Development and Evaluation of Fracture Mechanics Test Methods for Sandwich Composites

2013 Technical Review
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FAA Sponsored Project Information

- Principal Investigator: Dr. Dan Adams
- Graduate Student Researchers: Ryan Braegger, Zach Bluth
- FAA Technical Monitor: Curt Davies, David Westlund
- Collaborators: NASA Langley, NIAR, Boeing, Learjet, Airbus, UTC Aerospace Systems
RESEARCH OBJECTIVES:
Fracture Mechanics Test Methods for Sandwich Composites

- Focus on facesheet-core debonding
- Mode I and Mode II
  - Identification and initial assessment of candidate test methodologies
  - Selection and optimization of best suited Mode I and Mode II test methods
  - Development of draft ASTM standards
MODE I TEST CONFIGURATION:
Candidate Configurations Investigated

- Double Cantilever Beam (DCB)
- Piano Hinge
- Delamination
- Crack Tip
- Applied Load

- Clamped Double Cantilever Beam (DCB)
- Cantilever Blocks
- Piano Hinge
- Delamination
- Crack Tip
- Applied Load

- Three-Point Flexure
- Center Support Rod
- Left Support Rod
- Right Support Rod
- Crack Tip
- Delamination

- Single Cantilever Beam (SCB)
- Plate Support
- Piano Hinge
MODE I TEST CONFIGURATION: Single Cantilever Beam (SCB)

- Elimination of bending of sandwich specimen
- Minimal crack “kinking” observed
- Mode I dominant - independent of crack length
- Appears to be suitable for standardization
PARAMETERS INVESTIGATED:
Single Cantilever Beam (SCB) Test

- Specimen geometry
  - Length
  - Width
  - Initial crack length
- Facesheet properties
  - Thickness
  - Flexural stiffness
  - Flexural strength
- Core properties
  - Thickness
  - Density
  - Stiffness
  - Strength
- Mode mixity
  - Variations across specimen width
  - Variations with crack length
- Data reduction methods
- Thru-thickness crack placement
- Anticlastic curvature & curved crack front
  - Large rotations of facesheet
  - Use of facesheet doublers
  - Facesheet curvature effects
Concern: Excessive facesheet rotation

- Not representative of disbond in actual sandwich structures
- Geometric nonlinearity causes errors when using conventional data reduction method

Possible Solution: Use of facesheet doublers

- Reduce facesheet rotation required for disbonding
- Allow use of compliance calibration method of data reduction
EFFECTS OF FACESHEET DOUBLER:
Results of SCB Testing With Nomex Honeycomb Core

Adding doubler changes delivered $G_c$ values...
...and thru-thickness fracture locations!
NUMERICAL INVESTIGATION

Facesheet Thickness Effects

• Load applied in each model to produce same $G_T$ value
  – No doubler, “thin” doubler, “thick” doubler

• Considered crack growth at three through-the-thickness locations

• Investigate mode mixity (% $G_I$)

• Investigate orientation of max. principal stress for expected crack growth direction

Near interface

0.5 mm depth

1 mm depth
SUMMARY OF FINDINGS: Numerical Investigation

• SCB test appears to be Mode I dominant for all cases considered
• Small Mode II component produced by shear stresses in vicinity of crack tip
• Sign of shear stresses change as a function of:
  – Crack location in core
  – Thickness of facesheet
• Crack predicted to propagate closer to facesheet/core interface for thinner facesheets
EFFECTS OF FACESHEET CURVATURE:
Use of Climbing Drum Peel (CDP) Test

• Facesheet curvature during SCB testing is dependent on facesheet thickness
• High curvature produced with thin facesheets not representative of that seen in sandwich structures with disbonds
• Use of Climbing Drum Peel test permits testing with prescribed facesheet curvature
DETERMINATION OF ENERGY RELEASE RATE, $G_C$: Climbing Drum Peel (CDP) Test

Energy Release Rate, $G_{IC}$:

$$G_{IC} = \frac{(P_2 - P_1)(r_2 - r_1)}{w \cdot r_1}$$

$r_2$ = flange radius
$r_1$ = drum radius + facesheet thickness
$w$ = specimen width

CLIMBING DRUM PEEL (CDP) TESTING: Investigating Facesheet Curvature Effects

Standard CDP Fixture
ASTM D 1781
r = 2 in.

Large CDP Fixture
r = 6 in.

Very Large CDP Fixture
r = 12 in.
CLIMBING DRUM PEEL (CDP) TESTING: Investigating Facesheet Curvature Effects

Standard CDP Fixture
ASTM D 1781
r = 2 in.

