Simulation der Composite Prozesskette

Dr. R. M. Hinterhölzl, 4 A Technologie Tag, 3./4.3.2011

Lehrstuhl für Carbon Composites

gestiftet von SGL GROUP THE CARBON COMPANY

Overview

- Introduction to the LCC – Institute of Carbon Composite
- Process Simulation – Why?
- Simulation of the Draping Process
- Braiding Simulation
- Simulation of the Liquid Composite Moulding (LCM) Process
- Curing Simulation – Process Induced Deformation (PID)
- Conclusions and Outlook

Institute for Carbon Composites

Founded in Mai 2009 financially supported by the SGL Carbon Group

Professor Dr.-Ing. Klaus Drechsler

35 researcher

1 team assistant

2 workshop staff

Research focus: Material and process development

- Preform and Placement Technologies
- Matrix materials and Processing Technologies
- Simulation: Process simulation, Material modeling and Structural Analysis
- Testing Lab

Industrial Partners

SGL GROUP
THE CARBON COMPANY

KraussMaffei

Quickstep

Audi
Vorsprung durch Technik

Lehrstuhl für Carbon Composites

EADS

VOITH
Engineered reliability.

MAG

BMW

EUROCOPTER
AN EADS COMPANY

Research Network for Composite Materials

- Led by Prof. Klaus Drechsler
- 90 researcher / 1500 m^2 laboratory space - both to be increased
- Newest equipment in non-textile and textile preforming technology, infusion and fibre placement technology
- Partner in Carbon Composites e.V. (www.carbon-composites.eu)

Lehrstuhl für Carbon Composites
Stiftungslehrstuhl - TUM München

Werkstoffe
Fertigungsverfahren

Fraunhofer ICT
Projektgruppe - Funktionsintegrierter Leichtbau

Prozesstechnik
Industrialisierung

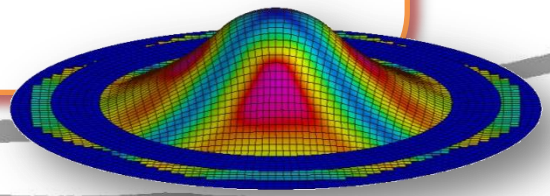
IFB
Institut für Flugzeugbau
Universität Stuttgart

Bauweisen
Leichtbau

Composite Simulation at the LCC

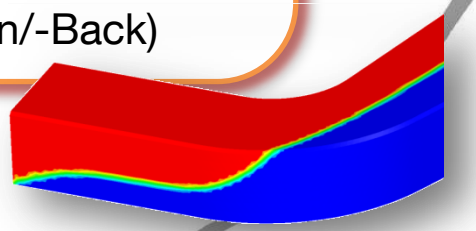
Preform-Simulation

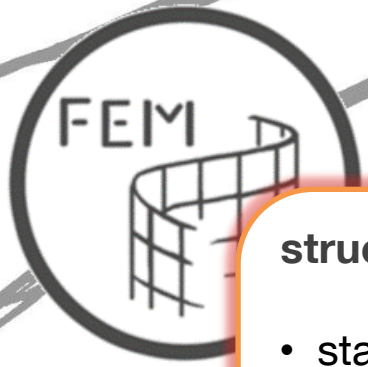
- structure of the semi-finished parts/ micromechanics
- draping simulation
- braiding simulation



Infiltration / Curing Simulation

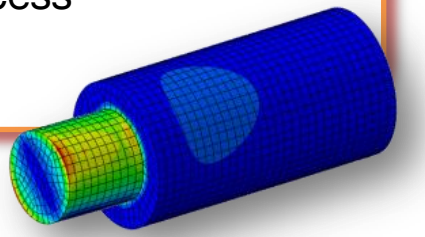
- resin flow simulation
- curing simulation
- process-induced deformation (Spring-In/-Back)

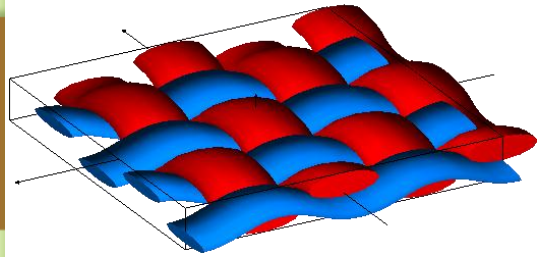




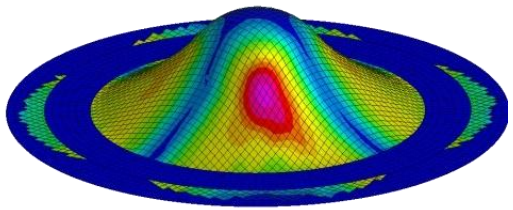
structural simulation

- static / dynamic
- consideration of the manufacturing process

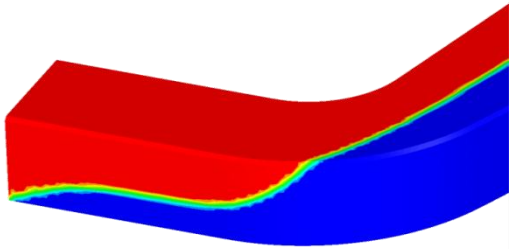




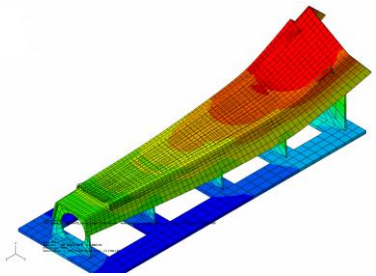
Semi-finished part structure: micro-/mesomechanics



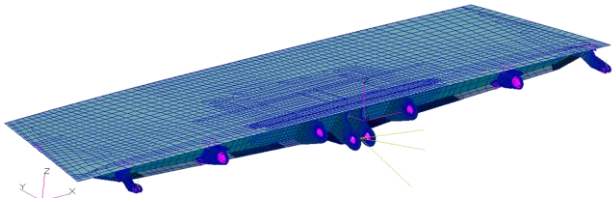
FE draping simulation



LCM simulation: flow front



curing- and distortion simulation



structural component simulation

Manufacturing Process Simulation – Why?

