Systematic approach for an FE-based process simulation framework for wet compression moulding of continuously reinforced composites

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Keywords:
- FE-Forming Simulation
- FE/CV
- Wet Compression moulding (WCM)
- Viscous Draping
- FSI
Outline

- Introduction of Wet Compression Moulding Process
- Systematic Approach for an macroscopic FE-based Framework
- Current research and findings
- Recap and Conclusion
- Roadmap
Introduction of Wet Compression Moulding Process
Introduction & Motivation
Wet compression moulding process

Figure 1: Illustration of the WCM-Process (adapted from [Pop18], based on [Ber16])

Figure 2: Subdivision of the viscous draping into process phases

Viscous Draping phase
- Coupled phase
- Fluid phase

- \( \vec{f}_{\text{Draping}} > \vec{f}_{\text{Fluid}} \) ~ 70%
- \( \vec{f}_{\text{Draping}} \approx \vec{f}_{\text{Fluid}} \) ~ 25%
- \( \vec{f}_{\text{Draping}} < \vec{f}_{\text{Fluid}} \) ~ 5%
Systematic Approach for an macroscopic FE-based Framework
Systematic Approach
Applied macroscopic breakdown in terms of modelling

- Large deformations
- Lagrangian formulation in FE-based simulation approaches
- Intra-Ply & Interface mechanisms $f(\eta, \nu)$
- Several macro. modelling approaches in literature [Wil08, Haa13, Ger13, Boi15, Mac16, Boi16, Guz16, Dör17, Sch17, Boi18, Dör18a, Pop18a, Hen19]

![Diagram](image)

- Eulerian Formulations (FV)
- Lagrangian formulation with control volumes (FE/CV) [Bus90 Tru93, Jos00]
- Simultaneous fluid progression and forming simulation [Pop18b]
- Curing [Ber16]

![Diagram](image)

- Viscous draping
- Fluid progression
- Coupled effects (FSI)

Which mechanisms require modelling?

- infiltration-dependent draping behaviour
- Permeability-dependent fluid progression
- Accurate process boundary conditions
- Fiberwashing, Impregnation, Cavity pressure

Figure 3: Deviation of the main process mechanisms regarding modelling
Current research and findings

Viscous Draping
Current research and findings
Viscous draping

Intra-Ply & Interface mechanisms $f(\eta, \nu)$

- Membran behaviour
- Bending behaviour
- Contact behaviour

Experiments with a modified infiltrated bias-extension test (IBET) [Pop18a]

- Viscous draping
- Experiments with a modified infiltrated bias-extension test (IBET) [Pop18a]

Figure 4: Test setup for the characterisation of infiltrated membrane behaviour

Figure 5: Exemplary result – dry vs. infiltrated membrane behaviour

Is this mechanisms worth modelling?

Yes, shear response is viscosity- and rate-dependent!
Current research and findings

Viscous draping

Intra-Ply & Interface mechanisms $f(\eta, \nu)$

<table>
<thead>
<tr>
<th>Membran behaviour</th>
<th>Bending behaviour</th>
<th>Contact behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constitutive equations:</strong></td>
<td><strong>→ hyperviscoelastic model [Pop18a]</strong></td>
<td></td>
</tr>
<tr>
<td>$\Psi(I_1^e, I_2^e, I_{12}^e, I_{12}^v) = \Psi_{\text{elong}}(I_1^e, I_2^e) + \Psi_{\text{shear}}(I_{12}^e, I_{12}^v)$</td>
<td>with $G_{12}(I_{12}^e)$ &amp; $\eta(I_{12}^e, I_{12}^v)$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: Exemplary result on component level in terms of shear angle distribution

Do this mechanisms require modelling? Yes, viscosity- and rate-dependent membrane behaviour with impact on component level!
### Current research and findings

