Predicting Failure in Composites

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www.bris.ac.uk/composites
Overview

- Fracture is complex, with interacting damage modes
- Discrete nature of fracture is crucial
- Cohesive zone interface elements are very effective at representing discrete fractures
- Good predictions can be made provided correct failure mechanism is captured
- Range of examples:
  - Un-notched and notched tension
  - Defects
  - Impact
  - Tapered laminates
  - Fatigue
Importance of discrete failure

- Low transverse strength causes early matrix cracks and delaminations
- Form discrete fractures that join up and interact
- Provides alternative mechanism to unload fibres
- Important in controlling ultimate failure
- Homogeneous models can represent reduction in stiffness due to damage
- Cannot capture discrete nature of final fracture
Other examples of discrete failure

- Fibre dominated failure of quasi-isotropic carbon/epoxy in tension
  Factor of 3 variation in strength with stacking sequence and ply block thickness

- Ply drops – complete block of material can shear out

Wisnom, 2010
Interface elements

- Interface elements relating tractions to relative displacements are a good way to model discrete failures.
- Unify stress-based and fracture mechanics approaches to failure.
- Can handle initiation and propagation.
- Physically realistic and numerically convenient approach.
- Can be applied to both delaminations and discrete transverse cracks.
- Interface elements available now in many commercial programs.

Ply interface
Coincident nodes

Damage initiation locus:
\[
\left( \frac{\max(\sigma,0)}{\sigma^\text{max}} \right)^{\alpha} + \left( \frac{\sigma_{\text{II}}}{\sigma^\text{max}} \right)^{\alpha} = 1
\]

Fully debonded locus:
\[
\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IC}} = 1
\]
Interaction of delamination and matrix cracks

- IM7/8552 carbon-epoxy laminate
- \((45_4/90_4/45_4/0_4)_s\) layup
- Uniaxial tension loading
- Fails by delamination before fibre failure
- Cohesive elements at all ply interfaces
- Potential splits also represented with interface elements
Comparison with experimental observations

Interaction of delamination and cracks captured
Predicted failure stress within experimental scatter

<table>
<thead>
<tr>
<th></th>
<th>45/90</th>
<th>90/-45</th>
<th>-45/0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.53%</td>
<td><img src="Image1" alt="Image" /></td>
<td><img src="Image2" alt="Image" /></td>
<td><img src="Image3" alt="Image" /></td>
</tr>
<tr>
<td>(344 MPa)</td>
<td><img src="Image4" alt="Image" /></td>
<td><img src="Image5" alt="Image" /></td>
<td><img src="Image6" alt="Image" /></td>
</tr>
<tr>
<td>0.65%</td>
<td><img src="Image7" alt="Image" /></td>
<td><img src="Image8" alt="Image" /></td>
<td><img src="Image9" alt="Image" /></td>
</tr>
<tr>
<td>(414 MPa)</td>
<td><img src="Image10" alt="Image" /></td>
<td><img src="Image11" alt="Image" /></td>
<td><img src="Image12" alt="Image" /></td>
</tr>
<tr>
<td>0.74%</td>
<td><img src="Image13" alt="Image" /></td>
<td><img src="Image14" alt="Image" /></td>
<td><img src="Image15" alt="Image" /></td>
</tr>
<tr>
<td>(422 MPa)</td>
<td><img src="Image16" alt="Image" /></td>
<td><img src="Image17" alt="Image" /></td>
<td><img src="Image18" alt="Image" /></td>
</tr>
<tr>
<td>0.77%</td>
<td><img src="Image19" alt="Image" /></td>
<td><img src="Image20" alt="Image" /></td>
<td><img src="Image21" alt="Image" /></td>
</tr>
<tr>
<td>(413 MPa)</td>
<td><img src="Image22" alt="Image" /></td>
<td><img src="Image23" alt="Image" /></td>
<td><img src="Image24" alt="Image" /></td>
</tr>
<tr>
<td>Final failure</td>
<td><img src="Image25" alt="Image" /></td>
<td><img src="Image26" alt="Image" /></td>
<td><img src="Image27" alt="Image" /></td>
</tr>
</tbody>
</table>

Hallett et al, 2008
Extended FEM

- Some effect of assumed relative split locations
- XFEM allows automatic split insertion

Iarve et al, 2011
Open hole tension

- Hexcel IM7/8552
- \((45_m/90_m/-45_m/0_m)_n\) layup
- All specimens scaled
- Two methods of thickness scaling
- Complex damage development:
  - Matrix cracking, splitting, delamination

Hallett et al, 2009
Finite element analysis

Interface elements between all plies
Potential splits within plies

LS_Dyna
Weibull fibre failure criterion

\[ \sum_{i=1}^{\text{No. of Elements}} V_i \left( \frac{\sigma_i}{\sigma_{\text{unit}}} \right)^m \geq 1 \]
Predicted damage, $t=4\text{mm},d=25\text{mm}$