- **Aviation industry**

  approx. 50% of the structure are made out of Composite: fuselage, frames, stringers, skins,…

  ⇒ High volume

  ⇒ Bigger parts

  ⇒ Need for process optimization

  ⇒ Need for automation

- **Automobile industry**

  Serial production with very high volume, short cycle time, robust processes

From hand lay up to (partly) **automated** serial production

⇒ Automation

⇒ Shorter cycle times

⇒ Process reliability

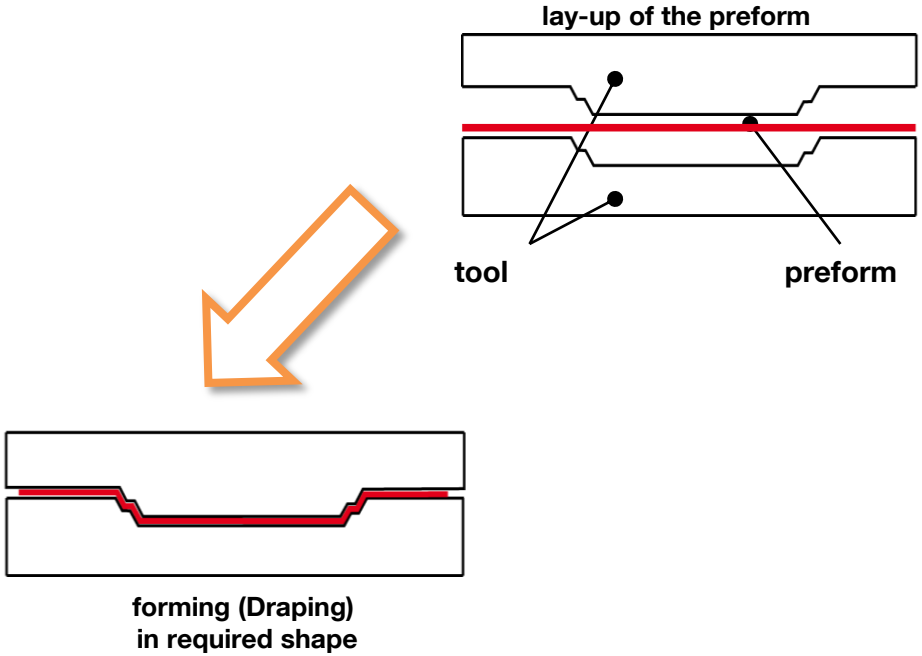
⇒ Short design and development time

further and new developments and optimization of manufacturing processes

Simulation of the Draping Process

Draping Simulation

- definition [techn.]:
  - „ method of forming fabrics onto a curved surface“ (near-net-shape forming)
- issue:
  - local change of fibre architecture during the draping process
  - potential wrinkling of the preform on forming double curved surfaces
- goals:
  - process optimization (geometry and arrangement of the flat form, prediction of fibre direction and defects, etc.)
  - basis for LCM- and curing simulations, structural analysis
  - flat pattern generation
  - virtual material characterization

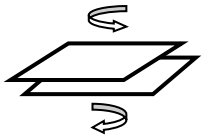


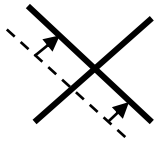
Airbus A380 – pressure calotte

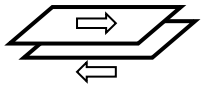
Mechanical Behavior

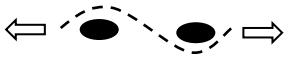
- preforms
  - non-crimp fabrics (NCF), woven fabrics, UD, etc. (dry and pre-impregnated)
- deformation modes

Inter-fibre shear

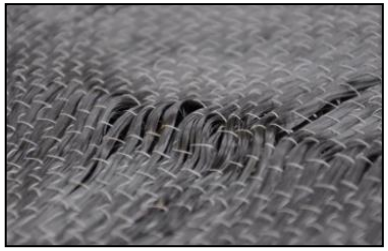

Inter-ply shear

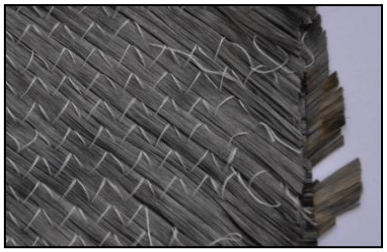

Inter-fibre slip

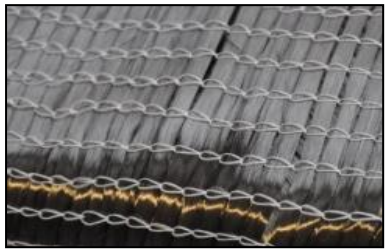

Inter-ply slip


fibre straightening
(woven fabrics)

- defects


wrinkling (out-of-plane buckling)

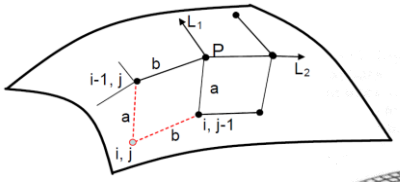

fibre pull-out

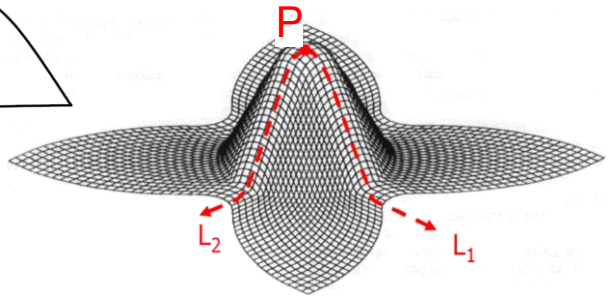

gaps

Numerical Approaches

kinematic approach

- pin-joint method [Mack 1950]
- purely geometrical approach
- computation of the fibre direction

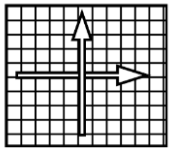


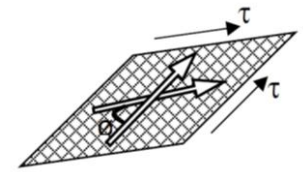


$$(x_{ij} - x_{i-1,j})^2 + (y_{ij} - y_{i-1,j})^2 + (z_{ij} - z_{i-1,j})^2 = a^2$$
$$(x_{ij} - x_{i,j-1})^2 + (y_{ij} - y_{i,j-1})^2 + (z_{ij} - z_{i,j-1})^2 = b^2$$
$$F(x_{ij}, y_{ij}, z_{ij}) = 0$$

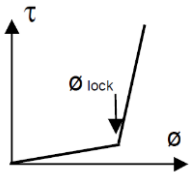
finite element approach

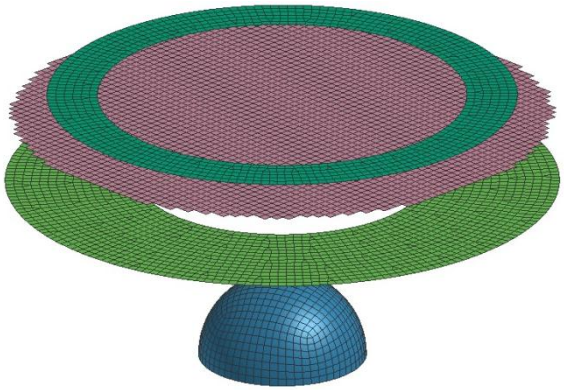
- modelling of the preform on ply-level with shell elements
- simulation of the draping process and the tools
- consideration of forces, friction, velocities, etc.
- prediction of deformation modes and defects in the preforms





de Luca - 1998



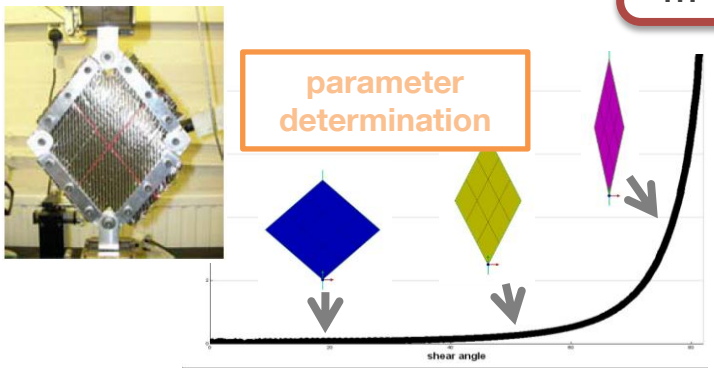


level of detail

Simulation

Material characterization (simulation of the material behavior)