#### Viscous draping

**Intra-Ply & Interface mechanisms** $f(\eta, \nu)$

<table>
<thead>
<tr>
<th>Membran behaviour</th>
<th>Bending behaviour</th>
<th>Contact behaviour</th>
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<tbody>
<tr>
<td>Large macroscopic slip during forming (Lubrication between the single plies)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscoelastic contact modelling required [Hüt17, Pop19 (accepted)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numerical modelling approach using the penalty-method [Pop19a based on Dör18b]:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Membran behaviour
  - Normal
    - $c_N$, $d_N$
    - $\xi_3, \dot{\xi}_3$
    - $N = \begin{cases} 
      0, & \xi_3 \geq \xi_3^{max} \\
      c_N^T \xi_3 + d_N \dot{\xi}_3, & 0 \leq \xi_3 < \xi_3^{max} \\
      c_P^T \xi_3 + d_P \dot{\xi}_3, & \xi_3 < 0 
    \end{cases}$ (no contact, adhesion, penetration)

- Bending behaviour
  - Tension
    - $c_N^T$, $\xi_3^{max}$
  - Pressure
    - $c_P^T$

- Contact behaviour
  - Tangential
    - $\xi_T, \dot{\xi}_T$
    - $d_T$
    - $c_T$
  - Normal
    - $N$

**T**

\[ T = \begin{cases} 
  c_T \xi_T + d_T \dot{\xi}_T, & \Phi \leq 0 \text{ (sticking)} \\
  \tau_T^{crit}(p, \eta, \dot{\xi}_T) \frac{\dot{\xi}_T}{\|\dot{\xi}_T\|}, & \Phi > 0 \text{ (sliding)} 
\end{cases} 

Iso. Yield function $\Phi$
Current research and findings
Viscous draping

Intra-Ply & Interface mechanisms $f(\eta, \nu)$

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<tr>
<td>Blank holder</td>
<td>Stamp</td>
<td>Laminate</td>
</tr>
<tr>
<td>Force-BC</td>
<td>Displacement-BC</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9: Exemplary simulation setup comprising 2 plies (0/90°,±45°) [Pop19a]

Figure 10: Results of the aver. Contact slip and state during forming [Pop19a]

Do this mechanisms require modelling?

Definitely. Beyond that, tangential with low transversal pressure and adhesion is currently investigated!
Recap and Conclusion
Recap and Conclusion
Applied macroscopic breakdown in terms of modelling

Current research and findings
- Infiltration- and rate-dependent Intra-Ply & Interface mechanisms
  - Membrane
  - Bending
  - Contact
- Sensitivity analysis of combined mechanism currently investigated

Current research and findings
- Lagrangian formulation with control volumes (FE/CV) within 2D Approach [Pop18b]
- 3D-Darcy approach required to account for suitable process boundary conditions
- Corresponding forming model required (compaction) → CS or Solid shell

Viscous draping
Fluid progression
Coupled effects (FSI)

Membrane
Internal ply structure [Dör17]

Not covered yet

Figure 11: Recap and current conclusion
Roadmap
Outlook and Roadmap
Macroscopic WCM-process simulation model

Research motivation in terms of process modelling
- Which mechanisms require modelling?
- Which mechanisms need accurate/effective modelling?
- How sufficient are theses approaches?
- How much effort has to be taken into material characterization?
- Are we able to predict complex coupled process effects?

Objective
Wet compression moulding process simulation module (Abaqus)

Legend:
S = Conv. Shell (cont. Thickness)
CS = Continuum Shell (variable thickness)
<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dör17</td>
<td>Dörr, D., Schirmaier, F.J., Henning, F., Kärger, L., A viscoelastic approach for modeling bending behavior in</td>
<td>Finite Element forming simulation of continuously fiber reinforced composites, Composites:</td>
<td></td>
</tr>
</tbody>
</table>


**Literature**

Hüt17  

Sch17  

Boi18  

Dör18a  

Dör18b  

Pop18a  

Pop18b  

Hen19  

Pop19a  

Pop19b  
Poppe et al: Comparative experimental and numerical analysis of bending behavior of dry and infiltrated woven fabrics, Composites Part A (under revision)
Thank you! Do you have any Questions?

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Special gratitude: To the German State Ministry for Science, Research and Art of Baden-Württemberg (MWK) for the funding of the project “Forschungsbrücke Karlsruhe-Stuttgart”