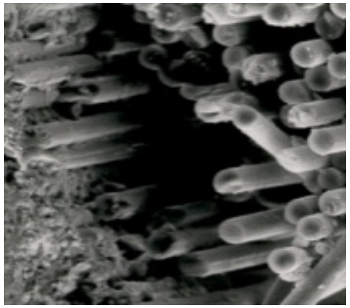

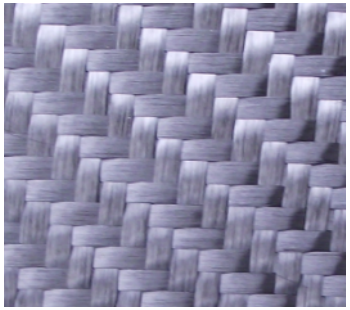

New Developments to Capture the Manufacturing Process of Composite Structures in LS-DYNA

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DYNAmore GmbH

LS-DYNA Developer Forum
Filderstadt, 24.09.2013

Composites

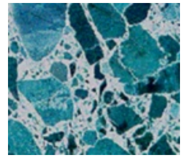
- A composite is a combination of two or more materials, differing in form or composition on a macroscale. The constituents do not dissolve or merge completely into one another, but can be physically identified and exhibit an interface.

- Historical facts
  - straw was used by Israelites to strengthen mud bricks
  - plywood was used by the ancient Egyptians

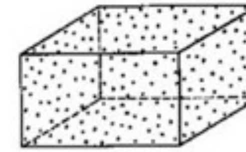
- Today, carbon/glass fibers reinforced polymers gain in importance as lightweight structures for automotive and aerospace industries
  - Increasingly demanding regulations for carbon dioxide emission
  - These materials allow for the manufacturing of geometrically and functionally more complex parts than most standard materials

Classification based on reinforcing material structure

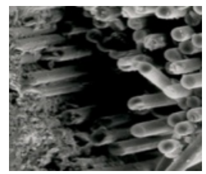
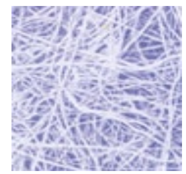
- particulate composite materials:




Concrete
(cement/stone/steel)

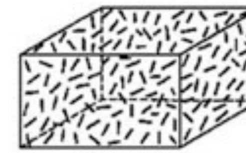


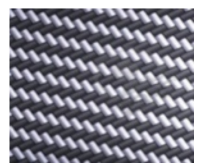
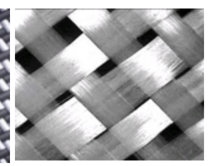
- fibrous composite materials:

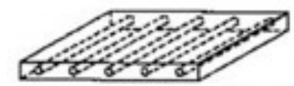
Short fiber
reinforced polymers
(glass/PP)

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

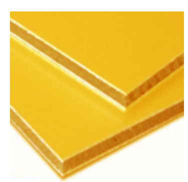
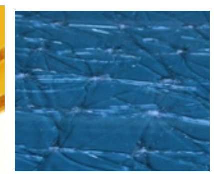


Continuous fiber
reinforced polymers
(glass/carbon/PA/PP/EP)



- laminated composite materials:

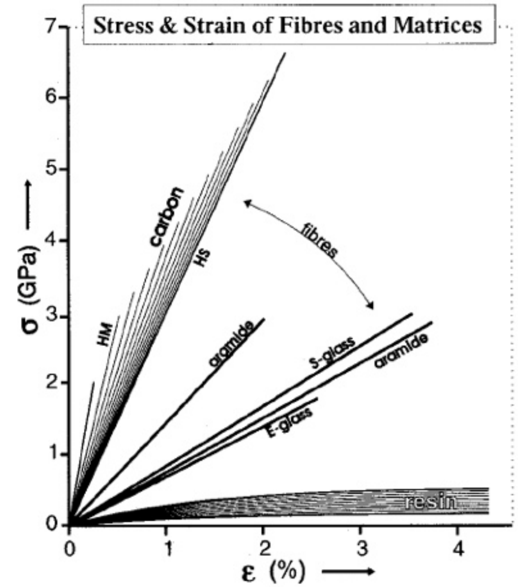



Sandwich/Laminates
(alloy/polymer/glass/PVB)

- combinations of the above types

Properties of continuous fiber reinforces plastics (FRP)

- Fibers show higher strength and stiffness than material in bulk form
  - Fewer internal defects
  - Aligned crystalline structure
- Strongly anisotropic tensile response
  - Typical stiffness ratio: 20:1 – 100:1
  - Fibers linear elastic, matrix non-linear
- Non-linear shear response



➡	The fiber orientation is the most important characteristic for structural stiffness and load bearing capacity

➡	A thorough understanding of the manufacturing process is extremely important

Agenda

- Process simulation for thermoplastic pre-pregs
  - Introduction
  - Material formulation
  - Examples

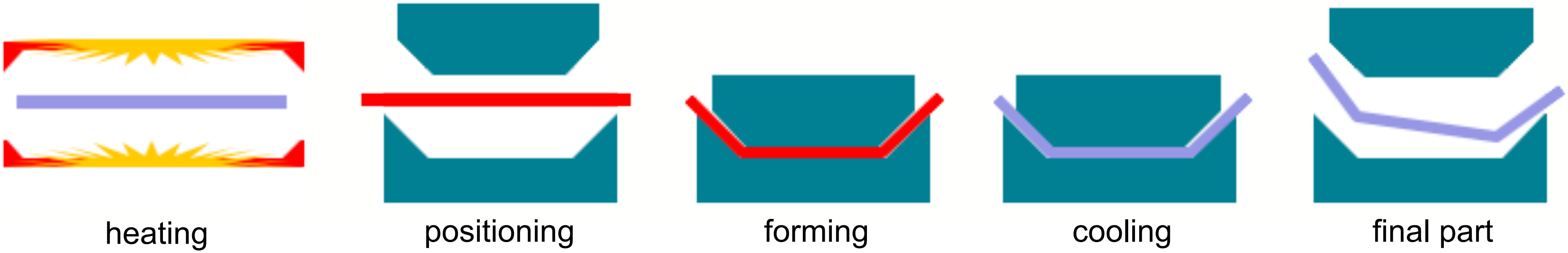
- Process simulation thermoset matrix materials
  - RTM process
  - Wet molding

- Summary

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 elastio-plastic solid

- Process overview



- Process is reversible as no chemical curing occurs

- Relatively short cycle times can be realized

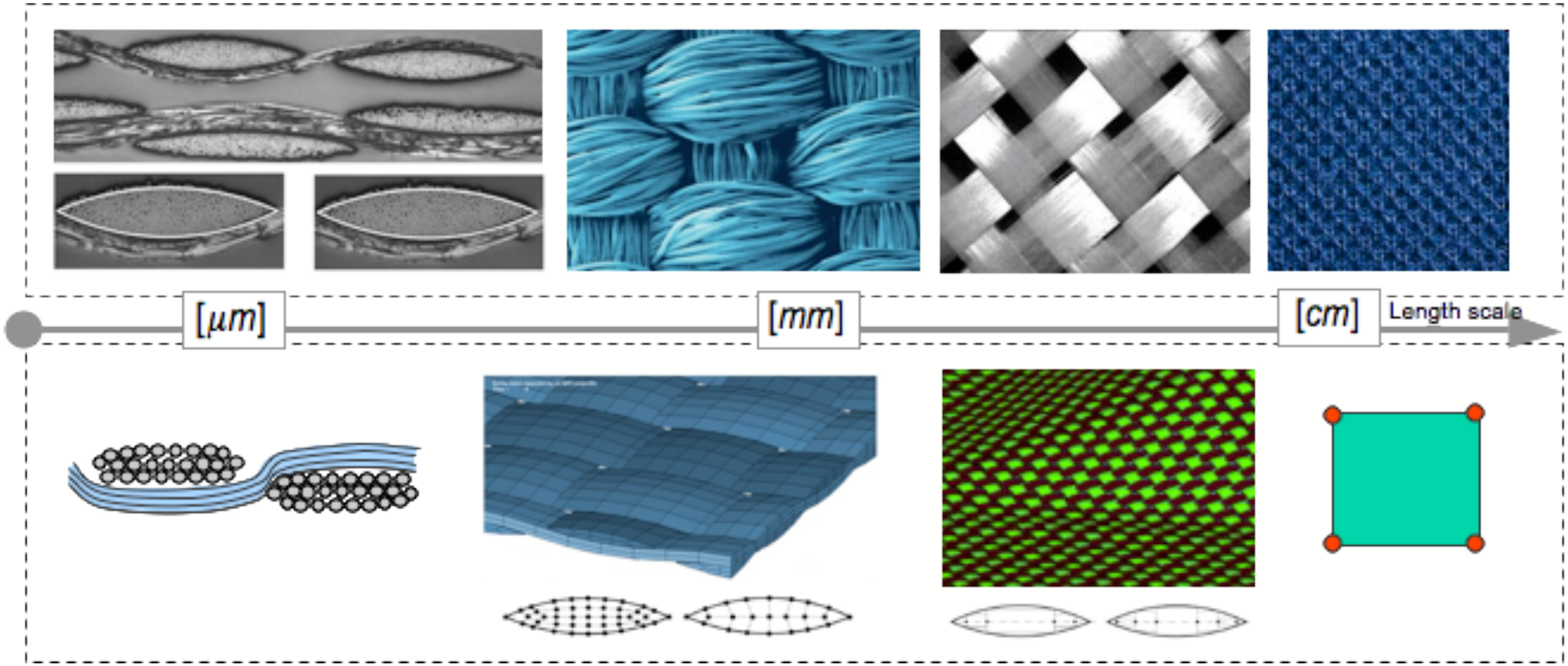
Thermoplastic pre-pregs – modeling aspects

