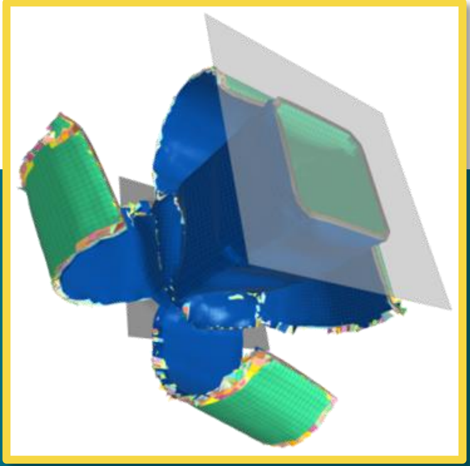
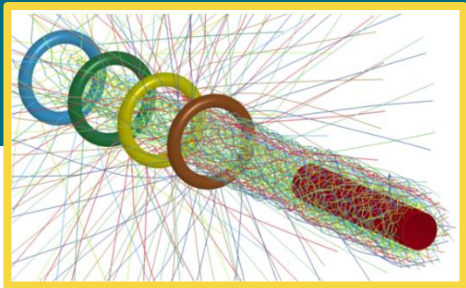
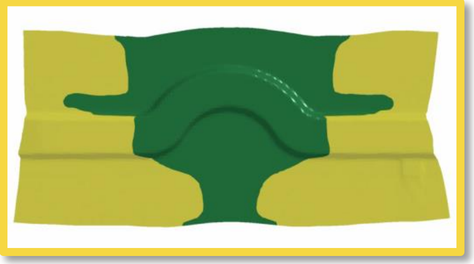






Process simulation of continuous fiber reinforced plastics

C. Liebold

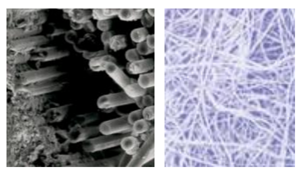
DYNAmore GmbH, Stuttgart

DYNAmore – Webinar
Stuttgart, 27-Nov-14

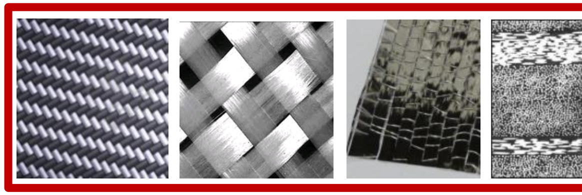
Definition & Classification

Definition: **Composite materials**, often shortened to composites or called composition materials, are **engineered** or **naturally** occurring materials made from **two or more constituent materials with significantly different physical or chemical properties** which remain separate and distinct within the finished structure.

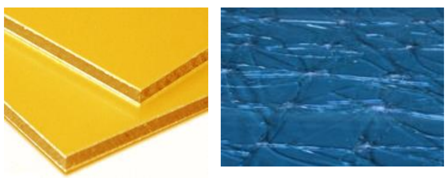
Concrete
(cement/stone/steel)



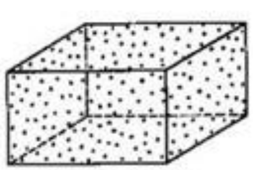
Short-/long fiber
reinforced polymers
(glass/PP)

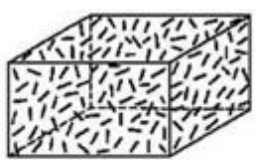


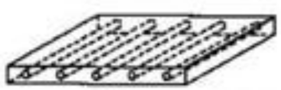
Continuous fiber
reinforced polymers
(glass/carbon/PA/PP/EP)



Sandwich/Laminates
(alloy/polymer/..glass/PVB/…)





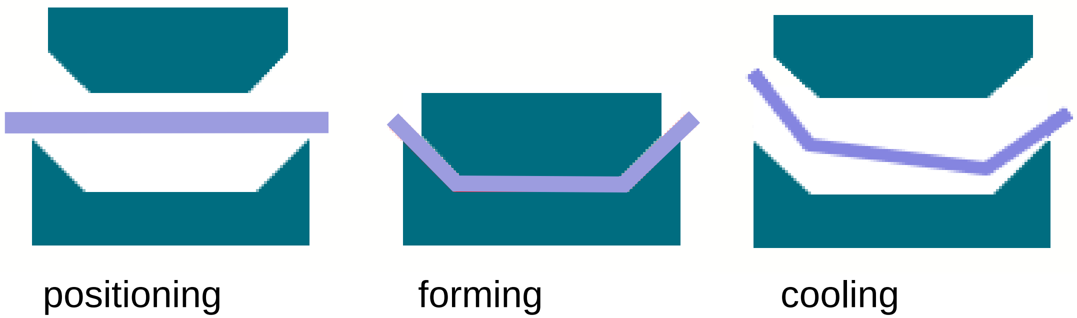


Agenda

- Modeling aspects of process simulations for continuous fiber reinforced plastics:
  - Draping
  - Thermoplastic prepregs
  - Braiding
  - Resin transfer molding (RTM)
  - Wet moulding
- Process Chain – Example (TPult)
- Conclusion and Outlook

Draping – process overview

- Process overview



- Process is reversible since no resin is used
- It is usually a preliminary step prior to an infiltration process (e.g. RTM)
- Relatively short cycle times can be realized

Draping:

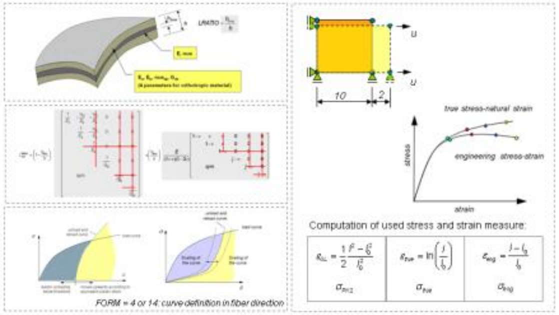
Fabric materials available for draping simulation

MAT_34	MAT_234	MAT_235

MAT_34

Simulation on cm-scale: MAT_FABRIC (#34)

A special membrane formulation is automatically invoked

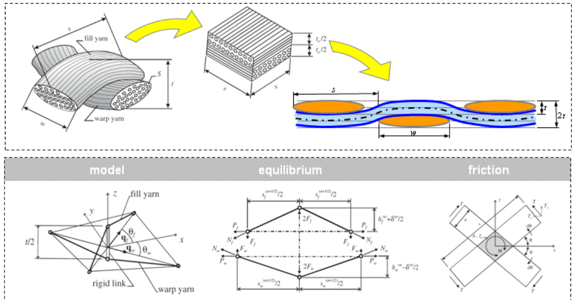


New in R7.0: bending stiffness

MAT_234

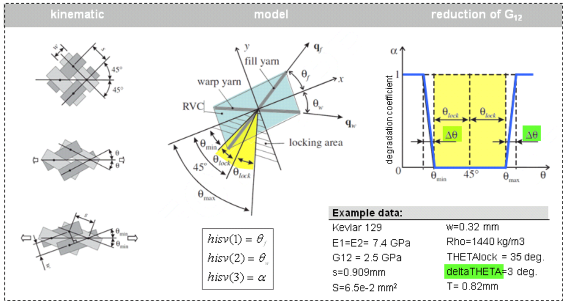
Simulation on cm-scale:
MAT_VISCOELASTIC_LOOSE_FABRIC (#234)

Micro-mechanical approach :
Mathematical description of geometry and kinematic of symmetrical woven fabric



Simulation on cm-scale:
MAT_VISCOELASTIC_LOOSE_FABRIC (#234)

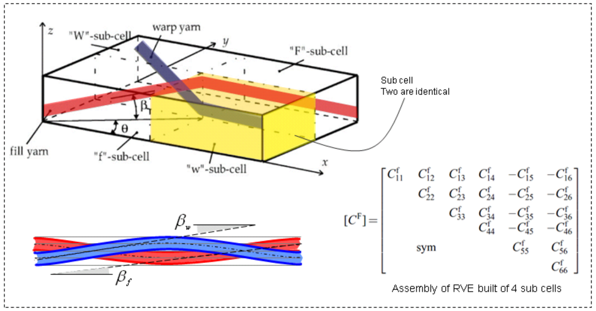
Taking locking angle through reduction factor for G_{12} into account
Visco-elastic enhancement for higher strain rates



MAT_235

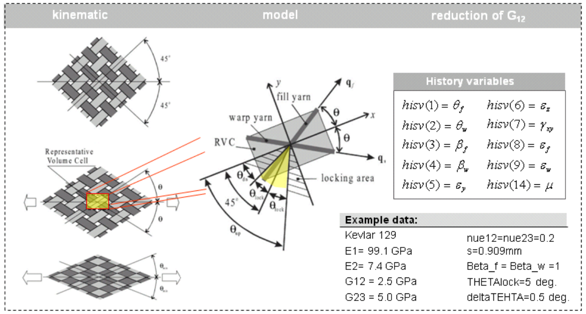
Simulation on cm-scale:
MAT_MICROMECHANICS_DRY_FABRIC (#235)

Micro-mechanical approach with homogenization strategy (RVE):
Mathematical description of symmetrically woven fabric



Simulation on cm-scale:
MAT_MICROMECHANICS_DRY_FABRIC (#235)

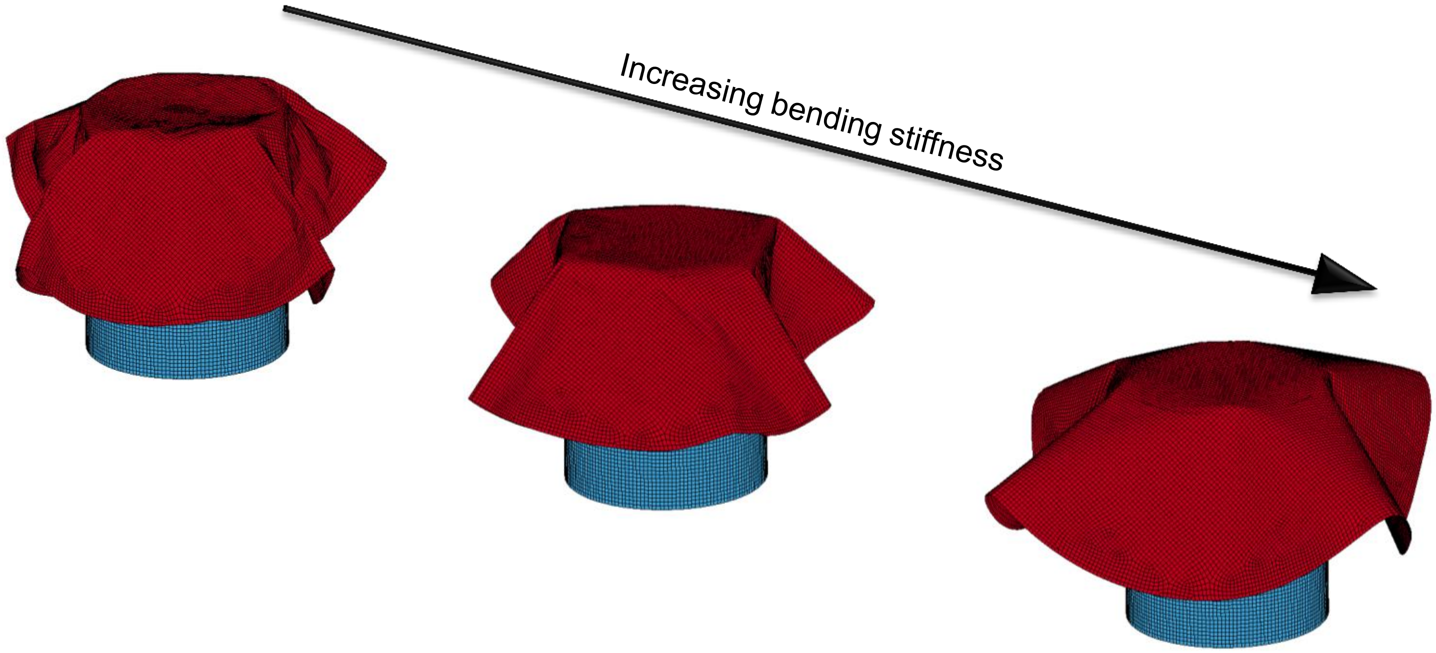
Micro-mechanical approach with homogenization strategy (RVE):
Mathematical description of symmetrically woven fabric