- Picture Frame Test
- …

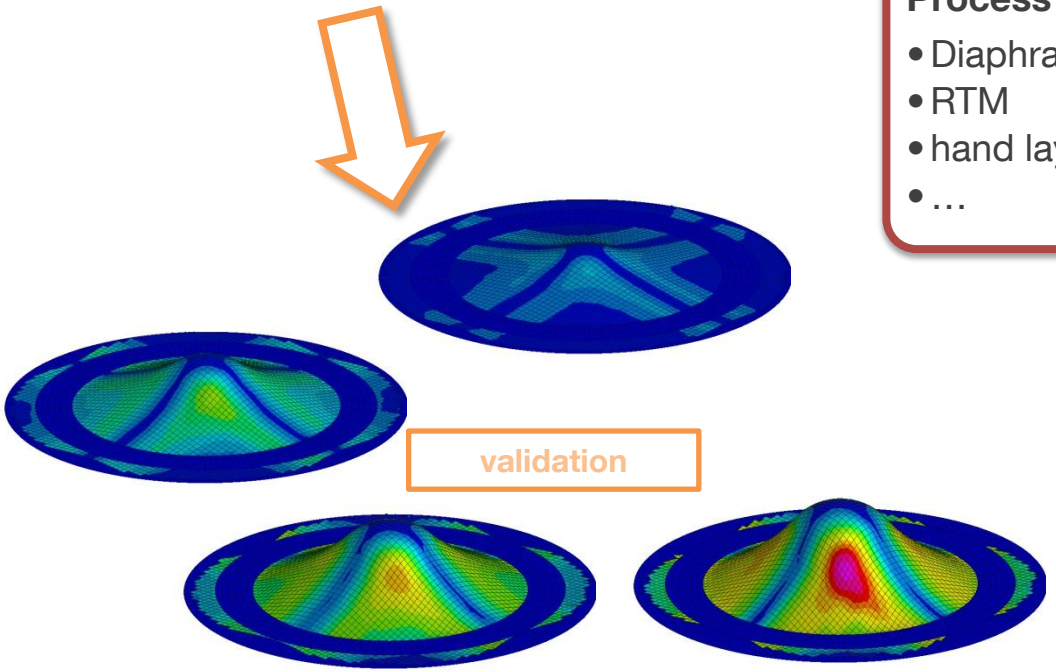


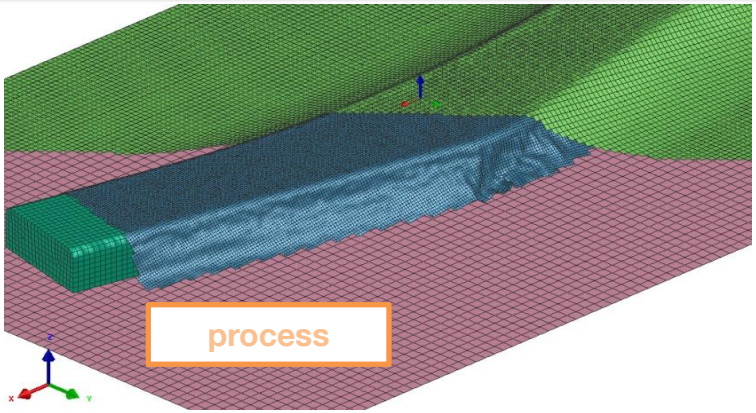
Validation on test geometry

- Hemisphere-Draping
- …

Process simulation (desgin and optimization)

- Diaphragm-Forming
- RTM
- hand lay-up
- …





Braiding Simulation

Material Modeling of Carbon Fibre Reinforced Braided Composites

Braiding Simulation – Challenges and Goals

- Braiding process:
  - preform technique with a good potential towards automatisation
  - application: aircraft frames, integral components, crash tubes

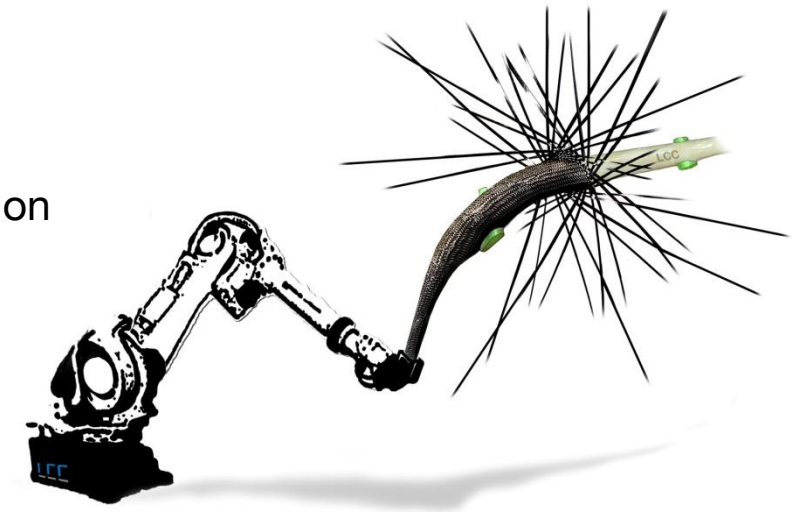


Fig. Maypole braiding process with robot

- Material properties:
  - material properties in the braidings are considerably influenced by manufacturing parameters
  - most current analysis procedures are only valid UD composites
    → only limited validity for braidings
    → Nowadays design and optimization of braided structures is only conducted by testing

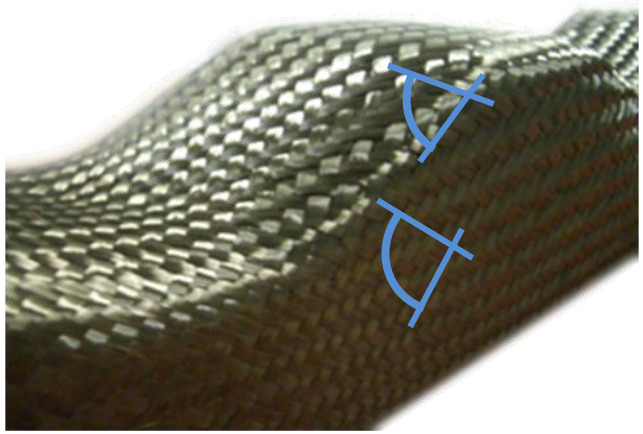


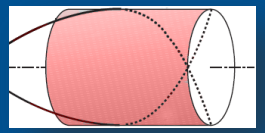
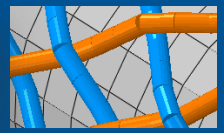
Fig. Varying fiber orientation [FACC]

- Goals:
  - approach towards the integral analysis of complex formed braided structures
  - numerical optimization of the braided structures and the braiding process

