High resolution CT-scans of fiber reinforced materials and technical textiles: analysis and potential for numerical simulations

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Europe’s largest Textile Research Center

German Institutes for Textile and Fiber Research Denkendorf (DITF)

1. Institute for Textile Chemistry and Chemical Fibers
2. Institute of Textile Technology and Process Engineering
3. Center for Management Research
4. Denkendorf Product Service Ltd.
Competence in Textile Research

Research from molecule to product along the entire textile process chain
Application-oriented research with pilot plants (140 industrial projects per year)
Focus on Technical Textiles and Life Science

Technology transfer center and production for the industry

Knowledge transfer in the whole textile value chain: “Making knowledge productive”
German Institutes of Textile and Fiber Research Denkendorf (DITF)

- Founded in 1921
- Foundation under public law
- approx. 310 employees (50% scientists)
- Turnover: 28.3 million €
- 75% application oriented research with industry, 25% production
- Patents: 70
- QM-Systems to DIN EN ISO 17025 (DAkkS) and DIN EN ISO 13485 (BSI)
Finite-Element-Simulation at ITV: micro/meso-models considering real structure

- spinning
- weaving
- knitting
- braiding
- composite

FEM-draping a clamped knitwear by a sphere

FEM: draping an aramid fabric over a part

FE-Simulation of a braiding process

FE-Simulation of a knitting process

FEM: warp knitting of multiaxial fabrics
1. Introduction

2. Generating precise fabric models to compute permeability by CFD codes.

3. Computing permeability of fabrics using new software module of VGStudio MAX

4. “Real” permeability by analyzing resin consolidated composite parts

5. Development of an in-situ CT test stand

6. Conclusion and outlook
1. Introduction

- To produce composite parts there are various processes as:
  - Vacuum Assisted Resin Transfer Molding
  - Wet Molding
  - Resin Transfer Molding (RTM)

Process Overview of the Resin Transfer Molding

[Source: Benteler SGL]
1. Introduction

- Design mold process as RTM to produce composite parts is still a trial and error process.
- Tools of simulation of the filling process are available but do lack in prediction quality due to **unknown local permeability values** (essential material data for RTM-process simulation !)

Simulation of Infiltration using LS-DYNA [Source: Dynamore]
1. Introduction

RTM infiltration process is influenced by many parameters:

- Resin property (viscosity, material & curing behavior)
- Process parameter: pressure, temperature, time:
  - interaction resin /rovings can change of orientation and packing density
- Reinforcement fabric:
  - roving yarn count (diameter and number of filaments)
  - roving preparation (filaments stick together)
  - fabric structure, number an orientation of layers, connection thread
- Shape of the composite part:
  - draping the plane fabrics to the form leads to numerous and extensive changes of roving course: change of orientation and packing density
  - compression by closing form leads to closing gaps
1. Introduction

Example: Simulation of draping of 4 layers of unidirectional carbon fabrics to a complex shape

- change of fibre orientation, packing density and so permeability!
2. Generating precise fabric models to compute permeability by CFD codes

Non-crimp fabric 610 g/m²: Carbon 50K/50K, sewed, +/-45°

Result of the fiber orientation analysis performed with VG-Studio Max

High resolution CT-Scan at ITV by GE nanotom m
2. Generating precise fabric models to compute permeability by CFD codes

non-crimp fabric 610 g/m²: Carbon 50K/50K, sewed, +/-45°
2. Generating precise fabric models to compute permeability by CFD codes

virtual cut area: basic unit

result of exact surface determination of this area
2. Generating precise fabric models to compute permeability by CFD codes

Extracting roving surface for CFD-computation
2. Generating precise fabric models to compute permeability by CFD codes

Extracted first layer: fine modeled FE-mesh
2. Generating precise fabric models to compute permeability by CFD codes

- extraction of fabric layers (roving surface) and sewing threads by VG fibre material analysis:
  - precise fabric model as base for composite models
  - enables CFD-Simulation to compute permeability
2. Generating precise fabric models to compute permeability by CFD codes

Use of high resolution CT scans to gain simulation models for detailed flow (CFD) simulations and determination of permeability tensor using OpenFoam

**CFD model requires:**

- Enormous meshing work
- Periodical boundary conditions
- Smooth continuous surface
- No gaps, holes

Leads to

- Time consuming modelling work
- Extreme computation time

Other „practical“ solution to compute permeability?

[Source: FluiDyna, Gaudlitz, Bachschuster]
Computation of permeability by CFD with idealized models and acceptable effort is possible, database for different loading conditions.
3. Computing permeability of fabrics:

- Computation of material property „permeability“:
  - High resolution CT-Scans contain all important structure and fibre information to perform a infiltration simulation to compute permeability values.

- New software modul for VGStudio MAX 3 (beta version):
  - steady flow computation of an incompressible fluid through „gaps“ of „porous“ material.
  - flow is driven by definition of pressure difference between two parallel planes.
  - boundary condition are „closed“ oder „constant gradient“.
  - automatic computation of the permeability tensor by a serie of flow simulations.