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

- Matrix
  - Temperature-dependent 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 – modeling aspects



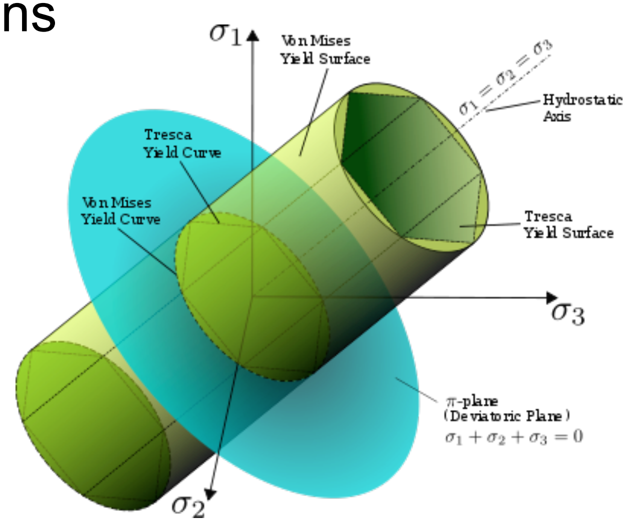
- For applications in mind we have to deal with complex simulations
  - Homogenized macroscopic approach is preferable
  - Matrix and fibers should both be accounted for by constitutive model
  - Sheets should be discretized with shell elements

Thermoplastic pre-pregs – material formulation

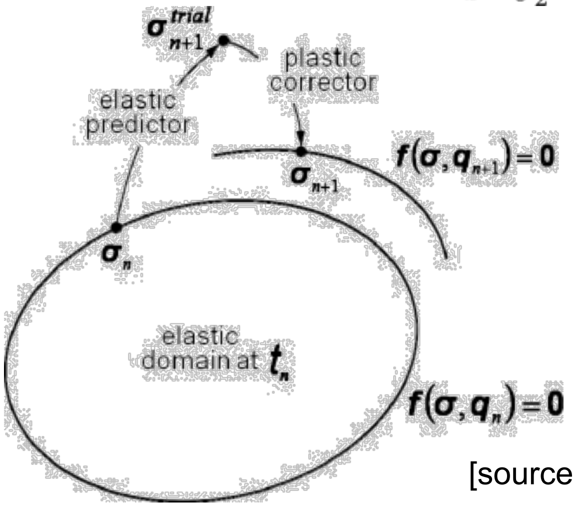
- Additive split for matrix and fiber contributions

- 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



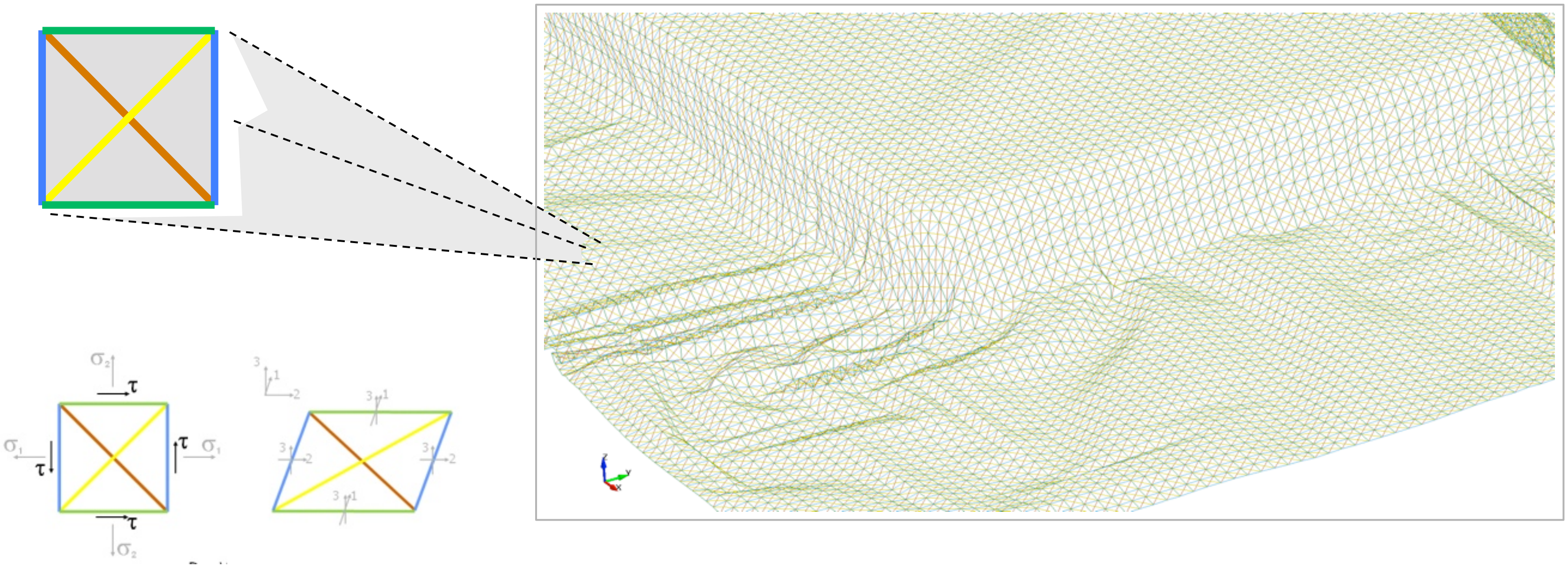
[source: www.wikipedia.de]



[source: Neto et al, 2008]

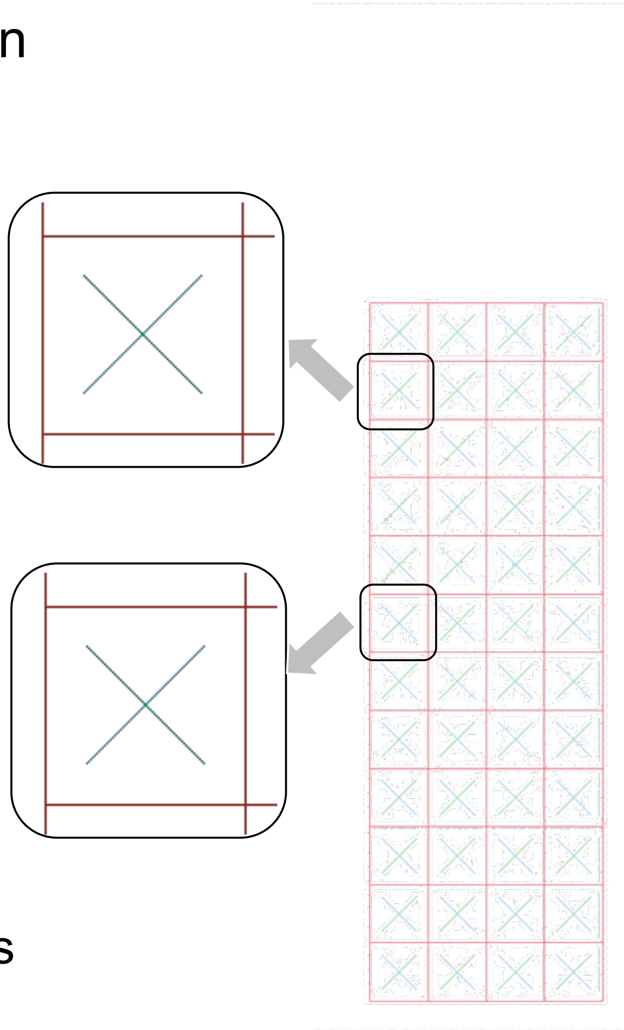
Thermoplastic pre-pregs – fiber contribution