Braiding Simulation – Modeling and Data Flow

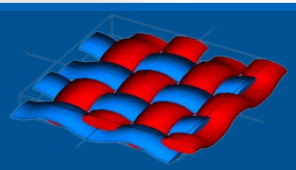
Estimation on the braid architecture

- polished specimen
- FE-braiding process simulaition

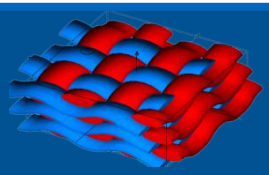
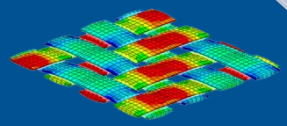
Unit Cell

- geometrical representation of firbe architecture
- yarn properties



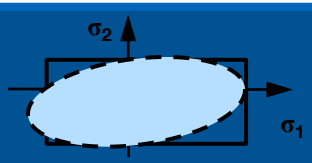
Stiffness

- analytical methods (e.g. WiseTex)
- FE modeling (arbitrary FE-Code)

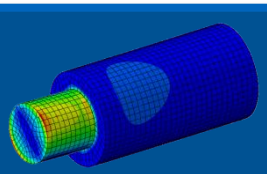
Strength

- FE modeling of yarn and matrix including damage
- development of a failure surface



Structural simulation

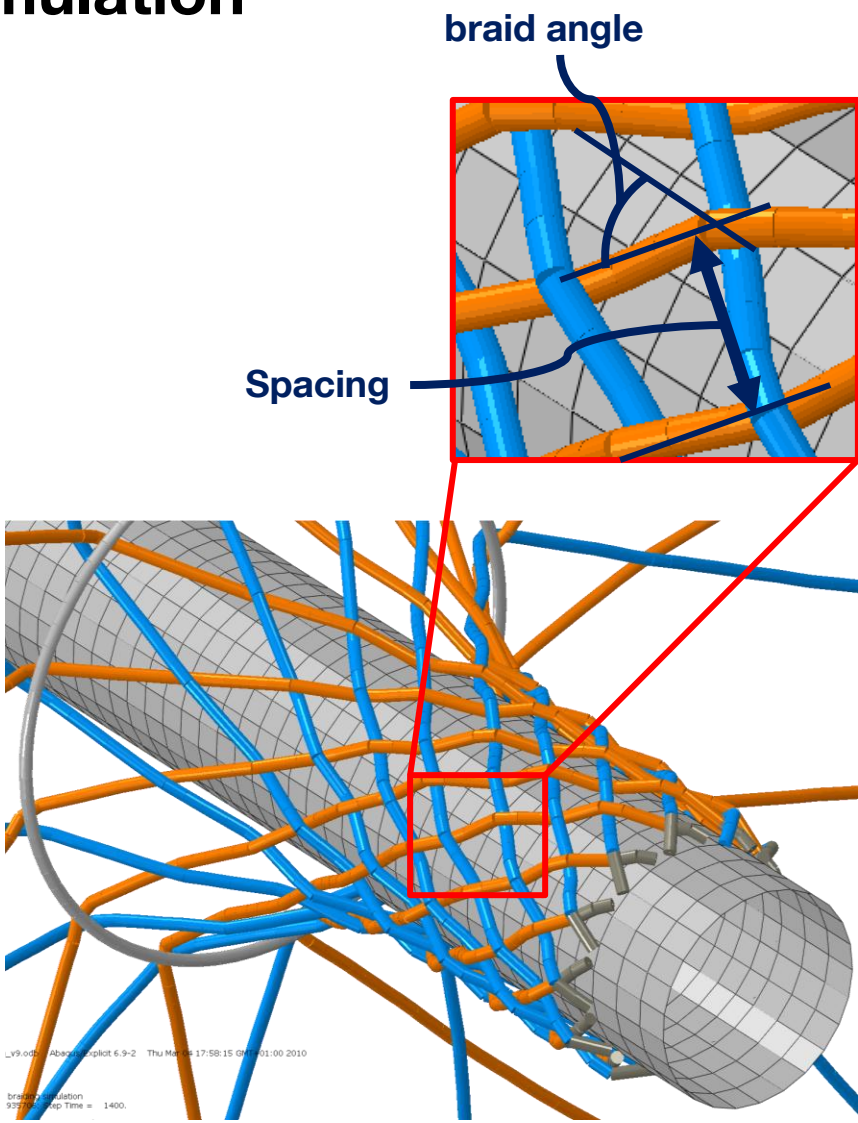
- component simulation with shell/solid elements (arbitrary FE-Code)
- alternative: meso moedling on component scale



Braiding Simulation – Braiding Process Simulation

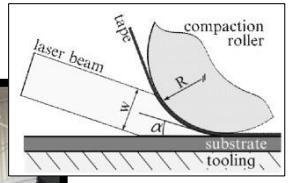
- Modeling the real manufacturing process using an explicit FE-Solver (e.g. Abaqus/Explicit, PAM-Crash)
- Rovings are represented by truss- or beam-elements
- Consideration of friction between rovings and guide ring

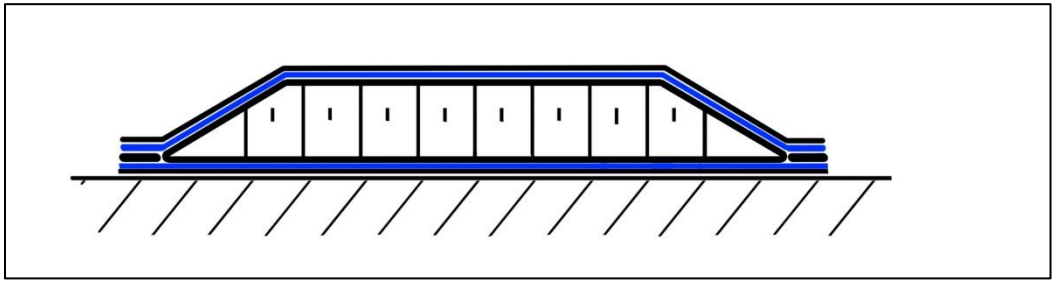
- Results:
  - producibility of components, braid architecture: braiding angle,
    spacing, roving-cross section
- Status:
  - numerical sensivity analysis, CPU time optimization, GUI development, interfaces, validation



Simulation of the Automated Fiber Placement Process (AFP)

Overview

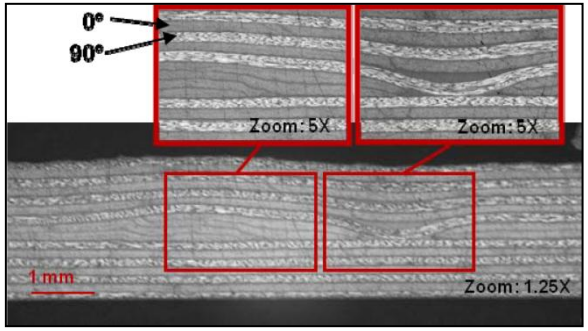




Placement – scenario [LCC]

Compaction

Consolidation [Boeing]



Process induced effects
[Croft et al., 2011]