Draping:
enhancements for *MAT_034

- Material describes an orthotropic material behavior
- Requires discretization with membrane elements
- Allows to add a bending resistance by defining an additional elastic coating in the material card

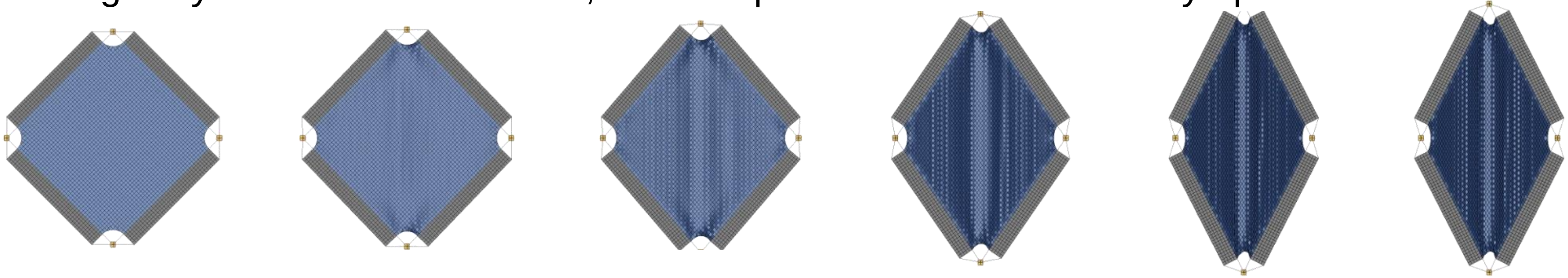
Example: Tablecloth with varying coating stiffness

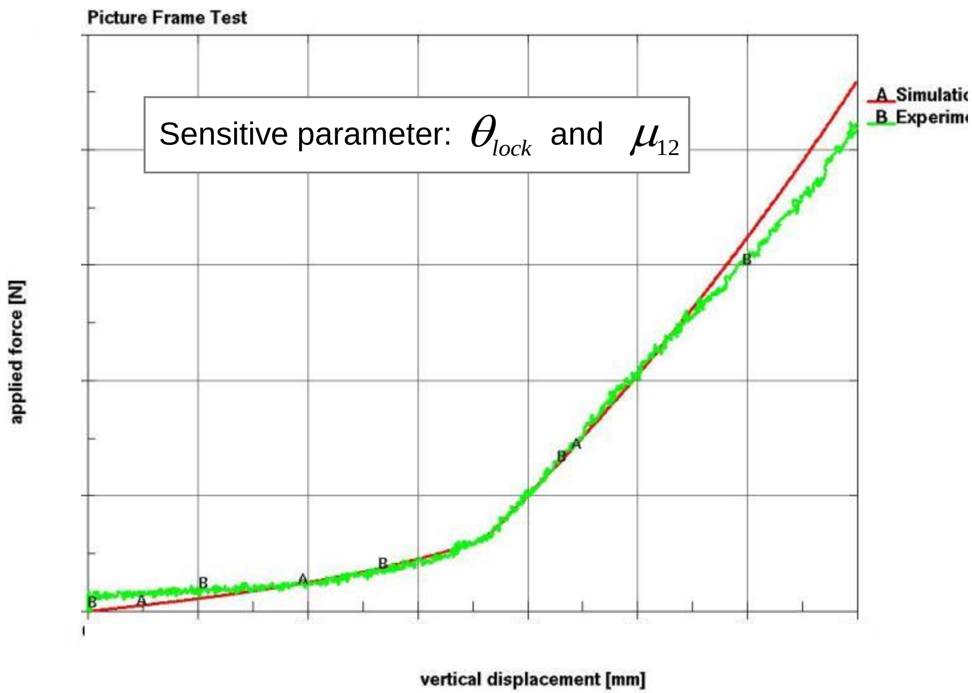


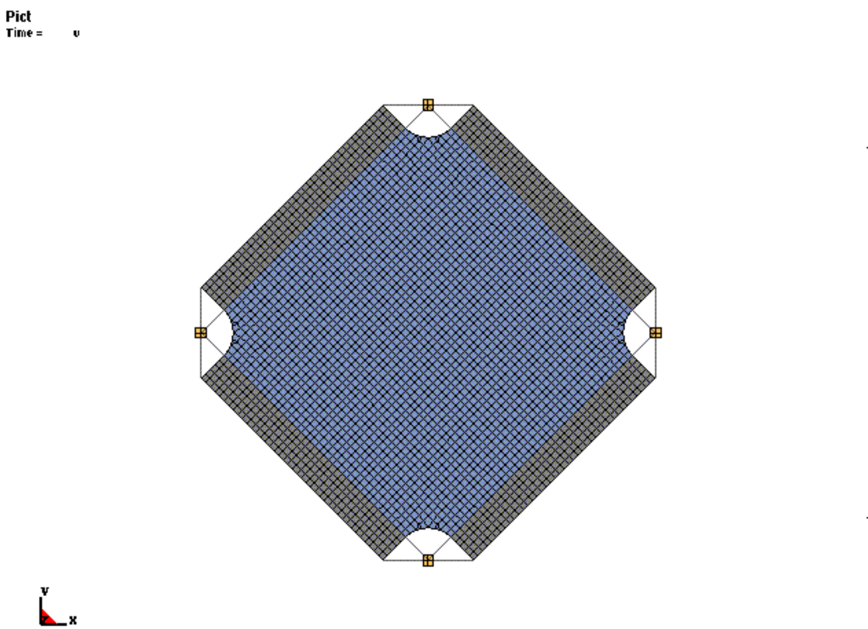
Draping:

material characterization for *MAT_MICROMECHANICS_DRY_FABRIC

Single layer membrane element; Material parameters determined by optimization



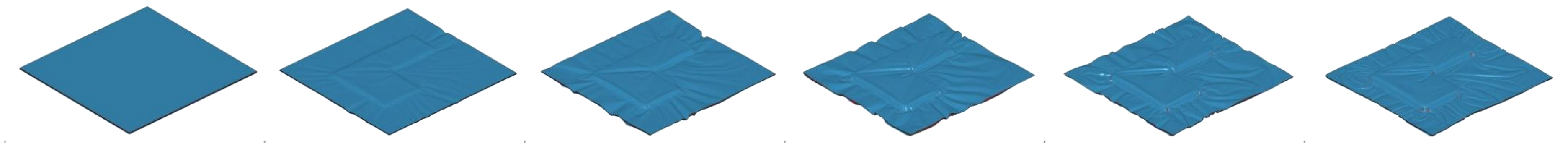


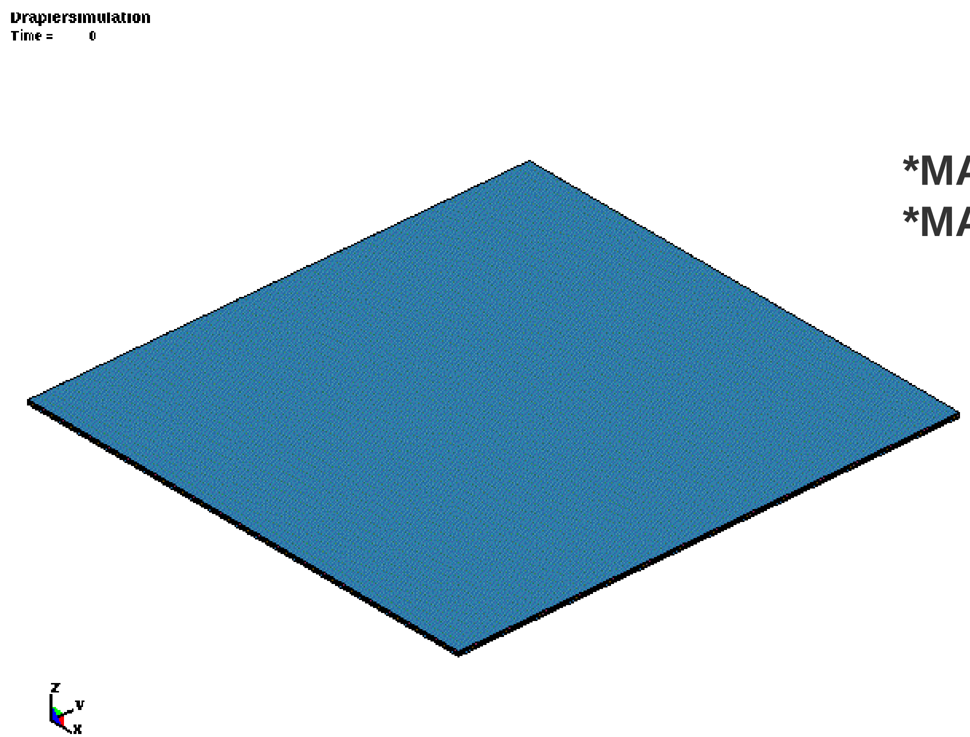


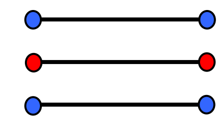
Draping:

different discretizations and lay-ups

Membrane formulation with coincident, elastic shell
Three element layers stacked with contact formulation



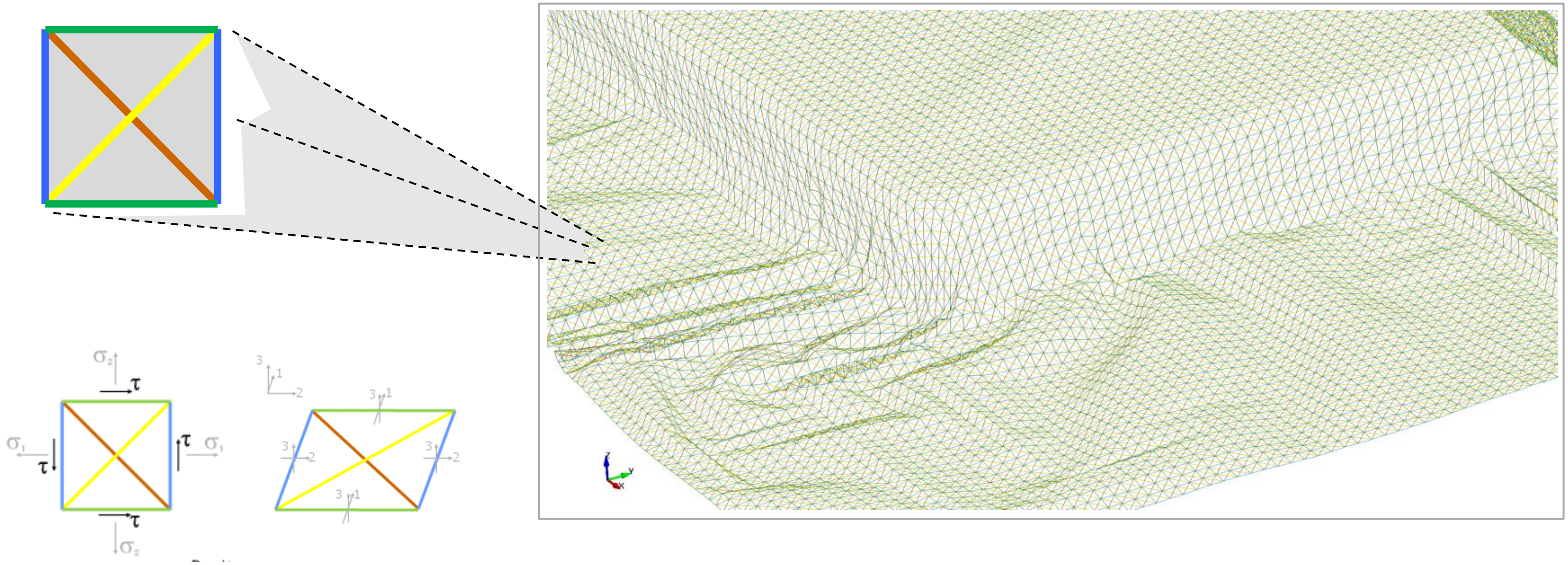




***MAT_MICROMECHANICS_DRY_FABRIC /**
***MAT_ELASTIC incl. lay-up**

Draping:
using discrete elements to consider strong anisotropy

Modeling woven fabrics with beam elements:
Warp and weft direction *MAT_LINEAR_ELASTIC_DISCRETE_BEAM (MAT_066)
Diagonal behavior modeled with *MAT_CABLE_DISCRETE_BEAM (MAT_071)