- Motivation:
  - Woven fabric can be simulated using beam elements
  - Different element formulations for warp/weft direction and diagonals
  - Non-trivial parameter identification and validation
  - High modeling complexity



Thermoplastic pre-pregs – fiber contribution

- Anisotropic and hyperelastic material definition
- Discretization with shell elements, where the fiber families are represented by vectors stored at the integration points
  - Its initial orientation $\vec{m}_i^0$ is an input parameter
  - current configuration is given as $\vec{m}_i = \underline{F}\vec{m}_i^0$
- Behavior under compression / tension
  - Elongation can easily be computed using the current length λ_i of vector $\vec{m}_i$
  - Load curve defines stresses for given λ_i
- Shear response
  - Based on the angle between neighboring fibers
  - Load curve defines stresses for given angle



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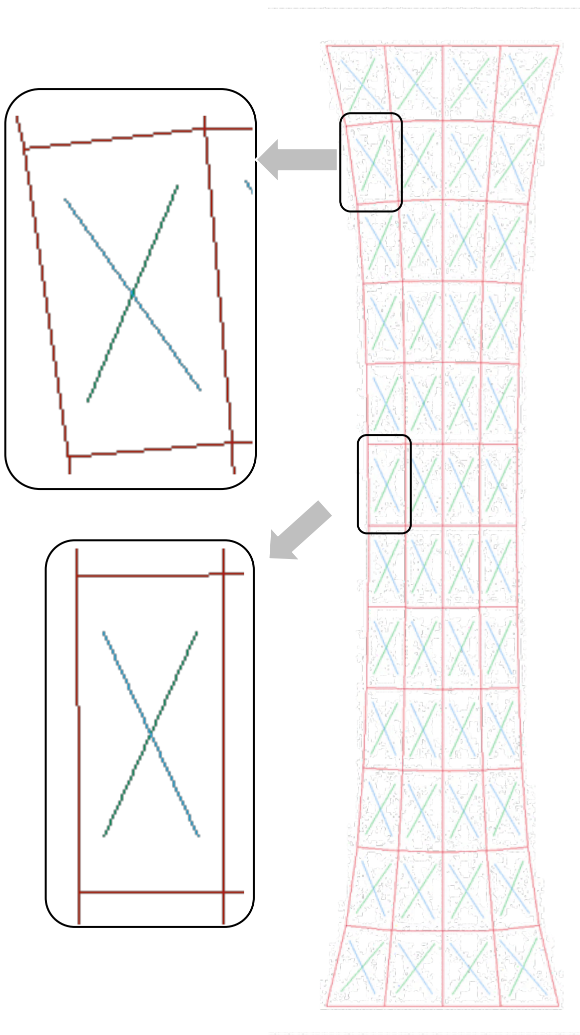
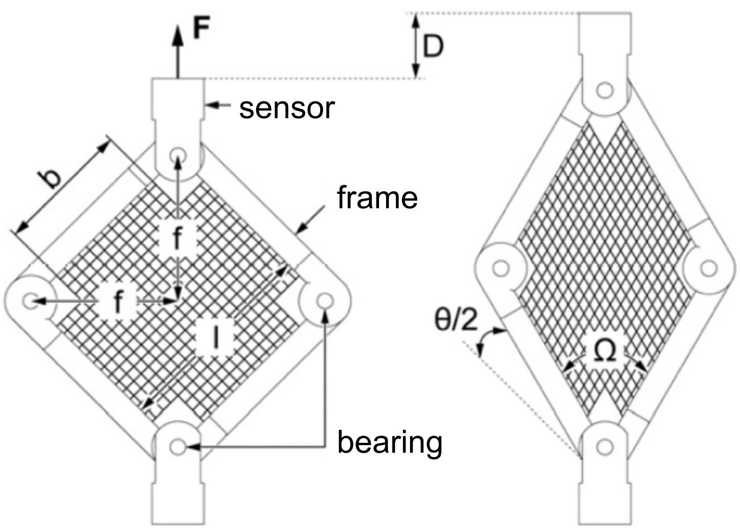
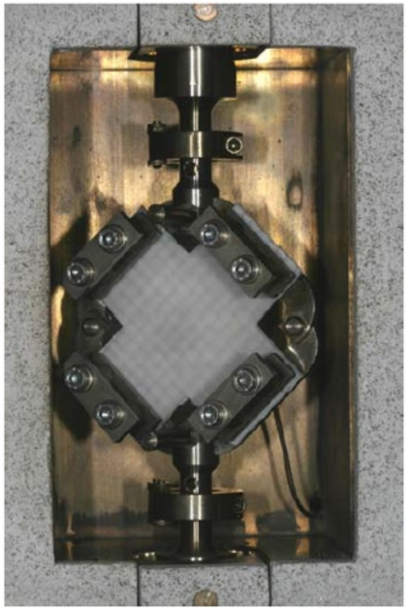


Thermoplastic pre-pregs – picture frame test

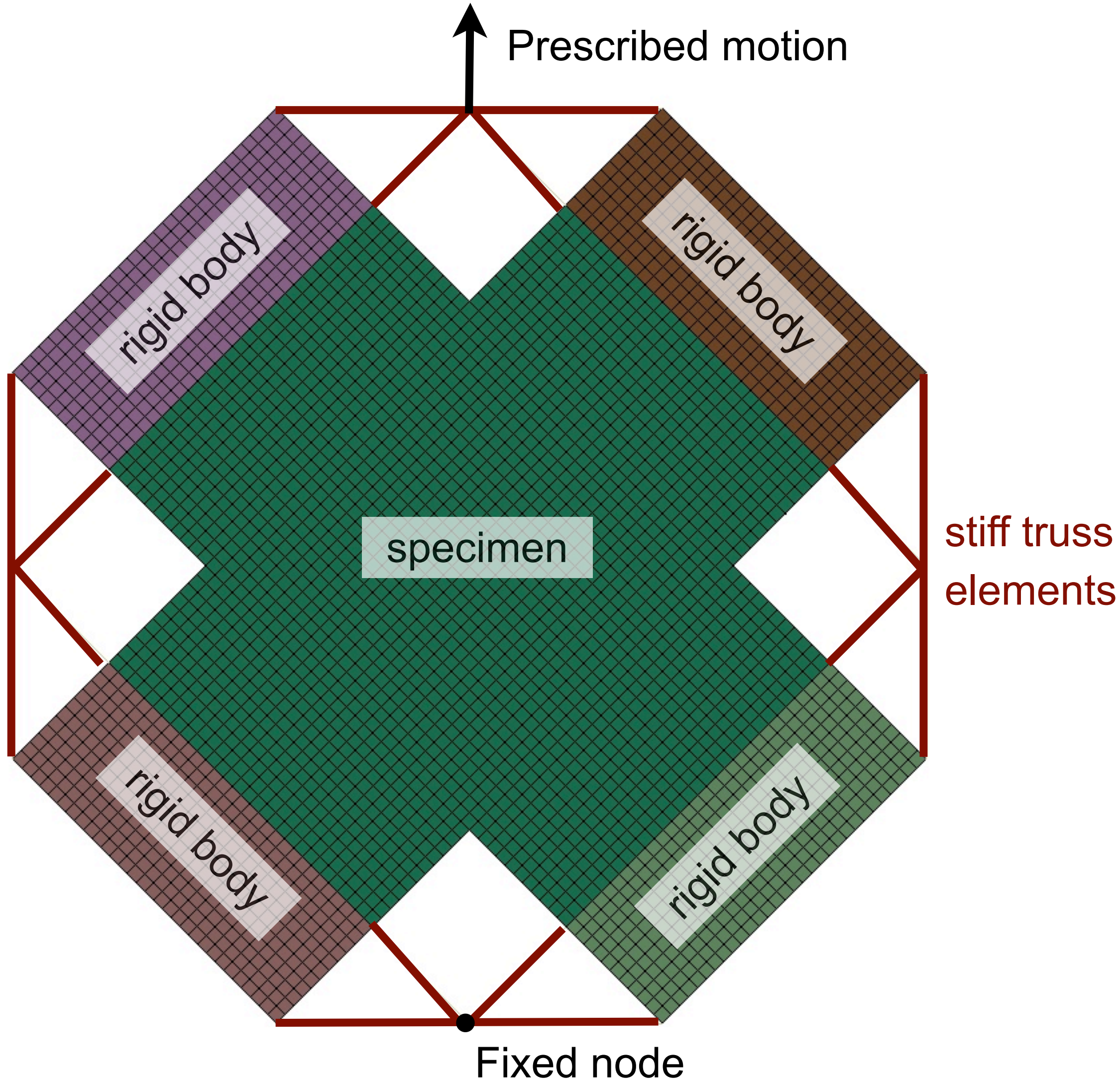
- Standard experimental set-up to characterize shear behavior
- Results show significant temperature dependence
  - At low temperature, matrix material dominates
  - At high temperature, behavior similar as for dry fabric material





