Progressive Damage Characterization of Stitched, Bi-axial, Multi-ply Carbon Fabrics Composites

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Outlines

- Brief Material Description
- Aims
- Experimental Set-up
- Results
- Conclusions and Future Works
Multi-axial Multi-ply Carbon Fabrics (MMCFs)
also known as
Non-Crimp Fabrics (NCF)

**Production:**
Tows are spread in plies with any chosen orientation and then they are stitched together

**Advantages:**
- Unidirectional-straight reinforcement leads to better mechanical properties (No-crimp);
- Reinforcement orientability;
- Good drapeability and permeability;
- Manufacturing time reduction.
Material (II)

**Bi-axial (0/90°) Multi-ply Fabric**

**Reinforcement**
- Producer: Seartex Gmbh
- Architecture: Bi-axial 0°/90°, 24K, T600
- Ply Areal Density: 150±5% g/m²
- Stitching Yarn: Polyester (PES)
- Stitching Pattern: Tricot-Warp
- Areal Density: 6±5% g/m²
- Fabric Areal Density: 325g/m² (exp.)

**Resin system**
- Producer: Shell ®
- Resin: Epikote® 828 LV
- Hardener: Epikure® DX 6514
- Mixing Ratio: Resin/Hardener = 100/17

**Lay-up**
- 8 fabrics (16 plies) symmetrical lay-up
- [ (0/90) / (90/0) / (0/90) / (90/0) ]₅
- Final Thickness: ~ 3.5 mm
- Volume fraction: Vᵢ ~ 40%

**RTM Process’ Parameters**
- Mold Vacuum: 0.4 ÷ 0.6 bar
- Injection Pressure: 2 ÷ 4 bar
- Injection Temperature: 40°C
- Injection Time: 20 ÷ 25'
- First Cure: 70°C / 60'
- Final Cure: 160°C / 60'

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Stitching induced Fabric defects:

- **INTRA-layer CHANNELS**
  - MD Channels $\approx 0.56$ mm
  - CD Channels $\approx 0.28$ mm

- **INTER-layer GAPS**
  - 0/0° Gaps $\approx 60 \mu$m
  - 90/90° Gaps $\approx 80 \mu$m
Main Goal

DAMAGE CHARACTERIZATION under Quasi-static loads

Intermediate steps:

• Damage evolution monitoring during quasi-static tensile tests along characteristic material directions;
• AE parameters analysis in relation to applied strain;
• Direct Damage Observation by the mean of NDT;
• Evaluation of the stitching role on damaging process
**Experimental Set-Up (I)**

**Damage evolution monitoring**

**Tensile tests according with ISO 527-4**

- 3 test direction: Machine, Cross and Bias directions;
- 100 kN INSTRON 4505;
- 50mm gage length axial extensometer
- Imposed displacement:
  - 1 mm/min along MD and CD
  - 3 mm/min along BD

**Acoustic Emission Records**

- 2 broadband transducer
- Digital wave equipment

**Electrical Resistance Technique**
Results
Results

Damage evolution monitoring

Stress and AE parameters vs strain

Machine Direction Charts

- Stress vs Strain
- AE Event Counts vs Strain
- Energy Index vs Strain
- Cumulative Energy Index vs Strain

Transition strain $\varepsilon_0$
Results

Damage evolution monitoring - AE

Stress and AE parameters vs strain

Bias Direction Charts

- strain vs events
- strain vs stress
- strain vs energy
- strain vs cumulative energy

Results

Damage evolution monitoring - ER

Joule Effects evaluation

Unloaded specimen with applied current
Thermocamera

Test in light-protected area to avoid noise effects

Joule Effect on Specimen

Temperature Increment (°C)

Current Intensity (mA)

Temperature Increment vs Applied Current
Results

Damage evolution monitoring - AE

ER results

Stress vs Strain

Normalized Resistance

\[ R^* = \frac{R - R_0}{R_0} \]

Transistion strain \( \varepsilon_a \)

Transistion strain \( \varepsilon_b \)
Experimental Set-Up (II)

Damage Observation by NDT

To identify damage at different levels of evolution

- 3 different strain levels have been chosen

Machine and Cross direction

- $\varepsilon_1 = 0.2\%$
- $\varepsilon_2 = 0.8\%$
- $\varepsilon_3 = 1.3\%$

Bias direction

- $\varepsilon_4 = 1\%$
- $\varepsilon_2 = 6\%$
- $\varepsilon_3 = 9.8\%$

Tensile tests were stopped at strain $\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$