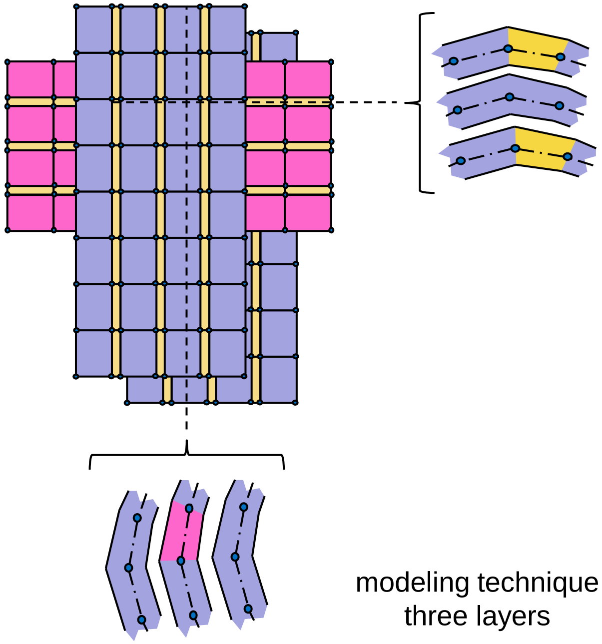


This approach allows also to model positive and negative shear loading.

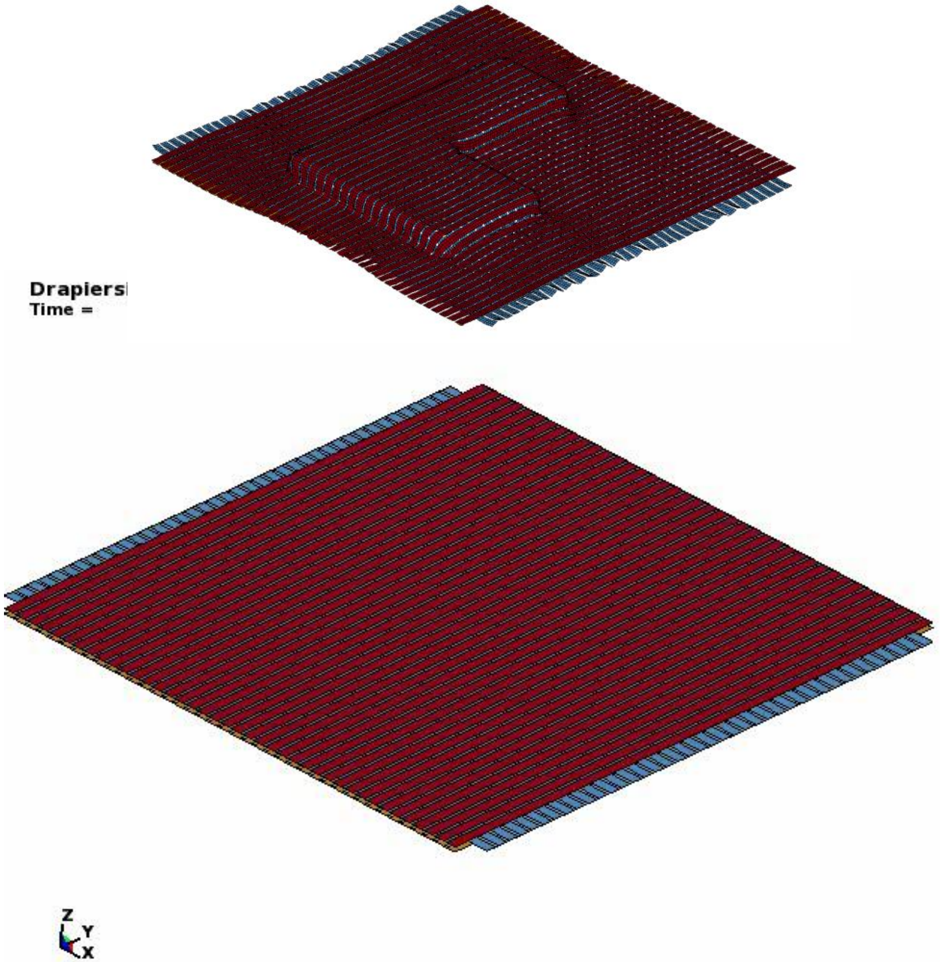
Optional matrix may be represented with shell elements and elastic/plastic material.

Draping:
stacked shell lay-up to consider anisotropy

Some fabrics (preforms) show extreme orthotropic behavior. Here modeling with shell elements using different constitutive models is possible. For stacked preforms a similar approach in finite element modeling is of course possible: Multiple layers of shell elements.

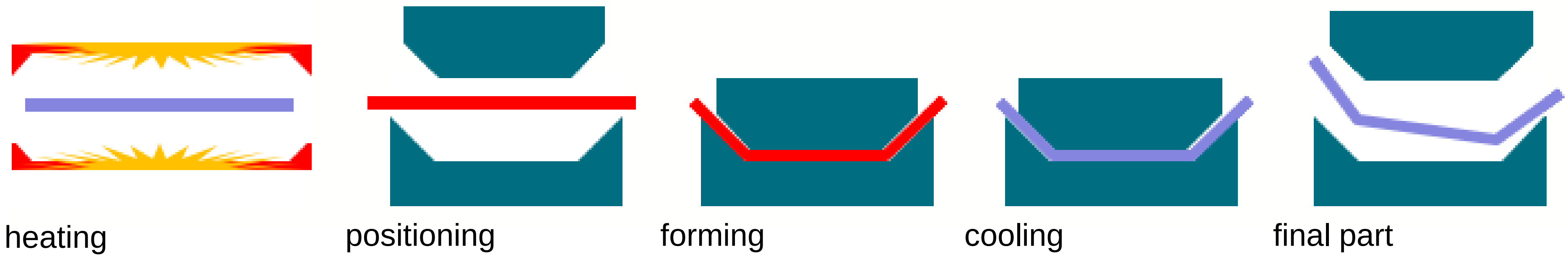


modeling technique
three layers



Thermoplastic pre-pregs – process overview

- Properties of thermoplastic matrix material
  - At high temperature, molten material behaves like a viscous fluid
  - At low temperature, material can be described as an elasto-plastic solid
- Process overview



- Process is reversible as no chemical curing occurs
- Relatively short cycle times can be realized

Thermoplastic pre-pregs – modeling aspects

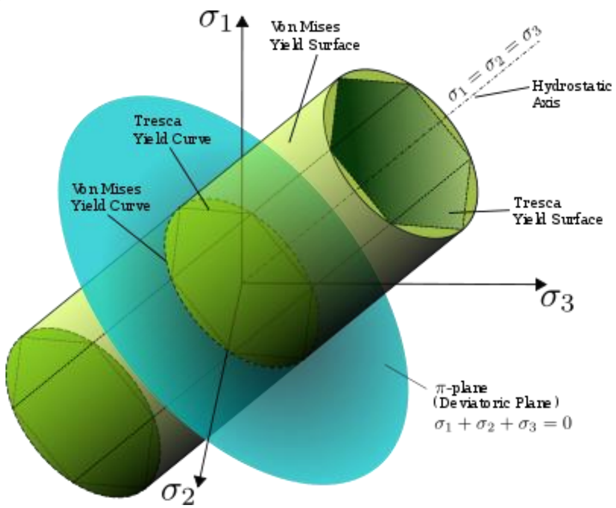
- Thermo-mechanical coupling crucial for predictive simulation study
  - Well-established feature of LS-DYNA

- Matrix
  - Temperature-depend elastic properties
  - Decreasing yield stress value for increasing temperature
  - Non-linear relation between yield stress and equivalent plastic strain

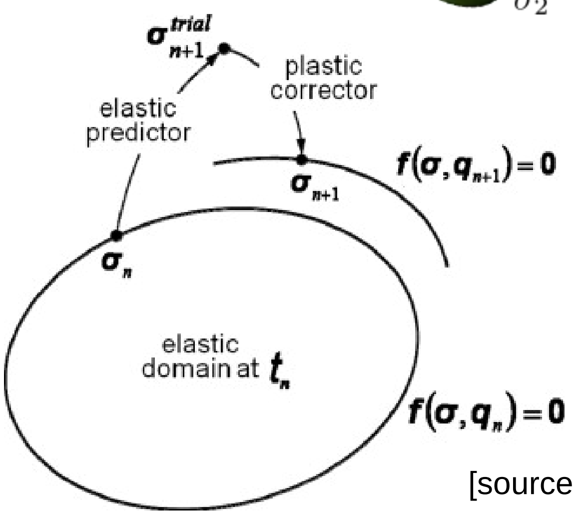
- Reinforcement
  - Strong anisotropy
  - Almost linear stress response of the fibers to elongation
  - Non-linear behavior for shear deformation

Thermoplastic pre-pregs – material formulation

- Additive split for matrix and fiber contributions
- Matrix formulation
  - Elastic properties are defined with load curves w.r.t. to temperature
  - Van-Mises yield criterion is implemented
  - Yield stress is given by load tables w.r.t.
    - Temperature
    - Equivalent plastic strain
  - Return-mapping algorithm