Thermoplastic pre-pregs – picture frame test

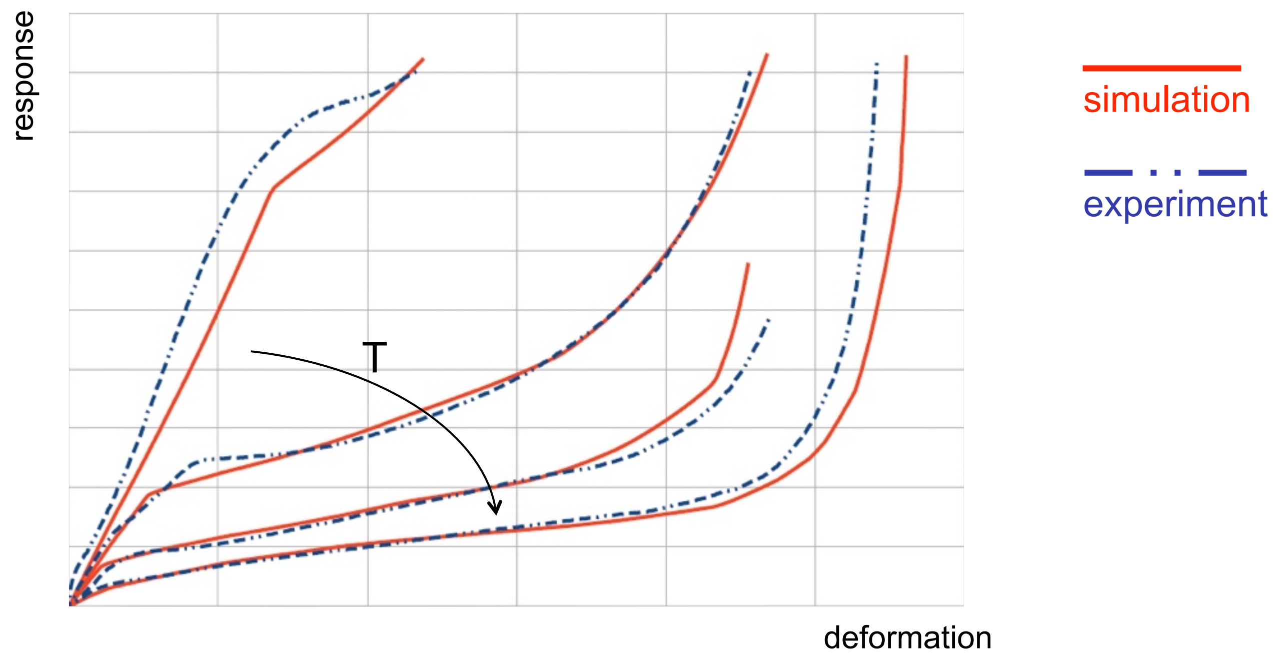
- Model:



Thermoplastic pre-pregs – Validation

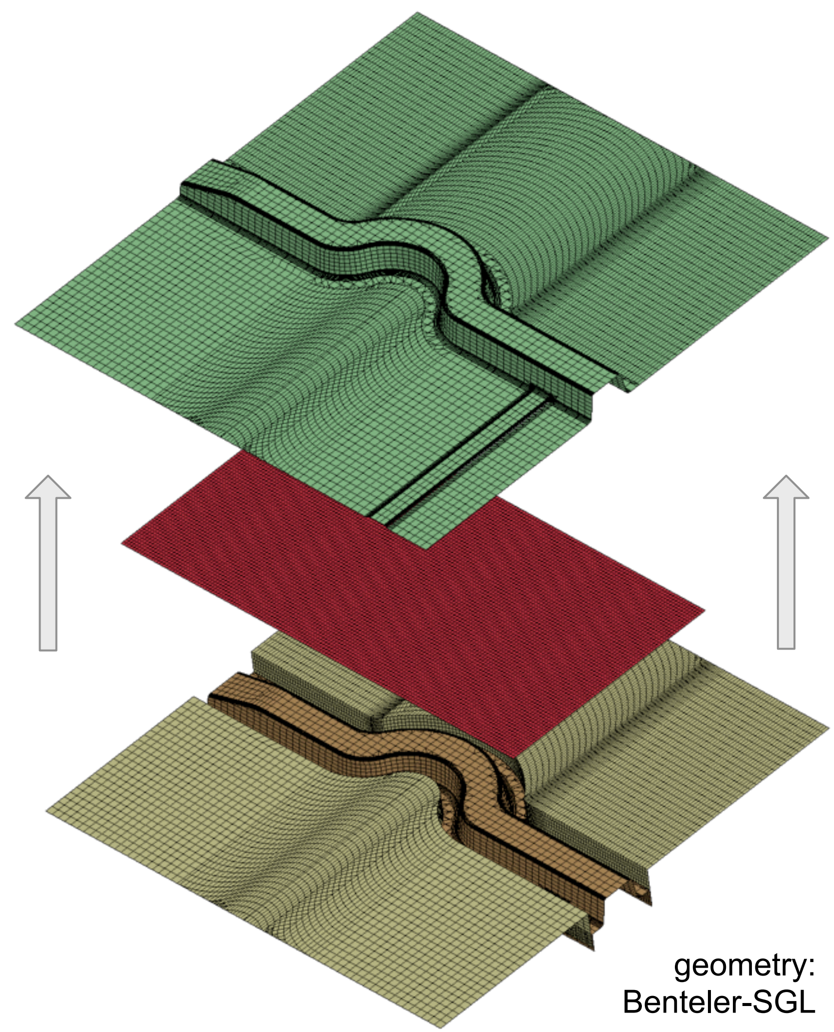
- Picture frame test is simulated for different temperatures

