Process Simulation of Composites

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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, for automation

Automotive 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

new developments and optimization of manufacturing processes
Manufacturing in Aerospace and Automotive Industry

Aerospace

[Image: Aircraft manufacturing process]

Hours, Days

[AIRCRAFT]

Automotive

[Image: Car manufacturing process]

Seconds, Minute(s)

[BMW]
Overview

- Motivation
- Introduction of LCC
- Forming Simulation
  - Draping Simulation
  - Automated Fiber Placement (AFP) Process Simulation
  - Braiding Process Simulation
- Simulation of Liquid Composite Moulding (LCM) processes
- Determination of Process Induced Deformations (PID) & Curing Simulation
- Simulation Platform
- Conclusion - Outlook
Institute for Carbon Composites

- Founded in Mai 2009 financially supported by the SGL Carbon Group
- Professor Dr.-Ing. Klaus Drechsler
- ~60 Researchers
- 1 Team Assistant
- 5 Technical Employees
- 2 Office locations in Garching
- 3 lab locations in Garching and Ottobrunn
Research Groups

- **Process Technology for Fibers + Textiles**
  - Automated Fiber Placement
  - Braiding
  - Tailored Textiles

- **Process Technology for Matrix Materials**
  - Hybrid Materials + Structures
  - Tooling Systems
  - Production Systems

- **Simulation**
  - Preform + Flow Process Simulation
  - Compaction, Curing and Deformation
  - Material Modeling and Structural Analysis

- **Material Behavior and Testing**
  - Composite Testing Lab
  - Test Method Development
  - High Strain Rate Behavior

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Process Simulation of Composites
Simulation of composites

Semi-finished part structure: micro-/mesomechanics

FE draping simulation

LCM simulation: flow front

Structural component simulation

Curing- and distortion simulation

PACC AG
Preform Process Simulation
Overview

• Motivation for Process Simulation:
  • Analyze the influence of process parameters on produced preforms → increase knowledge of the process
  • Optimization of the process and of produced geometry
  • Generate input for further analysis (LCM, Curing/PID, Material Modeling)

• Main research activities
  • Draping Simulation
  • Automated Fiber Placement
  • Braiding Process Simulation
Draping Process Simulation
Goals of Draping Simulation

- Process development / optimization
  - Geometry and alignment of the flat preform
  - Drapeability (feasibility study)
  - Prediction of draping defects
  - ...

- Part design (design to process)
  - Prediction of fiber alignment
  - Prediction of fiber volume fraction
  - ...

- Embedding in process simulation platform:
  - LCM simulation
  - Curing and PID simulation
  - Structural simulation
Requirements for Draping Simulation

- **Textiles**
  - woven, Non-Crimp Fabrics (NCF), UD, etc.
  - dry or pre-impregnated

- **Deformation modes**
  - Shear
  - Bending
  - Elongation
  - Inter-ply Motion
  - Intra-ply Motion

- **Defects**
  - Wrinkling / Folds
  - Loops
  - Gaps / Voids
  - Fiber Pull-Out
  - Damage of Stitching
**Numerical Approaches for Draping Simulation**

**Kinematic Approach**
- pin-joint method [Mack 1950]
- purely geometrical approach
- computation of the fiber direction
- direct cut geometry generation

\[
\begin{align*}
(x_{g} - x_{g-1})^2 + (y_{g} - y_{g-1})^2 + (z_{g} - z_{g-1})^2 &= a^2 \\
(x_{g} - x_{g-1})^2 + (y_{g} - y_{g-1})^2 + (z_{g} - z_{g-1})^2 &= b^2 \\
F(x_{g}, y_{g}, z_{g}) &= 0
\end{align*}
\]

**Finite Element Approach**
- modeling 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
Comparison of the Different Approaches

**Kinematic Approach**
+ fast & easy to use
+ many software available
+ good interface to structural analysis
- no material behavior
- no process influence
- poor results for complex shapes