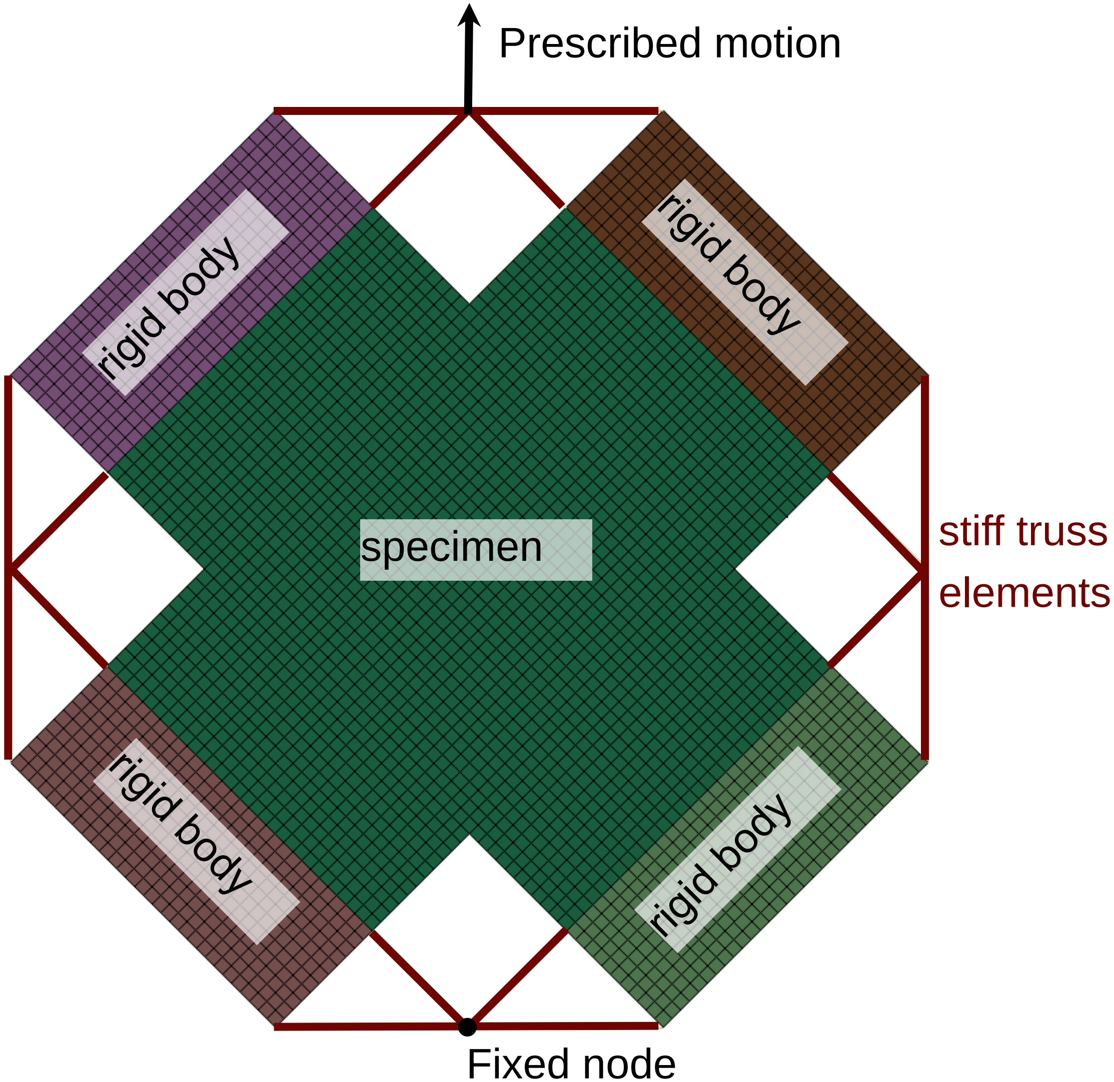
[source: www.wikipedia.de]



[source: Neto et al, 2008]

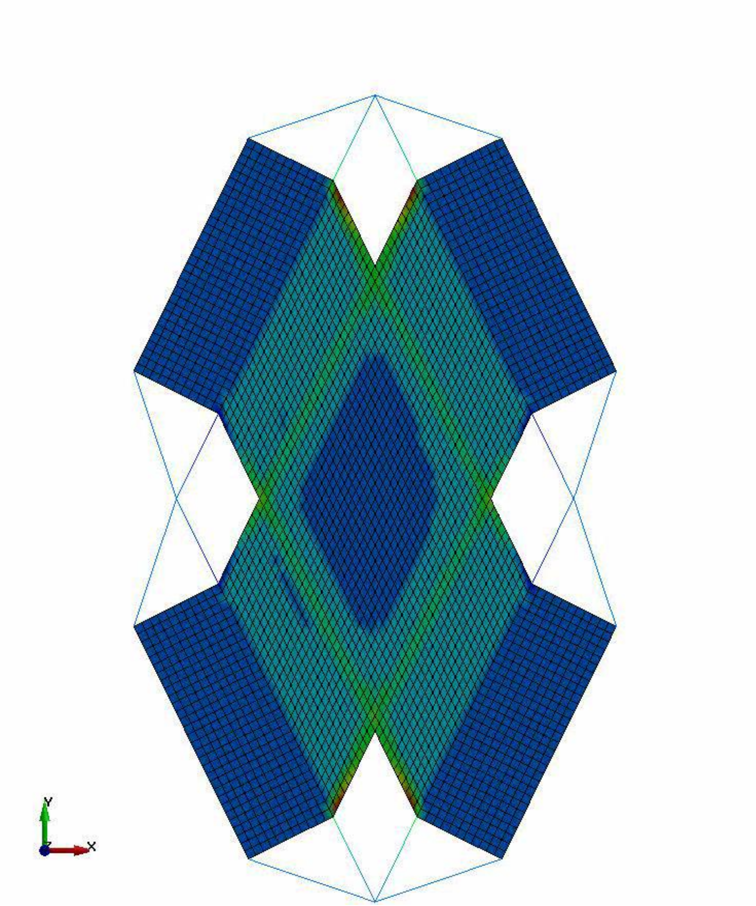
Thermoplastic pre-pregs – picture frame test

- Model:

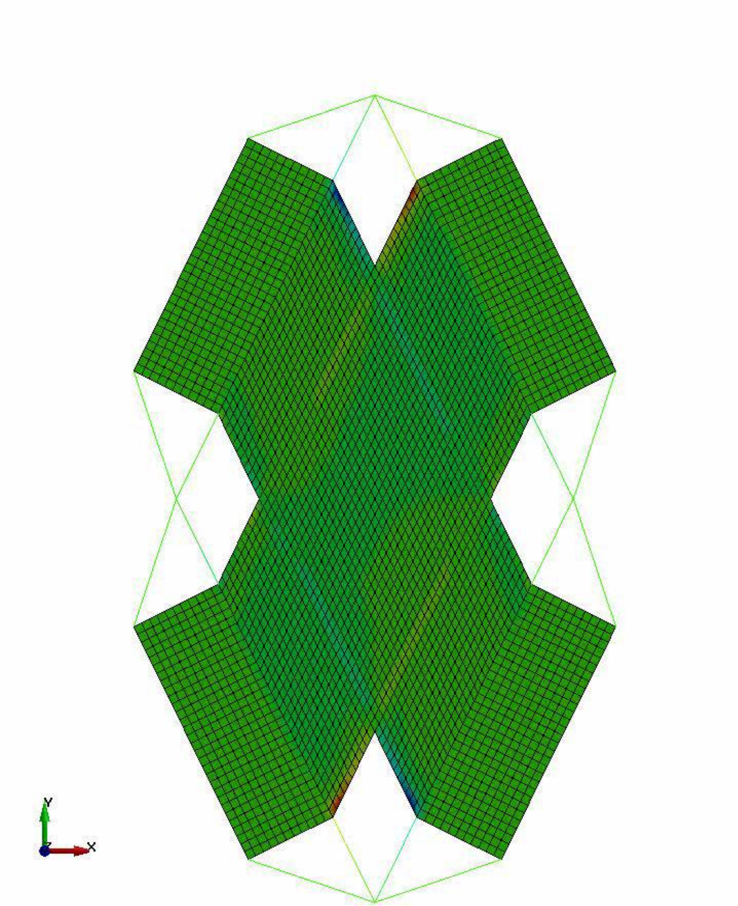


Thermoplastic pre-pregs – Validation

- Simulations allow very high shear deformations



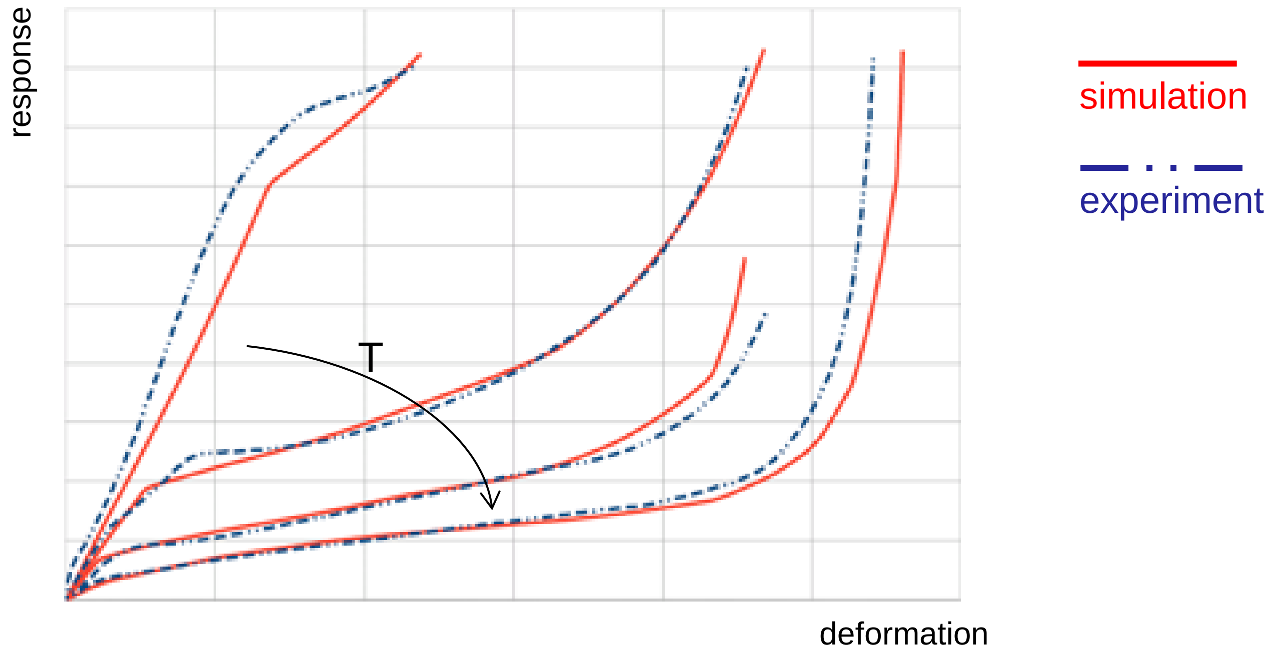
y-stress



xy-stress

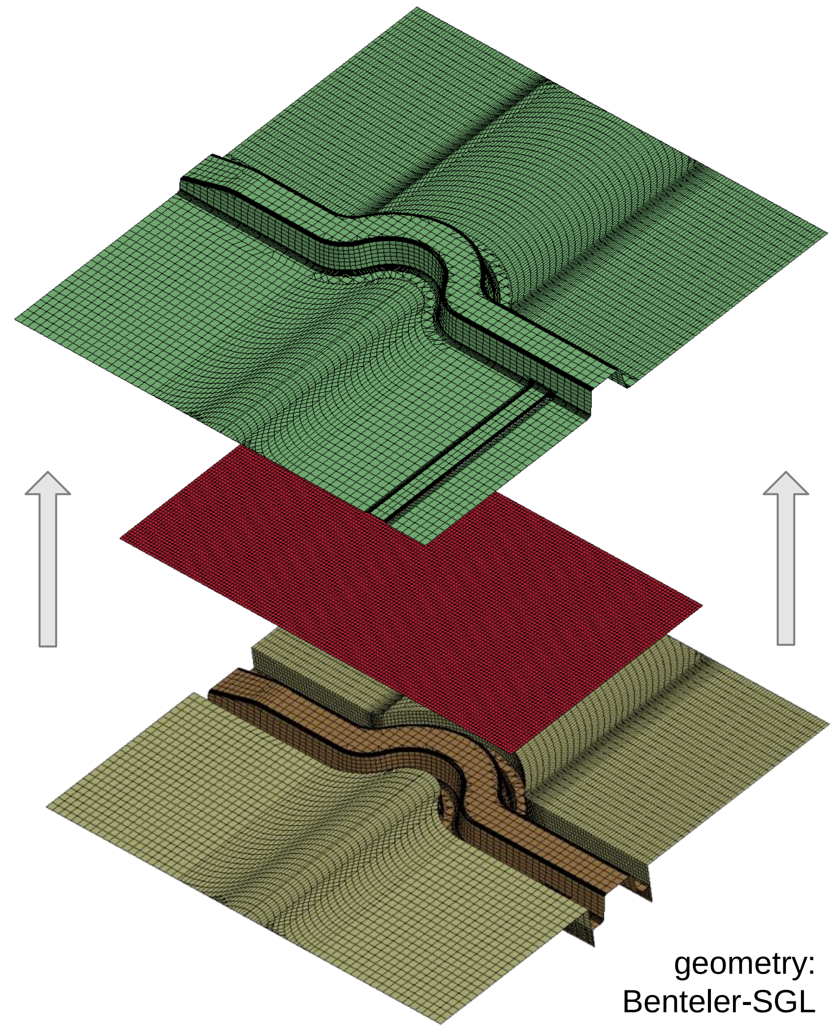
Thermoplastic pre-pregs – Validation

- Picture frame test is simulated for different temperatures
- Simulation result show good agreement with experimental data
  - Realistic non-linear shear behavior of fabric (highest temperature)
  - Effect of matrix curing with decreasing temperature is well captured