AFP - Process parameters

- Heat transfer
- Process temperature
- Process time
- Tow deformation
- Process pressure
- Tow stiffness
- Tow preparation
- Acceleration
- Tow tackiness
- Tow stiffness
- Angle

Simulation of the Liquid Composite Moulding (LCM) process

Simulation of the LCM process

Definition

- *Simulation of the impregnation of a fiber preform with the matrix material*

Challenges

- Material characterization
- Modeling real resin flow phenomena

Goals

- Tool design and injection scheme
- Optimization of injection scheme
- Process time prediction
- Design of robust processes

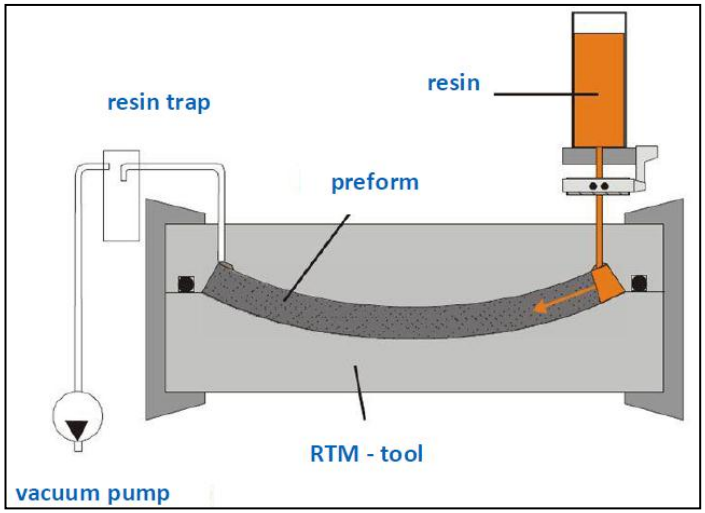


Fig.: RTM-Process

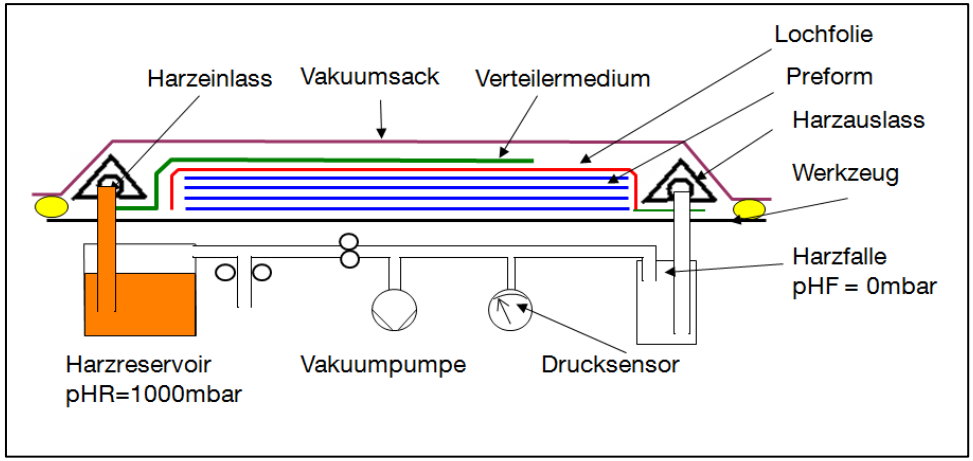


Fig: VARI-Process

Determination of Permeability

Definition (lat.: *permeare* = ‚to pass‘)

→Permeability of a porous media

<u>Darcy‘s law</u>

$$\underline{v} = -\frac{\underline{\underline{K}}}{\mu}(\nabla p)$$

$\underline{v}$: flow velocity
$\underline{\underline{K}}$: permeability tensor
μ: viscosity
∇p: pressure gradient

Remark.:
μ = f (temp., degree of cure)
K = f (Fiber: material, surface;
Preform: type, layup, …)

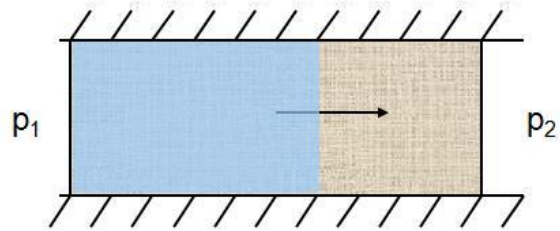


Fig.: 1D-flow method

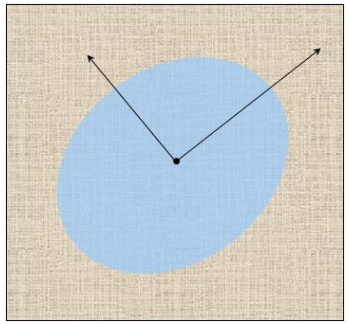


Fig.2: Radial-flow method

Determination

- Experimental
  - 1D-flow method
  - Radial-flow method (2D)
  - 3D-flow method
- Numerical
  - Multi-scale approach
    - Modeling of the textile (e.g. using WiseTex)
    - CFD-calculation on meso-level
      (e.g. simulation with unit cell using FlowTex)
      → Abstraction of the results to the
      macro level (permeability tensor)

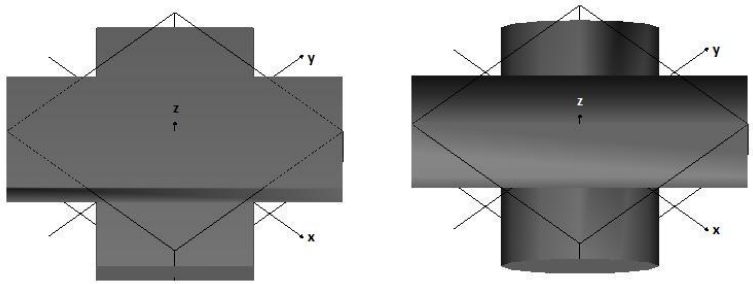
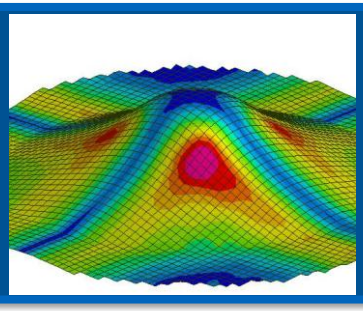


Fig.2: Unit cell model in WiseTex

Coverage of the Process Chain

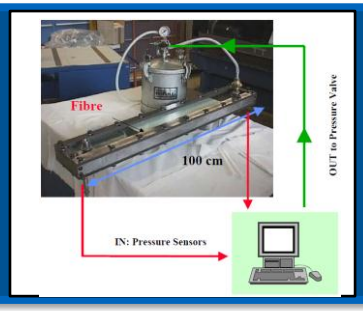
Preforming

- Draping, Braiding, Filament winding, …
- Simulation of the preform process



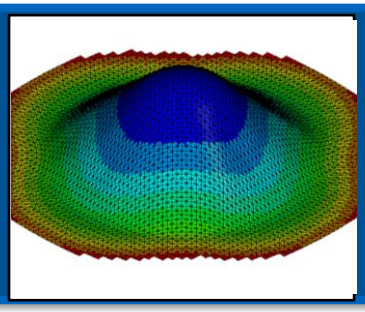
Determination of the permeability

- Experimental: Determination of the permeability with a test bench
- Numerical: Modeling of the Preform / Interface to the preform simulation