**Finite Element Approach**
+ accurate results even for complex shapes
+ accounts for material and process influence
+ prediction of draping defects possible (wrinkles, gaps, etc.)
- higher computational effort
- material testing required

Catia CPD (Kinematic Simulation)  
Experiment  
PAM-FORM (FE Simulation)
Finite Element Approaches for Draping Simulation

**Macro-FE Approach**
- modeling 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

**Meso-FE Approach**
- modeling of the preform on yarn-level with 2D/3D elements
- simulation of Unit Cells deformations
- consideration of friction between yarns, weaving structure,…
- prediction of deformation modes and behavior of units cells
- Not yet suitable for forming simulation (computational cost) on part scale
Simulation Procedure

Material characterization (simulation of the material behavior)
- Picture Frame Test
- ...

Validation on test geometry
- Hemisphere
- Double Dome
- ...

Process simulation (design and optimization)
- Diaphragm draping
- Drape forming
- Hand lay-up
- ...

Parameter Determination

Validation

Saertex
Material Characterization Devices at LCC

- Picture Frame Test
- Tensile Test
- Cantilever Test
- Bias Extension Test
- Friction Test
Validation

Material card has to be validated before applying the simulation on actual processes

1. Set up of **validation process**
2. **Simulation** of validation process
3. **Measurement** method to compare simulation and test results
Example:

FE Simulation of Diaphragm Process
Example – Simulation of Single Diaphragm Process

Principle:
Draping of a textile with a silicone membrane (diaphragm)

- Placing the fabric over the tool
- Lowering the edges of the membrane
- Applying a vacuum between tool and membrane
- Thermal binder activation

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Simulation of the Diaphragm Process

Modeling
- Macro-scale simulation with PAM-Form (ESI Group)
- Material 140 – „biphase shell element material with thermo-visco-elastic matrix and elastic fibers“

Setup
- Draping of a biaxial NCF over a generic helicopter frame
- Modeling of membrane, fabric, tool and table
- Same sequence as in experiment
Characteristics of the Diaphragm Process

- Relative movement between membrane and textile
  --> Results in high friction forces

- Anisotropic friction between membrane and textile
  --> Orthotropic friction coefficient needs to be defined
Simulation Results for Single Ply Draping

Experiment

+/-45 NCF

Simulation

-/+/45 NCF

(Eurocopter DE)
Example:

FE Simulation of locally stitched NCF Forming
Local Stitching

NCF preform stacks are locally stitched together for better handling

- Stitching can influence the draping result
- Influence of the local stitching needs to be investigated

Sewing of Preform Stack

Lay-up on Tool

Draping of Stitched Preform Stack

Final Part: Pitch Horn

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Single-Lap Shear Test

Purpose of test

- Investigation of initial state: pretensed stitch <> slack in stitch
- Influence of the stitching on the textile
- Stress-Strain behavior of the textile in the stitching vicinity
Modeling the Stress-Strain behavior of the Stitching

- Only normal stress are applied on PLINKS
- Definition of a Load-Displacement curve for PLINKS elements

**Phase I:** Slack phase $\rightarrow$ Lap Shear Test

**Phase II:** Fibers deformation $\rightarrow$ Lap Shear Test

**Phase III:** Stitching thread elongation $\rightarrow$ Bias Extension Test

\[ F_{\text{max}}: \text{Maximum bearable force} \rightarrow \text{Lap Shear Test} \]
Simulation of double diaphragm forming process

- Comparison on a real forming process: generic double curved helicopter frame
- FE meshing automatically created from CAD data
Comparison

<table>
<thead>
<tr>
<th>Layup</th>
<th>Region</th>
<th>Average angle difference</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0/90 // -/+45]</td>
<td>a</td>
<td>1,89°</td>
<td>1,07</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>4,7°</td>
<td>5,28</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>13,15°</td>
<td>6,85</td>
</tr>
</tbody>
</table>