- 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



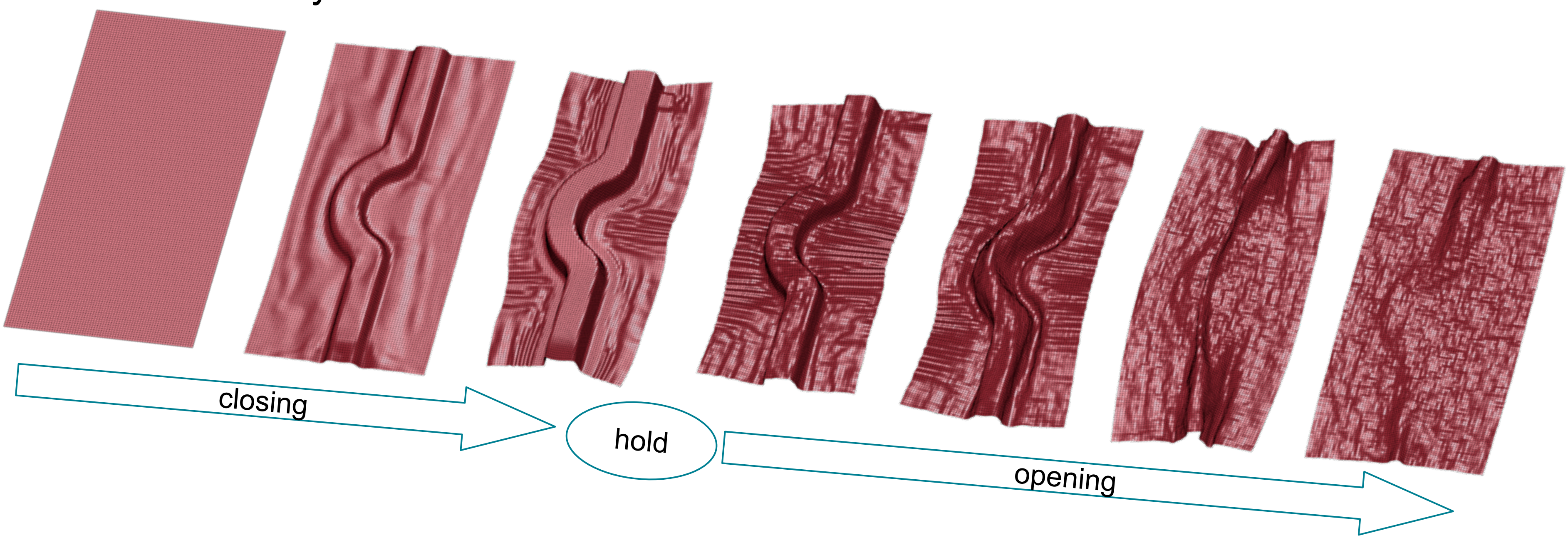
Thermoplastic pre-pregs – Stamping

- 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



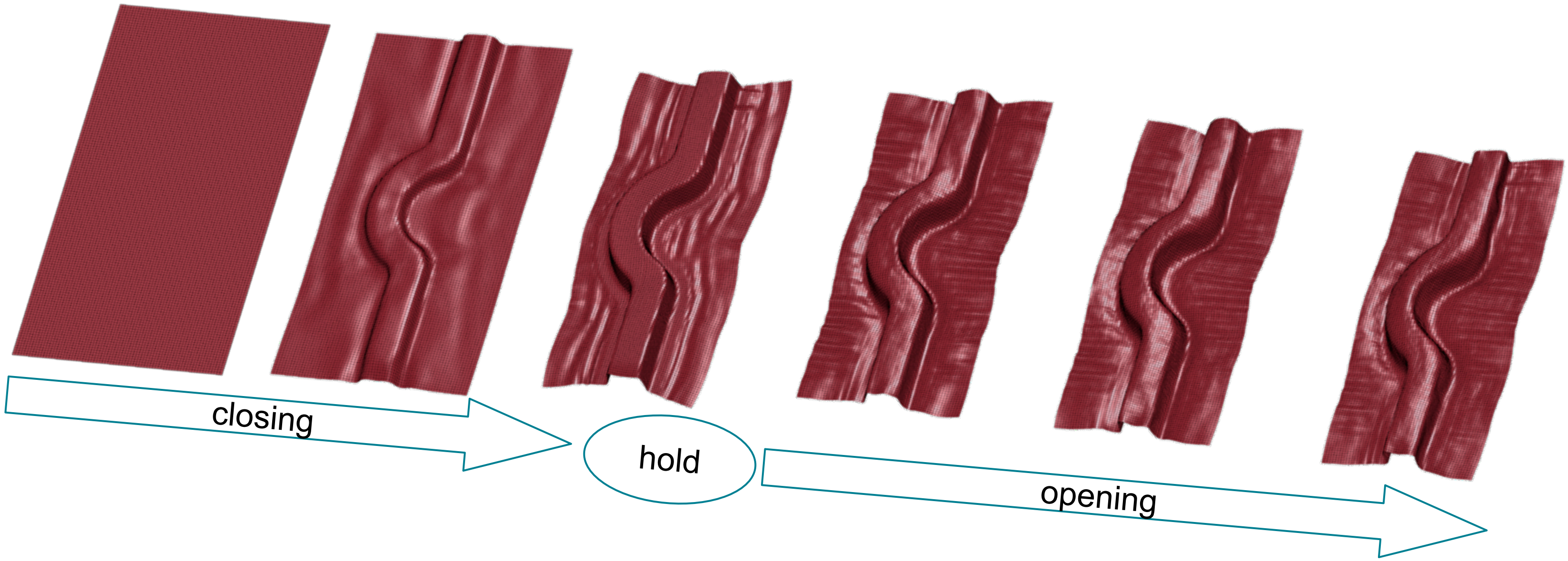
Thermoplastic pre-pregs – Stamping

- Closing and opening at a constant temperature of T_m (molten phase of matrix material)
- Deformation is governed by properties of the fabric
  - Very low plastic deformations induced
  - Many wrinkles form



Thermoplastic pre-pregs – Stamping

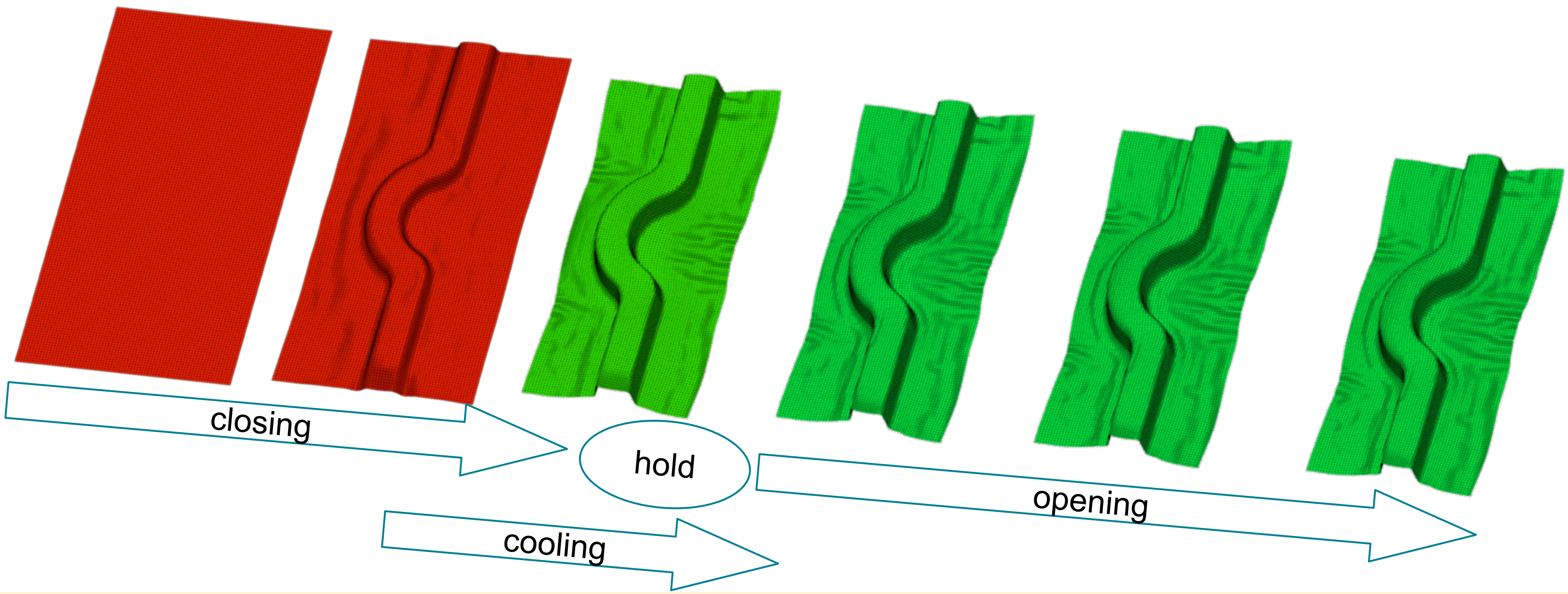
- Closing at T_m, cooling down to T_c (cured material) with closed tools, and opening at T_c
- Matrix shows elasto-plastic behavior
  - Plastic deformations are induced, but significant spring-back
  - Still visible influence of fiber orientations on deformation pattern



Thermoplastic pre-pregs – Stamping

- T_m up to t=70 ms, then cooling down (13 ms) to T_c
- Opening at a constant temperature T_c

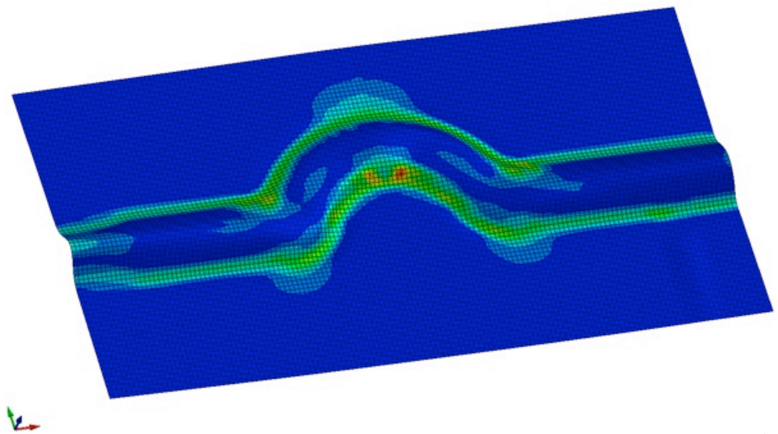
- Significantly reduced spring-back
- Only few wrinkles form



