Meso-scale strain mapping in Plain and UD woven composites

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Textile Composites

Plain weave
5-end sateen weave
braided structure
Non-crimp fabric (NCF)

3D weaves
Motivation

• In dry textiles, interaction between reinforcing and binding tows results in local perturbations.
• Processing (compaction, drape etc) leads to further tow geometry changes in Textile Composites
• Limited experimental data is available on local strain distribution
Strain Measurement

- Strain Gauges
- Bragg grating sensors (>100µm dia)
- DIC
- Reinforcing fibers as strain gauges
Outline

• Reinforcing fibers as strain gauges (gauge length = 2 μm)
• Geometry of balanced Plain Weaves
• Strain gradients in ‘plain weave’ textile composites
• Prediction of limit strengths
• Geometry of UD weaves influenced by compaction
• Strain gradients in UD composites
• Discussion
Optical/Raman microscope

- Video Camera
- Sample
- Holographic Filters
- Slit
- Diffraction Grating
- Spatial Filter
- Rejection Filter
- CCD Camera
- Laser Source
- Laser spot size: 2 μm
- Computer Interface

Laser spot size - 2 μm
Raman Spectrum

Kevlar 49

1610 cm\(^{-1}\) Band
Aromatic Ring Stretching Mode

Full Raman Spectrum

Stress-induced Band Shift
Strain-Induced Band Shifts

SINGLE FIBER DEFORMATION

Stress-strain curves

Raman band shifts
## Plain Woven PBO Composites

![Image of PBO fibers]

### Table of Properties

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fiber treatment</th>
<th>Resin system</th>
<th>Ends/cm</th>
<th>Picks/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBO 1</td>
<td>corona treated</td>
<td>A</td>
<td>9.2</td>
<td>9.2</td>
</tr>
<tr>
<td>PBO 2</td>
<td>corona treated</td>
<td>B</td>
<td>9.2</td>
<td>9.2</td>
</tr>
<tr>
<td>PBO 3</td>
<td>as spun</td>
<td>B</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Linear density (Tex)</th>
<th>Number of filaments</th>
<th>Fiber diameter (μm)</th>
<th>Density (g/cc)</th>
<th>$E_{11}$ (GPa)</th>
<th>$E_{22}$ (GPa)</th>
<th>$G_{12}$ (GPa)</th>
<th>$\gamma_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.5</td>
<td>250</td>
<td>12</td>
<td>1.54</td>
<td>180</td>
<td>0.91</td>
<td>1.02</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Raman Deformation Mapping

The laser beam was always polarised parallel to the axis of both the fibres and the applied force.

The woven composites were deformed in the axial direction.

Fibre deformation was mapped during the deformation of the woven composites. The overall composite strain was determined from the strain gauge.
1D Strain Distributions along tow centre line

PBO1

PBO2

PBO3
# Lenticular Geometry

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yarn width (mm)</th>
<th>Yarn (t) thickness (mm)</th>
<th>(R) Radius of lenticule</th>
<th>φ (deg) Off-axis angle</th>
<th>(A) mm² Yarn cross-section area</th>
<th>(ρₜ) yarn packing factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBO1</td>
<td>1.1</td>
<td>0.074</td>
<td>4.11</td>
<td>7.7</td>
<td>0.0542</td>
<td>0.6655</td>
</tr>
<tr>
<td>PBO2</td>
<td>1.1</td>
<td>0.103</td>
<td>2.98</td>
<td>10.6</td>
<td>0.0753</td>
<td>0.478</td>
</tr>
<tr>
<td>PBO3</td>
<td>1.02</td>
<td>0.129</td>
<td>2.06</td>
<td>14.3</td>
<td>0.0885</td>
<td>0.4069</td>
</tr>
</tbody>
</table>
Computing 2D strains in a tow

Half of Tow is monitored
PBO1: ACP 523 0.4% strain

strain distribution across tow width
Elastic Properties

Exx

- Experimental (GPa)
- Analytical
- FEM
## Strength & Failure Strains

<table>
<thead>
<tr>
<th>Composite</th>
<th>Exp, Strain %</th>
<th>Exp, Strength (GPa)</th>
<th>FEM, Strain %</th>
<th>FEM, Strength (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBO-523</td>
<td>2</td>
<td>0.63</td>
<td>2.25</td>
<td>0.601</td>
</tr>
<tr>
<td>ACP</td>
<td>2.6</td>
<td>0.56</td>
<td>2.86</td>
<td>0.5383</td>
</tr>
<tr>
<td>PBO-525</td>
<td>2.8</td>
<td>0.51</td>
<td>3</td>
<td>0.5267</td>
</tr>
<tr>
<td>ASM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Experimental limit strain (%)**

- $y = 1.0933x$
- $R^2 = 0.9746$

**Exp limit strength (GPa)**

- $y = 0.9774x$
- $R^2 = 0.6569$
UD weave or uni-weave

Unbalanced plain weave with majority of fibers (98%) in warp direction)
Geometry of UD woven fabric
Tow geometry after compaction
Model Kevlar UD composite
Axial strains plot along tow centreline
Axial Strains across tow width

Narrow section

Wide section
FE Predictions on carbon UD laminate

- Tow properties at 0.577 fiber volume fraction
  - $E_{11}=133.86\text{GPa}$, $E_{22}=7.251\text{GPa}$
  - $G_{12}=8.78\text{GPa}$, $V_{12}=0.302$

<table>
<thead>
<tr>
<th>Results</th>
<th>FE prediction</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Modulus</td>
<td>129.1 GPa</td>
<td>128 GPa</td>
</tr>
</tbody>
</table>
FE prediction of axial strains across tow width
Discussion

• Meso-scale strain gradients in textile composites can be measured using reinforcing fibers as strain gauges, with a gauge length of 2µm.
• Kevlar, PBO have been used as strain sensors. Future plans to use high modulus carbon fibers.
• Influence of tow distortions due to stitching, 3D weaving can be assessed.