Margossian et al, Comp. Part A, 2014
Automated Fiber Placement (AFP) Process Simulation
Overview – Simulation of the AFP – Process

Placement – scenario

Validation

Simulation Model

Therm. and mech. material models

[15.5.2014]

Process Simulation of Composites
Research Activities at the LCC

1D – Simulation:
- Calculation of the time-dependent mech. compaction behaviour
- Simulation of the transient heat transfer

2D – Simulation:
- Prediction of the mech. and therm. behaviour of the process
- Simulation of bridging of the tape
- Modeling of tack

3D – Simulation:
- Mech. placement on complex geometry possible
- Prediction of the complete thermal history of the placement process
**AFP – Process Simulation: Example**

- Gap- / Overlap detection
- Compaction / Debulking
- Bridging
- Temperature distribution

⇒ **Define reliable process window**

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**Fig. 1:** Gap in Simulation

**Fig. 2:** Compaction behaviour of a Slit-Tape

**Fig. 3:** Sim. Bridging

**Fig. 4:** Surface temperature distribution
Braiding Process Simulation
**Braiding Process Simulation**

- **Goals of braiding process simulation**
  - Process parameters have a strong influence on braided structure
  - Mandrel shape defines contour of structure
  - Modeling the real manufacturing process using an explicit FE-Solver (e.g. Abaqus/Explicit, PAM-Crash) to analyze correlation between process parameters and braided structure

- **Rovings are represented by truss- or beam-elements**

- **Consideration of friction between**
  - roving-roving
  - rovings-guide ring
  - rovings-mandrel
Simulation of Liquid Composite Moulding (LCM) processes
Motivation

Goals

• Prediction of process parameters
  • Tool pressure
  • Flow front velocity
  • Fill time
  • Prediction of defects (dry spots, pores)
  • Cure kinetics / Heat transport

• Optimization of injection schemes

• Tool design

• Design of robust processes

Challenges

• Material characterization
  • Preform
  • Resin

• Capturing influences of preceding process steps (such as textile handling, preforming)
Flow processes in porous media can be described by the Navier-Stokes equation:

\[ \rho \frac{\partial v}{\partial t} = -\nabla P + \nabla \cdot T + f \]

By homogenization of the media (e.g. by volume averaging) and introducing some assumptions, the flow can be described by Darcy’s law:

\[ v = \frac{K}{\mu} (\nabla P - \rho g) \approx \frac{K}{\mu} \nabla P \]

Darcy’s law relates the flow front velocity \( v \) to the applied pressure gradient \( \nabla P \) with the proportionality constants permeability \( K \) and viscosity \( \mu \).

Permeability is a material parameter of the fiber preform:
- Material
- Layup
- Fiber orientation
- Compaction state

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**Tab.1:** Summary of assumptions for validity of Darcy’s law

- Newtonian Fluid
- Constant Viscosity
- Homogeneous, Inelastic Porous Medium
- Neglecting of Gravity and Capillary Forces
- Low Flow Velocity (\( Re < 1 \))
- Saturated Flow
- Neglecting Intra Yarn Flow

**Fig.1:** Illustration of flow fronts (Real vs. Darcy) within an textile preform
Permeability Testing for LCM Processes

(lat.: *permeare* = 'to pass')

**Description**

In the 3D case the permeability can be noted as a 2nd order tensor.

\[
K^* = \begin{bmatrix}
K_{11} & 0 & 0 \\
0 & K_{22} & 0 \\
0 & 0 & K_{33}
\end{bmatrix}
\]

The tensor can be diagonalized with a rotation of the global coordinate system to a coordinate system spanned by the major permeabilities (cf. Eq.1).