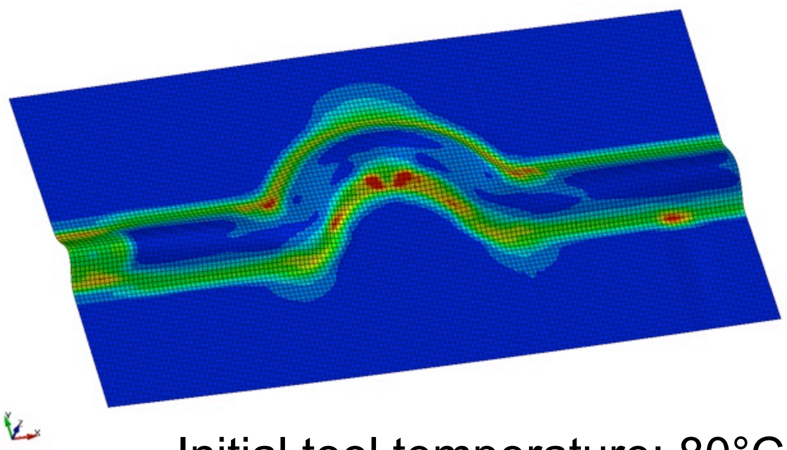
Thermoplastic pre-pregs – Stamping

- Preliminary simulation for a thermo-mechanically coupled system with simplified material parameter set

- Initial temperature of the pre-preg is 200°C
- Color-coded is plastic deformation



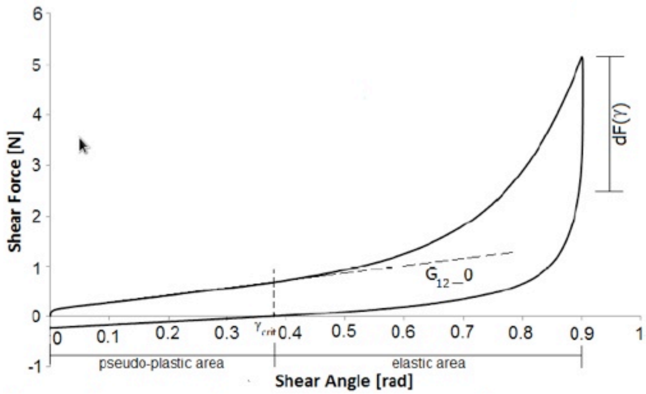
Initial tool temperature: 200°C

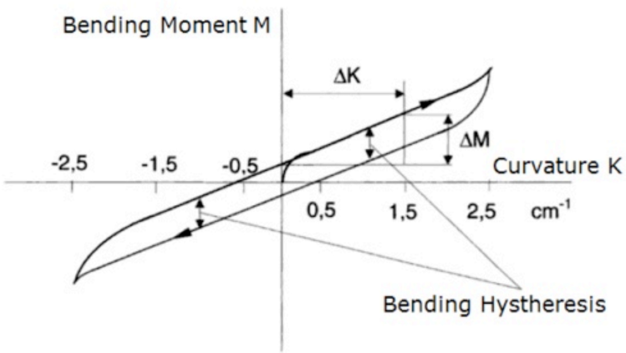


Initial tool temperature: 80°C

Thermoplastic pre-pregs – Work in Progress

- Presented results generated with user defined material in LS-DYNA
- Implementation as standard material *MAT_249 with
  - Extension for rovings and strain-rate dependency for matrix formulation
  - Elasto-plastic formulation for shear and bending of the fibers





[source: Döbrich et al, 2012]

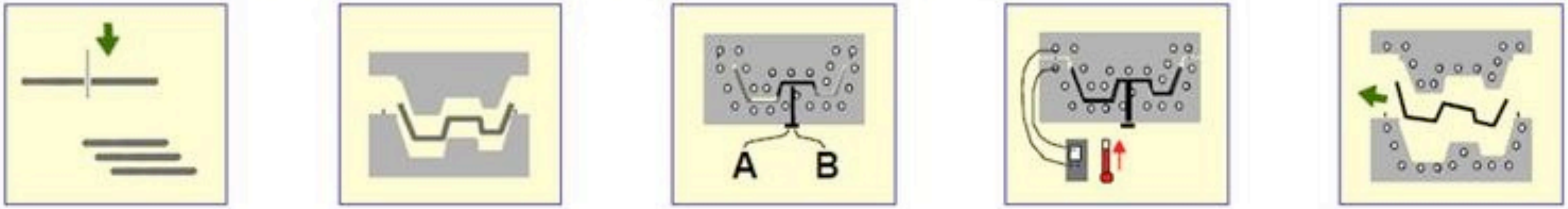
- Improved post-processing capabilities in LS-PrePost
- Tools to map results onto the mesh for crashworthiness simulations

Agenda

- Process simulation for thermoplastic pre-pregs
  - Introduction
  - Material formulation
  - Examples
- Process simulation thermoset matrix materials
  - RTM process
  - Wet molding
- Summary

Resin Transfer Molding (RTM) – process overview

- 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

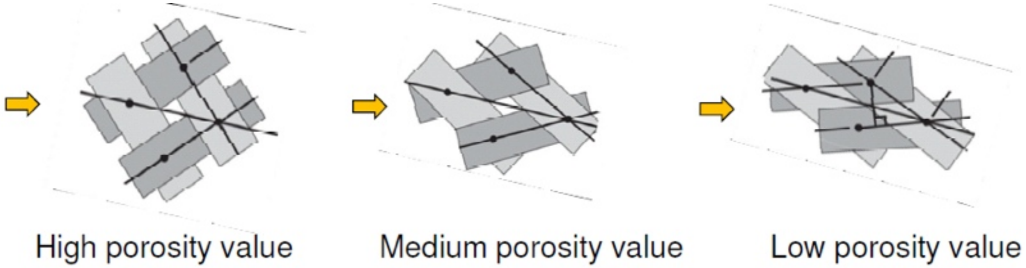


preparation of textile | draping | infiltration | curing | final part

[source: Benteler-SGL]

Resin Transfer Molding (RTM) – Modeling aspects

- Infiltration is a 3D flow problem through a porous media
- Infiltration process depends on quality of the draping as local porosity depends on
  - Orientation of the fibers
  - Packing density of the fibers

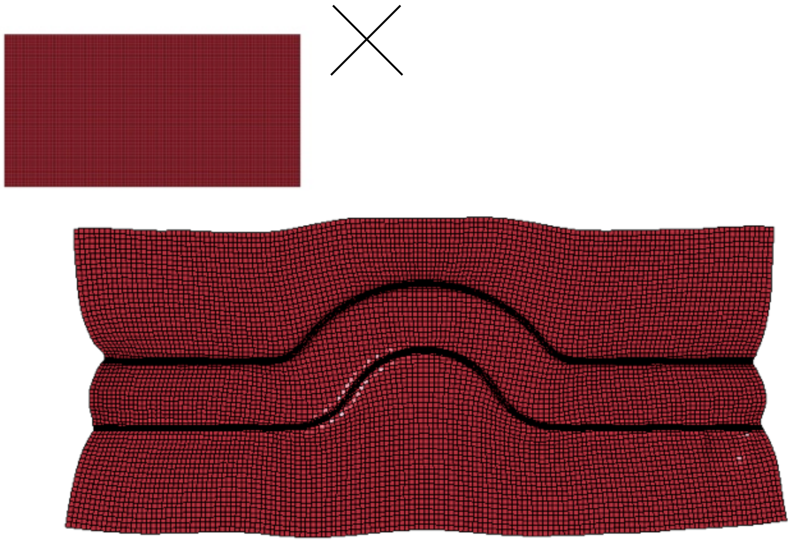


- Flow of the resin can lead to displacements and deformations of the fabric and a fully coupled fluid-structure interaction (FSI) simulation might be necessary