Properties of Permeability Experiment: Analysis 1 of Volume 1

<table>
<thead>
<tr>
<th>Setting</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Permeability [m²]</td>
<td>3.98e-11</td>
</tr>
<tr>
<td>Total Volume Transport [m³/s]</td>
<td>1.45e-09</td>
</tr>
<tr>
<td>Imposed Pressure Gradient [Pa/m]</td>
<td>687</td>
</tr>
<tr>
<td>Relative Error</td>
<td>0.000040</td>
</tr>
<tr>
<td>Total Number of Iterations</td>
<td>10000</td>
</tr>
<tr>
<td>Void Fraction [%]</td>
<td>81.78</td>
</tr>
<tr>
<td>Effective Void Fraction [%]</td>
<td>81.73</td>
</tr>
</tbody>
</table>
3. Computing permeability of fabrics: Non-crimp fabric under shear loading

- Investigation of change of permeability by shear loading
- Requires special well defined sample preparation

Special test device for shear loading

Textile sample under shear load

unidirectional (UD) carbon fabric defined clamped under tension loading

unidirectional carbon fabric under defined shear loading:

- special frame for CT-scan is glued to the deformed fabric

result of CT-scan
(7,7µm resolution)

selected area
to compute
permeability
(20mmx18mm)

sample ready to scan

settings in the „Permeability Experiment“ analysis window

result of steady flow computation: Visualisation of stream lines (velocity)

- porosity plot
- stream lines and velocity
3. Computing permeability of fabrics: Complex braiding structures

Braiding mandrel made by 3D-printing (PA)

Real braiding and virtual (FEM) process simulation

CT-scan of produced part: ROI shows analyzed area
3. Computing permeability of fabrics: Complex braiding structures – surface

- Result of the surface determination: “sharp” and “well balanced” settings

- surface “sharp” defined
- surface “well balanced” defined
3. Computing permeability of fabrics: Complex braiding structures – in-plane flow

Top view a): Stream lines (max. flow in gaps between braided yarns and mold)

Bottom view b): reduced flow because of virtual vacuum foil considered by ROI

mandrel (here mould)
represents vacuum foil
3. Computing permeability of fabrics: Complex braiding structures – influence

- Best results possible of CT scan by setting grid size to CT-Scan resolution, but leads to:
  - high amount of RAM required (considered area with 40µm exceeds available 256GB)
  - very long computation time (several hours)

<table>
<thead>
<tr>
<th>Simulation cell size (grid)</th>
<th>Absolute permeability ((10^{-9} \text{ m}^2))</th>
<th>Absolute permeability ((10^{-9} \text{ m}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>48 µm</td>
<td>60 µm (1.5 x Voxel)</td>
<td></td>
</tr>
<tr>
<td>Surface detection sharp</td>
<td>2.03</td>
<td>1.99</td>
</tr>
<tr>
<td>Surface detection well balanced</td>
<td>0.91</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Influence of surface detection and cell size for flow computation

- For this fabric difference between 48 and 60µm was only 3.3%
- Performed surface detection has much more influence to the result
- Investigations are ongoing referring influence parameter and transversal flow
- CT analysis to the by VARI- (vacuum assisted resin infusion) infiltrated part
3. Computing permeability of fabrics: Complex braiding structure- verification

- Verification of simulation by comparison between reality and simulation results:
  - Direct comparison of braiding angles at various “hot spots”
  - Exporting fibre orientation tensor, importing and visualization of extracted orientations in FE-software LS-PrePost containing simulation model

Result of the fiber orientation analysis to 3D-CT Modell using VGStudio max
4. “real” permeability by analyzing resin consolidated composite parts

Demonstrator „cap profile“, detail scan

Sample cut out of „cap profile“ (14mm x 11mm), 5µm resolution

- CT-scan shows complete structure, layers, imperfections, air pockets
- Enables extraction of relevant fiber information (orientation, distribution, fiber volume content)
4. “real” permeability by analyzing resin consolidated composite parts

Demonstrator „cap profile“, detail scan

➢ using fibre orientation analysis of VG all 8 layers of the UD-fabric can be extracted: 0/90/+45/-45/-45/+45/90/0° fibre orientation.
4. “real” permeability by analyzing resin consolidated composite parts

1. Determination of fibre surface

2. Steady flow computation

- areas of resin removed
- definition of „Inlet“ and „Outlet“
4. “real” permeability by analyzing resin consolidated composite parts

\[
P = 1 \text{ Pa} \\
P = 0 \text{ Pa} \\
V = 0 \text{ (sealed)}
\]

stream lines

[Source: Dr. J. Fieres, Volume Graphics GmbH]
A loading test device for µ-CT is under development by Kammrath & Weiss GmbH and ITV Denkendorf (cooperation project). This high precise test device will be adopted to GE nanotom m first, available for other CT later on.

**Features:**
- No X-ray absorbing parts in the beam
- Exchangeable load cells up to 5kN
- Upgradeable to various loading conditions
- Easy and reliable clamping
- High flexibility referring applications

**Test methods**
- Tensile
- Compression
- Bending
- Shear
- Torsion …

Please contact us, if there are wishes referring special requirements, they can still taken into account at this development stage
6. Conclusion

- New possibilities by high resolution CT-Scans at high quality (low noise ratio) to investigate fabrics and composite parts with nanotom m at ITV.

- New possibilities by new analysis features of VG Studio Max referring fibre orientation and permeability analysis of fabrics and composite parts show great potential. Investigations referring permeability computation still going on.

- Combining CT-analysis and numerical Simulation (FEM/ CFD) will lead to many advantages in composite area e.g. improvement of production processes by:
  - More precise simulation models, verification
  - Getting material data by CT-analysis as input for numerical simulations
  - More reliable mold (e.g. RTM) process simulations by knowing local permeability values
  - Deeper material understanding

- In-situ loading test device for µ-CT is under development, first results will be available in 2016. This will increase the filed of applications of µ-CT and also FE-Simulation in a big scale
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