**Determination**

- Experimental
  - 1D-flow method
  - Radial-flow method (2D)
  - 3D-flow method
- Numerical (Multi-scale approach)
  - CFD-calculation on meso-level based on representative volume elements (RVE)
  - Abstraction of the results to the macro level as permeability tensor

Fig.1: 3D permeability tensor

Fig.2: In-plane test setup

Fig.3: Off-plane test setup
Numerical Method - Overview

- Fabric Scan
- "Grey Box" Software Tool (Matlab)
- Image Analysis
- Textile Modeling
- Permeability Calculation
- Material Data
- Material Card
- RTM Process Simulation (PAM-RTM)
  - Draping Simulation
  - Process Parameter
  - CAD

Fig.1: Fabric Scan
Fig.2: Image Analysis
Fig.3: Textile Model [WiseTex, KU Leuven]
Determination of Process Induced Deformations (PID) & Curing Simulation
Motivation: Dimensional Control on Stiff Structures

- Geometrical deviations on stiff structures result in
  - Additional rework effort and / or high mounting forces required,
  - Expensive iterative tooling adaption.
Curing simulation - goals

- **Primary:**
  - Determination of process induced deformations (dimensional accuracy)
  - Evaluation of the effects of residual stress (dimensioning)

- **Secondary:**
  - Process optimization (cycle time)
  - Process control (interaction between parallel simulation of physical curing process)
Methodologies for determination of process induced deformations (PID)

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)

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

Evaluation of Residual Stresses, Optimization of Process Control

PID Quantification (Dimensional Control)
Simplified Approaches for PID Determination

Utilization of simplified approaches for strain anisotropy

\[ \alpha_{m,eq} = \alpha_{m,therm} + \alpha_{m,chem} \]

Fig. 1: Thermal and effective chemical shrinkage are projected on the matrix coefficient of thermal expansion

Fig. 2: Experimental Spring-In data presents target variable for determination of \( \alpha_{M,eq} \)

Fig. 3: Verification of \( \alpha_{m,eq} \) on linear-elastic FEA of cool down step
Process simulation including curing: application flow on the example COMPRO

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

Figure: Experimental determination of effective HTC

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

Figure: modulus development

Thermo-chemical module
- reaction kinetics
- heat conduction

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

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

Johnston A., Hubert P., 1996

COMPRO is a commercial composite processing software: Convergent Manufacturing Technologies, Canada
Characterization for Process Simulation

Resin Cure Kinetics

Viscosity Development

Cure Shrinkage

Modulus Development

Database
Curing / PID simulation - results

- **Quantities:**
  - Deformations
  - Residual stress
  - Spatial distribution of fiber volume fraction
  - Time history of temperature evolution on the part
  - Final degree of cure distribution
  - Glass transition temperatures

- **Assessment a priori concerning:**
  - Mounting tolerances, dimensions of tooling
  - Load bearing capacity
  - Part’s quality (sufficient degree of cure, glass transition temperatures, hot spots (resin degradation))

- **Optimization via variation of**
  - Geometry
  - Material selection
  - Lay-up
  - Process cycle

Fig. 1: Spring-In of a generic C-frame after curing

Fig. 2: Temperature Distribution on a Frame Section at the End of 2nd Ramp [simulated utilizing Compro2D and Raven, Convergent Manufacturing Technologies, Vancouver, Canada]
Simulation Platform
Simulation Platform

- Material Modeling
- Forming Simulation
- Structural Analysis
- Compaction, Curing and Consolidation
- Flow Process Simulation

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Process Simulation of Composites
Process Simulation Platform - Example

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

Preform Characterization
- Experimental
- Numerical

LCM-Simulation
- Tool design, Process time prediction
  (Flow front velocity, pressure distribution)
- Process optimization
- Curing simulation (for PID investigations)
Conclusion - Outlook
Manufacturing
Geometry, Quality
(Waviness, Porosity, etc.)

In-service,
Recycling
Allowable Damages
Repair

Robust Design
via Simulation as Built

Product Development
Design, Process Simulation,
Structural Analysis, Testing,
Quality Assurance,…

Thank you
for your attention!

Geometry

Effects

Design to fiber

Design to process

Material