Thermoplastic pre-pregs – example

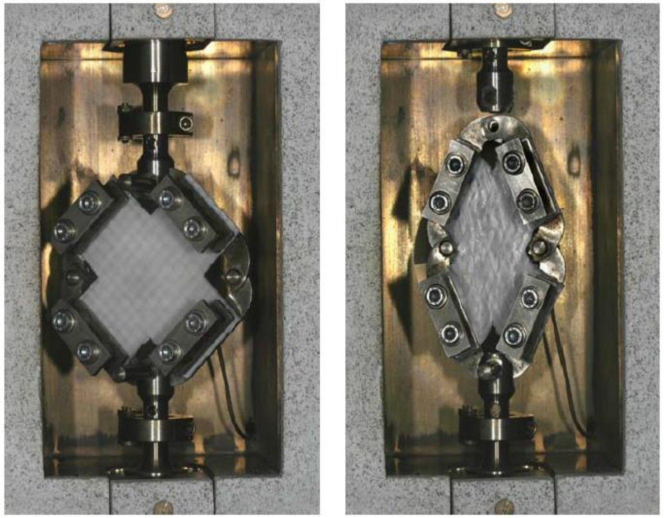
- Tool is closed within 80ms, kept closed for 3ms, and opened within 56.5ms
- Thermo-mechanical coupling between working piece and tools can be included

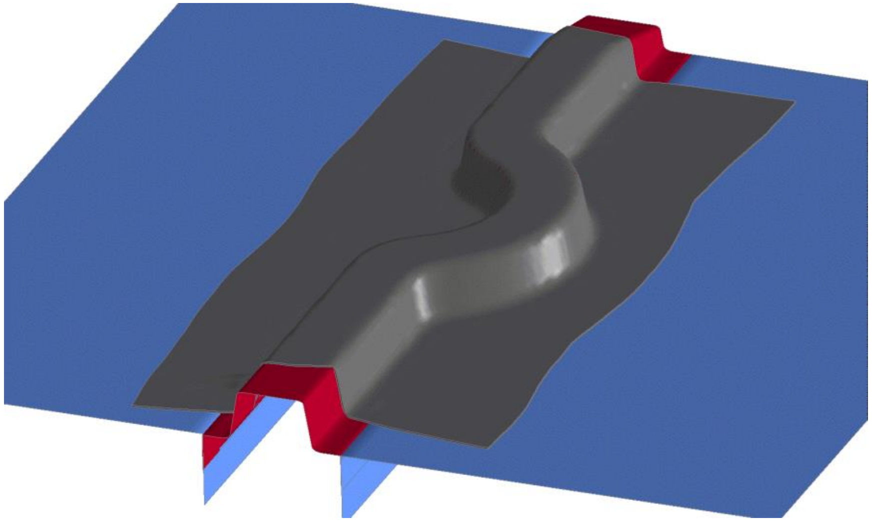


geometry:
Benteler-SGL

Thermoplastic pre-pregs – example

- Tool is closed within 80ms, kept closed for 3ms, and opened within 56.5ms
- Thermo-mechanical coupling between working piece and tools can be included
- Material parameters for matrix and textile from picture frame test
- 2 fiber families
  - ±45°
  - Woven structure





Braiding

- A **braid** (also referred to as a **plait**) is a complex structure or pattern formed by intertwining three or more strands of flexible material

- Due to its high complexity, the braiding process requires a little more effort than the already presented processing steps within Finite Element simulations

- Usually, beam elements are used to simulate the braiding process

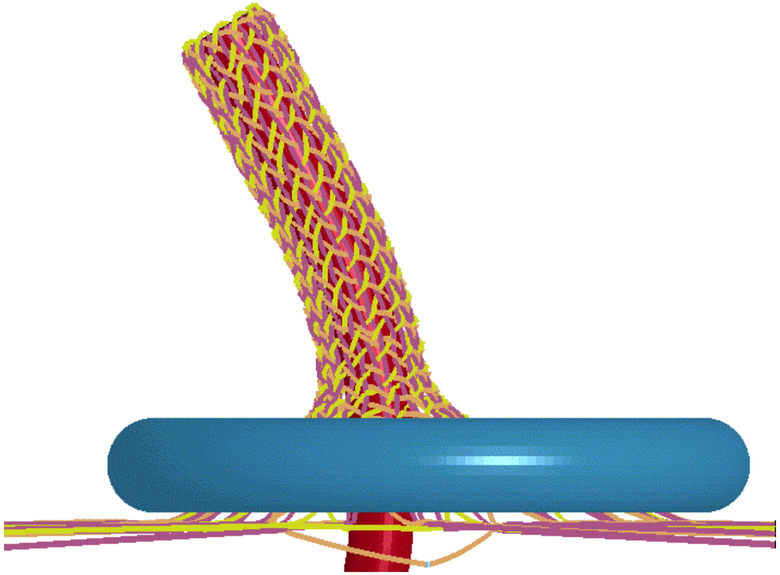
- The usage of shell elements is also conceivable but even more complex and time consuming

Braiding simulation approaches

- `*ELEMENT_BEAM`
- 25236 beam elements, 52 discrete elements
- 96 rovings
- mppR6.1.2 – s - Rev. 85139
- 325 h, 36 min, 29 sec on 16 processors
- ~10.250.000 cycles
- dt = 2.75E-05
- problem time: 300 ms

- Intel(R) Xeon(R) CPU X5570 @ 2.93GHz

- 0.64% element processing
- 92.85% contact processing



*ELEMENT_BEAM_SOURCE

	1	2	3	4	5	6	7	8
Card 1	BSID	BSNID	BSEID	BSNELE	LFED	FPULL	LMIN	

BSID: Beam source ID

BSNID: Beam source node ID – different from the node to which the new element will be connected to

BSEID: Beam source element ID – all new generated beam elements will be connected to this element

BSNELE: number of elements that can be generated

LFED: max. length of elements after pull-out.

FPULL: initialforce

LMIN: min. length at pull out

Main advantage:
- simple pre-processing
- no discrete elements needed → higher accuracy for full component simulation
- a little less calculation time

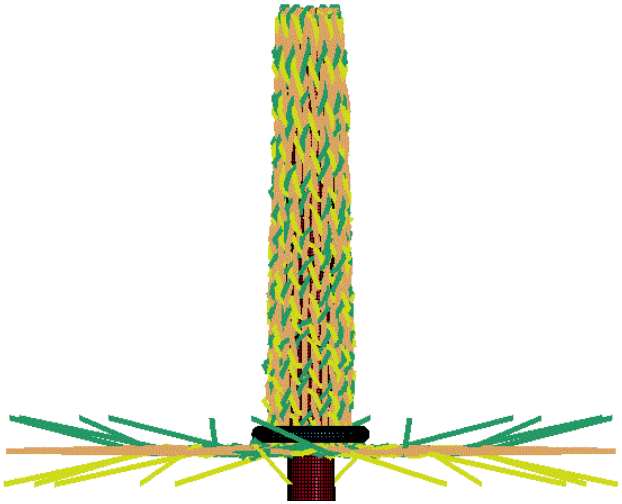
So far, this works for:
- ETYP 3 (truss) & *MAT_ELASTIC
- ETYP 6 (discrete beam/cable) & *MAT_CABLE_DISCRETE_BEAM

Braiding simulation approaches

- `*ELEMENT_BEAM_SOURCE`
- 1800 beam elements at the beginning, 100 elements can be generated for each roving à 2 mm.
- 48 rovings
- mpp – s – dev - 89714
- 13 h, 46 min, 55 sec on 16 processors
- ~4.630.000 cycles
- dt = 6.48E-05
- problem time: 300 ms

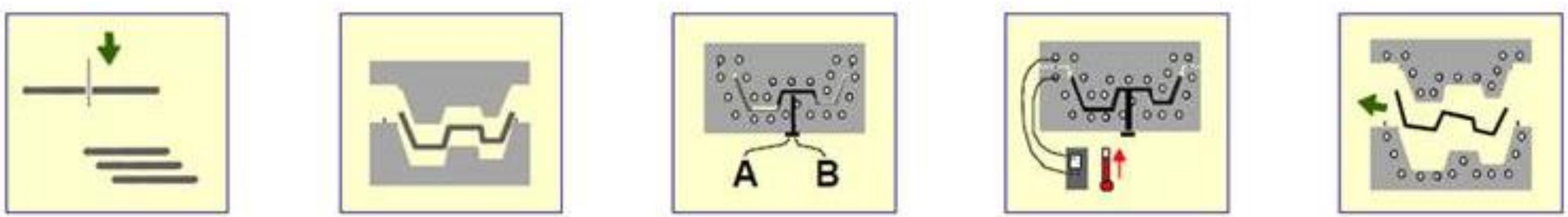
- Intel(R) Xeon(R) CPU E5-2670 0 @ 2.60GHz

- 0.59% element processing
- 72.97% contact processing



Resin transfer moulding (RTM)

- In general, thermosets (e.g. epoxy) have superior mechanical properties as compared to thermoplastics
- All manufacturing processes involve a chemical curing of a liquid resin
  - Curing is induced by high temperatures and chemical additives
  - Chemical reactions of curing are nonreversible
- Process overview

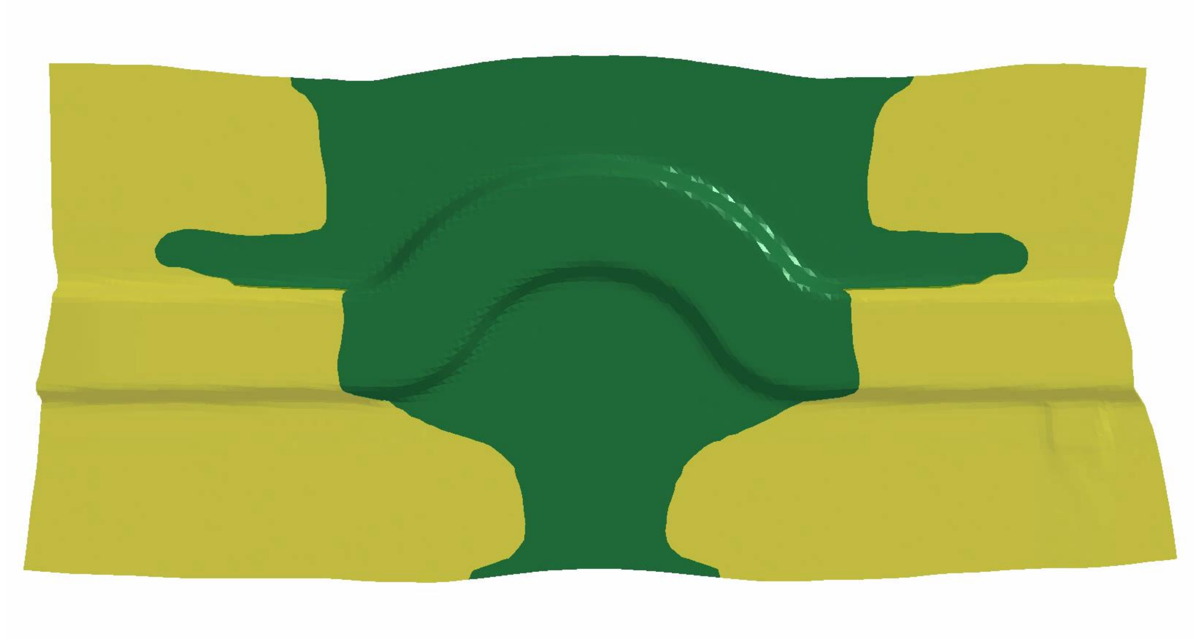


preparation of textile | draping | infiltration | curing | final part

[source: Benteler-SGL]