LCM-Simulation

- Tool design, Process time prediction (Flow front velocity, pressure distribution)
- Process optimization
- Curing simulation (for PID investigations)



Fields of research

1. Determination of material and process parameters
   (+ their changes during the process)
   - Viscosity (while curing)
   - Permeability for saturated and unsaturated flow
2. Characterization of 3D flow
   - Spatial material properties (e.g. thickness permeability)
   - Flow phenomena in thick preforms
3. Investigation of the impact of different states of compaction
   - Thickness distribution of a textile after preforming (e.g. draping)
     → RTM tool: inhomogeneous state of compaction
   - Difference of open- and closed-mould processes
4. Modeling of real features in a preform
   - Overlaps
   - Hems
5. Characterization of the influence of imperfections
   - Race-Tracking
   - Fiber-Washing

Fig.1: CAD model of automotive component

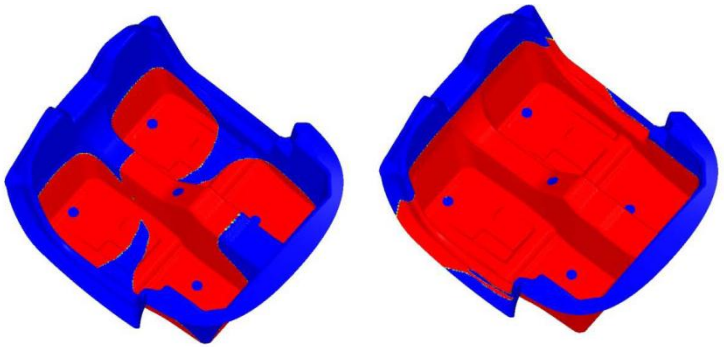


Fig.2: Filling simulation with modeling of overlapping areas

Profits of simulating the resin infiltration

- Tool design
  - Securing expensive investments for RTM tools
    e.g. reducing the risk of dry spots

- Estimation of process parameters

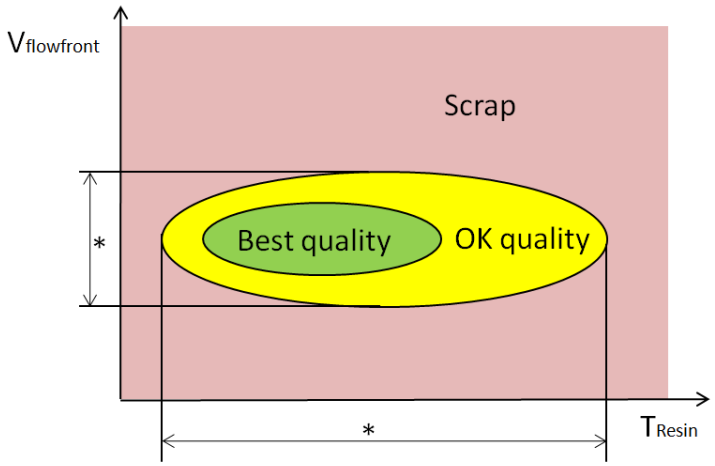
  Various geometries and fiber architectures
  → Prediction of
    - process time
    - flow front propagation
    - imperfections

- Design of robust processes

  Simulating variations within the process chain
    - Semi-finished product
    - Preforming and Handling
    - LCM process

  Definition of Quality Gates for each step
  →Less scrap parts and more reproducible output

Fig.: RTM tool (source: Eurocopter)

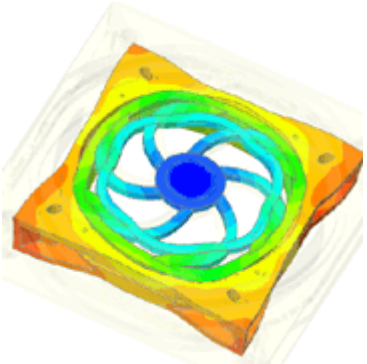


* Accetable range

Determination of Process Induced Deformations (PID) & Curing Simulation

Definition „Springback“ / process – induced deformations (PID)

- Process-induced (permanent) deformations occuring among composite parts after curing are often called „Springback“. Characteristics can be distinguished by the kind of deformation.



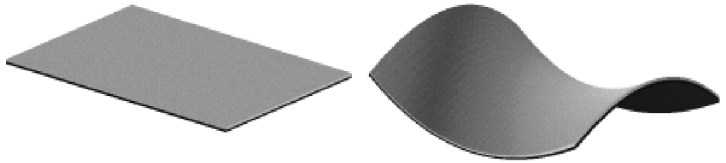
http://www.moldex3d.com/jla/en/index.php?option=com_content&task=blogcategory&id=26&Itemid=177

Shrinkage

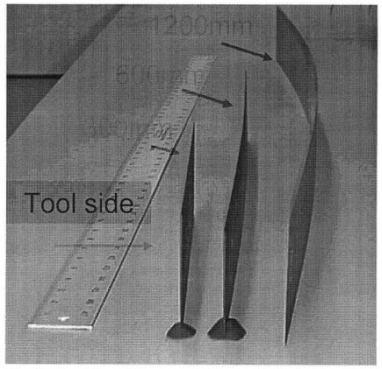
Spring-In

PID
“Springback “

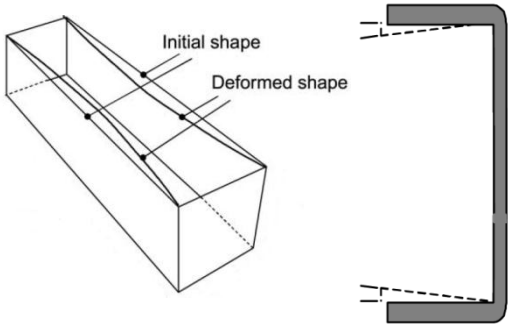
Warpage



Svanberg, 2002



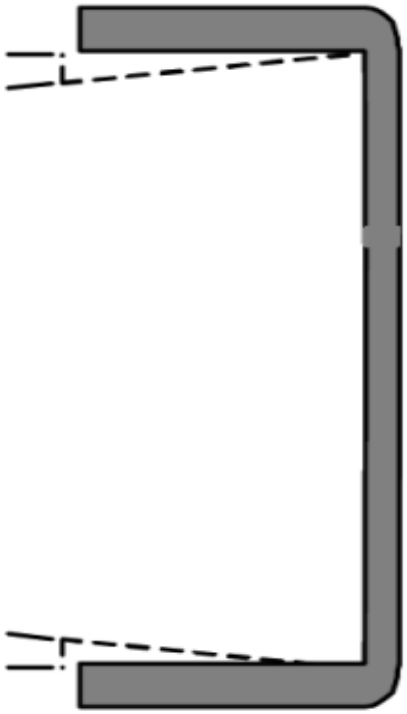
Twigg, 2001



Fernlund et al, 2003

Intention for the “a priori” Determination of PID

- Knowledge of PID can be used to **virtually adopt tooling** in order to manufacture parts with high dimensional accuracy in first shot to
  - avoid or reduce costly iterative tooling optimization,
  - ensure mountability (stiff structures!),
  - avoid or reduce additional rework of joining areas.



