Non-destructive characterization of wrinkle morphologies in composite materials by means of experimentally validated finite element analysis

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Agenda

- Motivation
- Test plate fabrication
- Infrared thermography and digital shearography
- Finite element model
- Results and discussion
- Conclusions
Motivation

**Fig. 1** Manual ply layup (Source: FACC)

**Fig. 2** Automated Fiber Placement (Source: PAG)
Motivation

Fig. 3 Compression test of UD-laminate – comparison of planar vs. wavy specimen.
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Test plate fabrication
Two-step manufacturing method of cross-ply test plates
Test plate fabrication
Realized wave configurations and their position in the laminate

<table>
<thead>
<tr>
<th>Wave position</th>
<th>Laminate thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>center</td>
<td>8 mm</td>
</tr>
<tr>
<td>center</td>
<td>10 mm</td>
</tr>
<tr>
<td>bottom</td>
<td>10 mm</td>
</tr>
<tr>
<td>top</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

Wave 1:
A=2mm, L=15mm

Wave 2:
A=2mm, L=10mm

Plate 1
Plate 2
Plate 3
Plate 4

Wave 1
Wave 2

~400 mm
~150 mm
Test plate fabrication
Optical microscopy images of polished samples
Agenda

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Infrared thermography (IRT)

Test set-up

(a) transmission mode  
(b) reflection mode  
(c) heat flux evaluated at the cross-sectional area

High-resolution infrared camera FLIR X8400sc
Infrared thermography (IRT)
Principle of active infrared thermography testing of out-of-plane fiber waviness

Thermography:
Bundling, respectively spreading of heat flux

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Early signal shape
Smeared signal due to lateral heat flow

Exitation

Reflection top

Transmission top

Reflection bottom

Transmission bottom
Digital shearography

Test set-up

a) reflection mode at top side

b) reflection mode at bottom side
Digital shearography
Principle of shearography testing of out-of-plane fiber waviness

Shearography:
Negative thermal expansion of carbon fibers in fiber direction leads to an indention on the top surface or a bulk on the bottom surface, respectively.
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Finite element model
General modelling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$ [g/cm³]</td>
<td>1.56</td>
</tr>
<tr>
<td>Conductivity longitudinal, $k_{\text{long}}$ [W/mK]</td>
<td>7.0</td>
</tr>
<tr>
<td>Conductivity transversal, $k_{\text{trans}}$ [W/mK]</td>
<td>0.7238</td>
</tr>
<tr>
<td>Specific heat, $C_p$ [J/kgK]</td>
<td>895.376</td>
</tr>
<tr>
<td>Young’s modulus longitudinal, $E_{\text{long}}$ [GPa]</td>
<td>171.42</td>
</tr>
<tr>
<td>Young’s modulus transversal, $E_{\text{trans}}$ [GPa]</td>
<td>9.08</td>
</tr>
<tr>
<td>Shear stiffness, $G_{12}$, $G_{13}$ [GPa]</td>
<td>5.29</td>
</tr>
<tr>
<td>Shear stiffness, $G_{23}$ [GPa]</td>
<td>3.98</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu_{12}$, $\nu_{13}$ [-]</td>
<td>0.32</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu_{23}$ [-]</td>
<td>0.43</td>
</tr>
<tr>
<td>Coefficient of thermal expansion longitudinal, $\alpha_{\text{long}}$ [K⁻¹]</td>
<td>-5.5E-6</td>
</tr>
<tr>
<td>Coefficient of thermal expansion transversal, $\alpha_{\text{trans}}$ [K⁻¹]</td>
<td>2.58E-5</td>
</tr>
<tr>
<td>Heat transfer coefficient (surface film coefficient), $U$ [W/m²K]</td>
<td>10.0</td>
</tr>
</tbody>
</table>
Agenda

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# Results

Infrared thermography (experiment)

<table>
<thead>
<tr>
<th>Infrared thermography</th>
<th>Plate 1 position center</th>
<th>Plate 2 position center</th>
<th>Plate 3 position bottom</th>
<th>Plate 4 position top</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffusion time results in transmission mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results
Infrared thermography

Comparison of the temperature profile of the experiment (blue) and simulation (red) of the undisturbed region
Results
Infrared thermography

Temperature differences at 15 seconds of plate 3 with wave 1 obtained from (a) experimental setup and (b) FEM simulation.
Results
Infrared thermography

Representative FEM result of the spreading (a) and bundling (b) heat flux due to excitation on the top and bottom side, respectively, for plate 2 containing wave 1
Results
Infrared thermography

Comparison of measurement (blue) and simulation (purple).

a) Plate 1, wave 1, at 10 seconds, reflection mode, analyzed on the top side;
b) Plate 2, wave 2, at 10 seconds, transmission mode, analyzed on the bottom side
Results
Infrared thermography

![Graphs showing results of FEM simulations in reflection (a) and transmission (b) modes.](image)

Resulting signals obtained from FEM simulations in a) reflection mode and b) transmission mode.
Results
Digital shearography (experiment)

<table>
<thead>
<tr>
<th>Plate 1</th>
<th>Plate 2</th>
<th>Plate 3</th>
<th>Plate 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>position center</td>
<td>position center</td>
<td>position bottom</td>
<td>position top</td>
</tr>
</tbody>
</table>

Digital shearography

Results shown for 20 s excitation
Results
Digital shearography

(a) Experimental and (b) simulation results of the digital shearography. First derivative of the deformation on the basis of grey values. Plate 1, wave 1, excited and evaluated on the top side.
Representative deformation, i.e. displacement in y-direction, of a coupled temperature-displacement simulation of plate 1 containing wave 1 with an excitation from the top side at t=60s
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Conclusion

• Great potential for the detection of embedded out-of-plane fiber waviness
• **Infrared thermography**: possible to determine the defect as well as the orientation of the fiber waviness from the appearance of the resulting signal. The wavelength can also be determined accurately.
• **Digital shearography**: Qualitative investigation. Wavelength was clearly detectable based on the signal of the deformation gradients

Outlook

• Several additional variations of wave configurations and positions, i.e. wavelengths, amplitudes and depths in the laminate
• Describe the relationship between the depth position of the wave and the intensity and duration of the signal.
• The presented NDT results are one part of several comprehensive research projects on fiber waviness including:
  • Formation mechanisms in manufacturing
  • Simulation and material modelling
  • Multiscale modelling
  • Testing
Abstract: Out-of-plane fiber waviness, also referred to as wrinkling, is considered one of the most significant effects that occur in composite materials. It significantly affects mechanical properties, such as stiffness, strength and fatigue; and, therefore, dramatically reduces the load-carrying capacity of the material. Fiber waviness is inherent to various manufacturing processes of fiber-reinforced composite parts. They cannot be completely avoided and thus have to be tolerated and considered as an integral part of the structure. Because of this influenceable but in many cases unavoidable nature of fiber waviness, it might be more appropriate to consider fiber waviness as effects or features rather than defects. Hence, it is important to understand the impact of different process parameters on the formation of fiber waviness in order to reduce or, in the best case, completely avoid them as early as possible in the product and process development phases. Mostly depending on the chosen geometry of the part and the specific manufacturing process used, different types of fiber waviness result.
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