Resin transfer moulding (RTM)

- Preliminary simulation with isotropic porosity
- Mesh obtained from draping simulation
- Flow induced by pressure inlet
- One injection point for resin
  is considered (blue)



*ALE_ELEMENT_POROSITY

```
*ALE_ELEMENT_POROSITY
$#------1|---------2|---------3|---------4|---------5|---------6|
$#      ieb        iee     ilocal        vid1       vid2
$#      a11        a12        a13         b11        b12        b13
$#      a21        a22        a23         b21        b22        b23
$#      a31        a32        a33         b31        b32        b33
```

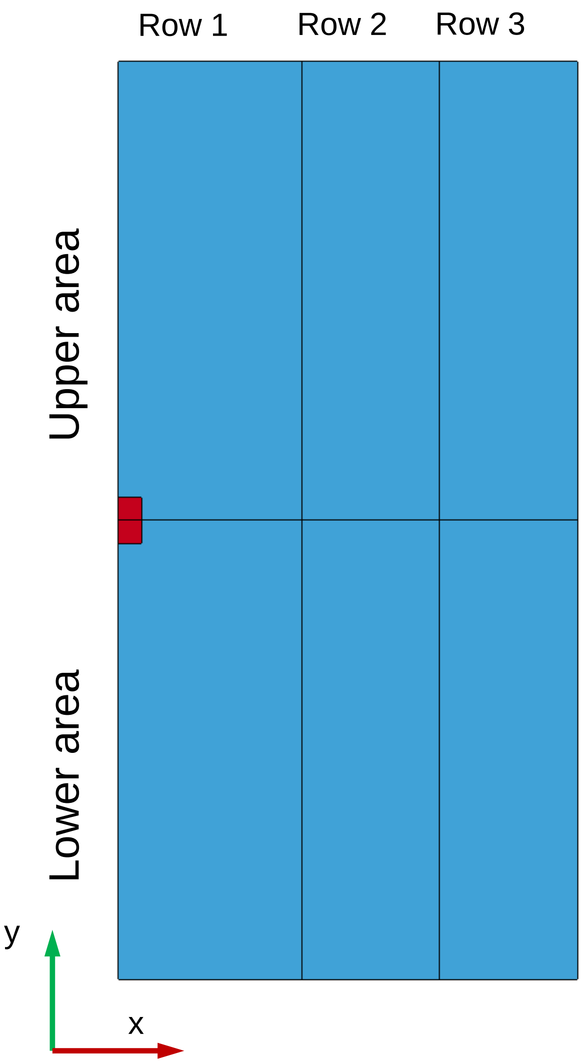
- ieb — element ID start
- iee — element ID end
- ilocal = 0/1 — use element coordinate system or not
- vid1, vid2 — vectors defining local coordinate system
- a_ij, b_ij — A, B matrix

*ALE_ELEMENT_POROSITY - examples

- Plate separated into 6 zones
- Four cases tested:

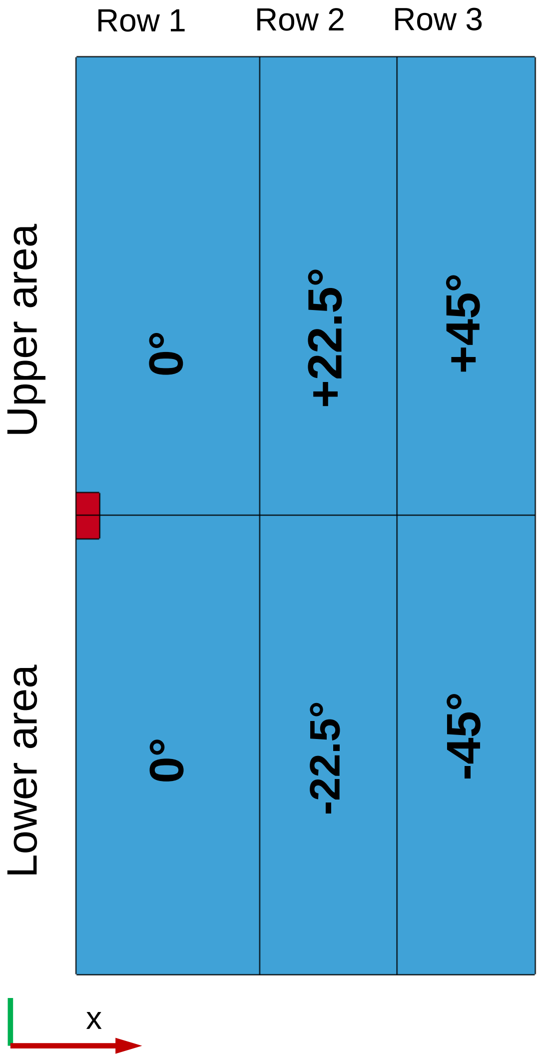
  1. full orthotropical permeability
  2. higher permeability in x-direction
  3. +/- 45°
  4. 0°, +/- 22.5°, +/-45°

- Slightly non-symmetric results for the last three cases due to lower permeabilities in the upper areas.



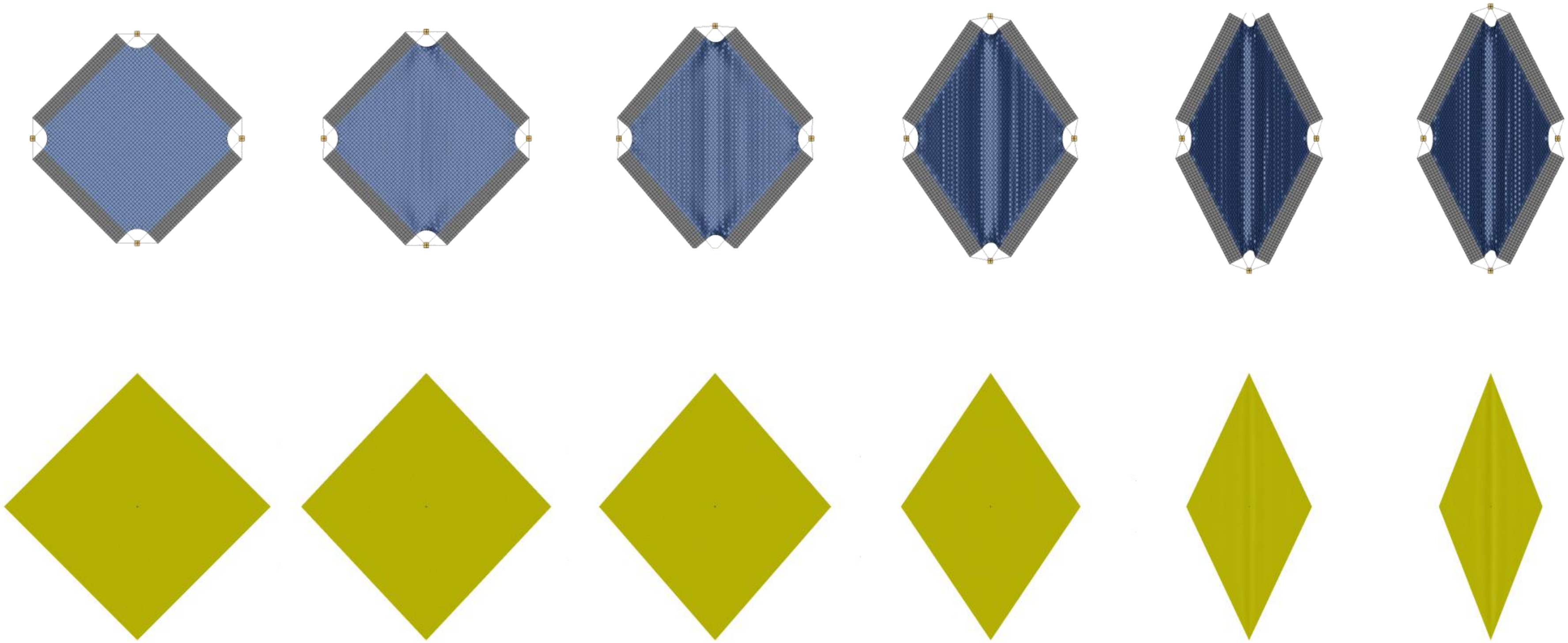
*ALE_ELEMENT_POROSITY - examples

4. 0°, +/- 22.5°, +/-45°



Resin Transfer Molding (SwimRTM)

- Use results gained from picture frame tests to gain information about the behavior of the resin infusion



Wet moulding

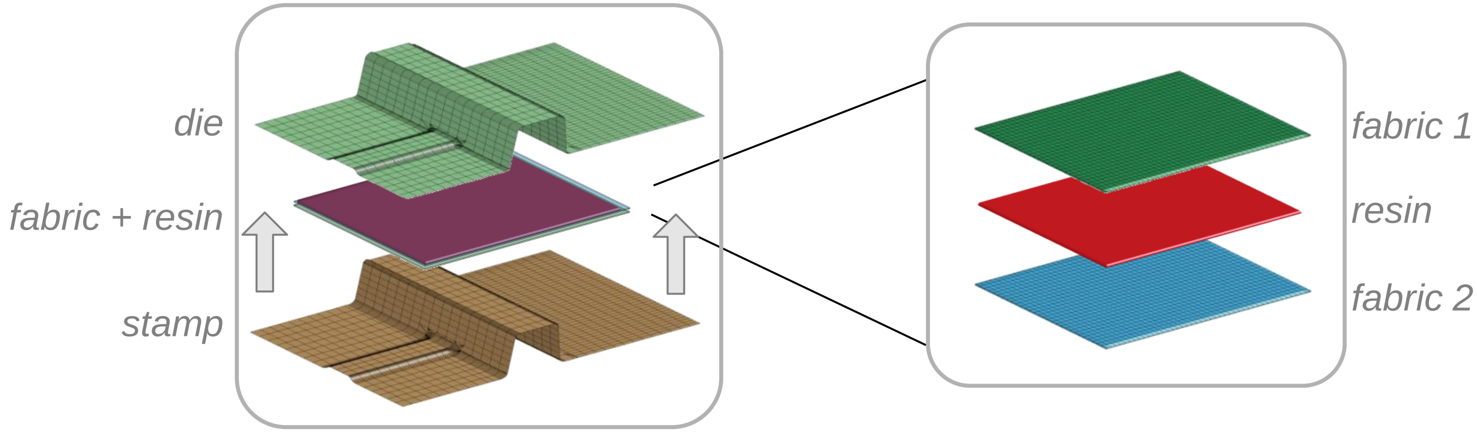
- Basically, a simulation requires the same numerical tools as RTM
- Draping and injection are done in one single step
- Simulation more complex
  - Fluid-structure interaction plays an important role
  - Fluid domain, viscosity, and porosity change during the simulation
- Process overview

preparation of textile | impregnating | forming | curing | final part

[source: Benteler-SGL]

