Damage Tolerance and Notch Sensitivity of Composite Sandwich Structures

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JAMS 2019 Technical Review
May 22-23, 2019
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• **Primary Collaborators:**
  Boeing (Charles Park), Hexcel (Lance Smith)
  Materials Sciences Corporation
  ASTM D30 (Composites)
Project Overview: Primary Research Emphases

Sandwich Fracture Mechanics
• Development of standardized test methods for facesheet/core disbond growth
• Building block approach for assessment of disbond growth in sandwich structures

Sandwich Damage Tolerance
• Assessment of predictive capabilities for damage formation and growth
• Development of standardized test methods for damage tolerance

Sandwich Notch Sensitivity
• Assessment of predictive capabilities for sandwich composite notch sensitivity
• Development of standardized test methods for notch sensitivity
Status Update: Mode I Sandwich Fracture Mechanics Test Method

Completed three rounds of ASTM balloting; fourth upcoming

Recent changes:
- Mode mixity: “Mode I dominant”
- Acceptable disbond location: within top one-fourth of core

Discussion of remaining issues:
- Procedure for disbond initiation toughness
- Accelerated loading rate to produce acceptable disbond growth rate and test time
Current SCB Discussion Item: Pausing Test for Crack Tip Measurement

- Current procedure leads to long test times
  - 5-30 minutes without initiation toughness measurements
  - 10-60 minutes with initiation toughness measurements
- Accelerated loading rate requires pausing for crack length measurement
- Minimal crack growth observed while paused under load
- Modified procedure under review by Sandwich Disbond Task Group
Recent Focus: Single Cantilever Beam (SCB) Fatigue Test

- Follow-on *Standard Practice* to existing SCB test
- Several previous individual efforts within CMH-17 Sandwich Disbond Task Group
- Draft test procedure identified for upcoming round robin testing
- Sandwich specimens to be fabricated at University of Utah and distributed to round robin participants
  - IM7/8552 woven fabric prepreg facesheets
  - Nomex honeycomb core
  - Metlbond 1515-4 film adhesive
Recent Focus: Sandwich Mixed Mode Bend (MMB) Test

- Enlarged/simplified version of test fixture used for composite laminates (ASTM D6671)
- High percentage Mode II possible (up to ~80%)
- Round-robin testing exercise planned
- Draft ASTM standard in progress
- Collaboration with DTU (C. Berggreen)
Status Update:
Mode II Separated End-Notched Flexure (S-ENF) Test

- Modified three-point flexure test
- Use of tensioned wire to achieve facesheet/core separation
- No core removal required
- Adjustable wire height and span
- High % Mode II (>80%) for all sandwich configurations studied
- Cell buckling at crack tip with no crack growth for some honeycomb core configurations
- Under further investigation with FAU collaborators (L. Carlsson)
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Damage Tolerance Test Methods For Sandwich Composites

In the initial stages of ASTM standardization

Edgewise Compression After Impact

- Preferred damage tolerance test method for laminates
- High interest level for sandwich composites
- Second ASTM balloting in Summer 2019

Four-Point Flexure After Impact

- Constant bending moment and zero shear in damaged section
- Damaged facesheet can be loaded in compression or tension
- Initial ASTM ballot submission in Summer 2019
Damage Progression in Sandwich Composites: Testing to Evaluate of Predictive Capabilities

- Damage progression in facesheets
  - Interlaminar delamination (Mode I and II)
  - Laminate tension (±45 layup)
  - Open-hole tension
  - Open-hole compression

- Damage progression in core
  - Flatwise compression
  - Flatwise shear

- Damage progression in sandwich composites
  - Sandwich interface disbond (Mode I and II)
  - Sandwich open-hole shear
  - Sandwich open-hole flexure
  - Sandwich open-hole compression
Progressive Damage Analysis of Sandwich Composites

AB AQUS with NDBILIN

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

B-Spline Method (BSAM):

- Stand-alone software
- Developed by AFRL, UDRI, UTA
- Discrete damage modeled using Regularized Extended Finite Element Method (Rx-FEM)
  - Matrix Cracking
    - Multiple failure criteria for damage onset
    - Damage propagation using cohesive zone method
  - Delamination using cohesive zone method
  - Fiber failure using Critical Failure Volume or CDM
Damage Progression in Facesheets: Analysis of ±45 Laminates in Tension

- Simulation of unnotched and open-hole tension testing
- IM7/8552 carbon/epoxy, [45/-45]_{2S} laminates
- Matrix shear modulus, strength and damage parameters calibrated using measured stress-strain behavior
  - NDBILIN: bilinear response
  - BSAM: non-linear response
Damage Progression in Facesheets: 0/90 Cross-ply Open-Hole Tension

- [0/90/0]_T laminate representing sandwich facesheet
- NDBILIN predicts notch sensitivity
- BSAM predicts notch insensitive (Less than 4% error)
- BSAM requires fine mesh for a converged solution

![Graph showing Load vs. Strain for OHT [0/90/0]_T with Test, NDBILIN, and BSAM data points.]

![Images of X-Ray CT, NDBILIN, and BSAM analyses.]

X-Ray CT

NDBILIN

BSAM
Damage Progression in Core: Flatwise Compression/Shear

- Honeycomb core loaded until core collapse in both compression and shear
- NDBILIN parameters fit to stress vs strain curves
- Used to predict open-hole shear test results

![Flatwise Shear Test](image1)

![Compression Test](image2)

![Compression Test](image3)

![Shear Test](image4)
Test Method Development: Notch Sensitivity of Sandwich Composites

• Open Hole Compression and Open Hole Flexure test method development for ASTM standardization (Draft standards in progress)
• Used for assessment of progressive damage analysis methods
• Open Hole Shear test designed to focus on progressive core damage during three-point flexure loading
Damage Progression in Sandwich Composites: Analysis of Open Hole Shear Tests

- Unnotched and notched four-point flexure testing
- Core modeled with NDBILIN
- Slight over prediction of max load in open hole shear test

Sandwich Open-Hole Shear Failure

Model Deformation

![Graph showing load vs. extension for unnotched, notched, and NDBILIN models.](image)
Damage Progression in Sandwich Composites: Analysis of Facesheet/Core Disbond

- Calibration of interfacial cohesive zone
  - Mode I Sandwich SCB

Single Cantilever Beam Test

SCB Model Displacements

Load vs Displacement Data
**Damage Progression in Sandwich Composites: Analysis of Open-Hole Flexure Test**

- 90% load X-ray CT shows minimal damage progression
- NDBILIN overpredicting damage and under predicting failure load

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**Compression Strength Comparison**

- Notched
- FEM

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**DIC Strain**

**NDBILIN Damage Prediction**

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X-Ray CT

(Courtesy of Southwest Research Institute)
Out-of-plane displacements observed in DIC measurements
First mode facesheet buckling observed
Global buckling due to failure on non-DIC facesheet
Deformation caused by post failure eccentric loading
BENEFITS TO AVIATION

- Standardized test methods to assess facesheet/core disbond growth in sandwich composites
- Evaluation of current numerical capabilities for predicting notch sensitivity and damage tolerance of sandwich composites
- Standardized test methods to assess notch sensitivity in sandwich composites
- Standardized test methods to assess damage tolerance in sandwich composites
- Dissemination of research results through FAA technical reports and conference/journal publications
Questions?

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Thank you.