Damage inspection by NDT
## Experimental Set-Up (III)

### Damage Observation by NDT

#### Ultrasonic C-Scan

- **HFUS 2000 Ultrasonic system**
- **Transducer**: 5 MHz, pulse-echo type
- **Resolution**: 375 μm (max)
- **Oscilloscope**: digital, 175 MHz

#### X-Ray Radiography

- **Philips HOMX 161 - AEA Tomohawk software**
- **CCD**: 1024 x 1024, 12 bit
- **Shutter speed**: 25 frame/s

### X-Ray Source Parameters

- **Voltage**: 80 - 100 KV
- **Current**: 0.3 A
- **Iris opening**: 80%

### Contrast Media

- **Di-iodomethane**, 24 hours bath
Results

Damage Observation by NDT

C-Scan Images

MACHINE Direction

CROSS Direction
Results

Damage Observation by NDT

C-Scan Images

BIAS Direction

![C-Scan Images]

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Results

Damage Observation by NDT

Greyscale Histograms

Damaged Area

<table>
<thead>
<tr>
<th>Strain Level</th>
<th>MD and CD</th>
<th>BD</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε1</td>
<td>0.2%</td>
<td>1%</td>
</tr>
<tr>
<td>ε2</td>
<td>0.8%</td>
<td>6%</td>
</tr>
<tr>
<td>ε3</td>
<td>1.3%</td>
<td>9.8%</td>
</tr>
</tbody>
</table>

Damaged Areas at different strain levels for each test direction

- Machine direction
- Cross direction
- Bias direction
Results

Damage Observation by NDT

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Results

Damage Observation by NDT

X-Ray

BIAS Direction

$\varepsilon_1 = 1\%$

$\varepsilon_2 = 6\%$

$\varepsilon_3 = 9.8\%$

5 mm
Results

Damage geometrical aspects

Damage Pattern measurements

- Side radiographies indicate that damage seems distributed repetitively into single fabrics which are randomly stacked;
- Pixel’s intensity is plotted along section;
- Signals are processed with FFT to have main characteristics distances between damages;

Results

Damage geometrical aspects

**Damage Pattern measurements**

<table>
<thead>
<tr>
<th></th>
<th>1st period L1</th>
<th>2nd period L2</th>
<th>3rd period L3</th>
<th>4th period L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>2.63 mm</td>
<td>3.44 mm</td>
<td>4.97 mm</td>
<td>7.47 mm</td>
</tr>
<tr>
<td>CD</td>
<td>5.6 mm</td>
<td>n.p.</td>
<td>n.p.</td>
<td>n.p.</td>
</tr>
<tr>
<td>BD (+45°)</td>
<td>2.3 ± 2.77 mm</td>
<td>3.46 ± 4.61 mm</td>
<td>5.54 mm</td>
<td>6.93 mm</td>
</tr>
<tr>
<td>BD (-45°)</td>
<td>5.54 mm</td>
<td>n.p.</td>
<td>n.p.</td>
<td>n.p.</td>
</tr>
</tbody>
</table>

Characteristic distances are close to unit cell characteristic dimensions;

Stitching pattern superposed with ultrasonic images coincide well with damage pattern.

DAMAGE INITIATE and DEVELOPS FROM STITCHING INDUCED DEFECTS
Conclusions

- Damage has been initially monitored in its evolution by AE recordings and Characteristic regions has been appreciated;
- Different damage mechanism grow at different strain levels;
- Typical damage modes has been observed by non-destructive X-Ray and Ultrasonic techniques;
- Along MD and CD:
  - After initial micro-cracks, damage develops steadily, interesting mainly the matrix, until high strains are reached;
  - At high strains, when matrix cracking mechanism saturate, damage interests longitudinal fibers and grows unsteady till final collapse.
- Along BD:
  - Because of matrix dominated characteristic, stiffness decrease quickly has matrix damage starts to grow;
  - At high strains, some matrix cracks merge together into edge-to-edge flaws that grow leading to final separation of specimen.
- Damage grows following a typical pattern which characteristic lengths are very close to stitching pattern geometry;
- Stitching induced defects are damage nucleation regions.
Future Work

- Damage monitoring by refined DC technique;
- Damage mode direct identification by optical microscopy;
- FE Numerical simulation of damage development.
Thank you for attention.

Any questions?