Factors of Influence on Springback

- Different sources specify the drivers of the different mechanisms widely consistently:
  - [1] NASA research paper dealing with experiment series on composite angles analyzed with a Taguchi method
    (minimization of variation, general: robust design and processes)
  - [2] Fernlund, 2003, [4] Svanberg, 2002 and [7] Johnston, 1997: documentation of research work for deformation prediction employing process simulation

Factors	Effect[1]
Thermal expansion	Large
Cure shrinkage	Large
Laminate lay-up	Large
Cure temperature	Large
Mould thermal expansion	Large
Void content	Medium
Thermal gradients	Medium
Fibre content gradients	Medium
Cool-down rate	Medium
Cure time	Small
Fibre content	Small
Mould material surface	Small
Mould corner radius	No[2]
Mould thermal conductivity	No[3]

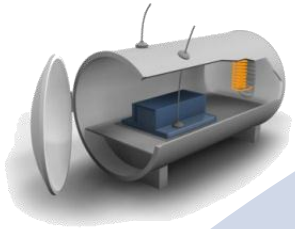
1. The effect of the factors is classified in Large, Medium, Small and No effect on shape distortions.
2. May be important if this leads to a local thickness and fibre content variation.
3. The mould thermal conductivity is important if it is low. This may lead to unexpected temperature variations at the mould surface.

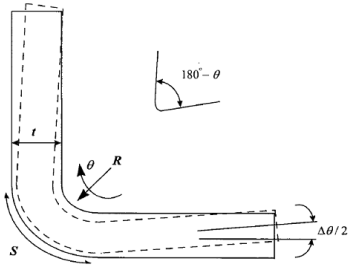
Representative Table, from Svanberg, 2002

<u>Note:</u>
Mold thermal expansion and the concerning fraction of PID are linked via the tool-part-interaction

Methodologies for determination of PID

increasing level of detail and modeling effort



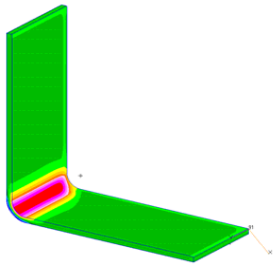


$$\Delta\theta = \theta\left[\frac{(CTE_\theta - CTE_R)\Delta T}{1 + CTE_R \Delta T}\right]$$

Analytical:
Estimation of deformation for simple geometries

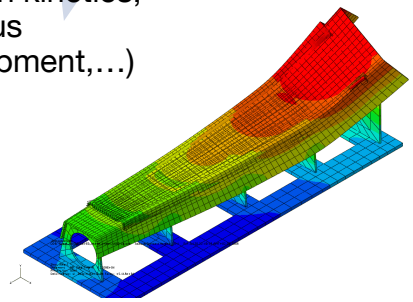
Experimental:
Iterative optimization of final part shape

Phenomenological:
Summarization of different mechanisms with one actuating variable (enhanced CTE)



$$\alpha_{m_{eq}} = \alpha_{m_{therm}} + \alpha_{m_{chem}} = \alpha_{m_{therm}} + \frac{\Delta V}{3 \cdot \Delta T}$$

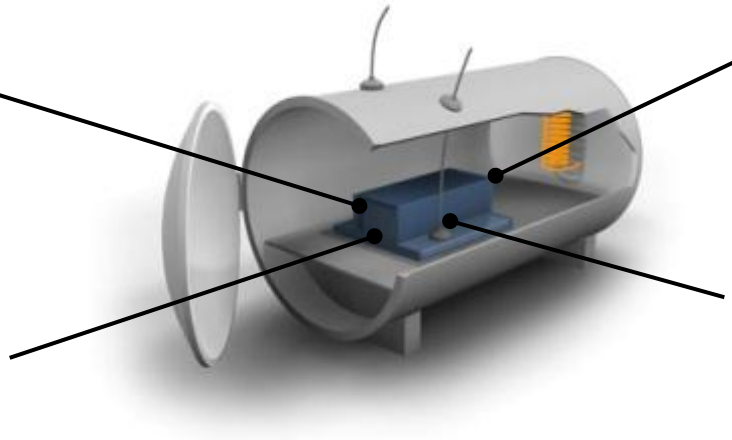
Curing simulation:
Simulation of all relevant mechanisms (e.g. reaction kinetics, modulus development,…)



Process simulation - General Approach

- Evaluation of relevant mechanisms

tool-part-interaction → constraint stress released during tool removal



heat transfer → temperature gradients

Resin hardening → modulus development (residual stresses), resin cure shrinkage

…

- Chances:
  - simulation of real mechanisms
  - influence of single factors evaluable
  - identification of main drivers
  - validation done for parts of variable complexity
- Problems:
  - massive effort for experimental material parameter determination
  - computational costs (number of DOFs due to FE analysis of coupled problems)

Process simulation – Application Flow on COMPRO

Virtual autoclave
- heat transfer autoclave gas → part-tooling-assembly
- feedback control autoclave

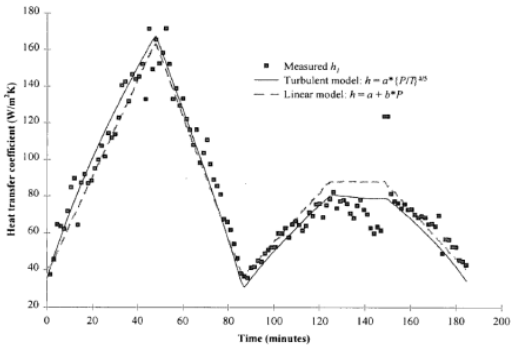


Figure: Experimental determination of effective HTC

Thermo-chemical module
- reaction kinetics
- heat conduction

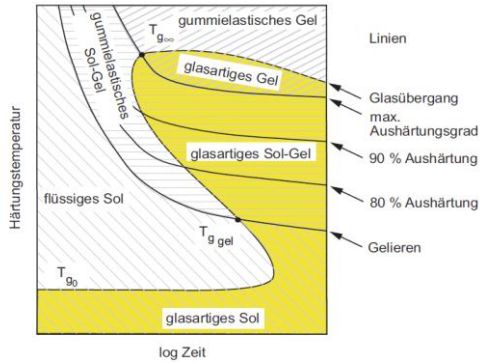
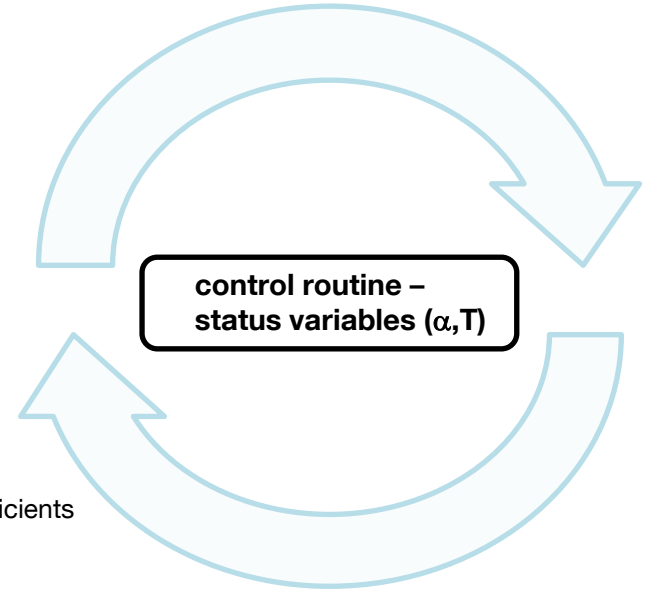


