Planar Delamination Behaviour of Composite Laminates under Out-of-plane Loading

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Delamination initiation and propagation in CFRP composite laminates

• ZwickRoell testing equipment
• Janugaon vijay kumar, IJIET, 2013
• Comac C919, Aviation Week, 2022
Unidirectional delamination growth

Different interfaces

- Ramji et al, Composites Science and Technology, 2020
Different interfaces

- Ramji et al, Composites Science and Technology, 2020
Unidirectional delamination growth

Different interfaces

\[ \frac{da}{dN} = C(f(\Delta G, G_C, G_{th} ...))^n \]

Mike van der Panne, Master’s thesis, TU Delft, 2022
Planar / Multidirectional delamination

- Global 0//0 interface
- Observation
- Measurement
- Characterization

CFRP panel

Circular delamination
New test methodology
Semi-complex configuration

Out-of-plane indentation

Support frames
Clamp frames
Specimen
Indenter

DIC cameras
AE sensors
New test methodology

Semi-complex configuration

Out-of-plane indentation

Pulse echo
C-scan

DIC cameras

AE sensors
Test configurations - Planar Central Loaded Split (PCLS)

<table>
<thead>
<tr>
<th>Label</th>
<th>Stacking sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCLS(0//90)</td>
<td>[(0/90/45/-45)s/(90/0/45/-45)s]</td>
</tr>
<tr>
<td>PCLS-R(0//90)</td>
<td>[(0/90/45/-45)s/(90/0/45/-45)s]</td>
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<td>PCLS-R(0//0)</td>
<td>[(0/90/45/-45)s/(0/90/45/-45)s]</td>
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</tbody>
</table>
Planar delamination pattern - C-scan

- Delamination growth at mid interface
- PTFE insert
- Migrated delamination growth

- Loading and Scanning

- PCLLS (0/90)
- PCLLS-R (0/90)
- PCLLS-R (0/0)
Planar delamination pattern - cross-section

- Mid interface delamination
- Migrated delamination growth

Crack propagation direction:
- 0//0
- 0//90

PCLS-R
- (0//0)
- (0//90)
Planar / Multidirectional delamination

CFRP panel fixed in a frame

- Observation
- Measurement
- Characterization
Monitoring delamination process with DIC

- PCLS 0//0
- Embedded delamination
Monitoring delamination process - DIC

- PCLS-R 0\!/0

![Diagram showing delamination propagation and surface curvature](image)
Monitoring delamination process - DIC

- **PCLS-R 0//90**

![Graph showing surface curvature vs. displacement](image)

- Around 7mm
  - Plateau stage

![Diagram showing delamination propagation](image)

- Delamination propagation
Monitoring delamination process - AE

- PCLS 0//90

Estimations of delamination initiation and propagation

Further qualitative analysis of the damage modes is required.
Force–displacement behaviour & Compliance analysis
Numerical simulation & its validation with DIC

- Numerical model
- DIC analysis
Conclusions
Conclusions

A new test methodology has been developed

Revealing planar delamination behaviour under quasi-static out-of-plane loading:
- Continuous stiffening behaviour
- Planar delamination pattern: delamination propagation and migration
- Monitoring delamination process by using DIC and AE

How can we characterize planar delamination

Measurement of planar delamination growth

Criterion for planar delamination growth

\[
\frac{d?}{dN} = C(f(\Delta G, G_C, G_{th} \ldots))^n
\]

Thank you!

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# Monitoring delamination process - DIC

<table>
<thead>
<tr>
<th>PCLS 0//90</th>
<th>Curvature plotting from DIC analysis</th>
<th>TOF C-scan</th>
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<tr>
<td>w (mm)</td>
<td>2.51</td>
<td>4.40</td>
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<tr>
<td>w (mm)</td>
<td>1.87</td>
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<td>6.90</td>
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<tr>
<td>w (mm)</td>
<td>2.16</td>
<td>3.54</td>
<td>6.70</td>
<td>7.60</td>
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</tbody>
</table>
1-D Delamination ➢ Mode I fatigue delamination

- Cameselle-Molares, 2019
Monitoring delamination process - AE

- PCLS 0//0

![Diagram showing AE amplitude (dB), accumulative AE energy (aJ), and accumulative AE counts. The diagram includes a graph with a grid and the following annotations:

- **The first significant increase**
- **Increase in the density of AE hits**
- **Around 7 mm**

Legend:
- 2
- 3
- 1
- 4

Displacement (mm)
Mode II dominant delamination

- Amaral et al, Engineering Fracture Mechanics, 2018
Impact–induced delamination

- UT extended segmentation
- CT segmentation

- Ellison et al, Journal of Composite Materials, 2018