NOTCH SENSITIVITY OF COMPOSITE SANDWICH STRUCTURES

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FAA Sponsored Project Information

- Principal Investigators: Dr. Dan Adams
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  Oregon State University
Outline

• Brief updates: Previous research
  – Sandwich fracture mechanics
  – Sandwich damage tolerance

• Sandwich notch sensitivity investigation
  – Test method development
  – Numerical modeling – progressive damage analysis
Status Update:
Mode I Sandwich Fracture Mechanics Test Method

Single Cantilever Beam (SCB) Test Method

• Draft ASTM standard completed
• International round-robin test program initiated
  • 7 test labs with previous SCB testing experience
  • Sandwich specimens fabricated, testing initiated
**Status Update:**

Development of Sandwich Damage Tolerance Test Methods

- Draft standards of CAI completed
- Draft standard for 4-Pt. Flexure After Impact under development
- Follow-on “scaling” effort underway through Air Force SBIR program

![Compression After Impact (CAI)](image1)

![4-Point Flexure After Impact (4-FAI)](image2)
Background:
Notch Sensitivity of Sandwich Composites

- Notch sensitivity test methods for monolithic composites are reaching relatively high levels of maturity
  - ASTM D 5766 – Open Hole Tension
  - ASTM D 6484 – Open Hole Compression
  - Out-of-plane shear (Parmigiani)

- Less attention to notch sensitivity tests methods of sandwich composites
  - Currently no standardized tests for notch sensitivity

- Failure prediction of notched monolithic composites is receiving considerable attention
  - Reduced focus on analysis of notched sandwich composites
Research Objectives: Notch Sensitivity of Sandwich Composites

- Initial development of notched test methods and associated analysis methodologies for composite sandwich panels
- Documentation notched testing and analysis protocols in Composites Materials Handbook (CMH-17) with Parmigiani group (OSU)
- Explore development of new ASTM standards for notch sensitivity of sandwich composites
Testing Considerations:
Sandwich Open Hole Compression

• Test fixture/Specimen support
  – End supports
    • Clamping top and bottom
    • Potting
  – Side supports
    • Knife edge
• Specimen size
  – Separation of central hole and boundary effects
  – Production of acceptable strength reductions
• Specimen alignment
• Strain measurement

Open hole compression fixture for monolithic composites
Sandwich Open Hole Compression: Aspect Ratio Investigation

- Investigate the separation of central hole to the load boundary effects by examining the strain fields of different H/W ratios.
- Select a H/W ratio that produces an acceptable strength reduction.
- Provide more test data to calibrate material parameters in ABAQUS/NDBILIN.
Current Focus: Investigating Aspect Ratio

- Carbon/epoxy facesheets, Nomex honeycomb core
- Sized to 4.0 in. wide and 2/3 in. hole diameter (W/D = 6)
- Heights of 6.0 in., 8 in., and 10.5 in.

H/W = 1.5  H/W = 2.0  H/W = 2.6
Current Focus: Investigating Aspect Ratio

- Max strength decreases significantly from $H/W = 1.5$ to 2.0
- Separation of notch effect from boundary in strain field
Testing Considerations: Sandwich Open Hole Flexure

- Test fixture/specimen support
  - Inner span
    - Separation of notch and loading boundary effects
  - Outer span
    - Develop sufficient bending moment
    - Ensure failure in inner span
- Specimen size
Sandwich Open Hole Compression: Aspect Ratio Investigation

- Investigate the separation of central hole to the load boundary effects by examining the strain fields of different inner span to width (L/W) ratios
- Select a L/W ratio that produces an acceptable strength reduction
- Provide more test data to calibrate material parameters in ABAQUS/NDBILIN
Current Focus: Investigating Aspect Ratio

- **Sandwich configuration:**
  - Carbon/epoxy facesheets, ½ in. Nomex honeycomb core
  - 0.5 in. diameter central circular hole
  - 3 in. width x 32 in. length

- **Investigating effect of inner span**
  - Inner spans of 3 in., 6 in., and 9 in.
  - Constant applied moment
    - Outer span – Inner span = 20 in.

\[ \frac{L}{W} = 3 \]
Current Focus:
Investigating Aspect Ratio

- No significant difference in max strength
- Far field reached at L/W = 2.0

Sandwich Open Hole Flexure Aspect Ratio Comparison

Normalized Strength

<table>
<thead>
<tr>
<th>Aspect Ratio (L/W)</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
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Analysis of Notched Sandwich Specimens

ABAQUS with NDBILIN:

- User-defined nonlinear material model (UMAT) for ABAQUS
- Developed by Materials Sciences Corp.
- Stiffness degradation based progressive damage model
  - Lamina level stiffness degradation
  - Max. stress, max. strain or Hashin failure criteria for damage onset
  - Bilinear stiffness response used to model material damaged state
  - “Built in” laminated plate theory for elements
Failure Analysis of Notched Sandwich Specimens
Development of Modeling Approach

