FAILURE OF NOTCHED LAMINATES UNDER OUT-OF-PLANE BENDING

Presenter: Tim Kennedy
Failure of Notched Laminates Under Out-of-Plane Bending

• Motivation and Key Issues
  – Design tools for composite aircraft structure subjected to out-of-plane loading

• Objective
  – Determine the modes of failure and evaluate the capability of current models to predict failure

• Approach
  – Four-point Bending Tests
  – Stress Concentration Factor Calculations
  – Progressive Damage Modeling
FAA Sponsored Project Information

- Principal Investigators & Researchers
  - Tim Kennedy & Sergio Gonzalez

- FAA Technical Monitor
  - Curt Davies and Lynn Pham

- Other FAA Personnel Involved
  - Larry Ilcewicz

- Industry Participation
  - Gerry Mabson (Boeing)
  - Tom Walker (NSE Composites)
Bending of a Notched Laminate
Notch Lengths: 2a = 1 inch & 2a = 4 inches
Test Specimens

BMS 8-276 Carbon Fiber Tape

Laminate Types
- 10% 0° Plies
- 30% 0° Plies
- 50% 0° Plies

Laminate Thicknesses
- 20 plies Thick
- 40 plies Thick

Notch Lengths
- 1 inch
- 4 inches
Stress Concentrations in Notched Laminates Under Bending

Plate Theory
- Without transverse shear effects (CPT)
- With transverse shear effects (RPT)
Stress Concentration Around a Circular Hole

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Mesh for 0.25-in Diameter Hole
3-D Solid Elements Around Hole

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Mesh for 1–in Long Notch
Mesh for 4-in Long Notch

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Design for Membrane Loading

Far Field Strain $\varepsilon_{\text{allowable}} = a + b/K + c/K^2$

$K =$ Strain Concentration Factor at Hole
20 Plies with 10% 0-degree

![Graph showing strain concentration factor against notch length for Solid, Shell, and Classical models.](image-url)
Strain Distribution Through Thickness at Hole

- Solid Elements
- Shell Elements

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20 Plies with 30% 0-degree

Strain Concentration Factor

Notch Length (in)

Solid
Shell
Classical
Conclusions on Strain Concentration Factors

• Classical plate theory under-predicts strain concentration factors
• 3-D effects have an influence at the edge of the notch
ABAQUS Progressive Damage Model

• Damage Initiation – Hashin Theory
  – Fiber Tension
  – Fiber Compression
  – Matrix Tension
  – Matrix Compression
Damage Evolution

Strain Softening

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Damage Evolution

- Damage Parameters: $d_f$, $d_m$, $d_s$

$$C_d = \frac{1}{D} \begin{bmatrix} (1 - d_f)E_1 & (1 - d_f)(1 - d_m)\nu_{12}E_2 & (1 - d_f)(1 - d_m)\nu_{21}E_1 & 0 \\ (1 - d_f)(1 - d_m)\nu_{12}E_2 & (1 - d_m)E_2 & 0 & 0 \\ 0 & 0 & (1 - d_s)GD \end{bmatrix}.$$
4-Point Bending Test Fixture

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Simulation of the 4-point Bend Test
# Laminate Test Matrix

<table>
<thead>
<tr>
<th>Laminate</th>
<th>% 0-deg plies</th>
<th>No. of Plies</th>
<th>Notch Length</th>
<th>Test Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>10</td>
<td>20</td>
<td>1 in</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>30</td>
<td>20</td>
<td>1 in</td>
<td>X</td>
</tr>
<tr>
<td>N1</td>
<td>50</td>
<td>20</td>
<td>1 in</td>
<td>X</td>
</tr>
<tr>
<td>F*1</td>
<td>10</td>
<td>40</td>
<td>1 in</td>
<td>X</td>
</tr>
<tr>
<td>AR1</td>
<td>30</td>
<td>40</td>
<td>1 in</td>
<td>X</td>
</tr>
<tr>
<td>AN1</td>
<td>50</td>
<td>40</td>
<td>1 in</td>
<td>X</td>
</tr>
<tr>
<td>F4</td>
<td>10</td>
<td>20</td>
<td>4 in</td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>30</td>
<td>20</td>
<td>4 in</td>
<td>X</td>
</tr>
<tr>
<td>N4</td>
<td>50</td>
<td>20</td>
<td>4 in</td>
<td>X</td>
</tr>
<tr>
<td>F*4</td>
<td>10</td>
<td>40</td>
<td>4 in</td>
<td></td>
</tr>
<tr>
<td>AR4</td>
<td>30</td>
<td>40</td>
<td>4 in</td>
<td></td>
</tr>
<tr>
<td>AN4</td>
<td>50</td>
<td>40</td>
<td>4 in</td>
<td></td>
</tr>
</tbody>
</table>

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Strain Growth in Laminate P
Strain Growth In Laminate F*
### Laminate Failure Moment

<table>
<thead>
<tr>
<th>Laminate</th>
<th>Test Failure Moment</th>
<th>Theory Failure Moment</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>192 in-lb/in</td>
<td>189 in-lb/in</td>
<td>1.6%</td>
</tr>
<tr>
<td>N1</td>
<td>263 in-lb/in</td>
<td>273 in-lb/in</td>
<td>3.8%</td>
</tr>
<tr>
<td>F1</td>
<td>634 in-lb/in</td>
<td>747 in-lb/in</td>
<td>17.8%</td>
</tr>
<tr>
<td>AR1</td>
<td>712 in-lb/in</td>
<td>960 in-lb/in</td>
<td>34.8%</td>
</tr>
<tr>
<td>AN1</td>
<td>901 in-lb/in</td>
<td>1272 in-lb/in</td>
<td>41.1%</td>
</tr>
<tr>
<td>P4</td>
<td>168 in-lb/in</td>
<td>165 in-lb/in</td>
<td>1.8%</td>
</tr>
<tr>
<td>N4</td>
<td>224 in-lb/in</td>
<td>222 in-lb/in</td>
<td>0.9%</td>
</tr>
</tbody>
</table>
Compression Side Failure
Compression Side Failure
A Look Forward

- Remaining Work to Complete Project
  - 41 Four-point Bending Tests
  - Damage Model with Delamination
Questions?