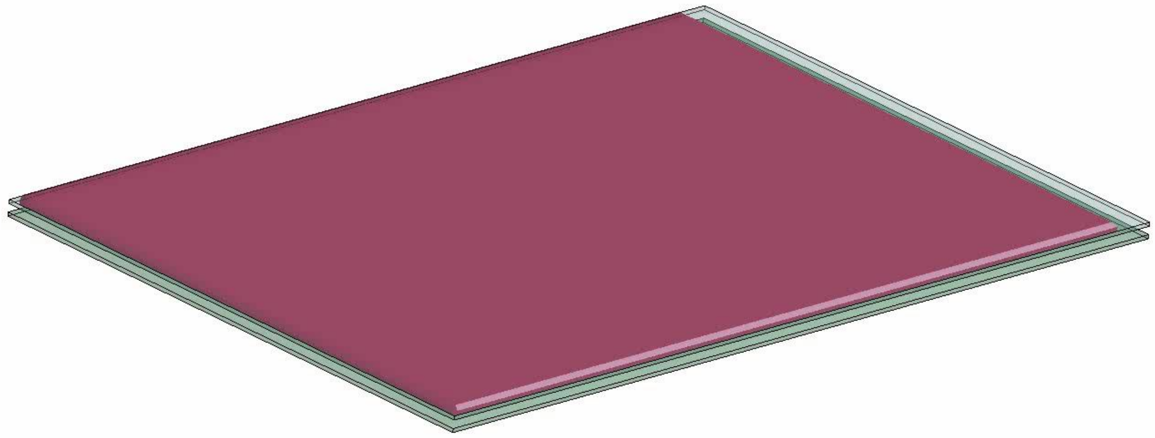
Wet moulding

- Constant isotropic porosities assumed
- Cartesian background fluid grid (not shown)



Wet moulding

- Constant isotropic porosities assumed
- Cartesian background fluid grid (not shown)

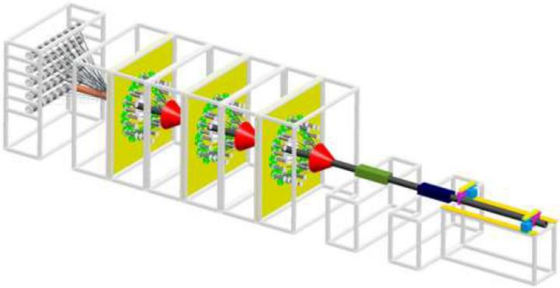


Process chain – example (Tpult)

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

- Why run braiding simulations?
  - Predict the roving layup prior the actual braiding process
  - Get information about the influence of roving pre-tensioning and friction btw. the rovings and the core/braiding rings



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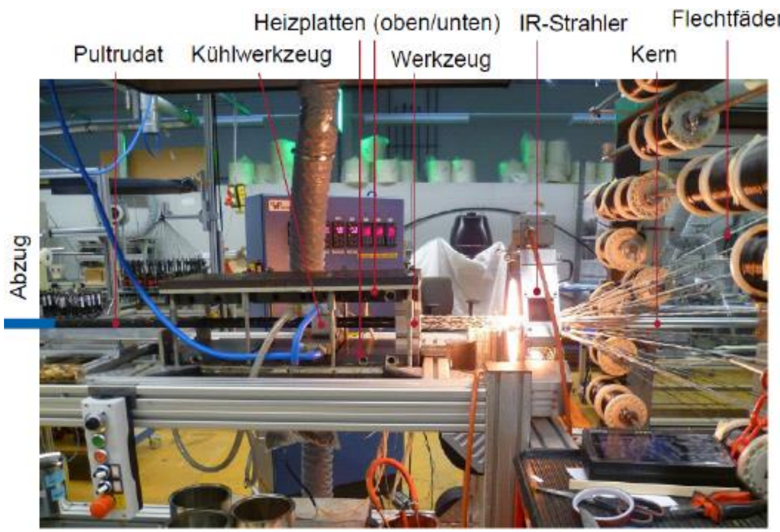
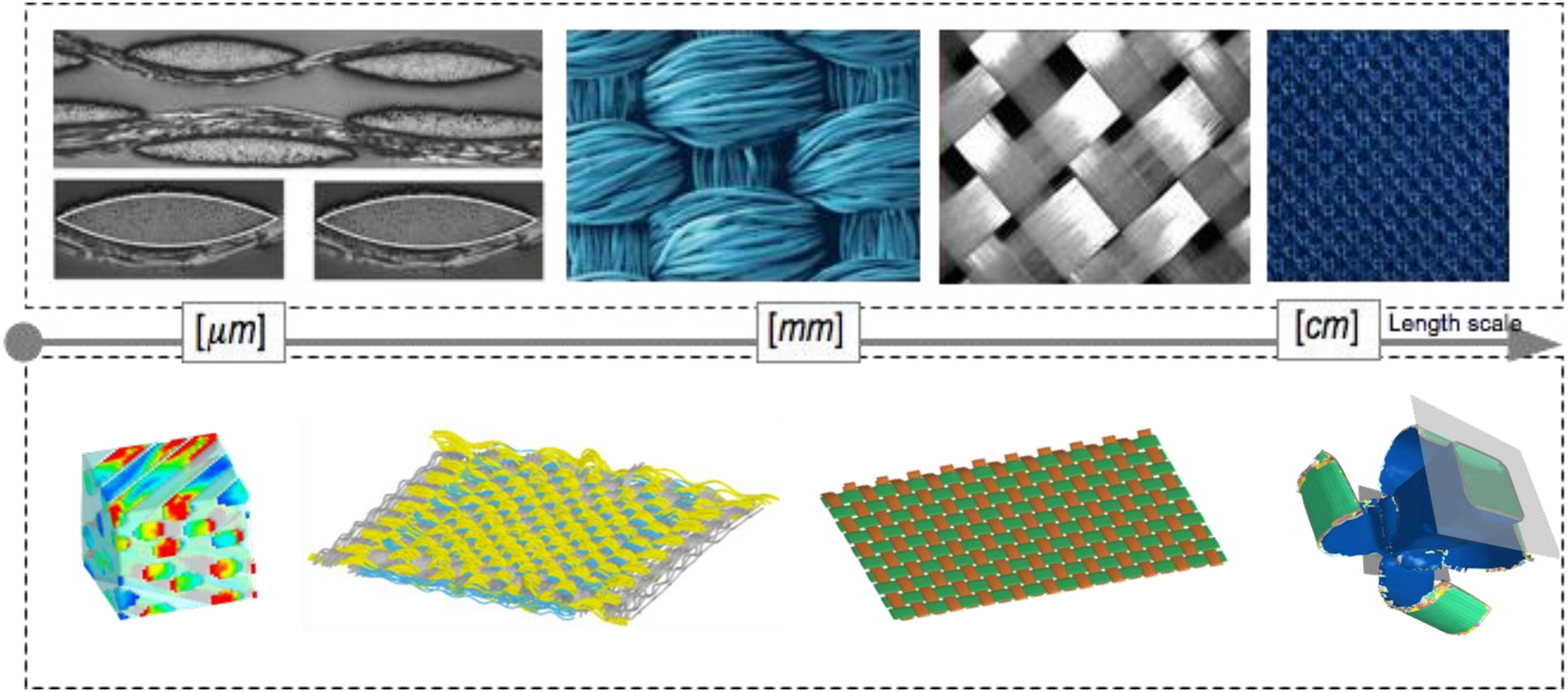
DYNA MORE

- Government funded research-project Tpult:
  - Braiding on one core with four braiding machines in a row with rovings using a thermoplastic resin
  - Re-heating of the resin for further forming steps



Modeling aspects

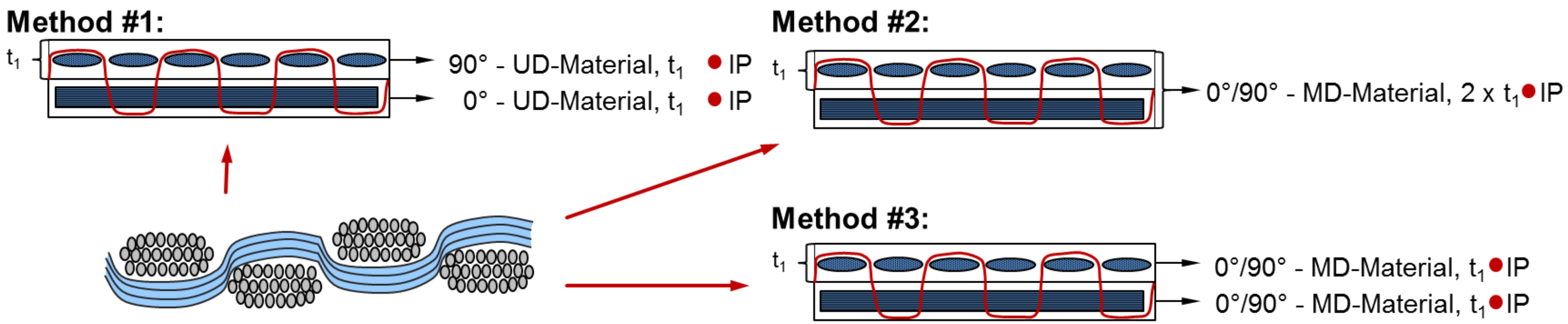


- For applications in mind we have to deal with complex simulations
  - Homogenized macroscopic approach is preferable
  - History variables have to be transferred properly
  - Sheets should be discretized with shell elements (~ 3 – 5 mm)

Modeling aspects

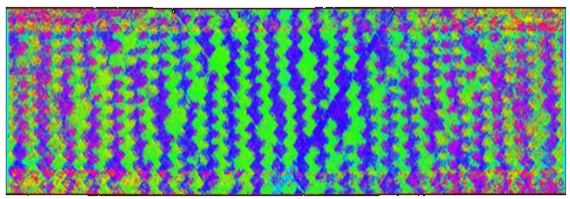
- Different approaches to model the different materials (e.g. woven & non-crimp fabric)

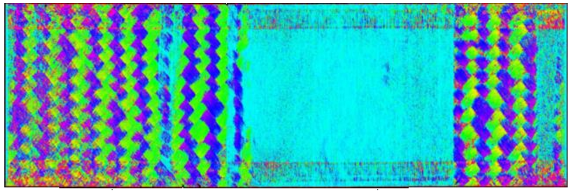
- Material parameters can be smeared over several layers or can be considered seperately

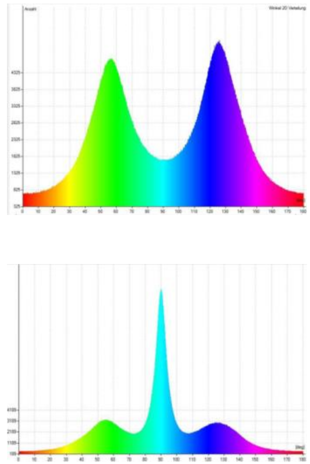


Mapping of CT-data

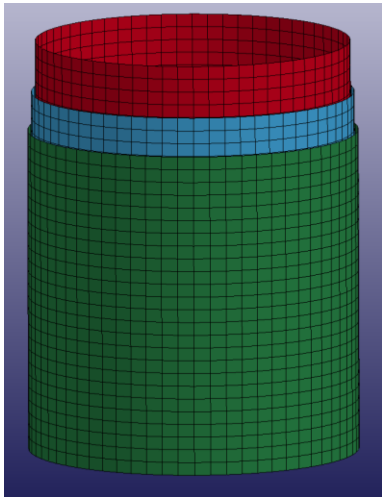
- Consider fiber orientations gained from CT-scans