• Modeling of damage progression in facesheets
  – Analysis of interlaminar disbond (Mode I and Mode II)
  – Analysis of laminate open-hole tension test
  – Analysis of laminate open-hole compression test

• Modeling of damage progression in sandwich composites
  – Sandwich interface disbond
  – Sandwich open hole compression test
  – Sandwich flexure test
Damage Progression in Facesheets: Analysis of Interlaminar Disbond

- IM7/8552 testing using ASTM D5528

![DCB Load vs Displacement Graph]

- Experimental Fatigue Precrack
- Experimental Non-precrack
- Analytical Model

Displacement (in) vs Load (lbf)
Damage Progression in Facesheets: Analysis of Interlaminar Disbond

- IM7/8552 testing using ASTM D7905
Damage Progression in Facesheets: Analysis of Open Hole Tension Tests

- Simulation of open hole tension testing of IM7/8552 carbon/epoxy laminates (ASTM D5766) $[0/90/0]_T$
- Comparison with results from mechanical testing
  - Ultimate strength
  - Stress vs. strain plots
  - Strain fields from Digital image correlation
  - Damage progression using X-ray CT
Damage Progression in Facesheets: Analysis of Open Hole Tension Tests

- Good agreement on stiffness response
- Similar full field strain response

![Graph showing Open Hole Tension](image)

**Open Hole Tension**

- Stress (psi)
  - Experimental
  - Finite Element Model

![Finite Element Prediction](image)

![Experimental Result](image)
Damage Progression in Facesheets: Analysis of Open Hole Tension Tests

90% max load

Matrix damage

Delamination

NDBILIN

X-ray CT
Damage Progression in Facesheets: Open Hole Compression Testing & Analysis

- Mechanical testing of 1.5 in. wide specimen, 0.25 in. dia center hole (ASTM D6484)
- Two IM7/8552 carbon/epoxy laminates:
  
  \([0_{5}/90_{5}/0_{5}]_{T} \quad [0/90/0]_{5T}\)

- Comparison with results from mechanical testing
  - Ultimate strength
  - Damage state using X-ray CT

![Open Hole Compression Test](image)
Damage Progression in Facesheets: Open Hole Compression Analysis $[0_5/90_5/0_5]_T$

- X-ray CT
  - Matrix damage
  - Delamination
- NDBILIN
  - Matrix damage
  - Delamination

90% max load
Damage Progression in Facesheets: Open Hole Compression Analysis $[0/90/0]_{5T}$

90% max load

Matrix damage

NDBILIN

X-ray CT

View A-A
Damage Progression in Facesheets: Comparison with Experimental Results

• Similar damage progression and strength in tension test
  – Little difference between model with and without cohesive elements

• Model over predicting strength on OHC specimens

• Compression failure modes not predicted in model
  – Investigating ABAQUS buckling solution
Initial Failure Analysis:
Sandwich Open Hole Compression Test

- Good agreement with measured stiffness
- Over prediction of notched compression strength
- Investigating cohesive elements between facesheet and core

![Graph showing Open Hole Edgewise Compression](image)

- Open Hole Edgewise Compression Chart
- Experimental and FEM predictions

![AB AQUS/NDBILIN Prediction](image)

- ABAQUS/NDBILIN Prediction

![DIC Results](image)

- DIC Results
Future Work:
Notch Sensitivity of Composite Sandwich Structures

- Investigate buckling solution for compression tests
- Inclusion of ABAQUS cohesive elements at facesheet/core interface
- Investigate additional notch configurations
SUMMARY: Benefits to Aviation

- Standardized damage tolerance test methods for sandwich composites
- Development of notch sensitivity testing and analysis methods for sandwich composites
- Scaling of test results for application on composite sandwich structures
Thank you for your attention!

Questions?
Investigate additional notch configurations
One sided (single facesheet) hole
Tension
Edge v-notch flexure
Out of plane shear (Mode III)
In-plane biaxial tension/compression
Sandwich Open Hole Compression: Investigating Aspect Ratio

- Notch strength decreases relatively more than unnotched
- Out of plane deformation

Sandwich Open Hole Compression Aspect Ratio Comparison

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<td>H/W = 1.5</td>
<td>Unnotched: 1.20, Notched: 0.40</td>
</tr>
<tr>
<td>H/W = 2.0</td>
<td>Unnotched: 1.00, Notched: 0.40</td>
</tr>
<tr>
<td>H/W = 2.6</td>
<td>Unnotched: 0.80, Notched: 0.40</td>
</tr>
</tbody>
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H/W = 1.5
H/W = 2.0
H/W = 2.6
Analysis of Notched Sandwich Specimens: Sensitivity Study

- Material properties
  - Tension/compression
- Mesh density
- Mesh orientation
  - Notch centric
  - Fiber aligned mesh
- Solution type
- Solution parameters
  - Step size
  - Viscous damping

Damage parameters

Notch-centric mesh

Fiber-aligned mesh