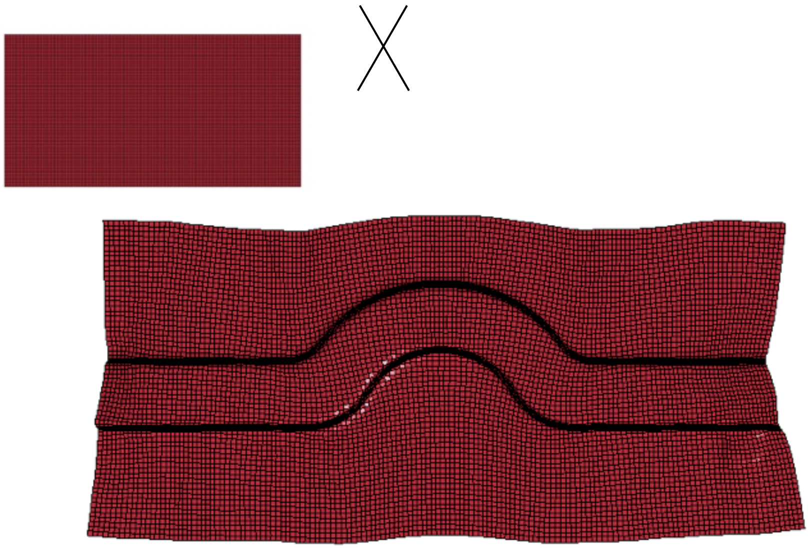
Resin Transfer Molding (RTM) – Draping in LS-DYNA

- Dry fabric can be modeled with
  - *MAT_034, *MAT_234, *MAT_235, …

- The new material formulation (fiber contribution) can be used
  - Simple and flexible material input
  - No restriction w.r.t. element formulation or usage in laminates



fiber orientation ±45°, final state

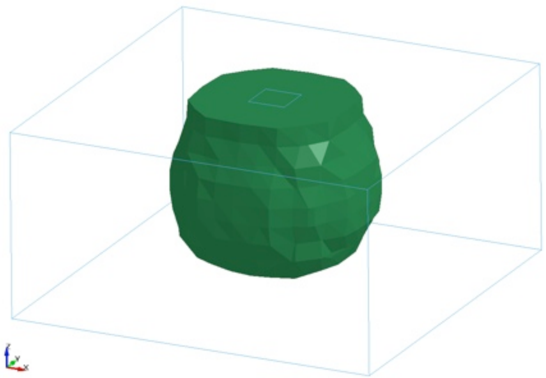


fiber orientation ±60°, final state

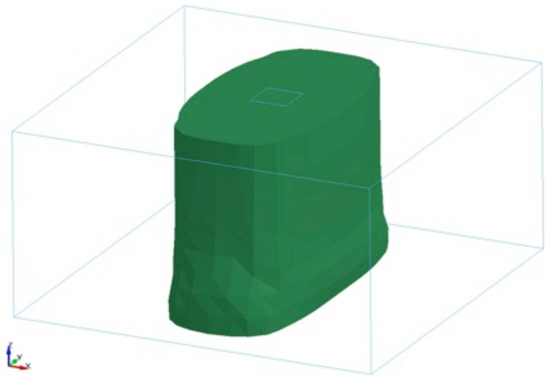
Resin Transfer Molding (RTM) – LS-DYNA

3D flow problems through a porous media can be modeled in LS-DYNA using keywords:

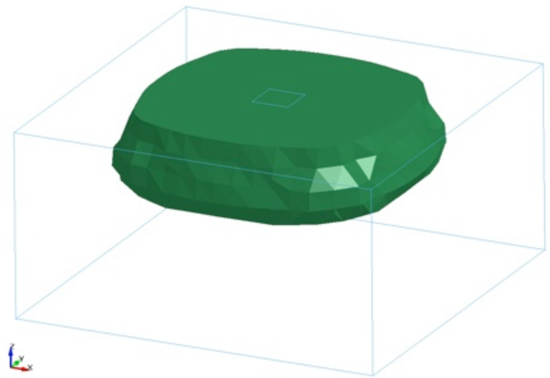
- *LOAD_BODY_POROUS
  - Non-isotropic porosity definition
  - Permeability defined either w.r.t. element or global coordinates
- *CONSTRAINED_LAGRANGE_IN_SOLID
  - additionally supports fully coupled FSI simulations



same porosity in all directions



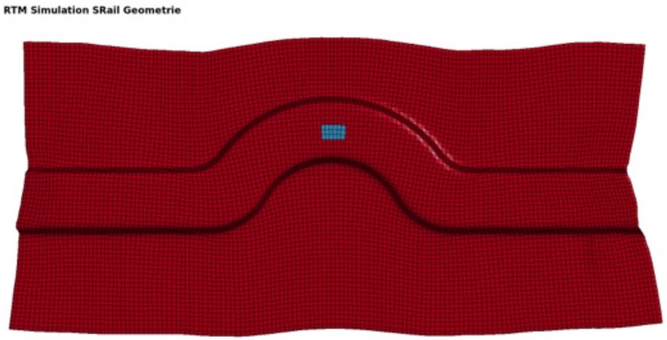
Low porosity in x-direction

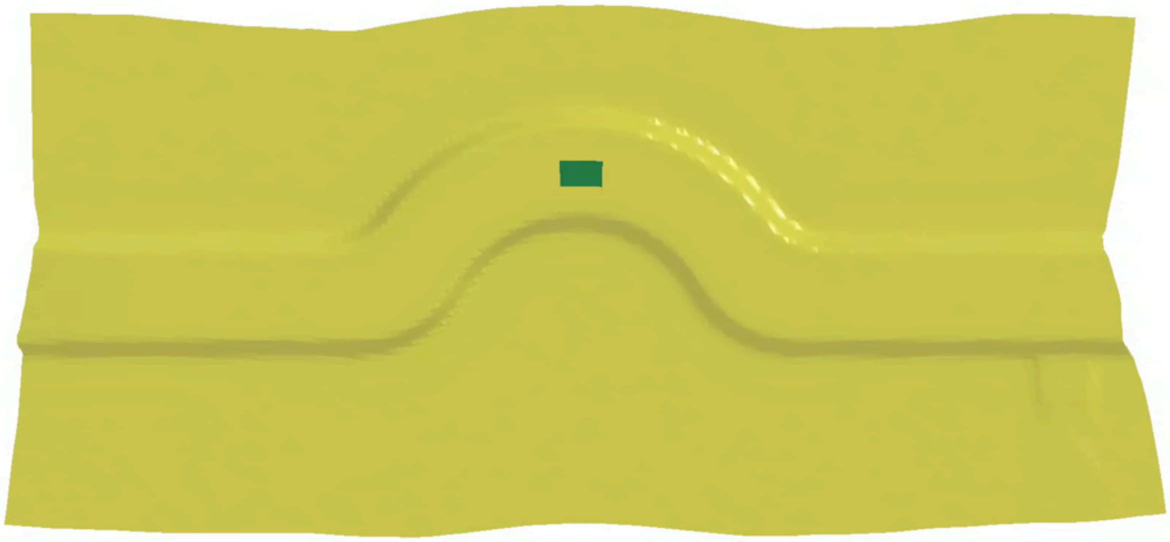


Low porosity in z-direction

Resin Transfer Molding (RTM) – Simulations

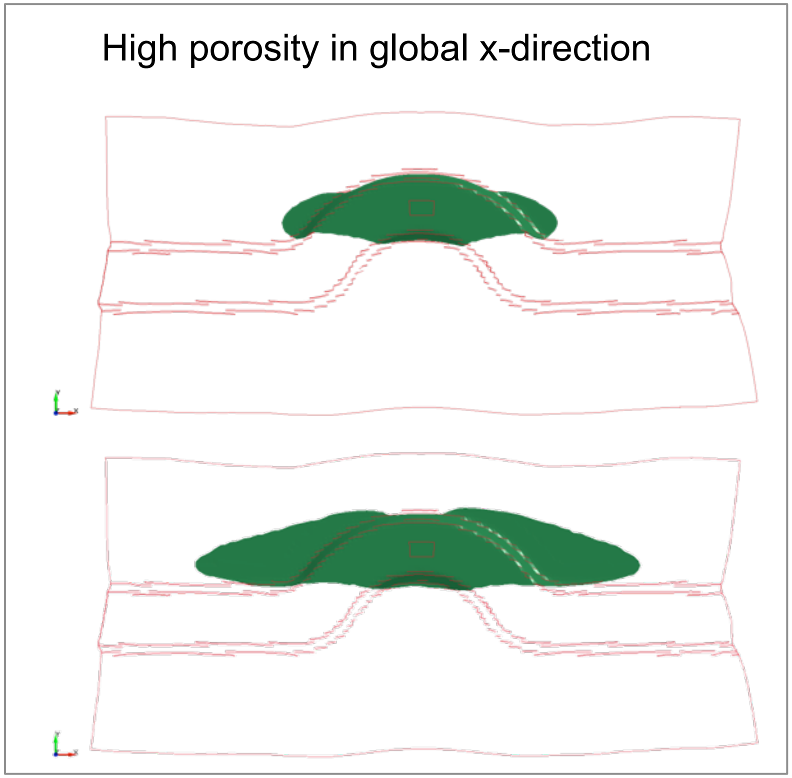
- Preliminary simulation with isotropic poros
- Mesh obtained from draping simulation
- Flow induced by pressure inlet
- One injection point for resin
  is considered (blue)