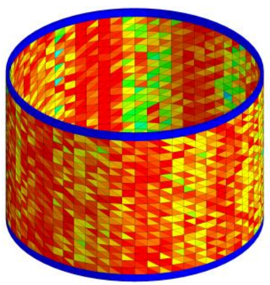


Orientation distribution

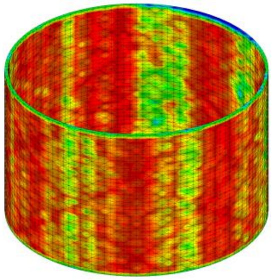


- Qualitiy of the results is mesh size dependent

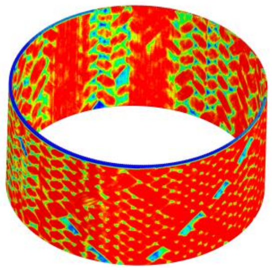
Coarse Mesh

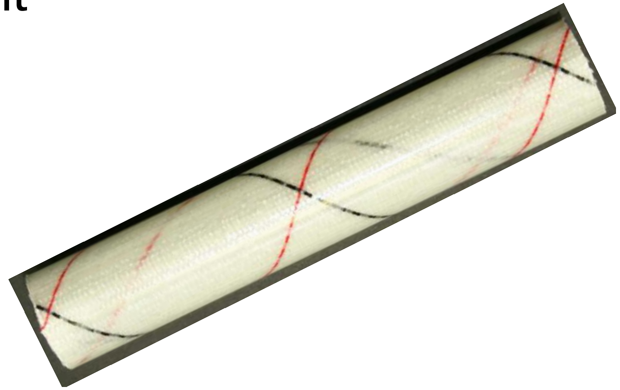


Mean Mesh



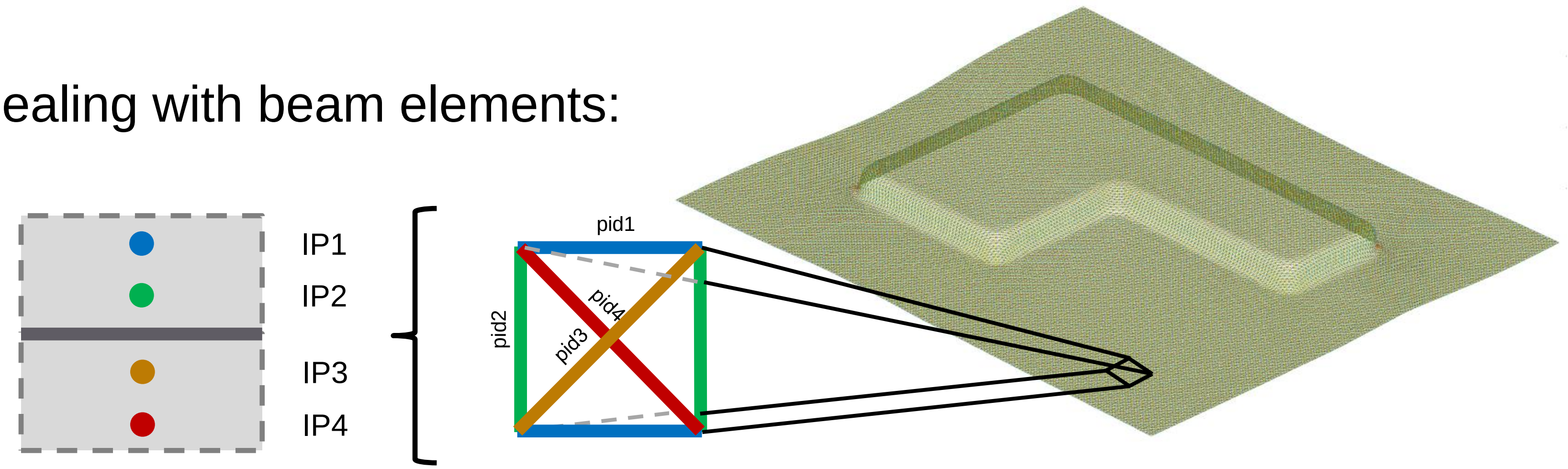
Fine Mesh



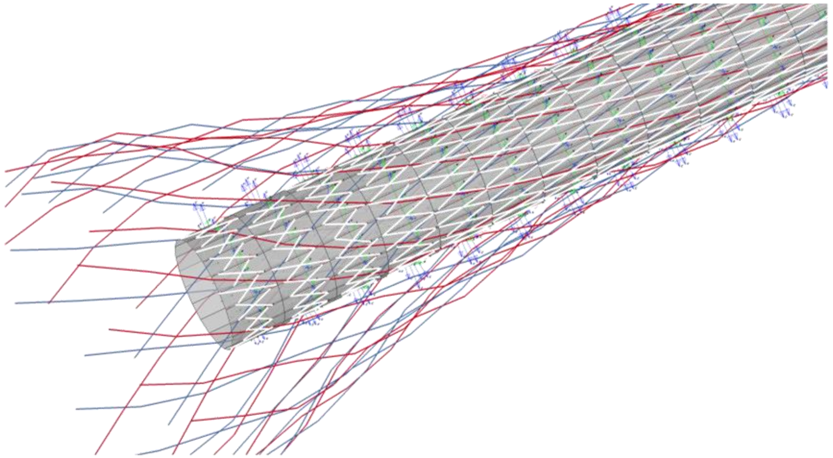


Mapping example

- Dealing with beam elements:

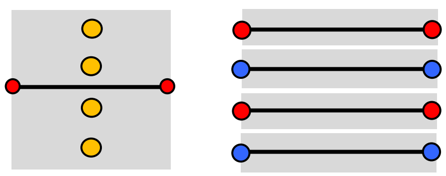


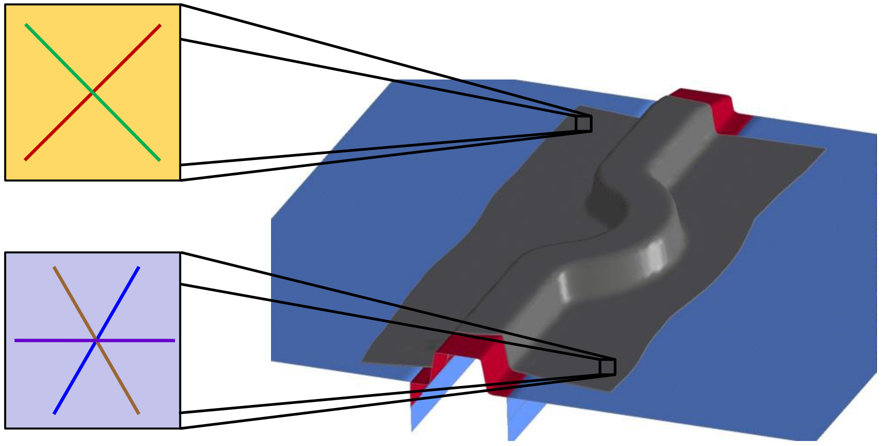
- Mapping can be performed in different ways
  - One direction for each integration point
  - Usage of a multi-directional material



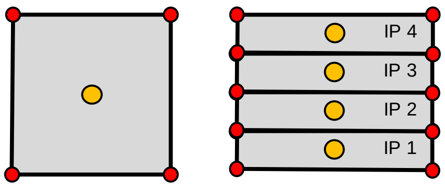
Mapping example

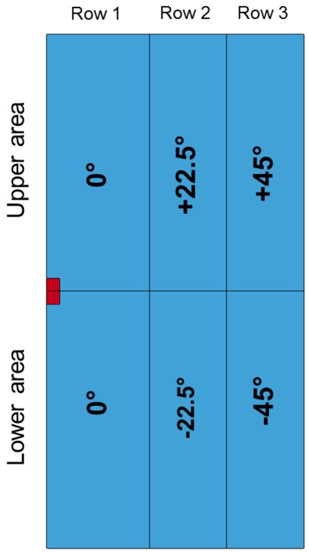
- Draping simulations are usually performed using (stacked) shell elements.





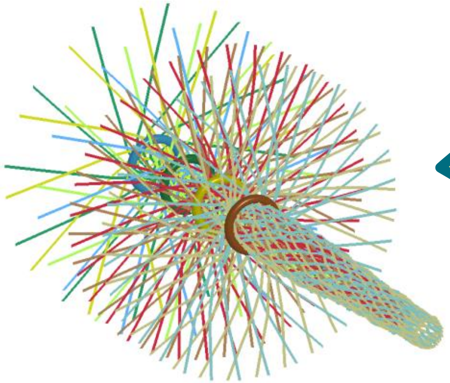
- For further infiltration with ALE, results have to be mapped on (stacked) solild elements using a porosity tensor.



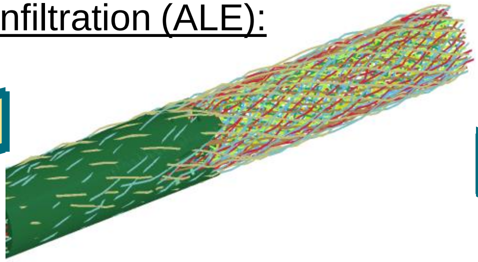


Process chain

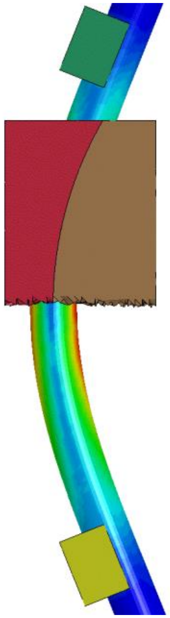
Braiding:



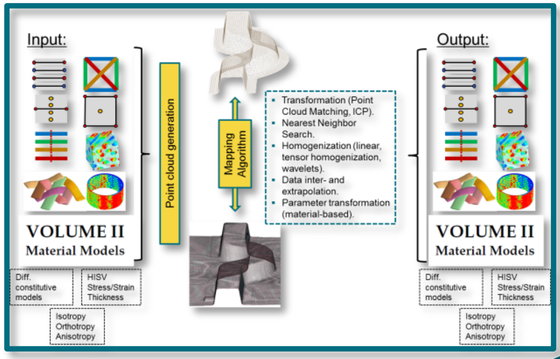
Infiltration (ALE):



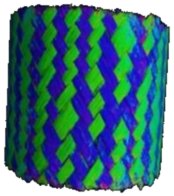
Forming (MAT_249):

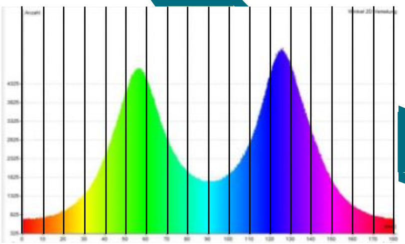


Mapping:



Experimental validation:





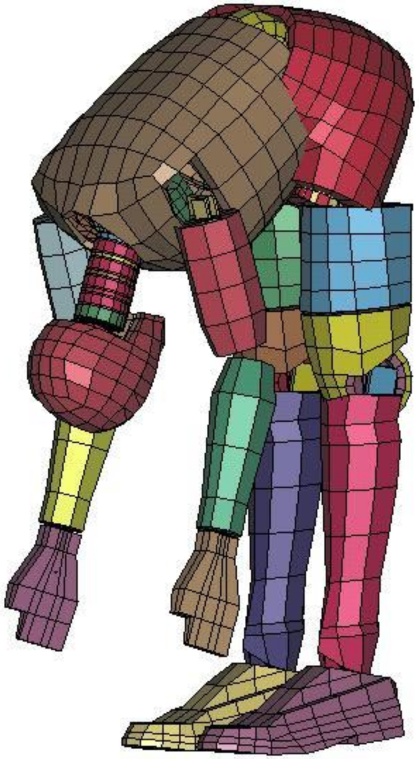
Conclusion and Outlook

- There are quite a few ways to consider the several steps along the process chain for continuous fiber reinforced plastics with LS-DYNA.

- Further enhancements might be made towards
  - Strain-rate dependency for thermoplastic pre-preq forming.
  - Mapping of CT-Scan results
  - Mapping for short fiber reinforced plastics
  - Enhancements of history-variable transformation for all different kinds of element types and discretization schemes

- Evaluation of the introduced simulations is done within several BMBF-funded research projects (T-Pult, SWIM-RTM, ARENA2036,…)

Thank you for your attention!



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