural performance of composite parts is highly affected by local draping effects
- Reproduction and quantification of draping effects on structural and coupon level
- Comparison of the experimental and numerical results of coupons with waviness show a good agreement for a high amplitude to wavelength ratio
- Good local agreement of the draping simulation with the experimentally determined draping map, but the resolution of the experimental map must be refined through an improved evaluation method
- Numerically predicted position and magnitude of the draping effects are transferred from the draping simulation to the structural simulation

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ICCM 22 2019 – Melbourne, 12-16th August 2019

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