Figure: Time-Temperature-Transition-(TTT) Diagram



Johnston A., Hubert P., 1996

Stress module
- modulus development related to resin degree of cure, temperature
- resin cure shrinkage and thermal expansion coefficients

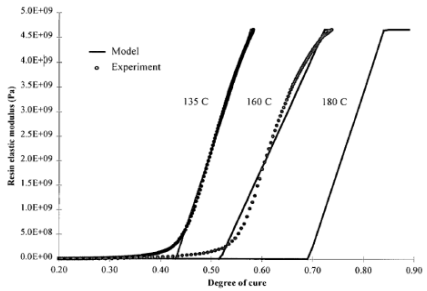


Figure: modulus development

Flow Module
- resin flow due to laminate compaction (viscosity, permeability)

→ variations in wall thickness and fiber volume content

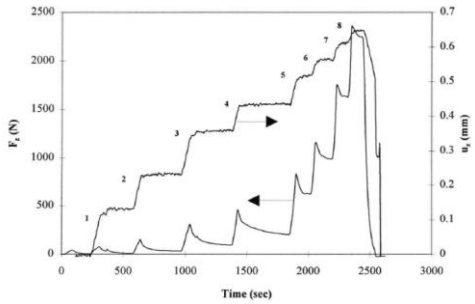


Figure: Force-Displacement-Diagram Fiber Bed Compaction

Process simulation – Output and Evaluation

- Output variables:
  - Deformations
  - Stresses
  - Final resin degree of cure distribution
  - Distribution of fiber volume fraction
  - Temperature field
  - Glass transition temperatures

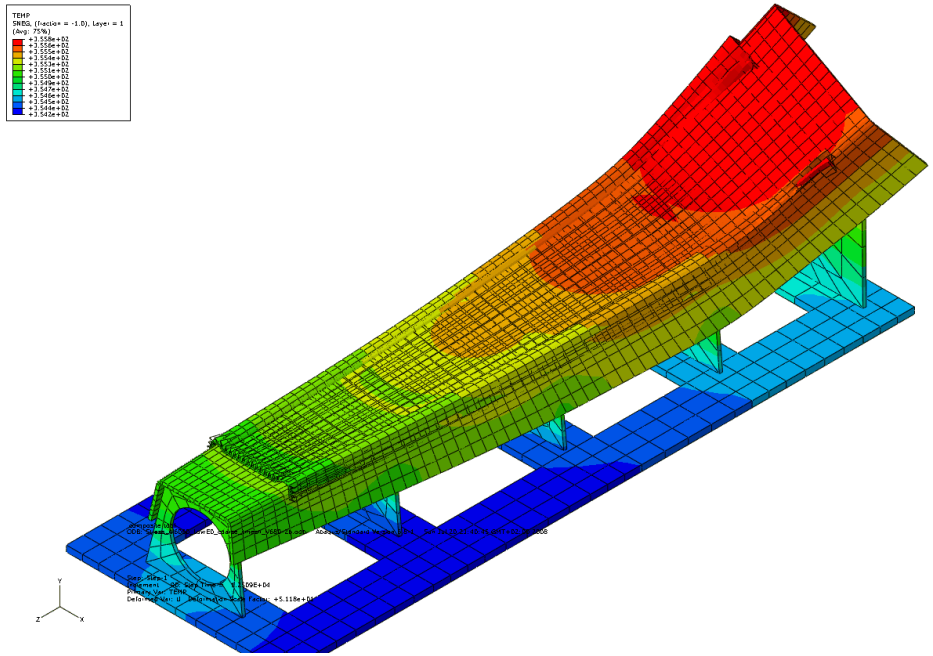


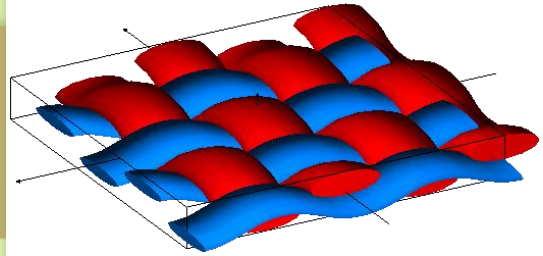
Figure: Temperature distribution on deformed frame (CMT)

- Evaluation a priori concerning:
  - Tooling dimensioning, mounting tolerances
  - Part's inner quality (sufficient resin degree of cure, glass transition temperature, peak temperatures during cure (resin degradation)

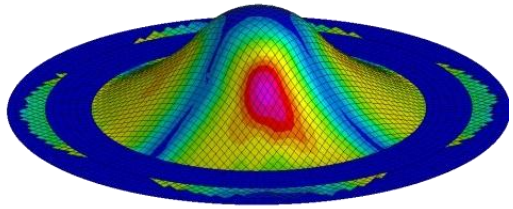
Conclusion

- Close interaction in-between production and simulation (process simulation and structural simulation) is strongly required
- Process simulation supports the development and optimization of the manufacturing process (cycle time, process robustness, etc.)
- Simulation of individual process steps (draping, LCM, curing,…) and their dependency on each other is possible
- Process simulation supports the part design

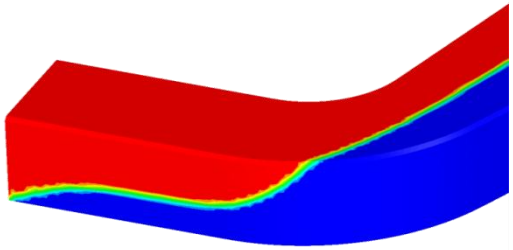
  $\Rightarrow$ fibre orientation defines stiffness and strength of the part
- Goal is the simulation of the whole composite manufacturing process



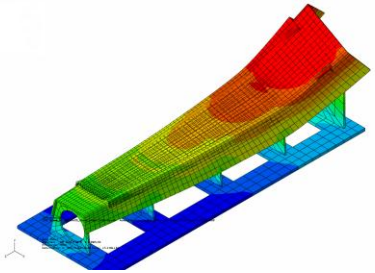
fabric structure:
micro- /mesomechanics



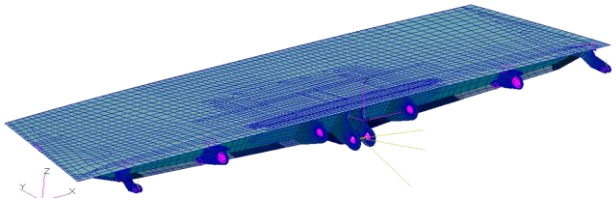
FE-drapingsimulation



LCM-simulation of resin flowfront



curing- and PID-simulation



part simulation

Thank you for your attention!