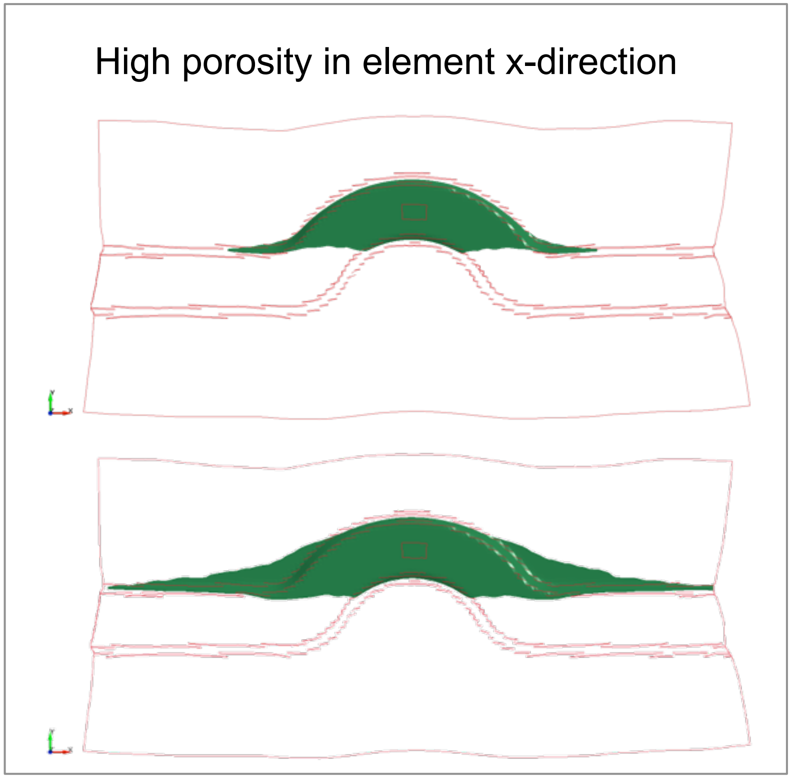




Resin Transfer Molding (RTM) – Simulations

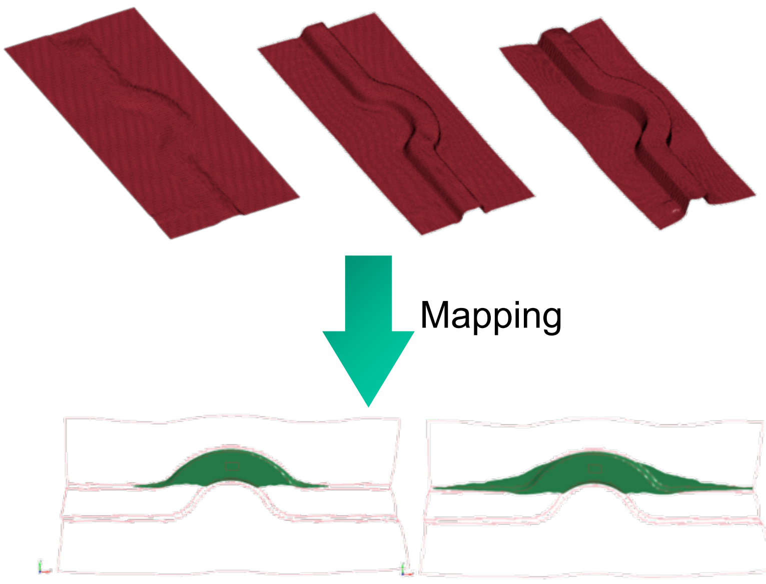
- Defining the porosity with respect to the element coordinate system:
  - Easy to specify a porosity for example in thickness direction even for curved geometries
  - Important if the geometry results from a previous draping simulation





Resin Transfer Molding (RTM) – Work in Progress

- Draping results generated with user defined material in LS-DYNA
- New *MAT_249 will have an option for dry fabric
- Mapping tools to transfer draping results onto infiltration simulations to close process chain
- Close collaboration with LSTC
  - Input of porosity tensors to model truly anisotropic permeabilities
  - element-wise input of this tensor, which is necessary for the mapping



Wet molding – process overview

- Draping and injection are done in one single step
- Process overview

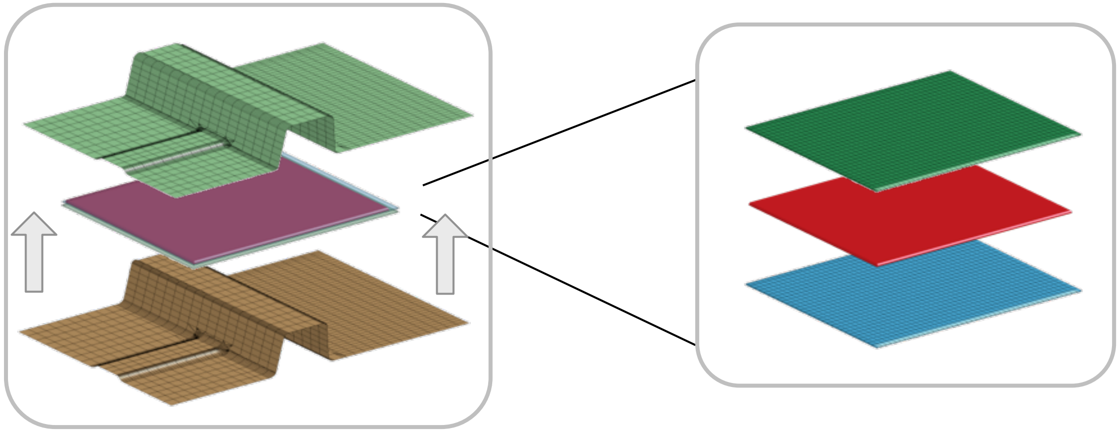
[source: Benteler-SGL]

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

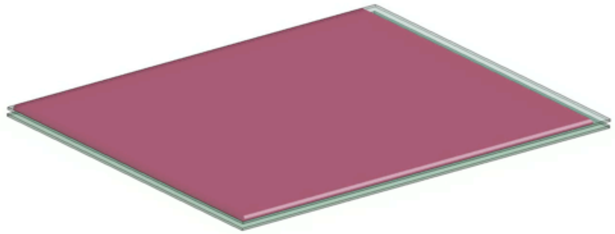
- Basically, a simulation requires the same numerical tools as RTM
- Simulation more complex
  - Fluid-structure interaction plays an important role
  - Fluid domain, viscosity, and porosity change during the simulation

Wet molding – preliminary simulations

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



- Next steps (with LSTC)
  - New ALE mesh motion strategy
  - Empirical relation between fabric deformation and porosity



Agenda

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Summary

- Simulation of complete process chain for thermoplastic pre-pregs:

- Thermo-mechanical coupling possible in LS-DYNA

- Novel, flexible, homogenized material formulation
  - Thermo-elasto-plastic constitutive model for the matrix material
  - Anistotropic hyperelastic description for the reinforcing fibers
  - Simple and flexible input
  - No restrictions w.r.t. to element formulation

- Simulations show excellent agreement with picture frame tests results

- Preliminary stamping simulations very promising

Summary

- Thermoset matrix material:
- Properties of dry fabric can be modeled with new material formulation
- Infiltration as 3D-flow through porous media using the CLIS-keyword
- Work in progress:
  - Mapping from draping results to locally varying porosities for RTM
  - Coupling of fiber deformations to permeabilities for wet molding

Thank you very much for your attention!

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