Large CDP Fixture
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Very Large CDP Fixture
r = 12 in.
PRELIMINARY:
Effects of Facesheet Curvature on Apparent $G_c$

- $[0/90/0]_{nT}$ IM7/8552 carbon/epoxy facesheets
- 3 lb/ft$^3$ Nomex honeycomb core

![Bar chart showing the average $G_c$ for 3, 6, and 9 ply facesheets at different CDP configurations: 2 in., 6 in., and 12 in. SCB.](chart.png)
Effect of Facesheet Thickness:
Single Cantilever Beam (SCB) Specimens

Change in fracture location with facesheet thickness

3 Ply Facesheet 6 Ply Facesheet 9 Ply Facesheet
Effect of Facesheet Thickness:
6 in. Radius Climbing Drum Peel (CDP) Specimens

Minimal change in fracture location with facesheet thickness

3 Ply Facesheet  6 Ply Facesheet  9 Ply Facesheet
Effect of Facesheet Curvature
3 Ply Facesheet Specimens

Minimal change in fracture location with facesheet curvature

SCB  2 in. CDP  6 in. CDP  12 in CPD

![Tested Portion](image)

![Untested](image)

![Precrack](image)

![Graph](image)
RESULTS FROM NUMERICAL INVESTIGATION: Predicted Depth of Crack Growth in Nomex Core

- **Increasing depth of crack for increasing facesheet thickness**
- **Crack location independent of test method**

<table>
<thead>
<tr>
<th>Test Method</th>
<th>3 Ply Facesheets</th>
<th>6 Ply Facesheets</th>
<th>9 Ply Facesheets</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCB</td>
<td>0.25 mm (0.010 in.)</td>
<td>0.75 mm (0.030 in.)</td>
<td>1.0 mm (0.039 in.)</td>
</tr>
<tr>
<td>2 in. CDP</td>
<td>0.38 mm (0.015 in.)</td>
<td>0.75 mm (0.030 in.)</td>
<td>1.0 mm (0.039 in.)</td>
</tr>
<tr>
<td>6 in. CDP</td>
<td>0.38 mm (0.015 in.)</td>
<td>0.75 mm (0.030 in.)</td>
<td>1.0 mm (0.039 in.)</td>
</tr>
<tr>
<td>12 in. CDP</td>
<td>0.38 mm (0.015 in.)</td>
<td>0.75 mm (0.030 in.)</td>
<td>1.0 mm (0.039 in.)</td>
</tr>
</tbody>
</table>
SUMMARY OF PRELIMINARY FINDINGS:
Facesheet Thickness Effects

- SCB test results show differences in apparent $G_c$ values and through-thickness locations of crack growth as a function of facesheet thickness
- CDB test results to date do not indicate differences in apparent $G_c$ or through-thickness locations of crack growth as a function of facesheet thickness
- Numerical simulations suggest through-thickness locations of crack growth is a function of facesheet thickness for all test methods investigated
- Additional testing to be performed using specimens from single sandwich panel
MODE II TEST METHOD DEVELOPMENT: Challenges in Developing a Suitable Test

- Maintaining Mode II dominated crack growth with increasing crack lengths
- Obtaining crack opening during loading
- Obtaining stable crack growth along facesheet/core interface

Mixed Mode Bend

Cracked Sandwich Beam with Hinge

Delamination Hinge
SELECTED MODE II CONFIGURATION:
End Notched Sandwich Test

- Modified three-point flexure fixture
- High percentage Mode II (>80%) for all materials investigated
- Semi-stable crack growth along facesheet/core interface
- *Appears to be suitable for a standard Mode II test method*
ADDRESSING CRACK GROWTH STABILITY: Specimen Span Length and Precrack Length

- Selection of proper precrack length/span length predicted to produce stable crack growth
- Test results have confirmed this prediction

![Graph showing required displacement for crack growth vs. precrack length/span length.](graph.png)
END-NOTCHED TEST CONFIGURATIONS:
Three-Point Flexure Vs. Cantilever Support

Monolithic Composites:
3 Point End Notch Flexure (3ENF)
(Currently proposed for ASTM standardization)

Sandwich Composites:
End Notch Cantilever (ENC)
END-NOTCHED TEST CONFIGURATIONS:
Three-Point Flexure Vs. Cantilever Support

End Notched Flexure
(Unsymmetric bending)

End Notched Cantilever
(Symmetric bending)
MODIFIED MODE II CONFIGURATION

End Notched Cantilever (ENC) Test

- Cantilever beam configuration
- Upward or downward loading
- Performance meets or exceeds 3-point flexure configuration for all sandwich configurations considered to date
- Requires specialized fixturing
- Allows for reduced specimen length
- Currently under further examination
CURRENT STATUS:
Fracture Mechanics Test Methods for Sandwich Composites

• Completion of remaining testing and analysis
• Documentation of findings
  – FAA Reports
  – Journal publications
• Submission of Draft SCB Test Method to ASTM D30
• Summary of findings at European Honeycomb Sandwich Disbond Growth Workshop (EASA, Cologne, June 2013)
SUMMARY

Benefits to Aviation

- Standardized fracture mechanics test methods for sandwich composites
  - Mode I fracture toughness, $G_{IC}$
  - Mode II fracture toughness, $G_{IIC}$
- Test results used to predict disbond growth in composite sandwich structures