<table>
<thead>
<tr>
<th>Stress level (MPa)</th>
<th>Location of interlaminar interface</th>
<th>Location of splitting within plies</th>
</tr>
</thead>
<tbody>
<tr>
<td>152</td>
<td>$45^\circ/90^\circ$</td>
<td>All layers (superimposed)</td>
</tr>
<tr>
<td>184</td>
<td>$90^\circ/-45^\circ$</td>
<td></td>
</tr>
<tr>
<td>423</td>
<td>$-45^\circ/0^\circ$</td>
<td></td>
</tr>
<tr>
<td>372</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Damage mechanisms captured well
- Good correlation of test and analysis failure stresses
Overheight Compact Tension specimens

- Fibre failure catastrophic in open hole specimens
- OCT tests produce gradual failure
- Specimen size supposed to be sufficiently large to allow development of damage “process zone” ahead of notch tip
- Two stacking sequences – dispersed and blocked plies
- IM7/8552 carbon/epoxy

Li et al, 2013
• Multiple potential crack sites inserted ahead of notch tip
• Interface elements between all plies
• Fibre failure modelled by progressive Weibull criterion

\[ \sum_{i=1}^{\text{No. of Elements}} V_i \left( \frac{\sigma_i}{\sigma_{\text{unit}}} \right)^m \geq 1 \]

• Maximum stress element is removed
• Load redistributed by FE
• Weibull criteria re-evaluated at next time increment
Layup $[45_4/90_4/-45_4/0_4]_s$ (4mm)

- Thick ply blocks promote matrix cracking and delamination
- $0^\circ$ ply cracks ahead of the notch blunt crack
- No fibre failure observed
- Failure by pullout of $0^\circ$ ply block
Scaled Centre Notch Tension tests

In-plane scaled IM7/8552 [45/90/-45/0]_4s laminates

Central-crack and open-hole specimens

C=3.175mm, 6.35mm, 12.7mm, 25.4mm

Failure of specimens

X Xu
Size effects in notched laminates

- Strength reduces with size, but less than predicted by LEFM
- Similar scaling trends for open holes and centre notches
- Specimens with cracks stronger than holes!
Failure mechanism (fixed scale)

Interrupted tests (95% failure load):

- Single 0 degree ply
  - C=3.175mm
  - C=6.35mm
  - C=12.7mm
  - C=25.4mm

- Central double 0 degree ply
  - C=3.175mm
  - C=6.35mm
  - C=12.7mm
  - C=25.4mm
FE modeling

- Delamination elements between all plies
- Potential split elements along multiple paths at crack tips
- Weibull failure criterion and element removal for continuous fibre failure
FE mesh (Baseline c=3.175mm)

Mesh size 0.06mm
Failure mechanisms (Baseline \(c=3.175\text{mm}\))

- Fibre failure growth before final failure in single 0 plies
- No fibre failure in central double 0 plies
- Matches experimental observations
Failure mechanisms (Scaled up c=25.4mm)

- Fibre failure growth before final failure in ALL plies
- Consistent with experimental observations
Results correlation

- Good overall correlation
- FE is able to predict damage and scaling trends
- Damage zone size increases with specimen size, and so fracture toughness increases
Out-of-plane wrinkling compression test

Specimen 3 - Final 4 frames @ 90,000 FPS

IM7/8552 [+45, 90, -45, 0]_3S

M Jones
Analysis results – compression

- 3D FE model with cohesive elements at all interfaces
- Captures delamination initiation from the edge
- Failure at 455 MPa cf experimental average of 457 MPa

Delamination at 45/90 interface observed in experiment

Major delamination at the 45°/90° ply interface

S Mukhopadhyay
Impact and compression after impact

- Impact damage mechanism with multiple delaminations well captured

- CAI response can also be modelled

R. Sun
Prediction of delamination in tapers

Experimental failure load (SD=0.6 kN)

L. Kawashita
Fatigue delamination growth

- Novel cohesive formulations can model fatigue as a function of the SERR amplitude and number of cycles.
- Paris-law regime, R-ratio (trough/peak loads) of 0.1.
- Envelops of forces and displacements modelled.

\[ F_{\max}, F_{\min} \]

\[ \sigma_{\max}, \delta_{\max} \]

\[ \sigma_{0}, \sigma_{\text{final}} \]

\[ G_{\text{initial}}, G_{\text{final}} \]

\[ t, t-\Delta t, t_{\text{initial}} \]

\[ \tau, \tau_{\text{final}} \]

\[ \delta_{t}, \delta_{t+\Delta t} \]

\[ \sigma_{\text{max}}, \delta_{\text{max}} \]

\[ \sigma_{0}, \delta_{0} \]

\[ \Delta F, \Delta \tau \]

\[ \text{FE force or displacement}, \text{Cohesive model assumption} \]

P. Harper
Model-test correlation: cyclic loading

- **pristine**
- **defect**

Thin Section Stress [MPa]

- FE, pristine
- Exp, pristine
- FE, defect
- Exp, defect

Delamination from ply drop

Cycles

Open hole tension fatigue

Experimental Fatigue Results

4x4 (Fine) Mesh at 40%, 50%, 60% and 70% Cyclic Fatigue Load

O. Nixon-Pearson
Conclusions

- Discrete delaminations and splits are crucial in controlling failure.
- Good predictions can be made provided mechanisms are correctly captured:
  - Notched and unnotched tension
  - Tapered laminates
  - Impact and compression after impact
  - Defects e.g. out-of-plane wrinkling
- Approach also works for fatigue.
Papers